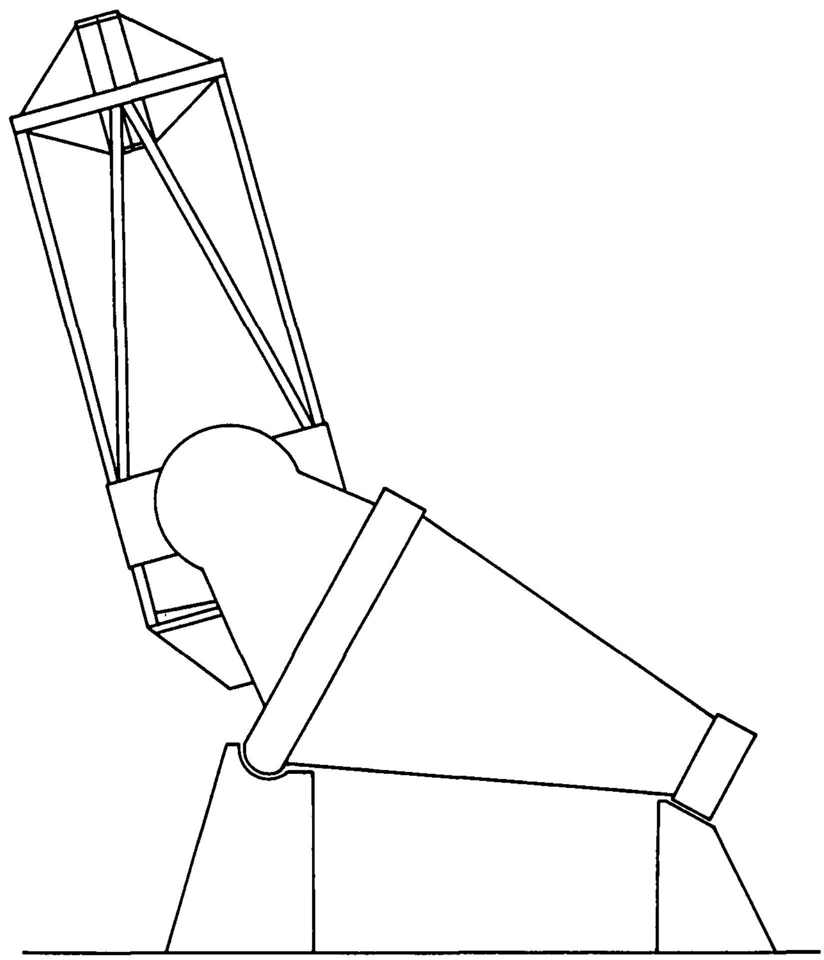
ESO/CERN CONFERENCE ON

LARGE TELESCOPE DESIGN

Geneva, March 1-5, 1971



PROCEEDINGS

Edited by :

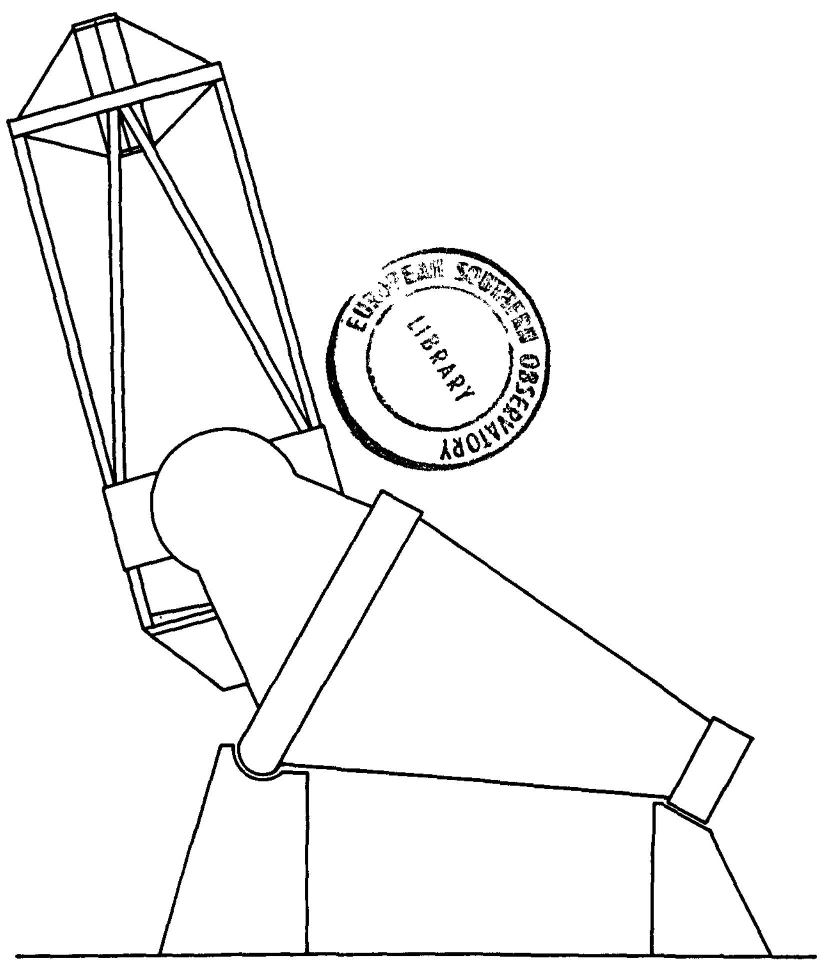
Richard M. WEST

June 1971

ESO/CERN CONFERENCE ON

LARGE TELESCOPE DESIGN

Geneva, March 1-5, 1971



PROCEEDINGS

Edited by :

Richard M. WEST

June 1971

Preface

Observational astronomy anno 1970 is characterized by the development, more or less simultaneously, of many large telescope projects. In the mid-fifties, European astronomers, soon afterwards to be organized more formally in the European Southern Observatory, took up the plan for a telescope comparable to the Lick 120", and eventually settled for one of 3.6 meters. AURA and Cerro Tololo Interamerican Observatory followed with projects of their 150" telescopes, and similar ones were undertaken by the Anglo-Australian Group, the Canadian Group, the Max-Planck Institute and the French National Group. Elsewhere projects of this size are under study. Soviet astronomers are nearing completion of their 6 m telescope.

Collaboration on the ESO Project between ESO and CERN, commenced on September 16, 1970, led these two organizations to convene representatives of all major telescope projects, as well as some astronomers of the largest observatories, in order to review these projects, their current status and the experiences gained. From March 1 to 6, 1971, 114 participants from 16 countries gathered at CERN, Geneva. 42, mostly review papers, were presented in 16 sessions in the CERN Council Room, most of them followed by lively discussion.

For the ESO Group at CERN, and we believe also for attendance from most of the other groups, the Conference has been a most instructive and stimulating experience. This volume presents the papers and principal parts of the discussions. Being aware of the short lifetime of the value of reports of this character, we have sought for a form of publication which allows quick production. That we have succeeded in realizing it we owe to the excellent collaboration of the participants and particularly to the persistent efforts of the editor, Dr. Richard M. West.

We gratefully acknowledge the collaboration of all those who have contributed to the effective proceedings of the Conference; a special word of thanks is due to Miss Yvonne Henry of the Conference Office of CERN.

A. Blaauw

Editor's note

This volume was prepared for publication with the principal aim of having it ready for distribution as soon as possible after the necessary amount of editing. Much time was gained by the use of offset techniques.

Most of the manuscripts were received during the conference. The discussions were tape-recorded and edited from the transcribed text. Since the authors have had no possibility to check the final version, the editor should be held responsible for inaccuracies and errors which might have crept in.

The publication of these proceedings would have been impossible without the competent and energetic collaboration of Mrs. Yvonne Smith (ESO TP Division, Geneva) and Miss Eva Rothstein (ESO, Hamburg), who did the painstaking typewriting, and the critical and efficient proof-reading of Dr. Else Görner (ESO, Hamburg). I extend to them my sincere thanks for their great help!

The support and advice of the Printing Department of CERN and of "Imprimerie du Courrier - Genève" is gratefully acknowledged.

European Southern Observatory,
Office of the Director
Hamburg, June 4, 1971

Richard M. West

LIST OF PARTICIPANTS

ALVENSLEBEN, A. von	Bundesministerium für Bildung und Wissenschaft, Postfach 9124, 5300 Bonn 9, Germany
BABCOCK, H.W.	Hale Observatories, 813 Santa Barbara Street, Pasadena, California 91106, USA
BAHNER, K.	Landessternwarte Heidelberg-Königstuhl, 69 Heidelberg, Germany
BARANNE, A.	Observatoire de Marseille, 2, Place le Verrier, Marseille 4, France
BARR, L.D.	Kitt Peak National Observatory, AURA, 950 North Cherry Avenue, P.O. Box 4130, Tucson, Arizona 85717, USA
BAUERSACHS, W.	ESO TP Division, c/o CERN, 1211 Genève 23, Switzerland
BAUSTIAN, W.W.	Kitt Peak National Observatory, AURA, 950 North Cherry Avenue, P.O. Box 4130, Tucson, Arizona 85717, USA
BAYLE, A.	REOSC, Chemin des Graviers, 91-Ballainvilliers, France
BEHR, A.	Hamburger Sternwarte, Gojenbergsweg 112, 205 Hamburg 80, Germany
BELLY, P.-Y.	INAG, Observatoire de Meudon, 92-Meudon, France
BERTIN, B.	INAG, Observatoire de Meudon, 92-Meudon, France
BERTOLA, F.	Università di Padova, Istituto di Astronomia, Vicolo dell'Osservatorio, 5, Padova, Italy
BICHARA, M.	CERN, 1211 Genève 23, Switzerland
BLAAUW, A.	ESO, Office of the Director, Bergedorfer Strasse 131, 205 Hamburg 80, Germany
BLICHFELDT, M.	ESO TP Division, c/o CERN, 1211 Genève 23, Switzerland
BLOEMKOLK, J.	ESO, Office of the Director, Bergedorfer Strasse 131, 205 Hamburg 80, Germany
BORGMAN, J.	Dept. of Space Research, University of Groningen, P.O. Box 800, Groningen, The Netherlands
BOURDET, Mme	INAG, Observatoire de Meudon, 92-Meudon, France
BROWN, D.S.	Grubb Parsons, Walkergate, Newcastle upon Tyne NE6 2YB, England
CAYREL, R.	INAG, Observatoire de Meudon, 92-Meudon, France

CHARVIN, P.	INAG, Observatoire de Meudon, 92-Meudon, France
CHIVENS, C.	Boller & Chivens, 916 Meridian Avenue, South Pasadena, California 910 30, USA
CLOP, R.	Observatoire de Marseille, 2, Place le Verrier, Marseille 4, France
CONNES, P.	Laboratoire Aimé Cotton du C.N.R.S. II, Campus d'Orsay, Bâtiment 505, 91-Orsay, France
COUTREZ, R.	Université Libre de Bruxelles, Institut d'Astronomie et d'Astrophysique, Avenue F.D. Roosevelt 50, B-1050 Bruxelles, Belgium
CRAWFORD, D.L.	Kitt Peak National Observatory, AURA, 950 North Cherry Avenue, P.O. Box 4130, Tucson, Arizona 85717, USA
CUISENIER, M.	Observatoire de Meudon; 92-Meudon, France
DELHAYE, J.	Observatoire de Paris, 61, Avenue de l'Observatoire, Paris XIV, France
DENNISON, E.W.	Hale Observatories, 813 Santa Barbara Street, Pasadena, California 91106, USA
DITTMAR, D.	The University of Texas at Austin, Department of Astronomy, Austin, Texas 78712, USA
DOSSIN, F.	Université de Liège, Institut d'Astrophysique, Avenue de Cointe, 5, B-4200 Cointe-Ougrée, Belgium
EGGMANN, E.	Dilworth, Secord, Meagher and Associates Ltd., 4195 Dundas Street West, Toronto 590, Ontario, Canada
ELSÄSSER, H.	Max-Planck-Institut für Astronomie, 69 Heidelberg-Königstuhl, Germany
ELVIUS, A.	Stockholms Observatorium, S-133 00 Saltsjöbaden, Sweden
ESPIARD, J.	REOSC, Chemin des Graviers, 91-Ballainvilliers, France
FARRELL, J.C.	Dilworth, Secord, Meagher and Associates Ltd., 4195 Dundas Street West, Toronto 590, Ontario, Canada
FEHRENBACH, Ch.	Observatoire de Marseille, 2, Place le Verrier, Marseille 4, France
FERN, D.	Freeman, Fox and Partners, Victoria Street 25, London, England
FLORENTIN NIELSEN, R.	Astronomical Observatory, Brorfelde pr. 4340, Tølløse, Denmark
FUNKE, G.	Natural Science Research Council, Wenner Gren Center, Box 23 136, S-104 35 Stockholm 23, Sweden
GARWIN, R.	IBM, Thomas J. Watson Research Center, P.O. Box 218, Yorktown Heights, New York 10598, USA
GASCOIGNE, S.C.B.	Mount Stromlo & Siding Spring Observatories, Private Bag, Curtin, P.O., A.C.T. 2605, Australia
GOLAY, M.	Observatoire de Genève, CH-1290 Sauverny, Switzerland

HACK, M.	Osservatorio Astronomico, Via G.B. Tiepolo n. 11, I 34131 Trieste, Italy
HAMPTON, G.H.	CERN Administration, 1211 Genève 23, Switzerland
HECKMANN, O.	Schmiedesberg 2b, 2057 Reinbek, Germany
HERATY, R.R.	Owens-Illinois Development Center, 1020 N. Westwood Ave., Toledo, Ohio 43607, USA
HERBIG, G.H.	University of California, Lick Observatory, Santa Cruz, California 95060, USA
HOLMBERG, E.	Uppsala Universitets Astronomiska Observatorium, Box 515, S-751 20 Uppsala 1, Sweden
HOOGHOUDT, B.G.	Ir. B.G. Hooghoudt, 10 Prinsenlaan, Oegstgeest, The Netherlands
JASCHEK, C.	Observatorio Astronómico, La Plata, Argentina
JENTSCHKE, W.K.	CERN, 1211 Genève 23, Switzerland
KÖHLER, H.	Carl Zeiss, 7082 Oberkochen, Postfach 35/36, Germany
KOPYLOV, I.M.	Spetsialnaja Astrofizicheskaja Observatorija, Ulitsa Bereznogo 167, St. Zhelenchukskaja, Stavropolskij Kraj, USSR
KÜHNE, Chr.	Carl Zeiss, 7082 Oberkochen, Postfach 35/36, Germany
KUIPER, B.	CERN PS Division, 1211 Genève 23, Switzerland
LALLEMAND, A.	Observatoire de Paris, 61, Avenue de l'Observatoire, Paris XIV, France
LARRETGERE, O.	Serete études, 164, Rue de Rivoli, 75 Paris 1, France
LARSSON, M.	Société des Engins MATRA, Avenue Louis Bréguet, 78 Vélizy, France
LAUSTSEN, S.	ESO TP Division, c/o CERN, 1211 Genève 23, Switzerland
LORENSEN, S.B.	University Observatory, 3, Øster Voldgade, DK 1350 Copenhagen K, Denmark
MACLEOD, G.R.	CERN DH Division, 1211 Genève 23, Switzerland
MALM, B.	ESO TP Division, c/o CERN, 1211 Genève 23, Switzerland
MAURICE, E.	ESO, Casilla 11P-Correo 9, Santiago de Chile, Chile
MERLINI, N.	Via Montebello, 80, 50123 Firenze, Italy
MONNET, G.	ESO TP Division, c/o CERN, 1211 Genève 23, Switzerland
MULLER, A.	ESO, Office of the Director, Bergedorfer Strasse 131, 205 Hamburg 80, Germany
MUNRO, I.	Grubb Parsons, Walkergate, Newcastle upon Tyne NE6 2YB, England
NEVEN, L.	Observatoire Royal de Belgique, 3, Avenue Circulaire, Bruxelles 18, Belgium

ODGERS, G.J.	Dominion Astrophysical Observatory, R.R.7, Victoria, B.C., Canada
OKE, J.B.	Hale Observatories, 813 Santa Barbara Street, Pasadena, California 91106, USA
OORT, J.H.	President Kennedylaan 169, Oegstgeest, The Netherlands
PEARSON, E.T.	Kitt Peak National Observatory, AURA, 950 North Cherry Avenue, P.O. Box 4130, Tucson, Arizona 85717, USA
PLATNER, D.	ESO TP Division, c/o CERN, 1211 Genève 23, Switzerland
POPE, J.D.	Anglo-Australian Telescope Project Office, c/- Department of Education and Science, P.O. Box 826, Canberra City, A.C.T. 2601, Australia
POUCHON, M.	Balzers AG, 9496 Balzers, Liechtenstein
POULEAU, J.	Société des Engins MATRA, Avenue Louis Bréguet, 78 Vélizy, France
PRICE, J.B.S.	Grubb Parsons, Walkergate, Newcastle upon Tyne NE6 2YB, England
RAMBERG, J.M.	ESO, Office of the Director, Bergedorfer Strasse 131, 205 Hamburg 80, Germany
RANDALL, L.K.	Kitt Peak National Observatory, AURA, 950 North Cherry Avenue, P.O. Box 4130, Tucson, Arizona 85717, USA
RAVAUT, M.	INAG, Observatoire de Meudon, 92-Meudon, France
REDDISH, V.C.	Royal Observatory, Edinburgh 9, England
REDMAN, R.O.	University of Cambridge, The Observatories, Madingley Road, Cambridge CB 3 OHA, England
REIZ, A.	University Observatory, 3, Øster Voldgade, DK-1264 Copenhagen K, Denmark
RICHARDSON, E.H.	Dominion Astrophysical Observatory, R.R.7, Victoria, B.C., Canada
RICHTER, W.	ESO TP Division, c/o CERN, 1211 Genève 23, Switzerland
RICKARD, J.	ESO, Casilla 11P-Correo 9, Santiago de Chile, Chile
RIGHINI, G.	Osservatorio Astrofisico di Arcetri, Largo Enrico Fermi, 5, Firenze, Italy
ROOSEVELD VAN DER VEN, J.F.	ESO TP Division, c/o CERN, 1211 Genève 23, Switzerland
ROSINO, L.	Università di Padova, Istituto di Astronomia, Vicolo dell'Osservatorio, 5, Padova, Italy
RULE, B.H.	Hale Observatories, 813 Santa Barbara Street, Pasadena, California 91106, USA
SCHARNWEBER, P.	ESO TP Division, c/o CERN, 1211 Genève 23, Switzerland

SCHNELL, W.	CERN ISR Division, 1211 Genève 23, Switzerland
SCHWERER, A.	INAG, Observatoire de Meudon, 92-Meudon, France
SCHWESINGER, G.	Carl Zeiss, 7082 Oberkochen, Postfach 35/36, Germany
SECORD, Ll.C.	Dilworth, Secord, Meagher and Associates Ltd., 4195 Dundas Street West, Toronto 590, Ontario, Canada
SHAW, E.N.	CERN Public Information Office, 1211 Genève 23, Switzerland
SISSON, G.M.	C.A. Parsons & Co. Ltd., Heaton Works, Newcastle upon Tyne NE6 2YL, England
SOLF, J.	Max-Planck Institut für Astronomie, 69 Heidelberg-Königstuhl, Germany
STRÖMGREN, B.	University Observatory, 3 Øster Voldgade, DK 1350 Copenhagen K, Denmark
SWINGS, P.	Université de Liège, Institut d'Astrophysique, Avenue de Cointe, 5, B-4200 Cointe-Ougrée, Belgium
TEXEREAU, J.	Observatoire de Paris, 61, Avenue de l'Observatoire, Paris XIV, France
TINBERGEN, J.	Kapteyn Sterrewacht, Roden/Drente, The Netherlands
VAUGHAN JR., A.H.	Hale Observatories, 813 Santa Barbara Street, Pasadena, California 91106, USA
VELGHE, A.G.	Observatoire Royal de Belgique, 3, Avenue Circulaire, Bruxelles 18, Belgium
VRIES, M. de	Kapteyn Sterrewacht, Roden/Drente, The Netherlands
WALLENQUIST, A.	Norrlandsgatan 34D, S-752 29 Uppsala, Sweden
WEST, R.M.	ESO, Office of the Director, Bergedorfer Strasse 131, 205 Hamburg 80, Germany
WESTERLUND, B.E.	ESO, Casilla 11P-Correo 9, Santiago de Chile, Chile
WILSON, R.N.	Carl Zeiss, 7082 Oberkochen, Postfach 35/36, Germany
WISKOTT, D.	CERN DD Division, 1211 Genève 23, Switzerland
WLERICK, G.	Observatoire de Paris, Section d'Astrophysique, 92-Meudon, France
WYNNE, C.G.	Imperial College of Science and Technology, Applied Optics Section, Department of Physics, Prince Consort Road, London SW7, England
ZILVERSCHOON, C.J.	CERN PS Division, 1211 Genève 23, Switzerland

PROGRAMME OF MEETINGS

CONTENTS

MONDAY, MARCH 1

AFTERNOON SESSIONS

Chairman: B. Strömgren

Opening Words by the Director General of ESO

A. Blaauw

Ladies and Gentlemen:

I have the pleasure of welcoming you to this conference on behalf of the European Southern Observatory and the European Organization for Nuclear Research, ESO and CERN. We are gratified to see that so many of those whom we have invited from all over the world have found it possible to join us this week. We have in our audience astronomers, engineers and other representatives of, I believe, all the large telescope projects now being undertaken. I mention, in alphabetical order, the Anglo-Australian project, the project of AURA, the Canadian project, the Las Campanas project initiated by the Carnegie Institution, the French national project INAG, the German project planned by the Max-Planck Institut für Astronomie, the Italian national project, the Soviet 6 meter project, and, of course, that of ESO. We also enjoy the company of some experts from private firms engaged in telescope projects, and hope to profit from their advice. For us, from CERN and ESO, it is a particular pleasure to have with us also some of the members of our Councils and their advisory committees, whose deep interest in our project will be essential for its completion.

Some of the projects listed are well advanced, with their telescopes expected to be in operation in a few years; others are still in the initial stages. We clearly witness nowadays a very important development in astronomical instrumentation. Within 10 years an array of telescopes with apertures between 3 and 4 meters and only two larger ones will be in operation, from which an enormous flow of observational data is to be expected, with strong impact on astronomical research. This will be particularly felt for southern hemisphere astronomy, which so far had no instruments larger than the 74 inch of the Radcliffe Observatory in Pretoria. Yet, in the southern sky some of the most fascinating objects for astronomical research can be observed. I mention the Magellanic Clouds; the central regions of our stellar system, the Galaxy; its southern spiral structure; studies of southern extragalactic stellar systems - nearby systems and those at cosmological distances, etc.

This is not the first large conference on the design of major telescopes. In April 1965 a symposium under the auspices of the International Astronomical Union was devoted to this subject in the United States. In December 1966, a symposium was held at Tucson, Arizona on Support and Testing of Large Astronomical Mirrors. Five years have elapsed since then and a new review of the programmes and problems appears to be in order.

This time we meet on the grounds of the European Organization for Nuclear Research. It is on these grounds that the European Southern Observatory established about half a year ago its Division for the design of the large telescope and for the development of the initial auxiliary instrumentation. This environment will certainly be somewhat strange to astronomers who are used to developing their instrumentation at astronomical institutes. The Council and Directorate of the European Southern Observatory chose to seek the collaboration of CERN in the expectation that ESO might, in many respects, profit from instrumental developments within this establishment which contains such a large variety of technical facilities and expertise. We have already experienced in the course of these past months the stimulating influence of these surroundings and feel that therefore this place is a particularly suitable one for having our conference.

Our programme will cover different aspects of telescope design. After hearing about the present status of the various projects, we shall start out to review the optical properties of telescopes and then consider problems concerning the mountings. For the most advanced telescope projects the design can probably be little influenced any more by inspiration or by suggestions from these first technical sessions, but they should be of great interest to those projects still in the first stage of planning.

We next proceed to developments in telescope control and data handling; here I believe we are in the midst of rapid developments of great interest to any current telescope project. Towards the end of the conference, we hope to discuss the more unconventional items, and one of those I wish to bring to your attention is that of the telescope use for other than the regular night observations. Day-time use of large instruments is receiving increased attention in view of the development of infrared techniques. Naturally, we also have in mind that day-time use might double the effectiveness of the instruments we build. Another item of interest in this connection is the employment of the coudé apparatus by means of a secondary telescope during the time when the main telescope is in another mode of operation.

It goes without saying that apart from the presentation of the introductory papers and their subsequent discussion, one of the main motives for organizing this conference was to have an opportunity to bring together many of those who are now engaged in problems with which we at ESO and CERN are struggling. We sincerely hope that you will all profit as much as we anticipate to do from the formal and the informal discussions with our colleagues from the other projects, and that in this way this conference may contribute to future astronomical research on a world wide basis.

I wish you all a very profitable meeting.

Welcome by the Director General of CERN

W. Jentschke

It is a great honour for me to welcome you, who have come from all parts of the world, to this Conference on Large Telescope Design on behalf of the European Organization for Nuclear Research. I do this with great pleasure for several reasons.

Astronomy and Physics have always been intimately connected and it is essential for the progress of both fields to keep the closest ties. Recent developments in high-energy astrophysics stress this need even more. The discovery in both radio-astronomy and optical astronomy of the gigantic quasi-stellar objects and of other sources of high-frequency radiation point out the existence of phenomena dominated by high-energy physical processes. The reactions which are artificially created in our laboratories at the highest energies may play an important role in the understanding of these phenomena.

An extraordinary new common field of astrophysics, cosmology, general relativity and elementary particle physics has been found. Fascinating prospects of collaboration open up.

Therefore, we are all very pleased here at CERN that, as Professor Blaauw has mentioned, the Councils of ESO and CERN have agreed to a collaboration between the two Organizations in connection with the construction of the large 3.6 meter telescope destined to be erected at ESO's Observatory in Chile. Since the building of this instrument requires a considerable amount of new developments in the field of optics, in the field of mechanical design, electronics and automation, CERN is glad to help with its experience in some of these fields.

This co-operation is facilitated by the similarity of the organization of ESO and CERN. Both are joint enterprises of European scientists - aimed at conducting research at a level beyond that which can be reached by single scientific institutes.

It gives me great pleasure to state that this similarity goes even further. Several members of the Council of ESO, including its President, are also members of the Council of CERN!

Last but not least, I see in this gathering of scientists from all parts of the world the determined intention of the scientific community for a world wide co-operation. We also at CERN work in this same spirit.

All of us at CERN wish you a very pleasant stay in Geneva. We are here to help you and to discuss with you problems of common interest. We are convinced that this conference will be a success. The impressive number of large telescopes when installed will make it possible to explore the largest distances of our universe, likewise the new gigantic particle accelerators will shed new light on the infinitely small distances of our world.

REPORTS ON

TELESCOPE PROJECTS

PRESENT STATUS of the ANGLO-AUSTRALIAN TELESCOPE

H. Wehner
(Read by J.D. Pope)
AAT Project Office

In April 1967, agreement was reached between the British and Australian Governments to build a 150-inch optical telescope for observations of the southern sky. Two major stipulations were included in the agreement:

(1) That the design of the telescope should follow closely that for the telescopes being designed at the time for the Kitt Peak National Observatory and the Cerro Tololo Interamerican Observatory. We are very grateful for the help we have received from the staff of the two observatories; it permitted us to save an appreciable amount of time and cost.

(2) That the telescope should be established at Siding Spring mountain near Coonabarabran, New South Wales, where the Australian National University had already a number of smaller telescopes in operation. The ANU selected this site for the establishing of an observatory (initially the field station of the Mount Stromlo Observatory) after an extensive survey of numerous sites throughout Australia (south of -30° latitude).

Until recently the Project was directed by a Joint Policy Committee consisting of three British and three Australian members. This committee has now been changed into the Anglo-Australian Telescope Board. The Board will later be responsible for the running of the completed facility.

The engineering and contractual aspects of the Project are executed by the staff of the Project Office, located in Canberra, under the direction of a Project Manager. Consultants are called in as required.

Contractually the Project is divided into several sections:

1. Mounting
2. Optics and tube
3. Drive and control

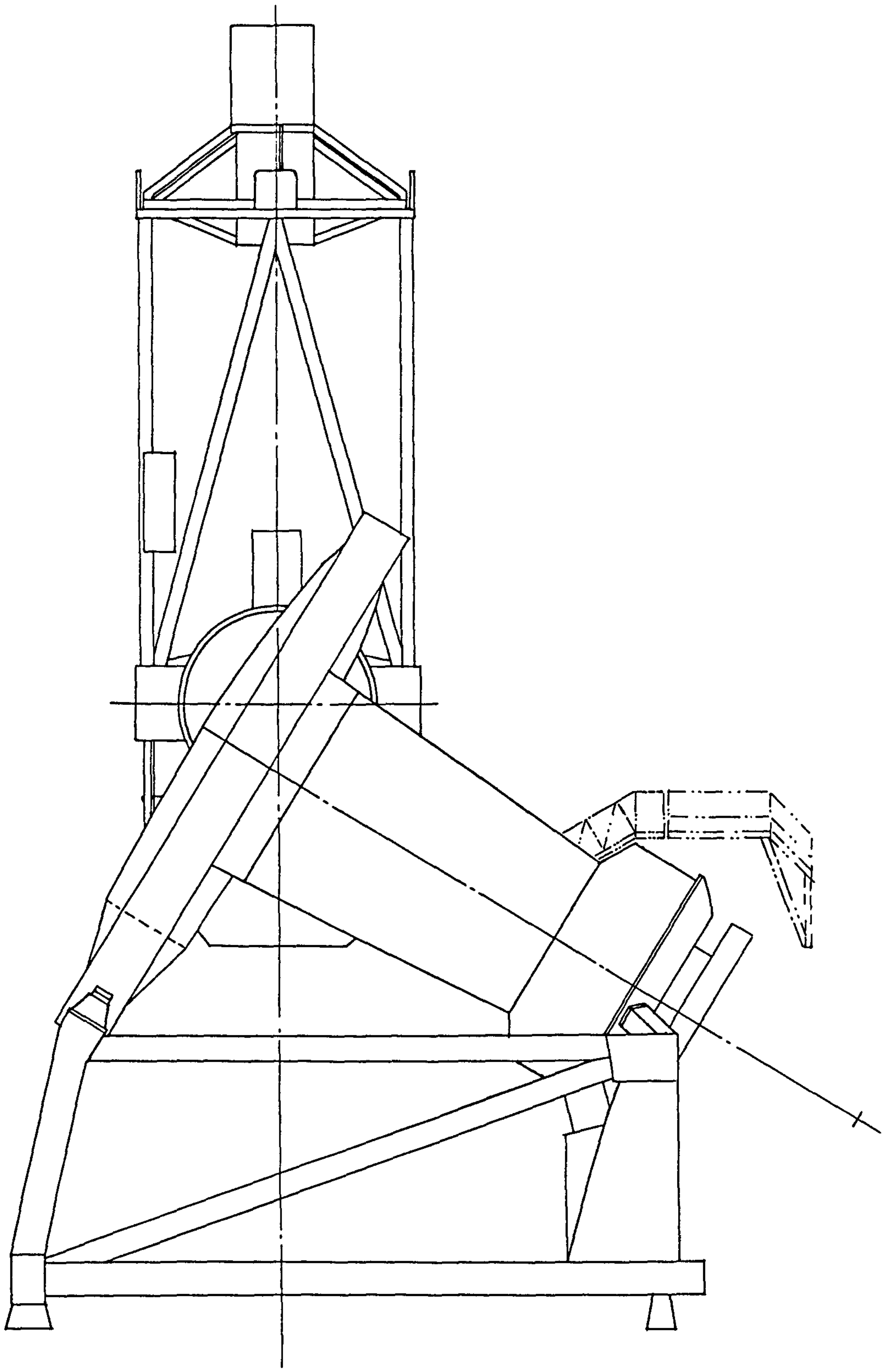


Fig. 1 Anglo-Australian 150-inch telescope.

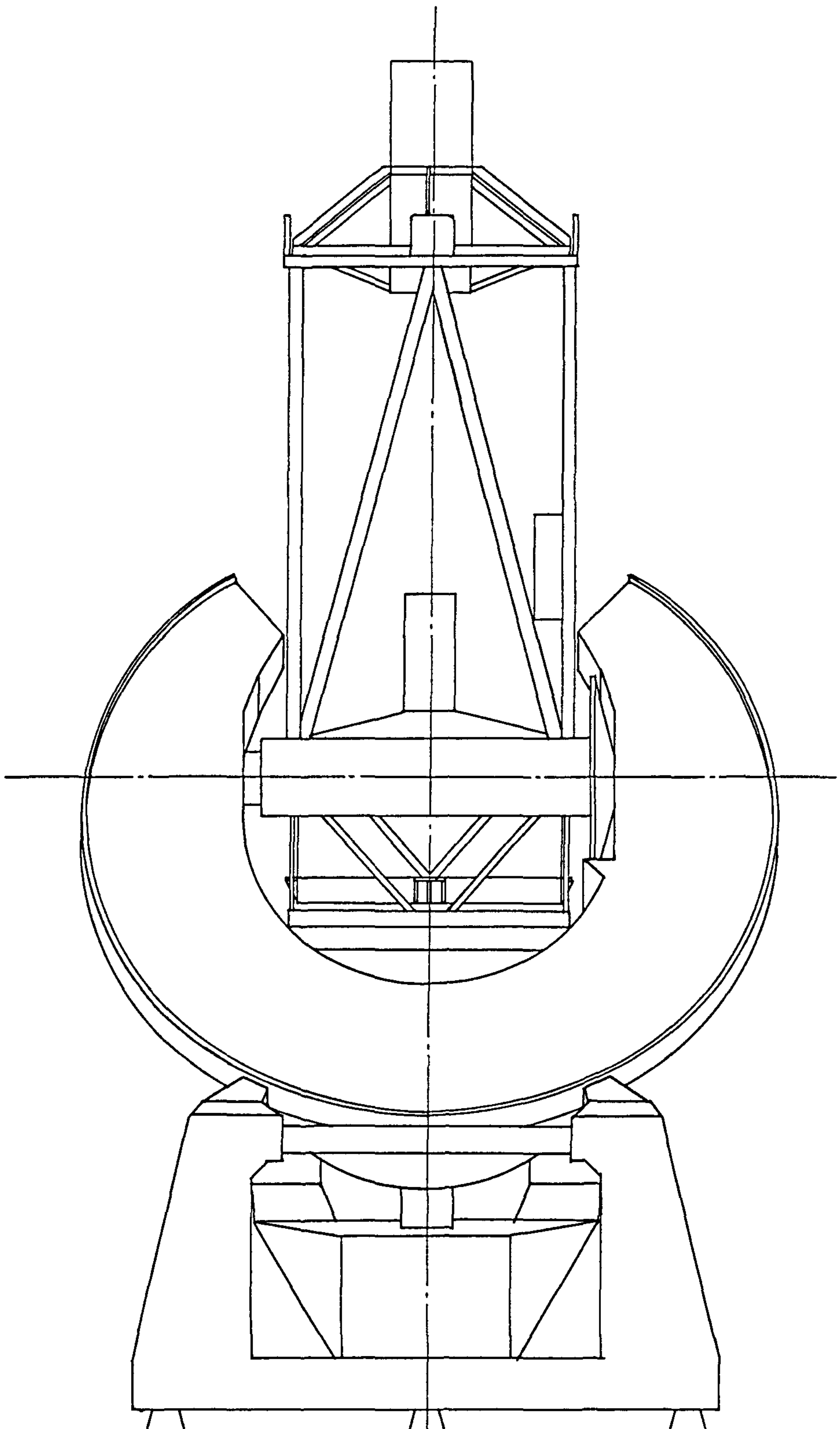


Fig. 2 Anglo-Australian 150-inch telescope.

4. Control computer and data interface
5. Instrumentation, acquisition and guiding units
6. Auxiliary equipment (i.e. aluminizing plant)
7. Building, dome and site.

Of these items 5. to 7. are made up of several contracts:

(1) The telescope is equatorially mounted. The polar axis structure comprises the horseshoe south bearing, two connecting struts and the north journal structure. These items are steel weldments, the horseshoe being assembled from three parts. (Fig. 1, 2)

The south bearing is cylindrical with a radius of the running face of 6.10 meters, whilst the north bearing is a 0.76 meter wide zone of a sphere of 3.07 meter radius, where the center of the sphere is 6.41 meters distant from the south bearing center.

The polar axis structure turns on five oil pad bearings, two for the south bearing and three for the north bearing. These bearings are in turn supported by a base frame structure which rests on the telescope support pier. Provision has been made for a damping drive.

The declination axis of the telescope lies within the central plane of the horseshoe, but it is offset from the centerline of the polar axis by 1.07 meters upwards. This results in a near uniform cross-section of the horseshoe structure below the declination axis and improved natural balance. This offset effects, of course, the routing of the coudé light beam between mirrors 4 and 5 but with the strut design adopted it is easily contained within the structure.

The declination axis bearings are housed inside the arms of the horesehoe but as close as possible to the tube center-section. The bearings have been designed such that radial and axial loads are supported by independent bearings. The radial bearing is a single cylindrical roller bearing mounted in a flexible diaphragm which will deflect under axial loads. The axial bearing is a multiple cylindrical roller thrust bearing. In order to maintain uniform load distribution on the thrust bearing under conditions of differential deflection between tube center-section and horseshoe the bearing is mounted on an annular hydraulic thrust pad.

The tube center-section is a steel weldment which, with an approximate weight of 42.000kilograms, is the heaviest single part of the telescope.

Smaller items, if this term can be applied to any part of the telescope, include motorised counterweights for the three axes of balance adjustment, the primary mirror dust cover and iris assembly, the main gearwheels and electrical cable wrap assemblies for both polar and declination axis as well as the Cassegrain observer's cage, access walkways, ladders and the oil hydraulic supply.

The manufacture and erection of all items under this heading form the mounting contract. This contract has recently been placed.

(2) The telescope will have four possible optical arrangements:(Fig.3)

(a) prime focus f/3.3
(b) Cassegrain focus f/8
(c) Cassegrain focus f/15
(d) Coudé focus f/36

The optical parameters are given in the table(Fig.4).

The primary mirror and the f/8 Cassegrain secondary will be a Ritchey-Chrétien pair which assures a wide corrected field and also facilitates the design of prime focus correctors where a highly corrected field up to 1 degree diameter will be available.

All mirror blanks are made from Cervit. The primary mirror of 3.9 meter diameter is supported axially by 33 air pads and 3 defining pads each having an effective support area of about 670 square centimeters. The radial support is achieved by 24 mechanical (lever) support units acting on pads cemented to the circumference of the mirror. The secondary and coudé flat mirrors have a vacuum axial and a mercury band radial support system which includes three axial defining points, the axial position of which can be varied remotely for collimating purposes.

The tube is designed following Serrurier's principle with upper and lower Serrurier trusses connected to each other and to the tube center-section at the upper face of the center-section. Deflection considerations prohibited the convenient solution to mount all secondary mirrors and the prime focus observing facility in one unit at the top of the tube. Instead three tube top-end assemblies will be provided:

(a) prime focus instrument and corrector mounting and prime focus observer's cage,

(b) f/8 secondary,

(c) f/15 and f/36 secondaries in a flip-flop mounting.

The top-end assemblies will be interchanged by overhead crane using a lifting frame attached to a 7 ton hoist permitting semi-automatic operation.

In order to reduce the complexity of the secondary mirror and prime focus instrument mountings the focusing drive system is common to all top-end assemblies and is mounted on the top ring of the upper

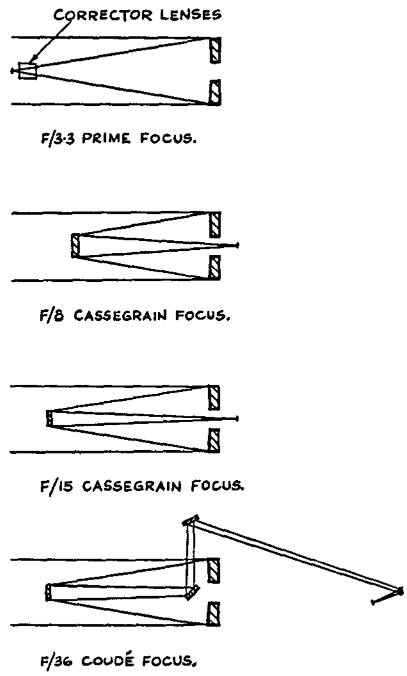


Fig. 3 Optical configurations of Anglo-Australian 150-inch telescope.

F/ RATIO	EFFECTIVE FOCAL LENGTH (METRES)	SCALE.			FIELD DIA.	
		PER MM.	PER. 1'.	PER. 1''.	MINS.	MM.
3·3	12·700	16·2''	3·7 MM	62μ	60	220
8	31·115	6·7''	9·0 MM	150μ	39	355
15	58·166	3·5''	17·0 MM	283μ	15	249
36	140·720	1·5''	41·0 MM	684μ	5	200

Fig. 4

Serrurier trusses. The top-end assemblies are located on and clamped to four linked focusing slide assemblies.

The use of Cervit optics greatly increases the stability of the optical configuration during temperature changes. It is therefore possible to attribute any axial changes in the separation of optical components, and hence focus, to structural causes. In order to eliminate or at least greatly reduce these focus changes during observations, a Cervit rod is provided which spans the distance from the primary to the Serrurier truss top ring where a position sensing transducer determines the error in optical separation and drives the focus control to the optimum position.

Together with the necessary sky baffles and dust covers, the mirror support system air controllers and other smaller items, the optics and tube structure form a contract which was let about one year ago. To date the primary mirror is ready for polishing, the secondary mirrors are ready for figuring and good progress has been made in the manufacture of the tube structure, primary mirror cell and support system.

(3) Two design studies were carried out elsewhere for the Project; one to investigate the relative merits of a worm gear drive, a friction drive and a spur gear drive, and the other to design in detail the chosen drive system.

The telescope's hour angle and declination axes are to be driven by trains of spur gears with identical ratios. The final gearwheel will be 3.66 meter diameter and will have 600 teeth which will be ground as accurately as possible. Each axis will be driven by two motors and two gear trains which will be independent of each other except for a spring-loaded idler pinion which will mesh with both trains to provide a preload which will eliminate backlash from the final meshes.

A torque-limiting clutch will be included in each drive train to avoid gear damage in the event of seismic shocks or accidental collisions.

Independent gearboxes with drive pinions meshing also with the 3.66 meter diameter drive wheels will be provided on each axis to drive encoders and synchros. A 15-bit fine absolute encoder will be geared up from the axis by 1:40 making each bit approximately equal to 1 arc sec. A 5-bit coarse absolute encoder will be geared down by 32:1 from the fine encoder thus providing a total unambiguous range of 288° for each axis.

A 48.000 count per turn incremental encoder will be geared up by 1:13.5 from the fine absolute encoder thus having a ratio of 540:1 relative to the telescope axis, i.e., each count represents exactly

0.05 arc seconds at the telescope axis.

A rate generator will be used to produce drive signals in the form of a train of pulses whose pulse repetition frequency determines the drive rate for the appropriate telescope axis. This rate generator will consist basically of a decimal rate multiplier and will have the capability of direct control by the computer or of being controlled manually to produce a composite output determined by the required track, set, guide and trail demands.

It is intended that systematic errors due to refraction, gearing (lower frequency), structural alignment and structural flexure will be corrected by the computer which will control the output of the rate generator in such a way as to overcome these errors. The residual random and higher frequency errors will be dealt with by the auto-guider to the limit of its capability.

(4) A computer system will form an integral part of the AAT.

One basic purpose for incorporating a computer is to facilitate the control of the telescope, a second is the control of astronomical observations and the real-time processing of the data.

After being specified by the Project Office, a design study of the computer system was carried out elsewhere.

The principal uses for the computer can be summarized as follows:

(a) To improve the setting and tracking accuracy of the telescope by calculating and inserting corrections for systematic errors such as:

(i) gear errors
(ii) structure flexure errors
(iii) servo control errors

(b) To control the rates of slewing and setting so that the least time is wasted in carrying out these operations.

(c) To control the dome and windscreen positions.

(d) To interface with and control auto-guider units which will include devices for offsetting, rotation of instrument mount, focusing etc.

(e) To calculate apparent star positions by making corrections to given coordinates for epoch, precession, nutation, aberration, proper motion and refraction.

(f) To read and convert the encoders which provide information on the telescope and dome positions and to display the output on control desk indicators.

(g) To control and read the status of equipment associated with the starting-up, running and closing-down of the telescope and of any other equipment which should be monitored.

(h) To assist in engineering maintenance by monitoring pressures, temperatures, supply voltages, etc. and by controlling system engineering tests.

(i) To maintain a record of operating sequences for use by astronomers and engineers.

(j) To monitor meteorological instruments and initiate any operations required by the conditions monitored.

(k) To control and read the status of astronomical instruments.

(l) To accept data from astronomical instruments and provide some real-time data processing capacity so that decisions can be made automatically or manually relating to the observing programme, e.g., whether a particular observation should be continued or not.

(m) To activate a display system to give basic telescope and astronomical observing instrument status, performance and output information.

(n) To provide programming and ordinary data processing facilities at times when the telescope is not being computer-controlled.

(5) The Project will provide the telescope with basic instrumentation. The items included in this plan are to be designed and built under individual contracts by the Royal Greenwich Observatory, the Mount Stromlo Observatory or other manufacturers. None of these items have progressed beyond the design stage.

(a) Photographic equipment for both Cassegrain and prime focus is being developed by the Project Office.

(b) An intermediate-dispersion spectrograph for use at the Cassegrain focus is being developed at the RGO.

(c) A fast Cassegrain spectrograph has been specified by MSO but will be built elsewhere.

(d) Single and two-channel photometers will be built at MSO. The design for these has been started whilst the optical design for a single-channel scanner is under consideration.

(e) The Project will provide a 15 centimeter beam diameter coudé spectrograph. The optical specifications for this instrument are essentially complete, although detailed design has not yet begun.

(f) The prime focus photographic equipment mounting will include a simple offset guide facility. This is being designed at the Project Office for manufacture elsewhere.

(g) Much progress has been made with the design both optical/ mechanical and electrical of the Cassegrain acquisition and two-probe autoguiding units. Specifications for the unit will be produced shortly for detailed design and manufacture elsewhere.

(6) No contracts have been placed as yet for items of auxiliary equipment. Included under this heading are aluminising plants (where a large plant, a small plant with a capacity of up to 60 inch diameter mirrors and a small plant for overcoating are proposed); handling equipment for items of telescope optics and instrumentation; special handling tackle and trolleys; workshop machinery; room furniture and items of similar nature.

(7) The telescope is to be housed in a concrete building topped by a rotating steel dome. The elevation of the telescope declination axis is 29.5 meters above the ground level. The nominal dome diameter is 36.5 meters.

The telescope rests on a concrete slab which is supported from the rock foundation by a circular pier. This slab also supports the four coudé spectrograph frames. The surrounding building contains seven floors of which the upper three house the telescope control equipment, darkrooms, spectrograph rooms, etc. The lower floors contain auxiliary facilities, offices, library, loading bay, etc.

The dome has an up-and-over shutter and double windscreens which form a slit aperture through which the telescope observes. The slit width is 5.5 meters.

The contract for the construction of the building was let late last year. This contract contains sub-contracts for dome, electrical services, air conditioning and ventilating services and lifts. To date concrete work for the first 6 meters of building is complete.

Site services are complete. In conjunction with the Australian National University previously existing services were expanded to cater for the increased demand for electricity, water, telephone, etc.

A utilities building has been erected which houses the main mechanical workshops, building air conditioning machinery and site electrical services including a 400 KVA diesel-driven standby generator. A visitors' building has been completed. It will house a descriptive display which visitors can view on their way to and from the telescope viewing gallery.

Acknowledgment

The writer wishes to thank the Anglo-Australian Telescope Board for permission to publish this paper.

DISCUSSION

FEHRENBACH: What is the reason for the choice of f/15 Cassegrain focus?

POPE: I think there was a desire to provide a suitable f-ratio for photometers and also to enable the use of instruments which have been designed for existing telescopes with that f-ratio.

FEHRENBACH: Very cheap instruments!

POPE: Yes.

FEHRENBACH: You will have coma in that way.

POPE: But it is only intended for use with on-axis instruments.

HERBIG: What was the coudé beam diameter?

POPE: 15 centimeters. Only 6 inches.

HERBIG: Why that particular choice?

POPE: Well, we are starting off with a simple and inexpensive system. There are provisions for up to a 24 inch collimated beam at a later date. We shall build the whole of the coudé spectrograph facility in stages, and stage one is only for a 6 inch beam.

BORGMAN: Does the Anglo-Australian project include a primary or a Cassegrain cage?

POPE: Yes, the prime focus upper end does include an observer's cage, but we are still in the process of designing this. As for the Cassegrain cage, the design for this is even more uncertain and we are apprehensive about methods of access to the Cassegrain cage. There is a desire for astronomers to be able to enter and leave the cage at all positions of the telescope, and we are finding this a very hard condition to satisfy. But we are planning for a Cassegrain cage.

FEHRENBACH: How long does it take to change from one type of focus to another?

POPE: It takes 30 minutes to remove one upper end and substitute another.

FEHRENBACH: Is it foreseen to do this during the night?

POPE: Yes.

DITTMAR: What do you mean by the"semi-automatic" nature of your cage changes? Could you go into that a little bit more?

POPE: It means that all the positions of the hoist, the length of traverse, the rotation of the dome, the height of the hook, all are pre-programmed and are controlled by means of microswitches. So that it shouldbe, in principle, possible just to press an initiating button and - apart from actually hooking on to the upper ends - the hoist should do the interchanging by itself. The clamping system on the end of the telescope is motorized and it has all appropriate interlocks.

FEHRENBACH: Have you place to store the top ends?

POPE: We have three top ends and we have provision in the building for the storage of this.

FEHRENBACH: And the optical adjustment should be good?

POPE: We sincerely hope so.

FEHRENBACH: Don't you need some adjustment?

POPE: We are planning for the upper end to go into position and for observing to start straight away. Whether we shall achieve this, only time will tell.

ROOSEVELD VAN DER VEN: You had a commission to study friction drive, worm drive and gear drive. What was the reason you accepted the gear drive, and are there any experiences with that type of drive?

POPE: I know that one reason is that the designers were concerned about the overrun of the telescope due to its inertia damaging the worm gear.

DENNISON: Would you describe again the encoder system?

POPE: There is an absolute coarse and fine encoder, and an incremental encoder.

BORGMAN: When you mentioned the parameters that you would take into account in the computer control of the drive, I understood that you would take into account flexure and refraction, but you did not mention the orbital aberration of the earth which may come up to 20". Is this indicative of the accuracy that you expect for the apparent pointing of the telescope?

POPE: I don't know if there is any provision for this at all. You will have to ask the astronomers in our team. But we are aiming at a final pointing accuracy of 10".

LAUSTSEN: To what extent will you be able to run the telescope without the computer?

POPE: I expect it will not have the corrections for flexure. The pointing error will be worse and so on, but we do intend to be able to run the telescope completely, should there be a failure of the computer.

ZILVERSCHOON: I understand that you placed the contract of the sub-structure of the big bearings in Japan. Was this a purely economical choice or was it difficult to get good tenders altogether?

POPE: We went to Japan purely for economic reasons. The technical ability is available in many other countries, but not surprisingly we had our lowest bid from Japan.

BAHNER: What is the time schedule for the completion of the instrument?

POPE: We are hoping that the telescope will start to become operational in 1974.

HECKMANN: What is the altitude of the mountain and the height of the crossing point of the telescope axes above the ground?

POPE: The altitude is about 4000 feet (1300 m), and the height above the ground is about 30 meters.

AURA'S TWO 150-INCH TELESCOPES
Status Report*

D. L. Crawford

Kitt Peak National Observatory**

As most of you are aware, our project is now nearly ten years old, and it is, therefore, a bit hard to summarize our history or status in a short time. I would like to describe a bit of the original philosophy, however, for it set many of the goals of our project. We wanted to design and build a large telescope to work on limit problems of research, for the amount of funds we felt could be obtained, and to do so as rapidly as possible without paying the cost premiums of a "crash" program. Therefore, we adopted many of the design concepts of the 200-inch and 120-inch telescopes. We were most fortunate to have had the sincere and detailed advice and encouragement of the staffs of the Hale and Lick Observatories, and we are most indebted to them for the secure beginnings of our program and their further advice throughout it. Individuals from other observatories were of great help as well, but I would like to single out Dr. Ira Bowen and Mr. Bruce Rule for their continual advice and encouragement to us.

We did really new conceptual design work only where we felt it necessary, based on the experience of ourselves and others, and in areas where obvious advances in the state-of-the-art so indicated: specifically, the material of the optical blanks, the geometrical optical design, the drive and control system, and the versatility of the upper end of the telescope (though the 200-inch led the way) based on our experience with the 84-inch telescope. We also put (and still do put) major emphasis on the Cassegrain rather than the prime focus observing position.

The size of 150-inch was chosen as being large enough to allow research at the limit (compete with the 200-inch) and to have an adequately large prime focus observing cage, yet small enough to be designed and built for about ten million dollars. As it turned out, the mirror blank came out at 158-inches, or 4.0 meters. We had chosen f/2.8 as the prime focal ratio, and we held the focal length constant, so now we have about an f/2.6 system.

----

* Presented, in somewhat modified form, at this conference and at the Optical Society of America meeting in Tucson, April 5-8.

** Operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

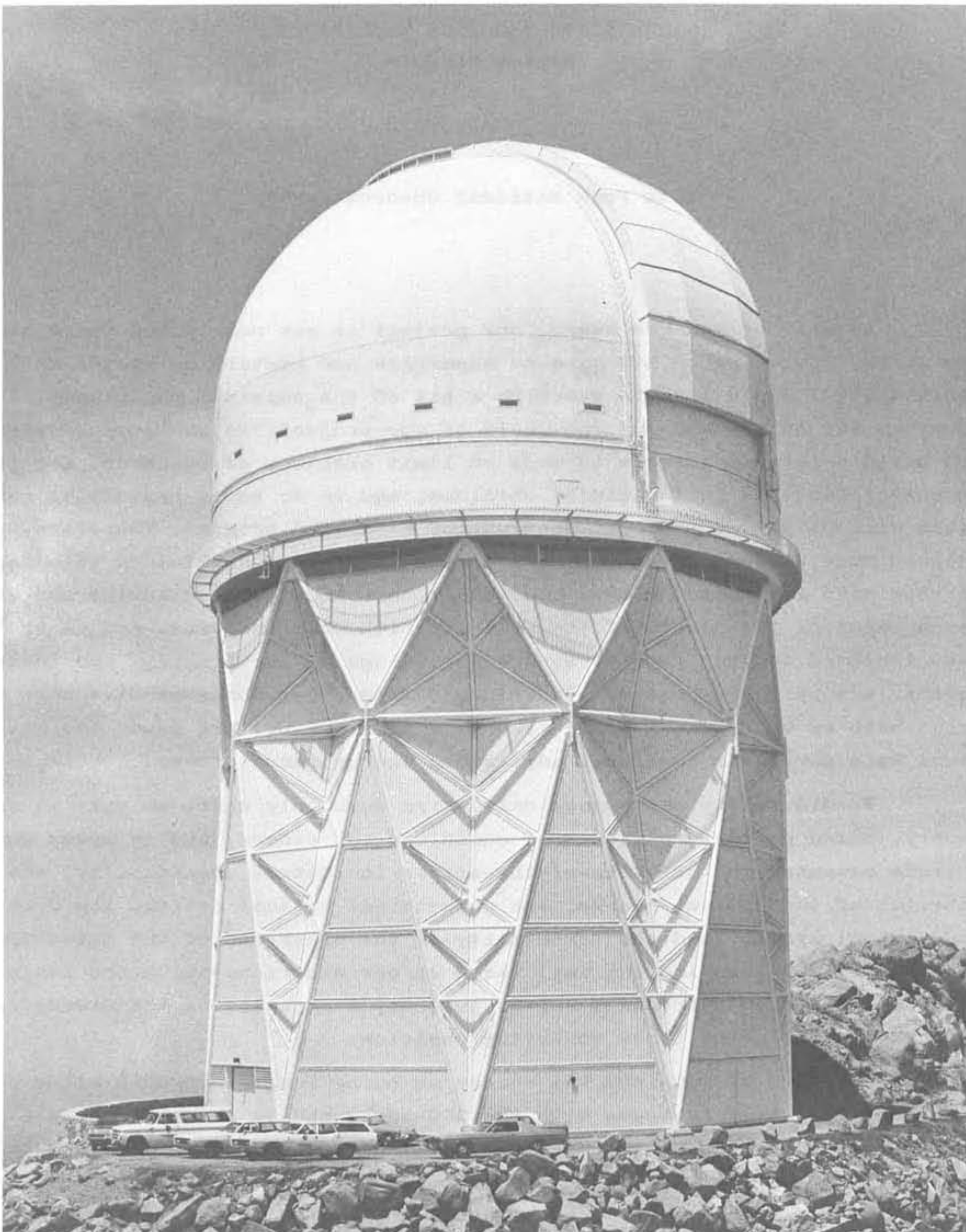


Fig. 1 The completed building and dome on Kitt Peak. The structure is about 100 feet in diameter and 180 feet high.

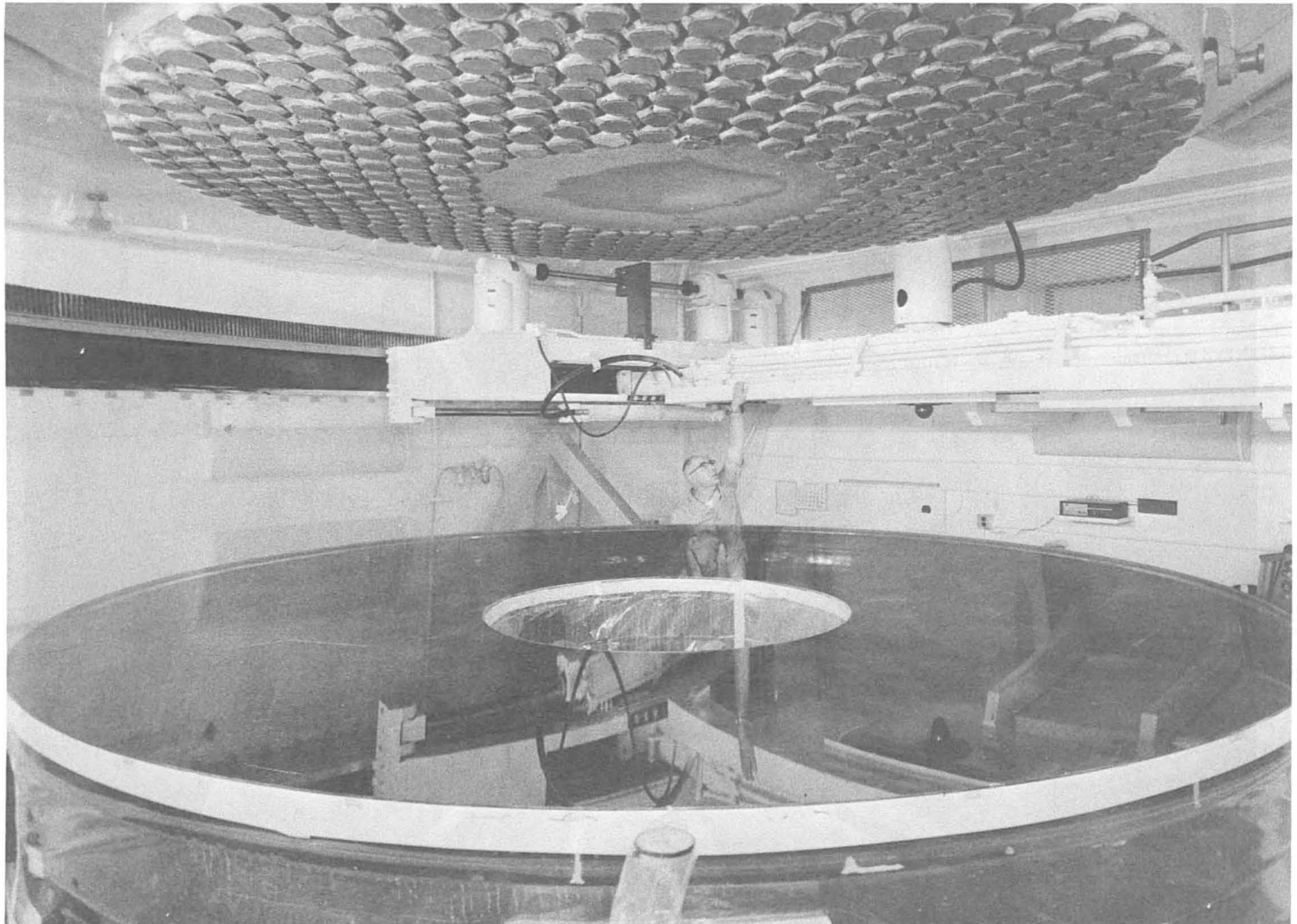


Fig. 2 The fused quartz mirror blank on the grinding machine. Above it can be seen the "full sized" grinding tool used in the early stages in the grinding and polishing cperation.

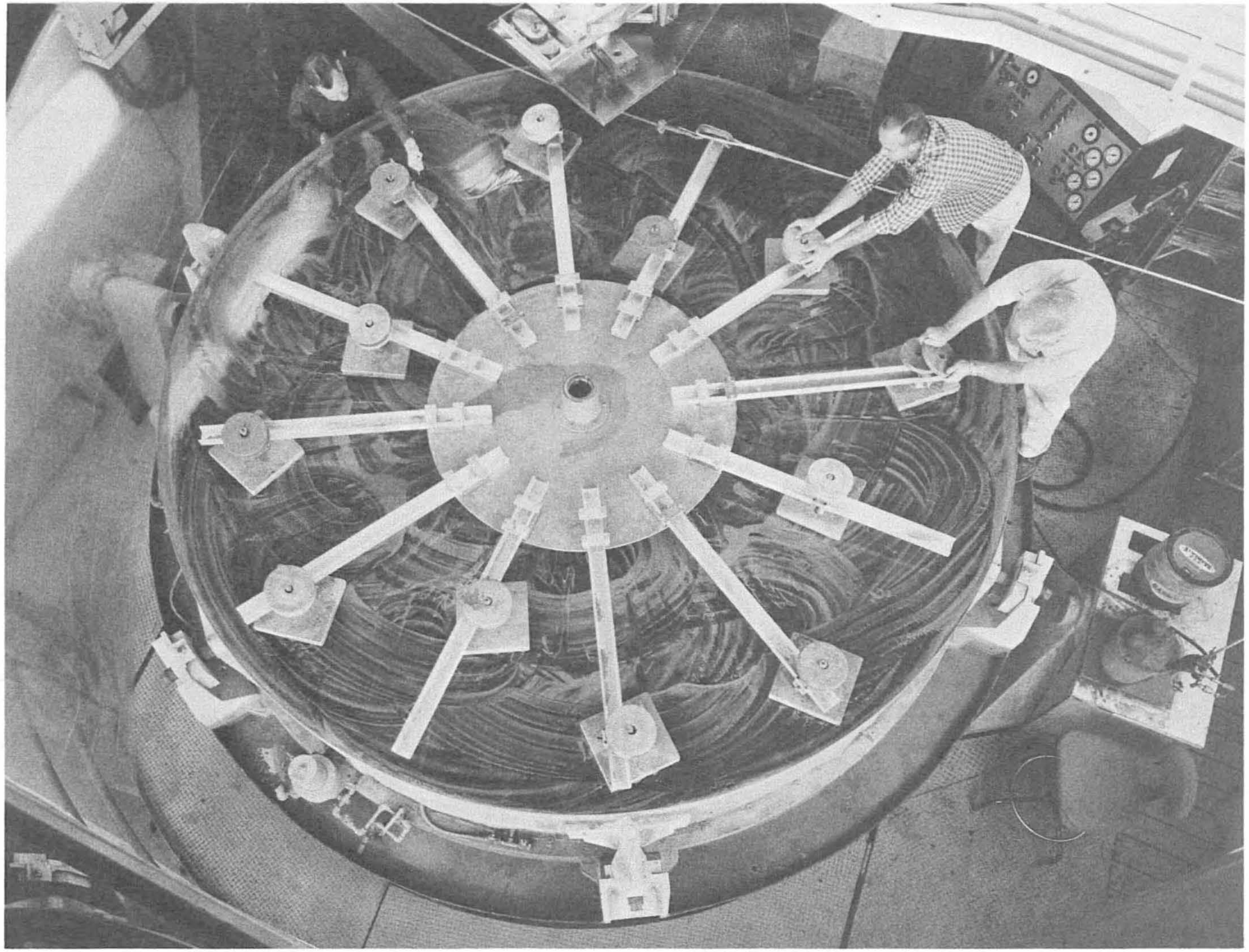


Fig. 3 The large mirror blank being ground with multiple tools. Such a system was used to grind in the aspheric curve.

We also chose a Cassegrain ratio of f/8 as a convenient ratio for photometry and spectroscopy and for limit-type direct photography. We adopted a Ritchey-Chrêtien optical system for the Cassegrain as offering a wide field with no correcting lenses, and with that type primary surface prime focus correctors are a bit easier to design than with a parabola. The coudé system is f/30 with five mirrors and the final optical beam in a horizontal plane.

As you can see, many phases of the original concept were compromises, but we feel offer much versatility without compromising efficiency. I still believe, or maybe hope, that we have made the right choices.

We had one great advantage also, when in 1967 the Ford Foundation offered $5,000,000 if the National Science Foundation would match it to enable us to build a nearly identical telescope in Chile. Though we were nearing the final detailed design of the telescope and associated facilities, we were able to incorporate the second telescope into the program and managed to bid the fabrications together late in 1967. We were thus able to save money and time on the Chile program. I feel we gained a lot of efficiency by doing the two together, and I hope we have justified our sponsors' faith in us.

Additional details of our past status, etc., are given in Kitt Peak Contributions 92 (The Kitt Peak 150-inch Telescope), 98 (Problems of Constructing Large Telescopes), 294 (Optical Astronomy's Two New 150-inch Telescopes), K-1087 (Summary of Automation on the AURA 150-inch Telescopes), IAU Colloquium No. 11 (Summary of Automation on the AURA 150-inch Telescopes), IAU Symposium No. 27 (The Construction of Large Telescopes), Mirror Support Symposium (Support and Testing of Large Astronomical Mirrors), Sky and Telescope, Sept 69 (Giant Mirror Blanks Poured for Chile and Australia), and Sky and Telescope, Nov 69 (Photo Album of Kitt Peak's 158-inch Telescope Building).

Now to some details of our current status: Optics: The KPNO-designed large grinding and polishing machine has been in operation now for over three years and is performing very well. In the first year we figured the 100-inch Hindle test sphere for the secondary mirror. The blank was a cast aluminium, ribbed structure, with the ribs and front surface about three inches thick. Since then, we have been grinding, polishing, figuring and testing the 158-inch diameter, 24-inch thick fused quartz mirror blank supplied to us by the General Electric Co., Lamp Glass Division, Cleveland, Ohio. The blank is solid with a 52-inch diameter center hole. We are in the very final stages of the figuring now, and have currently (April 1971) a light concentration of 50% within an image diameter of 0.3 seconds of arc, 80% within 0.5 seconds of arc, and 96% within 1.0 second of arc, based on Hartmann tests in the optical shop (light path vertical) and with the blank supported on what is essentially a duplicate of the final mirror back support. We hope to be finished shortly, but would like to keep going as long as we see signs of progress.

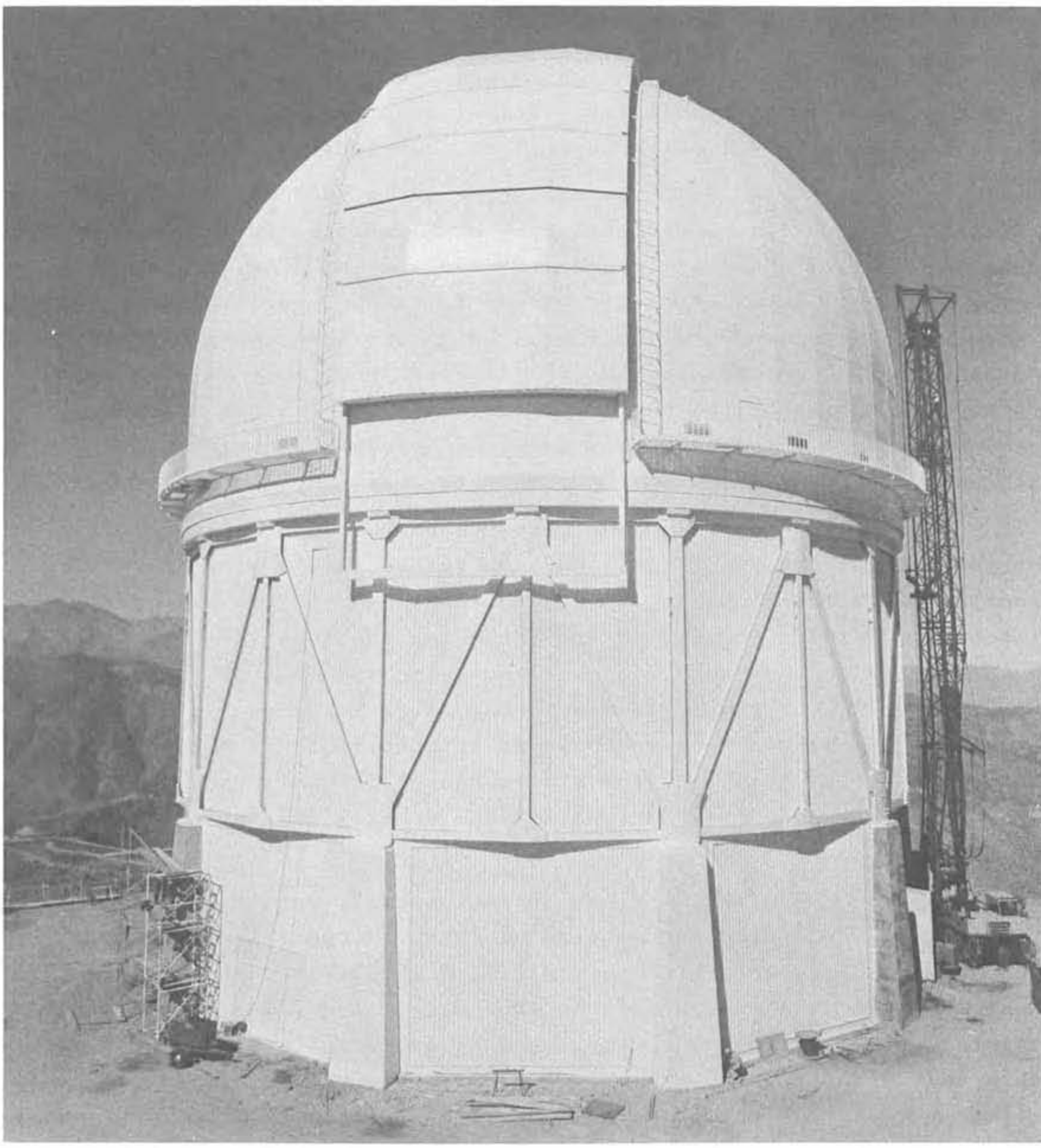


Fig. 4 The nearly completed 150-inch building at Cerro Tololo. The rotating dome is essentially identical to that at Kitt Peak.

The mirror blank for the second telescope has been obtained from Owens Illinois, Toledo, Ohio, who were low bidders on this primary, as well as for the secondary mirrors for both telescopes. All of these blanks are Cer-Vit. We are currently working on the secondaries for the KPNO telescope, and will begin the primary for the CTIO telescope as soon as we take the KPNO primary off the large grinding machine.

The building and dome at Kitt Peak are finished. The design is by AURA and Skidmore, Owings and Merrill, Chicago, Illinois. The prime contractor for the construction (and for the CTIO dome material) was Sundt Construction Co., Tucson, the low bidder of ten groups. Great care was taken to minimize adverse thermal effects and to have the facility as functionally efficient as possible. Of course, we have already found several areas of design where we'd do things differently next time.

We have been the "contractor" for the building and dome at CTIO, shipping most of the material from the United States and erecting the structure ourselves. The work there is finished as well, except for numerous items on our final "check list".

The large aluminizing chambers have been obtained from High Vacuum Equipment Co., Hingham, Massachusetts, who were low bidder for the two tanks. Both chambers are now located in the buildings and have been thoroughly ckecked out and tested, and they operate very well.

The mounting concept was designed by AURA in the beginning and in the final stages, with Westinghouse Electric Corp., Sunnyvale, California, and with W. R. Lydster, San José, California, in between. The low bidder for fabrication of the mountings was Western Gear Corp., Lynwood, California and Everett, Washington. The heavier pieces (horseshoe, south journal, and center section of the tube) were built in Japan, under subcontract from Western Gear. Boller & Chivens, South Pasadena, California, was the subcontractor for the prime focus and secondary assemblies. At present, the base frame is installed in the dome, the drives are finished, and most other pieces are in various stages of shop assembly at Everett, Washington. Complete assembly in the dome is expected before the end of the year. The Western Gear contract included the electrical and control components of the mounting as well, and a subcontractor, United Power of Seattle, has completed this phase of the contract.

As might have been expected, there have been millions of small problems and several large ones on the way to the present status. Many of the most difficult engineering problems have been in the "interface" areas, between components or contracts, and in the human engineering and handling aspects. Some of these problems are not yet adequately solved.

I'll say little here about instrumentation for the telescope, for that is a whole separate area of work and problems. We expect to have a complement of guiders, plateholders, spectrographs, and photometers ready

Fig. 5 Part of the base frame of the telescope mounting assembled in the dome at Kitt Peak. Located at the top are two of the oil pad bearings.

when the telescope goes into semi-regular use.

A final few words about schedule and budget are in order, I think. Our initial budget was \$ 10,000,000 for each telescope. The first telescope bore most of the design cost and the second one had a premium for remote construction. We are still running within that budget (set about 10 years ago). The breakdown is approximately 4 million for the building and dome, 2.5 million for the mounting and controls, 1.5 million for the optics, 1 million for the initial instrumentation, and 1 million for design and other items. Our initial schedule was about 10 years for "completion" of the first telescope and we are close to that. I hope we'll have "first-light" early in 1972, and semi-regular use for research by the end of 1972, with the CTIO telescope about 1 to 1 1/2 years later. Throughout the program we have attempted to use selected modern management tools, for planning, schedule, and control of budgets, manpower and time. I believe these techniques have been most useful.

At present we have 30 people on our staff involved in the basic telescope program and another six on its instrumentation. You can take it from me personally that it is and has been a major effort - lots of blood and hard work by many people - to design and build these two large telescopes. We have had some excellent people, both on our staff and in the contractors' crews, to enable us to do this. Our responsibility to our sponsors and to the future of the telescopes, on this \$ 20,000,000 program of two 4-meter telescopes, is severe, and we hope yet to live up to it by the successful completion of the construction program.

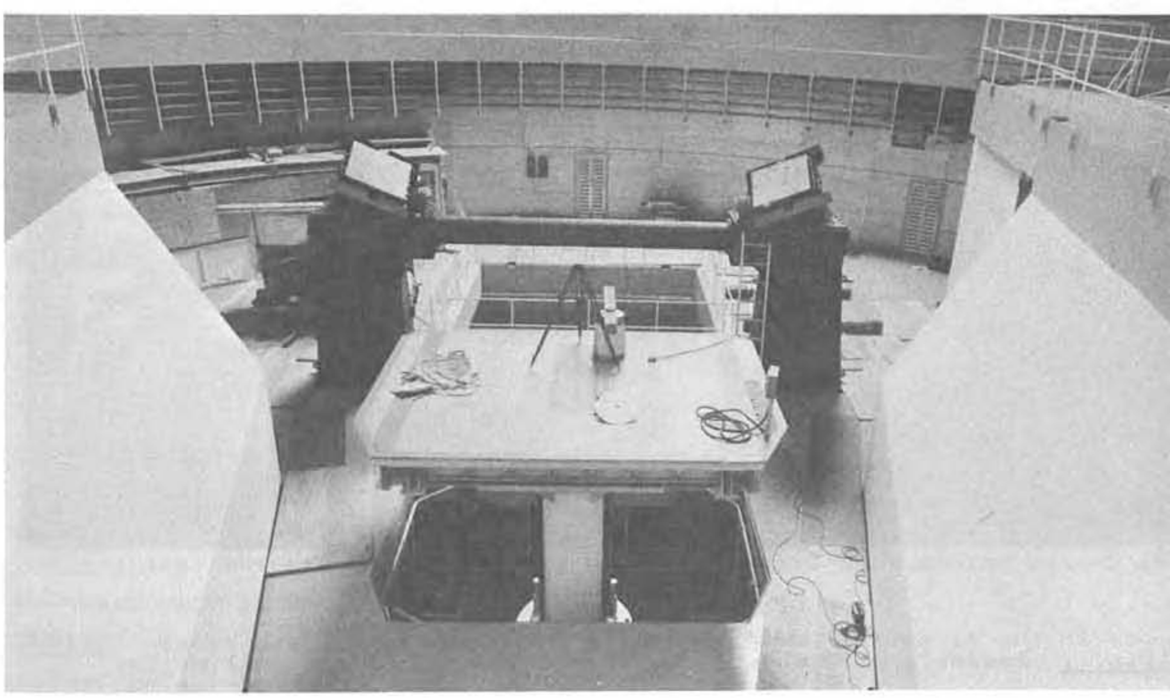


Fig. 6 Another view of part of the support frame of the telescope. Also seen in the photograph, the mirror lift elevator that will be used to remove the mirror and cell from the telescope for aluminizing.

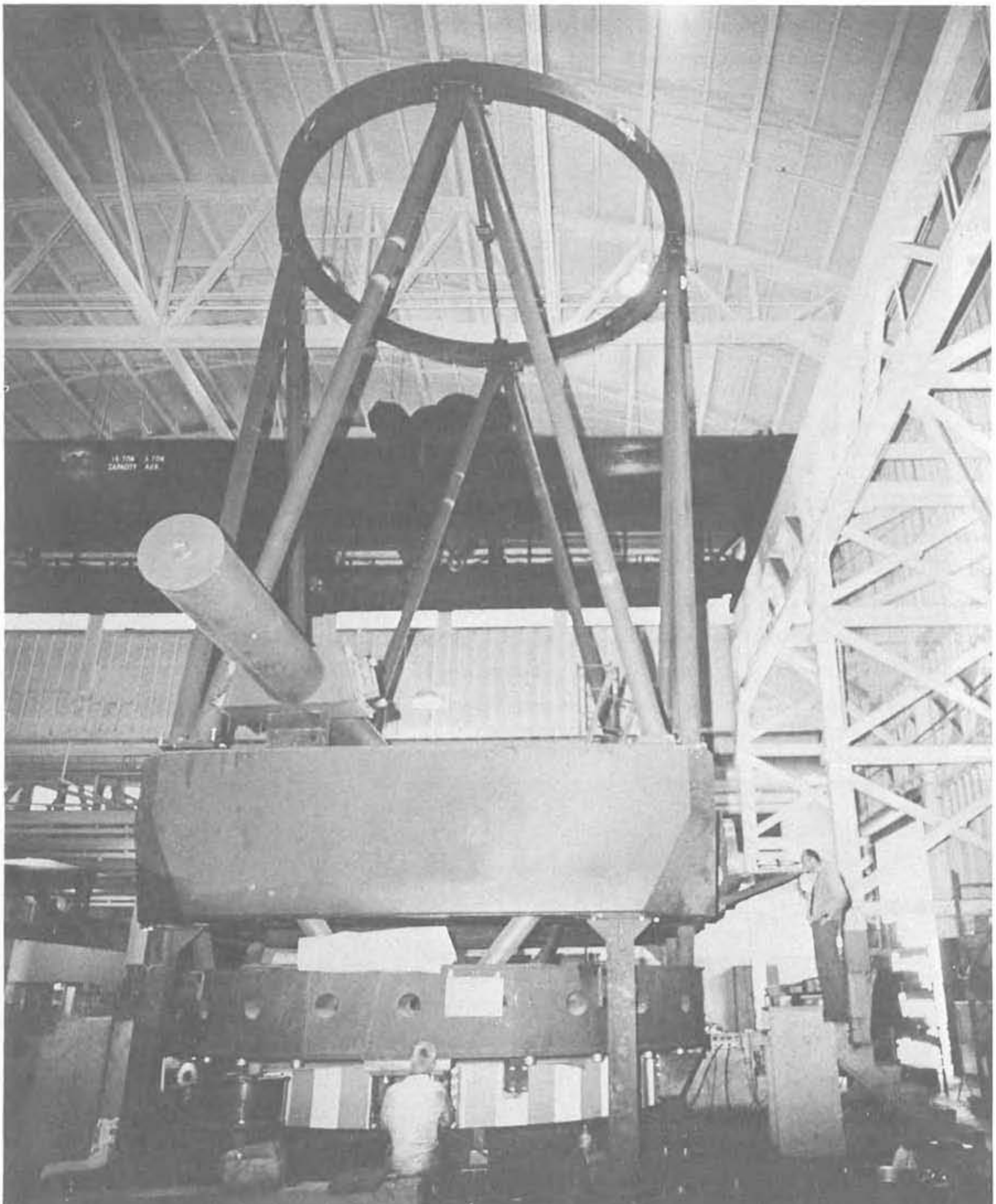


Fig. 7 Assembly of the tube center section and mirror cell at the factory.

DISCUSSION

DOSSIN: Is the Hartmann test, that we have seen, made when the mirror is in the cell, or just of the mirror alone?

CRAWFORD: Tests are made with the mirror on the grinding machine, but located on what is very nearly the final back support of the mirror. We only made tests with the light path vertically. To answer a question which I am sure is coming up: light concentration in the image with 90% certainty is about equal to that which we now have with the 84" and which the 200" and the 120" have.

FEHRENBACH: Is the polishing finished now?

CRAWFORD: I think we will have some more hours' work on the primary mirror for Kitt Peak. We are very close to not removing any more glass, but before we take it off we want to understand thoroughly all the testing procedures we have. We feel this is no loss of time, because the Kitt Peak one is not needed yet. Anything we learn now will save us on the second one, and it is the second one that we want to be the better one, because it is going to where the sky is a bit better. So again we have an advantage.

FEHRENBACH: Have you made a test of the smoothness of the figure?

CRAWFORD: There appears to be some lumpiness, but it is not severe in the final image.

FARRELL: Has any attempt been made to separate the errors which may arise due to figuring and those due to the support system, i.e. the actual support system in this case?

CRAWFORD: We have attempted to look into any errors coming into the support system and, as far as I know, have not detected any yet. We think the ones which are there now are mostly due to the figuring.

LAUSTSEN: Will you aluminize the mirror when it is in its cell?

CRAWFORD: We take the support system out but leave it on the cell and aluminize with the surface horizontal.

FARRELL: What is the reason for aluminizing the mirror in its cell, and taking all of the hardware away from it?

CRAWFORD: We have tried to minimize the amount of problems in handling we would have in the various pieces. Looking at the systems design we thought that this approach would offer us the least problems.

CHARVIN: Do you intend to protect the aluminium with some kind of dielectric layer, for instance Al_2O_3?

CRAWFORD: We certainly do not expect to overcoat the primary. Maybe on the secondaries, but as of now, no. But we will plan to realuminize rather often, and wash very often.

HERBIG: Is it possible to wash the primary without taking it out of the telescope?

CRAWFORD: Yes.

KÜHNE: Have you finished one or possibly all of the secondaries? If yes, how have you tested them?

CRAWFORD: No, the one f/8 secondary is now beginning figuring. We don't expect it will be finished until the end of this calendar year. We expect to test it with a Hindle test sphere, which is finished, as well as with some wave shearing interferometry.

HERBIG: May I ask if you would comment on the effects at the coudé focus due to polarization at those steep angles on the flat mirrors?

CRAWFORD: In this telescope all the angles are $< 90^\circ$. We have found that indeed there are polarization effects, and light losses with the 84", where we have a steep angle of one of the mirrors. Our coudé here and the 150" does have 5 mirrors however. We would hope to coat some of them and also perhaps develop, as some of the other groups are, a longer f-number coudé with more coating, but we have certainly noticed the problem with the 84".

FEHRENBACH: You have no idea of changing the f/30 coudé?

CRAWFORD: No. We may build another longer focus one, but we certainly won't change the f/30.

ELSÄSSER: What are the reasons that you give the Cassegrain focus higher priority than the prime focus? Are these only technical reasons or astronomical reasons?

CRAWFORD: Well, we think they're mostly astronomical reasons, because our astronomers, including myself, are rather Cassegrain orientated. We have done very effective work with the 84" Cassegrain focus. We think that the difficulties of operating the Cassegrain are much less than at the prime focus, and that the f-numbers for design of spectrographs and such things are extremely handy. We also think that the limit photography will be done at the Cassegrain. We believe that the light losses at the Cassegrain due to the secondary mirror are no more than we would have through the correctors and with the difficulties in the design of the prime focus.

BORGMAN: What is the height of the Cassegrain cage?

CRAWFORD: About 7 feet.

BORGMAN: So an observer could stand upright there?

CRAWFORD: That's right - even Ed Dennison!

BLAAUW: Is the Cassegrain cage a permanent feature of the telescope? Can you take it off and do you feel limited by the space within the cage for what you want to put there, considering your priority for the Cassegrain focus?

CRAWFORD: It is semi-permanent. That is it could not be removed during the night to change instruments. However, we can put in instruments like a Cassegrain spectrograph and take it out without removing the cage. But to get the whole cage out would be quite a few hours' work. We find that the biggest difficulties in the cage are trying to design it for high effectiveness for different instruments. The very large Cassegrain spectrograph is quite different than the direct photography thing with the eyepieces. To fill the cage up with a chair that moves around, takes up a lot of space. It's very difficult to make a total system design for all instruments and all astronomers. Astronomers are quite a bit different as we all know, and the human engineering aspects are very difficult.

BLAAUW: How much space do you have between the focus and the bottom of the cage?

CRAWFORD: From the focus to the floor of the cage is between 5 and 6 feet.

ODGERS: What was decided with regard to the drives?

CRAWFORD: Our drives are done. We have a large helical gear with a two motor drive on them and direct couple. It's rather like that which John Pope described in general, differing in quite a number of the details. The declination drive is about the same as the right ascension.

ZILVERSCHOON: Do you intend to pre-assemble the telescope in the United States or do you assemble it right away completely in Chile? Are there parts that you would like to test out in assembly?

CRAWFORD: When we bid the contract for the mounting, we did not require complete assembly. We felt that the number of manufacturers who would bid on it including complete assembly would be too small. We are helped somewhat in that the contractor has the responsibility for assembling the first mounting on Kitt Peak. The second one for Chile we will store near Seattle until the first one is working satisfactorily; then we will take it to Chile and assemble it ourselves. The second pieces, which may be some different, will not be erected before they are at Chile, but we will have had some help by having the Kitt Peak ones erected first.

I did not mention the time schedule, but we expect the contractor to have the telescope together on Kitt Peak at the end of this calendar year. He says before that, but we don't believe him. It will take most of next year to debug it, tune it up, put in the optics, tune them up, so we would expect a reasonably full operation by the end of next year. Some time next year, when we have confidence that no unforeseen problems are coming up with the mounting, and when we can free some of our crew who has been watching the contractor on Kitt Peak and making the telescope work, then we will go to Chile with that crew and begin putting the second one together. That will take at least 6 months or more and another year to really get it working, so perhaps the operation in Chile will start at the end of 1973.

ROOSEVELD VAN DER VEN: Do you have main contractors for the main parts or have you separated them yourself?

CRAWFORD: The building and dome contract included the dome and building for Kitt Peak, and the dome for Chile. The one for Kitt Peak was erected by the contractor. In Chile we have built the building ourself and erected the dome which was supplied from the contractor ourself. The two mountings are with one contractor who had numerous sub-contractors. We obtained the mirror blanks from a contractor but have been doing the optical work on them ourselves. And a great deal of the miscellaneous was our own. Some of the design was by outsiders but the great majority by ourselves.

MALM: You mentioned some figures on how many people you had involved in the project. How much does this work include; is it pure planning, or does it also include any construction work? How much manpower have you put into the software?

CRAWFORD: It includes the people doing the optical work (about four or five), and most of the rest are mechanical and electrical engineers. It does not include any of the construction force in Chile which was as high as 120 at one time, and is now down to about 15. Of this perhaps half was taken from our regular crew that developed our 84" and other things, and the rest have been put on for the program and unless we have other programs after this, they will be let go. At present we have put essentially no work at all into the software.

BAUERSACHS: I would like to know the reasons why you made your buildings of steel structure and not of concrete?

CRAWFORD: We worked very closely with an architectural and engineering firm; they preferred the steel and we did not object that strongly. We also felt that in Chile, at quite a remote site, steel offered a definite advantage of being an erector set. We build all the pieces, take them down and just bolt them together. We wanted to save work and problems in the field as much as possible.

BAUERSACHS: Do you intend to save time?

CRAWFORD: Yes, we think it will also save time. It probably did not save money, but what the difference is, is not too sure. The erection on Kitt Peak was also partly pre-fabricated. Pieces were made in a city where the labour costs were lower, taken to the mountain and put together. If we were starting again right now, we would look very carefully at doing more of concrete than what we have done on the first one especially at Kitt Peak. In Chile I think it would still be steel.

DOSSIN: What is the price of the building compared to the dome in the total of 4 millions?

CRAWFORD: The dome is 1,2 million. Remember, the prices are based on 1967 dollars also - this is a non-negligible factor.

RAMBERG: Which steps have been taken in order to protect the Tololo telescope against seismic shocks?

CRAWFORD: We have designed every feature in the building for a horizontal force of 0.3 g. There was one rather severe shake since the building was put together and there were no problems of any sort.

THE LAS CAMPANAS OBSERVATORY

H.W. Babcock

Carnegie Institution of Washington

Early in 1971 the Carnegie Institution of Washington announced that a new 100 inch telescope would be built and installed at Cerro Las Campanas in Chile. This telescope, fully instrumented and of the most modern design, is being planned by the staff of the Hale Observatories (formerly known as the Mount Wilson and Palomar Observatories). The instrument is being funded basically from private sources, largely by a generous gift from Mr. and Mrs. Crawford H. Greenewalt. It will be known as the Irénée du Pont Telescope and will be the first large instrument of the new observatory that is being developed after an extended survey of possible sites in the Southern Hemisphere.

Recognizing the great value for astronomy of large telescopes south of the equator, the Carnegie Institution initiated a site survey in 1963. The Institution proposed to find the best observatory site in the Southern Hemisphere and to build there a 200 inch telescope with two smaller companion instruments. The project acquired the name "CARSO" for Carnegie Southern Observatory.

Because the quality of the astronomical seeing is fully as important as the aperture of the telescope, the site survey was conducted with principal emphasis on measurement of the seeing. For this purpose, four portable instruments of 8 inch aperture were built and equipped for continuous recording of the amplitude of image tremor of bright stars. These field instruments, known as astronomical seeing monitors (ASMs), were employed in investigations of sites in New Zealand, Australia, and especially in north central Chile. Other important considerations in site selection were the percentage of clear nights, dark skies - free from the glare of artificial lights, suitable altitude, good topography, and ample space for future expansion. With confirming evidence from other site surveys, especially that conducted by the Associated Universities for Research in Astronomy, it became evident that the coastal mountains of Chile in the latitude zone from about 27° South to 30° South were quite exceptional in quality. With support from the University of Chile and from AURA, the Carnegie Institution operated its ASMs for extended intervals on Tololo, Pachón, and Morado. One of the ASMs was also operated by the European Southern Observatory on La Silla. Other mountain sites investigated by the CARSO organization in the same

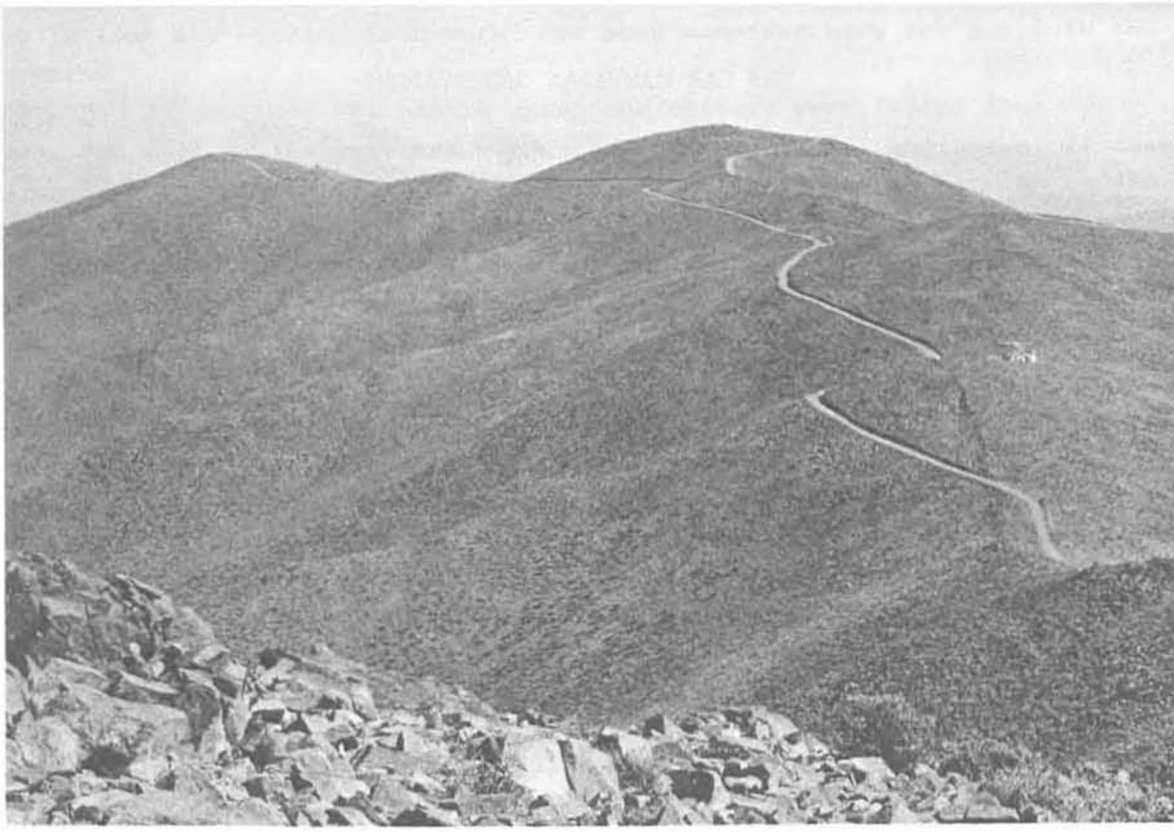


Fig. 1 Las Campanas ridge with access road.

Fig. 2 Erection of building for 40-inch telescope.

general vicinity were Guatulame, Papilones, El Toro, La Peineta, and Las Campanas. Analysis of the ASM records showed that the average amplitude of image tremor (equivalent to image diameter as seen with a large telescope) at the best Chilean sites was about 0.85 arc seconds, occasionally reaching an optimum and very exceptional value of about 0.3 arc seconds under the best conditions. This has been corroborated recently by reports that the average seeing at Tololo is somewhat better than 1 second of arc.

By 1968 the decision was made to locate the new Carnegie observatory on Cerro Las Campanas. This mountain is at a latitude of 29° South. It is 165 kilometers by road from the coastal city of La Serena and about 25 kilometers north of the European Southern Observatory at La Silla. The Carnegie Institution has purchased an area of some 206 square kilometers including the principal Las Campanas ridge which is about 5 kilometers in length and which runs in a direction slightly west of north from the 2460-meter (8200-feet) principal peak. The northern end of the ridge has an altitude of approximately 2220 meters (7400 feet). The prevailing nighttime breeze is from the north and in that direction there are for a great distance no other mountains of comparable altitude to produce turbulence in the air flow. Consequently, it is believed that many parts of the ridge are relatively free from any local turbulence. The ridge offers four principal summits for major instruments and an almost unlimited number of intervening sites for other installations.

Development of the Las Campanas site is well advanced. A good road has been completed from the valley to the summit and along the ridge. An adequate source of water has been developed and the water system is being installed. Temporary living quarters have been established and a permanent 12-room lodge for astronomers is being planned.

From the standpoint of administration and operation, the Las Campanas Observatory is the responsibility of the Carnegie Institution. It is hoped, however, that by agreement with the California Institute of Technology, Las Campanas will become a part of the Hale Observatories, together with the Mount Wilson Observatory, the Palomar Observatory, and the Big Bear Solar Observatory in California. The Carnegie Institution has, from the beginning of the project, planned Las Campanas as a facility available to the staff of the Hale Observatories and to guest investigators from other institutions. By agreement with the University of Chile, ten percent of the observing time on the Carnegie Institution's telescopes at Las Campanas will be available to Chilean astronomers on the basis of approved scientific programs.

The first telescope for the Las Campanas Observatory is an instrument of 40-inch aperture that has been built by the Boller and Chivens Division of the Perkin-Elmer Corporation. This instrument will be erected on Las Campanas within the next few weeks and it is expected that it will go into operation by the middle of this year. Two Cassegrain focal ratios will be available: f/13.5 and f/7. Ritchey-Chrétien optics are used, with a special Cassegrain corrector designed by Dr. I.S. Bowen to provide a flat field 3° on a side. It will be equipped with a two-channel digital photometer and with an image-tube Cassegrain spectrograph.

Under a special agreement with the University of Toronto, the University is planning to install a 24-inch telescope on the Las Campanas ridge. The University of Toronto will control the scientific operations of its telescope under an arrangement whereby the Carnegie Institution provides utilities and services.

The 100-inch Du Pont Telescope to which I have already referred is funded and the design and construction are expected to proceed on a 42-month schedule with completion in 1974. Mr. Bruce Rule of the Hale Observatories has been appointed Project Officer for this 100-inch telescope and is in general charge of engineering and construction. Dr. I.S. Bowen is a consultant. Other members of the staff of the Hale Observatories who share responsibility for the telescope are: Dr. Arthur H. Vaughan, Jr. (optical design and testing), Dr. J.B. Oke (auxiliary instrumentation), Dr. E.W. Dennison (computer control and electronic data system), and Mr. Bruce Adkison (site development). During the week I am sure that you will be hearing more about specific plans and details of the new telescope. Here, I shall just outline briefly some of our chief design considerations and principal specifications.

The telescope will be fork-mounted and the 100 inch primary mirror will have a focal ratio of 3. The tube will have a flip cage, providing an f/7.3 Cassegrain focal ratio and an f/30 coudé ratio. An extra plug-in secondary mirror will be used for special infrared observations at the Cassegrain focus, probably with an f/13 ratio.

We propose using lightweight secondary mirrors and a solid primary. A decision will be made quite soon as to the material of the primary, which will be either fused silica, ULE, or Cervit. Long-term stability of the optical figure is one of our primary concerns in choosing the material.

The 100 inch Du Pont Telescope will have the same limiting magnitude as the 200 inch Hale Telescope at Palomar Mountain but the field for direct photography will be much larger. A single-element quartz corrector in front of the Cassegrain focus will provide a field of 1.5 x 1.5 square degrees in good definition; only a moderate curvature of the plates (by vacuum) will be required. A novel coudé optical system with only three reflections is designedto permit high dispersion spectroscopy of far southern stars. This system will be applicable in the declination range from -20° to the South Pole. This can be achieved by reflecting the light from the coudé flat to to the south (away from the fork) to the coudé spectrograph which will be nearly horizontal and slightly above the level of the observing floor. The relatively small coudé flat mirror, under computer control, can be driven in both angle of incidence and in position angle in order to achieve this feature. Special design of the telescope tube will provide an opening on the south side with an adequate range of hour angle as well as declination for this coudé system. We believe that this three-mirror coudé system, designed especially for the far southern skies, will compete favorably with the five-mirror systems as used on larger telescopes. With the Du Pont Telescope, an alternative three-mirror coudé system of the conventional kind will also be available for stars north of declination -40°; this involves reflecting the light down through the hollow polar axis of the fork.

The telescope will be equipped with an advanced digital data system and with a computer capable of coordinating all principal operating functions. A full complement of auxiliary instruments is planned, including a broad-band photometer, infrared photometer, image-tube spectrograph, 500 channel spectrometer, échelle spectrograph, and image tubes, both conventional and digitized, for direct photography.

I think it is worthy of note that even in this day, a major, new telescope such as we are building can be constructed with private funds. This is heartening evidence of faith in the future of astronomy and in the remarkable observing conditions that are to be found in the country of Chile. Together with the European Southern Observatory and the Associated Universities for Research in Astronomy, the Carnegie Institution looks forward to an era of friendly scientific cooperation and to long and productive use of its new facilities by many astronomers.

DISCUSSION

ODGERS: I presume plans for the 100 inch will not affect the ultimate desire to have a 200 inch in Chile?

BABCOCK: Yes, that is correct. However I do expect we will be rather busy during the next year or two getting the 100 inch properly designed.

HERBIG: Could you give a short outline of the funds necessary for a 100 inch telescope?

BABCOCK: The overall expenses will probably approach $5.000.000. We are allowing a substantial sum for the auxiliary instrumentation, probably in the order of $750.000, but at this moment I would not like to attempt to further breakdown the budget.

CRAWFORD: Have you picked one of the knobs for the site yet?

BABCOCK: I believe I can say that the choice is down to the two knobs towards the northern end of the ridge. As I pointed out, these seem to offer the best conditions as far as any local turbulence is concerned. There are no other mountains for a great distance to the north.

BORGMAN: You mentioned that for infrared work a special secondary mirror would be incorporated. Is that only for the special f-ratio or are there other specifications involved?

BABCOCK: One other specification is required. The infrared observers prefer to wobble the secondary mirror with a small amplitude to move the object on and off the detector at a rate in the order of 15 - 20 Hz. So at best this is difficult. It can be done most easily with a relatively small secondary.

BORGMAN: This means then that the entire secondary mirror is going to wobble at 15 - 20 Hz?

BABCOCK: Yes, 15 - 20 Hz with a very small amplitude. I understand that the image need only move 5" - 10", but it is still difficult.

BORGMAN: Do you emphasize infrared work so much that among the peripheral equipment on the mountain you will have for instance a liquid helium plant, or is this something that you would leave to a joint effort of several observatories?

BABCOCK: Well, I would certainly not discount the possibility of one liquid helium plant for three observatories. I think the infrared observers can get by for some of the work with liquid nitrogen, but in other respects they may wish to go to liquid helium, and there is no doubt that such techniques are somewhat expensive, but they are probably worthwhile. The infrared observing conditions in Chile are said to be quite superior indeed to those usually experienced in northern latitudes.

ELSÄSSER: Do you know any numbers about the water content of the atmosphere in Chile?

BABCOCK: No, I have no figures on that, but I have heard it said by infrared observers that the infrared noise is definitely much lower than on such places as Palomar.

BORGMAN: We measured at La Silla on several occasions extinction coefficients of $0\overset{m}{.}2$ in the 20 micron region, which is blocked up by quite a number of water vapour bands. I think that this is highly superior to what you get in California and in Arizona.

THE CANADIAN 157 INCH TELESCOPE PROJECT

G.J. Odgers
Dominion Astrophysical Observatory

Detailed design work on this telescope began early in 1966 as a cooperative effort between astronomers of the Dominion Astrophysical Observatory (Victoria B.C.) and engineers of the firm Dilworth, Secord, Meagher & Associates, (Toronto, Vancouver), led by Mr. E. Eggmann. The initial design study was completed in March 1967 and published in two volumes. In October 1967, a 157 inch 17½ ton fused silica mirror blank was accepted from the Corning Glass Works. This blank has a central hole diameter of 36 inches and is 25 inches thick. The front surface of the blank is contoured to less than 1/8th of an inch of the intended final surface and to a radius of curvature of 893 inches. Tolerances on the physical properties of the mirror specifications were very similar to the CARSO specifications drawn up by Dr. I.S. Bowen, and were in fact improved by a factor of ten. There were no unfused areas detected at the sealed interfaces and no de-vitrification was noted in the entire blank. The maximum observed bi-refringence in 200 random readings taken from face to face and from rim to central hole was 2 millimicrons per centimeter. The estimated area of the finished surface occluded by open bubbles is $2\frac{1}{2}(\text{inches})^2$ (0.015%).

A polishing machine based on KPNO designs was constructed in Vancouver and completed in October 1967. This machine is capable of finishing mirrors up to 164 inches in diameter. In the same year, a 100 inch aluminum test mirror blank (Hindle sphere) was cast by ALCOA of Cleveland, Ohio. This mirror will be used to test the convex secondary mirrors of the telescope.

The site of the Canadian telescope was chosen in 1969, after three years of site surveys, as Mount KOBAU, latitude 49°7', height 6200 feet, near the west coast of Canada; this site has about 1400 usable nighttime hours p.a. and about 800 photometric hours, and the seeing is appreciably better than at Victoria. Unfortunately in 1967, after the initial studies were completed, after mirror blanks and polishing machine were purchased, and after a 13 mile road was constructed to the site, a severe difference of opinion arose among Canadian astronomers as to the desirabilities of the site. No better site in Canada was suggested, but in August 1968 a formal

Fig. 1 Mount Kobau access road.

Fig. 2 Mount Kobau.

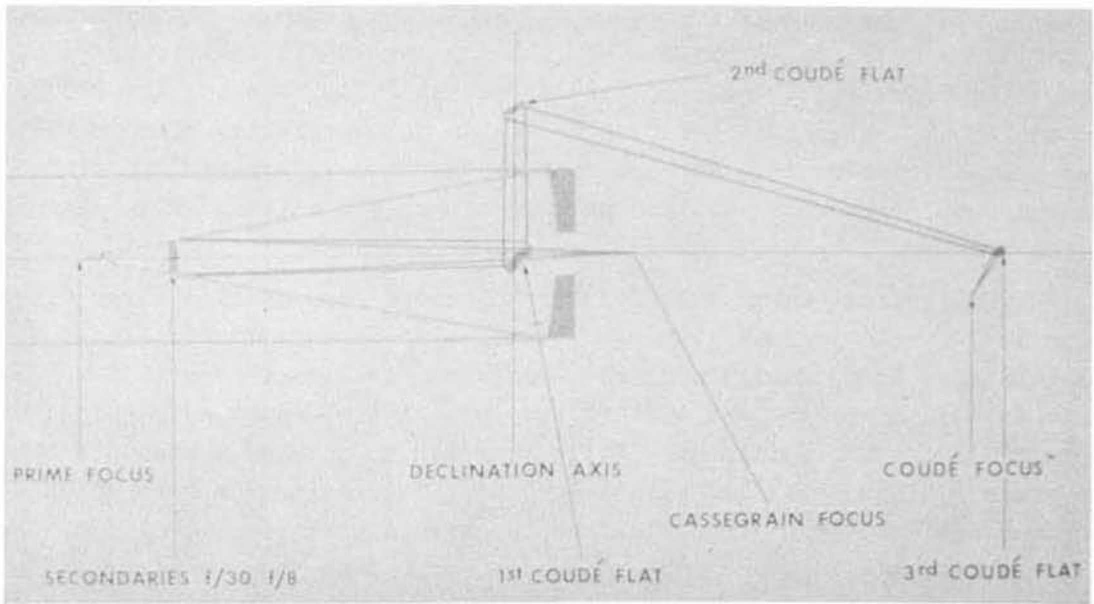


Fig. 3 Queen Elizabeth II Telescope optical systems.

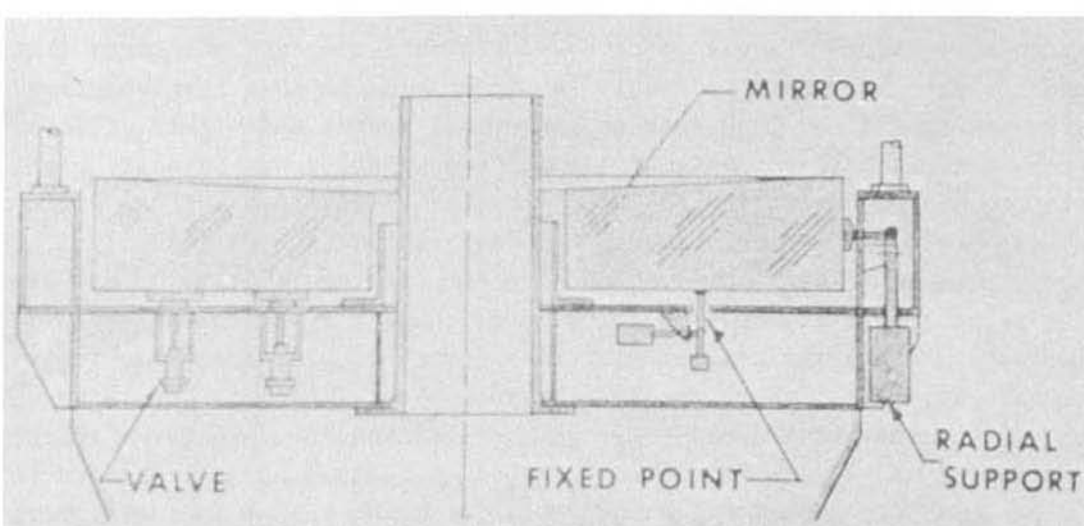


Fig. 4 Mirror, cell, radial ring and support system.

recommendation was made to the Government that the telescope be erected in Chile. The reaction of the Government was to cancel its participation in the project altogether. After this heavy blow, a group of six Canadian universities (WESTAR), with the assistance of the Dominion Astrophysical Observatory, is attempting to raise sufficient funds to bring the project to completion and a start has been made with the completion of an optical shop at the Observatory. At this moment, the shop is equipped to finish all the telescope mirrors except the primary mirror for which task an extension of the shop would be required.

The optical parameters for the telescope were decided after discussions in Victoria in 1964 with I.S. Bowen. The primary mirror is f/2.8 and the telescope is primarily a Ritchey-Chrétien instrument (f/8 at the Cassegrain focus) as are the two AURA telescopes. A fork-mount was decided on as suitable for the fairly high latitude after an intensive study of the performance of the Lick 120 inch telescope. This telescope generally performs well, but has large flexures in certain positions. However, the aperture ratio is f/5, the fork tines are very long, and the latitude lower, and it was calculated that by taking these factors into account no large flexures need occur. It was decided also to be able to cover all hour-angles so that circum-polar objects could be followed continuously, and for this reason a continuous cylindrical bearing was required as North bearing. Considerable work has been done in Victoria in an attempt to achieve the highest attainable accuracy and speed of the coudé spectrograph, and this aspect of the large telescope was regarded with the same importance as the Cassegrain focus. In an attempt to dispense with the large and cumbrous flat mirrors currently in use in large telescope coudé systems, (these mirrors are often difficult to remove for aluminizing and the large flat above the main mirror is difficult to support and impedes light-baffles etc.) and to replace them with smaller multi-coated and highly efficient mirrors, Dr. Richardson designed a trial system which has actually been installed and used with the 48 inch telescope at Victoria and has given very good results. Dr. Richardson will describe this system in detail but I would like to stress its advantages in simplifying large telescope design. There is no longer any need to force large coudé mirror systems into the telescope tube and the smaller mirrors are much simpler to design for mechanically. Also, there is a very strong case to be made for using highly efficient multi-coated mirrors wherever possible. A large telescope is a complex and expensive instrument used to collect as many photons as possible, and of the several hundred tons of mass, only a few milligrams of coating actually collect the light. Much more attention should be given to mirror-coatings than has been done in the past. For example current costs of 4 meter telescopes are about $12 million; an increase in efficiency of 10% is therefore worth over $1 million!

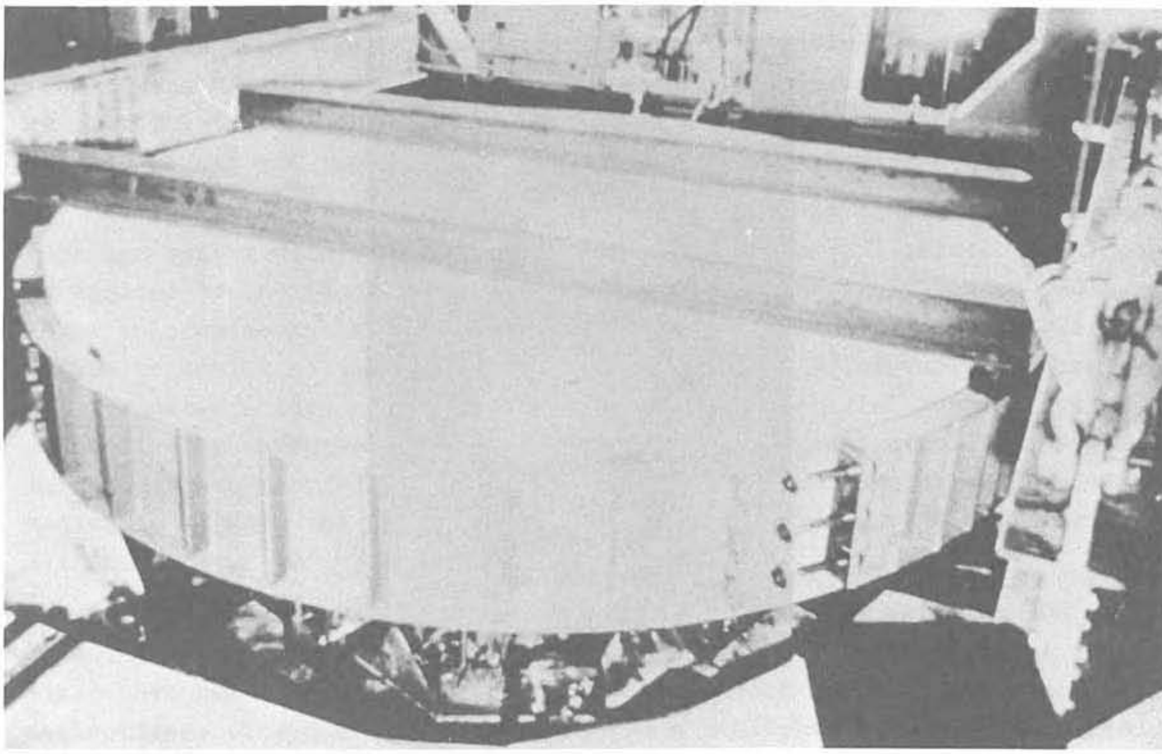


Fig. 5 The 157-inch blank.

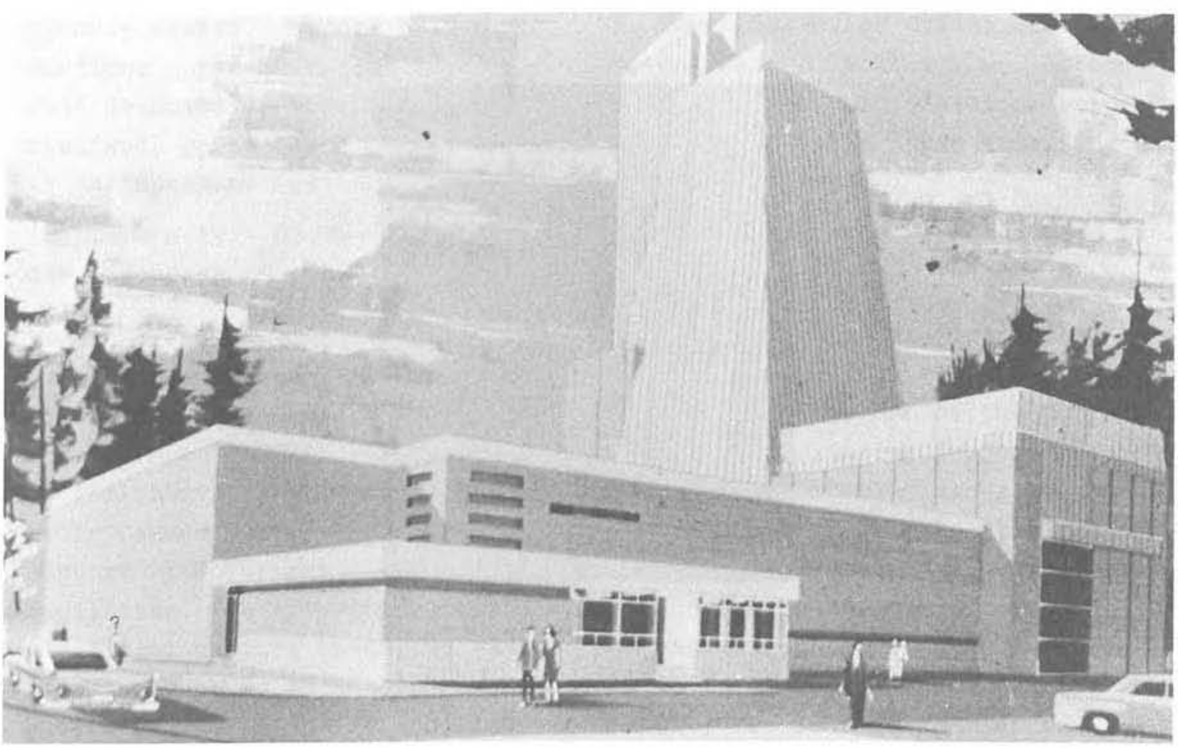


Fig. 6 Architect's conception of the optical shop.

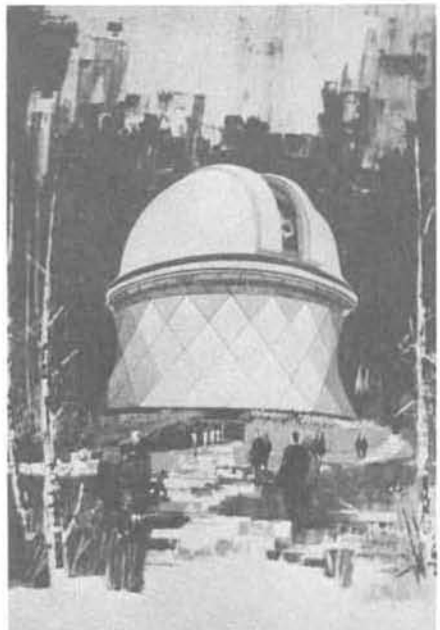


Fig. 7 Artist's conception of Mount Kobau National Observatory.

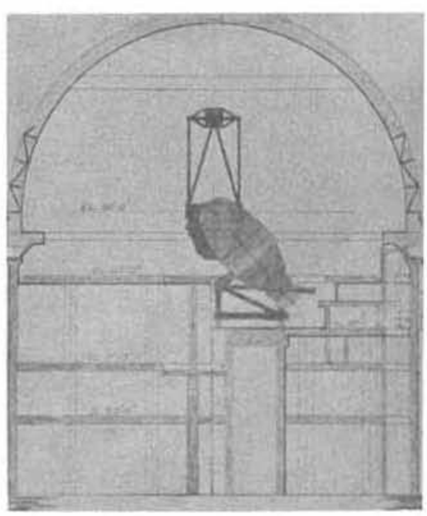


Fig. 8 Building and dome cross section.

High accuracy for radial velocity observations was a requirement of the Canadian telescope and hence rigidity specifications were strict, and to minimize flexure, exchangeable upper ends were designed which will be described later. The telescope setting accuracy was designed to be 6 seconds of arc and the flexural rigidity the same amount.

The mirror radial-support system was designed to use a counterweight leverage system with bearings, consisting of 32 separate units. The force is applied to the edge of the mirror through an adhesively bonded pad by a lever fulcrum mechanism which is self-regulating for all zenith angles. An intensive series of tests were made on the properties of various adhesives until a satisfactory material was obtained. In the axial support system, pneumatically energized bellows with a self-contained controller and force transducer was adopted. Each support has a pressure control which automatically adjusts the pressure of the bellows according to the mirror inclination.

The mounting as designed is a cantilevered fork weighing 108 tons, rotating about the polar axis on oil-pad hydrostatic bearings. The fork-tines have been kept short (14 feet to declination axis) to minimize their deflections. The South polar bearing has a hemispherical race 90 inches in diameter, and the North polar bearing at the base of the fork-tines has a cylindrical race 209 inches in diameter.

The telescope tube including the Cassegrain cage and instruments, primary mirror, support system and cell, lower Serrurier truss, center section, upper Serrurier truss and upper end weighs 75 tons. Mr. Secord will describe in more detail how some of the design specifications were realized, particularly the requirement for exchangeable upper ends, which is an important feature of this telescope.

(Editor's note: Ll.C. SECORD of Dilworth, Secord, Meagher & Associates Ltd. now discusses some of the engineering problems.)

I would like to continue from where Dr. Odgers has stopped by showing you another artist's conception, this time of what the Canadian dome might have looked like. This view as well as the one of the proposed optical shop is I think pertinent to a session on existing projects, for it is indicative of what can contribute to a project becoming non-existant. We in Canada were caught in the swing a decade ago of almost unlimited support by Governments and the public for universities and major research facilities. We were then trapped when the era of generous and often unquestioned support ended, by the over-emphasis we gave to non-scientific aspects, such as an access road to the site to highway standards and a public reception and an accompanying museum. Too late we learned our lesson in Canada, as we have not yet extracted ourselves from the stalemate that followed the loss of Government funding, even though the project has now been scaled back to its bare scientific features, and the total cost more

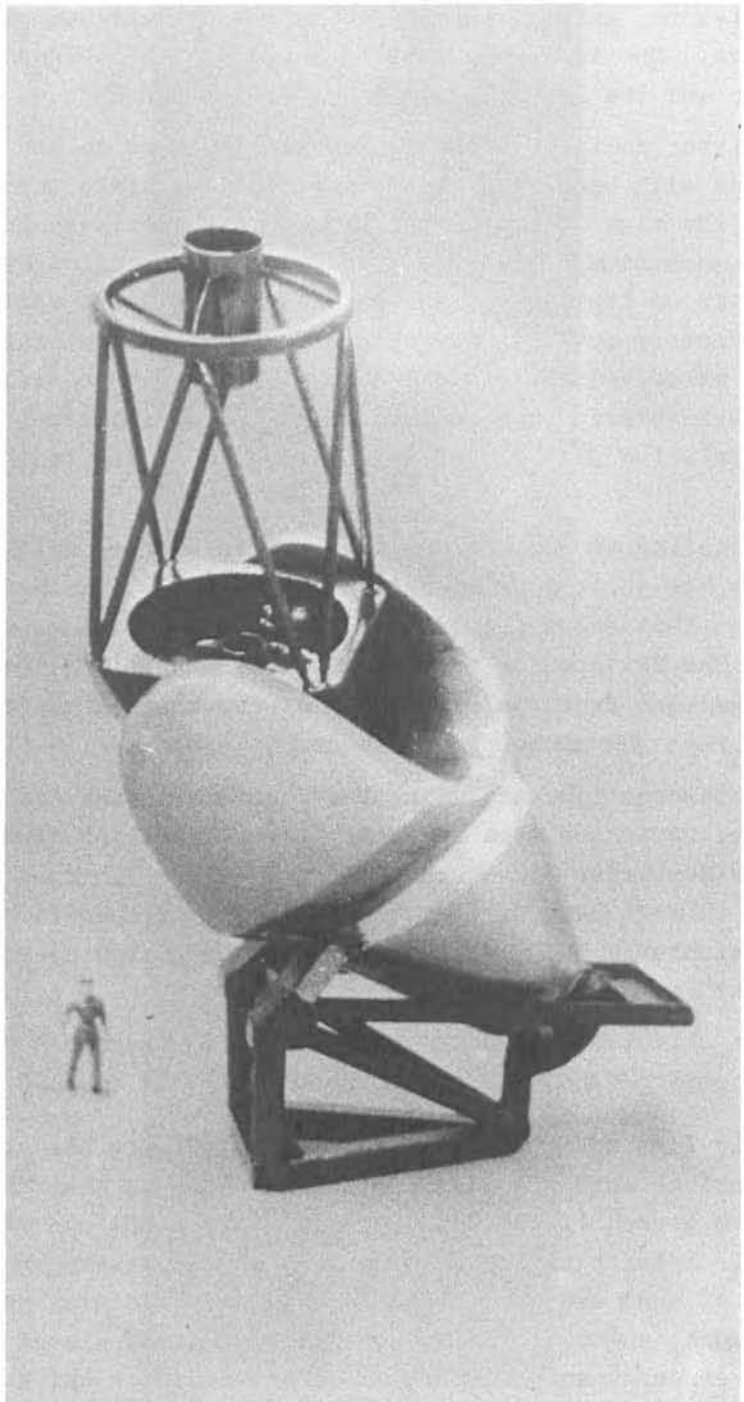


Fig. 9 A model of the Queen Elizabeth II Telescope.

than cut in half. While the project stalled before construction of the mount and the enclosure was started, a complete conceptual design of the telescope was finalized. Within this dome the four meter telescope was to be located some 25 meters above the ground and this was the arrangement selected. For a latitude of 49° 7' a fork-type mounting was clearly preferable, and a compact telescope evolved as revealed by the model. From the optical layout you will recall it is a multi-purpose instrument. The accommodation of different secondaries and a prime focus cage was achieved by exchanging complete upper ends. By this means, a complicated and heavy upper end was avoided and future flexibility preserved. In our northern latitude with extended twilights as well as unpredictable changes in the seeing quality, a rapid and convenient change from coudé to Cassegrain to prime focus was considered essential. Upper ends can be exchanged vertically as is done in the Lick and AAT projects. I would like to show you the alternative exchange concept that was proposed for the Canadian telescope, to avoid the loading, moving and unloading of optical assemblies by the rather lively cable system of an overhead crane. We thought that approach would be too risky to undertake at night and in a short time. In the proposed approach, the tube is driven to the horizontal when facing north. The upper end, which includes the spider arms and the outer support ring, is removed by a floor-mounted transfer machine and deposited onto a storage dolly. The alternative upper end is then lifted from its dolly and offered up to the Serrurier truss. It is locked in place with collimation and angular alignment obtained through locating pads at the four nodes of the truss. With this arrangement a night assistant should be able to effect the change in approximately 20 minutes.

DISCUSSION

DOSSIN: Is the idea of installing this telescope in Chile still a possibility?

ODGERS: No, there is no hope of Canadian funds to install this telescope in Chile! The Universities in Canada funds entirely from the provinces and would not contemplate putting it outside Canada.

STROMGREN: With Mt. Kobau at 49°, I understand you have a snow problem for the operation of the dome?

ODGERS: No, I think the snow problem has been exaggerated. We have had a 16 inch telescope operating there for several years, and there has been no

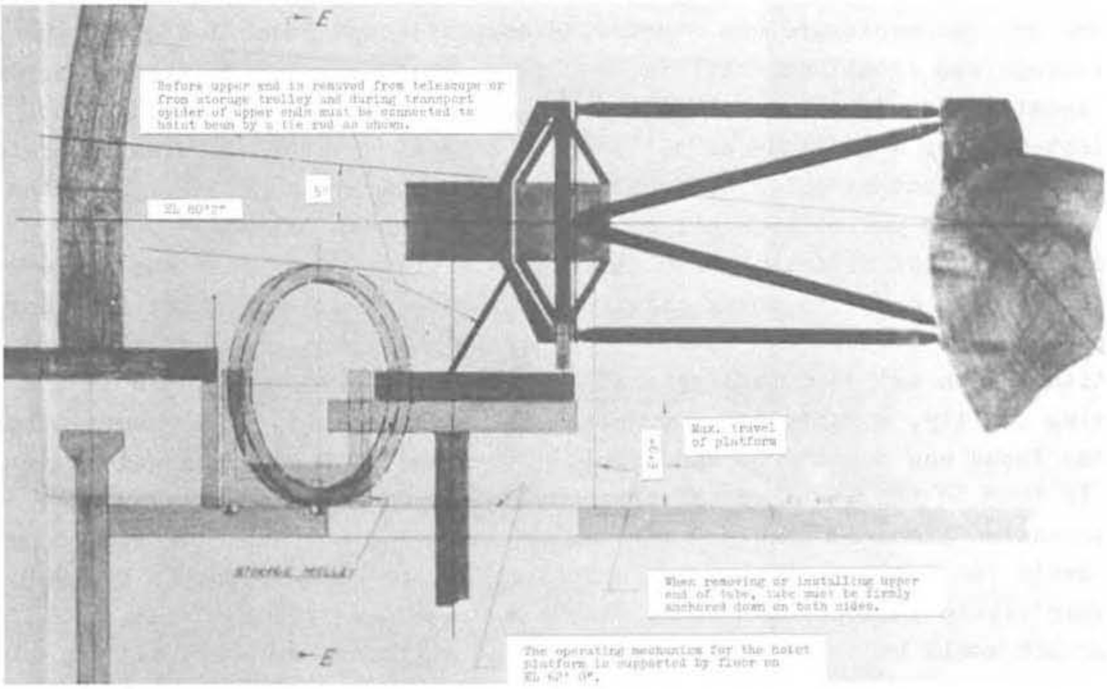


Fig. 10 Upper-end assembly.

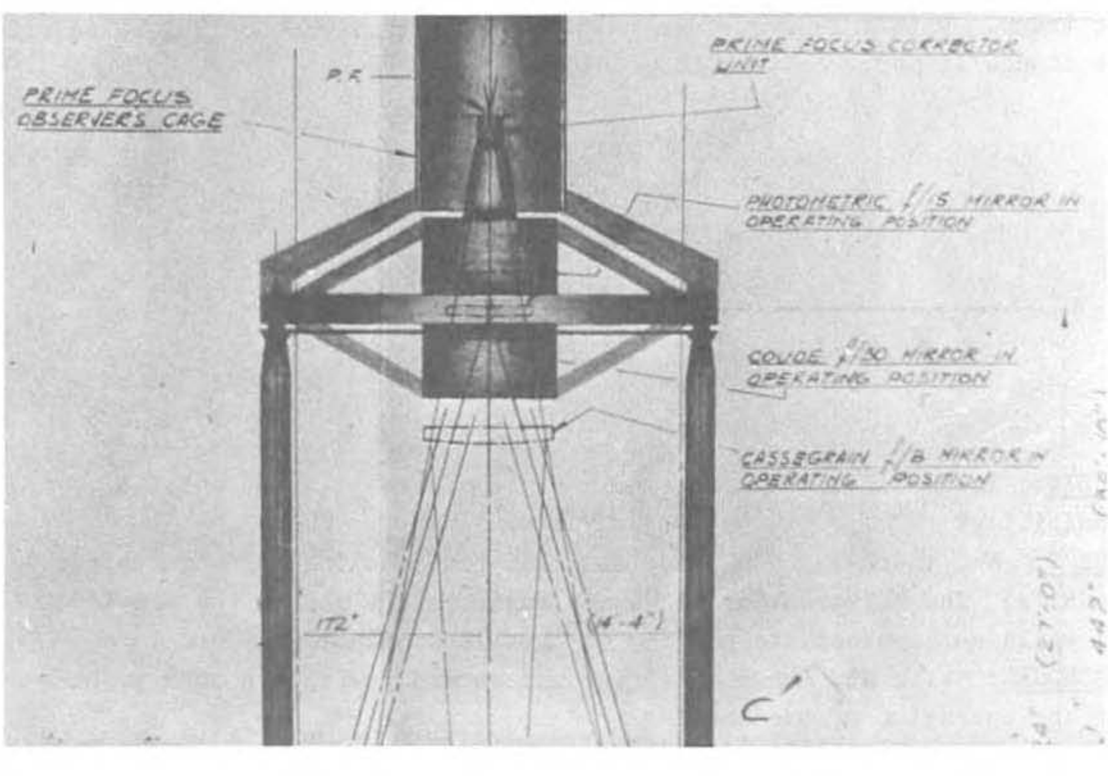


Fig. 11 Exchange of upper ends.

problem with snow interfering with dome operations. There is a snow clearance problem, but the total precipitation (30 inches per year) on Mt. Kobau is much less than at Mt. Palomar.

CAYREL: What is the gain in speed you expect from the use of coated mirrors for your coudé focus?

RICHARDSON: We expected about 40%, but it appears to be much more than that. I will be speaking about this tomorrow.

ODGERS: It is in fact about a magnitude isn't it?

RICHARDSON: It appears so.

HECKMANN: I think it would be interesting to learn something about your ideas on how to take off the mirror with its cell in order to realuminize it.

ODGERS: John Farrell, would you like to discuss this?

FARRELL: The plan for the realuminizing of the primary mirror was to have an elevator raised from below, which would be hydraulically compensated and support the mirror cell. The mirror cell would be lowered with the mirror once the Serrurier truss connections were unfastened, and the mirror would then be removed from the cell with the radial supports disconnected and so forth. The mirror would be lifted over to a cover for aluminizing and be aluminized in vertical position.

CAYREL: I found the time that you indicated for the exchange of the upper ends extremely short, do you have a special trick for that?

SECORD: Well, the times were determined by a motion study in the design program, and they are perhaps optimistic. The upper end can be disconnected from the truss by four motor driven screws, and the facility of being able to exchange the upper ends by a relatively small floor mounted rigid machine, and place the upper end in a trolley right at hand on the floor and pick up the other one is something that we think is feasible within the 20 minute time period.

DOSSIN: In case you plan to exchange the top end of the telescope with the tube in a horizontal position, do you then still need this large overhead crane in the dome, i.e. do you still need such a large dome?

SECORD: We as engineers do not think it is necessary to have such a large dome crane, but we have yet to find any of the operators of the observatory who are quite prepared to trust us on that. A 30 ton crane was proposed for this telescope, but I think that you can well get by with a mobile crane during original erection, and if you absolutely have to use a large crane after some 10, 20, 30 years or maybe never, you can then afford to bring in a mobile crane again. If you are going to do anything that needs a large crane capacity, it's rather an extensive program. So if you take away the handling of the mirrors from the overhead crane and do it by a separate transfer machine, I think that a smaller crane is quite satisfactory in the dome.

FEHRENBACH: I agree completely with you.

RANDALL: In one of your drawings you show the tube down at the horizon. Is

this actually right at the horizon or several degrees above the horizon where you move the secondaries on and off?
SECORD: The Canadian telescope had planned to do the exchange with the tube exactly horizontal.
RANDALL: Does this create problems with the primary mirror? Do you actually come off your support system or restrain it in some manner?
SECORD: Yes. During this period there is a supplementary planting force for the mirror back on its supports, from the rim of it.
DITTMAR: What were your ideas as far as focus and collimation on the exchangeable secondaries? Does each one of them have a separate system with read-outs?
SECORD: Yes, the collimation was central collimation. John Pope described in the Anglo-Australian project the focusing arrangement for the AAT which was the external ring. In this case it was proposed that the focusing would be done internally. For the collimation of the upper end to the tube, we proposed a spherical ball and a spherical seat, that would be located at the outer nodes of the Serrurier truss. There would be four of them, and the meeting face would be on the outer support ring of the upper end.
DITTMAR: Did you use a single focus motor for all upper ends?
SECORD: No. Each upper end had a separate focusing arrangement.
DITTMAR: Did you have an encoder on each one of them so that whenever you changed cages you just read out a new encoder to see which position to go to in order to focus?
SECORD: Yes, I believe that was the intention. The plan for these upper ends was that they would be mounted on their storage trolley, on the observing floor, and be available for advance instrumentation and preparing for the use on the upper end by the observing crew. So the intention was to have each upper end a self-contained unit by itself. There would be quick connect/disconnect electric cables to provide this read out once the upper end was installed on the truss.

(Editor's note: The discussion then turned to the flexure of the Lick 120 inch telescope.)

RULE: I must rise in defence of the engineers on the 120 inch. I think that this matter of the fork deflection is a serendipity design. As a matter of fact, as ill-informed as the engineers were, they did quite well since the fork was extended I believe some 7 feet without re-computing the fork deflections. The decision was made after the basic design was done. But it did turn out that these were all correctable, as Dr. Vasilevskis reported some time ago. But I think the deflections which did occur were not really in the original design.
BAUSTIAN: Actually the long fork or the location of the declination axis at the quarter point of the tube was fundamentally necessitated by the requirement of the Cassegrain focus without a folded spectrograph to be provided for, and therefore there are 7 feet of clearance between the

lower end of the tube and the fork. As it turned out, the astronomers that were interested in the Cassegrain focus left before the project was completed and as far as I know, there is at present no interest in the Cassegrain. But this specification did penalize the design of the telescope. The original deflection of 0.150 inches was figured in the preliminary outline and afterwards confirmed to within a few thousandths of an inch in the final design.

HERBIG: I think Dr. Odgers is unduly concerned about the 120 inch. Perhaps I should say something as a user of that machine. I think the designers did one thing that I admire very much, in that the coefficient of flexure of the fork and its dependence on zenith angle are almost identical to the first order term in atmospheric refraction. So that one can point the 120 inch to any part of the sky and set the dials directly to alpha and delta and ignore refraction and the star is always there!

BAUSTIAN: I would like to add a little design information in regard to the deflection of the fork mount. If you provide for a conventional three mirror coudé system, you tend to cut the strength of the side panel of the center section which then necessitates locating the declination bearing in the side panel of the center section, rather than in the more optimum location in the mirrors themselves, since the former arrangement will give an objectionable rotation of your field. We were aware of this at the time the 120 inch was designed, but if the telescope is lined up with the plane of the fork in the proper plane, you can then have a field rotation which can be corrected to a large extent by declination correction. I believe the Zeiss people have a solution to this problem by reversing the telescope at certain optimum positions.

ODGERS: Well, we stressed obtaining minimum flexure, but the solution which we have got would not go to the f/150 coudé which in fact has very small mirrors and no weight problem at all. I agree that the big flats were at all sorts of disadvantages.

HERBIG: Also, the field rotation, as Dr. Baustian said, can be completely compensated for by offsetting the polar axis in altitude and there is no field rotation as far as I have been able to tell from direct photography.

ODGERS: Well, I did not wish to criticize the engineers responsible for the Lick telescope, in fact we have adopted a fork. However, to come to the question of Dr. Herbig, how much does the beam wander on the collimator when the flexure is at its worst?

BAUSTIAN: The whole range is three eighths of an inch all over the sky.

TUESDAY, MARCH 2

MORNING SESSIONS

Chairman: B. E. Westerlund

PROJET DE TELESCOPE DE L'I.N.A.G.

par

R. Cayrel et P.Y. Belly

I.N.A.G.

ORIGINE ET HISTORIQUE DU PROJET

L'origine d'un projet de télescope optique français de 3.50 m ou 3.60 m de diamètre remonte à l'époque de la préparation du Vème Plan d'équipement de notre pays, vers l'année 1964. Le projet fut inscrit au Vème Plan pour un montant de 20 millions de Francs, représentant un peu moins de la moitié des crédits nécessaires, l'achèvement du projet devant être financé sur le VIème Plan.

Dès 1965 une campagne de prospection fut entreprise pour le site du télescope. Une dizaine de sites furent prospectés: dans les Pyrénées Orientales, dans les Alpes, en Corse et même à l'étranger en Espagne du Sud et Basse Californie mexicaine.

En 1967 le Centre National de la Recherche Scientifique programma 10 millions de Francs de son budget annuel pour le projet.

L'acquisition du disque du miroir primaire fut faite sur ce crédit, ainsi que les premières études.

En Janvier 1968 un organisme national fut créé au Centre National de la Recherche Scientifique sous le nom d'Institut National d'Astronomie et de Géophysique ayant, entre autres, vocation de mener les opérations d'investissements dans la discipline. Il devint responsable du projet. Une commission réunissant des Astronomes et des Ingénieurs fut mise en place pour la définition du projet.

La commission n'accepta pas de suivre fidèlement l'un des projets existants (ESO, Kitt Peak, ou Anglo-Australien) mais insista en faveur d'un projet ayant des caractéristiques propres.

CARACTERISTIQUES GENERALES DU PROJET

Je vais décrire, ci-après, le projet qui fut présenté à la commission en Mai 1970 sur les bases d'un ensemble de directives qui constituent ce que l'on pourrait appeler la philosophie générale du projet.

Ces directives sont les suivantes:

1. Avoir une optique de qualité suffisante pour ne pas dégrader les images de plus de 20% dans les meilleures conditions de turbulence atmosphérique.

2. Avoir beaucoup d'espace disponible pour l'instrumentation au foyer Cassegrain.

3. Avoir, à l'un des foyers, un champ de bonne définition et de pleine lumière de 30' de diamètre au minimum.

4. Avoir, à l'un des foyers, une ouverture numérique et une distance focale permettant d'obtenir la magnitude limite en photométrie à bandes larges en 3 à 4 heures de pose avec un récepteur d'image linéaire à haut rendement quantique du type caméra électronique.

Ces directives ont conduit aux choix suivants:

- Une monture de type Palomar. Ce choix satisfait au mieux la condition 2. et offre des avantages en ce qui concerne la manutention du miroir primaire pour sa réaluminure.

- Une structure du tube de type Serrurier. Il convient, pour respecter la condition 1., d'éviter tout décentrement relatif des miroirs primaire et secondaire supérieur à 0.5 mm et toute rotation du miroir secondaire supérieur à 30".

  La structure Serrurier est la plus favorable pour satisfaire ces exigences.

- Un miroir primaire d'ouverture numérique comprise entre 3.5 et 4.0. L'idée essentielle qui a motivé le choix d'un rapport d'ouverture un peu plus élevé que dans les autres grands projets est que la qualité d'un miroir dépend surtout de l'ampleur des pentes à réaliser par rapport à la surface sphérique la plus proche. Un miroir à f/3.75 présente des pentes deux fois plus faibles qu'un miroir à f/3.0 et la condition 2. a donc paru être plus facile à satisfaire avec un miroir à f/3.75 qu'avec un miroir à f/3.0. L'ouverture a ainsi été provisoirement fixée à 3.75. Les performances qui seront obtenues avec les miroirs primaires plus ouverts (ESO: 3.0, Kitt Peak: 2.8, Anglo-Australien: 3.3) achevés avant que le projet français soit figé seront un guide pour décider d'une révision éventuelle de cette valeur.

Les caractéristiques optiques sont les suivantes:

<u>Primaire</u>:	ouverture	f/3.75
	distance focale	13.50 m
	échelle	1" ⟷ 65 μ
	diamètre de la cage primaire	1.70 m

Cassegrain:	ouverture	f/11
	distance focale	39.40 m
	échelle	1" ⟷ 200 μ

Deux solutions ont été considérées pour le Cassegrain:

1. Solution Ritchey-Chrétien
   avec les coefficients de déformation asphériques b_1 et b_2 pour le primaire et le secondaire respectivement:

   $b_1 = - 1.004$

   $b_2 = - 5.28$

2. Solution "classique"

   $b_1 = - 1.0$

   $b_2 = - 4.14$

La première solution permet d'obtenir un grand champ au 1er foyer avec un correcteur nettement plus simple que la 2ème solution.

Coudé: f/34 avec 5 réflexions dont aucune n'est à grande incidence.

Il est prévu d'équiper le foyer coudé avec un spectrographe à réseaux de 60 cm, tracés par holographie.

Les changements de foyer ont été étudiés par échange d'anneaux de tête comme dans le télescope Anglo-Australien. L'échange se fait télescope vertical et demande environ 1 heure 30 minutes.

L'entraînement horaire est prévu sur pignon de grand diamètre solidaire du fer à cheval et non pas comme à l'ordinaire au palier opposé.

PLANNING ET REALISATION

Le projet n'est pas définitivement gelé. Nous étudions en particulier la possibilité de modifier le système coudé en y incorporant des miroirs traîtés de petit diamètre selon la technique utilisée avec succès par nos collègues canadiens. Une tête de télescope comportant la cage primaire et juste au-dessous une cage à flip-flop de 2 miroirs pouvant être indifféremment 2 miroirs coudé, 2 miroirs Cassegrain ou 1 miroir Cassegrain et 1 miroir coudé est à l'étude actuellement.

Le disque du miroir primaire, en Cer-Vit, a été achevé en Octobre dernier et réceptionné en Novembre chez Owens-Illinois. Ce disque de 3.60 m de diamètre et de 53 cm d'épaisseur au bord a toutes les qualités d'homogénéité requises par le contrat. Son coefficient de dilatation thermique est de $- 1.4 \times 10^{-7}/°C$.

Le projet sera définitivement figé avant la fin de l'année 1971 et, dans l'hypothèse la plus favorable, il sera réalisé à la fin de 1975.

DISCUSSION

WILSON: How should the 20% image degradation be understood?
CAYREL: It is defined by the diameter of the image at half of the peak intensity, and if the seeing is for instance 0".5, then an increase of this diameter to 0".6, due to imperfections of the telescope, would be tolerated.
HERBIG: Could you explain the 5 mirror coudé arrangement?
CAYREL: The beam is folded at 90° into the declination axis, and then returned to a flat which brings the beam horizontally into the coudé focus under the dome.
HERBIG: Why do you do it this way, rather than as in the Palomar 3 and 5 mirror system?
CAYREL: Well, the Palomar coudé is not horizontal, it is along the world axis. In the Las Campanas project you have a 3 mirror system, but it does not allow you to cover the whole sky.
SISSON: Have you decided how you are going to drive the polar axis yet?
CAYREL: No, that is still an open question which I think will be discussed later during the meeting (cf. B. Bertin's paper: "Driving the French 2 m and 3.60 m telescopes from the horseshoe").
BORGMAN: I would like to call your attention to the top which includes two mirrors and the primary cage. You emphasized in your introduction that you would like to see this telescope being used for infrared work. Now, if you flip down the Cassegrain mirror, you will have around the secondary mirror a source of strong black-body radiation, because the cage is much larger than the mirror. This is not very attractive for infrared work, and I am therefore in favour of changing the complete top units.

Another thing which I would like to remark upon is that you chose the Palomar mounting because you wanted to have plenty of room at the Cassegrain focus, for instance to include a Cassegrain cage. I understand that the 200 inch does not have a very spacious Cassegrain cage, maybe since it has been an afterthought. This Palomar mounting allows you to have more space, though if you copy it straight away, then you wouldn't have it.

MALM: You mentioned 1.5 hours for the top unit exchange. That is the highest value we have heard so far. Are you a bit pessimistic, or don't you have a semi-automatic method of making this exchange, or don't you find it necessary?

CAYREL: We have not put hard pressure on having that done in a very short time, because we did not intend to do it during the night. I have a breakdown of the 1.5 hours into parts of 5 minutes, 2 minutes, 3 minutes etc., and I don't pretend that something better can't be done, but if it is done during the day, we don't really need to go below that.

RICKARD: Have you considered other sites perhaps in the southern hemisphere for this telescope?

CAYREL: No we have not.

ZILVERSCHOON wants to know the estimated cost of the project.

CAYREL thinks it is somewhere around $10 - 12 million.

THE ITALIAN 3.5 M TELESCOPE PROJECT

G. Righini
Osservatorio Astrofisico di Arcetri

and

J.C. Farrell
Dilworth, Secord, Meagher and Associates Ltd.

The Italian telescope project was born about 10 years ago when the Ministry for Public Education at the request of the Italian Astronomers appointed an "ad hoc" Committee.

Originally the request encompassed a telescope with a primary mirror of 2.5 meters diameter with a prime focus, a Cassegrain and a coudé focus. It was soon recognized that the sum that the Government was willing to invest was reasonably sufficient for an Observatory equipped with a 3.5 meter telescope. This was the final choice of the Committee and consequently about the end of the year 1965 a bill was proposed to the Government for the complete financing of the National Observatory. The amount requested at that time was 5 million US dollars which was estimated adequate not only for the telescope but also for the buildings, the dome and part of the auxiliary equipment.

The National Research Council, which is also a Government body, but quite different from the Ministry of Education, having interest in the project offered financial support for about 30% of the total sum but unfortunately a conclusive agreement was never signed. Practical as well as economic reasons prevented the Government from bringing the bill for the National Observatory before the Parliament. At present the project has to rely upon appropriations for special purposes decided from year to year by the Ministry of Public Education and the National Research Council.

In spite of this awkward situation the project has had a good start, beginning about the end of 1969. It is now progressing slowly but steadily.

The optical parameters of the telescope which were outlined by the "ad hoc" committee are the following:

<u>Primary</u>:	Classical Parabolic Hyperbolic	
	Main Mirror diameter	350 mm
	Focal Ratio	f/4
	Angular Field	1° = 244 mm

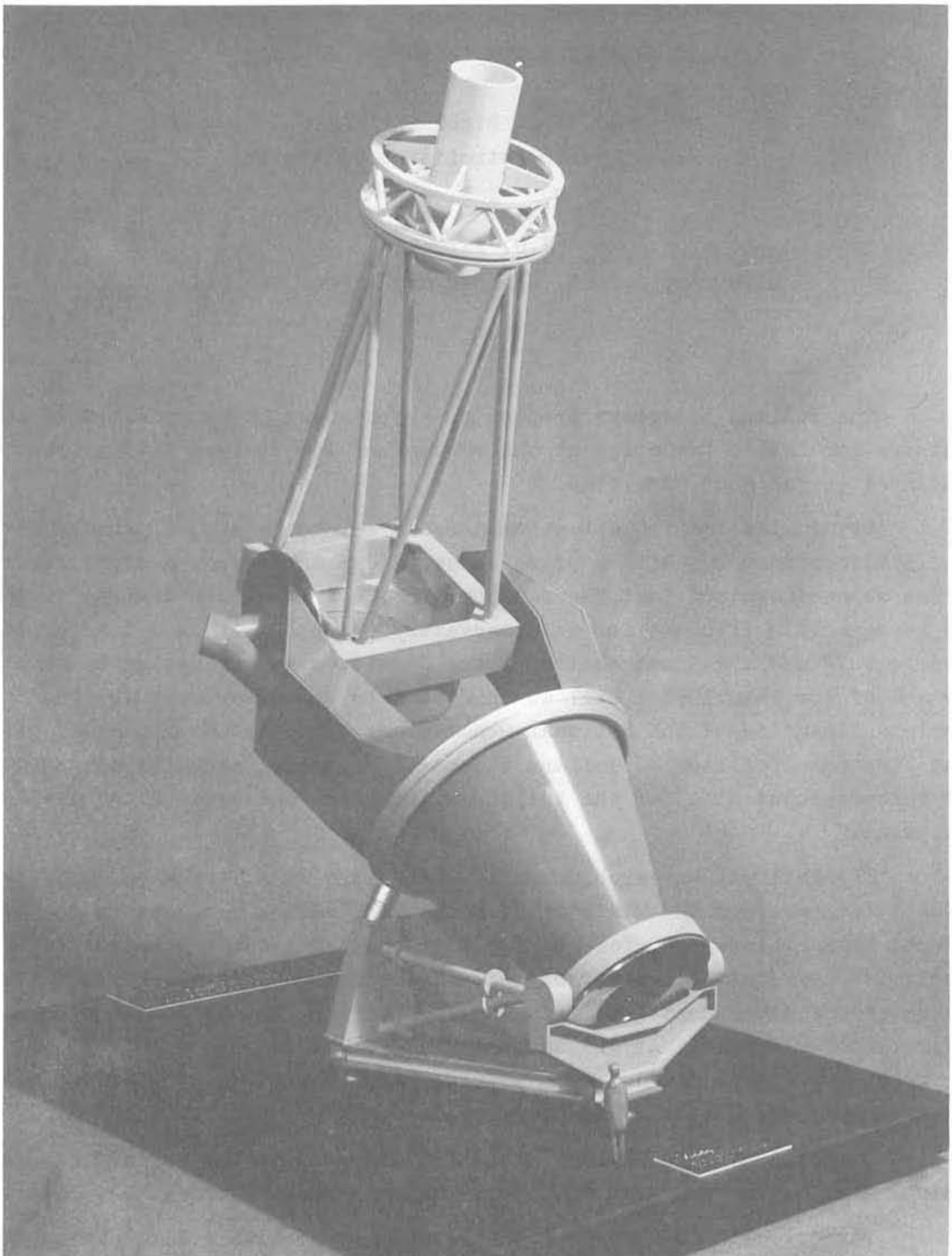


Fig. 1 The 3.5 m telescope of the Osservatorio Astronomico Nazionale.

Cassegrain:	Mirror diameter	1180 mm
	Focal Ratio	f/12
	Angular Field	20 arc minutes = 244 mm
	Focal Plane	2000 mm behind the vertex of the primary
Coudé:	Mirror diameter	1000 mm
	Focal Ratio	f/31.3
	Angular Field	4' arc minutes = 127 mm

The 3500 mm diameter mirror blank fabricated from U.L.E. (Ultra-Low Expansion glass) will be delivered by Corning Glass International about mid-September, 1971. Its thickness will be 580 mm and it will have a central hole 800 mm in diameter.

Dilworth, Secord, Meagher and Associates Limited of Toronto are presently designing the structure of the telescope. At this time the basic structural configuration of the tube and mounting has been established. The general configuration is shown in Figure 1 in the form of a model.

The mounting has been designed for a site latitude ranging between 37° and 40° north. The site testing survey which has been carried out in Italy during the past few years indicates that the seeing conditions are best for a large telescope between these latitudes. Detail studies are now being carried out at the four sites which promise better than average seeing. Italy itself is not the ideal country for the location of a large telescope because of its peculiar geographical structure. In any case, an average seeing condition of about 2 arc seconds occurs quite frequently for long periods of time in several locations. However, extremely good seeing of 1 arc second or less is quite a rare event.

The mounting is of the basic fork design. The pedestal is composed of a steel space frame which supports the fork on two oil pads at the north bearing and on a gimballed bearing system at the south end of the cone. The weight distribution of the structure is such that the center of gravity of the rotating portion of the telescope is in direct line with the reaction of the north hydrostatic pads. The result is that there is little or no net axial thrust along the polar axis. There is also little or no net moment about the north pads such that the lower south bearing is lightly loaded. It has been decided to replace the standard oil hydrostatic bearing by an anti-friction bearing. The additional friction of the mechanical type of bearing over that of the hydrostatic oil type will aid in damping vibrations that may occur due to external excitation.

The fork tynes which are fabricated of internally braced flat plates are rigidly connected to an extended portion of the lower cone. Internal bracing within the cone assures a completely built-in joint connection. The

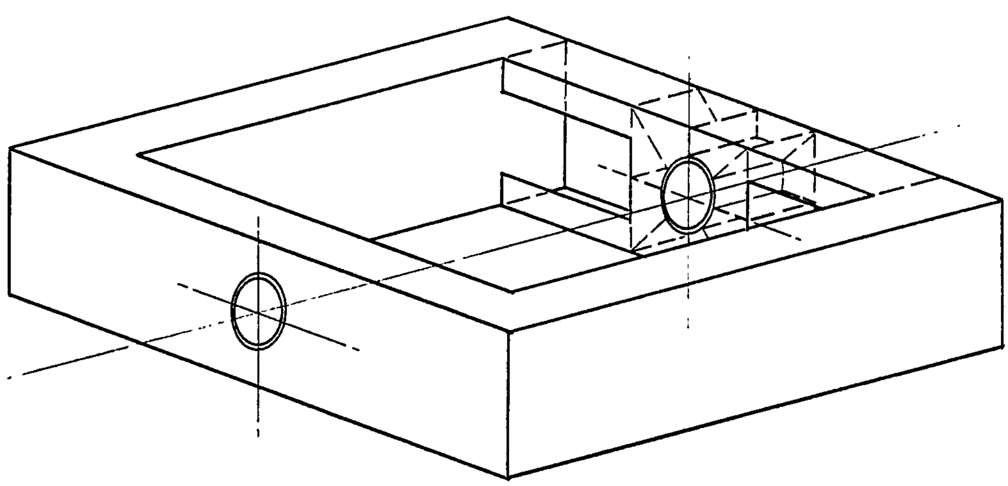


Fig. 2 Centre section.

declination bearings are mounted in rigid housings at the ends of the tynes. The structure of the fork is such that a five mirror coudé system can be used with the light beam passing through the fork tyne down through the inside of the cone to a driven fifth mirror which in turn folds the beam to the horizontal coudé room slit.

The fork tynes are to be designed to give a very small and nearly equal deflection for all hour positions.

The telescope tube is of the standard Serrurier type with the slight modification that both the lower and upper truss are connected to the top side of the center section.

The tube design is based on the principle of exchangeable upper ends. Two upper ends are employed:

(i) Prime focus assembly with an observer's cage,
(ii) Cassegrain-coudé combined assembly.

The upper ends are exchanged with the tube in the horizontal position by a specially designed machine located at the periphery of the dome and building. During exchange operations the tube will be restrained by tie-down facilities at the upper ends of the Serrurier trusses. Automatically activated quick release latches will be used to assist in shortening the time required for the upper end exchange. With semi-automatic operation it is anticipated that the exchange operation can be completed in about 20 minutes.

The center section is a combination of two box beams in the east-west direction connected to two reinforced channels in the north-south direction as shown in Figure 2.

The lower Serrurier trusses pass through the center section and are attached to the top flange of the mirror cell. A ventilation cowling with four radially mounted exhaust fans encloses the gap between the bottom of the center section and the top of the mirror cell. The details of the mirror cell may be seen in Figure 3.

The mirror is axially supported on 24 pneumatic pads combined with 3 axial defining units. The radial support is composed of 24 lever-fulcrum mechanisms with radial defining provided by 4 equally spaced temperature compensated units. Mirror position read-out is available for the radial and axial directions.

A motor driven Cassegrain instrument turntable is mounted on the underside of the cell. The coudé first flat support structure is a reinforced tube which is firmly mounted in the central hole of the mirror cell. Due to the large size of the first flat it will be necessary to remove the mirror and its cell when observing at the Cassegrain focus. It is anticipated that the flat will be temporarily stored in the fork tyne or center section.

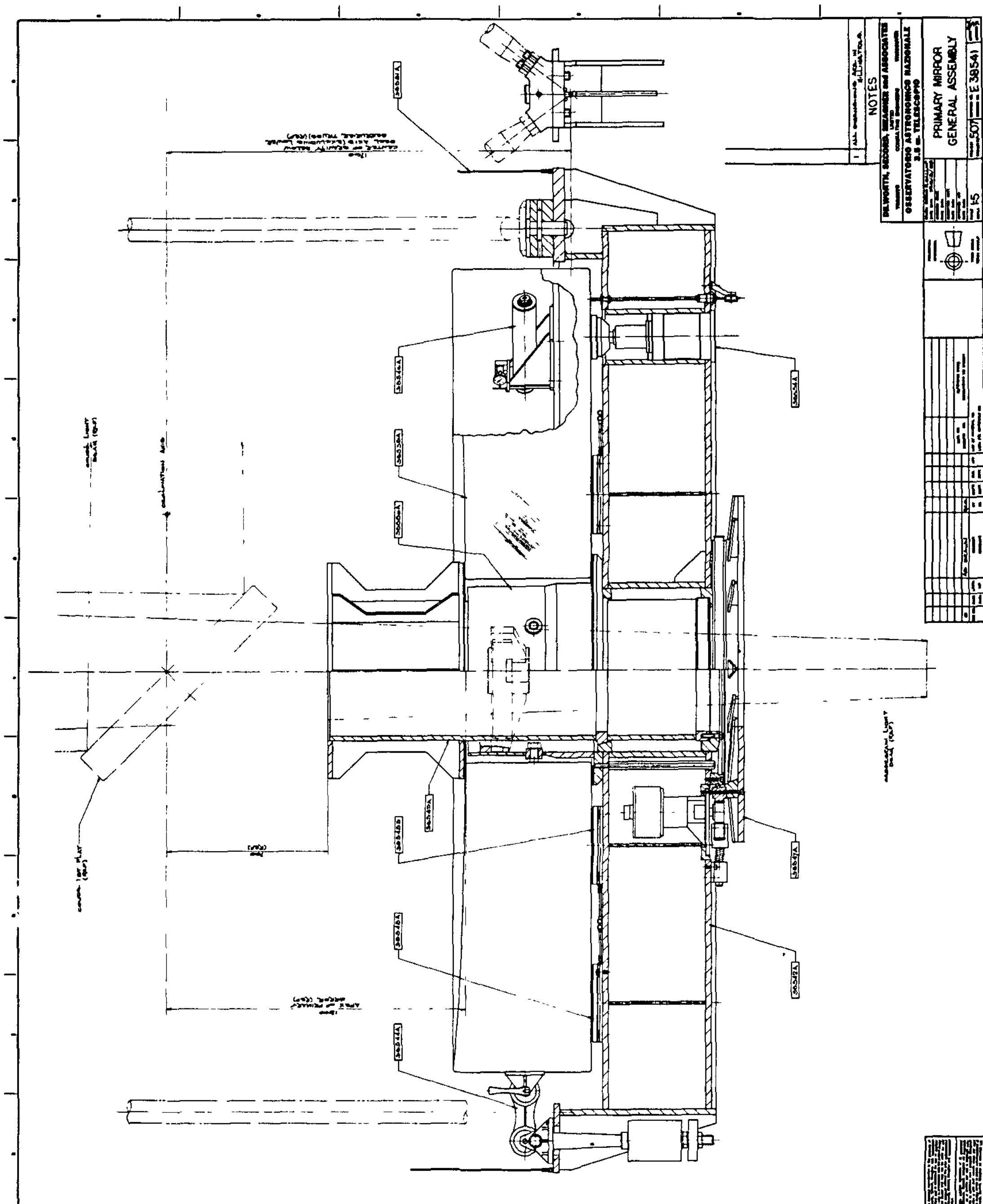


Fig. 3 Primary mirror. General Assembly.

Provisional space has been allotted for an observer and facilities at the Cassegrain focus. No definite solution as to the type of enclosure has yet been found. The clear space available behind the mirror cell is almost 2 meters. Instrument loads on the turntable of up to 1000 kgs may be accommodated.

DISCUSSION

BEHR: The length of the lower and the upper Serrurier system is quite different. Doesn't this introduce a number of difficulties?
FARRELL: Yes, it does introduce one primary difficulty of course, which is maintaining the balanced deflections. This has required that we move the connection of the Serrurier truss from the lower to the upper portion of the center section and that we reduce the sizes of the tubes to approximately 100 mm, and that the wall thickness be corresponding to give us the balanced deflection.
LAUSTSEN: As far as I could see from your drawings, you will have some limitation in space for the Cassegrain focus. Do you intend to have a Cassegrain cage, and how much space will you have in the cage?
FARRELL: At the moment, as you saw in the model, the facility at the Cassegrain focus is not yet defined. We have approximately six and a half feet available from the bottom side of the cell to the inside of the fork. One of the requirements of the design is that the tube shall reach the horizontal position in one direction and be able to reach 10° above the horizon in the other direction. This required that we lengthened the fork tynes, which on preliminary calculations doubled their deflection, and this gave us more room under the back of the cell.
DENNISON: The problem of the Cassegrain focus cage space may be helped a great deal by the use of high-sensitivity integrating TV-type systems which will enable the observer to operate from off the telescope and see the star fields as well and probably better than he would be able to see with the unaided eye at the telescope. We have had a system built for us which will do this and I just saw the first working version this last week. It is extremely impressive, and within a relatively short time I think the experience will be gathered which will probably indicate that the observer need not ride at the Cassegrain cage, but that it will be possible for him to operate very satisfactorily off the telescope.

FARRELL: Is this TV system possible for the prime focus cage as well?
DENNISON: Yes.

BORGMAN: If it were only that you want to get rid of the viewing of the field by the observer, there are of course remote TV devices, which are even superior to the eye observing directly into the eyepiece. But there are many other aspects of the observer needing him to be present close to the equipment, for instance servicing of cryogenic systems which is almost impossible to do remote controlled.

BAUSTIAN: I think this brings up the point that you should consider the communication between the Cassegrain cage and your control center. On the 150 inch at Kitt Peak, we have a so called gang-plank which gives us direct communication between the Cassegrain cage and the console floor. The other thing that I would like to point out is that with most of these large telescopes you will be some 6 or 7 meters in the air and from a point of safety both for personnel and equipment that may or may not sometimes get away from you, the cage does have a very specific use and I think it is a necessity.

FARRELL: In this particular design the level of the observer's floor is only 2 meters below the lower surface of the Cassegrain cage with the tube in the vertical position. With a yoke type mounting of course, especially in the Palomar design, you have more opportunity to build some access platform beneath it. We have not intended to do this with the fork design in this particular case.

BELLY: One of your goals was to have the weight of the cell equal to the weight of the mirror. What is the reason for that?

FARRELL: We have a feeling that it is advisable to try to keep the tube weight as low as possible. This is not to get into what one might term "light-weight design", but to design the structure more efficiently by using less steel and place it in the appropriate places so you develop the same strength with much less weight. If you take a cell which is approximately 18 inches deep, the equivalent strength of that would be something similar to 14 inches of solid steel, so there is of course no advantage, but if you can increase the depth of the cell an extra inch or two without decreasing the accessibility at the Cassegrain focus, then it is advisable to do so. This is of course contingent on the fact that you can balance the tube without severely limiting the flexibility of the upper ends, and the observing equipment that you can place there.

RULE: Is the radial support system to be push-pull?

FARRELL: Yes, that is correct.

FEHRENBACH: You have chosen ULE glass; do you think it is very important to have this type, which is more expensive than the normal Corning glass?

RIGHINI: We invited Owens Illinois and Corning to submit an offer for the blank, and Corning's was the more convenient.

FEHRENBACH: And the price was much lower?

RIGHINI: Yes.

FEHRENBACH: I think the next trouble in large telescopes will be the air layer on top of the mirror, so, when you go from the ordinary silica to ULE, you will have no difference in quality.

WILSON: Could you say something more about the reason for your decision to choose f/4 primary focus, is this technological or astronomical?

RIGHINI: We had a very long discussion, but the majority of the astronomers in Italy were in favour of an f/4 classical. This seems to us to be the best compromise between the different ideas, so the choice was on an astronomical basis.

DOSSIN: What kind of corrector do you use at the prime focus? You mentioned a field of one degree.

RIGHINI: We have not yet reached this point of development of our project, but we hope to have a corrector, perhaps with 2 or 3 optical elements in order to get a field of 1°.

OKE: Does the coudé flat just get tilted vertically or is it removed when the Cassegrain is used?

FARRELL: At the moment our initial assessment is that the coudé flat is too large to be rotated out of the Cassegrain beam and we are considering removing the coudé flat and storing it on the center section.

ROOSEVELD VAN DER VEN: What type of declination bearings are installed in your design?

FARRELL: I would like to pass it over to Mr. Eggmann who is involved in the declination bearing design.

EGGMANN: At the moment we intend to have roller bearings for the radial load, and two angular contact bearings face to face for the truss load.

THE PROJECT OF THE "MAX-PLANCK-INSTITUT FÜR ASTRONOMIE"

H. Elsässer

Max-Planck-Institut für Astronomie

German astronomers are in great need of modern equipment. The largest telescopes of the observatories in the Federal Republic of Germany are at present still of the 1 meter size. Participation of our country in ESO was an important step forward, but at the same time it became clear that the ESO facilities could not entirely satisfy our demands, and that a considerable improvement on a national level is most urgent.

Our efforts in this direction finally obtained the support of the Max-Planck-Society, and two years ago a new Max-Planck-Institute for Astronomy was founded. The Max-Planck-Society is an independent non-profit organization for basic research financed mainly by the Federal Government and the eleven states of our Republic. At present the Max-Planck-Society maintains about fifty research institutes in all fields of science, of those the Institute for Extra-terrestrial Physics in Garching/ München, the Radio-Astronomy Institute in Bonn with the 100 meter antenna, and our Institute in Heidelberg are all relatively young institutes devoted to research in astronomy and astrophysics. With regard to our institute, it is an essential aspect that all facilities can be used not only by members of the institute but by all German astronomers and guests from outside.

THE PROGRAM

The project we are realizing now consists of three components:

1. A new institute is built in Heidelberg with laboratories, workshops and offices for the development of new methods in optical astronomy and for the preparation and evaluation of observations performed at our observatories outside Germany. We think that it is essential to have this central institute within Germany near to a university and other scientific and technical centers.
2. A northern hemisphere observatory will be constructed in the Mediterranean area. This observatory for problems of the northern sky should not be too far away so that it can be used for the education of students also, but the climatic conditions must be much more favourable than those of our country.

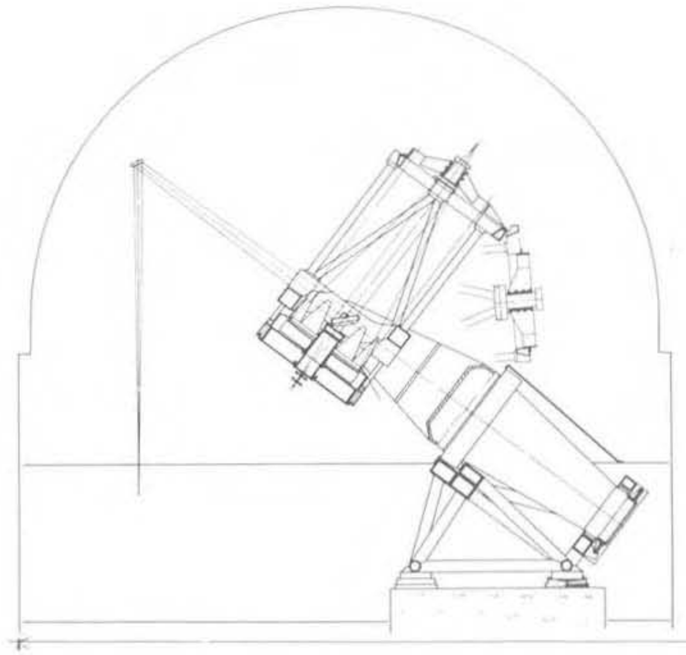


Fig. 1 2,2 m-R.Ch.-Telescope with polar-coudé.

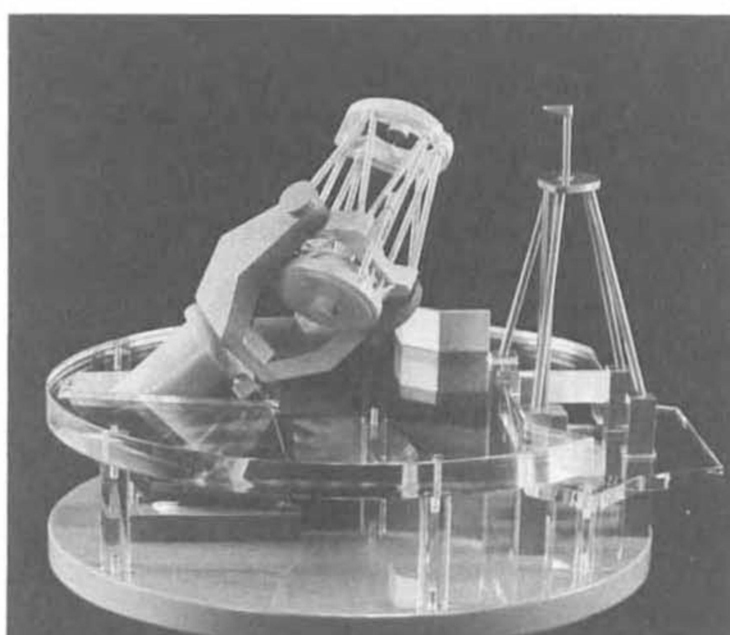


Fig. 2 Model of the 2,2 m-Telescope.

3. A southern hemisphere observatory will be created for southern sky observations.

The question of the locations for these observatories is discussed below.

THE TELESCOPES

The northern hemisphere observatory will be equipped with:

- a 1.2 m telescope of Ritchey-Chrétien type (primary focal ratio f/3, Cassegrain system f/8). This telescope was constructed by C. Zeiss Oberkochen and is almost completed at the time being.
- the Schmidt telescope of the Hamburg Observatory (80/120/240) which will be moved from Hamburg-Bergedorf to this new site.
- a 2.2 m telescope of Ritchey-Chrétien type with Cassegrain and coudé foci (focal ratios f/3 primary mirror, f/8, f/40). This telescope is under construction and will be delivered by C. Zeiss in 1973.

At our southern hemisphere observatory apart from smaller instruments,

- a 2.2 m telescope as a duplicate of the northern instrument will be set up. It is already ordered and will be delivered within about 18 months of the first one.

Before going on with this list, a few important details of these 2.2 m telescopes should be mentioned. The optical system corresponds to the strict Ritchey-Chrétien solution. For the Cassegrain focus, a two-lens-corrector calculated by Dr. Wilson will be available. It gives an excellent definition within a field of about 1 degree diameter which will be photographed on 30 x 30 cm^2 plates. I am sure that Dr. Wilson will report on his new corrector-systems in one of the next sessions. Both telescopes will be provided with fork mountings built by MAN as a subcontractor.

The coudé system is of the polar coudé type. The four-mirror system deflects the beam to the vertical direction. The beam can get out of the tube due to a twisted shape of the tube's central part which makes it necessary to reverse the telescope near the equator (Fig. 1). Stability and flexure of the tube were carefully studied. We intend to install a coudé laboratory with ample room below the observing floor. Fig. 2 shows a model of the 2.2 m telescope. The final mounting of mirror 4 will be different from that shown in this Figure, it will stand on a relatively high stable platform which is connected to the piers of the telescope and the coudé room.

All mirrors of the 2.2 m telescopes are made of Zerodur by Schott, a zero-expansion glass ceramics as Cervit. The primary mirror of the first telescope was delivered in July 1970 and is now in the polishing stage. The experiences with this new material are very satisfactory up to now. The axial support system of the primary mirror is of the type developed by Dilworth, Secord and Meagher in Canada. The radial support will be a push-pull system.

The telescope drive will make use of a Servalco torque motor which is controlled by a Honeywell H 316 computer. Details of this telescope control system are described elsewhere (Bahner and Solf, 1970).

The astronomer responsible for the 2.2 m telescopes is Dr. K. Bahner, the problems of the computer control system were studied at our institute especially by Dr. J. Solf.

In addition to the telescopes mentioned already for one of our both observatories

- a 3.5 m telescope will be constructed. We have ordered the disk for the primary mirror which will be made of Zerodur also and which shall be delivered by Schott in 1971 still. C. Zeiss has produced a design study which includes studies of the optical system, the mounting and problems of organization. At present we are negotiating with Zeiss about a contract and we hope to come to terms in the near future. But at this stage the details of the design are not yet fixed. At this moment it is not yet clear which type of mounting the 3.5 m telescope will be provided with. This choice depends not at last on the geographic latitude where the telescope will be installed.

SITES OF THE OBSERVATORIES

For our northern hemisphere observatory, the site selection was started years ago, prior to the foundation of the new institute, by a study of the meteorological conditions within the Mediterranean area. Cloud records of the weather bureaus were evaluated for a longer period, in addition information about cloudiness was derived from the ESSA satellite photographs. These valuable pictures are available for Europe day by day since 1966. In this way we became interested in regions of southern Greece on the Peloponnes peninsula and of southern Spain for further astronomical test observations. In Spain we could cooperate with the French group of INAG.

After about 2 years of seeing tests and measuring atmospheric extinction and other meteorological quantities, the Calar Alto mountain (2168 m above sea level) of the Sierra de los Filabres in the province of Almeria/Spain got first priority (Fig. 3). According to our experiences till

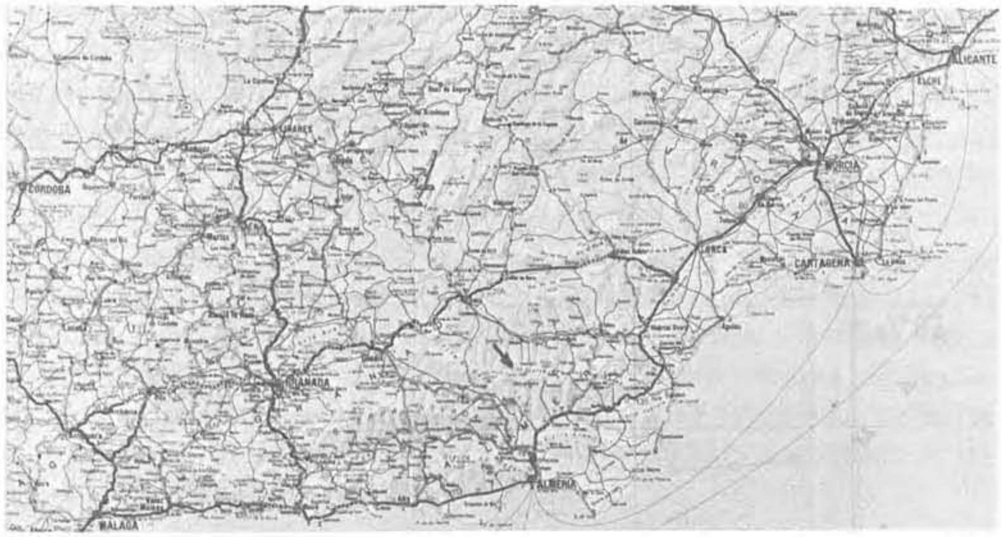


Fig. 3 The south-east region of Spain. Calar Alto mountain marked.

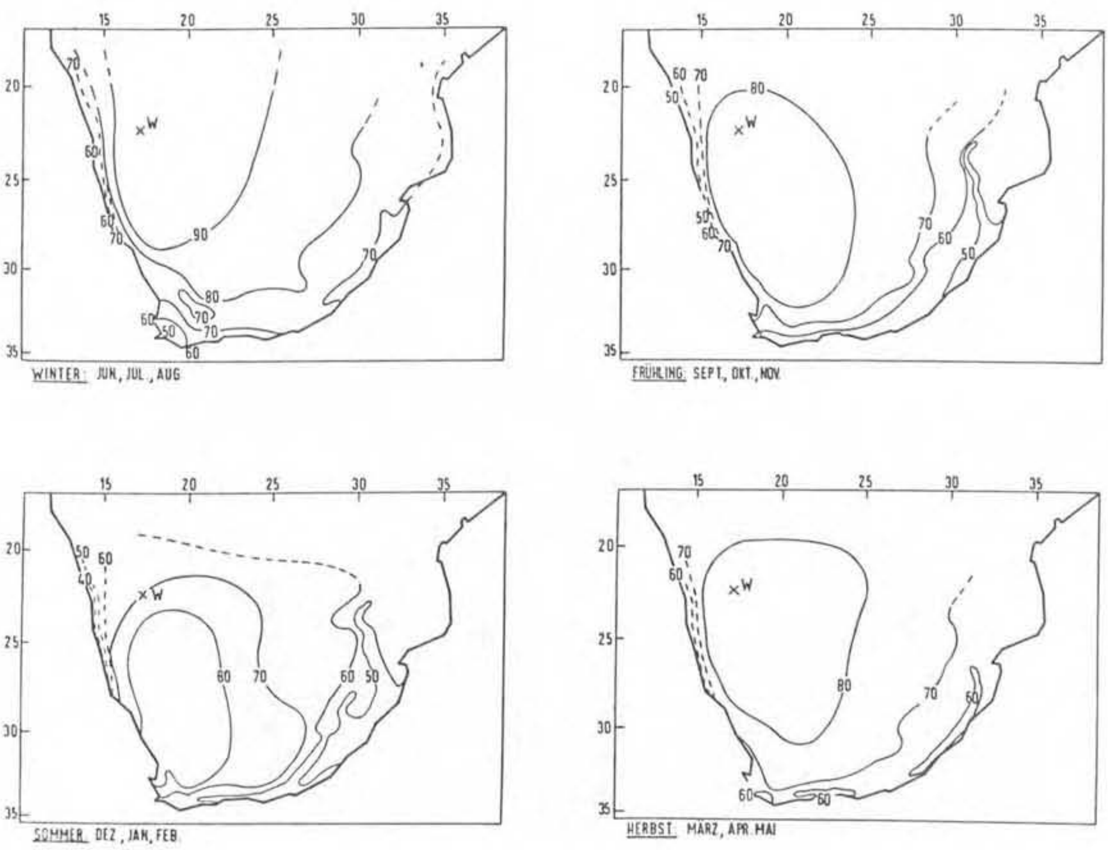


Fig. 4 Seasonal distribution of sunshine duration in South Africa (% of possible). W = Windhoek.

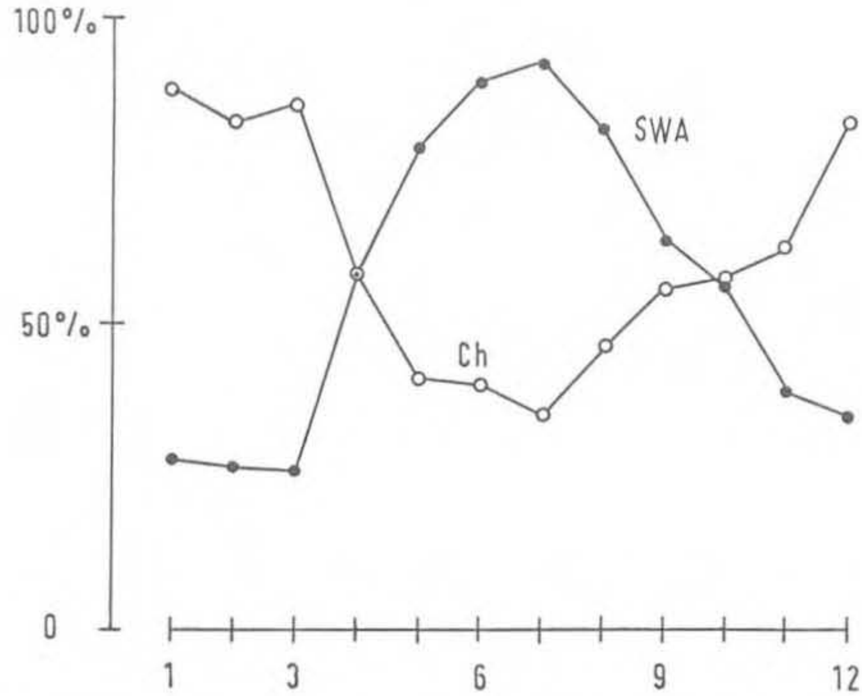


Fig. 5 Average annual variation of frequency of photometric nights (Chile) and days with ≥ 90% of possible sunshine duration (South West Africa). Percentage of possible.

Fig. 6 The Gamsberg tablemountain in South West Africa (2350 m).

now there we can expect about 1800 hours of observation per year. At present we are conferring with the Spanish Government; if an agreement can be made we intend to establish our northern hemisphere observatory there. A topographic survey of the mountain range in question and investigations of the soil, water supply etc. were already performed in 1970. We hope that the building activity can start soon.

The southern hemisphere observatory will be located either in Chile or in South West Africa. Nothing must be said here about the conditions in Chile, we are all aware of their excellent quality. But one may ask if a concentration of nearly all larger southern observatories in Chile is wise, or rather a more even distribution in geographical longitude is to be preferred. Besides such considerations we believe that South West Africa would be a good choice for the following reasons:

Her climatic conditions are the most favourable ones of South Africa. This is demonstrated by Fig. 4 which shows the seasonal distribution of sunshine duration (% of possible) for South Africa according to data of the Weather Bureau of South Africa (Schulze 1965). It is obvious that south of Windhoek the cloudiness is lowest on the average. As in the case of Chile a cold stream (Benguela Stream) goes up along the coast of South West Africa. ESO investigated farther southern parts of South Africa during the years before 1960.

The annual march of cloudiness is complementary to that of the La Silla and Tololo region in Chile. In South West Africa the good season occurs during winter from April to October. Fig. 5 shows for Chile the average number of photometric nights according to the ESO reports for the last five years (% of possible). For South West Africa we have not yet reliable information about annual nights. The diagram contains the average number of days per month with 90% or more of the possible sunshine duration derived from records in Windhoek during the 11 years between 1960 and 1970. According to our own experience in South West Africa since September 1970, the numbers of photometric nights are at least equal to or larger than those. The total per year derived from both curves of Fig. 5 is 219 nights for Chile and 206 days for SWA. At present we are performing a study of ESSA cloud pictures which we received from the National Climatic Center (USA) to get additional data for the comparison of Chile and South West Africa.

Since September 1970 we have made test observations on top of the Gamsberg, a table mountain 120 kilometers southwest of Windhoek at the edge of the Namib desert with an altitude of 2350 m above sea level. The plateau of this mountain is almost 3 kilometers long and about 700 m wide (Fig. 6). We were afraid that this might be too large and unfavourable for the seeing conditions at the plateau's center. Therefore, we started with recording temperature, humidity, and wind at 6 different places. No significant differences are found so far in the temperature and humidity variation between these various locations.

The average temperature amplitude (2 m above ground) during 100 nights amounts to 3°2 Celsius which we consider as a very favourable value. The average difference of the daily maximum and minimum in temperature up to now is 11° C, an unexpected low number. Seeing is recorded up to now by photographic star trails. For 80 % of the nights we found the r.m.s. amplitude of the image motion to be smaller than 0.8 seconds of arc. This quantity is the same as measured by the p.e. knife-edge monitor used in Chile. Our tests had to be made so far by means of simple equipment because access to the mountain's top was very difficult. But a primitive road is under construction and will be completed soon so that we can work with heavier and better instruments in the near future.

It seems to be especially desirable to compare the seeing at different sites with identical methods and equipment. We are now prepared to do this by photoelectric as well as by photographic means (Elsässer, 1970) and intend to start a campaign within some months for a comparison of the site in Spain, the Gamsberg in South West Africa and La Silla in Chile. This has to be done before the final decision on the location of our southern-hemisphere observatory can be made which we are keen to reach before the end of 1971.

Literature

Bahner, K. and Solf, J. : A Digital Computer as Process Controller of a 2.2 m-R.C.-Telescope. Proceedings IAU-Colloquium No. 11, Edinburgh 1970 (in press).

Elsässer, H. : Zum Problem der Seeing-Messung. Annalen Sternwarte Wien, Band 29, Nr. 2 (1970).

Schulze, B.R.: Climate of South Africa. Part 8. Weather Bureau of South Africa (1965).

DISCUSSION

RULE: Has there been a study made of the vibration or the stability of the stand required to the fourth mirror?

ELSÄSSER: It is better to pass on this question to Mr. Kühne.

KÜHNE: The calculations of the stability are not yet finished. It is foreseen to have 4 pillars to carry mirror 4 and we will have a tube which we can extend to the position for observation and retract when we use the

Ritchey-Chrétien focus, so that it will not be cut off in the polar region.

ELSASSER: The idea is to have a platform on which mirror 4 is mounted. This platform is relatively high, but according to the calculations, I think this is not dangerous.

LAUSTSEN: Will you have an unprotected beam of 20 meters or so in the dome? Have you investigated to what extent disturbances of the air will influence the seeing?

ELSASSER: We have not really studied it, but we are aware of this problem. We will take precautions to reduce the dome seeing as far as possible, for instance by some system of cooling the bottom of the observing platform.

LAUSTSEN: It is not the intention to include the beam in tubes?

ELSASSER: Not at the moment, at least not from the telescope to mirror 4!

CAYREL: Have you found any significant difference in seeing between the Sierra de los Filabres and the Sierra de Gador?

ELSASSER: No. the distance is only about 40 - 50 kms. The climatic conditions and everything else I think are very similar. We have made parallel observations on both mountains.

CAYREL: Yes, but the position with respect to the Sierra Nevada is different.

ELSASSER: Yes, that is right. And on Sierra de los Filabres you are more free to the predominant wind direction, which is northwest.

BEHR: It is very difficult to compare the results of different observers in different places of the world with different equipment. How is your seeing defined and how can it be compared with Dr. Babcock's results?

ELSASSER: We have recorded in South West Africa what we call "fast star trails", and the seeing is defined as a r.m.s. of the amplitude. But we have the impression from our own investigations that the seeing as measured with photoelectric seeing monitors is systematically smaller than what we get from the photographic star trails. This problem will now be studied with three identical photoelectric seeing monitors.

BORGMAN: What is your definition of the amplitude on the trail?

ELSASSER: It is half of the total spread. In other words the image diameters we expect are double what we measure in this way. I think this is confirmed by the results of ESO. ESO has published results about image diameters, estimated at the slit of the 60 " telescope, which are at least double this value; the maximum of the distribution lies between 1".5 and 2".0.

BORGMAN: Did not Dr. Babcock state that the average image diameter on the Las Campanas site would be in the order of 1" ?

BABCOCK: We could not really measure the image diameter, but with our portable photoelectric seeing equipment we reported the total amplitude. It is a difficult question to proceed from the measured amplitude as reported from the seeing monitors to the true image that one would observe with a large telescope. We don't really pretend that we can predict what that would be.

ELSASSER: I don't fully agree with Dr. Babcock. But I think we agree that it is really a problem to compare the seeing on different sites with different equipment. It is therefore our intention to make seeing tests with identical equipment at three different sites to get a differential measurement and not an absolute one.

BABCOCK: I agree that it is a very difficult thing, especially when the equipments are not really similar. One has to pay attention to the frequency passbands involved and to the techniques of automatic guiding and so forth, so one has to be extremely careful in these matters.

FEHRENBACH: You mentioned a mean temperature variation of 3.2° C. That is certainly small for European conditions but not for Chile.

ELSÄSSER: I think the mean value for La Silla is 2.7° C or something like this?

FEHRENBACH: Yes for the mean, but the mean is not a good indication. During the good nights you have a variation of 1 - 1.5° C.

ELSÄSSER: Of course, Dr. Fehrenbach, but 3.2° C is also a mean value.

THE SOVIET 6 m TELESCOPE PROJECT

I.M. Kopylov
Spetsialnaja Astrofizicheskaja Observatorija AN SSSR

INTRODUCTION

There has been definite progress in the development and extension of astronomical instrumentation in the USSR during the last ten years.

The excellent 80" telescope manufactured by Carl Zeiss in GDR went into operation at Shemakha Observatory some years ago.

A few smaller telescopes up to 60" in diameter have been built or are presently in the design stage.

The 102" telescope at the Crimean Observatory was mounted in 1960 and still remains the largest one in the USSR.

Exactly the same size telescope for Bjurakan Observatory in Armenia is now under construction.

Nearly ten years ago our Government, taking into consideration a request of the Academy of Sciences, adopted a decision about the design and construction of a large telescope and the creation of a new astrophysical observatory where the telescope was to be installed.

A committee was appointed for the supervision of this project, and at the same time about 15 expedition teams were organized in order to look for the best site for a new observatory within the territory of the USSR.

The staff of the instrumentation department of Pulkovo Observatory, at that time headed by our prominent optician, the late Prof. D.D. Maksutov, considered very carefully all aspects of the construction of this telescope. Considered were especially the mounting and the optical scheme. For example, rather seriously considered was a modified yoke type mounting (Fig. 1) which has now been realized with the Kitt Peak and Chile 158" telescopes of AURA and on which the AAT project is based.

Finally, in November 1960, the above mentioned supervision committee and the Astronomical Council of our Academy considered and approved the draft project of the telescope. A firm decision was taken to construct a 6 m (236") telescope with alt-azimuth mounting and therefore that telescope received the abbreviated name - BTA (Big Telescope with Alt-azimuth mounting).

Dr. Bagrat Ioannisiani was appointed head designer of the 6 m telescope. Formerly he and his staff had designed a 102" telescope for the Crimean Observatory.

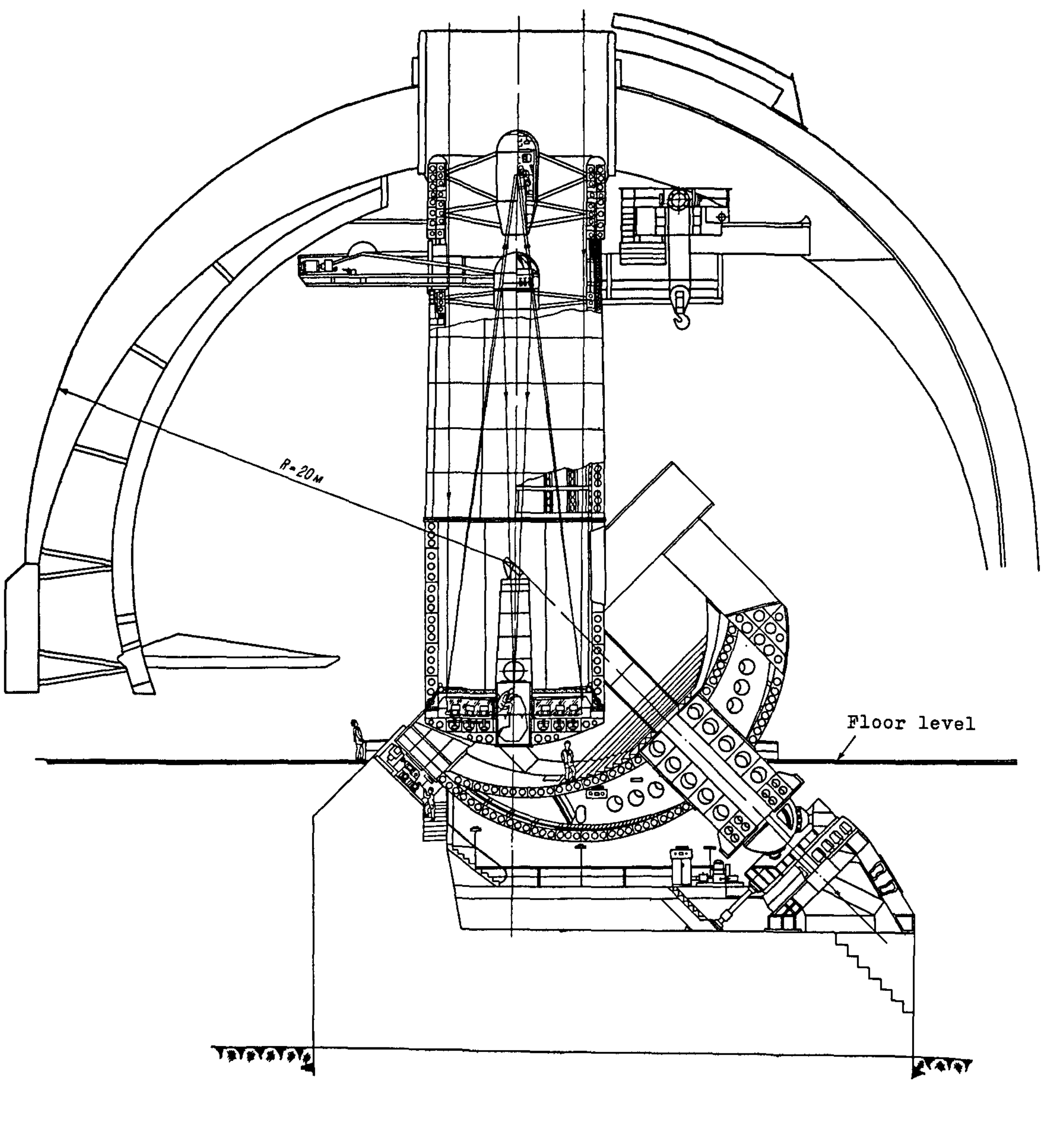


Fig. 1

The site of the new observatory was chosen on the northern slope of the Main Caucasus mountain chain, halfway between the Black and the Caspian Seas.

THE MOUNTING

An alt-azimuth mounting for a large telescope has several important engineering and astronomical advantages. The basic ones are:

a) The relative simplicity from the point of view of mechanics in comparison with any kind of equatorial mountings.

b) The loading on a vertical axis is symmetrical and constant. Rotation in azimuth creates no change in loading conditions and no elastic deformations.

c) The flexure of the tube is limited to one plane and depends on zenith distance only.

d) It is possible to use oil bearings for both axes.

e) The construction of the mirror support system is simpler than for any equatorial mounting. The loading reactions in the mirror are always in one plane.

f) The balancing of the telescope and its tube is rather simple. The tubes must be balanced in one plane only.

g) The light loss at the secondary focus is as small as possible - we have for instance only three mirrors - the main, the secondary and the flat mirror.

h) The maintenance of secondary foci is rather convenient. There are two observing platforms on either side of the tube on top of the vertical fork. The secondary focus spectrographs can be put into operation by a simple 90° - flipping of the flat mirror.

i) The mounting is independent of the latitude of the site.

The main disadvantages of this type of mounting are:

a) When tracking a celestial object both axes have to be turned at non-uniform speeds.

b) The field of view rotates continually.

c) There is a "dead" zone at the zenith point.

In order to overcome these difficult problems it is necessary to control alt-azimuth telescopes by digital techniques. For at least 12 years our astronomers have been concerned with the problems of special-purpose computers for control systems of large optical telescopes.

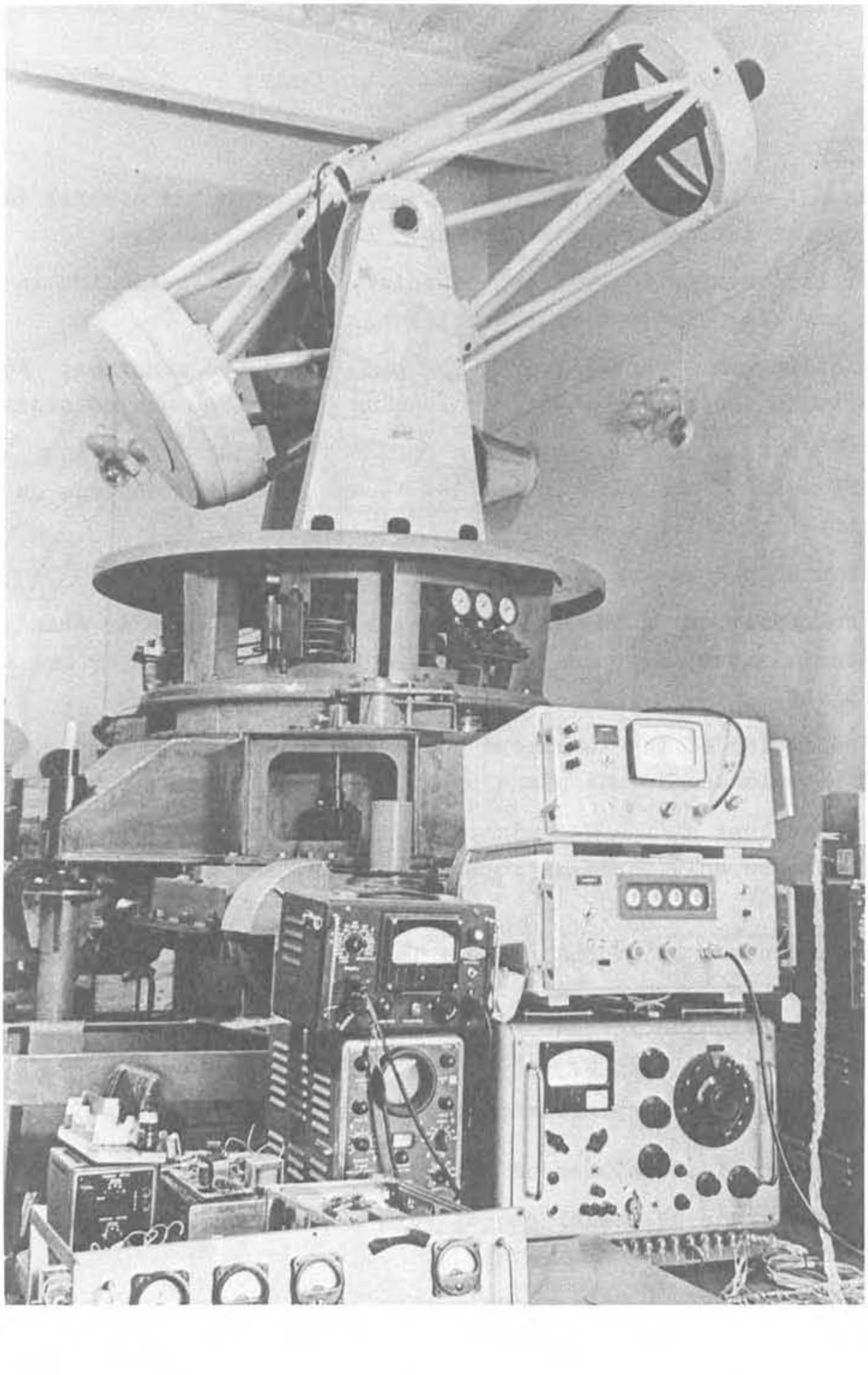


Fig. 2

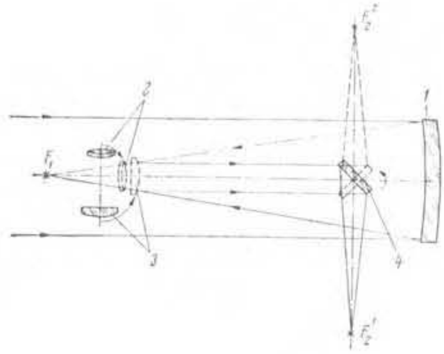


Fig. 3

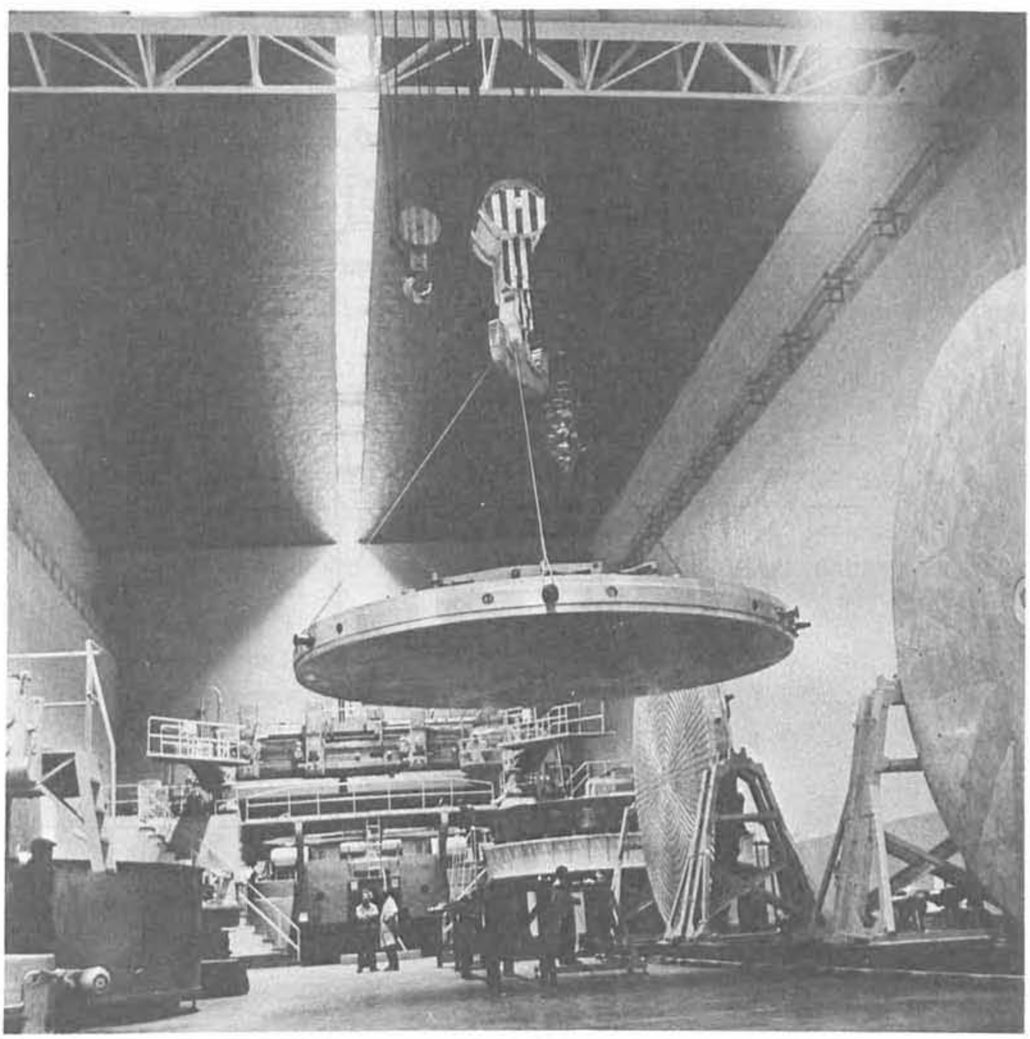


Fig. 4

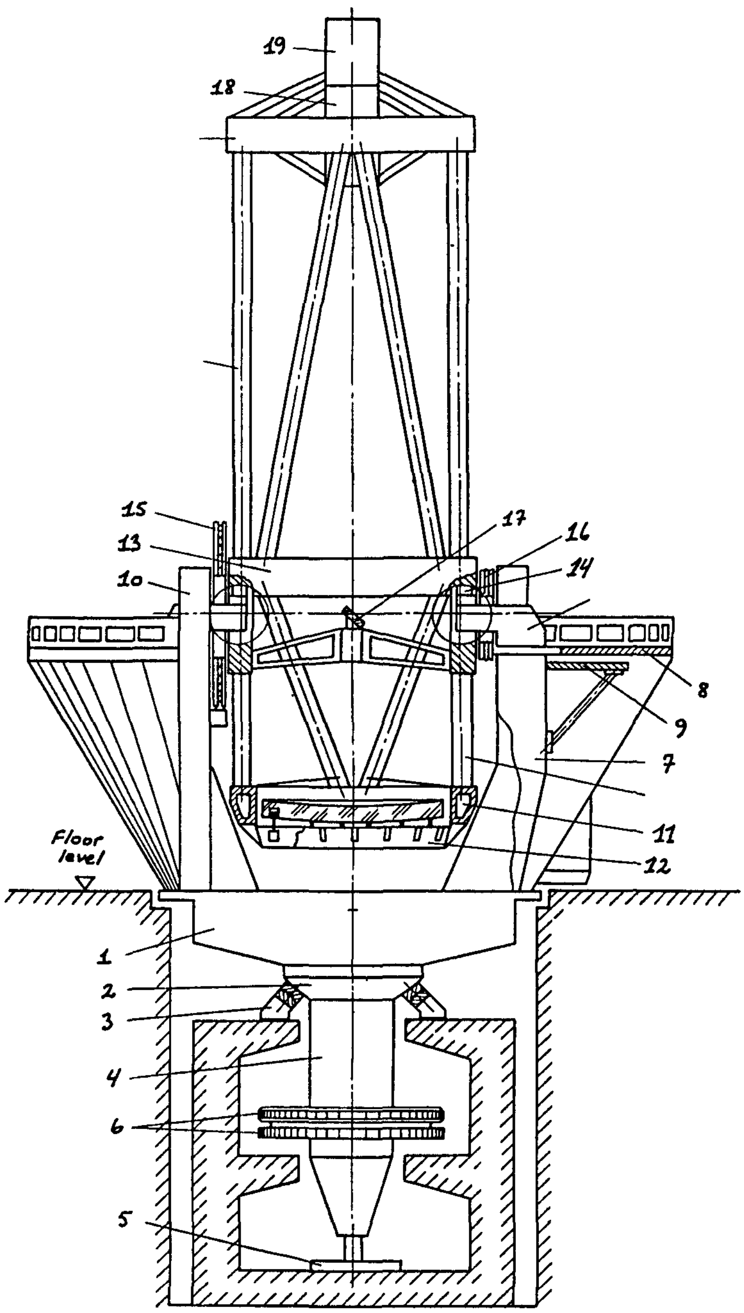


Fig. 5

A certain number of connected questions were checked with a small one-tenth scale model (Fig. 2) of the 6 m telescope which was constructed for this purpose. The model has been used for testing during several years by Dr. Ioannisiani's staff at Pulkovo Observatory. It is possible that we shall encounter some non-essential difficulties in the future, but we think now that our decision to select the alt-azimuth type mounting for such a giant telescope has been fully justified.

THE OPTICS

I would now like to say some words about the optics of the 6 m telescope (Fig. 3). The primary focus (F_1) is f/4 and the focal length is 24 m.

The 42 ton main mirror solid blank (1) which was cast and ground at the Optical Glass Works is a pyrex-type low-expansion borosilicate glass. The expansion coefficient is 3.10^{-6}°C $^{-1}$. The thickness of the mirror blank is 65 cm. The back surface of the mirror has a spherical form in order to diminish the thermal edge effect. In the back of the mirror blank 60 sockets are placed on four rings for accommodation of the mechanical support system. There is a central 50 cm hole.

The two-lens corrector (2) for the primary focus was designed by D.D. Maksutov and gives a flat field of 12' or, taking into account the seeing, of 22' in diameter.

The secondary, non-standard Nasmyth foci ($F_2^{\,1}$ and $F_2^{\,2}$) are f/31, and the focal length is 186 m. There are some additional lens correctors at the secondary focus to obtain a parallel beam, a slightly widened field etc.

The lens corrector (2) for primary focus and the secondary mirror (3) are placed inside the primary focus unit and can be interchanged rapidly.

Figure 4 shows the interior of the optical shop. The polishing machine is in the background. The main mirror on its cell can be seen to the right in the background. The mirror is now in the final test stage.

SOME MECHANICAL FEATURES

The principal mechanical elements of the telescope can be seen from the simplified drawing (Fig. 5).

The upper horizontal plane of the 100 ton platform (1) coincides with the observer floor.

The spherical ring (2) attached to the lower part of the platform rests on six oil pads (3). Three are fixed and the other three are floating.

The vertical axis (4) is attached by its upper end to the platform and has adjustment facilities (5) at the lower end. The spur and worm gears

(6) are used for fast and slow horizontal motions respectively.

The vertical piers (7) carry two observing platforms (8). The platforms (9) are used for the mounting of light-receivers (spectrographs, scanners etc.). Inside each pier are stairs and elevators (10) up to the observing platforms.

The telescope tube is of the usual Serrurier construction. To the lower ring (11) is attached the cell (12) with the main mirror. The center piece (13) of the tube is supported by oil pads (14) on the horizontal axis. To the outer side panels of the center piece are attached the worm gear (15) and a cable reel (16). The supports of a diagonal flat mirror (17) are always in a strained position. The diameter of the prime focus unit (18) and observer's cage (19) is 1.8 m.

There is a very convenient device for instant automatic balancing of the tube. Also, it takes only about two minutes to change the optical scheme. We can do it automatically from the central control desk.

A steel and concrete imitator of the primary mirror was designed and manufactured. It is used during preliminary tests of the mechanics and the control system of the telescope. It is not needed at this stage to have the main mirror in the telescope.

The large spectrograph (similar to the coudé one) will be installed inside one of the piers.

There is a guide tube (Ø = 70 cm, f = 12 m) with visual guide unit, photoguide system and TV control for identification of the field of view. This photoguide is an important part of the general control system.

THE CONTROL SYSTEM

The most complicated component of our project is of course the control system. It consists of:

a) Computer of digital type. This unit transforms the equatorial coordinates of the object and siderial time - (α, δ, S) - to azimuth angle, zenith distance and positional angle of field of view (A, Z, P), and to rate of change of these three quantities - $\dot{A}$, $\dot{Z}$ and $\dot{P}$.

Every eighth of a second (P and $\dot{P}$ every second) these data are sent to the servomotors of the telescope and every eighth of a second the computer receives from the encoder devices information on the real positions and speeds of the telescope units in order to compare them and then to make the decision about the next operation.

The computer calculates and takes into account the atmospheric refraction using the data on current pressure and temperature from corresponding encoders.

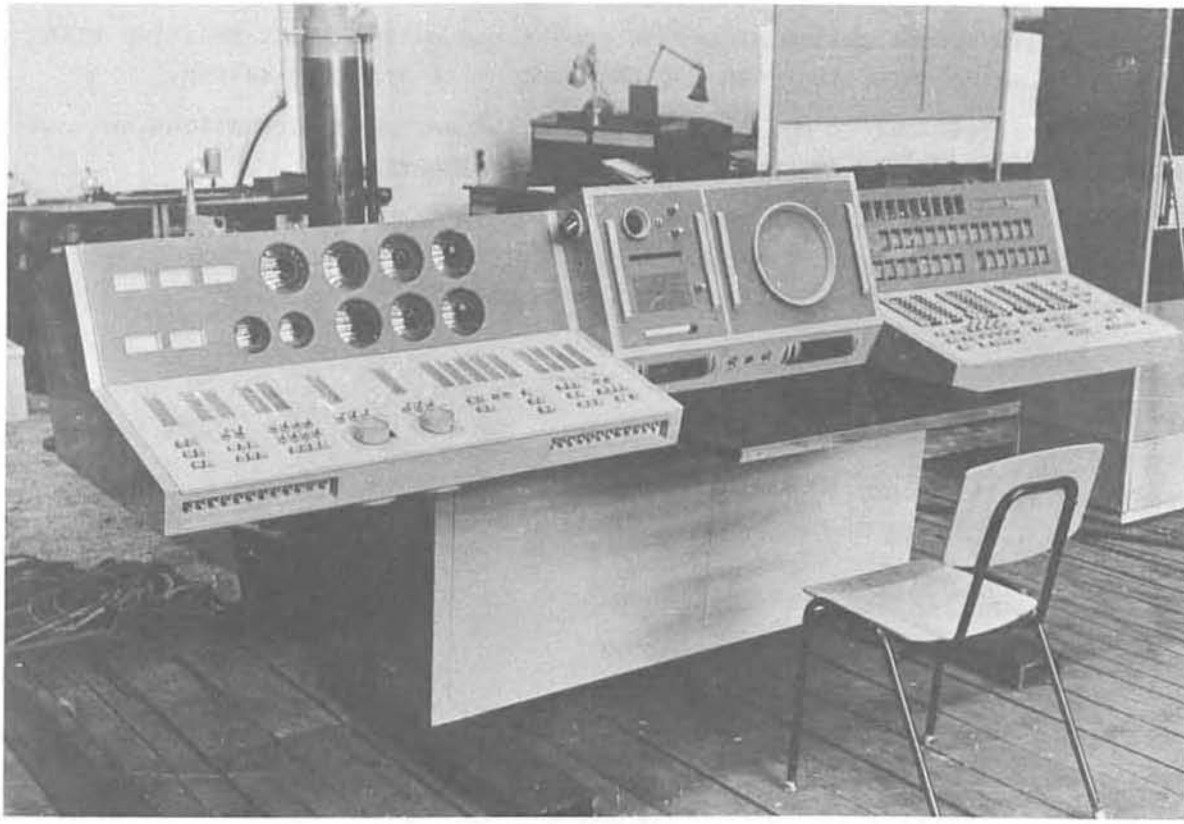


Fig. 6

Fig. 7

The control system of the telescope has output-input relation with the rotating drive of the dome for the purpose of synchronization.

The computer is doubled for accidental emergency situations and its most important blocks are automatically interchangeable.

The design of the computer allows us to take into account the dependence of the tube flexure on zenith distance after the real form of this dependence has been obtained.

b) The main control desk (Fig. 6) allows us to carry out almost all essential operations. The round TV screen in the middle section of the desk is now used for the identification of the stellar field of 30' or 9' seen through the auxiliary 70 cm guide tube. In the future we shall use this screen for checking the automatic TV guide.

BUILDING AND DOME

The building is a steel pillar construction covered on the outside with the large flat plates consisting of two aluminium sheets with insulation material between them.

The subterranian floor contains the oil supply device for azimuth rotation and a room for the lower end of the vertical axis of the telescope.

The ground floor contains a small mechanical shop for current repairs, some power and time equipment, a few labs and some auxiliary rooms.

The first floor is mainly used for the computers, photolabs and observing staff accommodation facilities.

The second observing floor includes an aluminizing plant, the central desk room and a visitors' gallery.

The building has two "ground-third floor" lifts and a load elevator.

The two walls of the dome have been constructed exactly as the walls of the building.

The power supply of the rotating dome is realized with cables. There is a windscreen.

There will be complete temperature control of the main mirror, the dome interior and the observing floor.

THE PRESENT STATE OF THE PROJECT

The road and power supply line were finished in 1967. The mechanical parts and control systems of the telescope were assembled a few months ago (Fig. 7).

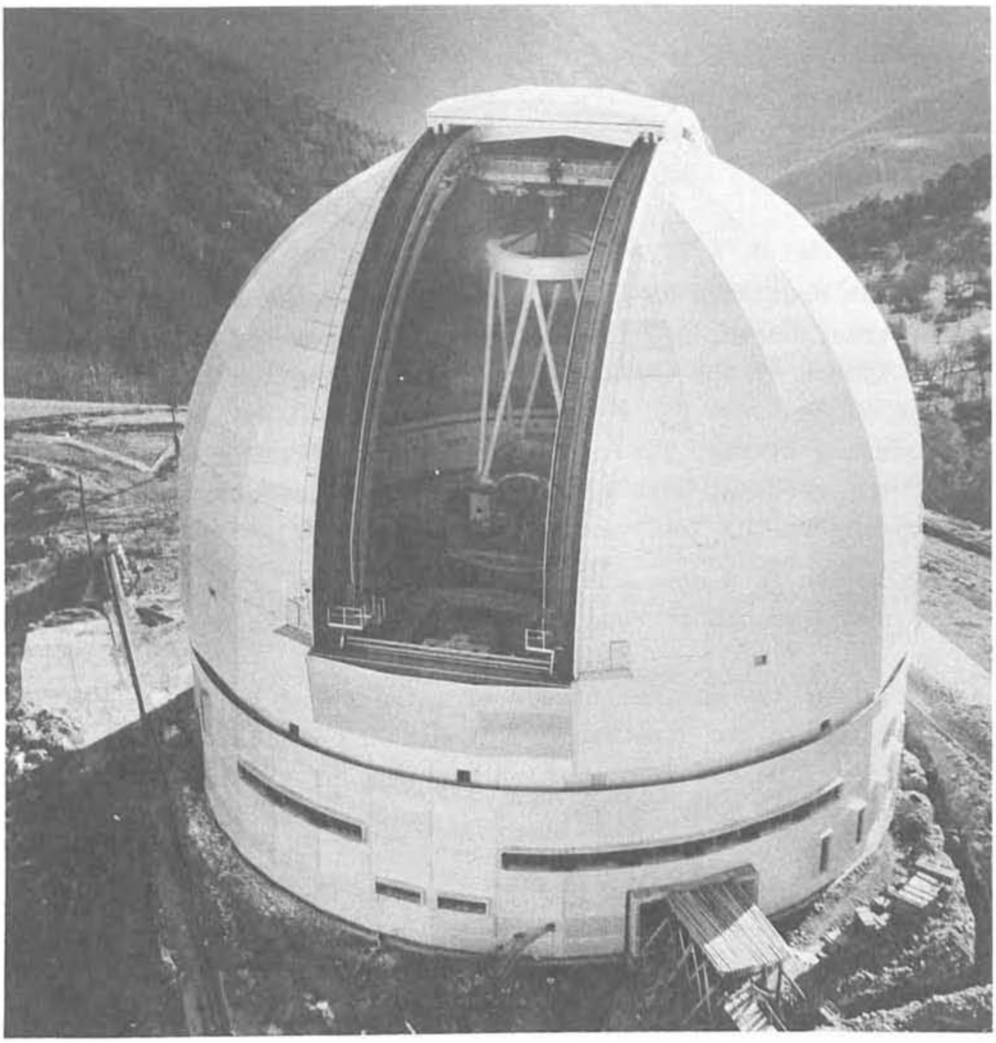


Fig. 8

The aluminizing plant is now being assembled. Our principal aim in the near future is to install this rather complicated technical device.

A more complete description of the telescope will be published soon (B.K. Ioannisiani, Proceedings of Special Astrophysical Observatory of the Academy of Sciences of USSR, Vol. 3, 1971).

DISCUSSION

HECKMANN: What precision do you require in the inclination of the vertical axis to the true zenith, and if you want to correct it, are you doing it with the tailpiece of the vertical axis and turning the axis on the spherical oil bearing?

KOPYLOV (pointing at Fig. 5): We have the possibility of correcting the position of the vertical axis with this device (indicated with 5 in Figure), and our accuracy to the true vertical is about 1".

KUHNE: The zenith is a singularity of the movement of the azimuth driving. What is the area you cannot reach in full operation in the vicinity of the zenith?

KOPYLOV: We chose the maximal speeds of rotation of the telescope in order to have the inaccessible zone smaller than 5° in radius.

BORGMAN: What is the expected guiding accuracy of the telescope?

KOPYLOV: I mentioned that the guide tube is only one part of our control system. We have three different parts of the control system: the first is the computer, the second is the photoguide, and the third the local photoguide for each light-receiver. We hope that these three parts of the control system will enable us to reach a precision of about 0".1 - 0".2.

BORGMAN: What will be the pointing accuracy? I presume that you have a presetting arrangement of α and δ and now I wonder how close does the telescope come through the computer to this preset (α , δ) ?

KOPYLOV: About 10".

DENNISON: You said the television guider was on a separate telescope. Do you plan to use the TV system to look at the primary image?

KOPYLOV: The TV system on the secondary tube is only for identification of the field of view and in order to have full control of the performance of the photoguide and maybe visual guiding. Our control system allows us to transform this TV system to a TV guide system in the future, and we have the possibility to use nearly the same kind of TV system for guiding at the prime focus.

DENNISON: Do you know some of the characteristics of the computer, for instance the word size or the amount of the memory, and are you planning to use your computer system for data collection also?

KOPYLOV: To my regret, I cannot communicate to you numerical data about our computer. The computer is used only for control of the telescope and has a rather standard program to compute A, Z, P, $\dot{A}$, $\dot{Z}$ and $\dot{P}$ with the refraction and different flexure of the tube taken into account. Our computer is doubled for this special purpose. We shall have a universal commercial computer of middle class for receiving data from spectrophotometers, photoelectric photometers etc. We think that in this way our situation is better.

MALM: You mentioned that the rotation of the field is a disadvantage. Could you explain a little bit more what problems you have found in designing this system, and how you have solved them?

KOPYLOV: I mentioned that our computer gives P and $\dot{P}$ to the servo motors of the telescope. In the upper part of the tube, inside the prime focus device, we have a kind of rotating table. The signal about position and speed of rotation goes to the servomotors there every second. And every second the computer receives a return signal and compares the real and the calculated position. We hope that this compensation of the rotation of the field of view will have an error of not more than one minute of arc. This is equal to a linear distance at the edge of the field of view of about 0.025 mm. At the secondary focus we also have an optical device for compensation for the rotation of the field of view, but the mechanical parts of these devices are nearly identical.

LAUSTSEN: You said that the motion around the two axes of non-uniform speed was a disadvantage for the altazimuth mounting, but is that really true? Also for equatorial mountings we intend to have in fact variable speeds around two axes, although it is very near 15" in one direction and zero in another direction. But we do intend to correct for various reasons so we do have variable speeds. So this is no real disadvantage for your mounting.

RICKARD: I would like to know a cost comparison between the altazimuth mounting and the standard fork mounting. It is at least the experience among radio astronomers that when they mount their radio telescopes altazimuth, they can save by almost a factor of five in some cases, and I call upon the experience of the Canadians building a 50 m telescope for approximately one fifth the cost the people at the National Radio Observatory did.

KOPYLOV: I have had the possibility to read an English report on a discussion of differences in cost between the equatorial and altazimuth mountings. We also looked into this question some years ago. I think that for such a large telescope like the 6 meter, the difference in the cost maybe about a factor of two, i.e. this mounting is two times cheaper than the equatorial.

FARRELL: What is the translation of the telescope tube when the tube is horizontal relative to the horizontal axis?

KOPYLOV: The thickness of the walls of the upper Serrurier trusses is about 26 mm and about 15 mm of the lower trusses. The staff of Dr. Ioannisiani calculated the flexure of the tube in different positions, and after the pre-assembly of the structure in the mechanical shop in Leningrad, when we had the possibility to measure the deflection, we found that the calculated and the measured flexures practically coincided. The upper part of the tube is shifted about 3 mm downwards and the shift of the lower part is practically the same, also about 3 mm.

FARRELL: Would you give us some details on the support of the main mirror and the secondary mirrors?

KOPYLOV: The support system of the main mirror is of the mechanical type and is relatively simple in comparison with other mechanical types for equatorial mountings. The cylinders have two counterweights in order to eliminate the load on the mirror, and these counterweights work only in one plane. It is possible to touch the mirror with a sensitivity of about 25 kilograms, and the support system for the secondary mirror is rather standard, but it is not so large, about 60 cm.

CHARVIN: What is the expected light concentration in the image?

KOPYLOV: We have not finished the figuring of the mirror, but we intend to have a disk of about 0".3 of 0".4, i.e. a Hartmann constant of 0.15 or 0.20. We should reach this figure in the final testing stage of the mirror.

RULE: Would you care to discuss the selection reasons for the spherical back on the mirror?

KOPYLOV: The thickness of the mirror is nearly equal throughout the diameter. The bottom surface is spherical and concentric but the upper surface is transformed to a parabola. We attempted using this shape of mirror to diminish the edge effect of temperature fluctuation.

DOSSIN: You have a central hole in your main mirror. Do you intend to use a Cassegrain focus?

KOPYLOV: No. This central hole is only for the purpose of centering the mirror and through it we support the shutter on a flat top.

SECORD: How many months have been required to figure your 6 meter mirror?

KOPYLOV: The grinding stage was finished in 1968, and in the beginning of 1969 the main mirror blank was transported to the polishing machine. We hope to obtain the final figure of the mirror this summer.

BELLY: Are you planning to use the f/4 prime focus without corrector for the photographic work?

KOPYLOV: The prime focus without corrector we shall use only for spectrographic observations. We have two lens correctors designed by Prof. Maksutov, and with them we have for the prime focus photography a field of 12' or 22'.

ODGERS: Dr. Kopylov, would you say something more about the astronomical quality of the site?

KOPYLOV: We have been studying this matter for three or four years now. There are about 220 clear or half clear nights and 120 absolutely clear nights. The elevation is 2070 meters, and there are no large cities or towns around the site. The transparency of the sky is very, very high. We expect that the image quality with this telescope will be about 1" - 1".5.

LE TELESCOPE DE 3.60 m ESO *

Ch. Fehrenbach

Président de la Commission des Instruments de l'ESO

INTRODUCTION

La convention créant l'Organisation Européenne pour des Recherches Astronomiques dans l'Hémisphère Austral ne fut signée qu'en 1962. Mais dès 1953, des études détaillées furent entreprises pour la construction d'un grand télescope.

Un télescope ne prend toute sa valeur que par la qualité du site dans lequel il est installé. D'où la nécessité de mener parallèlement l'étude de l'instrument et la recherche de son site.

Les trois possibilités : l'Australie, l'Afrique et le Chili furent envisagées dès le début. Le premier pays fut éliminé à cause de sa distance et de l'absence d'un relief suffisant dans les parties intéressantes. Des recherches approfondies furent entreprises à partir de 1953 dans toute la République d'Afrique du Sud et une station fut même installée à Zeekoegat et y fonctionna de 1961 à 1966. Mais les résultats obtenus ne furent pas jugés satisfaisants surtout comparés à ceux obtenus par nos collègues des Etats Unis au Chili et nous nous sommes ralliés au choix de ce pays.

Le rendement d'un grand instrument dépend de la qualité de son site : nombre de nuits claires, faible turbulence optique, petites variations de température pendant la nuit et si possible vent modéré.

L'installation même du télescope sur le site est important, son altitude au dessus du sol doit être d'au moins 25 m.

De nombreuses discussions, poursuivies notamment aux Etats Unis avec nos collègues américains, dont le Dr Bowen, Directeur de l'Observatoire du Mont Palomar, il résulte que la qualité d'un télescope est mesurée par le facteur D/t, où D est le diamètre du télescope et t le diamètre de l'image qu'il donne.

Il résulte de ceci qu'un télescope de 3 m dans un bon site doit être aussi efficace qu'un télescope de 5 m de diamètre situé dans un endroit où la turbulence est plus grande.

---

* See page 119 for English Summary.

LE SITE

Le télescope de 3,60 m de l'ESO sera installé sur un sommet de 2440 m d'altitude situé à La Silla à 600 km au nord de Santiago et à 100 km au nord de La Serena.

Sur ce site un certain nombre de télescopes ont été installés et confirment la qualité générale du site. Dans cette région, la qualité des images est souvent excellente ; le diamètre des images est souvent inférieur à 1", exceptionnellement la qualité des images peut correspondre à une turbulence de 0".1 . Par expérience les astronomes savent que les images obtenues par les grands télescopes sont de moins bonne qualité que celles mesurées avec de petits instruments. Des précautions très importantes doivent être apportées pour que le site ne soit pas troublé par des dégagements de chaleur. Le bâtiment et la coupole doivent être particulièrement soignés.

Le noeud de l'instrument sera situé à 25 m au dessus du sol. Le sommet choisi est bien dégagé, il comporte malheureusement une faille et l'implantation du bâtiment en est un peu tributaire.

LE TELESCOPE

Diamètre

Le diamètre envisagé était de 3 m, ce qui était réaliste à la fois du point de vue financier et du point de vue des conditions de réalisation dans un pays éloigné. Ce sont des circonstances accessoires qui nous ont amené à augmenter le diamètre.

Pour des grands télescopes, comme celui du Mont Palomar, l'observation au foyer direct n'est possible que si l'astronome est installé dans le tube. Un voyage d'étude à l'Observatoire de Lick a montré la quasi impossibilité de travailler correctement au foyer primaire d'un télescope de 3 m de diamètre, et il est apparu que le diamètre minimum nécessaire était de 3,50 m. Ce diamètre a été augmenté ultérieurement à 3,66 m parce que le disque de matière qui nous a été fourni avait ces dimensions ; il aurait été regrettable de le retailler.

Précision

Un miroir de télescope peut être considéré comme pratiquement parfait lorsque l'onde réfléchie ne diffère pas de $\lambda/4$ (conditions de Rayleigh) d'une sphère parfaite ; ceci correspond à une précision de l'ordre de 0,06 μ sur la surface du miroir. Il est essentiel de conserver cette précision malgré les flexions variables du disque au cours des observations et malgré les déformations thermiques. Naturellement les perturbations introduites par la coupole ne doivent pas être supérieures.

Matière des miroirs

Jusqu'en 1955 tous les grands miroirs de télescope étaient des disques de verre, notamment de pyrex. Il était important pour diminuer les effets thermiques de remplacer ce matériau par la silice fondue. Les verres du type Cervit ou Pyrocéram n'étaient pas encore commercialisés en 1955. L'ESO a donc décidé l'achat d'un miroir en silice fondue à la Société Corning.

La flexion du miroir dépend essentiellement du rapport Epaisseur/ Diamètre (E/D). Suivant la nature du système de support dorsal adopté il est possible de choisir des rapports compris entre 1/10 et 1/5. De nombreuses discussions eurent lieu au sein de la Commission des Instruments : en définitive, on a choisi un disque plein ayant un rapport : E/D = 1/7. Les propriétés des miroirs cellulaires ont été discutés. Le choix d'une structure cellulaire pour le miroir du Mont Palomar se justifiait par la quasi impossibilité de couler en une seule fois la masse de verre nécessaire. D'ailleurs la structure cellulaire est avantageuse pour l'équilibre thermique, elle est très importante dans le cas du verre. Mais cette structure entraîne des difficultés très grandes pour la construction du système de support. Il a résulté de ces discussions que le choix d'un disque plein s'imposait.

Les deux sociétés capables de fabriquer en 1960 un disque de cette dimension (masse de l'ordre de 10 tonnes) étaient les sociétés Corning et General Electric. Mais les deux sociétés ne pouvaient couler un disque d'une seule pièce. Le disque commandé à la société Corning Glass International, U.S.A., dont la proposition a paru plus intéressante, est constitué par sept hexagones de silice complétés par des triangles. On a apporté une attention toute particulière à la qualité de la couche supérieure. L'ensemble est porté à une température de l'ordre de 2500°C et ensuite refroidi lentement. Ce disque a été commandé en janvier 1965. Au cours du refroidissement le four s'est partiellement effondré et a amené une rupture du disque dont un tiers s'est détaché. La société Corning a essayé de réparer cette rupture par une nouvelle fusion. Cette opération ayant, selon toute apparence, réussi, nous avons fait une réception, sous condition, du disque en janvier 1967. Le disque a été livré à la société d'optique R.E.O.S.C. de Paris, choisie pour la taille. Durant le polissage du grand miroir dans les ateliers de cette société, il apparut que la couche supérieure n'était plus assez épaisse et que la surface définitive du miroir entamait les couches inférieures et un grand nombre de bulles apparurent. En accord avec la Société Corning, le disque a été renvoyé aux U.S.A. où une nouvelle couche d'environ 10 cm de très bonne qualité a été déposée par fusion sur le disque.

Le miroir ainsi amélioré s'est révélé de bonne qualité à l'exception d'une zone située près du trou central et provenant d'un incident de fabrication. Malgré cette imperfection, le miroir a été accepté, sous réserve que la société chargée du surfaçage puisse faire une réparation acceptable du point de vue optique. En fait, la Société REOSC a montré sa parfaite maîtrise en rebouchant le trou avec une portion de sphère rodée de la même silice, les dimensions du joint étant de l'ordre du centième de millimètre.

Les miroirs secondaires sont aussi en silice ; ils ont été commandés à la Société HERAEUS, qui nous a fait une offre plus intéressante.

En février 1967, en présence de MM. Heckmann et Fehrenbach, MM. Texereau et Espiard ont examiné le disque de silice dans les ateliers de la Société Corning. Des mesures de biréfringence ont montré que la trempe du disque pouvait être considérée comme très faible, nettement inférieure aux spécifications, elles sont pratiquement de révolution. Un procès verbal de cet examen a été publié dans le bulletin n° 2 de l'ESO.

Caractéristiques optiques du télescope

Dès l'origine, les astronomes étaient d'accord pour que le télescope comporte des foyers primaires, Cassegrain et coudé. Mais le choix des distances focales a été assez laborieux.

De longues discussions eurent lieu au cours d'un voyage qu'entreprirent MM. Oort, Heckmann et Fehrenbach aux Etats Unis en 1961.

A cette époque, les recherches faites de divers côtés ont montré que la magnitude limite qu'on peut attendre en photographie classique avec un grand télescope dépend non du diamètre du télescope mais de sa distance focale. Toutefois il faut prévoir une pose suffisante pour qu'avec les plaques photographiques alors en usage le fond du ciel donne une densité de l'ordre de 0,3. Ce résultat a été mis en doute ultérieurement, mais la solution que nous avons choisie n'est pas criticable, comme nous l'indiquerons. Il résulte de ces discussions, que le foyer le plus efficace correspond à un rapport F/D voisin de 6 ou 8.

De nombreuses discussions il a résulté qu'il n'était pas possible de construire un télescope de 3.50 m ouvert à F/6, car il serait trop long.

La seule solution acceptable est de construire un miroir primaire très ouvert F/D = 2,5 à 4 et de réaliser une combinaison Cassegrain du rapport voisin de F/6 ou F/8.

Le choix définitif est imposé par deux facteurs :

La dimension du miroir secondaire, qui est supérieure à 1 m, augmente beaucoup lorsqu'on passe de 2,5 à 4.

La difficulté de réalisation du miroir est beaucoup plus grande pour un miroir F/2,5 que pour un miroir F/4.

D'une discussion très serrée est résulté le compromis suivant :

Miroir principal ouvert à F/3

combinaison Cassegrain F/8.

Nos collègues américains, sous l'influence du Dr Meinel, ont choisi le rapport F/2,5 ; nos collègues français choisiront probablement F/3,75.

La taille du miroir de Kitt Peak à F/2,7 montre qu'on atteint effectivement là, la limite de l'état de l'art pour réaliser de façon correcte un grand miroir.

Le choix de F/30 pour la combinaison coudé a été fait à l'origine sans grande discussion.

Notre Commission a hésité quelque temps pour savoir si le foyer direct F/3 était utile. Il fut décidé que nous devrions le garder pour réserver l'avenir. En fait, actuellement il apparaît que ce foyer est important pour l'usage de plaques à grains fins et de filtres.

Forme du miroir : Parabolique ou Ritchey-Chrétien?

Jusque vers 1930 tous les grands télescopes avaient des miroirs paraboliques en général ouverts à F/6. Ces miroirs donnent au foyer primaire une image parfaite au centre du champ. Mais en dehors de ce point idéal apparaît une petite aigrette de coma, et l'image est très rapidement détériorée, le champ est petit. Si on se contente d'une image de 1", de diamètre, ce champ est réduit à un cercle de 1!5 de diamètre pour le rapport de F/3 et 6' pour F/6, ce qui correspond dans le cas du miroir de 3.60 m à des champs respectivement de 5 et 40 mm de diamètre.

En 1922, Henri Chrétien a indiqué qu'il était possible de corriger la coma au foyer Cassegrain en remplaçant le miroir parabolique par un miroir plus déformé et en lui adaptant le miroir secondaire qui donne une image stigmatique au centre du champ du foyer Cassegrain. Cette combinaison est aplanétique. Son champ est beaucoup plus grand. Le défaut qui subsiste, car il existe aussi pour la combinaison classique, est une courbure de champ et un astigmatisme correspondant. La courbure de champ est assez facile à corriger par une lentille de Piazzi-Smyth. H. Köhler a montré par un calcul fait pour l'ESO qu'il était aussi possible de corriger pratiquement l'astigmatisme en choisissant une forme voisine de celle de Chrétien combinaison quasi Ritchey-Chrétien.

Notre commission a décidé à l'unanimité le choix de cette combinaison malgré de fortes critiques que nous désirons analyser ici.

a) Le miroir de Ritchey-Chrétien ne donne plus des images stigmatiques au centre du champ du miroir principal. Cette image a un diamètre de 7". Il est possible de corriger ce défaut par l'interposition d'un correcteur, celui-ci est inutile pour le miroir parabolique, au centre du champ. Mais en fait, ce correcteur est aussi nécessaire pour le miroir parabolique car le champ de ce miroir est minuscule et doit être corrigé par une lentille du type de Ross.

En fait, il est plus facile d'obtenir une bonne correction au foyer primaire d'un Ritchey-Chrétien qu'au foyer d'un télescope parabolique (voir les travaux de Paul et autres, voir article de H. Köhler dans Bulletin ESO N° 2). Nos collègues du Mont Palomar qui connaissent bien le problème de leur miroir parabolique ont approuvé notre choix.

Des calculs exécutés par H. Köhler à Oberkochen et A. Baranne à Marseille ont montré qu'il était possible d'avoir avec des systèmes correcteurs relativement petits un champ de 1° de diamètre avec des images meilleures que $0\overset{''}{.}5$ au foyer primaire et un champ de 30' avec des images meilleures que $0\overset{''}{.}3$ au foyer Ritchey-Chrétien. Ce dernier foyer peut être utilisé sans lentille correctrice, une aberration sphérique résiduelle apparaît alors mais elle est absolument négligeable ($< 0\overset{''}{.}1$).

b) Le miroir Ritchey-Chrétien est plus difficile à réaliser. Ceci est vrai mais la déformation ne dépasse que de 20% la déformation du miroir parabolique. Cette difficulté supplémentaire ne paraît très importante à de nombreux opticiens et la qualité obtenue par la REOSC nous donne, a posteriori, raison.

c) La combinaison Ritchey-Chrétien serait plus sensible à des défauts d'alignement. Les calculs d'A. Baranne, confirmés ultérieurement par Zeiss, montrent qu'il s'agit là d'une opinion erronée. Les tolérances d'alignement sont pratiquement les mêmes à rapports d'ouverture égaux.

d) Le champ au foyer coudé est plus réduit. Cette objection est valable, mais le champ est en fait suffisamment grand.

En définitive notre choix est le suivant :

La forme du miroir principal est celle indiquée par Köhler, c'est un quasi Ritchey-Chrétien avec l'adjonction d'une lentille de quartz au foyer Cassegrain corrigeant non seulement la courbure de champ mais aussi l'astigmatisme. La forme du miroir secondaire est donnée par les calculs de Köhler. En fait, elle pourrait être retouchée après la réalisation du miroir principal si celui-ci était différent de sa forme théorique.

A. Baranne et H. Köhler ont calculé des correcteurs possibles pour le foyer primaire de ce miroir.

La combinaison de lentilles asphériques de Köhler, trop difficile à réaliser, n'a pas été retenue. Par contre, le correcteur de Baranne, de dimensions réduites (diamètre 30 cm), avec des lentilles sphériques ou très légèrement déformées, transparent à l'ultraviolet, permet d'obtenir des images pratiquement parfaites dans un champ de 1°. On améliore encore la qualité en réalisant deux correcteurs facilement interchangeables prévus pour les domaines ultraviolet, bleu et rouge, infrarouge.

Les verres des correcteurs de Baranne adoptés ont des dimensions relativement petites. Ils sont associés de façon permanente avec le porte-chassis de sorte que lorsqu'on change de foyer on change l'ensemble préréglé du correcteur et de la plaque photographique.

Il faut préciser ici, que le correcteur ne comporte que des lentilles de silice sphériques, la silice est transparente dans le domaine 3000 Å-1 micron. Avec un miroir parabolique classique, le correcteur aurait comporté des verres non transparents à l'ultraviolet et, de ce fait, il aurait été impossible de travailler dans la région comprise entre 3000 et 3500 Å.

Foyer coudé

Ce foyer est nécessaire car il permet d'installer a poste fixe des instruments auxiliaires de grande taille, très lourds ou très délicats dans un laboratoire à température constante.

Le travail au foyer coudé est devenu de plus en plus fréquent depuis 1950 lorsque sont apparus des instruments de plus en plus complexes tels que la caméra électronique, et l'interféromètre de Michelson à transformée de Fourier.

Un grand défaut de ce foyer provient du fait qu'il est nécessaire de renvoyer le faisceau lumineux dans le laboratoire fixe par au minimum deux miroirs supplémentaires. Il est essentiel de choisir une monture où ces miroirs sont aussi peu nombreux que possible et fixés définitivement. La monture anglaise à deux miroirs fixes est la meilleure connue de ce point de vue, mais elle est pratiquement irréalisable pour un télescope de 3.60 m de diamètre.

C'est le problème posé par ces nombreux et grands miroirs auxiliaires qui a amené certains astronomes à reconsidérer cette question (Richardson).

L'utilisation d'un foyer coudé ouvert à F/150 permettrait de réduire la taille des miroirs auxiliaires et de les rendre facilement interchangeables. Chacun des petits miroirs sera utilisé dans un intervalle spectral donné avec un revêtement réfléchissant de très haute efficacité pour ce domaine. Richardson a montré que le gain d'efficacité pouvait être considérable, d'autre part, l'expérience montre que l'état des surfaces des grands miroirs, qu'on hesite à manipuler, est très inférieure à la valeur idéale de 0.85, souvent admise pour une aluminiure fraîche.

Précision optique des miroirs

Nous avons déjà indiqué que la réalisation de la surface des miroirs devait être de l'ordre de $\lambda/4$ à $\lambda/8$ pour que la qualité des images ne soit limitée que par la diffraction.

L'exigence d'une telle précision, surtout en l'absence d'expérience, aurait augmenté considérablement le prix des appels d'offres.

La Commission des Instruments a préféré fixer des tolérances plus larges en demandant qu'au foyer du télescope Ritchey-Chrétien 75% de la lumière soit concentrée dans un cercle de 0".4 de diamètre. La tolérance au foyer coudé est de 75% de la lumière concentrée dans un cercle de 0".5 de diamètre.

Toutefois, la Commission s'est réservée la possibilité d'étudier avec la société d'optique chargée du surfaçage une amélioration ultérieure de la forme du miroir principal, sous la forme d'un avenant au marché.

La Commission des Instruments avait aussi décidé d'accepter éventuellement une méridienne légèrement différente de la figure théorique aux deux conditions suivantes :

1) que le calcul montre qu'il était possible de réaliser le miroir secondaire correspondant en gardant pratiquement l'aplanétisme du Ritchey-Chrétien ;
2) que la forme soit très régulière.

La façon d'entreprendre la taille du miroir a été longtemps discutée et diverses solutions ont été envisagées, parmi lesquelles la construction d'un laboratoire d'optique de l'ESO, d'un laboratoire commun à la France et à l'ESO et enfin le recours à des sociétés privées spécialisées dans la taille des grandes pièces d'optique. En définitive, c'est cette dernière solution qui a été retenue et après appel à la concurrence, la Société REOSC, Ballainvilliers 91 - France, a été choisie.

Le travail sur le disque définitif a été commencé en 1970. La réparation du défaut signalé a demandé 4 mois. Néanmoins, en février 1971, le miroir primaire est pratiquement terminé. La Société REOSC a effectué des tests de contrôle qui ont donné les résultats suivants : dans un cercle de 0".5 de diamètre, on trouve 94% de l'énergie au lieu de 75% prévus sur le marché. Dans un cercle de 0".24 de diamètre, on trouve 69% de l'énergie. Des examens faits à l'interféromètre montrent une surface très régulière sans mamelonnage.

Un contrôle très précis de ce miroir par les opticiens de l'ESO est actuellement préparé et si, comme nous le pensons, les résultats de la REOSC sont confirmés nous pourrons procéder à la réception du miroir principal. La forme de la méridienne est celle que nous avions imposée. Un contrôle de l'astigmatisme sera aussi fait. Les tests prévus sont : un examen de Hartmann avec de nombreux trous, un contrôle interférométrique à cisaillement d'ondes. L'ensemble de tous les miroirs secondaires est en cours de fabrication.

La construction et le contrôle de ces miroirs sont inséparables. La société REOSC a mis au point une méthode de contrôle basée sur l'utilisation d'équerres optiques. Cette méthode a été utilisée pour le contrôle du miroir Cassegrain du télescope de 1.52 m de l'ESO et a donné entière satisfaction.

Il y a un point important à souligner : la combinaison la plus difficile à réaliser est la combinaison Ritchey-Chrétien, le miroir secondaire convexe est très difficile à réaliser sans mamelonnages. Il est aussi très difficile à tester.

Diverses méthodes de tests ont été étudiées : aucune n'a été entièrement satisfaisante soit qu'elle ne donne pas d'information sur la forme même de la méridienne du miroir, soit qu'elle ne permet pas de tester tout le miroir. Une combinaison de ces méthodes permettrait un test complet mais pour un prix de revient élevé. On peut envisager deux solutions :

1) fabriquer une lentille de silice déformée réplique du miroir à contrôler. Cette lentille permettrait de faire des franges d'interférence entre les deux surfaces pratiquement mises en contact ; cette solution est extrêmement onéreuse ;

2) si les tests et mesures partiels sont satisfaisants, tester la combinaison sur le ciel et retoucher le miroir secondaire : le miroir primaire étant considéré comme parfait et servant de référence. Il ne doit en aucun cas être retouché pour améliorer l'image au foyer Ritchey-Chrétien.

La forme des miroirs coudé est celle qui donne une image stigmatique au foyer coudé. La coma résiduelle est plus grande et opposée à la coma qu'on obtiendrait avec un miroir principal parabolique.

Le champ utilisable est néanmoins suffisant :

F/30 Diamètre : 6'
F/125 Diamètre : 2'

Conditions astronomiques pour la monture

Précision des réglages : la précision nécessaire pour les réglages optiques résulte des calculs optiques faits par Baranne (Publications de l'Observatoire de Haute-Provence - volume 8). Le parallélisme des axes des deux miroirs doit être maintenu pendant la pose avec une précision de l'ordre de 20".

Le déplacement latéral des axes supposés parallèles ne doit pas dépasser 0.3 mm. Ces tolérances de l'ordre de quelques 10ème de millimètres concernent des pièces optiques séparées d'environ 10 m. Ces tolérances sont très petites. Il est important de remarquer que les petites flexions et déplacements mécaniques au cours du travail qui sont inévitables doivent être très réguliers et inférieurs aux tolérances de l'optique. Le principe même de la monture classique de tous les télescopes relie les miroirs par une structure métallique, qui devrait convenir à condition qu'elle ne présente pas de jeux mécaniques. Les défauts d'alignement dus à des variations thermiques ne paraissent pas très dangereux d'autant plus que le site du Chili présente des variations thermiques faibles au cours de la nuit. La seule variation que l'on peut craindre est une variation de la position apparente du foyer. Celle-ci ne se définit d'ailleurs pas uniquement que par la température de la monture mais aussi par la forme "thermique" du miroir. Le fait que le miroir soit en silice permet de penser qu'avec des précautions simples, par exemple l'isolement extérieur du barillet, la figure du miroir ne se déformera pas sensiblement ; un point beaucoup plus grave est qu'au voisinage d'un miroir de cette taille il se forme automatiquement une couche mince d'air froid au contact de la silice et que cette couche d'air peut donner des effets optiques considérables. C'est un problème qui n'a pas été envisagé dans sa totalité. Une variation de foyer au cours de la pose d'un cliché serait gênante, par contre la mise au point au début du travail paraît inévitable.

Pointage

Le but recherché est de pointer le télescope de telle façon que l'étoile pointée se trouve au centre du champ avec une précision à définir. Si l'observateur contrôle visuellement la présence de l'étoile ou s'il reconnaît le champ, l'expérience montre que cette précision doit être de l'ordre de 1'. Certains demandent une précision plus grande si on désire que l'étoile soit reçue dans le champ d'un instrument d'asservissement (de l'ordre de 5" ou même 1"). L'obtention de cette précision nécessite des réglages très précis.

Il est essentiel que l'axe de déclinaison soit perpendiculaire à l'axe horaire et à l'axe optique du télescope.

Le réglage doit être possible lors de la mise en place du barillet du grand miroir par une orientation d'ensemble du barillet du grand miroir.

Il est, de plus, nécessaire de pouvoir régler avec précision la direction des normales de tous les miroirs secondaires convexes et plans.

Toutes les flexions doivent rester faibles, sinon on pourrait, s'il s'agit de flexions et non de jeux, en tenir compte dans l'ordinateur qui asservira le télescope. L'ordinateur tiendra aussi compte de la réfraction qui mesure 1' à 45^{o} de hauteur et 30' à l'horizon.

Guidage

Le problème est, une fois l'étoile pointée, de la maintenir fixe dans le champ avec une précision de 0".1 ou mieux, et ceci pendant des durées de pose de quelques heures. Il est aussi important d'éviter, autant que possible, des rotations de champ. (La réfraction entraîne une rotation de champ inévitable, le champ au foyer coudé tourne.) Cette façon de poser le problème est un peu théorique car il ne faut pas oublier que dans le mouvement résultant il faut tenir compte des variations de réfraction régulières et accidentelles et des flexions inévitables. Le problème est extrêmement difficile et sa solution se décompose en plusieurs niveaux. On cherche à assurer au télescope entier le mouvement se rapprochant le plus du mouvement théorique ; le point essentiel est que ce mouvement soit très régulier. La précision finale s'obtient en déplaçant l'élement le plus petit, c'est-à-dire, dans le cas qui nous occupe, la plaque photographique, corrigeant la direction du télescope par l'observation directe d'une étoile. Cette observation peut être faite visuellement par l'observateur ou bien de façon automatique par un système photoélectrique.

Dans certains observatoires on préfère déplacer l'ensemble du télescope de façon très fine en asservissant le télescope par l'observation d'une étoile ; quoiqu'il en soit, l'observation d'une étoile paraît inévitable.

Si le télescope est réalisé de façon parfaite il n'est pas exclu de pouvoir étudier par ordinateur les flexions et de reconstituer le vrai mouvement. Il semble pour l'instant hors de question d'atteindre directement par une boucle ouverte la précision de $0\overset{''}{.}1$.

Le passage par un pointage fin en boucle fermée est inévitable.

Changement de foyer

Il est nécessaire d'étudier les méthodes qui permettent de passer rapidement de l'observation de l'un quelconque des foyers primaires, Ritchey-Chrétien ou coudé à l'autre.

Les changements de foyers sont nécessaires dans les cas suivants :

1) changements de programmes prévus ;
2) si les conditions sont différentes de celles prévues meilleures ou moins bonnes. Ce changement a pour but d'augmenter le rendement de l'instrument.
3) changements de programmes imprévus (phénomène astronomique imprévu : Nova, comète, etc...).

On peut discuter longuement pour savoir quels sont les changements les plus utiles ou les plus fréquents. L'idéal est, bien entendu, d'obtenir un passage très rapide de l'un quelconque de ces foyers aux deux autres. Ces changements ne sont pas faciles à cause de la dimension des miroirs auxiliaires, qui ont des masses de l'ordre de la tonne et doivent être mis en place avec les précisions indiquées plus haut (tolérances indiquées par les calculs de A. Baranne voir plus haut). Ces manipulations doivent se faire avec toute la sécurité nécessaire pour des pièces optiques très couteuses et pratiquement irremplaçables.

Nos collègues des observatoires étrangers ont adopté diverses solutions:

1) Tous les miroirs auxiliaires sont déposés dans le tube. Un dispositif électrique permet d'enlever le miroir de sa position de travail, de le stocker dans le tube et de le remplacer par un autre. Il est nécessaire qu'au cours de ces opérations l'équilibrage du télescope ne change pas. Le défaut principal de ce système est l'augmentation considérable du poids du tube, ce qui augmente ses flexions. Cette solution a été très fortement critiquée, mais elle donne entière satisfaction à l'Observatoire du Mont Palomar.

2) Toute la partie avant du télescope est interchangeable. C'est la solution adoptée à l'Observatoire Lick. Le changement du miroir plan se fait alors par un dispositif électrique. Ceci nécessite la manipulation de pièces très lourdes et leur réglage assez difficile. Ce changement ne peut généralement pas être pratiqué en cours de nuit et en général les changements

de foyers se font après des périodes d'observation de quinze jours ou plus.

Ceci présente de gros défauts :

a) impossibilité d'utiliser une moitié de nuit avec lune ;

b) impossibilité de changer de programme en cours de nuit même en cas de besoin : qualité exceptionnelle de la nuit, changement de temps, ou apparition d'un phénomène exceptionnel.

3) La solution étudiée par nos ingénieurs et adoptée par notre Commission consiste à construire une cage fixe dans laquelle on peut disposer des ensembles facilement manipulables :

a) le dispositif du travail au foyer primaire avec le siège de l'astronome ;

b) le support du miroir Ritchey-Chrétien avec son dispositif de mise au point ;

c) le support du miroir coudé avec son dispositif de mise au point.

Il est à noter que dans le cas du foyer primaire la cabine de l'astronome et les pièces optiques sont montées sur des araignées indépendantes afin d'éviter de transmettre des vibrations au système optique.

Les changements de ces éléments se font lorsque le télescope est en position horizontale. Ceci entraîne quelques difficultés, notamment pendant les changements de foyers le grand miroir est dans une position instable, ce qui entraîne des risques en cas de tremblement de terre ; il est difficile de régler dans cette position des instruments auxiliaires montés dans la cabine du foyer primaire.

Le système des mécanismes d'échange initialement prévu a été réétudié avec l'adjonction d'un certain nombre de moteurs auxiliaires pour assurer le mouvement de translation et de réglages fins des miroirs. Le système actuellement étudié (février 1971) est beaucoup plus lourd que celui qui était initialement prévu.

Comme nous l'avons déjà indiqué, suivant les idées de Richardson de l'Observatoire de Victoria, nous étudions la possibilité de remplacer le système coudé ouvert F/30 par un système ouvert à F/150, ce qui permet d'utiliser des miroirs à pouvoir de réflexion amélioré. Un avantage non négligeable de cette solution est qu'elle permet un passage très facile du foyer primaire au foyer coudé et vice-versa. En effet, le miroir convexe n'a plus que 25 cm de diamètre et il est possible de le laisser stocker dans la cabine du foyer primaire. Le passage au foyer Cassegrain n'est pas modifié dans cette solution.

L'étude de la solution F/150 est en cours.

Examinons ces deux variantes :

1) Foyer coudé F/30. Il est indispensable de conserver les trois systèmes de cages qu'il faut étudier en détail en soignant particulièrement

l'étude de leur stabilité.

2) Foyer coudé F/150. Dans cette solution le passage du foyer coudé au foyer primaire et vice-versa se fait par un montage en flip-flop à l'intérieur de la cage.

Mais l'étude de cette solution ne risque-t-elle pas de retarder l'ensemble du projet du télescope?

Dans cette variante le passage au foyer Cassegrain est résolu de la même façon que dans la variante 1. Mais le nombre de cages est réduit à deux.

La première cage comporte simultanément le foyer primaire et le miroir coudé ; la deuxième cage comporte le miroir Cassegrain. Le passage au foyer Cassegrain est identique à la solution retenue pour l'ouverture à F/30.

Type de monture

Nous avons examiné la possibilité d'utiliser une monture altazimutale. Mais cette solution où aucun axe de rotation n'est confondu avec l'axe de rotation de la terre présente de nombreuses difficultés et elle n'est intéressante que pour de très grands télescopes d'une taille supérieure à 5 m. La monture équatoriale a donc été adoptée.

La monture anglaise permet d'amener la lumière au foyer coudé à l'aide seulement de deux miroirs plans fixes. De ce point de vue c'est la solution la plus favorable, mais son principal défaut est son asymétrie qui rend probablement sa construction impossible pour un télescope de 3.60 m de diamètre. La monture anglaise nécessite une très grande coupole. Cette solution a été rejetée.

Les autres montures possibles sont la monture à berceau du type du Mont Palomar et la monture à fourche. La principale difficulté de la réalisation de la monture du type Mont Palomar est la grande taille du fer à cheval. Il est certain que c'est une excellente solution mais qui pose un certain nombre de problèmes mécaniques très difficiles.

La monture à fourche, telle qu'elle a été réalisée à l'Observatoire Lick, est très flexible et ses flexions sont particulièrement importantes lorsque le télescope s'écarte du méridien.

La solution adoptée par notre organisation est intermédiaire entre ces deux types. Il y a une certaine similitude entre notre solution et celle de Kitt Peak. Les deux solutions comportent un fer à cheval déporté vers le bas par rapport à la solution du Mont Palomar.

Dans la solution de Kitt Peak l'axe de déclinaison est placé au niveau du fer à cheval ; dans la monture de l'ESO l'axe de déclinaison est rejeté à l'aide d'une fourche en dehors du fer à cheval.

En résumé on peut dire que la monture de l'ESO est une monture à fer à cheval prolongé par une fourche. Cette solution a été adoptée pour réduire le diamètre du fer à cheval. L'étude mécanique de la flexion de la fourche doit être faite avec beaucoup de soins. Les deux flexions de la fourche, dans son plan et perpendiculairement à ce plan, doivent être aussi voisines que possible. Cette solution présente deux inconvénients :

1) il est assez difficile de démonter le barillet du grand miroir ;
2) l'existence même du fer à cheval qui ne permet pas de pointer l'horizon nord.

La solution adoptée pour l'axe polaire est analogue à celle réalisée par M. Strewinski pour le Télescope de Schmidt de l'Observatoire de Hambourg. L'axe polaire est constitué par une portion de sphère reposant sur deux paliers à huile.

Le maintien de l'axe de déclinaison dans une position fixe par rapport à la fourche est un problème difficile à résoudre du fait que cet axe a une position variable dans l'espace. Il est essentiel que le poids du tube soit également supporté par les deux bras de la fourche. Un étude d'un système sur palier à huile est en cours.

Du point de vue optique, la monture de l'ESO comporte 5 miroirs au foyer coudé. Le 5ème miroir renvoie la lumière dans une salle horizontale située sous le télescope. Ce miroir doit être animé d'un mouvement complexe lui permettant de diriger le faisceau de lumière dans 6 directions possibles. En pratique, ce miroir aura une monture altazimutale dotée d'un mouvement analogue à celui d'un miroir de sidérostat. Le mouvement sera contrôlé par un ordinateur.

Barillet et système de support des miroirs

Le système de suspension des miroirs a été étudié en détail lors du colloque de Tucson. Néanmoins, les divers groupes sont arrivés à des solutions différentes.

Le choix de l'ESO a été guidé par les considérations suivantes :

Le système de suspension dorsal nécessite des forces dont la précision doit être réalisée au millième. La solution retenue consiste à disposer 3 couronnes d'appuis concentriques comportant au total 30 systèmes de leviers astatiques et 3 appuis fixes. Ce système de leviers astatiques paraît le mieux adapté, mais le jeu dans les roulements à billes, ceci est un point un peu délicat. Le nombre et la répartition des appuis dorsaux ont été choisis en tenant compte de l'expérience de M. André Couder qui a réalisé plusieurs suspensions de ce type sur d'autres instruments. Un calcul effectué par Lemaître a permis de constater que les flexions étaient effectivement négligeables.

Le système de support latéral ne nécessite pas une très grande précision en position, mais une très grande précision dans la direction de ses forces qui ne doivent avoir aucune composante parallèle à l'axe optique. Ces forces sont variables en fonction de la position de l'appui sur le pourtour du miroir et de la direction de pointage du télescope. La répartition adoptée est celle décrite par Schwesinger.

Ce système pneumatique comporte 18 supports à régulation automatique de pression. La commande actuellement réalisée se fait par un asservissement mécanique. Le nombre total de supports latéraux est de 21. Par construction il est possible de régler avec une très grande précision la direction des forces latérales.

Les barillets des miroirs coudé, Cassegrain et des grands miroirs plans comportent également des systèmes de suspension. La solution de ce problème est difficile pour les miroirs Cassegrain et coudé du fait qu'ils travaillent la face réfléchissante dirigée vers le bas. Les barillets des grands miroirs et des miroirs secondaires doivent comporter des dispositifs de compensation thermique.

Le tube

La solution adoptée pour la plupart des grands télescopes est la monture dite de Serrurier. Dans ce type de monture le miroir principal et le miroir secondaire se déplacent leur axes restant parallèles. Ainsi aucun déréglage ne se fait ni de point de vue optique ni astronomique. Il est facile en général d'égaliser les deux déplacements : le grand miroir est très lourd, mais proche de l'axe de déclinaison et le petit miroir plus léger mais plus éloigné.

Dans la solution adoptée, la partie avant est du type Serrurier, mais cette solution s'est révélée irréalisable pour la partie arrière avec le grand miroir. La solution adoptée est un dispositif à barres de flexion qui nécessite des études supplémentaires pour sa mise au point. Il faut pouvoir régler le barillet en inclinaison, car dans le type adopté aucun déplacement du miroir n'est possible à l'intérieur du barillet. Ce problème doit encore être résolu.

On doit pouvoir fixer derrière le foyer Cassegrain des instruments pesant jusqu'à 500 kg. Ces instruments peuvent être encombrants et doivent pouvoir être tournés autour de l'axe optique. L'astronome doit pouvoir accéder facilement à ces instruments pendant les observations. Le foyer se déplace peu, mais il est situé près de la fourche de sorte que son accès est difficile.

Un avant projet d'un habitacle à claire voie fixé derrière le barillet et dans lequel l'astronome prendrait place, a été étudié. Cette solution n'est pas très satisfaisante ; il faudrait en réaliser une maquette et étudier simultanément une échelle d'observation mobile sur le plancher.

TELESCOPE AUXILIAIRE

Le grand spectrographe est un instrument très cher et il paraît judicieux de l'utiliser avec un télescope auxiliaire ayant un diamètre de l'ordre de 1 m qui permettrai d'atteindre des étoiles de 1.5 à 2 magnitudes plus faibles que le télescope principal. Ce télescope fixe sera complété par un sidérostat disposé sur un pilier spécial placé au nord du bâtiment. Il ne pourra être utilisé qu'avec un spectrographe.

LA COUPOLE

Le rôle de la coupole est important. Elle doit remplir plusieurs fonctions : abriter le télescope pendant la journée, protéger l'instrument du vent pendant les observations, et servir de support aux engins de montage et de démontage de télescope, au dispositif d'échange des cages du foyer primaire.

Une bonne coupole doit être bien isolée. Dans ces conditions les échanges thermiques entre l'extérieur et l'intérieur sont réduits au minimum et au début de la nuit l'instrument n'a pas une température très supérieure à celle de la nuit.

Les échanges thermiques sont proportionnels à la surface de la coupole dont les dimensions devraient être réduites au minimum, mais la nécessité de disposer d'un grand pont roulant de 25 tonnes augmente le diamètre de la coupole. Il serait utile d'étudier la possibilité de refroidir l'intérieur de la coupole pendant le jour.

La trappe d'observation a une largeur de 6 m. Deux solutions ont été étudiées pour sa fermeture : cimier classique ou nombreuses portes sur charnières ont été discutées par la Commission des Instruments.

La temperature constante de la salle du spectrographe est prévue à 20°. Une glace en silice traitée doit la séparer du télescope.

Comme il est inévitable d'avoir des sources thermiques dans le bâtiment - notamment la salle du spectrographe est plus chaude en hiver que la coupole -, il est nécessaire de prévoir dans le plancher séparant ces deux salles un dispositif enlevant la chaleur qui normalement passerait d'une salle à l'autre. Après des hésitations, la solution retenue est celle d'une coupole en acier peinte en blanc. Les conditions d'absorption étant bien meilleures pour une coupole peinte, une coupole en acier permet une structure plus solide ce qui facilite l'installation du pont roulant. Son prix est moins élevé.

La rotation de la coupole doit être très douce afin d'éviter de transmettre des vibrations au télescope et au spectrographe.

BATIMENT

Le bâtiment doit comporter deux structures :

1) les piliers reliant le télescope et les instruments de la façon la plus stable possible du sol;
2) le bâtiment proprement dit.

Ces deux parties doivent être isolées l'une de l'autre afin d'éviter la transmission des vibrations. Le bâtiment doit être bien isolé, il doit éviter de perturber thermiquement le site. Les études de site ont montré que le télescope doit être situé au moins à 25 m du sol. Le bâtiment doit naturellement comprendre les locaux nécessaires au service du télescope (laboratoires de photographies, salle de l'ordinateur, laboratoire).

Le dispositif d'aluminiure a été prévu au rez-de-chaussée et il sera desservi par un monte-charge spécial.

Du point de vue astronomique ce bâtiment devrait être le moins occupé possible pour éviter tout réchauffement de la température pendant le jour.

Un bâtiment à deux structures en béton armé a été étudié. Il serait utile de ne pas réaliser tous les locaux prévus pour pouvoir mieux adapter le bâtiment aux besoins futurs. L'architecte devrait étudier un bâtiment complet mais la construction effective des cloisons ne serait faite que sur demande.

L'ensemble bâtiments, télescope, coupole doit être conçu à résister aux chocs sismiques.

LES INSTRUMENTS AUXILIAIRES

Les instruments relativement légers, interféromètre, photomètre, etc. spécialement conçus pour le télescope, doivent être mis en place très rapidement. Ces instruments sont très divers et font partie du matériel de l'Observatoire, soit sont apportés par les équipes de missionnaires.

La place dans la cage du foyer primaire est petite et en principe les grands appareils auxiliaires seront disposés au foyer Cassegrain. Leur construction est plus facile pour le rapport d'ouverture F/8. Il est possible de travailler sans lentille auxiliaire au foyer Cassegrain.

L'instrumentation au foyer coudé permet d'envisager des spectrographes de grandes dimensions disposés dans un certain nombre de canaux. Il n'est pas question de construire immédiatement tous ces spectrographes, mais de disposer un premier instrument dans le canal qui sera également desservi par le télescope auxiliaire.

Les autres canaux restent naturellement disponibles pour y disposer des spectrographes de plus grandes dimensions ou de type différent ainsi que pour y installer des interféromètres et d'autres instruments auxiliaires.

Le choix entre les ouvertures F/30 et F/150 de la combinaison coudé n'est pas fait. Aucun problème ne se pose pour la combinaison F/30 pour laquelle nous avons prévu des chemins optiques de 18 m de long, ce qui permet d'utiliser des réseaux de 60 cm de diamètre qui ne sont d'ailleurs pas encore fabriqués.

Pour la combinaison F/150 un problème important est posé par la longueur des collimateurs, mais deux solutions sont possibles :

1) construire le spectrographe avec une ouverture à F/150 à l'aide d'un collimateur Cassegrain renversé ;
2) par un transport d'images passer de F/150 à F/30.

Ce transport d'images n'est pas difficile et peut être fait sans perte de lumière appréciable.

La description donnée ici est celle qui était adoptée en mars 1971. Mais divers changements plus ou moins importants résultent de la conférence actuelle.

DISCUSSION

BORGMAN: I would like to comment on the choice of changing the secondary units. This allows some freedom for future new auxiliary units. For instance I was thinking in this connection on a small wobbling mirror that could specify for infrared observations. Now I wondered a bit about the rather large cross section of the secondary unit that stays in place, because that will be determining the amount of 10 or 20 micron radiation that the detector has to see all the time. Has that been taken into account with the design?

FEHRENBACH states that the system of interchangeable top-units for the ESO telescope is a solution that has been decided on after lengthy discussions and not without hesitation. However, construction of new top-units for specific purposes will now be possible, also the top-unit for infrared work of which Dr. Borgman is talking.

What concerns the black-body radiation from the remaining telescope structure, one should not forget that this telescope is primarily an optical telescope and that special requirements, for instance for infrared astronomy, can only be met in as far as they do not interfere with this main purpose. It would also be undesirable to decrease the quality of night observations by having the telescope heated during day-time observations. It would therefore be a better solution to build a special telescope for infrared work as for instance the one Dr. Connes will speak about later, rather than to try to incorporate this possibility in the present design. An umbrella-rifle is neither a good umbrella, nor a good rifle!

SECORD: How do you maintain the collimation and the angular alignment after you have made an exchange?

FEHRENBACH: The alignment will be discussed later by Baranne. We have some ideas on how to ensure that adjustment would be correct after the exchange, which is of course a very important problem. We can, however, adjust this very easily by six computer driven motors. You can align x, y and the tilt without difficulties by means of the computer.

ELSÄSSER: I would be very grateful for some comments about the importance of the primary focus. Would it be a severe loss to have a telescope of this size without a primary focus?

FEHRENBACH: In the first design stage of this telescope, we had the impression that we did not need the primary focus. This would have decreased very much the price of the telescope, but it is very difficult to know the exact future of astronomy. When we started this project, the problem was to obtain a limiting magnitude as faint as possible, and at that time the long focal length of the Cassegrain Ritchey-Crétien was very nice, but now it has been proved that the primary focus is useful for plates that are not of the highest sensitivity. It is also useful for some problems in interferometry.

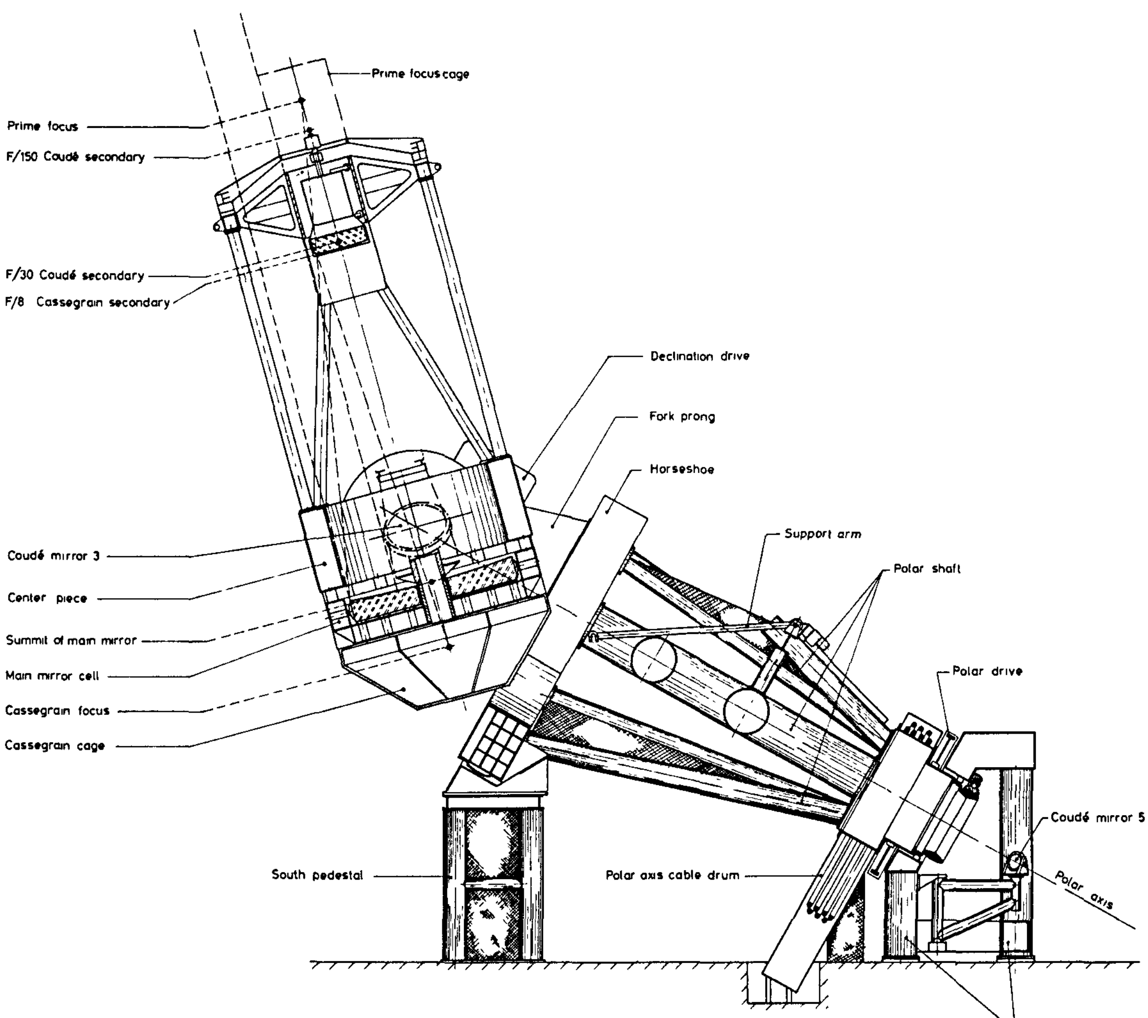


Fig. 1 Side view of ESO 3.6 meter telescope.

ENGLISH SUMMARY *

INTRODUCTION

The convention creating the European Southern Observatory (ESO) was signed in 1962, but some prestudies for the construction of a large telescope were carried out already in 1953. Also from 1953 a site survey was undertaken in the Republic of South Africa, and a ESO station was in operation at Zeekoegat from 1961 to 1966. Cerro La Silla in the northern part of Chile was finally chosen for the site of the observatory after careful comparison of the astronomical conditions in South Africa and Chile.

The efficiency of a large telescope depends very much on the quality of the site (i.e. many clear nights, small atmospheric turbulence, small temperature variations during the night, and low wind velocity), and the position at the site (e.g. altitude above the ground not less than 25 m). The quality of a telescope is measured as the diameter of the mirror divided by the image diameter; thus a 3 m telescope at a good site may well be just as efficient as a larger telescope at an inferior site.

THE SITE

The 3.60 m ESO telescope will be installed on Cerro La Silla at the altitude of 2440 m, approximately 600 km north of Santiago de Chile. The building will be erected on the main summit of the ridge with the telescope node 25 m above the ground.

Several smaller telescopes have been in operation at La Silla for some years; it has been found that the image diameter ("seeing") often is smaller than 1", and may even reach the exceptional value of 0".1.

THE TELESCOPE

Diameter

The originally anticipated diameter was 3.00 m. After certain considerations, especially the desirability of having a prime focus cage, it was increased to 3.50 m. When the main mirror blank was delivered it was decided to make use of its full 3.66 m diameter.

Precision

The mirror surfaces must be accurate to $\lambda/4$ = 0.06 micron. This precision must be maintained under actual observing conditions, i.e. thermal effects must be reduced as much as possible.

---

* Texte complet voir page 99.

Mirror material

In 1955 low expansion materials as Cervit and Pyrocéram were not yet commercially available. ESO therefore decided to use fused silica for the main mirror. A thickness to diameter ratio of 1:7 was adopted. The mirror blank was ordered in 1965 from Corning Glass International, U.S.A.. Seven hexagones and six triangles were fused together at $2500^{\circ}C$. During the cooling phase a rupture developed which was successfully repaired by Corning by repeating the fusion. The blank was accepted in January 1967 and delivered to the firm R.E.O.S.C. in Paris for figuring. It appeared later, during the grinding, that there would be an excessive number of bubbles in the final mirror surface, and the blank was therefore covered anew with a 10 cm silica top layer of very good quality. A fault in the surface (see the article of A. Bayle in this volume) was repaired by R.E.O.S.C..

In February 1967, ESO officials inspected the main blank (see ESO Bulletin No. 2).

The secondary mirrors (also silica) were ordered from the firm HERAEUS.

Optical lay-out of the telescope

Three foci have been envisaged: prime focus, Cassegrain focus and coudé focus. After detailed discussions, and taking into account that the limiting magnitude for photographic work with a large telescope is determined by the focal length only, the decision was made to have a F/3 primary mirror, a F/8 Cassegrain combination, and a F/30 coudé focus.

The mirror form

The ESO Instrumentation Committee has unanimously adopted a modified Ritchey-Crétien solution. The form of the secondary mirror for the Cassegrain focus has been calculated by H. Köhler (see the article in ESO Bulletin No. 2). The exact form for this mirror will depend on the final form of the primary mirror after polishing; a small deviation of the primary mirror from the theoretical form can be corrected for by slightly changing the form of the secondary mirror.

A. Baranne and H. Köhler have calculated correctors for the primary focus. The Baranne solution, which seems the most promising, calls for two correctors with silica lenses only, thus allowing observations in the spectral region from 3000A to 1 micron.

The images will be smaller than $0''.5$ over a 1° field at primary focus and smaller than $0''.3$ over a $0^{\circ}.5$ field at Cassegrain focus. Although the useful field in coudé focus has been somewhat reduced by adopting the modified Ritchey-Chrétien solution, it is still large enough ($0^{\circ}.1$) for usual coudé work.

The alignment of the optical system is described by A. Baranne in the present volume.

Coudé focus

This focus is necessary for heavy or complex equipment which cannot be carried by the telescope. A major difficulty is the necessity of two or more additional mirrors to direct the light beam to the fixed coudé focus. An English mounting cannot be used for such a large telescope. Due to the reflections in these mirrors some light will be lost, especially since the actual reflectivity of aluminized mirrors often is much lower than the ideal value of 0.85. The possibility of overcoming this problem by increasing the focal ratio has been discussed by Richardson (see the article in this volume). With F/150, the useful coudé field would be reduced to 2'.

Optical precision of the mirrors

The surface of the mirrors should be correct to $\lambda/4$ or even to $\lambda/8$. The ESO Instrumentation Committee has fixed the following tolerances: In Cassegrain focus 75% of the light must be within a circle of $0\overset{''}{.}4$ diameter, and in coudé focus 75% within $0\overset{''}{.}5$. It has been decided to accept a slightly different figure of the primary mirror, provided the Ritchey-Chrétien aplanatism could be preserved by correcting the secondary mirror, and that the form would be very regular.

The task of figuring the ESO 3.66 m mirror has been entrusted the optical firm R.E.O.S.C.. The work started in 1970. It took four months to repair the above mentioned fault. In February 1971 94% of the energy was within a circle of $0\overset{''}{.}5$ (75% tolerated) and 69% within $0\overset{''}{.}24$. The meridian curve was very close to the theoretical. Interferometry tests showed a very smooth surface. The opticians of ESO will further test the mirror with Hartmann tests and wave shearing interferometry.

The secondary mirrors are presently being figured. It will be very difficult to test the secondary Cassegrain mirror and various methods have been suggested. None of these is entirely satisfactory, and a series of tests will have to be carried out.

Astronomical conditions for the mounting

The necessary precision for the adjustment of the optical system has been studied by A. Baranne (Publication de l'Observatoire de Haute Provence, Volume 8). The axes of the two mirrors must be kept parallel with a precision of 20", and the lateral displacement (with parallel axes) must not exceed 0.3 mm. This precision is high, and the mirrors must be very well fixed in their cells. There will be little thermal influence on this adjustment because of the thermal stability during the night on La Silla. One could, however, fear a variation of the focal length due to the "thermal" figure of the mirrors and the temperature effect on the mounting. Another problem is the formation of a cold air cushion on top of the silica which might have optical effects. This problem has not yet been solved.

Pointing accuracy

A pointing accuracy of 1' is sufficient if the observer visually checks the presence of the star in the field, or if he recognizes the field, but an accuracy of 5" or even 1" may be desirable. This calls for very precise and preferably simple adjustments of all mirrors and full control of the flexures in the telescope. The computer will correct for flexure, atmospheric refraction and other effects.

Guiding

When a star has been centered, it should remain so within $0\overset{''}{.}1$ during several hours. This can be done either visually by the observer or by means of an automatic guiding system. Even a "perfect" telescope can not maintain a tracking of this precision with an open servo-loop, and a closed loop is therefore inevitable (see also the article by S. Laustsen and B. Malm in this volume).

Change of focus

A rapid change of focus is necessary in several situations: different programmes during the night at different foci, a change in the atmospheric conditions, or a sudden unexpected astronomical event (nova, comet, etc.). There are several methods for effectuating such a change:

1) All secondary mirrors are stored in the upper end of the telescope tube and brought into position automatically (200-inch Hale Telescope). This makes the upper end of the telescope rather heavy.
2) The whole top unit is exchanged (Lick 120-inch telescope). This excludes a change during the night.
3) The intermediate solution, which was studied by the ESO engineers and subsequently adopted by the ESO Instrumentation Committee, consists of three cages (prime focus cage, cage for Cassegrain secondary mirror, cage for coudé secondary mirror) to fit into the upper end of the telescope. The change is effectuated with the telescope in horizontal position and will probably last about 30 min or less.

The F/150 coudé system, suggested by Richardson, would diminish the size of the coudé mirrors (to about 25 cm) and the secondary coudé mirror could be carried by the cage for the secondary Cassegrain mirror, thereby reducing the number of cages to two. The F/30 coudé system will most certainly be conserved, but it is presently studied how the F/150 solution could be incorporated in the design without delaying the project.

Mounting

Various mounting types were studied and the adopted mounting is intermediate between a horseshoe and a fork mounting. This solution resembles the Kitt Peak design, although on the ESO telescope the declination axis is carried by a short fork on the horseshoe in order to reduce the diameter of the latter.

The polar axis is similar to that of the Hamburg Schmidt telescope (designed by W. Strewinski) and is supported on oil pads.

The possibility of supporting the declination axis on oil pads is being investigated.

The coudé focus arrangement comprises five mirrors. The fifth mirror directs the light beam horizontally into the coudé laboratory which is situated on the floor under the telescope; its motion will be computer controlled.

Mirror cell and support

The support system of the primary mirror will consist of thirty back supports distributed along three concentric circles and three fixed peripheral supports for the definition of the exact position and collimation of the mirror in the direction of the optical axis. The pneumatic side support has three defining supports and eighteen support bags. The pressure of these air bags is a function of the telescope tube position and is regulated by an air pressure control.

The tube

The upper part of the telescope is carried by a Serrurier truss, whereas the center section and the mirror cell are connected by six flexion bars. The Cassegrain focus can carry instruments weighing up to 500 kg. A study of the Cassegrain cage is under way. Some difficulties because of limited space between the back of the mirror cell and the horseshoe seem now to have been overcome.

AUXILIARY TELESCOPE

The large coudé spectrograph will not be idle when the other foci are in use. An auxiliary telescope (1 m) with a siderostate has been designed that will direct stellar light to this spectrograph. The limiting magnitude for this combination will be 1.5 to 2 magnitudes brighter than with the 3.6 m telescope.

THE DOME

The dome must perform various functions: Shelter the telescope during day-time, protect it against wind at night, and support the handling cranes and the cages. It must be well isolated and keep the night temperature during the day. The observing slit will be 6 m wide. The dome will be constructed of steel and painted white. No vibrations must be transmitted from the rotating dome to the telescope or the spectrograph.

THE BUILDING

The building must carry the telescope, the instruments, the dome and itself. For thermal reasons it will be covered with aluminium plates. It must be able to resist seismic shocks.

AUXILIARY INSTRUMENTS

There will be a number of ESO instruments, but visiting astronomers are also expected to bring along special equipment. Photometers, polarimeters, interferometers, spectrographs, etc., have been planned for.

This description of the ESO 3.6 m telescope was adopted in March 1971, but various - more or less important - changes have resulted from the present conference.

THE LA PLATA 84 INCH TELESCOPE

C. Jaschek

La Plata Observatory

The La Plata Observatory started the construction of an astrophysical observing station several years ago, equipped with an 84 inch reflecting telescope (215 cm). The telescope is a duplicate of the Kitt Peak National Observatory reflector and was constructed by the same manufacturers as its twin.

The telescope mounting is now in Argentina and the main optics has also arrived.

The spectrographs and other auxiliary equipment are planned to be constructed at the La Plata Observatory. The optical shop has just been finished.

The site where the station is to be erected was chosen several years ago, after a long site testing campaign, as previously reported. It lies in the vicinity of the Yale-Columbia-Cuyo Station in Argentina. The location is -31° 50' and +69° 25'. Its altitude is about 2000 meters. The site lies in the vicinity of the city of Barreal, 175 km by road from San Juan. The proportion of useful nights is of the order of 70%.

The terrain for the station has been provided by the Province of San Juan, from a large property purchased as an astronomical reservation.

Due mainly to financial difficulties and partially also because of faulty planning, it has not been possible to secure the money necessary for the dome and the additional installations. It is hoped, however, to obtain it this year, and in such a case the telescope could be working in 1974-5.

OPTICAL ASPECTS

TUESDAY, MARCH 2

AFTERNOON SESSIONS

Chairman: K. Bahner

OPTICAL DESIGN FOR LARGE TELESCOPES

R.N. Wilson
Carl Zeiss, Oberkochen

1. INTRODUCTION

This paper is intended to give a brief account of some of the work we have done during the last few years at Carl Zeiss, Oberkochen, on the optical design of telescopes.

It seems to me appropriate to begin with a brief comment on the role of the optical designer working in industry on astronomical instruments. His position is not the same as that of an optical designer who is also an astronomer. Many such astronomers are among the most skilled in the optical design profession and are in the fortunate position of themselves being able to judge what optical developments are meaningful and desirable for the advancement of astronomy. Those of us working in industry must be guided primarily by the problems presented to us by astronomers, but we may hope to indicate from our own experience possible lines of further development.

The developments with which we have been concerned are mainly based on the geometry of about f/3, f/8, f/15 - 35 suggested by Bowen(1), and on a Ritchey-Chrétien (R.C.)(2) or quasi R.C. design. We are well aware that there is a school of thought(3) which considers it a waste of an optical designer's time to occupy himself with 2-mirror aplanatic telescopes and that effort should be concentrated on Schmidt-type systems. Nevertheless, the fact that a high proportion of current developments in large(4) as well as medium and smaller telescopes are of the R.C. or quasi R.C. type seems to justify the assumption that this represents the mainstream of astronomers' views on present telescope design.

Our work has been mainly influenced by the ESO 3.5 m Project, the 1.52 m telescope for Vienna (now completed) and, above all, the 1.23 m, 2.2 m and 3.5 m instruments for the Max-Planck-Institute in Heidelberg. Our thanks are due to all those astronomers concerned with these projects for their suggestions and cooperation.

Since the coudé focus has only axial correction and presents no optical design problem, we have been essentially concerned with the secondary focus, the prime focus and the possibility of replacing this by a focal reducer. Since the secondary focus (~ f/8) is generally considered to be the most important observing station and most of our work has been concerned with it, I should like to begin with a discussion of correctors for this focus.

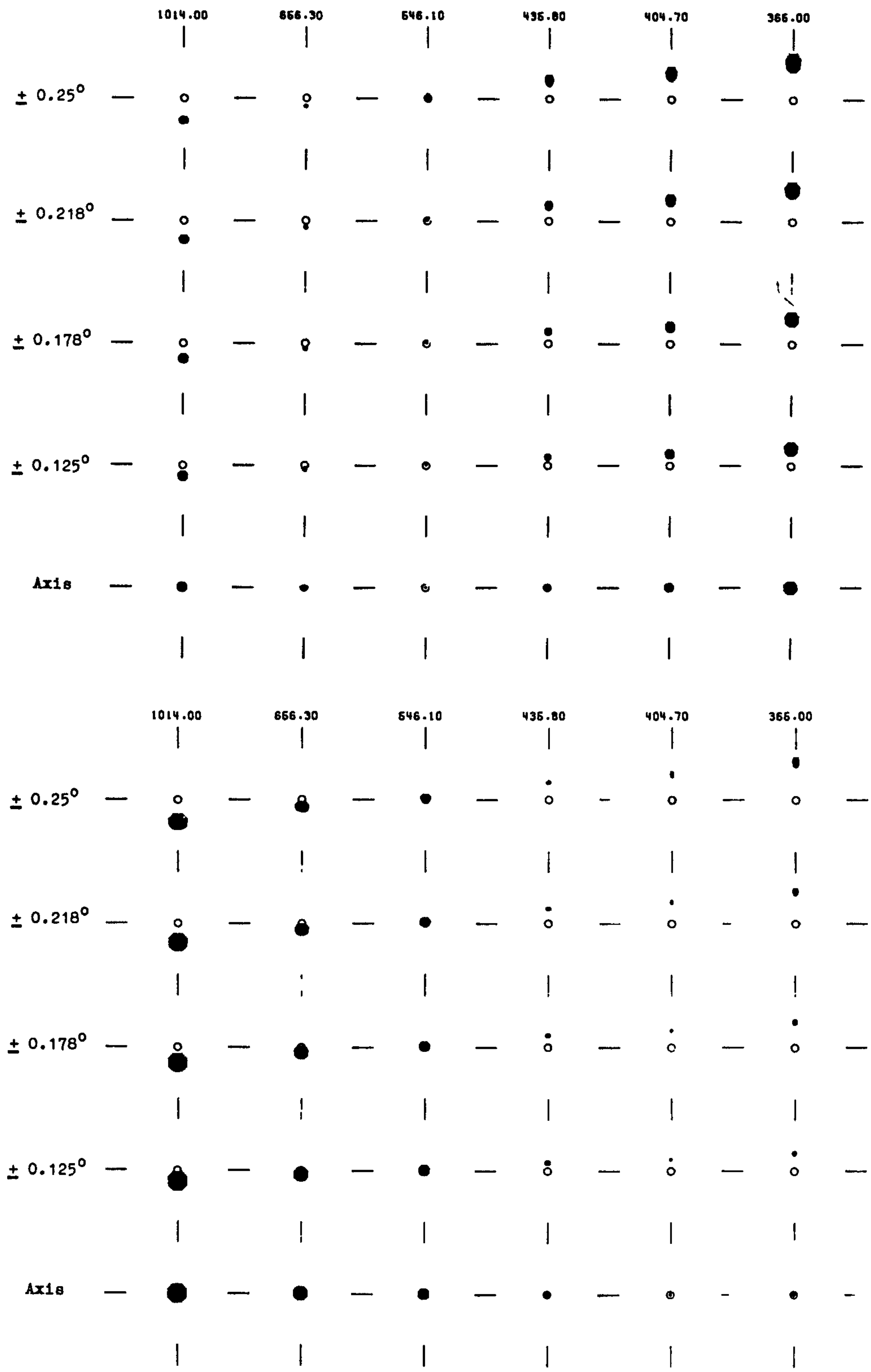


Fig. 1 3.5 m telescope for ESO. Quasi R-C focus. Field ± 0.25°. Singlet corrector. Spot diagrams for:
a) Best focus for 546 nm. (Circle = 0.18 arcsec = 25 μ)
b) Best focus for 405 nm. (Circle = 0.18 arcsec = 25 μ)

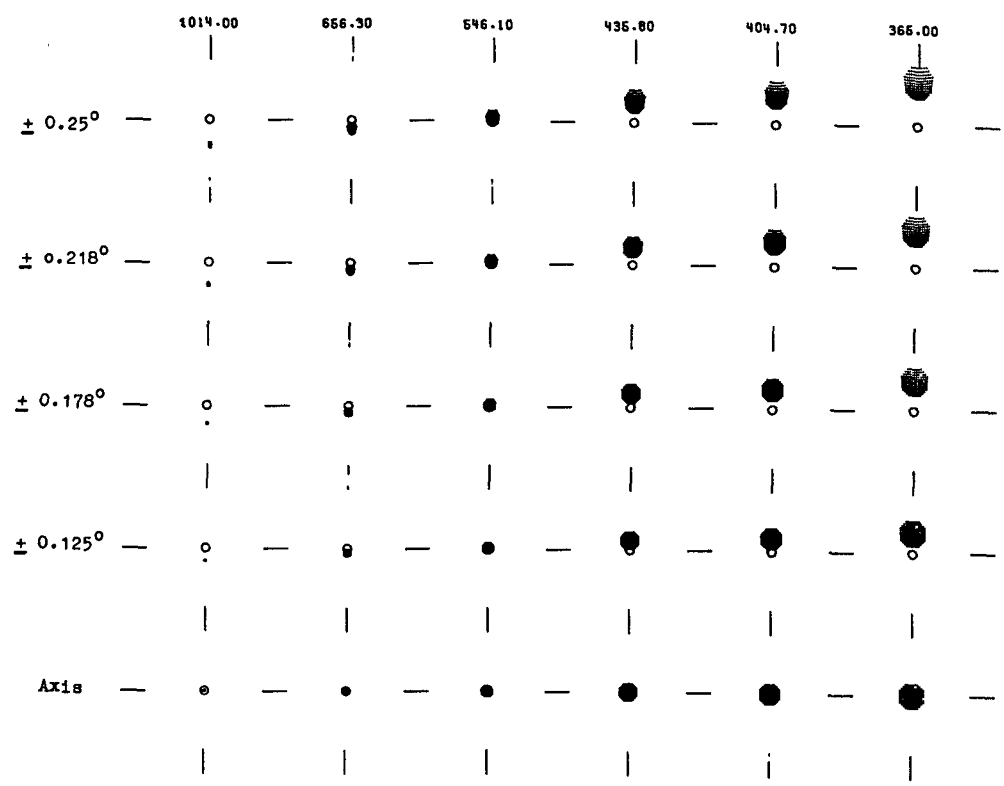


Fig. 1 3.5 m telescope for ESO. Quasi R-C focus. Field ± 0.25°. Singlet corrector. Spot diagram for:
c) Best focus for 1014 nm. (Circle = 0.18 arcsec = 25 μ)

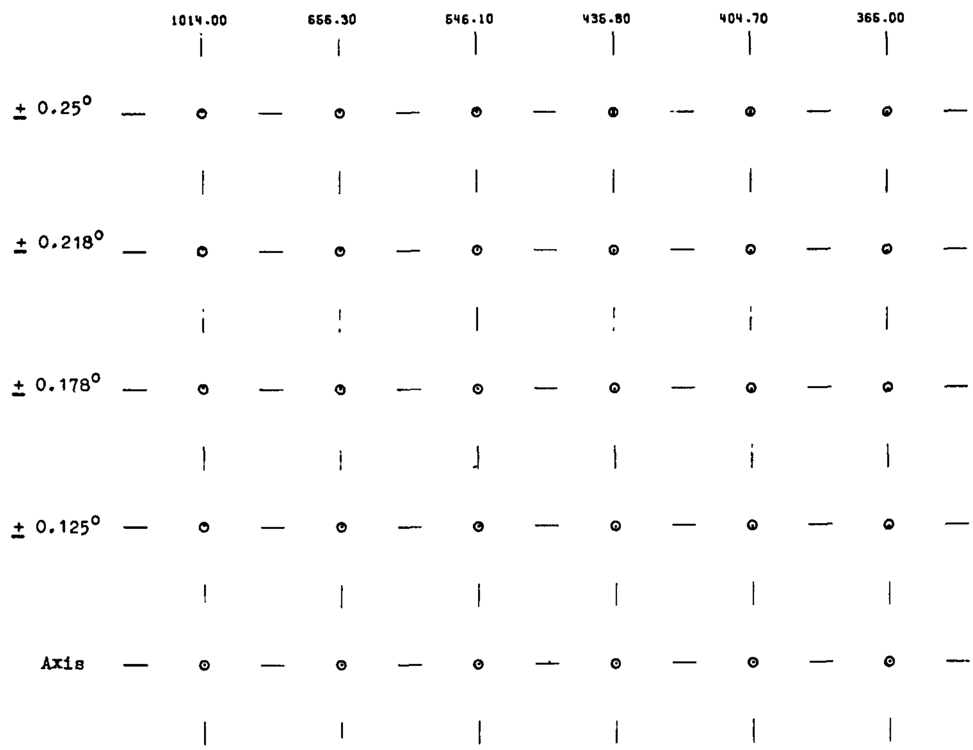


Fig. 2 3.5 m telescope for ESO. Quasi R-C focus. Field ± 0.25°. Doublet corrector. Spot diagrams to same scale as Fig. 1. (Circle = 0.18 arcsec = 25 μ)

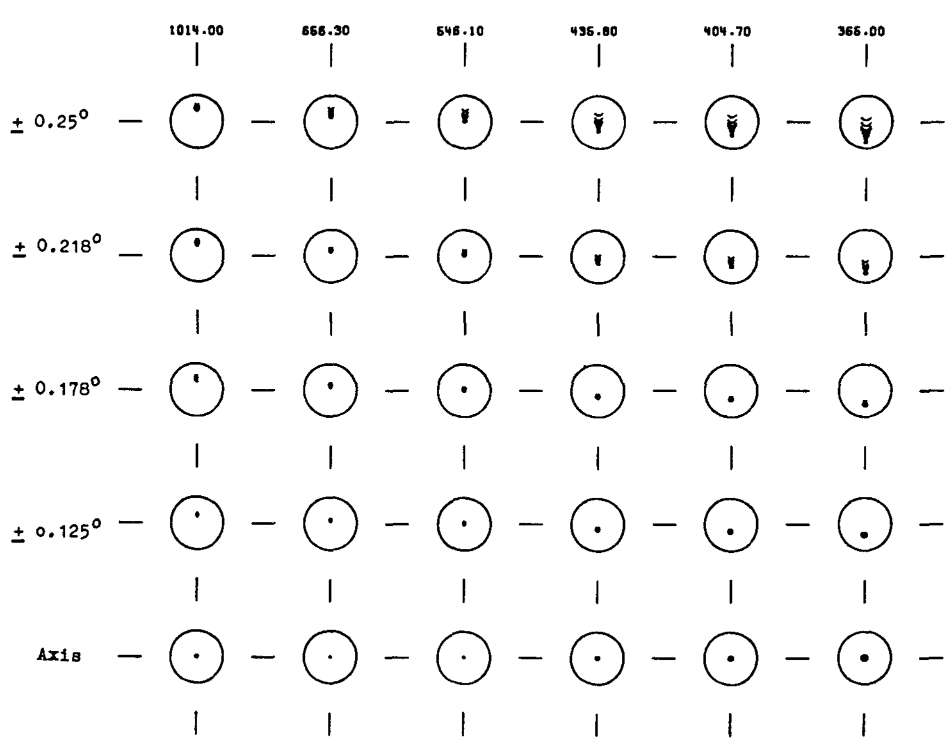


Fig. 3 3.5 m telescope for ESO. Quasi R-C focus. Field ± 0.25°. Doublet corrector. Spot diagrams as Fig. 2 with enlarged scale. (Circle = 0.18 arcsec = 25 μ)

2. SECONDARY FOCUS (~ f/8)

2.1 R.C. or quasi R.C.

Because of the limiting size of photographic plates, the angular field required is smaller with large than with medium or smaller telescopes. Whereas a 1 m telescope may well have a field of ± 0.75° or more, a 3.5 m instrument will not normally be used with plates larger than 30 cm x 30 cm corresponding to a field of ± 0.43°. Thus, types of corrector which are entirely satisfactory for large telescopes may be inadequate for smaller ones.

The oldest form of corrector is simply the field-flattening lens avoiding the necessity of a bent photographic plate. The uncorrected astigmatism is then the aberration limiting the field. It was pointed out by Köhler(5),(6) that it is possible to correct not only the Petzval corvature but also the astigmatism by shifting the lens a short distance inside the image plane. This solution was proposed for the 3.5 m ESO telescope*, the field specified being ± 0.25°. Figs. 1 (a,b,c) show spot-diagrams** for this system for an optimum focus at λ = 546 nm, 405 nm and 1014 nm respectively. The circle represents 25 μ or 0.18 arc sec. The fully uncorrected chromatic aberration is the most serious defect of this system, particularly the transverse chr. aberration. The longitudinal aberration can be focused out quite adequately for reasonable spectral regions, but the lateral colour is about 2 arc secs between 1014 nm and 365 nm. Some colour coma becomes noticeable in the violet. On the other hand, the solution has the advantage of giving only one ghost image compared with six from a two lens corrector. (This excludes ghost images produced by reflection between the emulsion surface and lens surfaces. A test photograph of the Pleiades with the 2-lens corrector of the Vienna telescope failed to show any trace of ghost images resulting from reflexion at the emulsion, although all six ghost images caused by reflexions between the lens surfaces were identifiable for Alcyone.) For limited spectral ranges its performance is within the original specification of 0.5 arc secs.

Bearing in mind that the lateral colour grows at least linearly with the field, the solution becomes unacceptable for the larger angular fields of smaller telescopes. This was the principal reason for the selection of the 2-lens corrector for the Vienna telescope. Following this experience, a 2-lens corrector was set up for the pre-determined ESO 3.5 m primary. The resulting corrector is roughly afocal and consists of two menisci with their

---

* Our calculations were performed for a 3.5 m primary. Since then, the telescope has been scaled up to 3.6 m.

** All the spot-diagrams in this paper are for a square element matrix of points in the pupil. The matrix constant is chosen so that about 120 - 130 rays are traced, taking account of obstruction by the secondary.

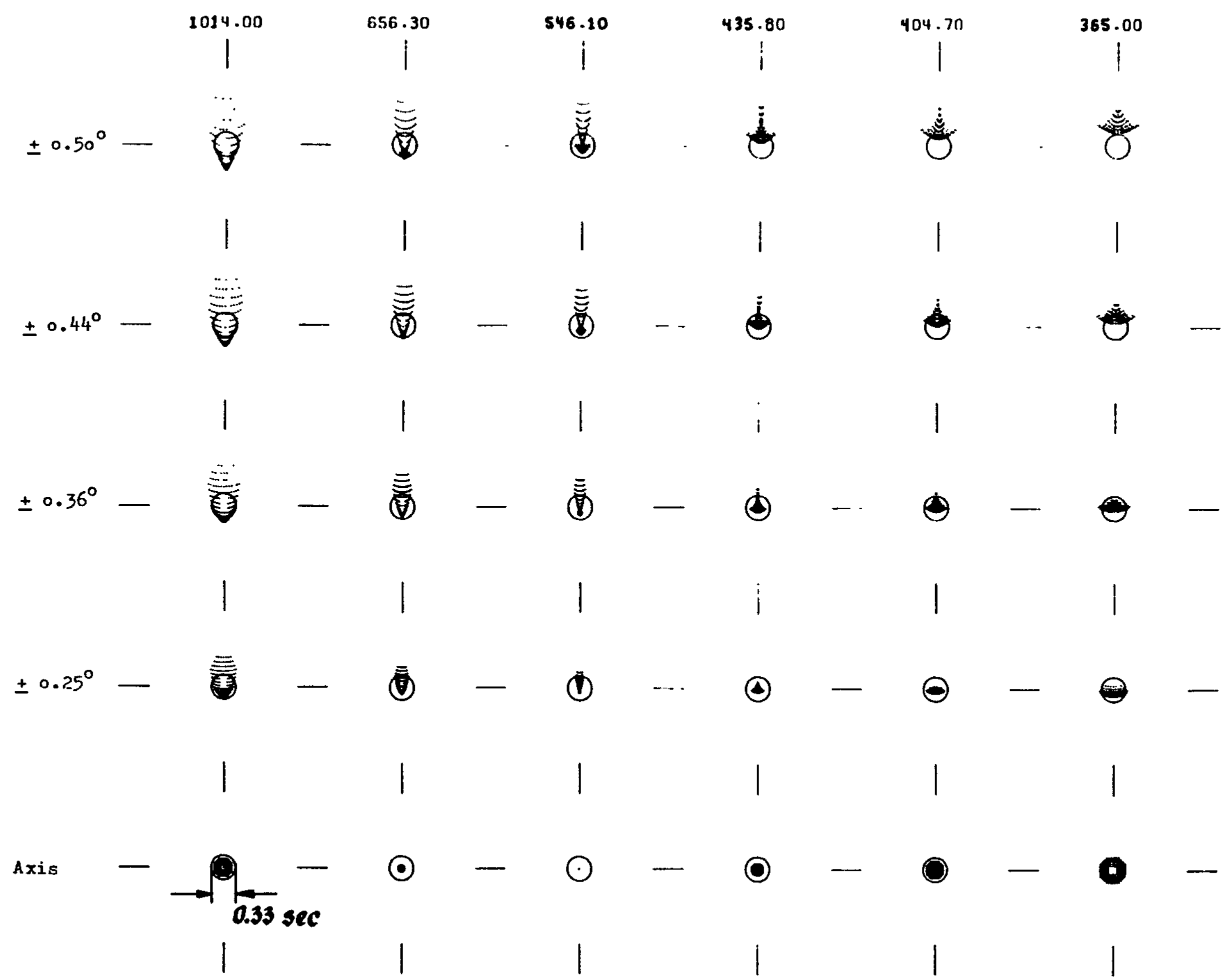


Fig. 4   1.52 m telescope with strict R-C mirror constants and doublet corrector of one material. Field ± 0.5°. Best focus for 546 nm. Spot diagrams. (Circle = 0.33 arcsec = 20 μ)

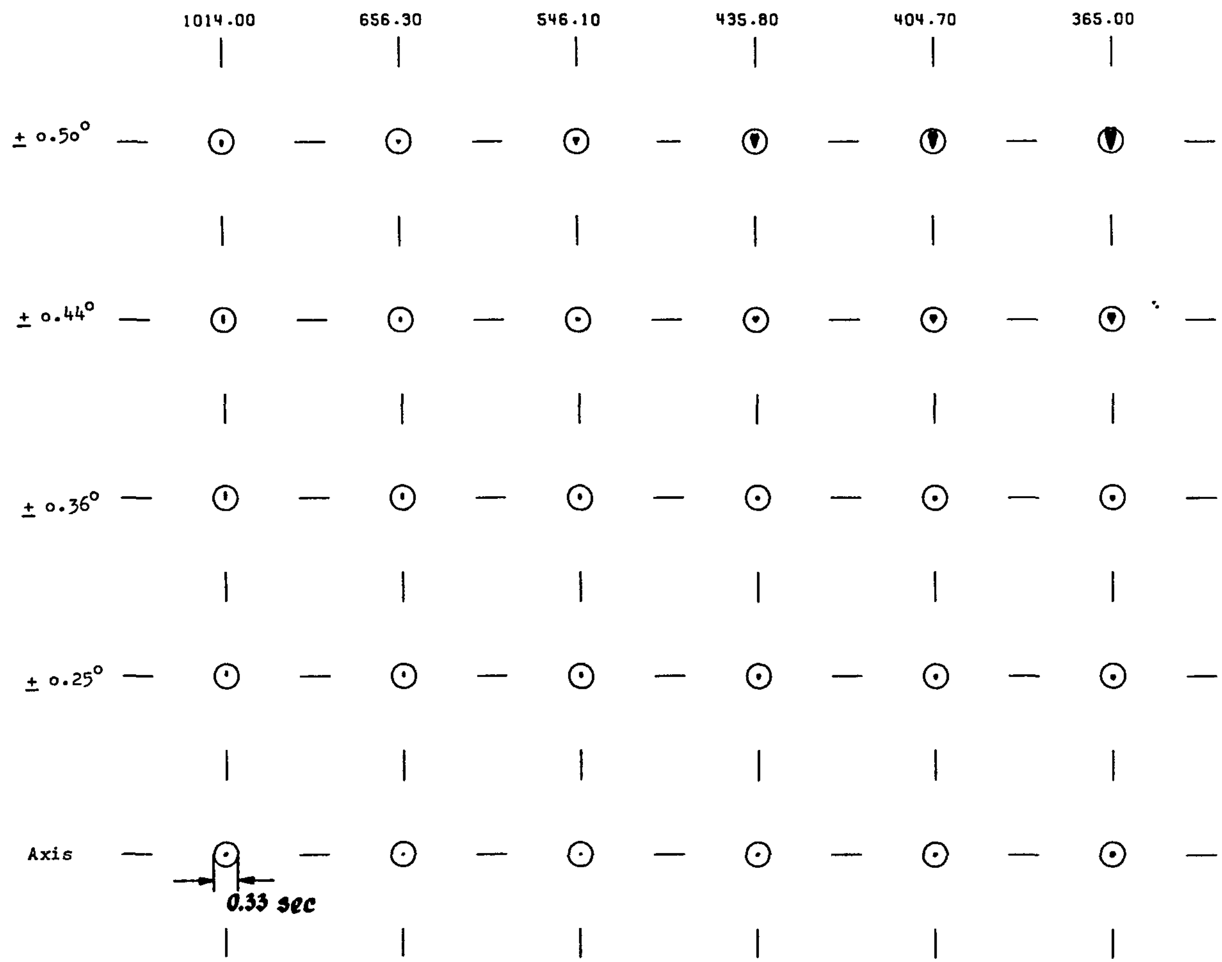


Fig. 5 1.52 m telescope for Vienna with quasi R-C mirror constants and doublet corrector of one material. Field ± 0.5°. Spot diagrams. (Circle = 0.33 arcsec = 20 µ)

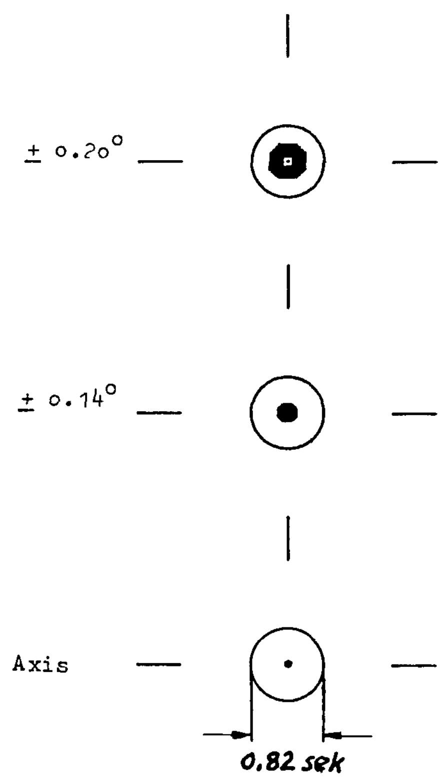


Fig. 6 1.52 m telescope with strict R-C mirror constants (as Fig. 4) without corrector. Spot diagrams for an optimally bent plate with radius 1410 mm. (Circle = 0.82 arcsec = 50μ)

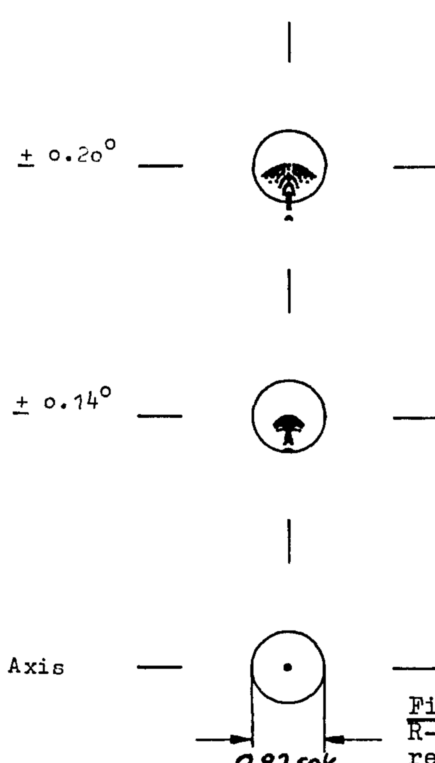


Fig. 7 1.52 m telescope for Vienna with quasi R-C mirror constants (as Fig. 5) without corrector. Spot diagrams for an optimally bent plate with radius 1371 mm. (Circle = 0.82 arcsec = 50μ)

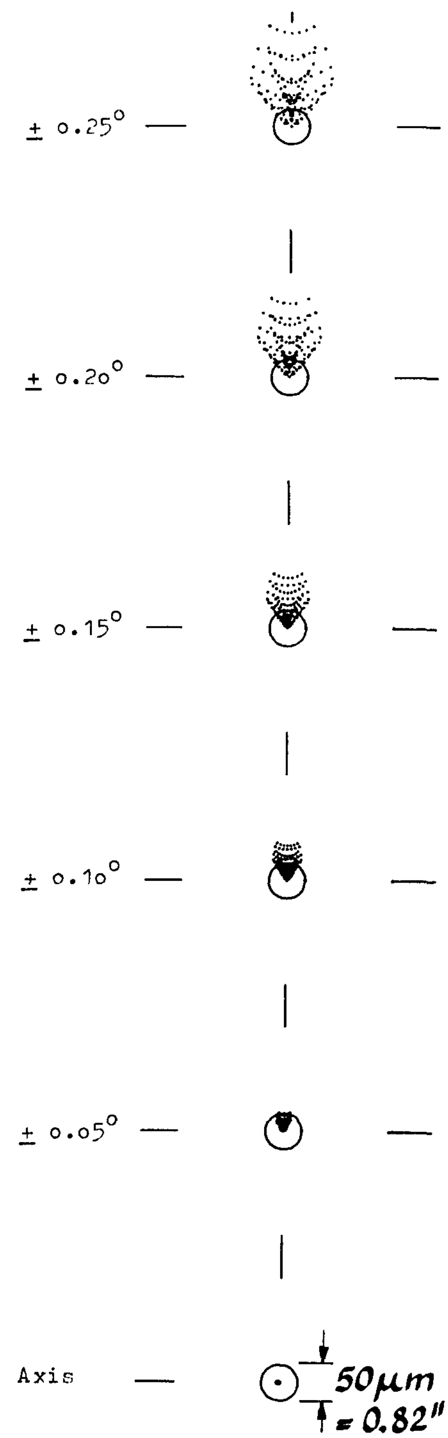
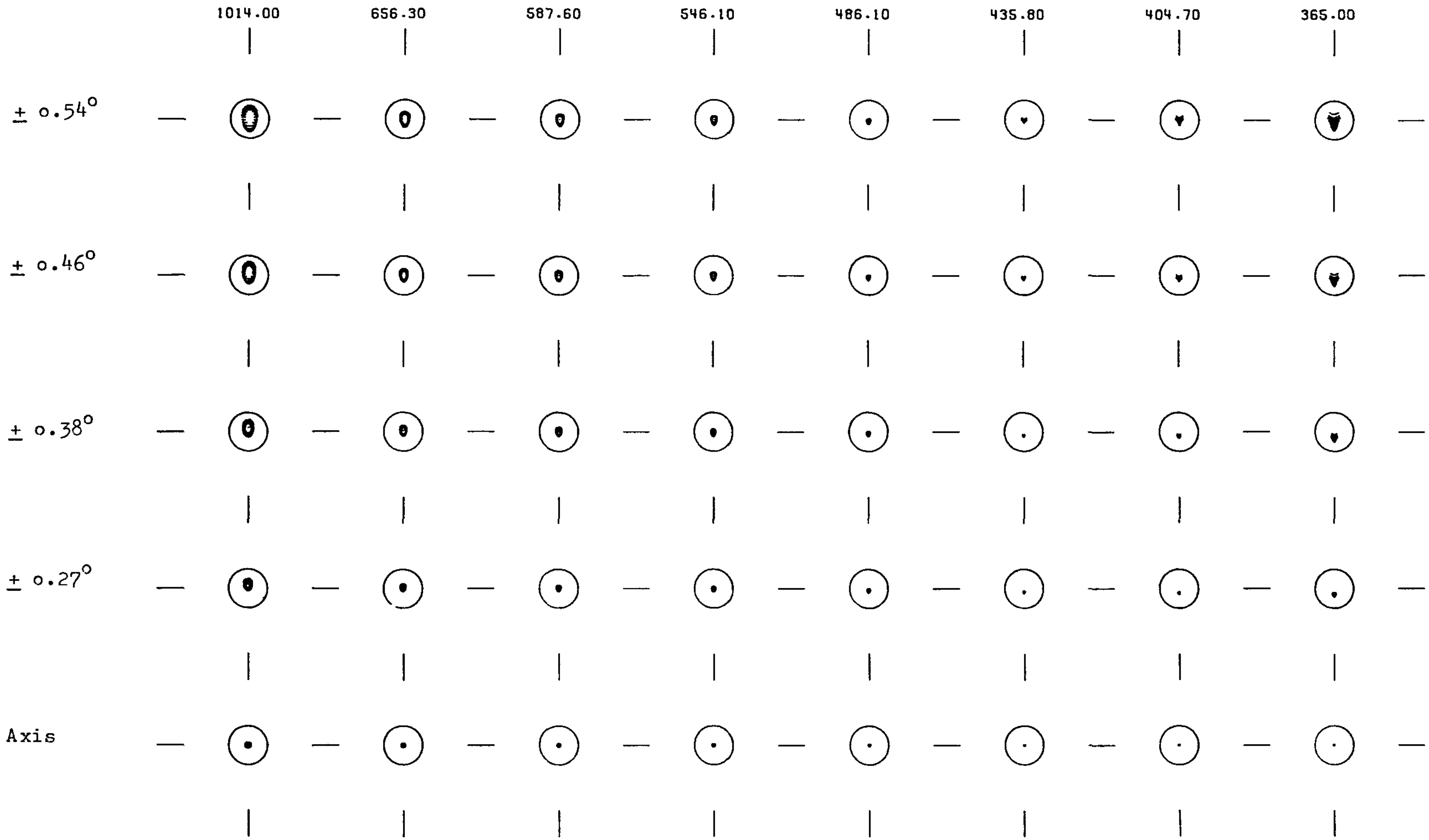


Fig. 8 1.52 m telescope with classical mirror form (paraboloid, hyperboloid) without corrector. Geometry as in Figs. 6 and 7. Spot diagrams for an optimally bent plate with radius 1539 mm. (Circle = 0.82 arcsec = 50μ) concave faces towards each other. Fig. 2 shows the spot-diagrams on exactly the same scale as those of Fig. 1. Fig. 3 shows the same spot-diagrams on a larger scale (circle again 25 μ or 0.18 arc secs.). The very considerable improvement given by two lenses as compared with one is evident.

It must be emphasized that both the singlet and doublet solutions for the ESO 3.5 m project as well as the doublet corrector for the Vienna 1.52 m telescope are quasi R.C., not strict R.C. solutions: the aspheric constants of the mirrors were free parameters during the optimization. (For the ESO doublet corrector the prime mirror was, in fact, pre-determined, but the aspheric constants of the secondary were free to vary.) The significance of this variation from the strict R.C. solution becomes marked for doublet correctors of one material (e.g. quartz) and typical fields for smaller telescopes (say ± 0.5° or more). This point is illustrated by the two solutions set up for the Vienna telescope. Fig. 4 shows spot-diagrams (circle 0.33 arc sec) for a doublet corrector of one glass type and a strict R.C. mirror system for the desired field of ± 0.5°. The coma, astigmatism and chromatic aberration can only be corrected up to a certain point and the spread of the spot-diagrams reaches about 1 arc sec at the extreme wave lengths for an optimum focus chosen for λ = 546 nm. Fig. 5 gives the equivalent spot-diagrams to the same scale for a doublet corrector of one glass type and a quasi R.C. mirror system. The only significant aberration residual is the colour astigmatism which is uncorrectable, but the worst spot-diagram is within 0.33 arc sec for one focus over the entire spectral range. The quasi R.C. solution was preferred[(7),(8)]; design data for a similar system are given in ref.(7).

The above mentioned quasi R.C. solutions show negligible change in the spherical aberration if the lenses are removed. The coma, on the other hand, is small but not negligible. A comparison between the strict R.C. solution for Vienna and the quasi R.C. colution, in both cases without lenses and with optimally bent photographic plates, is shown in Figs. 6 and 7 (circle 0.82 arc secs), corresponding to Figs. 4 and 5 respectively. Since the coma grows linearly with the field and the astigmatism quadratically, the coma becomes relatively less significant for larger fields. At ± 12 arc min the strict R.C. gives a symmetrical spot of about 0.40 arc secs, the quasi R.C. an unsymmetrical spot of about 0.63 arc secs. Fig. 8 shows spot-diagrams for the equivalent classical telescope, again for optimally bent plates (circle 0.82 arc sec). The spot-diagram (strongly comatic) is about 1.94 arc sec at ± 12 arc min.

Whether the coma residual shown in Fig. 7 for such quasi R.C. solutions without corrector is astronomically significant appears to be a matter for debate. A similar solution was chosen for the 1.23 m telescope for the Max-Planck-Institute, the with-lens field being very well corrected for ± 0.75°. The solution due to Gascoigne and Schulte[(9),(10)] (an aspheric plate and field-flattener) for the Cerro Tololo 1.52 m telescope is also a quasi R.C.



<u>Fig. 9</u> 2.2 m telescope with quasi R-C mirror constants and doublet corrector of one material. Optimized for blue. Field ± 0.54°. Spot diagrams. (Circle = 0.47 arcsec = 40 μ)

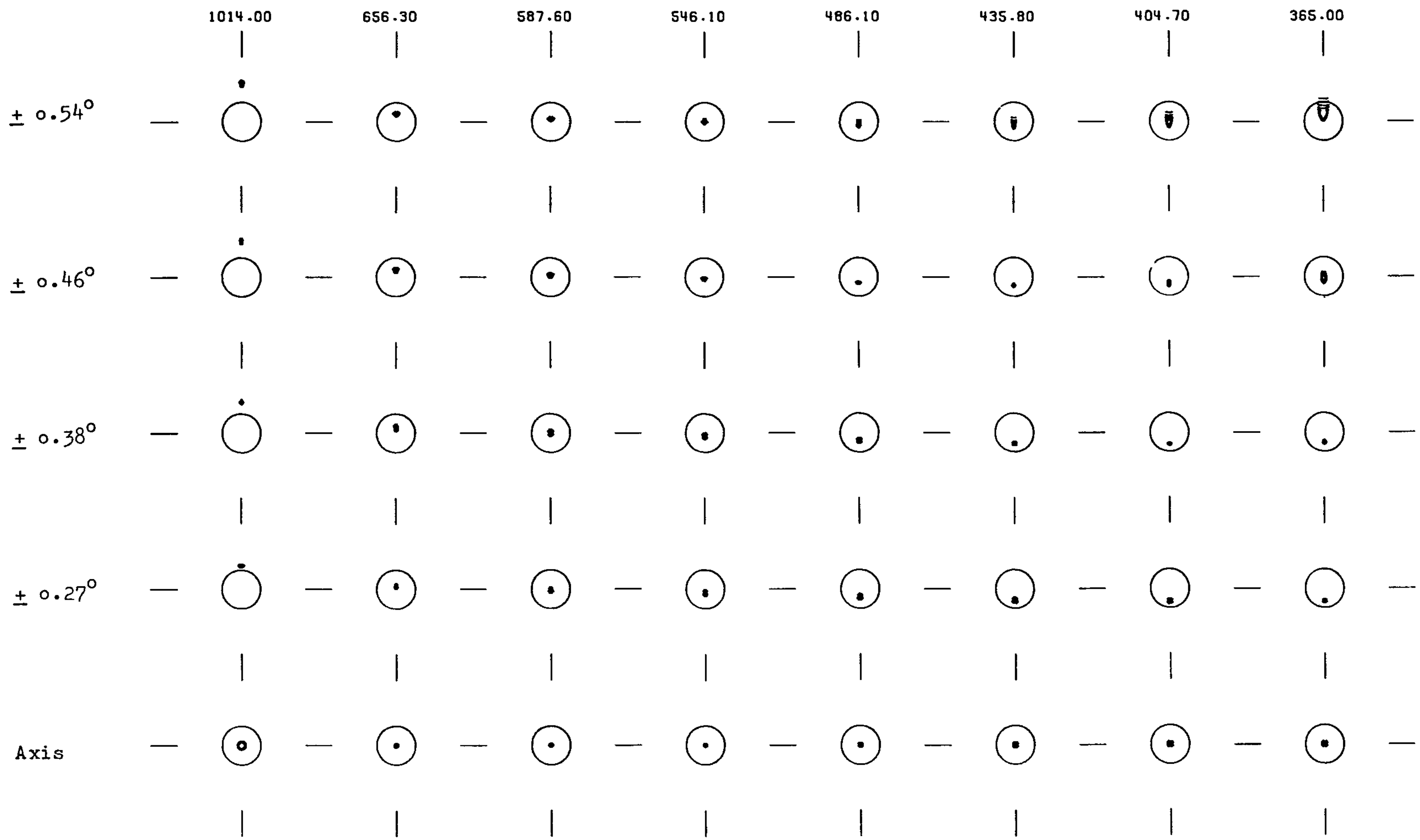
<u>TABLE 1</u>

Design data for 2.2 m telescope with quasi R-C mirror constants and doublet corrector of one material. Optimized for blue. Field $\pm$ 0.54°. Design corresponds to spot diagrams of Fig. 9.

Radius (mm)	Separation (mm)	Glass	n_e	$n_{656.3}$	$n_{404.7}$	n_{365}
-13200.[a] (free diameter)			1			
2200.						
	-4469.18		-1			
- 6816.[b]						
	5290.45		1			
973.9						
	44.0	Quartz	1.46013	1.45640	1.46968	1.47465
1667.2						
	127.88		1			
- 2035.8						
	35.0	Quartz	1.46013	1.45640	1.46968	1.47465
2643.1						
(back focus)	194.95		1			

a Aspheric $p = h^2/2r + (8.959638 \times 10^{-15})\ h^4$

b Aspheric $p = h^2/2r + (2.3393291 \times 10^{-12})\ h^4 - (1.3722965 \times 10^{-19})\ h^6$



<u>Fig. 10</u> 2.2 m telescope for MPI with strict R-C mirror constants and doublet corrector of two different glasses (PK 50 and BaF 3). Field ± 0.54°. Spot diagrams. (Circle = 0.48 arcsec = 40 µ)

TABLE 2

Design data for 2.2 m telescope for MPI with strict R-C mirror constants and doublet corrector of two different glasses (PK 50 and BaF 3). Field ± 0.54°. Design corresponds to spot diagrams of Fig. 10.

Radius (mm)	Separation (mm)	Glass	n_e	$n_{656.3}$	$n_{404.7}$	n_{365}
-13200.[a] (free diameter) 2200.			1			
	-4469.18		-1			
- 6816.[b]						
	5324.86		1			
1994.						
	37.98	PK 50	1.52232	1.51824	1.53294	1.53846
25140.						
	205.55		1			
- 999.						
	27.81	BAF 3	1.58565	1.57893	1.60460	1.61524
- 5065.						
(back focus)	89.07		1			

a Aspheric $p = h^2/2r + (7.306787 \times 10^{-15})\, h^4$

b Aspheric $p = h^2/2r + (2.1860958 \times 10^{-12})\, h^4 - (1.2105792 \times 10^{-19})\, h^6$

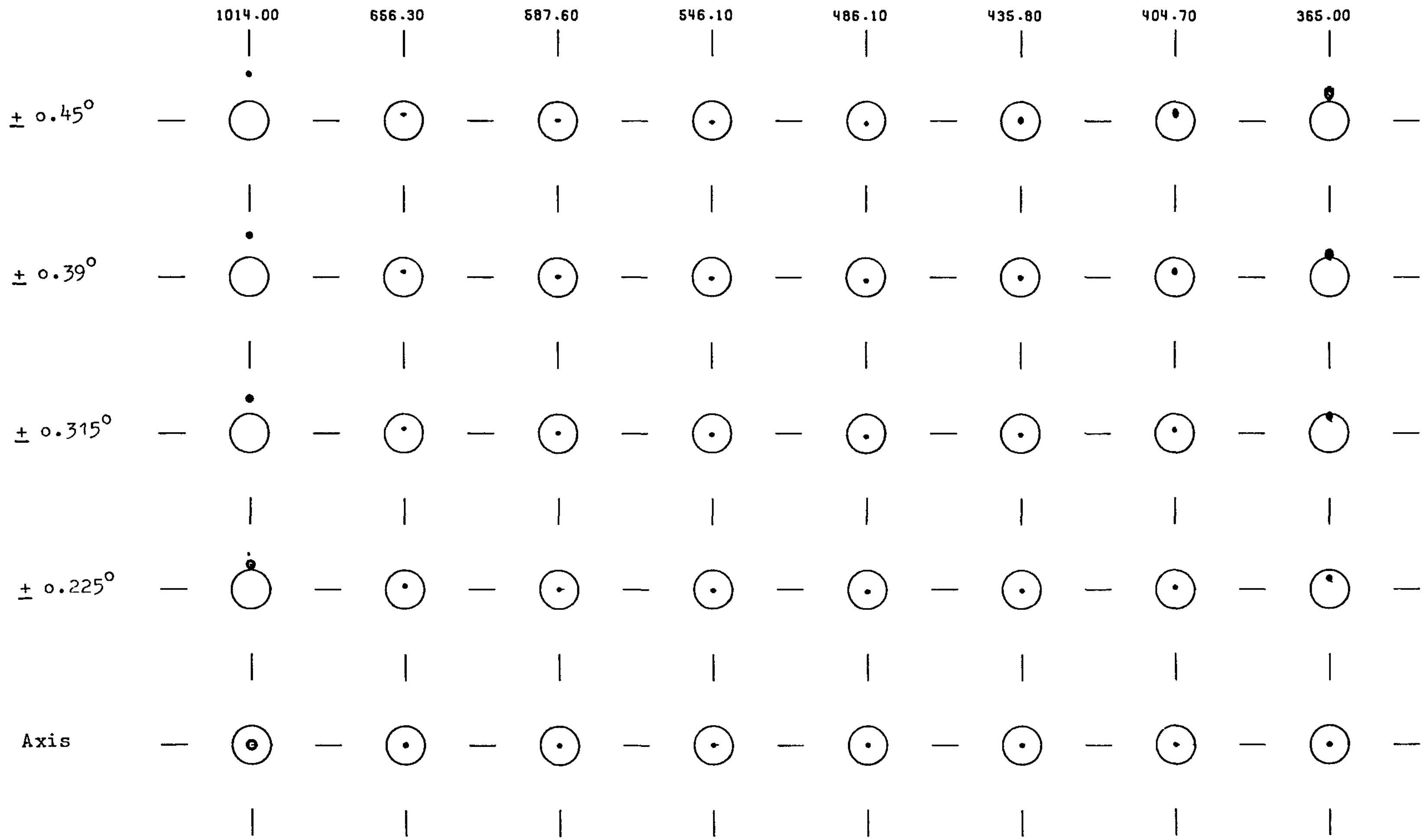


Fig. 11 3.5 m telescope with strict R-C mirror constants and doublet corrector of two different materials (Quartz and LLF 1). Field ± 0.45°. Spot diagrams. (Circle = 0.49 arcsec = 64 μ)

TABLE 3

Design data for 2.2 m telescope with strict R-C mirror constants and doublet corrector of two different materials (Quartz and LLF 1). Field ± 0.45°. Design corresponds to spot diagrams of Fig. 11. (Linear circle size for spot diagrams (64 μ) in Fig. 11 represents design scaled up for a 3.5 m telescope with identical geometry.)

Radius (mm)	Separation (mm)	Glass	n_e	$n_{656.3}$	$n_{404.7}$	n_{365}
-13200.[a] (free diameter)			1			
2200.						
	-4469.18		-1			
- 6816.[b]						
	5423.45		1			
814.11						
	29.32	Quartz	1.46015	1.45645	1.46972	1.47469
15169.46						
	94.10		1			
- 2284.65						
	23.03	LLF 1	1.55099	1.54457	1.56910	1.57931
1049.33						
(back focus)	110.14		1			

a Aspheric $p = h^2/2r + (7.306787 \times 10^{-15})\ h^4$

b Aspheric $p = h^2/2r + (2.1860958 \times 10^{-12})\ h^4 - (1.2105792 \times 10^{-19})\ h^6$

having a with-corrector field of ± 0.75° of excellent quality.

If a similar correction with a strict R.C. is possible obviously this is to be preferred. As mentioned above, the problem is less acute for the smaller angular fields of large telescopes and Wynne[(11),(12)] has designed a very good quartz doublet corrector for the Kitt Peak 3.8 m telescope while maintaining strict R.C. constants. Nevertheless, as Fig. 4 shows, this type of solution presents difficulties for larger angular fields.

The addition of a third (aspheric) corrector element brings a useful improvement[(13)], but more can be gained by relaxing the condition that both corrector lenses be of the same material. The field requirement of the Vienna telescope led us to investigate such a solution[(7)].

This aroused the interest of Dr. Bahner and a solution was set up for the 2.2 m telescope (MPI) whose manufacture is now underway. In fact, two solutions were set up for comparison: a quasi R.C. with two quartz corrector lenses ("Vienna type" - Fig. 9 - circle = 0.47 arc sec) and a strict R.C. with two corrector lenses of different glasses ("Two-glass type" - Fig. 10 - circle 0.48 arc sec). The balance of aberration residuals was optimized for this telescope in the visual - to - uv. The field covered is ± 0.54°. The two-glass strict R.C. solution is even better than the quasi R.C. except for the secondary spectrum and zonal error of the transverse colour. The secondary spectrum causes the center of gravity of the spot-diagrams to lie on a curve. As the two-glass solution requires a certain relative position of the glasses on the refractive index - dispersion diagram, this secondary spectrum could only be further reduced by using a short flint glass with a departure from the "normal" dispersion. Unfortunately, such short flint glasses have an appreciably higher uv-absorption than other glasses in the same region of the glass diagram. The Schott phosphor-crown glass (PK 50) gives some reduction in the secondary spectrum with acceptable absorption. The appropriate flint glass is then BaF 3. Tables 1 and 2 give the data for the systems shown in Figs. 9 and 10 respectively.

I am indebted to Dr. Bahner for pointing out that the atmospheric dispersion even for small zenith distances is comparable with the transverse colour of this system. With the usual formula for the atmospheric dispersion

$$\delta\varsigma = \delta n \cdot \tan z$$

we have for an air mass of unity and tan z = 0.1 a transverse colour $\delta\varsigma$ of 0.224 arc sec between 365 nm and 1014 nm, almost half the maximum value for the spot-diagrams of Fig. 10. Apart from the transverse colour, the only noticeable aberration is the - uncorrectable - colour Petzval sum. It is instructive to compare Fig. 10 (field ± 0.54°) with Fig. 4 (field ± 0.50°), the equivalent strict R.C. with two corrector lenses of the same material.

The only disadvantage of the above two-glass solution would appear to be the uv-absorption which is strong below 330 nm. If we replace the glass PK 50 with quartz and combine this with an appropriate flint such as LLF 1, the result is a correction comparable in all respects except that the transverse colour is worse. Since, however, for a 3.5 m telescope we only require a field of ± 0.43°, the transverse colour is no worse than that of the above PK 50 - BaF 3 corrector for a field of ± 0.54°. Fig. 11 (circle = 0.49 arc sec) shows the spot-diagrams, and Table 3 the data, for the quartz-LLF 1 strict R.C. system for a field of ± 0.45°. Apart from the transverse colour, it is diffraction limited over the whole spectral range and for the whole field. Furthermore, the uv-transmission extends down to about 310 nm. This seems a particularly interesting solution for large telescopes. Even more attractive in principle would be a combination of fluorite and K 10 but, in practice, blanks of fluorite are not available in the necessary diameter for large telescopes. The uv-transmission would be even better and the departure of fluorite from the "normal" dispersion would compensate (perhaps over-compensate) the secondary spectrum of the transverse colour. A combination of fluorite and quartz is at first sight attractive because of the uv-transmission, but the dispersion difference is too small to give a correction of comparable quality; furthermore the secondary spectrum of the transverse colour is appreciably over-corrected.

Fig. 11 illustrates that it is possible to reduce spot-diagrams for a large telescope to 0.1 arc sec or better over the whole field and spectral range using a two lens corrector and a strict R.C. solution. Since the best seeing available is considered to be about 0.3 arc sec, it may be asked whether such geometrical optical quality is significant. If the residual aberrations were the only source of error in the telescope, this might not be the case. However, there are a large number of factors affecting image quality. Some of these are often underrated, for example, the systematic errors arising from testing techniques in the manufacture of the mirrors. Compensation- (or Null-) systems[(14),(15),(7),(16)] are normally used for the primary, while the secondary is usually tested either by an auxiliary Hindle sphere or by a concave matrix aspheric (negative) which is itself tested by a compensation system. Systematic errors in the test set-up may be reproduced in the mirror surfaces. Similarly, it is a very difficult problem to adjust a telescope to sufficient precision and to reduce flexure effects on the image to values comparable with the best seeing. If, therefore, the spot-diagrams can be made small in comparison with the seeing without increasing the number of optical elements, the astronomer will have more chance of profiting from the best observing conditions.

Two-lens correctors for the secondary focus of the type described above are relatively uncritical regarding centering and figure. The problems associated with the secondary mirror are far more difficult.

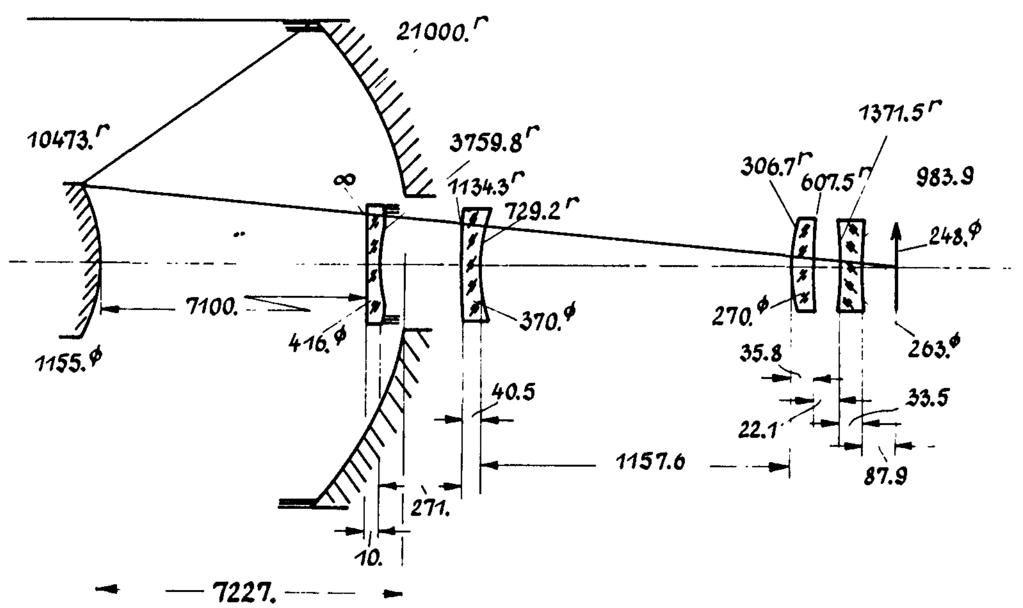


Fig. 12 Corrector for quasi Dall-Kirkham telescope (spherical secondary). Field ± 0.25°. Section through system (schematic).

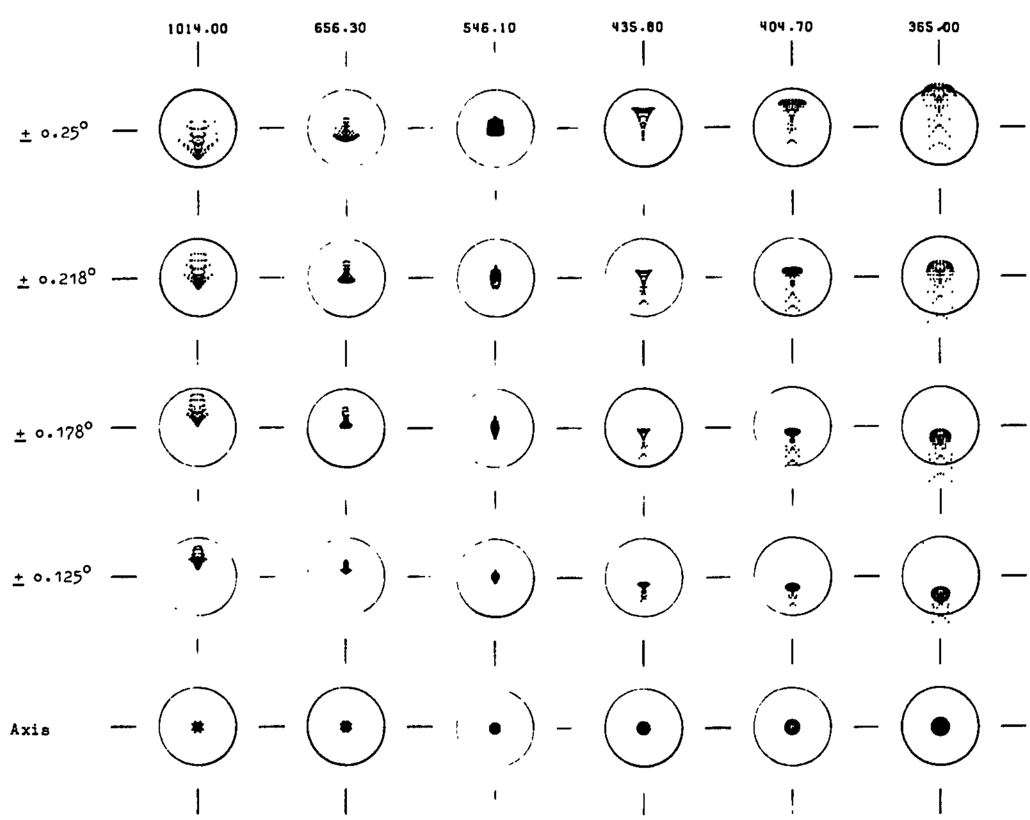


Fig. 13 3.5 m quasi Dall-Kirkham telescope (spherical secondary) with corrector of Fig. 12. Field ± 0.25°. Spot diagrams. (Circle = 0.50 arcsec = 68 µ)

2.2 Dall-Kirkham telescope

The Dall-Kirkham (D.K.) telescope (ellipsoidal primary, spherical secondary) offers no optical design advantages, but it possesses two considerable technical advantages. Firstly, the manufacturing problems for a spherical secondary are very greatly eased; secondly, the secondary is very much less sensitive to centering errors. I think there is no doubt, irrespective of where the telescope is manufactured, that a D.K. telescope would yield a better axial image than a classical or R.C. telescope.

A corrector for a D.K. telescope is more difficult than the correctors discussed above because of the relatively large coma, some 3 1/2 times that of a classical telescope. Its correction requires elements with a significant separation from the image plane. We have tried a large number of possible correctors, but the best results were achieved by a 4-element system shown schematically in Fig. 12. The spot-diagrams (circle 0.50 arc sec) for a field of $\pm$ 0.25° are shown in Fig. 13. The corrector consists of three lenses with spherical surfaces and a weak aspheric lens near the pole of the primary. During the optimization, the aspheric constants of the primary were free parameters. As a result, the spherical aberration for the mirror system without corrector is appreciable. We have not yet investigated the possibilities of a similar corrector with fixed D.K. constants for the primary mirror. Because of the complexity of the corrector, the advantage of the insensitivity of the secondary to decentering no longer applies when the corrector is used. The centering tolerance is then about the same as that of a classical or R.C. mirror system.

We have also tried a Wynne-Rosin-corrector[17],[18] consisting of a doublet about half way between the secondary and the image plane. The diameter of the lenses is inevitably large (in one solution about 700 mm) and we have not achieved as good a correction as with the 4-element corrector of smaller diameter shown in Fig. 11. Nevertheless, this corrector would appear to offer interesting possibilities for a D.K. telescope with a limited field.

3. PRIMARY FOCUS ($\sim$ f/3)

Our work in this focus has been mainly concerned with the 3-plate-corrector for the 3.5 m ESO telescope.

The suggestion for a corrector consisting of three aspheric plates and a field-flattening lens was made by Meinel[19], who worked out the third-order theory. Further development of this system was reported by Schulte[20]. Dr. Schulte kindly drew the attention of Professor Köhler to its possibilities and the system was optimized by my colleague Dr. Glatzel. The results of this optimization were those reported by Köhler[5],[6]. The form of the system is shown in Fig. 14 and the spot-diagrams in Fig. 15 (circle 0.5 arc sec). These spot-diagrams have been plotted to a scale identical with that of the following

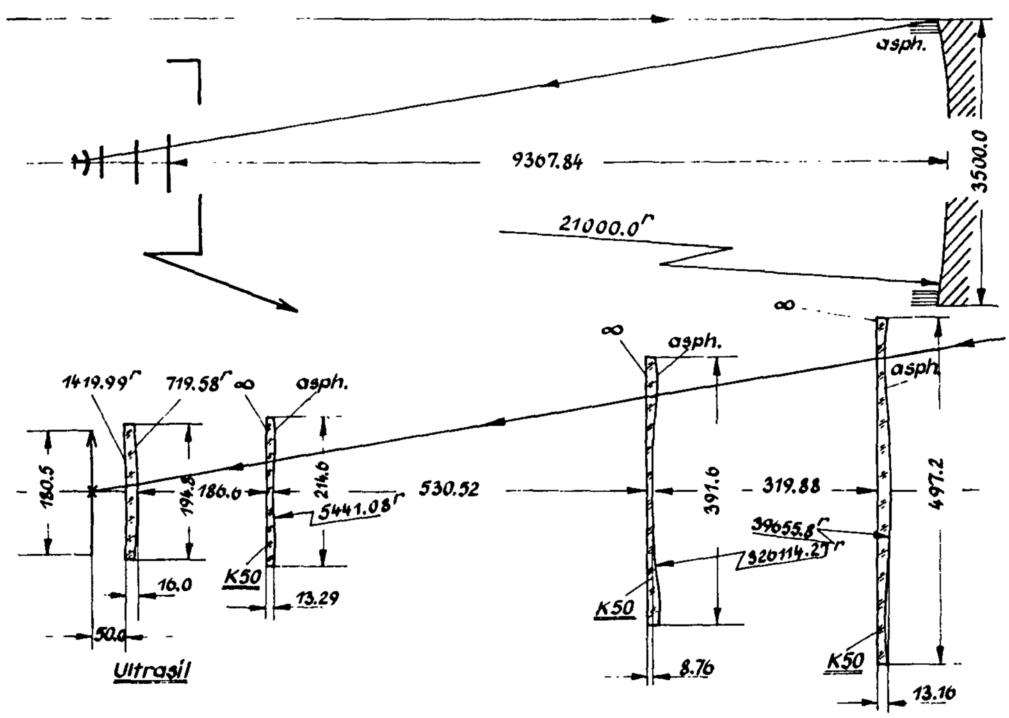


Fig. 14 3.5 m telescope for ESO. Plate corrector for primary focus. Section through system. (As published in ESO Bulletin No. 2)

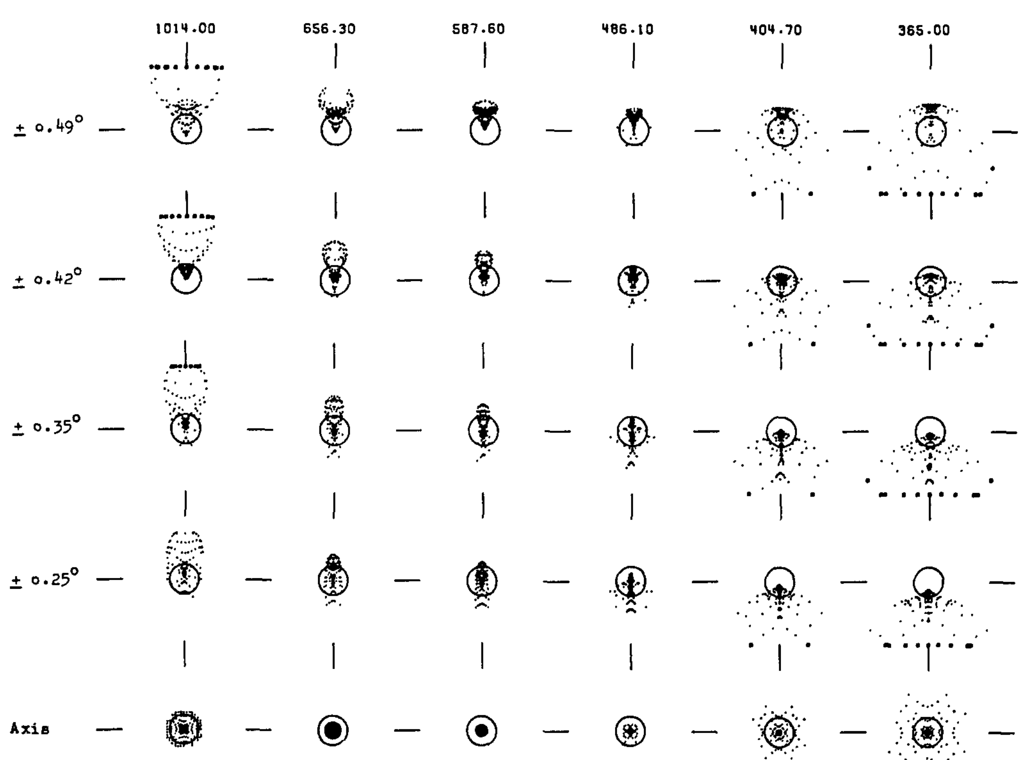


Fig. 15 3.5 m telescope for ESO. Plate corrector for primary focus. Field ± 0.49° (25% vignetting at edge field). Spot diagrams as published in ESO Bulletin No. 2. (Circle = 0.50 arcsec = 25 μ) Some spots fall outside the plot field as shown by bars.

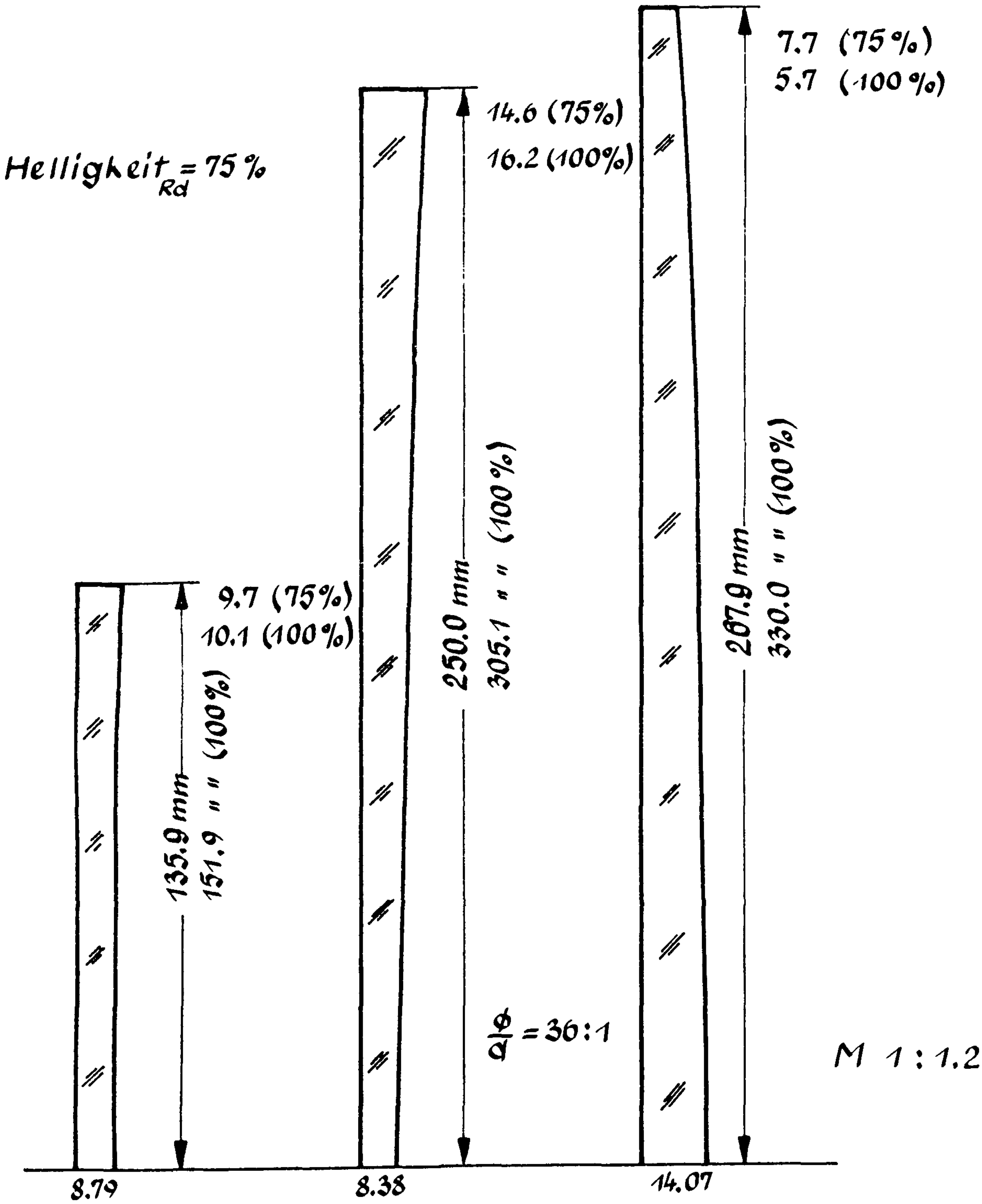


Fig. 16 3.5 m telescope for ESO. Modified plate corrector for primary focus with significant refracting power in the plates. Section through system.

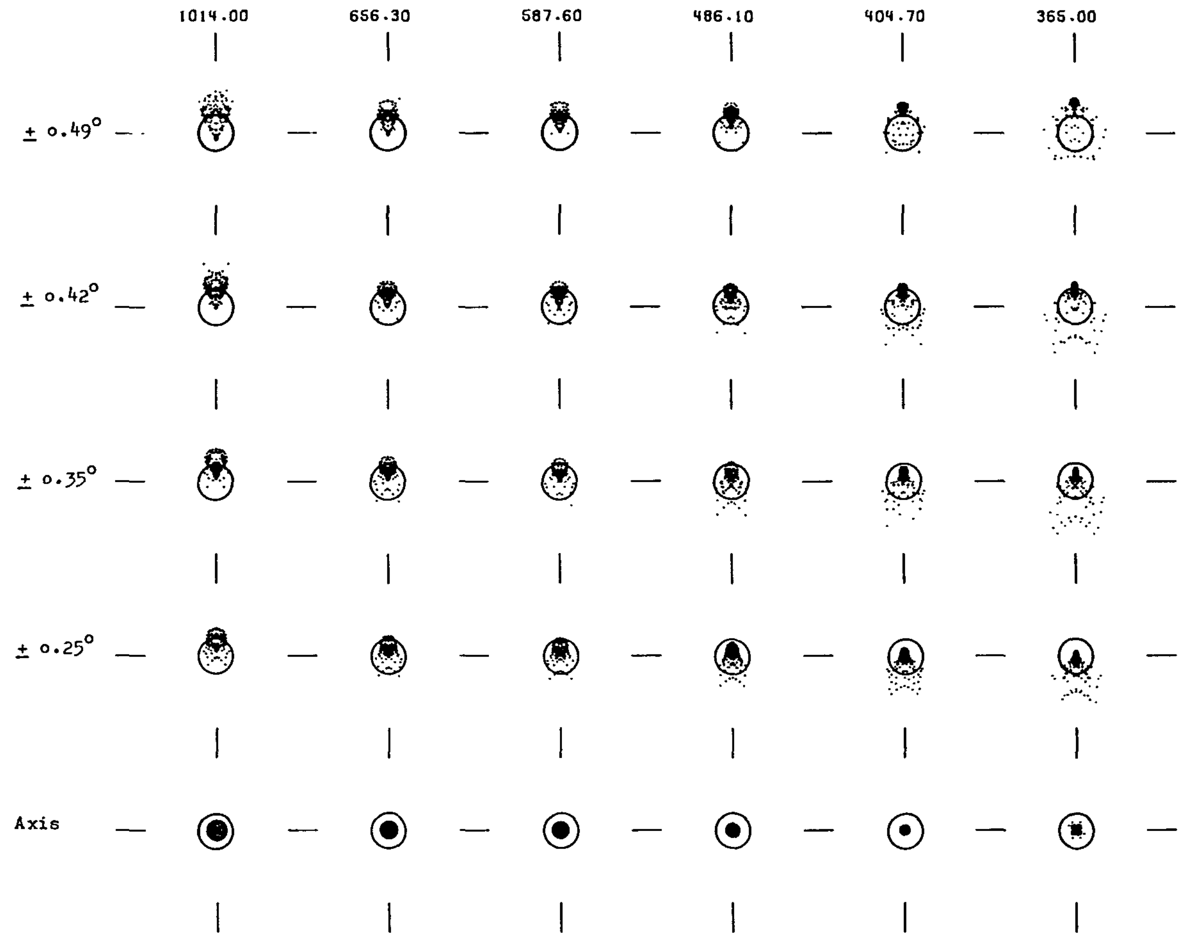


Fig. 17   3.5 m telescope for ESO with modified plate corrector for primary focus as shown in Fig. 16. Field ± 0.49° (no vignetting). Spot diagrams. (Circle = 0.50 arcsec = 25 μ)

Figures and the plot field is not large enough to contain the entire spread of the spots. (The presence of spots outside the plot field is shown by the short bars at the limit of the plot field.) This system has 25% vignetting at the edge of the field of ± 0.5°.

It is evident from an inspection ofthese spot-diagrams that three aberrations are mainly responsible for the spread: Gauss-error, colour coma and zonal astigmatism. The longitudinal colour of this corrector is negligible, a property which appears highly advantageous at first sight. This is not the case, however, since no possibility exists for an optimum balance with the Gauss-error. This is the reason why a lens solution such as that due to Wynne(11),(12) gives less chromatic spread of the spot-diagrams although the longitudinal colour is appreciably larger.

The higher order chromatic aberrations can only be improved if refracting power is introduced into the plates. Several years ago we decided to explore this possibility. The resulting plate form after considerable optimization is shown in Fig. 16 and the spot-diagrams of the new system in Fig. 17 (scale as in Fig. 15, circle 0.5 arc sec). The new system no longer has vignetting; the largest plate has a diameter of 660 mm. The improvement is evident. It is of considerable interest to compare this quality with that of the most excellent 3-lens design by Professor Wynne(11),(12) for the ESO primary. Spot-diagrams for the Wynne-system are shown in Fig. 18, again to the same scale as Figs. 15 and 17. These spot-diagrams are in excellent agreement with those published by Wynne(12).

There is little difference between the quality of the Wynne-3-lens system and the modified plate system. The optimization was broken off and the feasibility of manufacture of the plates investigated. The result was not very encouraging. The production of the plates in a conventional Schmidt-plate manner on a vacuum drum would require stresses up to 25 kg/mm^2, whereas the breaking limit of quartz is about 5 kg/mm^2. The presence of several aspheric surfaces often leads to strong asphericities because of compensations.

Although the plate system seems capable of further improvement, no further optimization has been performed because of the manufacturing difficulty. In view of this and the fact that four elements are necessary compared with three in the Wynne-solution, there seems no doubt that the latter is preferable. The plate system would have to be considerably further improved to justify the manufacturing difficulty.

The power distribution of the first two plates (positive, negative, starting at the largest plate) seems to be significant. This is the same power distribution as in the Wynne system or the Sonnefeld-Köhler system discussed below. This power distribution is favourable for the correction of the lateral colour aberration.

Recently, other work has been reported in which attempts to improve the performance of the plate corrector by the introduction of refracting power are described[21].

The Sonnefeld-Köhler system[22] consists of a roughly afocal doublet with the above distribution of power and an aspheric field-flattening lens. In the original design, the aspheric surface was introduced for the correction of distortion and has no particular significance for a telescope corrector. The position of the doublet (for a much smaller mirror) was a considerable proportion of the distance from image to mirror giving an equivalent doublet diameter for a 3.5 m telescope of some 1450 mm. Such a diameter is hardly realizable in practice but the correction of the chromatic aberrations dictates in any event that the lenses become smaller. In fact, optimization converted the system into a design quite similar in form and size to the Wynne-corrector. Further reduction in size worsened the monochromatic aberrations, particularly the coma. The limiting aberration is the colour coma.

It is quite possible that further optimization of the ESO 3-plate system, with adjustment of the thicknesses appropriate to aspheric lenses, would lead to a generalized aspheric 4-lens solution of the same basic type* as an aspheric Wynne- or Sonnefeld-Köhler-system.

The system due to Baranne[23],[24] is derived from a doublet type suggested by Paul[25]. The power distribution of the doublet elements is (as in the Ross corrector[26]) the reverse of that of the Sonnefeld doublet. Our limited experience of the Baranne-type corrector is that the astigmatism and lateral colour are more difficult to correct than in the Wynne-type.

Unless one is prepared to replace one or more of the lens elements of a lens corrector by two-glass doublets to improve the higher-order chromatic aberrations, there seems little possibility of further improvement of lens correctors for R.C. primaries of about f/3. The loss of uv-transmission and increased reflexion losses seem a heavy price to pay. The decision already taken for some projects to use two or more all-quartz systems designed for different wavelengths thus seems fully justified.

---

* The definition of a design "type" is a highly technical point and depends on the properties of the optimization program, its manipulation, and the extent of the knowledge of the designer regarding the properties of different systems with a similar basic power distribution. The German word "Ansatz" seems more appropriate to this situation than the usual English expressions "type" or "starting system".

4. FOCAL REDUCER

The subject of focal reducers (F.R.) invokes strong reactions among astronomers, for and against. Some optical elements are unavoidable - and astronomers are generally allergic to optical elements, particularly lenses. The suggestion of an investigation of this problem came from the Max-Planck-Institute for Astronomy in Heidelberg and was mainly carried out as part of the study for the MPI 3.5 m telescope. We are most grateful for many stimulating discussions with Professor Elsässer and Dr. Bahner.

It seems useful to list the properties that the ideal focal reducer might have:

a) It should optically replace the prime focus, providing a similar field with similar quality over the whole spectral range.

b) It should use the R.C. -secondary mirror. There would then only be R.C. and coudé-secondaries which could be changed by a simple flip-flop.

c) It should yield a convenient position for the final focus.

d) The final focus should be so arranged that image receiving apparatus can be used without causing unacceptable obstruction.

e) It should not cause construction problems such as a long fork overhang.

f) It should have as small a length and weight as possible to reduce handling problems.

g) It should have as few optical elements as possible.

h) It should contain only uv-transmitting elements.

Fulfilment of all these conditions is a very difficult problem and it may be doubted whether such a solution exists. Some compromise has to be made and the resulting solution will vary widely depending on which requirements are relaxed.

For example, relaxation of the requirement for an angular field equivalent to that of a prime focus corrector immediately makes a lens solution attractive; for the diameter and length of the system is dictated by the field size. Similarly, a lens solution may become attractive if the condition for good correction over the whole spectral range is relaxed in the sense that a narrow band filter is used. But it does not follow - because of the higher order chromatic aberrations - that this band will be variable. A variable narrow band filter eases the situation only with regard to longitudinal and lateral colour.

On the other hand, if condition a) is rigorously applied, the basic refracting power of the F.R. must almost certainly come from a mirror, the role of refracting elements being that of essentially afocal correctors in some form or other. This gets over the basic problem of chromatic aberration but leads to obstruction problems. In particular, requirement d) poses a

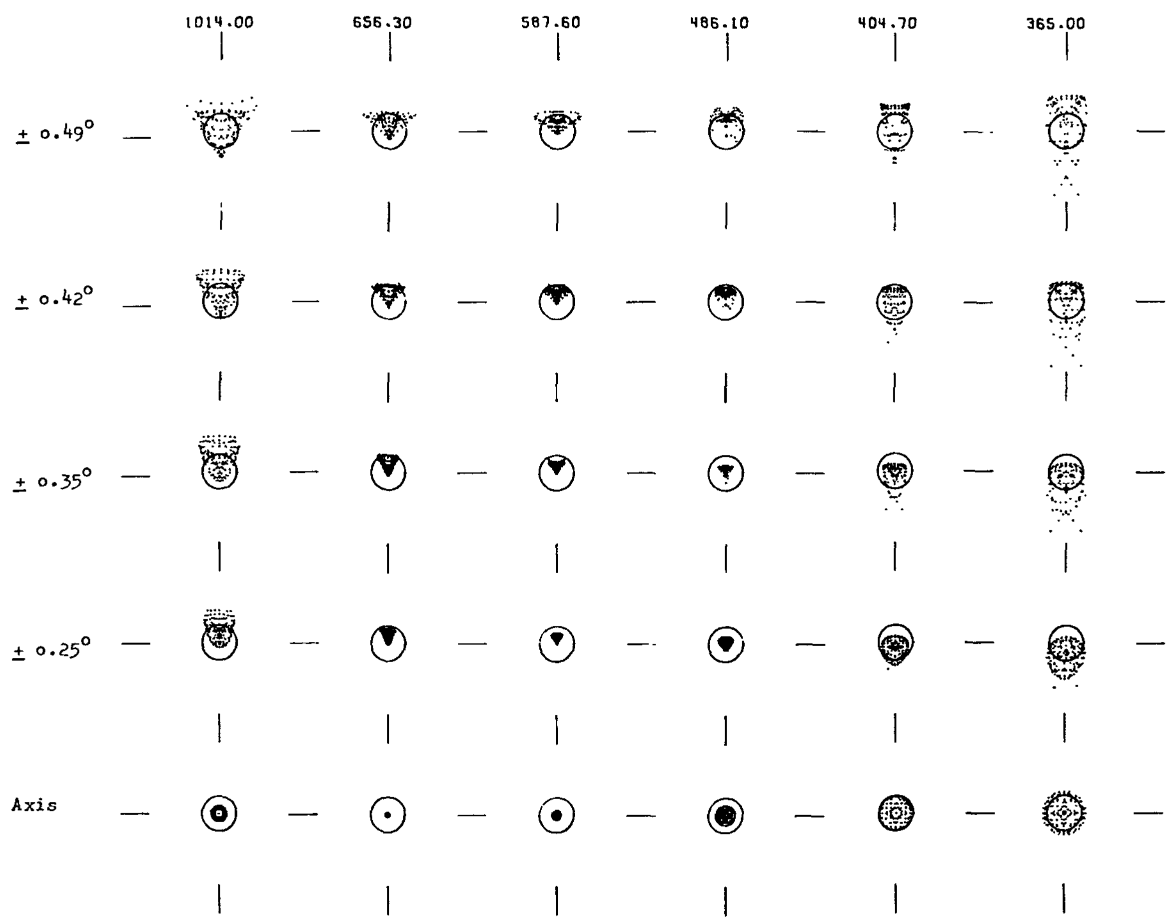


Fig. 18 3.5 m telescope for ESO. 3-lens prime focus corrector due to WYNNE. Field ± 0.49° (no vignetting). Spot diagrams. (Circle = 0.49 arcsec = 26 μ)

major problem. Furthermore, the fulfilment of a) together with e) and f) is in conflict with g) and possibly h).

Very attractive appear the 3-mirror solutions such as those proposed by Baker[27] or by Meinel and Shack[28],[29]. One of the systems Dr. Baker kindly showed me at the last IAU meeting seems to fulfil all the above conditions admirably except b), c) and d). But condition c) seems to have much weight with the majority of astronomers.

For the study for the 3.5 m telescope for the MPI we have tried to answer the following question: To what extent is it possible to fulfil the above conditions with a lens or mirror solution? Three types of system were investigated: a lens system without an intermediate image, a lens system with an intermediate image, and a mirror system. Within the scope of this paper, it will only be possible to give briefly some of the results. A more complete account will be published shortly in an optical journal[30]

4.1 Lens system without an intermediate image

Fig. 19 shows a section through a 5-lens system which has yielded quite interesting results for a reduction from f/8 to f/3. The basic problem with this approach is that the front lenses must be somewhat larger than the virtual image, leading to diameters up to about 650 mm for a field of ± 0.45°. The system must be relatively long to permit reasonable correction of the monochromatic aberrations. The entrance pupil is a long way in front of the system which therefore operates almost telecentrically. Fig. 20 shows the spot-diagrams (circle 0.98 arc sec). It is clear that the correction is within about 0.5 arc sec monochromatically, but that the higher order chromatic aberrations become serious even 50 nm away from the central wavelength. To improve these, the focal length of the F.R. would have to be reduced which makes the monochromatic correction more difficult. The system would thus only be satisfactory for a fixed narrow band filter. The solution is extremely favourable for conditions b), c), d) and e). Its length is only about 1300 mm.

4.2 Lens system with an intermediate image

This permits the use of a field lens, but has the disadvantage compared with the system without an intermediate image that the refracting power of the F.R. is about doubled (the reduction is from - f/8 to + f/3 instead of + f/8 to + f/3). A 7-lens system (field ± 0.45°) has been investigated with a total length from intermediate to final image of about 4 meters (Fig. 21), the largest lens diameter being 424 mm. The quality (Fig. 22) is inferior to that of the system without an intermediate image both monochromatically and chromatically, although it contains two more lenses. A lens system of this sort is not well suited to the reduction of such a large image and it would be best to relax radically the field requirement. This is essentially

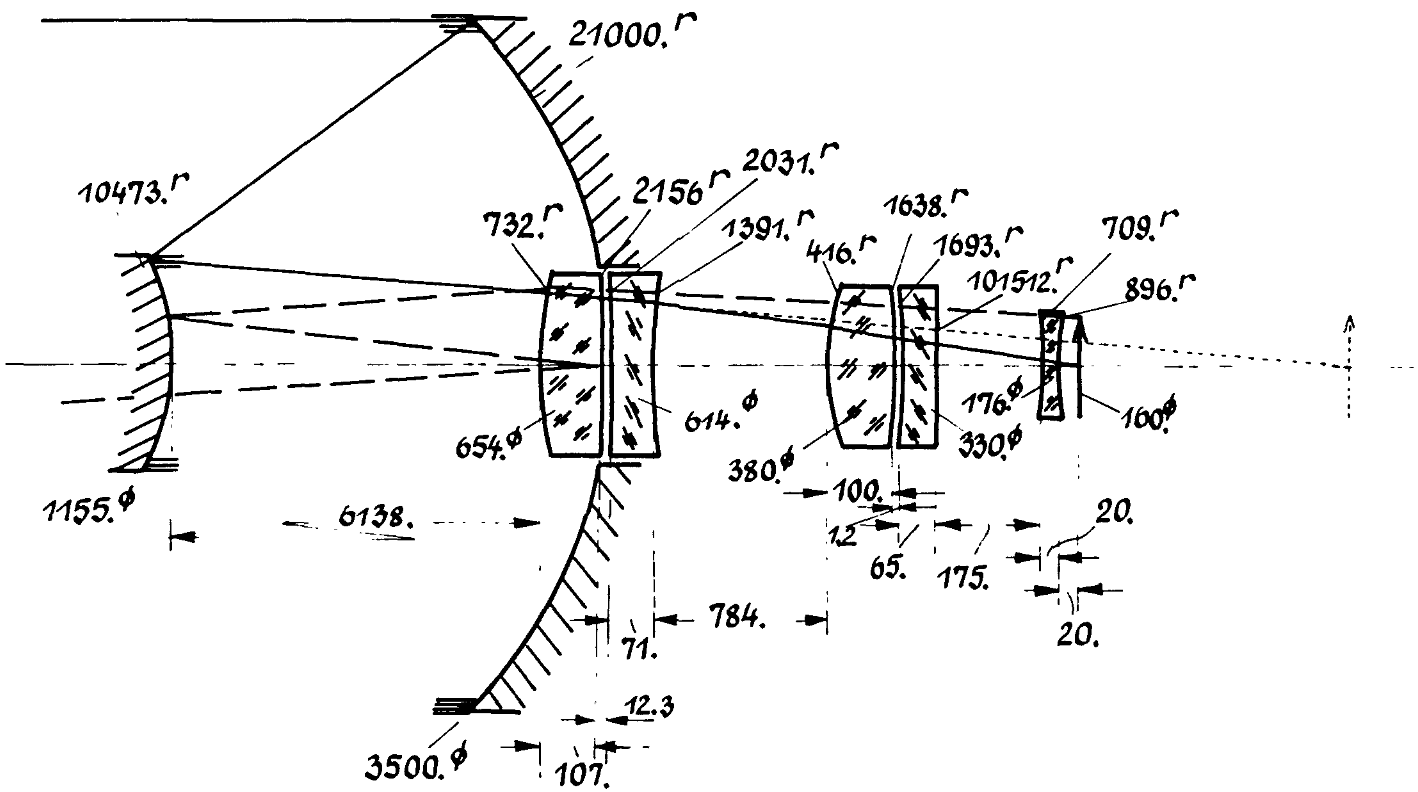
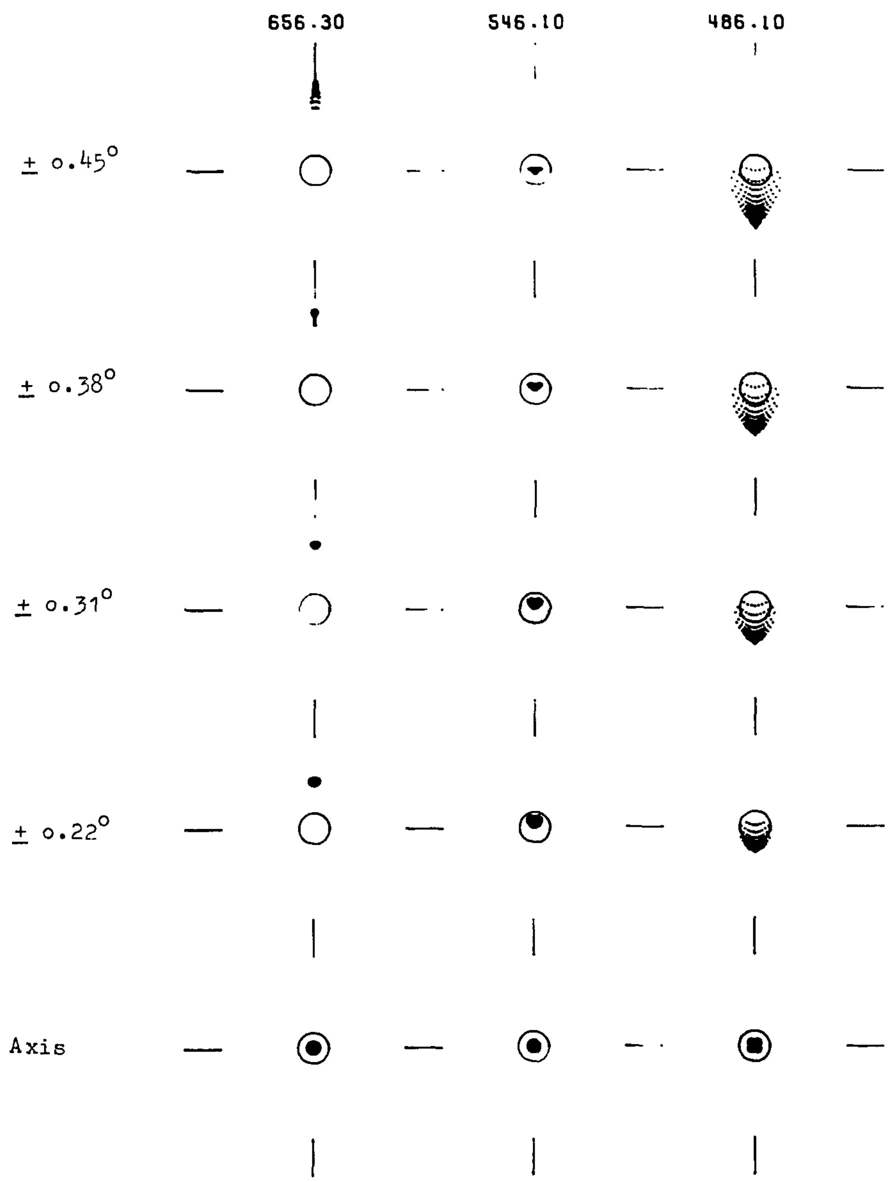


Fig. 19 Focal reducer for 3.5 m telescope. Lens system without intermediate image. Field ± 0.45°. Section through system (schematic).



<u>Fig. 20</u> Focal reducer for 3.5 m telescope. Lens system <u>without</u> intermediate image. Field ±0.45°. Spot diagrams. (Circle = 0.98 arcsec = 50μ.) Reduction f/8 to f/3.

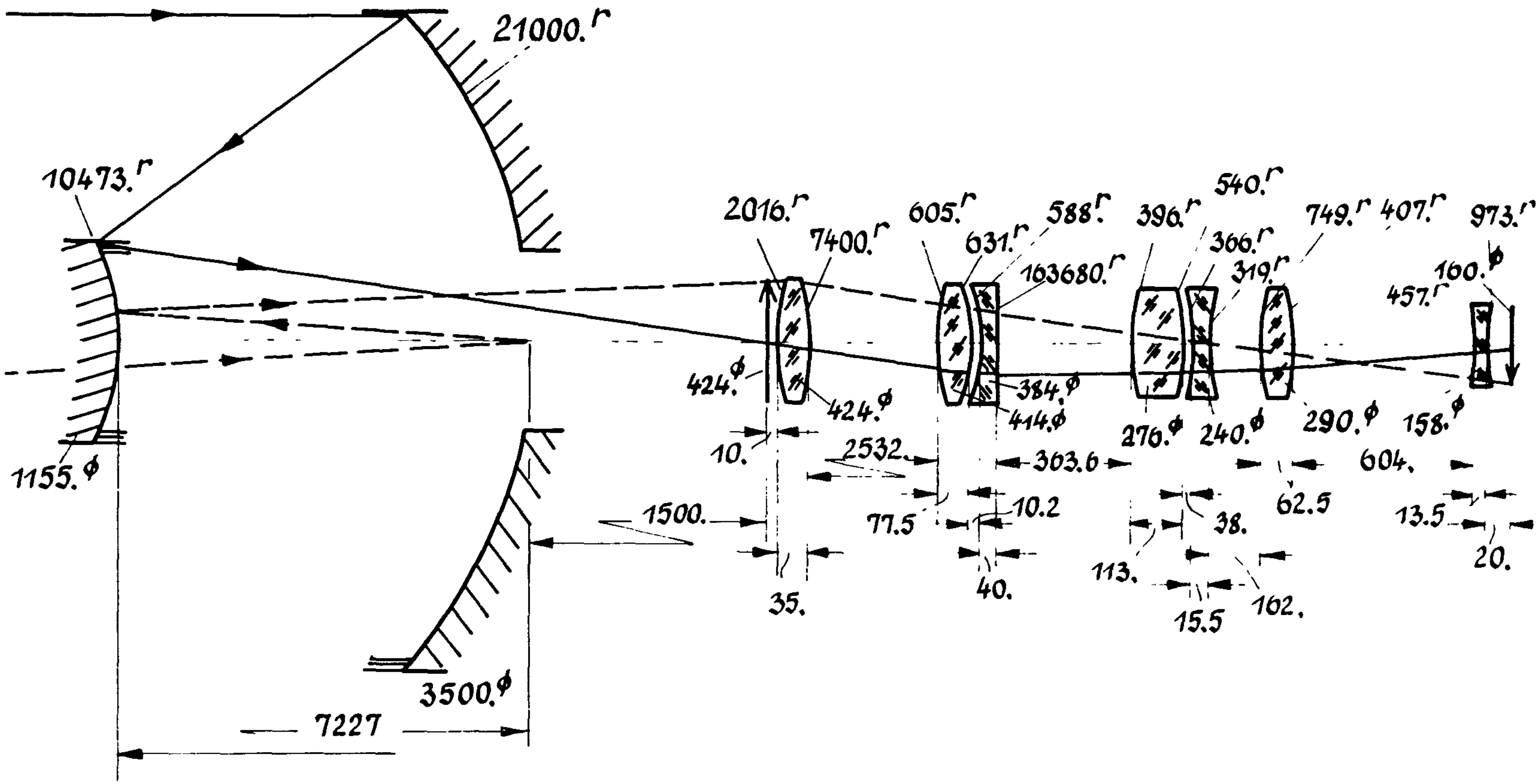


Fig. 21 Focal reducer for 3.5 m telescope. Lens system with intermediate image. Field ± 0.45°. Section through system (schematic).

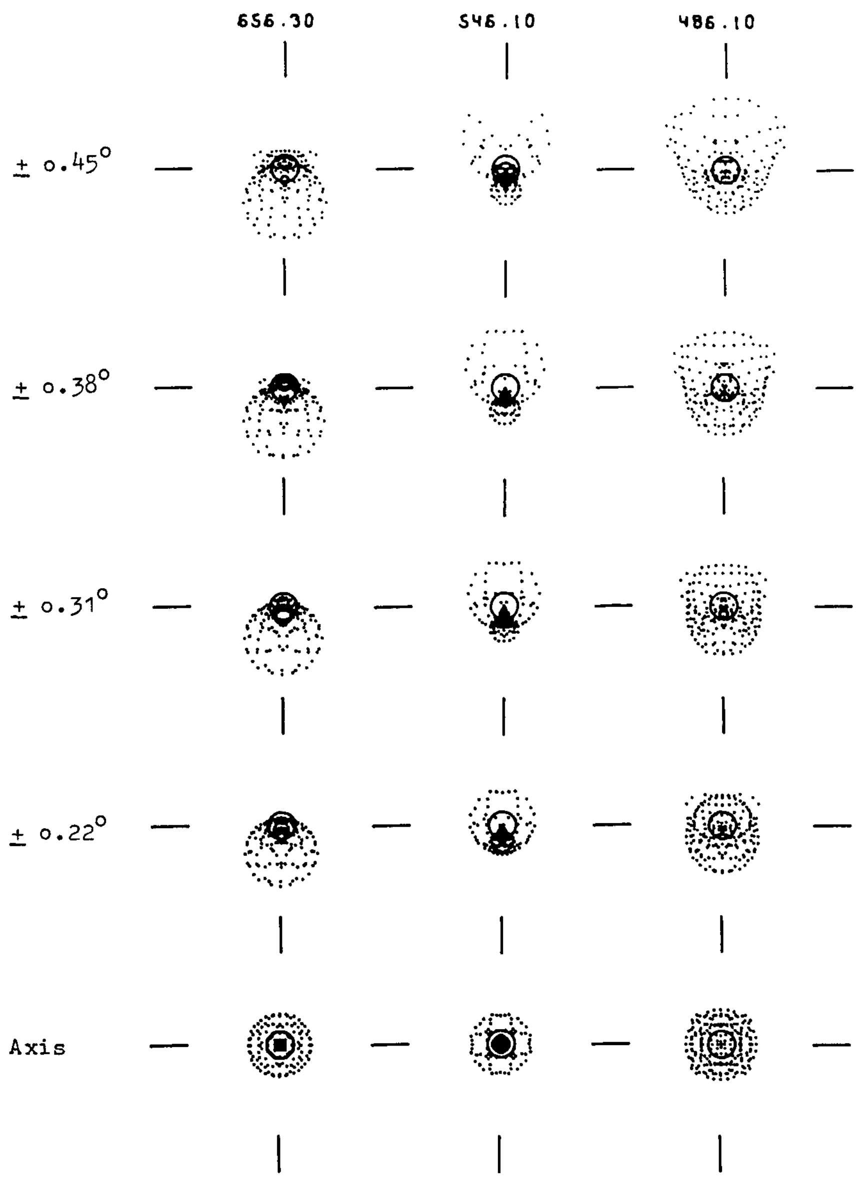


Fig. 22 Focal reducer for 3.5 m telescope. Lens system with intermediate image. Field ± 0.45°. Spot diagrams. (Circle = 0.98 arcsec = 50 μ.) Reduction f/8 to f/3.

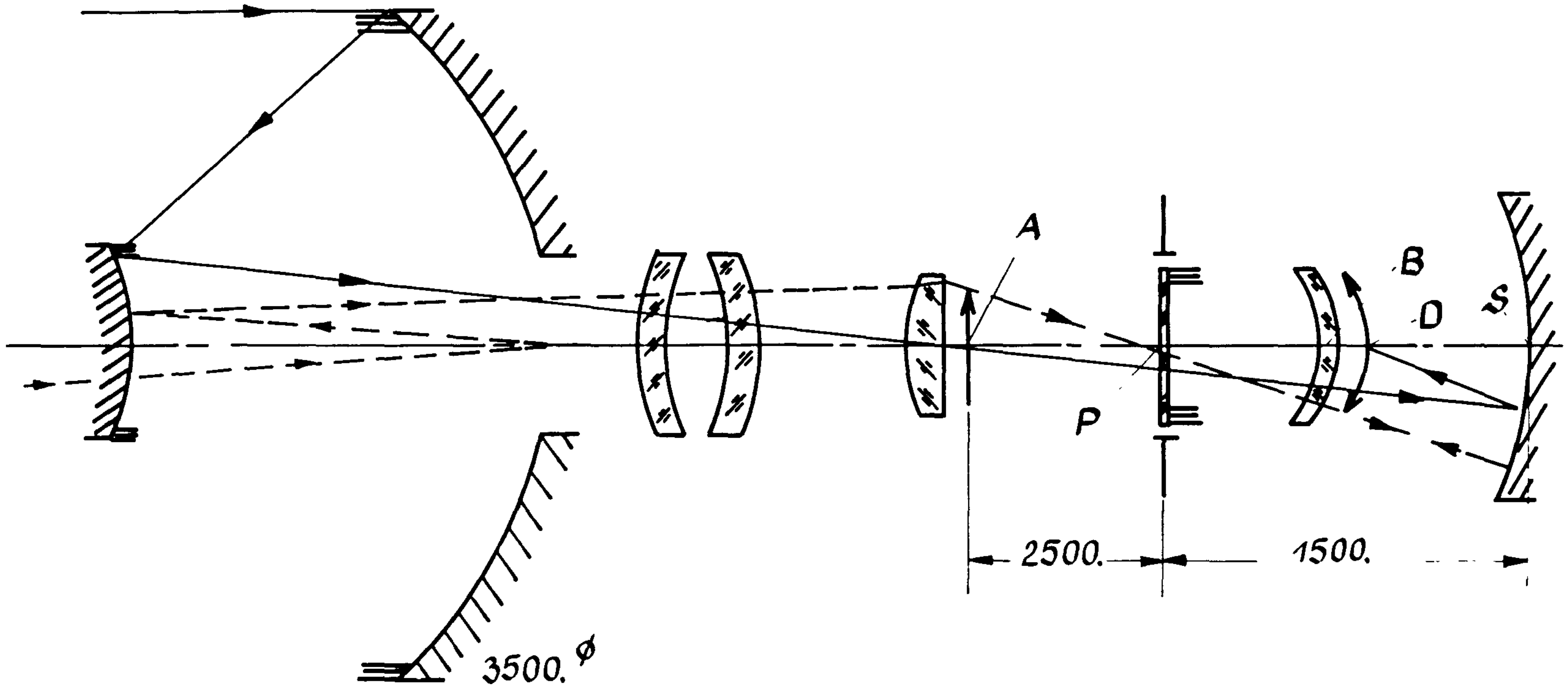


Fig. 23 Focal reducer for 3.5 m telescope. Mirror system with intermediate image. Field ± 0.5°. Geometry of a typical solution (schematic). Reduction f/8 to f/1.7.

the approach of Meinel and Wilkerson(31),(32). Their solution contains eleven lenses (1 thick field lens, 4 "collimator" lenses and the six lenses of a "Summicron" double Gauss type photoobjective including dense flint glasses with high uv-absorption). The field (± 0.229°) and the quality (about 2 arc secs between 656 nm and 405 nm) are not comparable with a prime focus corrector. This illustrates the difficulty of the problem, for the design is undoubtedly a very good one: it would be difficult to better it for the given system length of about 500 mm.

4.3 Mirror solutions

Courtès(33),(34) proposed mirror solutions for both primary and secondary foci and has reported very encouraging practical results for an F.R. used in the prime focus. This indeed seems the most promising approach if the basic condition a) is to be fulfilled. The main difficulty is the obstruction due to the receiver (condition d)).

In our analysis of the problem we came to the conclusion that a favourable geometry for the conditions listed would yield a reduction from f/8 to about f/1.7. A reduction to f/3 would be more favourable for the optical correction but could lead to problems of plate-holder obstruction unless the F.R. is made longer than the 4 m we chose for the length from the intermediate image to the F.R. mirror. Fig. 23 shows (schematically) a section through such a mirror F.R. The correction elements shown for the F.R. have been varied to give a variety of solutions with essentially the same geometry. The intermediate image has a diameter of 490 mm for an f/8 telescope of 3.5 m aperture and a field of ± 0.5° (cf. prime focus corrector). The final image after a reduction to about f/1.7 is about 108 mm. The diameter of the camera mirror is about 800 mm and the camera has a field of about ± 5°.

The philosophy of correction is somewhat different from that of Courtès. We have retained a corrector in front of the intermediate image because it gives independent control of the astigmatism and transverse colour without significantly affecting the aperture aberrations. This leads to a particularly well-conditioned solution matrix. Alternatively, the corrector can be considered as fixed in the sense that the intermediate image is corrected: the corrector can remain in place in the telescope while the F.R. (consisting of a field lens and camera) is replaced by a plate-holder when the R.C. focus is to be used instead of the F.R. On the other hand, the intermediate image corrector may be considered as an integral part of the F.R., in which case the correction of the intermediate image is immaterial. For photography in the R.C. focus, the F.R. would be removed and a separate corrector (normally, for a large telescope, with a smaller field) introduced.

The possible constructional arrangements for fitting a mirror-type F.R. with the basic geometry of Fig. 23 into the mounting of a 3.5 m telescope

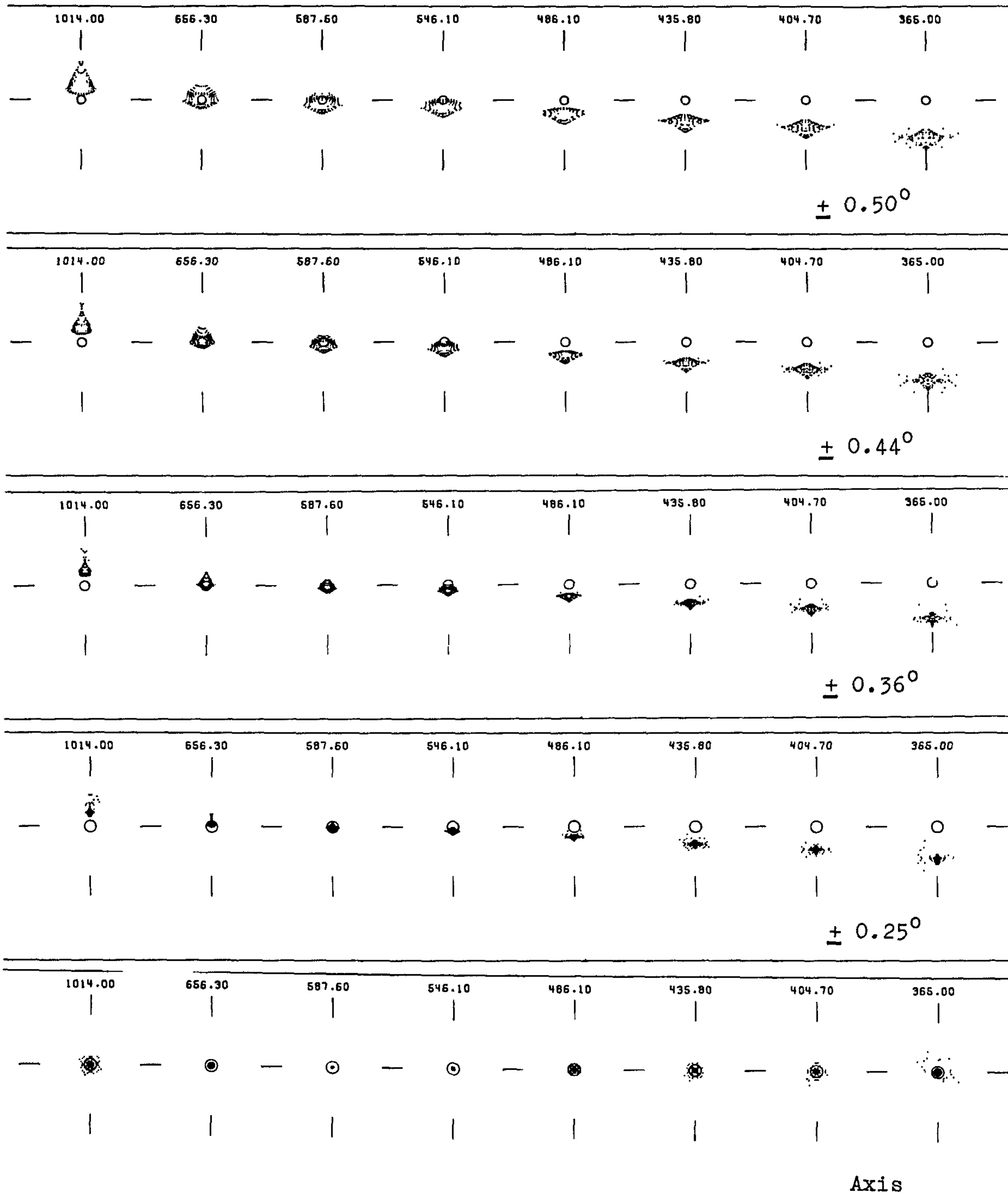


Fig. 24 Focal reducer for 3.5 m telescope. Field lens and Schmidt camera with shifted pupil. Spot diagrams. (Circle = 0.50 arcsec = 14 μ) Reduction f/8 to f/1.7. Image radius = 1221 mm.

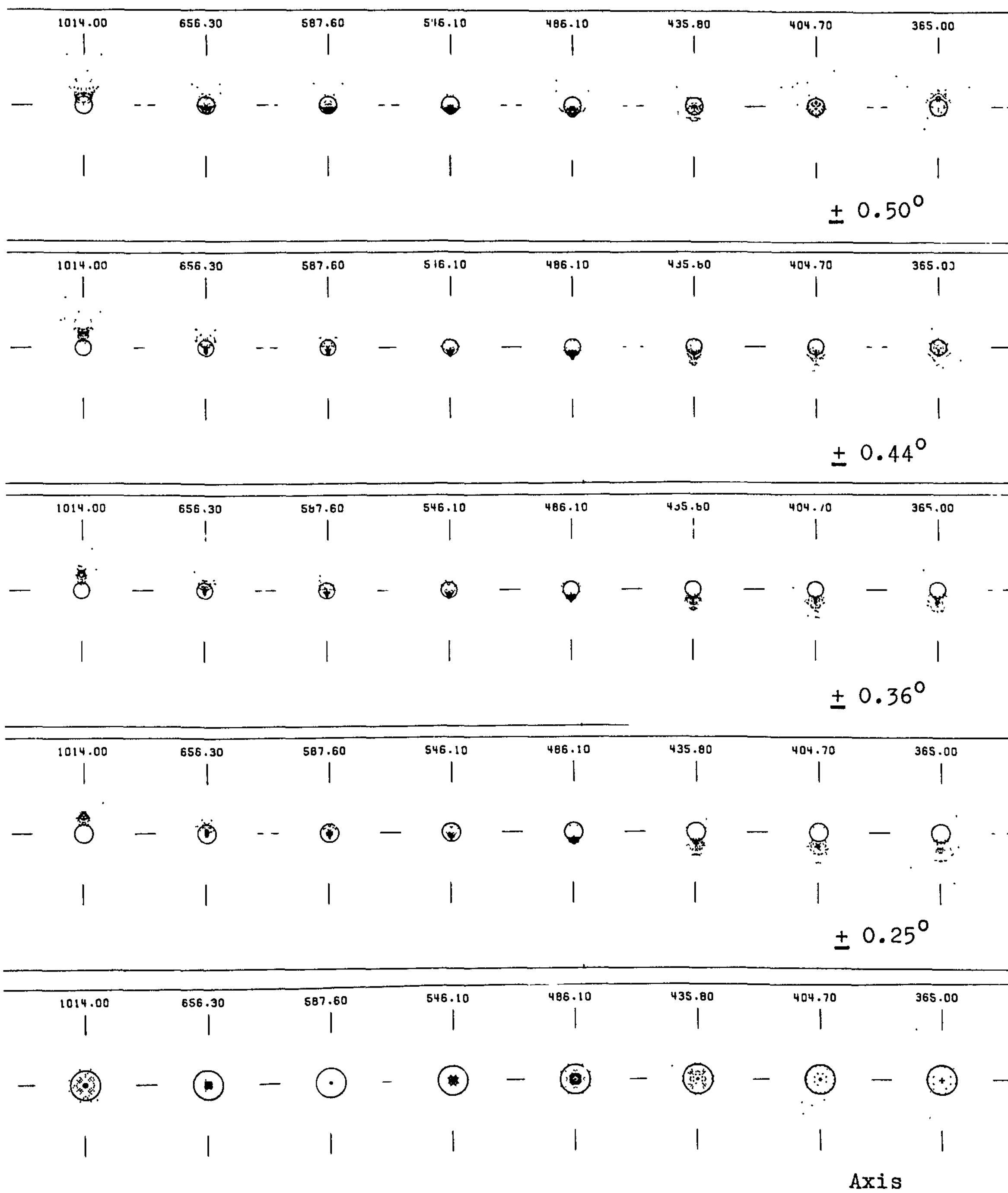


Fig. 25 Focal reducer for 3.5 m telescope. Doublet corrector (uncorrected intermediate image), field lens and Schmidt camera with shifted pupil. Spot diagrams. (Circle = 0.50 arcsec = 14 μ) Reduction f/8 to f/1.7. Image radius = 1060 mm.

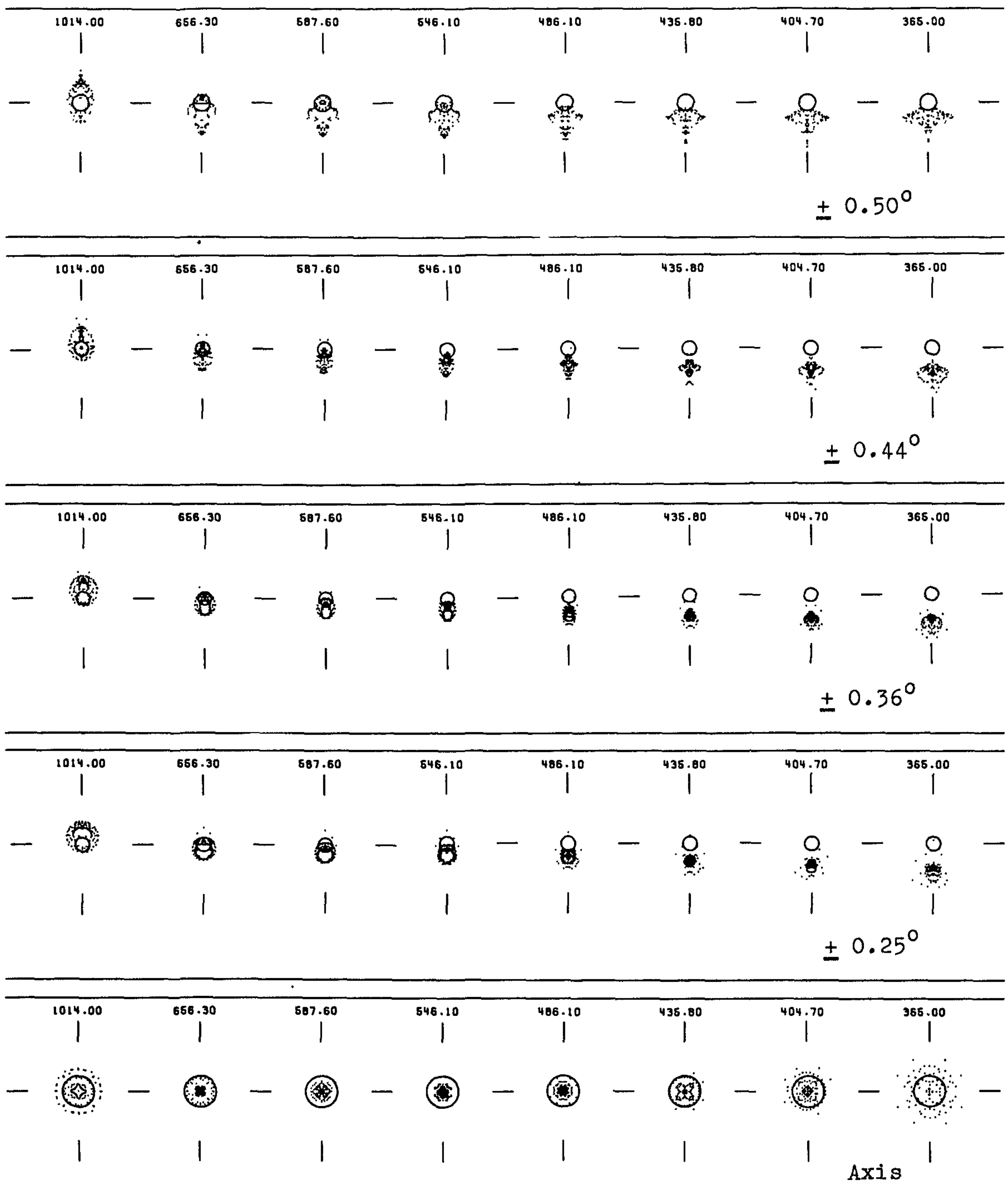


Fig. 26 Focal reducer for 3.5 m telescope. Doublet corrector (corrected intermediate image), field lens and Bouwers-Maksutov camera. Spot diagrams. (Circle = 0.50 arcsec = 14 μ) Reduction f/8 to f/1.7. Image radius = 1066 mm.

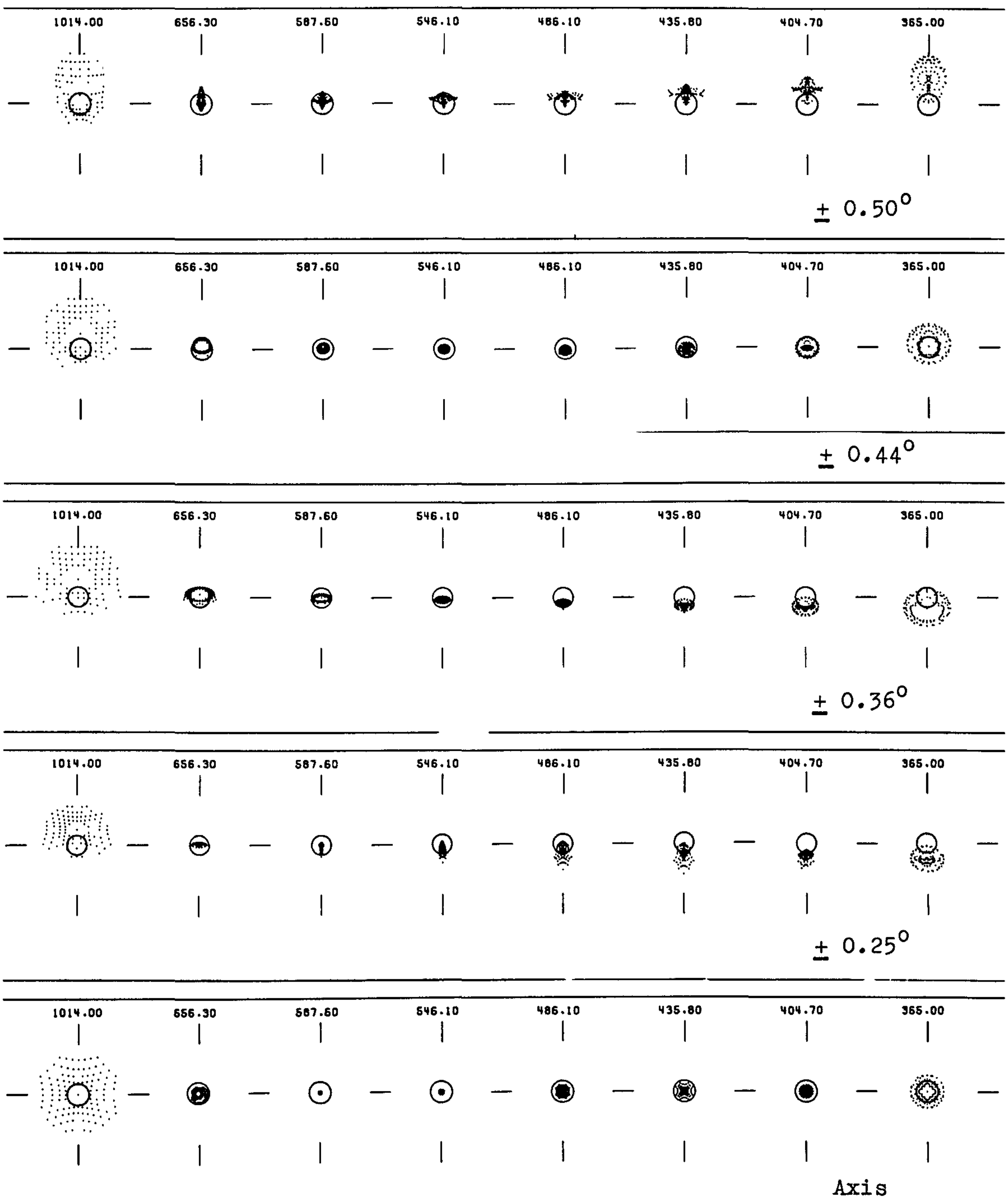


Fig. 27 Focal reducer for 3.5 m telescope. Doublet corrector (corrected intermediate image), field lens and Hawkins-Linfoot camera. Spot diagrams. (Circle = 0.50 arcsec = 14 μ.) Reduction f/8 to f/1.7. Image radius 1031 mm.

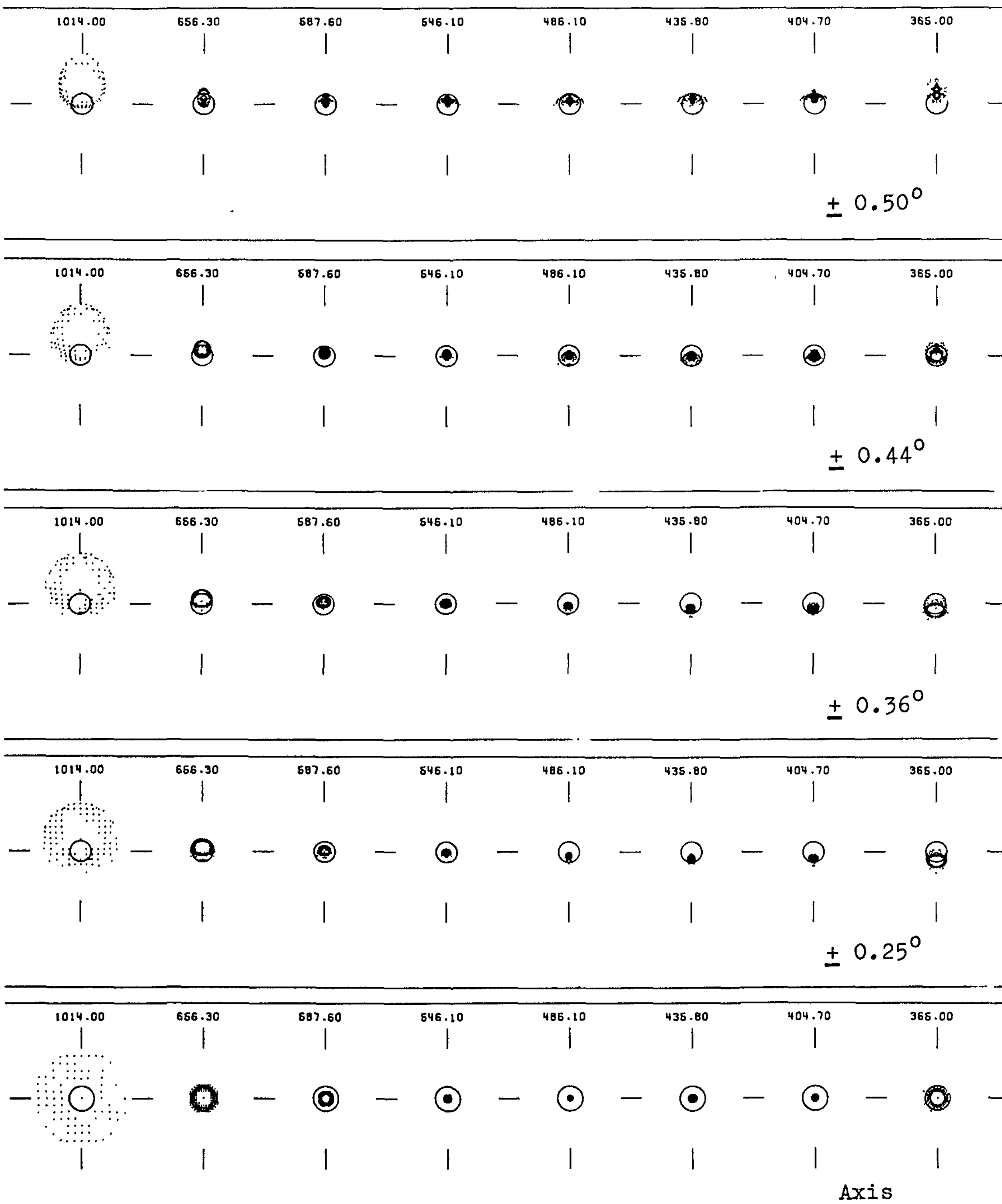


Fig. 28 Focal reducer for 3.5 m telescope. Doublet corrector (uncorrected intermediate image), field lens and Hawkins-Linfoot camera. Spot diagrams. (Circle = 0.50 arcsec = 14 μ) Reduction f/8 to f/1.7. Image radius = 964 mm.

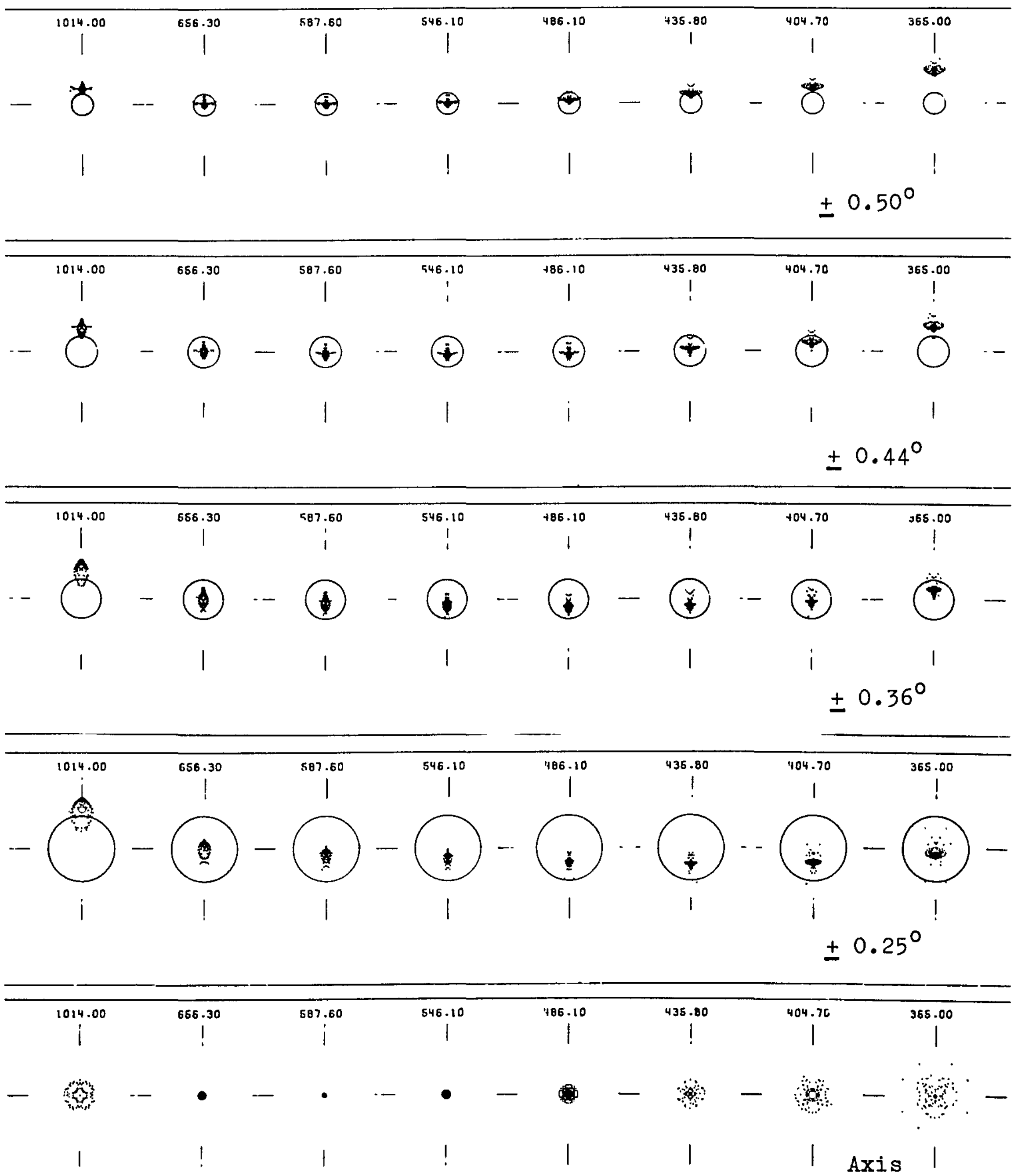


Fig. 29 Focal reducer for 3.5 m telescope. Doublet corrector (uncorrected intermediate image), 2 field lenses and Baker-type camera with 2 menisci and 1 plate. Spot diagrams. (Circle = 0.50 arcsec = 14 μ) Reduction f/8 to f/1.7. Image radius = 1052 mm. (Plot field for axial spot diagrams = 10 μ)

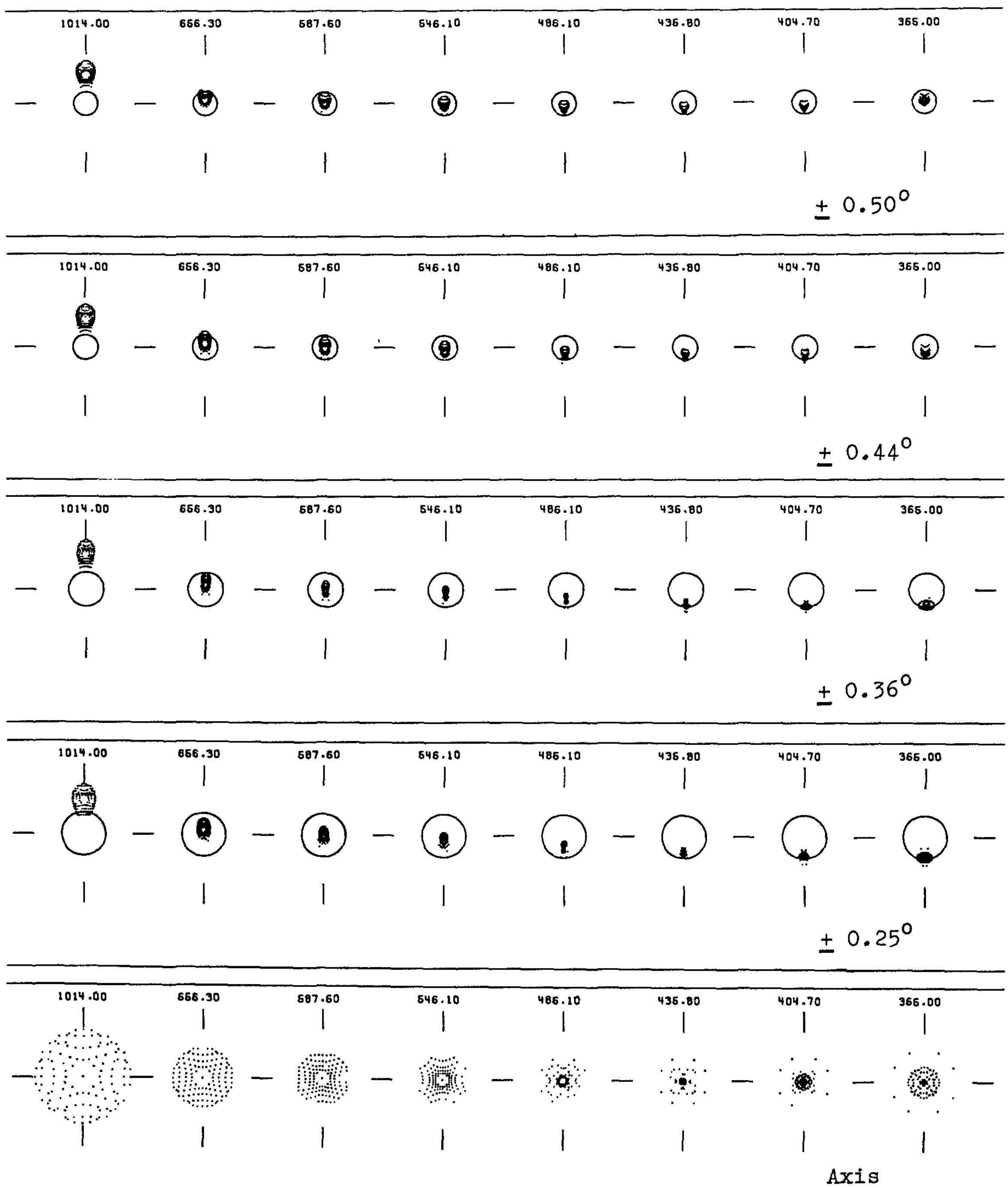


Fig. 30 Focal reducer for 3.5 m telescope. Doublet corrector (uncorrected intermediate image), field mirror and Baker-type camera with 2 menisci and 1 plate. Spot diagrams. (Circle = 0.50 arcsec = 14 μ.) Reduction f/8 to f/1.7. Image radius = 528 mm. (Plot field for axial spot diagrams = 12 μ)

have been analysed in the study for the MPI and will be discussed in a separate publication[30]. My present purpose is to show spot-diagrams for a number of different solutions in the hope that this may provide a basis for further development of F.R. mirror solutions. All are for a field of ± 0.5° with a circle size for the spot-diagrams of 0.5 arc sec.

4.3.1 Field lens and simple Schmidt camera

The uncorrected intermediate image has astigmatism of about 2.6 arc secs. The uncorrected Gauss-error of the camera and the pupil aberration caused by the field lens give a performance in no way comparable with a prime-focus corrector. A useful parameter is the pupil position relative to the Schmidt plate. The lateral colour amounts to several seconds of arc but can be somewhat alleviated by relaxing the astigmatism. Fig. 24 shows spot diagrams for a solution which seems to present a reasonable compromise.

4.3.2 Doublet corrector, field lens and simple Schmidt camera

The corrector in this case is the 2-glass corrector (see § 2.1) designed for the 2.2 m telescope of the MPI but other types of corrector could equally well be used. The important point here is that the lenses were allowed to vary during the optimization. Use of these parameters together with a variable pupil position leads to a vastly improved solution (Fig. 25) compared with Fig. 24. Both the astigmatism and the lateral colour are virtually negligible compared with the Gauss-error of the Schmidt camera and the colour coma largely caused by the simple field lens.

4.3.3 Bouwers[35]-Maksutov[36]-camera

This camera contains a Maksutov-type meniscus together with a plate for the correction of zonal spherical aberration. A corrector is present but in this case was not varied, i.e. the intermediate image is corrected. Fig. 26 shows the spot-diagrams for such a system. Further improvement is certainly possible if the corrector lenses are freed.

4.3.4 Hawkins-Linfoot[37],[38],[39],[40]-camera

This camera represents a considerable improvement in that the chromatic aberration of a concentric meniscus is corrected by a weak afocal doublet in the pupil. This element also contains the aspheric surface for the correction of the zonal aberration. Fig. 27 shows the spot-diagrams for such a system combined with a "fixed" corrector. The monochromatic performance is very good but the secondary spectrum arising from the small dispersion difference of the glasses in the doublet is noticeable in the curvature of the line of spot-diagrams for the edge field and in the additive effect of Gauss-error and secondary spectrum for 1014 nm. These effects cannot be removed by varying the corrector lenses but improvement in other respects, particularly transverse colour, is possible. This is shown by the spot-diagrams of Fig. 28.

4.3.5 Baker-2 Meniscus-Plate-type[38]-camera

This system has a meniscus on each side of the pupil which contains the aspheric plate for zonal aberration. All three elements can be of quartz and enable chromatic correction without secondary spectrum. Fig. 29 shows spot-diagrams for such a system. The corrector lenses here were variable parameters. Since this system is more sensitive to pupil aberration, the field lens was split into two. No circle is shown for the axis in Fig. 29 as it would be much larger than the plot field: the axial spot diagram even at 365 nm is only about 8μ or about 0.3 arc sec in diameter out to the extreme spots. The secondary spectrum of the transverse colour originates in the 2-glass corrector in front of the intermediate image.

4.3.6 Baker camera as in §4.3.5 but with a field mirror instead of 2 field lenses

A field mirror brings further improvement because of its perfect achromatism and improved spherical aberration (Fig. 30). The largest spot-diagram for the axis is again about 0.3 arc sec for 1014 nm. For this wavelength, the spot-diagram for the outer parts of the field somewhat exceeds 0.5 arc sec but is reduced by more favourable focusing. The zonal transverse colour and secondary spectrum originate entirely in the corrector.

This system was set up primarily to assess the correction advantages of a field mirror. Its realization would yield very compact solutions but there are serious obstruction problems. The field mirror has the disadvantage of being additive with regard to the Petzval sum of the camera, whereas a field lens is subtractive. Thus the final image radius for all the above solutions with a field lens (or lenses) is about 1050 mm whereas it is about 530 mm with the field mirror.

4.4 Conclusion

The above examples illustrate, for the somewhat arbitrarily chosen geometry, the improvement in quality the introduction of more elements can bring. Further variants are possible: for example, a Gascoigne-type plate corrector in front of the intermediate image instead of a two lens corrector. Conceivably, a similar correction to that shown in Fig. 25 may then be possible with a F.R. consisting of only 2 plates, a field lens and a spherical mirror. A departure from the spherical mirror may also bring advantages: Bahner[41] mentions interesting work in the USSR with such solutions. Finally, Schmidt- or Meniscus-Cassegrain solutions seem an interesting possibility for getting the light out in a direction such that condition d) may be fulfilled.

The feasibility of a F.R. in practice will depend on the number of elements astronomers are prepared to accept and I should much welcome a discussion on this point. Is the widespread scepticism justified in view of the possibilities of anti-reflexion coatings? Professor Elsässer commented to me recently that a F.R. should be considered as an ancillary piece of equipment for the secondary focus, just like a spectrograph. This seems a most pertinent comparison and the number of elements reasonable for a F.R. falls into a better perspective. Nobody expects a spectrograph to work without optical elements: a typical Cassegrain spectrograph of low f/number might contain a field lens, 2 collimator mirrors, a camera-mirror and two corrector elements. But the image it is accepting is a slit of negligible width and perhaps 40 mm length. Viewed in this light, a F.R. giving an excellent image (comparable with, or better than that of a prime focus corrector and with a higher aperture ratio) with, say, five correction elements, a field lens and a mirror does not seem excessively complex when one bears in mind that the image it is transferring is almost half a meter in diameter.

ACKNOWLEDGEMENTS

My thanks are due to many astronomers who have given advice or encouragement in connexion with this work. It is a pleasure to record my special debt of gratitude to Professor Elsässer and Dr. Bahner who initiated the large proportion of the design work which was concerned with the MPI projects. Finally, my warmest thanks are due to my colleagues Messrs. Buberl, Faulde and Müller for their assistance with the calculations.

The studies on which the present article is based have been supported by the Bundesminister für Bildung und Wissenschaft within the Technology Programme.

References

1. I.S.Bowen: Publ. Astron.Soc.Pacific 73, 114 (1961)
2. H. Chrétien and G. Ritchey: C.R.Acad.Sc.Fr. 185, 266, 1024 and 1125 (1927)
3. P.B. Fellgett: In "Optical Instruments and Techniques", Proceedings ICO 1969, Oriel Press, 475 (1970)
4. S.C.B. Gascoigne: Journal of Physics E (G.B.) 3, 165 (1970)
5. H. Köhler: ESO-Bulletin Nr. 2 (1967)
6. H. Köhler: Appl.Opt. 7, 245 (1968)
7. R.N. Wilson: Appl.Opt. 7, 253 (1968)
8. J. Meurers: Sterne und Weltraum 8, 195 (1969)
9. S.C.B. Gascoigne: The Observatory 85, 79 (1965)
10. D.H. Schulte: Appl.Opt. 5, 309 (1966)
11. C.G. Wynne: Appl.Opt. 4, 1185 (1965)

12. C.G. Wynne: Astrophys. J. 152, 675 (1968)
13. R.N. Wilson: Appl.Opt. 7, 1232 (1968)
14. A. Offner: Appl.Opt. 2, 153 (1963)
15. D.H. Schulte: Appl.Opt. 2, 141 (1963)
16. R.N. Wilson: Sterne und Weltraum 10, 32 (1971)
17. C.G. Wynne: Proc.Phys.Soc. B62, 772 (1949)
18. S. Rosin: Appl.Opt. 3, 152 (1964)
19. A.B. Meinel: Astrophys. J. 118, 335 (1953)
20. D.H. Schulte: Appl.Opt. 5, 313 (1966)
21. G.W. Wilkerson and J.D. Lytle: Opt.Sciences Centre Newsletter 2 (2), 35 (1968)
22. A. König und H. Köhler: "Die Fernrohre und Entfernungsmesser", Third Edition, 155 und 159 (1959)
23. A. Baranne: Publ. de l'Observ. de Haute Provence 8 (22), 75
24. A. Baranne: In "The Construction of Large Telescopes", Proc. IAU 27, Academic Press, 22 (1966)
25. M. Paul: Rev. d'Opt. 14, 169 (1935)
26. F.E. Ross: Astrophys. J. 81, 156 (1935)
27. J.G. Baker: Transactions of Inst. of Electronics & Electrical Engineers, March 1969
28. R.V. Shack and J.D. Lytle: Opt.Sciences Centre Newsletter 1 (1), 7 (1967)
29. A.B. Meinel: In "The Construction of Large Telescopes", Proc. IAU 27, Academic Press, 30 and 223 (1966)
30. R.N. Wilson and W. Buberl: (To be offered for publication in 1971)
31. A.B. Meinel: Astrophys. J. 124, 652 (1956)
32. A.B. Meinel and G.W. Wilkerson: Optical Sciences Centre Technical Report No. 7 (1968)
33. G. Courtès: Astr.J. 69, 325 (1964)
34. G. Courtès: In "The Construction of Large Telescopes", Proc. IAU 27, Academic Press, 37 (1966)
35. A. Bouwers: "Achievements in Optics", 1964
36. D.D. Maksutov: JOSA 34, 270 (1944)
37. D.G. Hawkins and E.H. Linfoot: M.N.R.A.S. 105, 334 (1945)
38. J.G. Baker: U.S. Patent 2 458 132 (1949)
39. W.R. Bradford: The Observatory 76, 172 (1956)
40. J. Davis: Quart.J.Royal Astron.Soc. 4, 74 (1963)
41. K. Bahner: "Teleskope" in "Handbuch der Physik", Bd. XXIX, 281, (1967)

DISCUSSION

BROWN: Have you calculated constructional tolerances for the prime focus corrector system you have been investigating, and if so do any of them show clear advantages from the constructional point of view?
WILSON: We have done very little work on the tolerancing of prime focus correctors, but so far it shows that the lens correctors are easier than the plate correctors. Our impression is that the tolerancing with lens prime focus correctors is a matter which is technically feasible.
BEHR: The focal reducers are of very great interest in combination with Fabry-Perot interferometry as Courtès has shown at the Haute Provence Observatory. Have you also studied solutions which are suitable for use in combination with a Fabry-Perot interferometer?
WILSON: No, but I have borne in mind that there may be a requirement for some sort of filter in focal reducers, particularly if they have got a low f-number like f/1.7. For example, the Hawkins-Linfoot achromatic plate could be considered as a positive lens which is virtually working as a collimator with some aberration, and the negative part of the plate would then de-collimate it, so I think there are some possibilities there, but we have not investigated them in detail.
WYNNE: The question was asked about tolerances on lens prime focus correctors. I have done a little work on this. A different type of prime focus corrector, a paraboloid corrector that Grubb Parsons have made for the Isaac Newton telescope, does require fairly colse tolerances on curvatures, but nothing beyond what can be done by careful measurement. The centering tolerances again are good commercial workmanship, but nothing miraculous. I have done calculations on the three spherical lens correctors like the Kitt Peak and the AAT types which have not yet been made. Again they are at a level which requires careful workmanship and particularly rather careful measurement of curvatures, but nothing that presents any serious problem to a high-grade glass shop.
WILSON: This is the sort of conclusion that we have come to as well.
WYNNE: I would like to say a word about the secondary focus corrector problem. On the question of the number of elements, my sympathies are rather with the astronomers. It seems a pity when you are short of quanta

to throw even a few away, and I think that rather careful consideration of the compromise that one makes in these correctors needs to be given rather more attention than has been done sometimes. Departing from the true Ritchey-Chrétien condition seems to me to be an unfortunate thing to do unless one is forced to do it. The true Ritchey-Chrétien has a reasonable field used alone with no additional elements beyond the two mirrors and particularly if you are prepared to bend the plate you can extend it significantly more. Professor Köhler's original Cassegrain focus corrector requires departing from the Ritchey-Chrétien condition so that you lose by coma the larger field that the two-mirror combination could have by itself. Monochromatically the spot size in the diagrams is very little reduced beyond what would have been obtained on the true Ritchey-Chrétien of the same size by bending the plate a bit. There is a large chromatic difference of magnification, so that with white light the results on the field would be considerably worse than on the true Ritchey-Chrétien of the same specification with a curved plate.

It seems to me that it is in fact possible to design two-element correctors for larger fields with a true Ritchey-Chrétien combination, and I was interested to see the Max-Planck-Institute is going back to this. As I showed in 1965 and over a wider field in 1968, there are two-lens solutions using silica for each element, which give a correction within about 0"5 over a ± 25' field. Now 0"5 is bigger than 0"25, but for earth-bound astronomy, is this difference worth paying some significant price for? And it seems to me that the astronomers who are planning these things need to give more careful attention than has been given in the past to the compromises that have to be made with these things.

WILSON: I don't think I need to comment on that. It is a comment in its own right.

DOSSIN: When you coat the lenses, you gain of course a lot in reflection, but you lose in the wavelength range, which means that you must have different correctors for different wavelengths.

WILSON: This is perfectly true. You can reduce the average reflectivity from 4% to about 2% in the range from about 365 nm to 1000 nm. If you go further into the UV then it becomes serious and in fact you lose more than you gain. So it is quite correct that one.would have to have two sets of correctors.

FEHRENBACH: In that case, the chromatic field aberration is not so important.

WILSON: Yes, the chromatic problem becomes appreciably less, but on the other hand you have to change the correctors if you change your region.

CRAWFORD: In the final optical design of these correctors, I think it is important to follow some of the rays through the system and see where the ghosts appear. Some of the design systems may vary tremendously from others, and especially with the compromise-type things that Dr. Wynne mentioned, it may be important where the light has gone that did not appear in the focus.

WILSON: This is a most interesting point. We have investigated the position of the ghost images in a doublet corrector for Vienna, and for the Max-Planck-Institute instrument which is about the same sort of design. To begin with I was rather worried about the appearance of such images, but I came to the conclusion - after Dr. Bahner had produced his first reaction to it - that in fact it is less serious than one would think at first sight. I considered the area of the seeing disc and then the area of the light beam of the defocused ghost image in the image plane and simply calculated the relative intensity of the light in these two patches. I came to the conclusion that the worst ghost image had a difference of the order of 15 magnitudes for a seeing disc of one arcsec and uncoated lenses. That means of course that if you happen to have Venus in the middle of your field and you are looking at a 20^m star, it is going to worry you. But it will still worry you even if you coat the system almost perfectly. Perhaps Dr. Bahner could make a comment here?

BAHNER: This figure is not very indicative of what really happens, but anyway in the Vienna system the brightest ghost image from a 9^m star is only just visible. That means that in a field of 1°, even close to the galactic equator, you have only two or three such images, a situation one could probably accept.

COUDÉ OPTICAL DESIGN

E.H. Richardson
Dominion Astrophysical Observatory
Victoria, B.C., Canada

INTRODUCTION

Today, specifications for large telescopes usually require the largest possible fields of good definition at the prime and Cassegrain foci, and almost all progress in the optical design of telescopes has been for these foci. By comparison, the coudé focus operates on-axis and the optical design is simplified, and usually consists of an aspherical secondary mirror followed by a series of flat mirrors leading the light out of the telescope to the coudé focus (which has the advantage of being stationary).

The support of these mirrors is usually an important feature of the mechanical design and dominates the design of the lower portion of the telescope tube. There, at the intersection of the tube axis with the declination axis, a flat mirror measuring about 1 meter, for a 3.6 meter telescope, must be supported, with provision for movement off-axis when the Cassegrain focus is used, and for complete removal for aluminizing. This expensive mechanical problem can be greatly reduced by the use of small mirrors, having a maximum diameter of about 250 mm (10 inches).

The use of small coudé mirrors was considered for the Canadian 3.8 meter (150 inch) telescope. In April, 1969, a small mirror system went into operation with the 1.2 meter (48 inch) telescope at the Dominion Astrophysical Observatory. This was done partly as a prototype for the 150 inch which meanwhile lost its funding.

In my view, the most important advantage of the use of small mirrors is that it makes it possible to use high reflectance coatings without sacrificing the ultraviolet because three or four small mirrors can be carried in a turret at each reflection point, each mirror being coated for a different wavelength region. Thus, the light flux reaching the coudé focus is increased to approximately that reaching the Cassegrain focus from an aluminum coated secondary.

The small mirrors cause much less central obscuration in the 1.2 meter telescope which not only causes an increase in light flux, but also improves the appearance of spectrograms taken with the superpositioning type of image slicer (1, 2) used at Victoria where the distribution of intensity across a spectrogram is that of a one dimensional image of the primary mirror. (See Figure 9).

---

1. Richardson, E.H., Brealey, G.A., Dancey, R., P. Dom. Ap. O., 14, 1.
2. Richardson, E.H., J.R.A.S. Can., 62, 313.

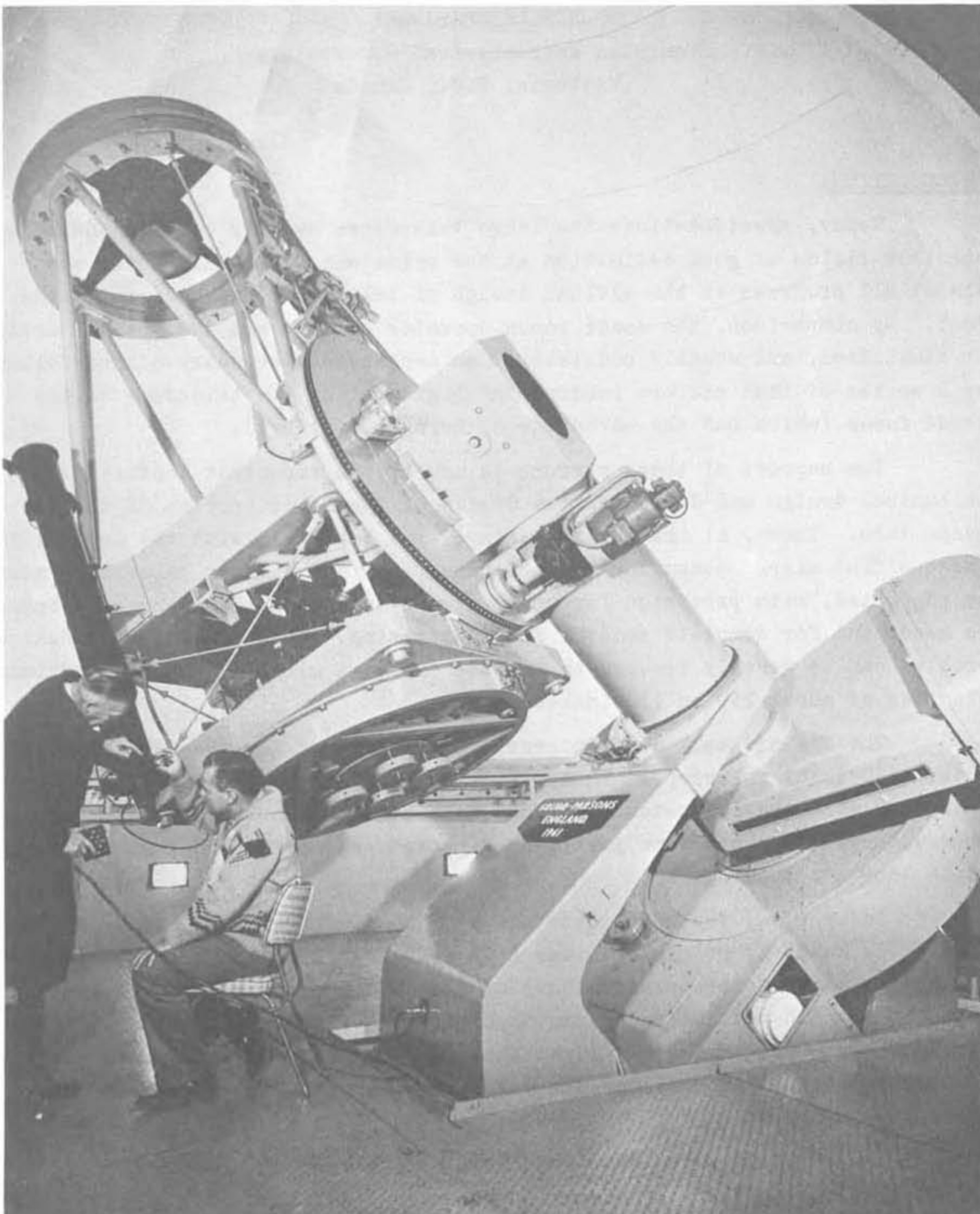


Fig. 1 The Dominion Astrophysical Observatory's 1.2 meter telescope prior to the installation of the small mirror coudé system.

Fig. 2 The 1.2 meter telescope with turrets of small mirrors and with the new coudé field viewer.

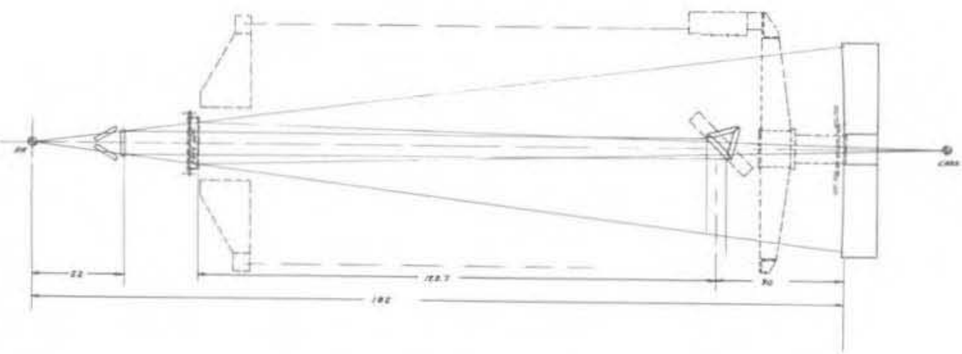


Fig. 3 Optical layout within the telescope tube of the small mirror system. The former first flat is shown in dashed outline.

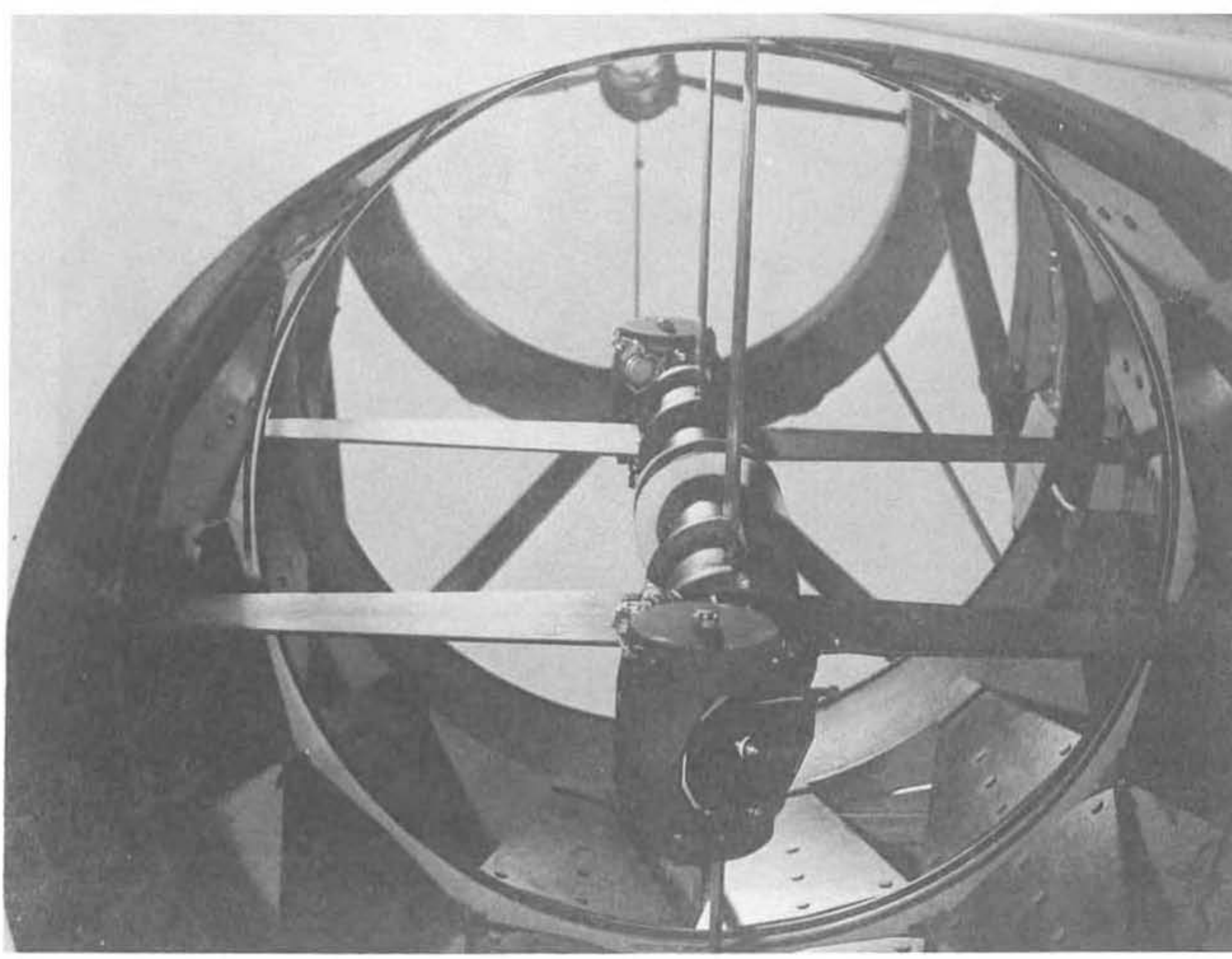


Fig. 4 Photo of the first turret of flat mirrors. The turret of secondary mirrors can be seen reflected in the primary.

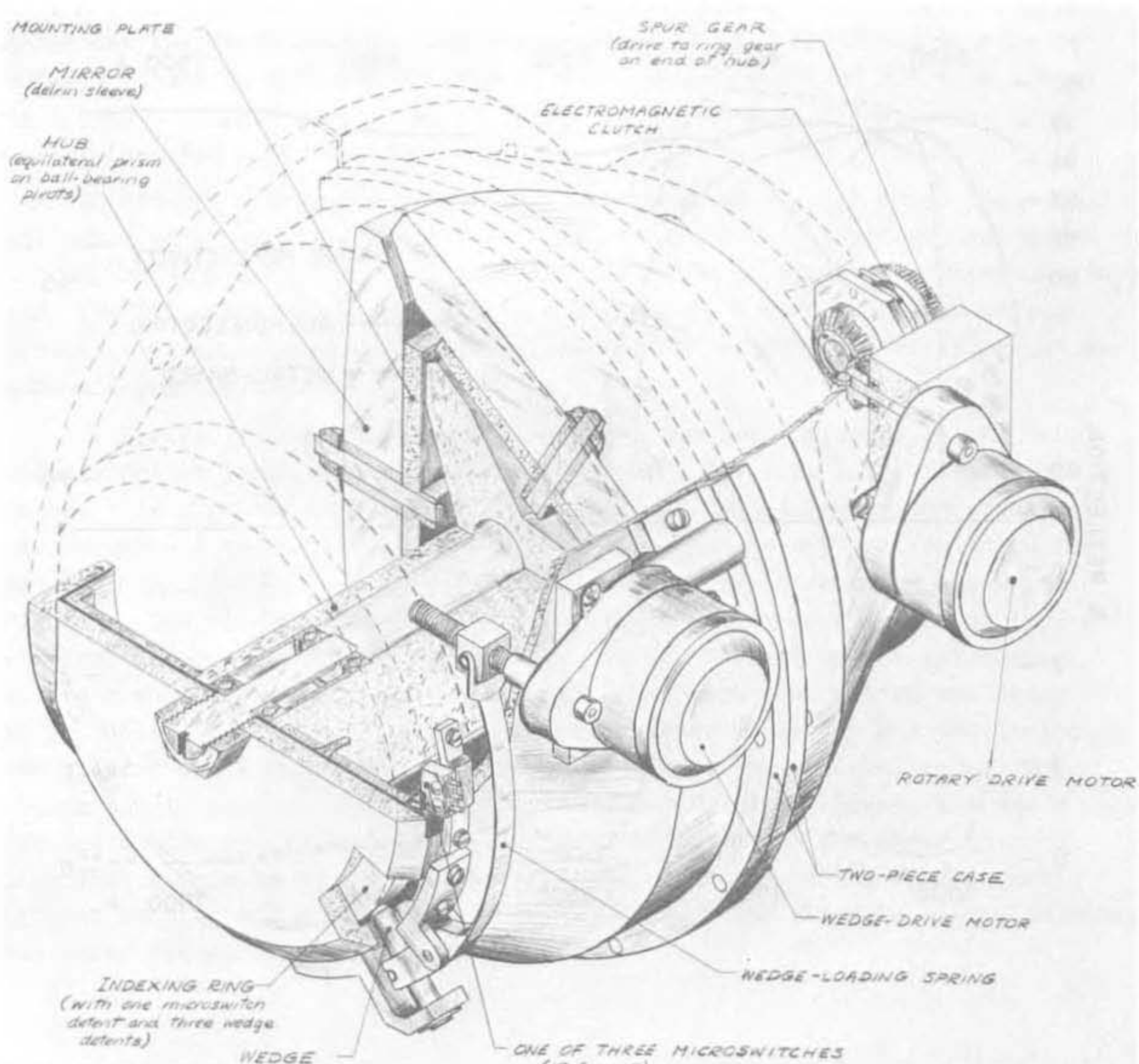


Fig. 5 Cut-away view of the turret of secondary mirrors.

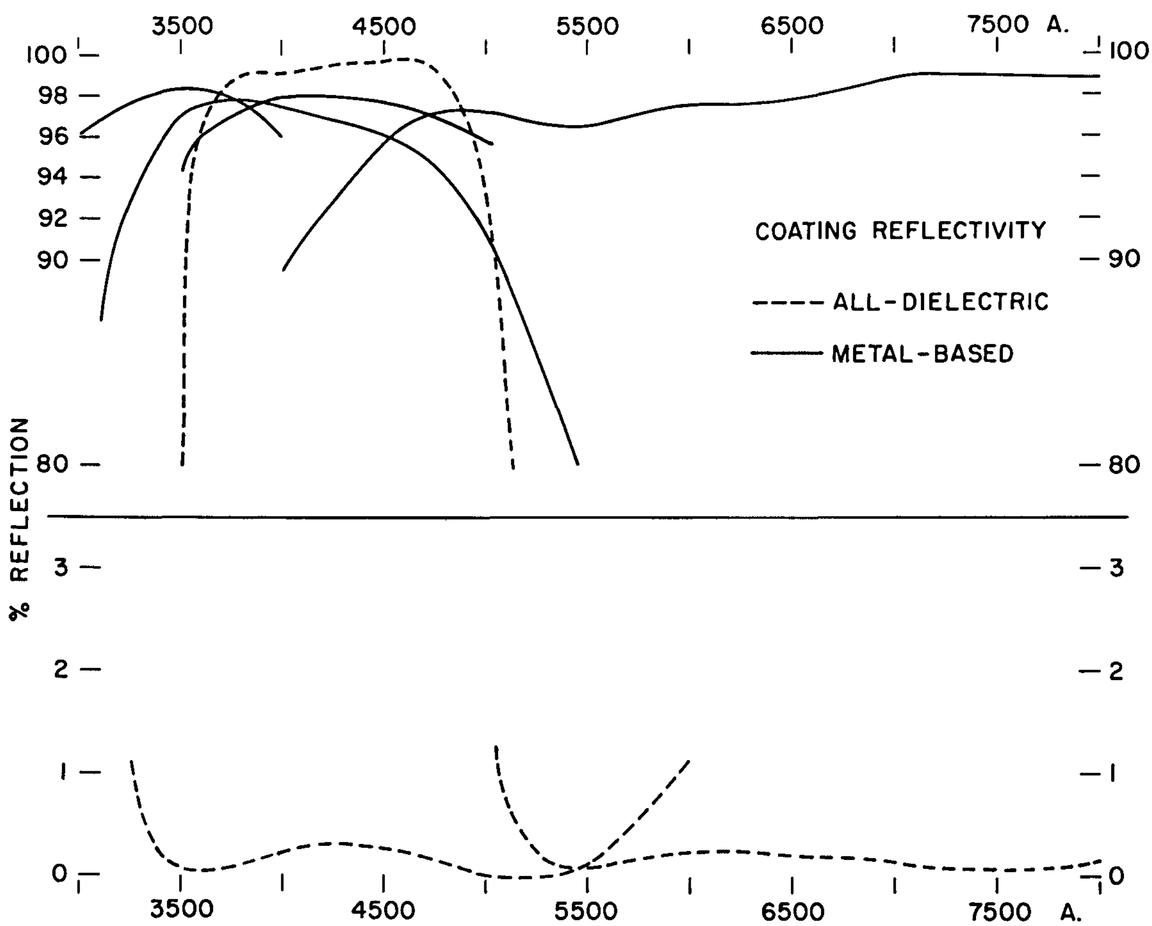


Fig. 6 Reflectivities of multi-layer coatings used at Victoria.

THE MODIFIED 1.2 METER TELESCOPE

The original, large coudé secondary can be seen in Figure 1, while Figure 2 shows the modified telescope (of 1.2 meters at the Dominion Astrophysical Observatory). One can also see the turret of 154 mm (6 inch) secondary mirrors, and two turrets of flat mirrors, one in the telescope tube and one in the polar axis. A new coudé field viewer is 1.16 meters long and is angled upward from the lower end of the polar axis.

The objective lens, of 154 mm aperture, has a focal length of 1.22 meter and the focal length of the eyepiece is 56 mm. The field of view to 50% vignetting is 6.6 minutes of arc, at a magnification of 303 with a 4 mm exit pupil. Light, converging at f/145, is directed into the viewer by a mirror inserted into the beam.

Off-set guiding is not usually practical at a coudé focus because of the small field of view. However, it might be possible to off-set and track "invisible" objects by computer control of a suitable tracking system. To this end, the 1.2 meter telescope will be converted to a spur-gear-plus-roller system, similar to that designed by D.Dittmar et al for the telescopes at the McDonald Observatory.

Figure 3 shows the optical layout of the small mirrors in the telescope. Dotted lines show the space occupied by the old, large first flat. Figure 4 is a photograph of the first turret of flat mirrors: the back of the turret and the turret of secondary mirrors can be seen reflected in the primary. A cut-away view of the turret of secondary mirrors is shown in Figure 5. One electric motor operates a dowell pin through a leaf spring, and a second motor rotates the turret. All turrets carried on the telescope rotate simultaneously and automatically. The mechanical system was designed by Mr. George Brealey and was manufactured commercially for $12.000 including new spiders and a manually operated turret located in the slit room. The mirror mounts include special self-preloading adjusting screws, and the mirrors carried on the telescope have not required adjustment since their original alignment two years ago. The optical parts were made in the Observatory's optical shop by Mr. Roy Dancey and Mr. J. Miller, and assembly on the telescope was under the direction of Mr. T. Bridge.

EFFICIENT OPTICAL COATINGS

At the moment, only two mirrors in each turret have high reflectance coatings, one for blue and one for the red. The third mirror was coated with aluminum for use as a spare, but in the near future these mirrors will be coated with very efficient but narrower band coatings giving a reflectivity of 98% or better in the region from 3650 A to 4850 A. The reflectivity curve for this all-dielectric coating is shown in Figure 6. The other high reflectance coatings are metallic-based. All of the coatings shown are used at the

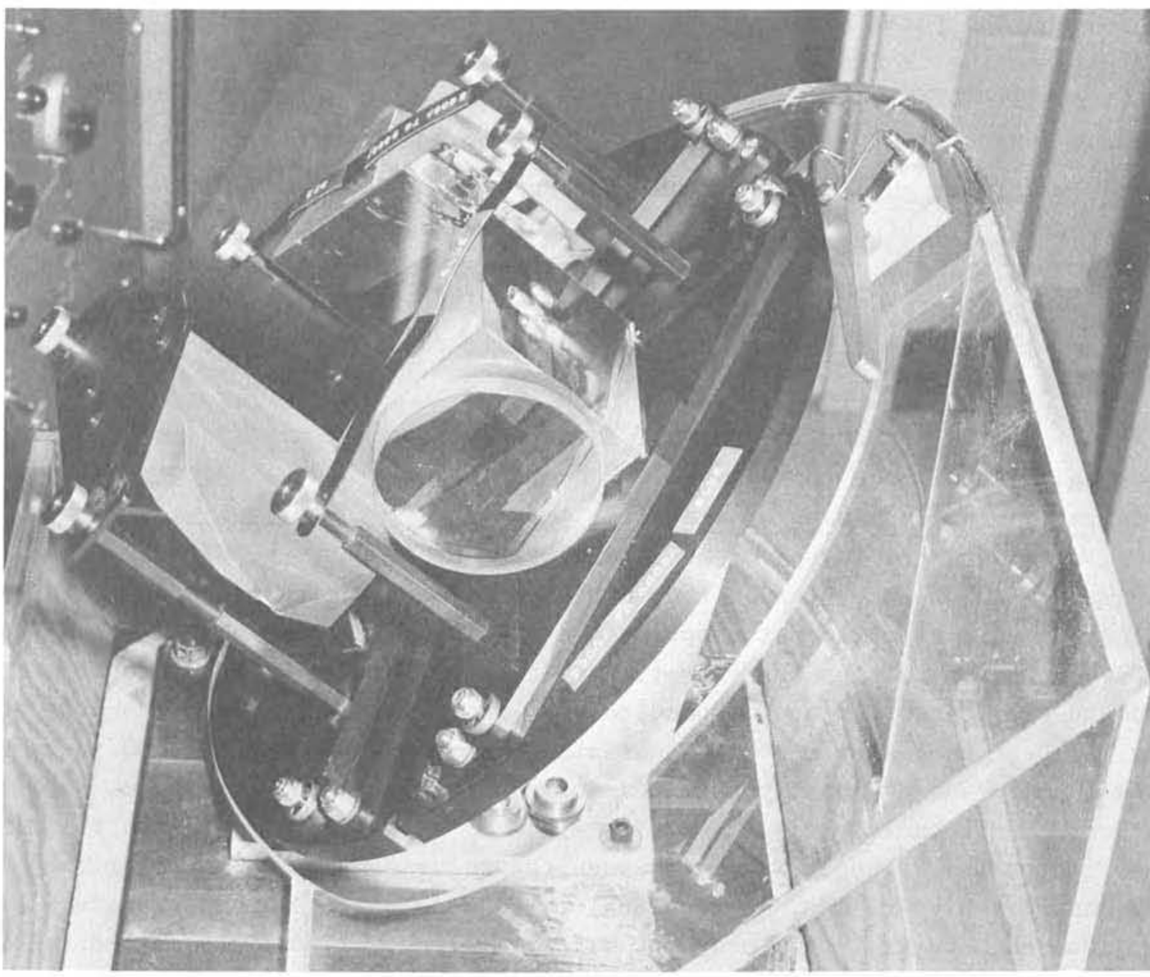


Fig. 7 Photo of lens-prism units mounted in the slit room.

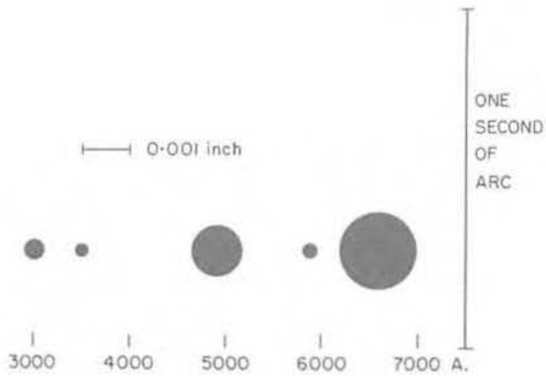


Fig. 8 Circles of confusion caused by the focal ratio changing lens designed for the blue region. The lens is made from fused silica and calcium fluoride.

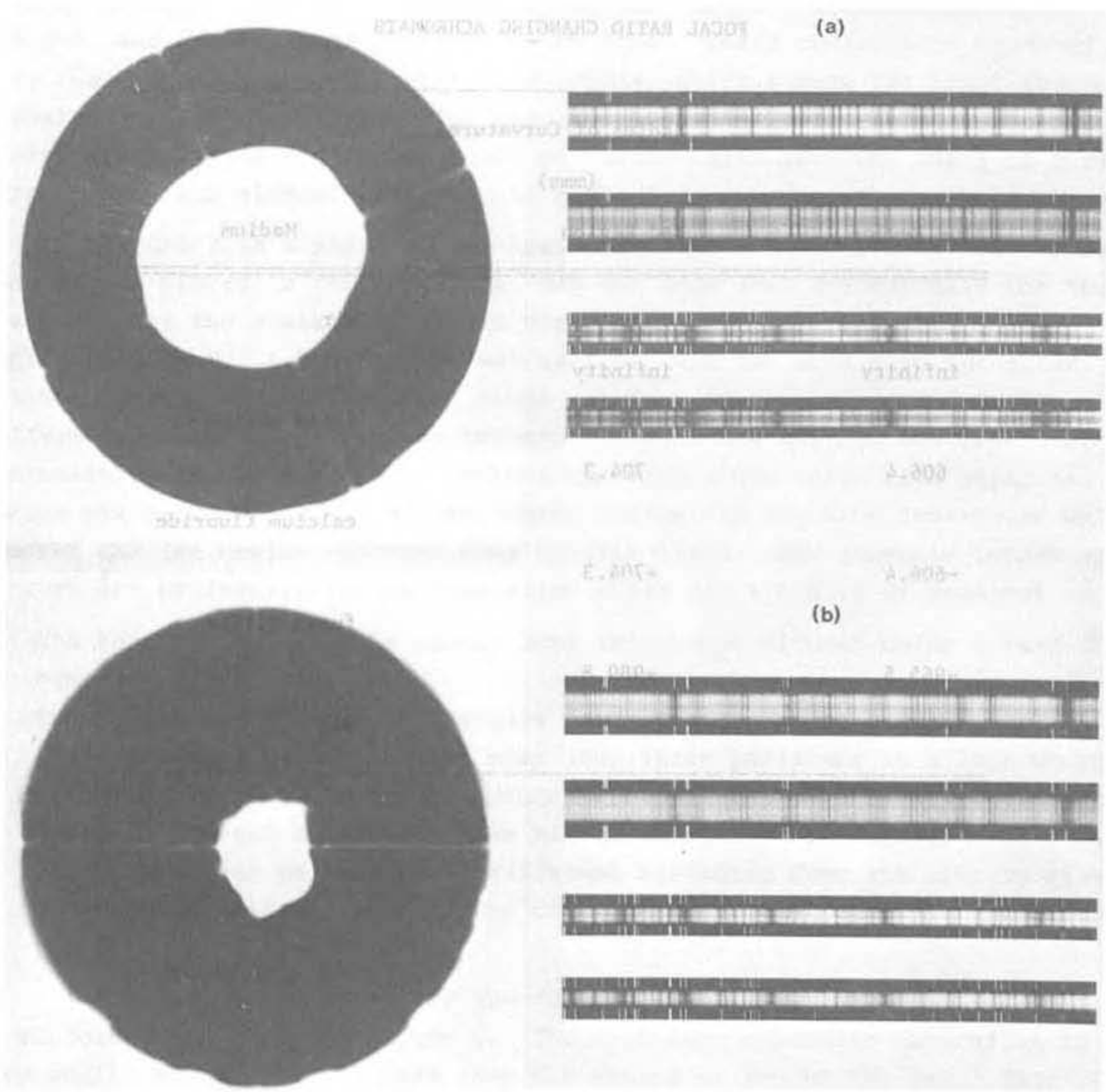


Fig. 9 Spectrograms taken at 2.4 Å/mm and at 6.5 Å/mm using image slicers, and cross sections of the coudé light beam with (a) the old large mirror system and (b) the new small mirror system.

TABLE I

FOCAL RATIO CHANGING ACHROMATS

Radius of Curvature (mms)		
Blue Region	Red Region	Medium
		air
infinity	infinity	
		fused silica
606.4	704.3	
		calcium fluoride
-606.4	-704.3	
		fused silica
-965.5	-989.8	
		air

Dominion Astrophysical Observatory on image slicers and/or telescope mirrors, and all were done in commercial coating laboratories.

CHANGES OF FOCAL RATIO

The low-reflectance coatings are required for image slicers and for focal ratio changing lenses located in the slit room and used with the small mirror coudé system. The primary focal ratio is f/4, which is changed to f/145 by the secondary, which is changed to f/30 at a turret in the slit room, 2 meters from the focus, holding two fused silica, calcium fluoride achromat lenses, 80 mms (3.25 inches) in diameter, one coated and colour corrected for the red, and one designed for use in the blue. These lenses were cemented onto fused silica, totally reflecting prisms, which turned the light horizontal and served to sandwich the calcium fluoride element between fused silica elements and thus keep it out of contact with air. The radii of curvature of the lens element are given in Table I.

Figure 7 is a photo of the lens-prism units. The red element cracked when it was placed in the cold dome, but has been used successfully for two years because the cracks (mostly in the calcium fluoride element) obscure negligible light. A hard cement was used to hold the lens onto the prism, but the calcium fluoride element could not take the strain caused by the difference in thermal expansion between fused silica and calcium fluoride. Fortunately, it was decided to replace the lens prism units with separate lenses and mirrors. After it was twenty months old the blue lens-prism unit cracked and its cracks obscured considerable light. The separate lenses and mirrors are preferable to the lens-prism units for a number of reasons:

1. The lens elements can be easily kept in contact without using a hard cement;
2. The blanks are cheaper and require less work to figure;
3. It is a simple matter to have more than three positions in a lens wheel to better match the high reflectance coatings (anti-reflectance coatings having different bandwidths than high reflectance coatings);
4. Lens wheels can be located at different distances from the slit to give a selection of focal ratios (the other lens turrets being set in no-lens positions).

Circles of confusion for the "blue" lens of Table I, computed by M. Fletcher, are shown in Figure 8. The secondary chromatic aberration is very small and amounts to less than 0.2 second of arc on the sky. This resolution would be three times better for a telescope three times larger, using the same lens, the same distance from the focus.

An incidental advantage of having a lens in the slit room is that it can be used to seal the polar axis against air currents without introducing an additional optical element.

TABLE II

OPTICAL SPACINGS OF 1.2 METER TELESCOPE

Feature	Large Mirror System (f/4 - f/30) Diameter (mm)	Separation (mm)	Small Mirror System (f/4 - f/145 - f/30) Diameter (mm)	Separation (mm)
Primary	1200		1200	
		-3336		-4318
Secondary	432		152	
		-1160		- 507
Image of Primary (by secondary)	424		143	
		4984		5314
Polar flat (2nd flat)	406		124 x 171	
		5715		5715
last flat			83 x 116	
		---		51
Lens	---		83	
		2019		1968
Slit (focal point)	(3 x 0.1 approx)		(3 x 0.1 approx)	
		----		1251
Image of image of Primary	---		43.6	
		4496		3245
Collimator	254		254	
		---		3246

Focal point if lens removed, i.e., virtual object for lens, 9710 mm from lens.

TABLE III

ALLOWED FLEXURES ETC. FOR 1.2 METER TELESCOPE

		For 2' (minute of arc) setting error		For 5% collimation error	
Element	Type of Flexure	Large Mirror System	Small Mirror System	Large Mirror System	Small Mirror System
Secondary	Rotation (axis parallel to surface)	3.2'	8.7'	31'	24'
	Translation (parallel to surface)	3.2mm	2.9mm	32mm	8.1mm
Polar Flat	Rotation	4.7'	12'	7.3'	2.3'
	Translation (perpendicular to surface)	15mm	73mm	15mm	5.1mm
Last Flat	Rotation	18'	18'	3.4'	1.1'
ALLOWED SLIT LENGTH (for collimator of 4496 mm focal length)				9.5mm	2.4mm

TABLE IV

EXPOSURE TIMES (1)

(Using 4-slice image slicers)

Region	Blue	Blue	Near IR
Dispersion (A/mm)	6.5	2.4	4.8
Magnitude	7.5 B-mag.	5.0 B-mag.	2.0 I-mag.
Average Exposure Times (minutes)	48	39	68
Range of Exposure Times	20 to 115	10 to 88	24 to 152
Range of Densities Above Fog at H	0.6 to 0.9	0.4 to 0.9	
Average Seeing (sec of arc)	3.3	3.8	4.0
No. of Plates	20	20	15
Projected Slit (mm)	0.02 x 0.5	0.016 x 0.8	0.032 x 0.8
Emulsion	IIa-O baked	IIa-O baked	IV-N hypersensitized

1. Richardson, E.H., Brealey, G.A., Dancey, R., P. Dom. Ap. O., 14, 1.

The use of focal ratio changing lenses moves the effective entrance aperture stop from the vicinity of the secondary mirror to a location inside the spectrograph between the slit and the collimator. When extremely long slits are used, it might be necessary to use a field lens immediately behind the slit in order to prevent overflow of a single element collimator (see Table III); on the other hand, one might take advantage of the lens to image the primary onto the small convex mirror of a Cassegrain collimator. These considerations do not apply with Victoria-type image slicers which have built-in field lenses.

FLEXURE TOLERANCES

Because the turrets of small mirrors are much lighter than the single large mirrors, one expects them to produce less mechanical flexure. Even when this is not the case, setting and collimation errors are negligible. Allowed translations and rotations of secondary mirrors and polar flat mirrors to produce a setting error of 2 minutes of arc and a collimation error of 5% are listed in Table III for the large and the small mirror systems of the 1.2 meter telescope. For setting error produced by rotation about an axis parallel to the surface of the mirrors, the small mirror system is 2.75 times more tolerant for the secondary, and 2.46 times more tolerant for the flat than the large mirror system. For example, reversal of the focussing mechanism of the 1.2 meter telescope rotates the secondary mirror which causes the image of a star to jump: the magnitude of this jump was reduced by about 60% when the small mirror system was installed. Similarly, figuring tolerance is relaxed and the seeing effect of turbulent air in the light path is reduced.

It is at the last reflection that rotation error causes the greatest collimation error, and here the small mirror system is three times less tolerant than for large mirrors. However, the allowed tolerance of 1.1 minutes of arc (which produces a 5% collimation error) is not stringent: even driven mirrors are expected to maintain greater accuracy, say 0.3 minutes of arc.

PERFORMANCE

The turrets are performing very satisfactorily. The system is reproduceable to better than 3 seconds of arc on the sky. This is, if one centers a star on the slit and then switches from, say, the red mirrors to the blue mirrors and then immediately back to the red again, the star reappears in virtually the same position. In this test, the "blue" star, i.e. when using blue mirrors, is displaced by about 6 seconds of arc from the position of the "red" star.

Used with image slicers, (3, 4) the exposure times are exceptionally short, and are listed in Table IV. The appearances of the spectrograms are shown in Figure 9b.

APPLICATION TO LARGE TELESCOPES

Although telescopes of all sizes can profit by the use of high reflectance coudé mirrors, the mechanical advantages are particularly important for large telescopes because of the massive reduction in weight and size of the flat mirrors.

Also, because the introduction of an additional mirror (on the polar axis) causes negligible light loss, there is less justification for going to the expense of eliminating one reflection by driving the last mirror. When the last mirror is not driven, the hole in the lower polar bearing can be made much smaller, the feed to the coudé viewer is simplified, the angle of incidence is constant (and the wavelength region for high reflectance is constant), and it is a simple matter to direct light to different focal points by rotation of the last turret to the appropriate fixed positions.

The use of small, high reflectance mirrors on a large telescope would decrease costs and permit the observation at high resolution of fainter stars than can be reached today.

DISCUSSION

ODGERS: Do you have any further comparisons with other coudé systems?
RICHARDSON discusses comparative exposure times which are given in Table I of Richardson, E.H. et al., Publ. Dom. Astroph. Obs., Vol. XIV, No.1, 1971. (Ed. note: This table has been reproduced on page 194 for convenience.)

ODGERS: Dr. Richardson's work is in some ways disastrous to Canadian astronomy; we have struggled for many years to get a large telescope, but now he has proved we don't need one!
CRAWFORD: One other thing that Richardson has maybe proven is that we should leave the coudé spectrographs out of the large telescopes entirely and save an awful lot of money and problems. You could instead build separately a coudé laboratory telescope, utilizing these kinds of techniques.
RICHARDSON: If you are going to gain by the large aperture and to have an efficient coudé system, then a large telescope would be the ultimate.
CRAWFORD: You could build a big coudé laboratory too!

---

3. Richardson, E.H., Brealey, G.A., Dancey, R., P. Dom. Ap. O., 14, 1.
4. Richardson, E.H., J.R.A.S. Can., 62, 313

COMPARATIVE EXPOSURE TIMES

Description of Standard Spectrogram								
Dispersion (Å/mm)	Projected slit (mm)	Region and Emulsion	Magnitude	Observatory	No. of Plates	Exposure Time (min.)	Seeing (arcsecs)	Comments
6.5	0.02 x 0.5	blue IIa-O baked	7.5 B-mag.	Victoria (48-inch)	20	48	3.3	
				Victoria	2	39.5	4.0	H.D. 108100
				Palomar (200-inch)	120	53.5*	1.8	
				Palomar	9	41*	1.75	
				Palomar	2	34*	1.0	H.D. 108100
				Kitt Peak (84-inch)	-	118	-	KPNO manual divided by four
				Stromlo (76-inch)	3	315	-	
2.4	0.016 x 0.8	blue IIa-O baked	5.0 B-mag.	Victoria	20	39	3.8	
				Palomar	(9)	87	1.75	calculated from data
				Palomar	(2)	58	1.0	on 9Å/mm plates
				Kitt Peak	-	190	-	KPNO manual divided by four
				Kitt Peak	1	1500	7	IIa-O emulsion
4.8	0.032 x 0.8	near IR IV-N hyper-sensitized	2.0 I-mag.	Victoria	15	68	4.0	
				McDonald (107-inch)	(4)	180	7.6	calculated from data on 1.9 Å/mm plates
				Kitt Peak	6	400	5.8	

* These exposure times are calculated from data on 9Å/mm plates and should be increased by 38% if it is assumed that the higher dispersion (6.5 Å/mm) is achieved at Palomar by using a camera of a longer focal length with the existing grating.

RICHARDSON: Oh, that's great, yes!

CRAWFORD: Mr. Barr will show a slide on a reasonably large coudé laboratory telescope which is in just the very conceptual design stages (cf. Barr: "An efficient coudé laboratory").

DENNISON: Is there any angle limitation with these special high reflectance coatings?

RICHARDSON: With extremely oblique angles you would begin to run into some difficulty. But most of our coatings have fairly few layers in which case they could operate well also at very oblique angles.

BELLY: Your system has three interchangeable mirrors. Do you think two mirrors only would be sufficient?

RICHARDSON: I think you could probably get away with two mirrors. We hope that eventually the coatings will be improved in their reflectivity from 3000 A to 4800 A. I would be more inclined to recommend - as you have very small mirrors anyway, and our system only costs $12.000 - that you go to a four mirror system. Some coating experts think that you should get a sort of enhanced gold for the yellow, because it is much more durable than the enhanced silver and durability does become important. And you certainly want to keep these mirrors clean and washed.

OKE: There are some advantages to the high reflection mirrors, which not only give high reflection on certain wavelength regions but give low reflections outside of that range. When you are using some of the tri-alkali cathodes which have a very wide sensitivity range, the problem of overlapping orders becomes very serious. There are enormous advantages if you could get rid of some of the filters you would otherwise use.

FEHRENBACH: Your gain is very high, and the reason is probably that the ordinary mirrors have not 80% of refracting power, but rather 60%, because it is difficult to change a big mirror so often.

ODGERS: I think that Dr. Richardson perhaps could have stressed a little more that the large coudé flats could be more efficient than they are, since there is a tendency to not aluminize them. They are awkward to get at, and they are left a little too long in the telescope, whereas these small mirrors present no trouble in keeping very clean and very efficient.

RICHARDSON: Thatis correct. If we take the difference between aluminium and the high reflectance coatings and the gain we get from the image slicers, then we should still be a magnitude slower than the 200". We have not yet got the high reflectance coatings into the spectrograph, that's coming next, so we are going to keep pushing. But I think it might be that our grating is very efficient. We happened to get a very good 154 mm grating with an 85% blaze efficiency, so we immediately ordered four more and made a mosaic; they all came out good.

FEHRENBACH: Have you a measurement of the reflecting power of the mirrors without coating?

RICHARDSON: No, we have not. But we are just getting our own coating plant and our own reflectometer and spectrophotometer for this.

CAYREL: What was the size of the gratings for the experiments on which you have given exposure times?
RICHARDSON: The first is a 154 mm. The other two for the high-dispersion blue and infrared was a mosaic of four 154 mm gratings.
CAYREL: Were the exposure times given with the use of an image slicer?
RICHARDSON: They all are, yes.
BAHNER: I wonder if someone would care to comment on the penalty you have to pay in going to an f/150 coudé. What I have in mind is the field.
RICHARDSON: This has not been a penalty for us because the slit can be made long enough. With our telescope we have a very adequate field, but you would have trouble with say a 3.6 m telescope where, unless you wanted to go to considerable expense in having rather large field changing lenses, you might only get $0.'5$ - $1.'0$ to 50% vignetting. But even at 50% vignetting, you are getting more through than you would without the system.
BAHNER: With a Ritchey-Chrétien primary mirror, you have a lot of coma in your coudé focus, which is magnified by the ratio of secondary magnification, i.e. you have 5 times as much coma at the same angle of field when going from f/30 to f/150.
RICHARDSON: I don't think it is a problem and in the coudé we usually want to work on-axis, with a single object. I think the coma is still not so bad that we could not look at a planet, which is the largest object that I am familiar with in observation at coudé.

ADDENDUM

Coudé Exposure Times in Chile*

The KPNO and CTIO Quarterly Report for October-November-December, 1970, notes that the exposure time with the 60-inch telescope on Cerro Tololo is 15 minutes for a star of 5th B-magnitude at 9 Å/mm broadened to 0.6 mm on IIa-O plates developed in D76; that is, 150 minutes for 7.5 magnitude. The exposure time would be 225 minutes for 7.5 mag at 6.5 Å/mm broadened to 0.47 mm if one assumes that the exposure time is proportional to the square of the dispersion. The equivalent Victoria exposure time is given above: 48 minutes.

Exposure times for the ESO 1.52 meter telescope on La Silla were provided by Marseille Observatory. At 12 Å/mm, the average exposure time (from three spectrograms) is 25 minutes, ranging from 16 to 32 minutes, for 7.5 B-magnitude and seeing of 1 to 2 seconds of arc. The exposure time at 6.5 Å/mm would be about 86 minutes.

At 3 Å/mm, the exposure time (from five spectrograms) is 150 minutes, ranging from 82 to 274 minutes, for 5.0 B-magnitude and seeing of 1 to 1.5 sec of arc. (Comparison with the 12 Å/mm result indicates that the exposure time is proportional to the cube of the dispersion.) At Victoria, 2.4 Å/mm spectrograms are obtained in 39 minutes average (see above).

Incidentally, the ESO 20 Å/mm spectrograph appears to operate with a high slit efficiency with the good seeing in Chile: the average exposure time (from nine spectrograms) is 6.7 minutes, ranging from 4.3 to 11.6 minutes, for 7.5 B-magnitude with average seeing of 1.5 sec of arc.

The manual for observers at La Silla, "The Spectrographs of the ESO 152 cm Telescope", gives the following exposure times for IIa-O baked plates developed in D-19.

Dispersion (Å/mm)	Projected Slit (mm)	Photographic Magnitude	Exposure (minutes)
20	0.27x0.020	7.5	8.5
12	0.25x0.022	7.5	26
3.3	0.25x0.021	5.0	120

----

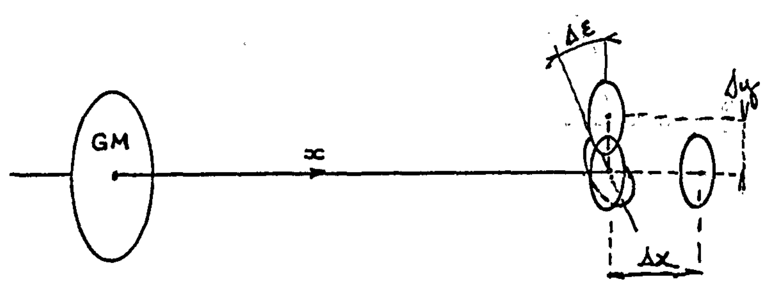
* not presented at conference; received April 25, 1971.

ALIGNEMENT DE L'OPTIQUE

A. Baranne
Observatoire de Marseille

Nous avons étudié dans le cas du télescope E.S.O. (Ø GM = 3.60 m; F/3, F/8) l'importance des aberrations d'excentrement au foyer Cassegrain. Rappelons brièvement ces résultats.

En supposant le miroir principal en place et on peut toujours se ramener à ce cas, les excentrements possibles se réduisent à 3 déplacements élémentaires:



Δx détermine la latitude de mise au point et n'est pas à proprement parler un défaut d'excentrement. Un excentrement Δy de 1 mm ou un excentrement $\Delta \varepsilon$ de 1 minute d'arc provoque une coma uniforme de 50 μ soit 0.25" au foyer Cassegrain.

Ces 2 excentrements peuvent d'ailleurs se compenser si l'hyperbole tourne autour de son foyer objet.*

L'optique étant en place dans le tube il est important que l'observateur ait à sa disposition un appareillage simple d'emploi lui permettant de reconnaître l'importance de ces excentrements.

Appareillage proposé:

- 4 miroirs sphériques de 100 mm de diamètre sont collés sur le miroir primaire, leur centre de courbure coïncidant avec le foyer paraxial du grand miroir.

- 1 miroir sphérique de 100 mm est collé sur le sommet du secondaire, son centre de courbure coïncidant avec le foyer Cassegrain.

* Ceci, dans le cas d'une combinaison parabole-hyperbole, est évident. Dans le cas d'une combinaison Chrétien, la compensation exacte de la coma uniforme produite par les deux excentrements s'effectue lorsque le secondaire tourne autour d'un point différent plus proche du sommet.

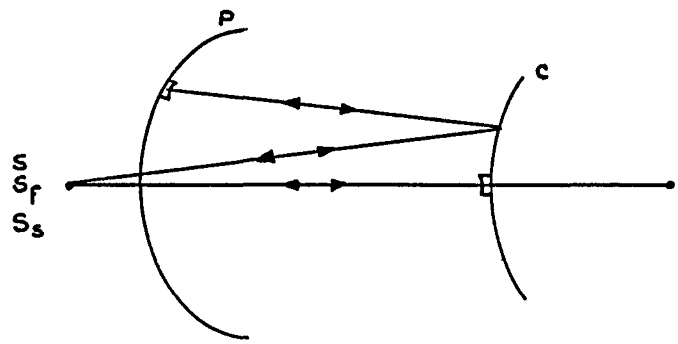
Comme nous allons le voir, ce système permet:

1. de retrouver rapidement un premier centrage après tout changement de foyer ou démontage de miroir.

2. de vérifier le centrage des deux miroirs pendant une pose et de maintenir ce centrage si nécessaire par un asservissement du secondaire.

<u>Précision de la mesure des excentrements</u>:

Pour évaluer cette précision nous pouvons supposer tous les miroirs parfaitement réglés. Nous étudierons les effets des excentrements Δy et $\Delta \varepsilon$ précédents.



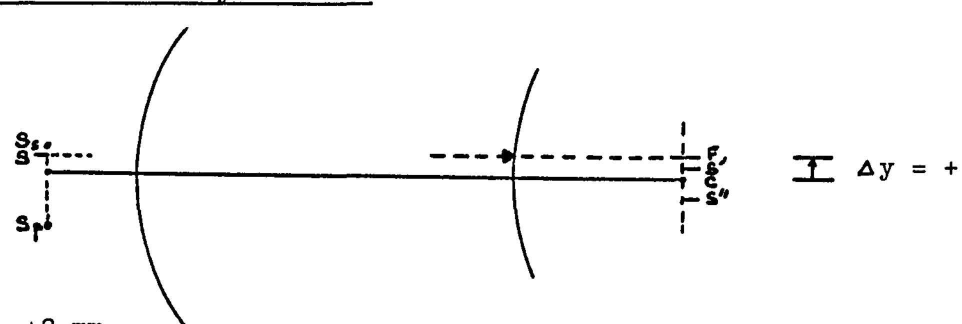
Une source S au foyer Cassegrain donne par autocollimation

1 image S_p (miroirs sphériques collés sur le miroir primaire)

1 image S_s (miroir sphérique collé sur le secondaire).

Dans un collage parfait et pour un réglage parfait ces deux images coïncident avec S si la source S est au foyer Cassegrain.

<u>Cas d'un excentrement Δy = + 1 mm</u>:



SS_s = +2 mm

SS_p = -3.4 mm

$S'F = 1/\gamma$

$CS' = 1 - 1/\gamma$ avec $CS' = S''C$

$S''F = 1 + (1 - 1/\gamma) = 2 - 1/\gamma$

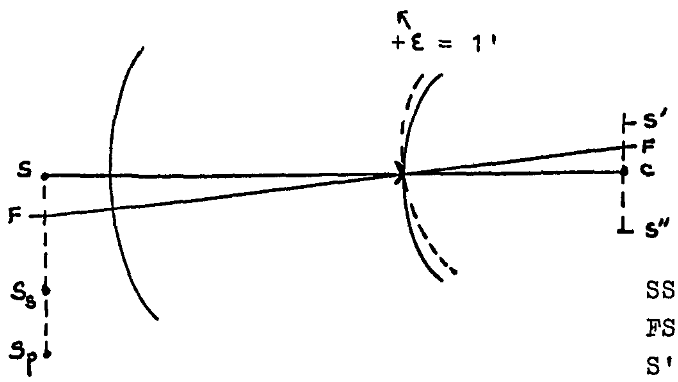
au foyer Cassegrain $\gamma(2 - 1/\gamma) - 1 = 2(\gamma - 1)$

$\gamma \# 2.7$

On constate que les deux images se déplacent en sens contraire avec un rapport des vitesses de (γ - 1) soit 1.7.

Cas d'un excentrement $\Delta\varepsilon = + 1'$:

Nous rappelons que cet excentrement déplace le foyer objet de l'hyperbole de + 1 mm et conduit à la même aberration qualitativement et quantitativement que l'excentrement précédent.



FC = 1

C = centre de courbure fixe des 4 miroirs

$SS_s = -2\gamma$

$FS' = 1$

$S'S'' = 4$

$FS'' = 3$

$SS_s = -5.4$ mm

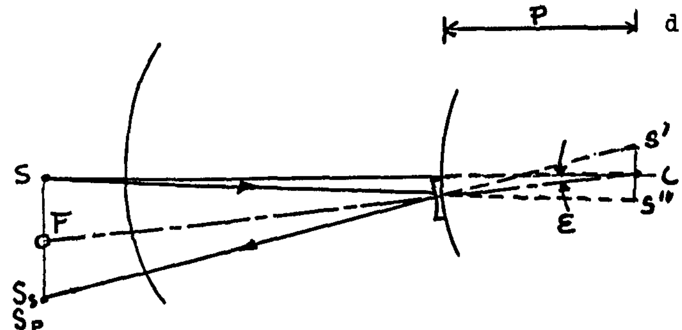
$SS_p = -10.8$ mm

au foyer Cassegrain $SS_p = FS_p + SF$
$= -4\gamma$

On constate que les deux images se déplacent dans le même sens avec un rapport des vitesses de 2.

Cas d'une rotation du secondaire autour du foyer primaire:

Rappelons que, dans ce cas, les deux excentrements précédents se compensent.



p distance Foyer primaire - miroir Secondaire

p = 3.3 m

$CS'' = CS'$ $SS_s = 2\ SF$

$FS_p = FS$

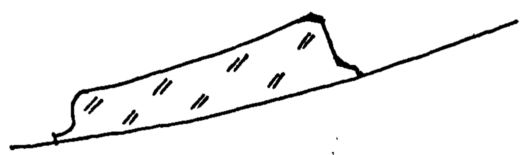
$SS_s = SS_p = 2p\,\varepsilon\,(\gamma + 1)$

si $\varepsilon = 1'$ $SS_s = SS_p = -7.5$ mm

On constate que les deux images se déplacent ensemble.

Mise en place des miroirs de repérage:

Les miroirs-repères sont mis en place à l'atelier. Lors des aluminiures successives du grand miroir, ces miroirs seront difficiles à nettoyer. Pour faciliter cette opération, la firme REOSC a proposé de les polir sur la tranche et de leur donner le profil ci-dessous.



Ils seront essayés et ajustés à la demande à l'aide des méthodes de test. Une minute d'erreur sur l'angle du prisme provoque une erreur transversale de 3 mm sur la position de leur centre de courbure. On peut assurer vraisemblablement une meilleure coïncidence des centres des 4 miroirs collés sur le primaire grâce à deux paramètres que l'on peut faire jouer lors du collage: distance à l'axe et rotation de chaque miroir mais on ne peut pas à l'atelier prétendre repérer les foyers primaire et Cassegrain de façon définitive.

Dans la même opération seront connus les sommets des miroirs, centres des déformations. Le sommet du primaire sera repéré par rapport au trou central, le sommet du secondaire sera marqué d'une croix (en fait sur le petit miroir concave collé). Pour chacun des deux miroirs est donc défini ainsi un axe dit axe d'atelier.

Montage de l'optique:

,es axes d'atelier sont des simples repères matérialisés qui vont servir d'abord lors du montage à blanc du télescope à l'atelier de mécanique.

ɾsqu'on mettra en place le grand miroir, on fera coïncider l'axe a du grand miroir avec l'axe mécanique du tube en ajustant une première fois les barres de flexion prévues à cet effet. (Cela revient à placer les centres de courbure des 4 miroirs collés sur le primaire au centre de l'araignée du foyer primaire les réglages de cette araignée étant en leur point milieu, on tiendra compte dans ce réglage de l'orthogonalité nécessaire de l'axe de déclinaison et de cet axe d'atelier.)

L'axe d'atelier du grand miroir étant réglé et matérialisé par un télescope de pointage, on mettra en place le miroir secondaire. (Lorsque le secondaire sera réglé, c'est-à-dire lorsque sommet du miroir secondaire et centre de courbure du petit miroir concave seront sur l' axe d'atelier on s'assurera que les réglages de l'araignée sont suffisamment proches de leur point milieu.)

Ce réglage d'atelier permettra en outre d'observer sur place tous les phénomènes de flexions mécaniques, d'éviter éventuellement les déplacements brusques de l'image dus à des basculements de charges. Il faut bien remarquer à cet égard que l'étude et la correction de ces défauts est plus facile en usine que sur le site.

Réglage sur le site:

A partir du réglage d'atelier, la mise en place aux foyers primaire ou Cassegrain de l'ensemble correcteur-plaque photographique ne devrait pas poser de problèmes particuliers au spécialiste chargé du premier centrage sur le ciel. De l'examen du champ stellaire sera déduit l'axe optique définitif, les dispositifs d'autocollimation serviront alors à repérer les positions relatives des miroirs correspondant à ce centrage définitif et cela à partir du foyer utilisé. On peut très bien imaginer au bord du champ Cassegrain une source lumineuse et les deux images en retour diamétralement opposées alimentant un dispositif d'asservissement du secondaire.

On ne devra retoucher aux barres de flexion que si la latitude de réglage du miroir secondaire est trop faible.

Centrage du foyer coudé:

Un dispositif analogue permet de régler le foyer coudé. Un petit miroir concave marqué au sommet dont le centre de courbure est au foyer Cassegrain permet de mettre en place parfaitement le miroir secondaire.

On se sert pour cela du télescope de pointage à partir du foyer Cassegrain avant de mettre en place le miroir plan à l'intérieur du tube.

Une source au foyer coudé donne par autocollimation due aux quatre miroirs du primaire une image dont on assure la coïncidence au repère origine en réglant l'inclinaison du miroir à l'intérieur du tube. Après un démontage général des miroirs plans, une répartition non identique au réglage origine entre les angles des deux miroirs plans ne change rien à la qualité de l'image et le dernier réglage peut toujours être fait en ajustant le miroir du tube.

Référence

1. A. Baranne. Le Télescope Ritchey-Chrétien de 3.50 mètres. O.H.P. 1965
2. Correspondance du Dr. Martin Schwarzschild avec les professeurs A. Behr et O. Heckmann 1968 - 1969.
3. Rapports à la Commission des Instruments de l'E.S.O.
   A. Baranne. Octobre 1969.
   A. Behr, K. Bahner. Juillet 1970.
   G. Monnet. Decembre 1970.

DISCUSSION

BELLY asks if it would be possible to polish the small alignment mirrors directly on the surfaces of the primary and secondary mirrors.

BARANNE replies that this has been envisaged, but it would be a very difficult operation. He recalls that Malaise in Liège has investigated the possibility of polishing a zone around the central hole for alignment purposes. This is, however, not a very pleasant job after the surface of the large mirror has been finished. To make separate, small mirrors is much easier and certainly less dangerous.

REIZ: Would you comment on Malaise's suggestion to make a separate mirror to put in a recess in the hole instead of the 4 separate mirrors?

BARANNE finds this suggestion interesting, but the connection between the two mirrors must be absolutely rigid.

HERBIG: There has been described in the Journal of the Royal Astronomical Society of Canada, by Weylau at the University of Western Ontario, a system in which those collimating surfaces have been ground on the edge of the hole in the primary and in a separate surface at the center of the secondary. I think these optics were made by Boller & Chivens?

CHIVENS: Yes, this was done on a 48" at the University of Western Ontario and the surfaces were integral on both the primary mirror and the center of the secondaries. They worked out quite satisfactorily.

FEHRENBACH agrees that this is a valuable experience with a 48", but it may not be advisable on a 3.6 meter mirror.

BAYLE confirms that it is much easier for the optician to make the small (10 cm) auxiliary mirrors than to integrate them into an already finished surface.

BAHNER: Dr. Crawford, you have a Ritchey-Chrétien system operating with about the same tolerances for centering. What do you do about this? Do you feel a need for some means of checking on the centering?

CRAWFORD: Well, it certainly requires very good care. The only thing I can say that I would do about it is to hire very careful engineers.

MIRROR SUPPORTS

E. T. Pearson

Kitt Peak National Observatory*

INTRODUCTION

The topic of mirror supports would be very extensive. I will assume therefore that everyone here is already familiar with some mirror support system and can limit this talk to just some selected aspects of supports that might also be of interest to others with mirror support problems. The following then are brief notes which if not entirely clear might serve at least as an introduction to further discussion. All remarks are aimed at ground-based, reflector type telescopes with large mirrors; a "large" mirror is one where the environmental forces could conceivably distort the mirror surface enough to seriously degrade the optical performance.

PASSIVE VS ACTIVE SUPPORTS

Typically, a designer of mirror supports was given a list of specifications upon which to base a support design. These would include the optical design, surface tolerances, gravity orientations, weight limitations, etc., and also possibly factors such as maximum cost and delivery dates. The chosen design, once built and installed was left to do the best it could to keep the mirror surface within the design surface tolerance. This will be referred to as an open-loop or "passive" support system.

Corrections to the mirror figure not allowed for by a passive system may be desirable. Change in the optical figure as produced by the optical shop and corrections for thermo-elastic distortions are possible reasons for initiating a figure change. Systems which allow for mirror control on command as through a closed-loop servo control will be called "active" systems.

There are three mirrors at Kitt Peak where active supports are being considered; i) the 150" Stellar telescope primary mirror where the pressure controllers for the two rings of air pads may be adjusted manually or by a closed-loop servo from the load-cell output; ii) the McMath solar heliostat with curvature control to correct thermo-elastic distortions, and iii) the solar main mirror where we are investigating the possibility of

----

* Operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

polishing a spherical mirror and deforming it to an off-axis paraboloid in the telescope.

MIRROR-SUPPORTS-CELL UNIT

In the past, the mirror, the mirror supports and the cell were often treated as three independent entities. Not only should the three be designed as a unit, but in operation it should be treated only as a unit. All focusing and collimation necessary in the telescope should be done to the unit, not just the mirror. Any movement, translation or rotation, of the mirror relative to the supports generally results in a degraded performance of the support system.

ANALYSIS VIA COMPUTER PROGRAM

Use of large digital computers has greatly facilitated the prediction of thermo-elastic distortions of a mirror surface for a given support system. There are two basic types of programs: i) finite difference, and ii) finite element. The difference between them is that "finite difference" implies a numerical solution to a set of differential equations that apply to the structure as a whole written in finite difference form, whereas "finite element" implies that the structure is composed of discrete elements, each element contributing a known displacement-stress contribution to the whole structure. There is variety and complexity in both types: in finite difference, there is a choice of differential equations that apply to the structure and in finite element there is a choice of basic building elements to be used to approximate the structure. Each type has advantages and disadvantages.

I would personally recommend that an organization interested in computer analysis of mirrors/supports be familiar with both types in order to choose the more appropriate one in each case. In general, lightweight mirrors would be analyzed with finite element programs and solid mirrors by finite difference programs.

MIRROR DEFINITION

Mirror definition (preventing unwanted translation and/or rotation of the mirror) should be accomplished such that the definition force or reaction is indistinguishable from a support force. When the defining forces are regular support forces, the only distortion due to defining is caused by residual errors in the support system.

Although the defining reaction should be the same as a support force, the device producing the force may be basically different from the regular supports. For example, the axial definition of the 150-inch primary mirror is produced by three load cells that replace three of the support air pads in the outer ring of supports. The load cell reaction has the same value and location as an air pad would have for supporting the mirror. Another example where this idea may be used is for the mirror entirely supported by a pressure or vacuum over the back surface. Three areas may be vented to the atmosphere. These vented areas then provide a three point defining force that has the equivalent reaction per unit of area as the back surface pressure.

LIGHTWEIGHT MIRRORS

The new "zero-coefficient" of thermal expansion materials now available have done much to alleviate thermo-elastic distortions. However, these materials have not reduced thermal inertia or weight problems. In addition they have actually increased the differential expansion between the mirror and mounting, including the supports and cell.

One way to alleviate weight and thermal inertial problems is to use a "lightweight" mirror design. We now have three "lightweight" mirrors at Kitt Peak: the 84-inch Stellar telescope primary, patterned after the 200-inch Palomar, a new 50-inch telescope primary machined from CERVIT* to 30% of its original solid weight, and the 52-inch f/8 secondary for the 150-inch Stellar telescope, also machined from CERVIT, but to 70% of its original weight. This latter mirror is of a different design philosophy than the others in that material was removed in such a way so as to meet three criteria: i) the weight per unit back surface area is uniform for each zone, ii) the center of gravity (c.g.) of each zone lies in a plane, and iii) the back surface center of pressure of each zone passes through the c.g. of each zone. Thus the convex mirror has the overall structural properties of a flat mirror and will be supported by a uniform air pressure back support and a mercury band edge support. This support system should compliment the lightweight mirror design.

One difficulty with "lightweight" designs is the choice of supports. The support design should always be made an integral part of the mirror cell unit but it is doubly important in lightweight designs. Many lightweight designs were predicated on the assumed support-induced bending stresses in a horizontal position. As the mirror is rotated to other orientations the design has severe limitations. In addition, local deflections around concentrated support forces become large, and if they also coincide with the mirror surface they can have a bad effect on the final image. The support forces must be carefully considered in the mirror design.

----

* Trade Mark Owens Illinois

OPTICAL SHOP

If possible the mirror should be tested in its final support system in the optical shop and figured until the surface is adequate. While seldom done, there are many advantages to testing the mirror in several positions from horizontal to vertical. For the case of the 150-inch primary, the back supports were used on the polishing table since the mirror is tested without being removed from the table in the vertical tower above the table. However, there are also auxiliary supports on the table for the grinding and polishing work.

When the mirror is not tested on its final telescope support system, but on some convenient optical shop support (e.g. a band, with the mirror in a vertical position), then the final mirror surface in telescope operation is not known. Many times even the effect of the optical shop support is unknown or variable. The band is a good example. Theoretically, the band support is a uniform normal pressure over the lower half of the mirror. In practice, due to friction between the band and mirror (this friction increased by the addition of small rubber blocks) the pressure is not uniform and shear forces are developed. The resulting mirror figure is not only unknown but variable, i.e. depending on the exact manner of loading the mirror into the band, the support forces will vary and so, therefore, will the mirror figure.

To avoid this variable nature of the band support, we are presently designing bands made from roller-chains. There should be very little friction in the rollers, resulting in a fairly uniform normal-force support, a good approximation to a theoretical band. In addition, for larger mirrors, a split band may be used instead of a single band exactly at the c.g. position. This alleviates local edge effects on the mirror surface (even more applicable for "lightweights" than for solids).

SUMMARY

A great deal of effort has been made to minimize elastic distortion problems from mirror supports (passive support systems). Further gains may be made in the field of active supports.

Integrating supports (including definition) with the mirror and cell and introduction of the final supports in the optical test procedure will prove advantageous. There must also be some effort placed in integrating the mirror-support-cell unit with the handling (maintenance) procedures, since mirrors require frequent realuminizing.

New materials, fabrication techniques, mechanical, pneumatic and electrical devices, computer technology, etc. have opened up vast new possibilities for mirrors and their supports.

DISCUSSION

RULE: I understand you are now using a lever system for the radial support on the 150" and it is push-pull?

PEARSON: Yes. When we originally thought of supporting the mirror with a push-pull system there were some people who were against bonding on to the mirror. Therefore, we designed a counterweighted lever system for the hole edge (push only) and another lever system for the outside edge (push only). We showed through analysis that 50% of the weight carried by the outer edge system and 50% on the hole system was a very good support; in fact, 50-50 was about optimum. When the decision was made to bond pads onto the mirror edge, we just removed the hole supports since the counterweights were the correct size for a push-pull support system at the outer edge.

RULE: Have you looked further into the bonding of the support to the glass? There was some area in thermal effects which were discussed in the last conference (Symposium on Mirror Supports, Tucson 1966) which were never quite resolved.

PEARSON: The bonding study was made by Dilworth, Secord, Meagher and Associates, Ltd. We bond on four small Invar pads for each of the 24 supports. These have a tie-in point with an H-shaped plate. The four areas are an attempt to get away from a highly localized load. All pads are Invar, and Invar and quartz have close thermal expansion coefficients.

SCHWESINGER: You mentioned a light weight mirror with 70% weight reduction. Could you briefly describe its structure?

PEARSON: It was produced by Owens Illinois and made of Cer-Vit. You start with a solid mirror, a plug is taken out and cleaned up and then they come in and machine out cavities. The cavity is of hexagonal shape with a wall thickness of about one quarter of an inch.

SCHWESINGER: Is the figure of 70% calculated or measured?

PEARSON: The measured weight was about 490 pounds, and the calculated weight was reasonably close to that. It is a machining process that can be controlled very well.

HERATY: It was about 67% lightweighted, and weighed originally about 1490 pounds.

PEARSON: There is a problem with the light-weight mirror when it is vertical, particularly around the supports. We are finding out by computer analysis that the top surface deflections due to its own weight are usually larger (peak to peak) than of a solid mirror of the same size. The reason is that most of the deflections occur around the support points so you try to build as good, if not a better support system for the lightweight as you do for a solid. You pay extra for the usual lightweight; the cost of the lightweighting was about 40% of the blank cost for our f/8 secondary and was about 200% of the blank cost for the 50-inch primary. So you are paying quite a penalty for that additional light-weighting and then you may still

WEDNESDAY, MARCH 3

MORNING SESSIONS

Chairman: J. B. Oke

A NOTE ON TESTING PRIME FOCUS CORRECTORS

S.C.B. Gascoigne
Mount Stromlo and Siding Spring Observatories

Planning for the Anglo-Australian Telescope calls for the construction of three prime focus correctors, with main properties as follows:

Corrector	Field Diameter	Wavelength range (nm)	Diameter of largest element
Aspherical plate	7 - 10 arc min	300 - 1000	13.8 in.
Doublet	25	365 - 850	10.0
Triplet	60	380 - 600	17.9

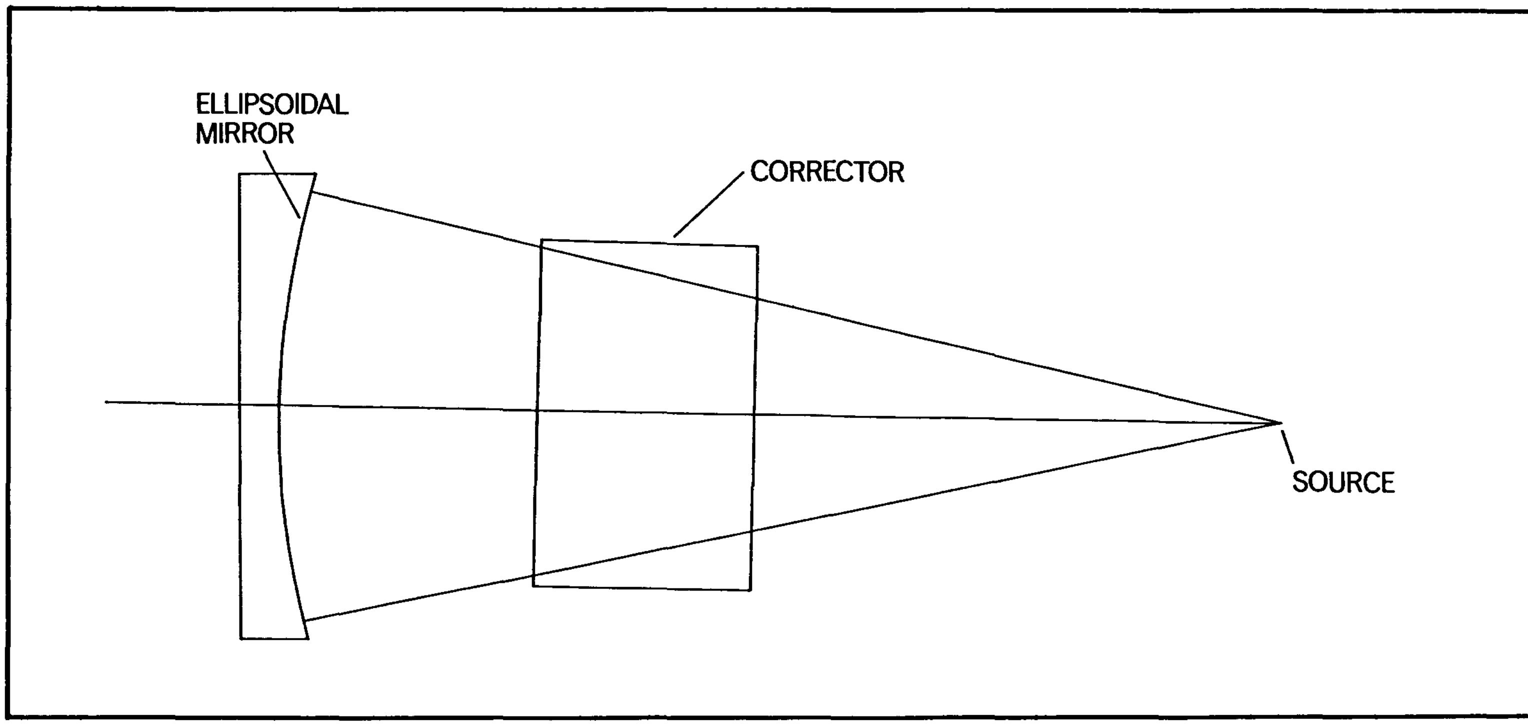
They have been designed by Wynne. The aspherical plate is intended as a minimum-glass corrector for prime-focus instrumentation. The correctors will be completed before the telescope, so that the problem of testing them arises, especially in the case of the single plate, where testing is an integral part of the manufacturing process. This plate presents an unusual problem, in that it has the same shape but is of opposite sign to a Schmidt plate (in our case, an f/2.5 Schmidt plate). The surfaces of the doublet and triplet are spherical and can be made by standard methods.

The only really satisfactory way of testing correctors is with the telescope for which they have been designed. Failing this, they can be tested on-axis with an arrangement like that shown in the figure. This is not a test of the design, but it does enable us to check whether most of the manufacturing tolerances have been met (all of them in the case of the aspherical plate). The test requires an auxiliary mirror which, seen from its centre of curvature has the same spherical aberration as the primary at its prime focus. To the third order one can show without difficulty that this requires

$$(1 + b_1)\, f_1 = 8 b_a f_a$$

where the subscript 1 refers to the primary, a to the auxiliary, and b has its usual meaning as asphericity coefficient. If the primary is a hyperboloid, a good approximation in most cases, the higher order terms will agree closely.

In our case $1 + b_1 = -0.1733$, $f_1 = 500$, and $b_a f_a = -10.84$, so that the auxiliary mirror is an ellipsoid. Choosing $f_a = 25$ inches as a convenient focal length, the diameter will be about 16 inches, and the eccen-



Auto-collimation test for prime focus correctors.

tricity 0.658 ($e^2 = -b_a$), implying foci at conjugate distances 30.2 and 145.9 inches. The ellipsoid will be about 23 wavelengths aspherical. It does not need to be so large as to accommodate all of the largest corrector - an on-axis test with the full beam will be sufficient. The figuring of a mirror to these specifications is a non-trivial but not a major optical problem. problem.

DISCUSSION

WILSON: I find your method of testing extremely interesting. We test Schmidt plates at Carl Zeiss with a similar arrangement but we usually use a spherical mirror and a compensation system or a null-system and I am wondering whether you have considered such a method here. One could use a spherical mirror, and then a null-system to correct the aberration. If you use an aspheric mirror to produce your null-system, which is your method essentially, then you have to have a null-system to test your mirror. I am wondering whether the direct method of a null-system would not be easier in the end.
GASCOIGNE: We did consider this in fact, although not at any great length. The ellipsoid has the very convenient property that it can be tested at the conjugent focii. We used various arrangements and this on the whole seemed to be the more economical.
WILSON: That seems to be a most elegant way of doing it.
BROWN: We looked in some detail at the costing of alternative test methods of this sort for the AAT correctors, and we concluded that if you already had a suitable test sphere of about the right size, it was marginally cheaper to use this and build yourself some form of compensator to do this sort of testing. But if you did not, then it was cheaper to start from scratch, make your ellipsoid, test at its own conjugents and use this. It is a delicate balance.

CONTROLE PAR SPHEROMETRIE DES GRANDES SURFACES ASPHERIQUES

J. Espiard
REOSC

INTRODUCTION

Les miroirs des Télescopes Astronomiques construits aujourd'hui ont à la fois un grand diamètre et une longueur focale relativement courte. De plus, la méridienne nécessaire à la réalisation de l'aplanétisme de l'ensemble instrumental s'éloigne plus du cercle que ne le fait la parabole. La "déformation" atteignant ainsi de nombreuses dizaines de microns, il est très difficile de l'obtenir par le seul polissage à partir d'une surface que le travail de douci aurait seulement amené à la forme sphérique. Il est nécessaire de chercher à obtenir au mieux la forme définitive dès le travail au corindon et à l'émeri fin, c'est-à-dire avant que tout contrôle optique soit possible.

Nous décrivons ici la construction et le mode d'emploi de nos sphéromètres, qui permettent de déterminer la forme de la méridienne d'une surface non réfléchissante jusqu'à une fraction de micron, de telle sorte que le premier poli laisse voir seulement des défauts de quelques franges.

SPHEROMETRES

Les SPHEROMETRES R.E.O.S.C. sont des sphéromètres rectilignes, c'est-à-dire que les trois touches sont alignées, ce qui simplifie beaucoup les mesures et les calculs.

Ils sont constitués d'un corps tubulaire en acier, de section rectangulaire, pour les plus grands, et d'un corps en acier taillé dans la masse pour les plus petits.

Ils comportent à une extrémité une bille d'acier aisément remplaçable; au milieu une vis à pas fin munie d'un frein énergique; à l'autre extrémité un micromètre de mécanicien ou un palpeur électrique selon la précision désirée (voir Fig. 1 et 2).

Ils sont munis de 2 vis de calage du côté de la bille, et d'une seule du côté du palpeur. Ces trois vis munies de touches en rilsan permettent de poser l'instrument sans heurt sur la surface optique. Ils sont en outre munis d'un contrepoids latéral afin que pendant la mesure le sphéromètre s'appuie

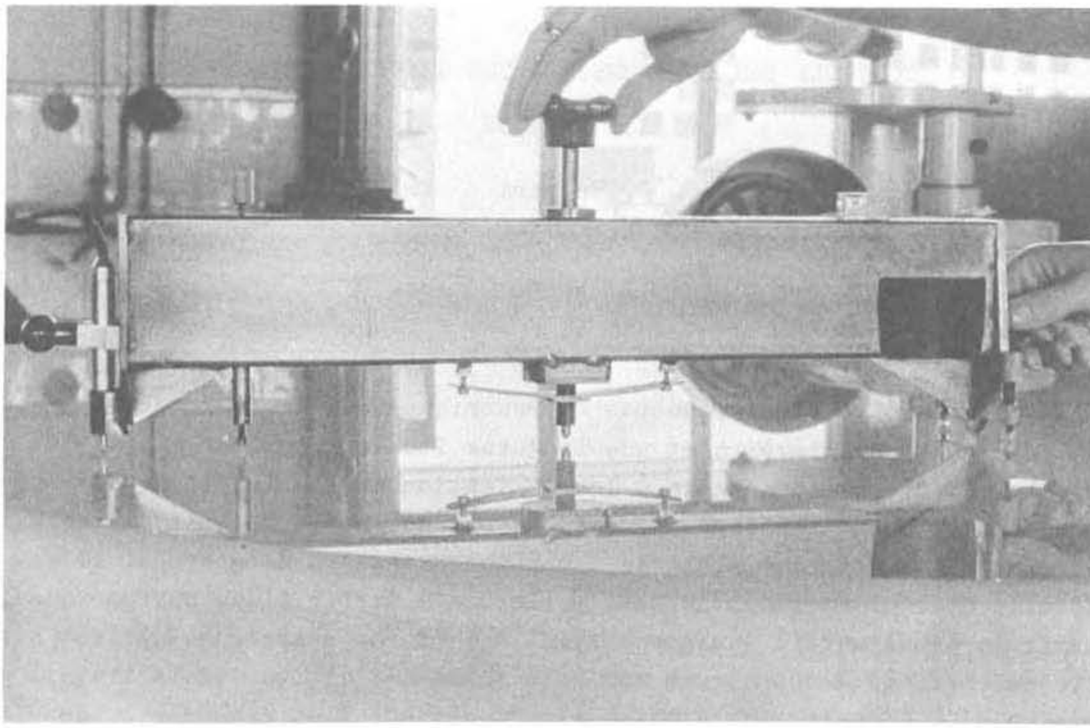


Fig. 1

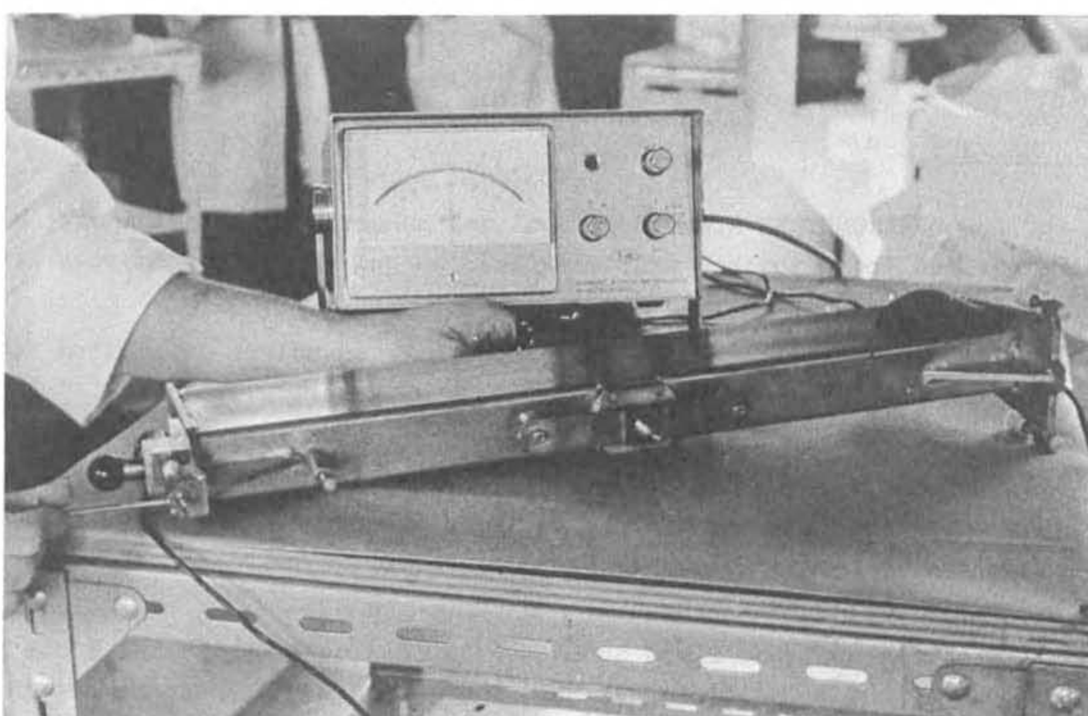


Fig. 2

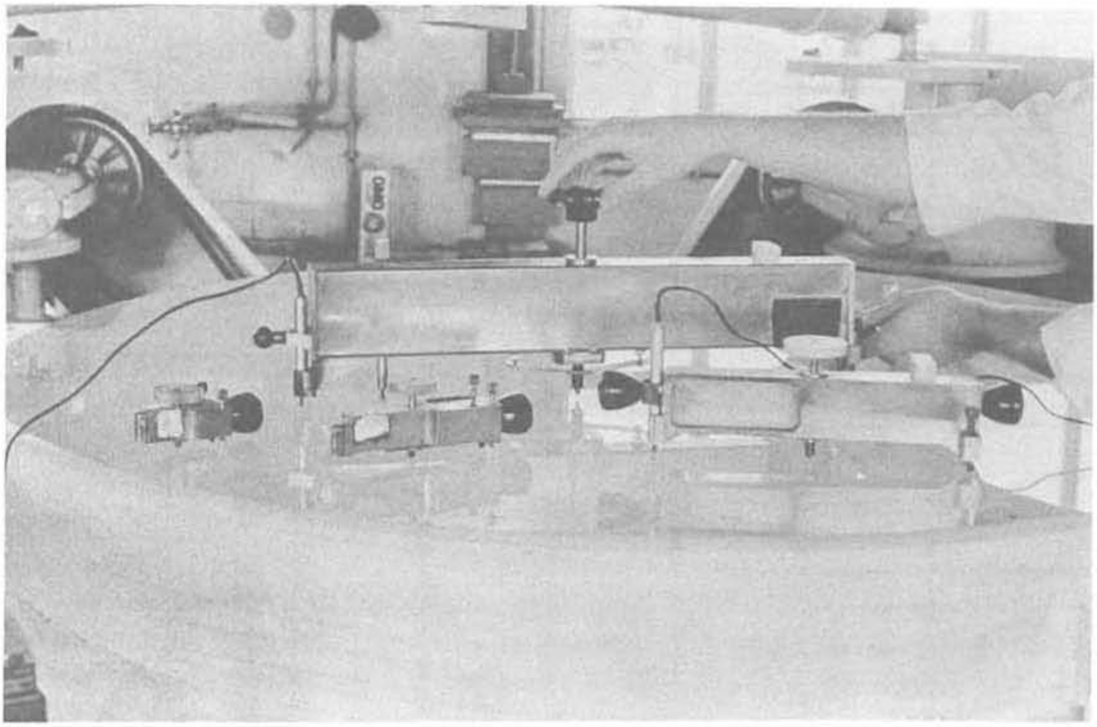


Fig. 3a

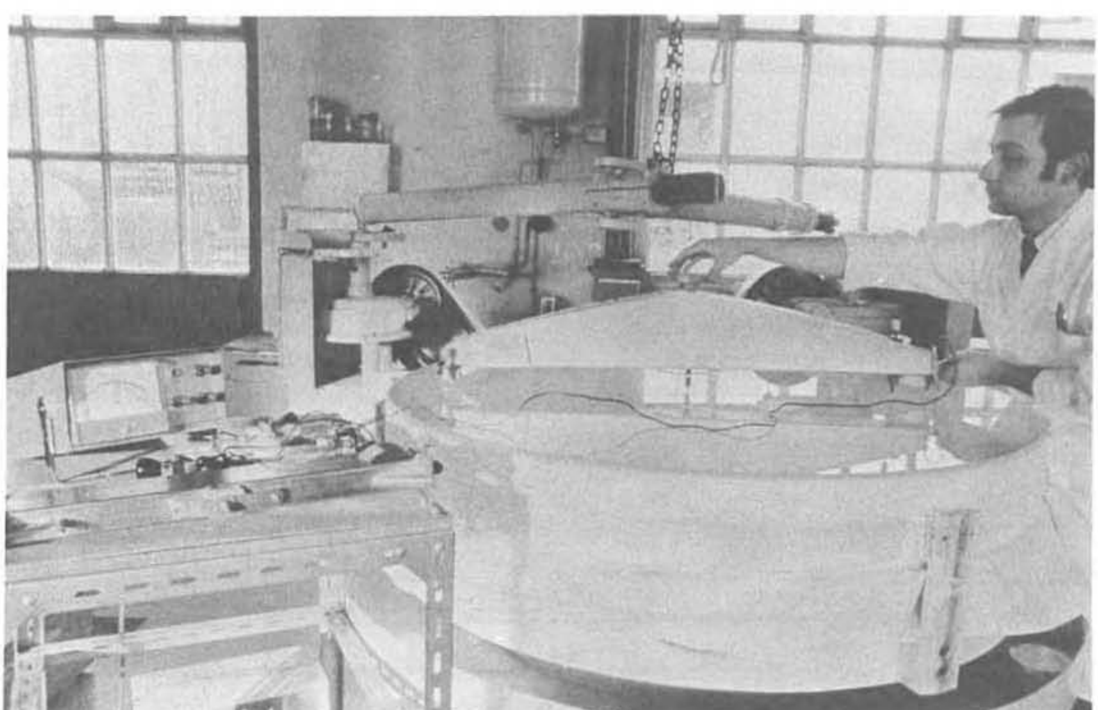


Fig. 3b

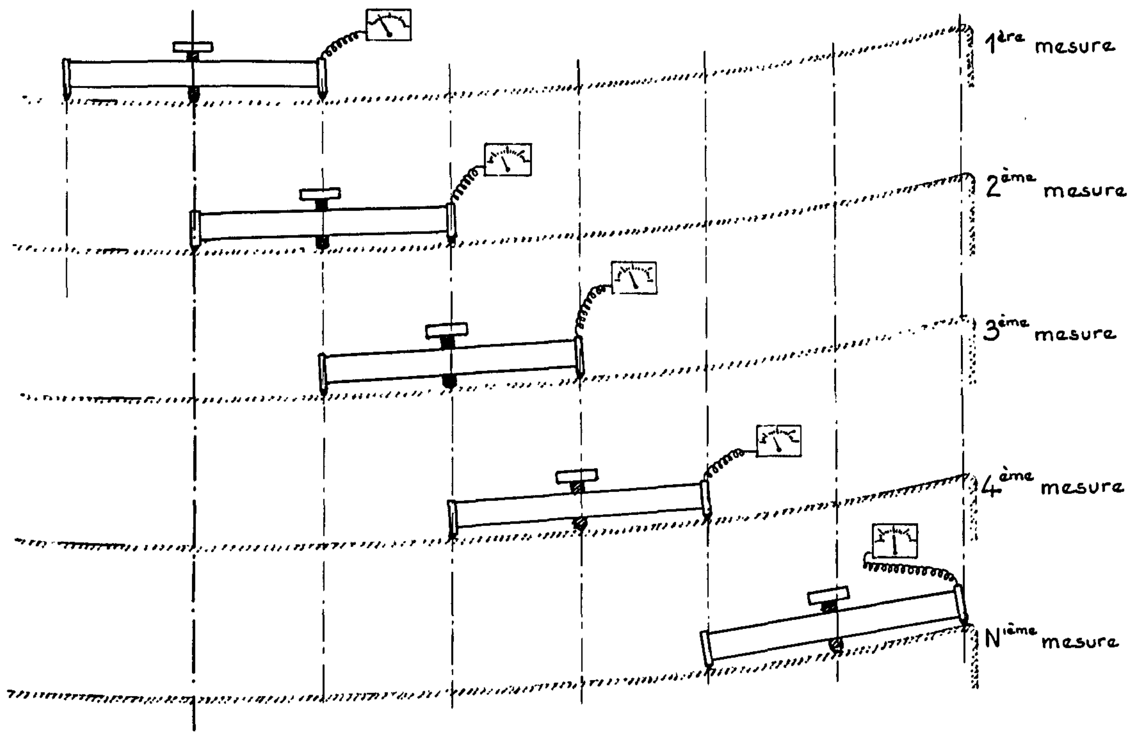


Fig. 4 Mode opératoire.

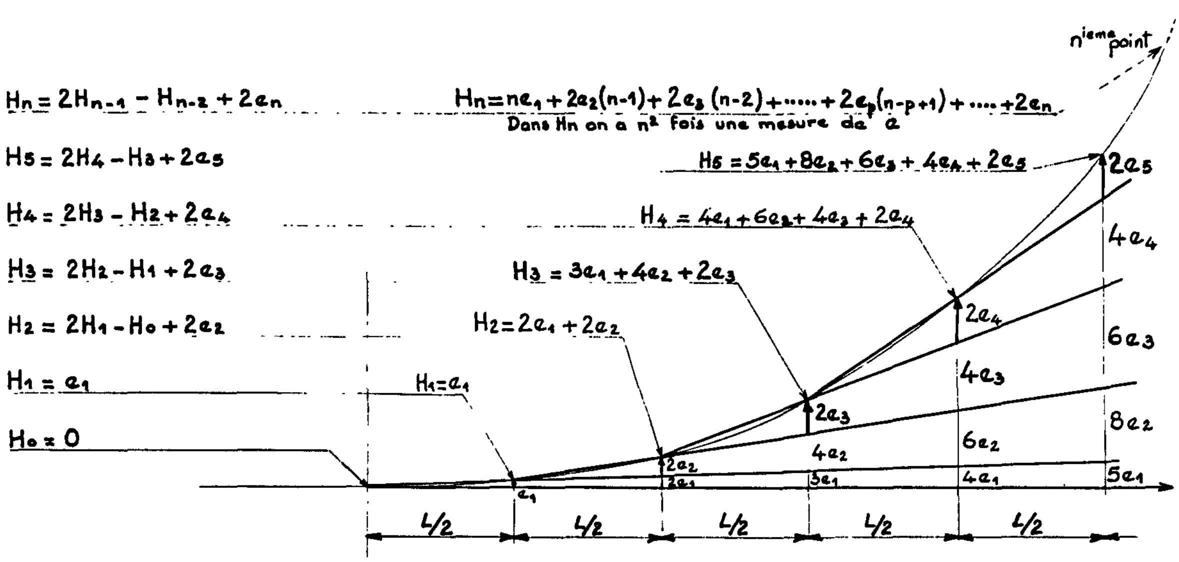


Fig. 5 Représentation schématique du calcul du profil de la surface.

sur la bille, sur la vis centrale et sur la vis de calage latérale du côté du contrepoids, les deux autres vis étant desserrées. Le palpeur n'appuie que faiblement sur la surface. Un niveau à bulle fixé sur le dessus du sphéromètre permet de régler l'aplomb de l'instrument par la manoeuvre de la vis côté contrepoids. Le corps est entièrement recouvert électrolytiquement d'une mince couche de cuivre destinée à empêcher l'échauffement que produirait le rayonnement I.R. issu du manipulateur. Des poignées en matière isolante permettent de les manoeuvrer sans que les mains échauffent par contact.

Notre jeu comporte actuellement des sphéromètres de longueur totale, entre le palpeur et la bille, aux valeurs suivantes: 1 m, 500 mm, 250 mm, 125 mm, 62.5 mm (voir Fig. 3a et 3b).

METHODE DE MESURE

Le SPHEROMETRE ayant été au préalable étalonné sur un plan avec des cales JOHNSON de telle manière que la flèche soit celle de la sphère de référence choisie, on place le sphéromètre une première fois (Fig. 4) sur la surface, la vis centrale coïncidant avec le sommet de cette surface. La mesure donne 2 e, qui est égale à 2 fois la différence H_1 entre la flèche f_s de la sphère et la flèche f_m du miroir mesuré. On a $H_1 = e_1$. On déplace alors le sphéromètre sur un rayon de la surface, pas à pas, à chaque fois d'une valeur égale à sa demi-longueur: on pose par exemple la bille à la place exacte précédemment occupée par la vis, et l'on obtient les valeurs 2 e_1; 2 e_2 etc...

On trace alors (Fig. 5) une représentation graphique simplifiée des différences totales de flèches entre la sphère et la surface en étude en portant en abscisse n fois la demi-longueur du sphéromètre et en ordonnée les valeurs 2 e des différentes mesures suivant la formule de la Figure 5.

On a calculé d'autre part les valeurs 2 e pour la surface théorique et la sphère de référence choisie; on calcule les valeurs H et on trace la représentation graphique suivant le même procédé. Chacune de ces représentations n'est pas rigoureuse, mais la différence entre les deux courbes est d'autant plus conforme à la réalité que cette différence est plus petite.

Si l'on se rapporte aux valeurs de H exprimées en fonction des valeurs de e (Fig. 5) on voit que pour H_n l'erreur sur la mesure des quantités 2 e est multipliée par n^2.

Pour éviter l'accumulation de ces erreurs nous choisissons pour commencer le tracé de la courbe (Fig. 6) un sphéromètre suffisamment grand pour n'avoir à le reporter que 2 ou 3 fois, ce qui donne 2 ou 3 points précis. Nous prendrons ensuite le sphéromètre 2 fois plus petit avec lequel on recommencera toutes les mesures. Ce sphéromètre n'est pas étalonné directement,

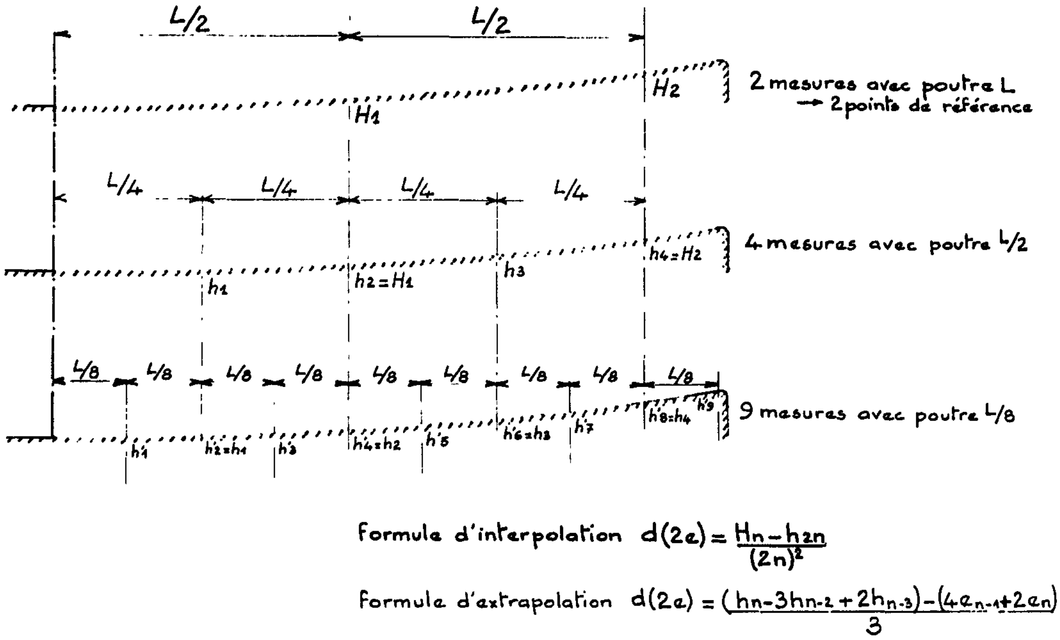


Fig. 6 Représentation schématique d'une série de mesures.

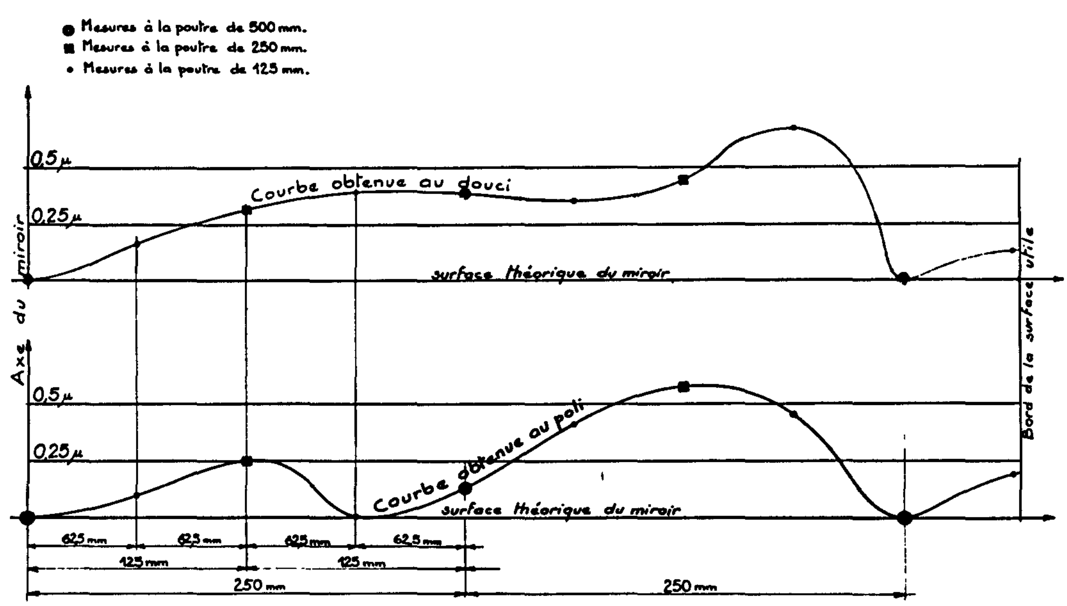


Fig. 7 Miroir Cassegrain-coudé du télescope ESO de 3.6 m. Ecart entre la surface du miroir et la surface théorique.

mais, par la manoeuvre de la vis centrale et par celle du palpeur, on règle celui-ci au zéro lorsque le sphéromètre est placé au centre de la surface. On obtient les valeurs provisoires 0 ; e'_1 ; e'_2 ; e'_n et on calcule les valeurs définitives en utilisant les formules d'interpolation ou d'extrapolation de la Fig. 6.

La précision obtenue avec le palpeur électrique est de 0.2 μ pour les surfaces jusqu'à 1.3 mètres de diamètre, et elle est encore supérieure au micron pour les surfaces de 3.6 mètres de diamètre. Les mesures demandent cependant pour arriver à ces précisions d'être effectuées avec grand soin.

Si le rayon de courbure au sommet de la surface théorique varie sensiblement, c'est-à-dire si la focale du miroir bouge, les différences des flèches entre la nouvelle sphère de référence et la nouvelle surface théorique varieront très peu. On peut donc changer la sphère de référence, c'est-a-dire ajouter ou retrancher quelques microns aux flèches mesurées sur la surface réelle obtenue sans changer sensiblement les ordonnées de la courbe représentant les déformations de la surface par rapport à la nouvelle sphère de référence et chercher ainsi quelle est la surface théorique satisfaisant à la déformation voulue qui coïncide le mieux avec la surface obtenue.

EXEMPLE PRATIQUE D'EXPLOITATION DES MESURES

Les différentes formules précédentes et leur enchaînement se programment aisément sur un calculateur électronique OLIVETTI P102, les résultats intermédiaires étant stockés et relus sur bande perforée. Le programme se compose de quatre séquences, la dernière étant celle qui est appelée pour la lecture des résultats. La liste des instructions de programme est en annexe.

Pour un contrôle du miroir de 3.66 mètres de diamètre, en utilisant les poutres de 1 mètre, 0.5 et 0.25 mètre, nous procédons comme suit: (voir Table 1).

En ayant calculé auparavant la valeur des quantités H correspondant à la méridienne théorique, il est facile d'obtenir directement les différences entre la surface du miroir en usinage et la surface parfaite.

Il serait possible d'utiliser en plus la poutre de 125 mm qui donnerait un point tous les 62.5 mm en combinant de manière différente les séquences de calcul.

La Fig. 7 représente l'état actuel contrôlé par cette méthode du miroir convexe de 1.20 m de diamètre du foyer Cassegrain-coudé du Télescope E.S.O. de 3.66 mètres.

TABLE I

Séquence à appeler	Poutre utilisée	Mesures à introduire au clavier
V	1 mètre	2 e_1
		2 e_2
	0.5 mètre	2 e_1
		2 e_2
W	0.5 mètre	2 e_3
		2 e_4
Y		2 e_5
V	0.25 mètre	2 E_1
		2 E_2
W		2 E_3
		2 E_4
		2 E_5
		2 E_6
		2 E_7
		2 E_8
		2 E_9
		2 E_{10}
Y		2 E_{11}
Z LECTURE DES RESULTATS.		

Nous obtenons ainsi un point de la méridienne tous les 125 mm.

olivetti programma ~~101~~ 102
calculateur électronique

Titre	Controle à la poutre			
Date (m, a)	Code (classe)		Nbre de cartes	Nbre d'instructions
			1	72

INSTRUCTIONS DE PROGRAMME

CARTE N° ______

REG. 1				REG. 2				REG. F				REG. E				REG. D			
1	A	V		25	D		↑	49	B	/	↕	73				97			
2	S			26	A	S		50	D		↓	74				98			
3	B	/	↑	27	C		↑	51	B	/	+	75				99			
4	S			28	C	/	↓	52	C	/	−	76				100			
5	B	/	↓	29	A	/	↑	53	B		+	77				101			
6			+	30	D	/	↑	54	B		+	78				102			
7	A	S		31			X	55	A		←	79				103			
8	B		↑	32	C		+	56	C		←	80				104			
9			↕	33	B		−	57	C	/	↕	81				105			
10			−	34			−	58	C		↓	82				106			
11	A	/	↑	35			−	59	B		↕	83				107			
12	D	/	↑	36	D	/	↕	60	W			84				108			
13			:	37	B	/	↓	61	A	Y.		85				109			
14	B	/	↕	38	D		+	62	S			86				110			
15	B	/	+	39	A		+	63	B	/	↓	87				111			
16	A	/	↑	40	S			64			+	88				112			
17	D	/	↑	41		•	+	65	C	/	−	89				113			
18			:	42	B	/	+	66	B		+	90				114			
19	A		←	43	D	/	↕	67	B		+	91				115			
20	C	/	↕	44	D	/	−	68	A		←	92				116			
21	B		←	45	A	/	↑	69	Y			93				117			
22	V			46	D	/	↕	70	A	Z		94				118			
23	A	W		47			:	71	◊			95				119			
24	S			48	B	/	+	72	Z			96				120			
REG. 1				REG. 2				REG. f/				REG. e/				REG. d/			

CONTENU DES REGISTRES

Registre	Contenu
M	
A	
R	
b/	Stockage
B	id
c/	id
C	id
d/	id
D	id.
e/	
E	
f/	Instructions
F	id.

CONSTANTE SUR ~~CARTE~~ BANDE				CONSTANTE SUR CARTE			
H du point de reference	←		↕				↑
			↑				↑
			↑				↑

DISCUSSION

WLERICK asks until what stage in the figuring of a mirror the spherometry is performed.
ESPIARD answers that this is done until the surface is close enough to the final shape to make an optical control worthwhile. The spherometry greatly helps in having as little material as possible to be removed in the polishing. The method has been applied to the main and the secondary mirror of the ESO 3.6 m telescope, and is presently in use for a 1.50 m f/3 Ritchey-Chrétien mirror for the Observatoire de Bologne. It has also been used for a 1 meter mirror for Torino, and so far, all results have been very satisfactory.
RIGHINI wants to know along how many meridians the measurements are made.
ESPIARD replies that generally only one meridian is measured. By various methods (Hartmann-test etc.) it has been proved that the rotational symmetry is highly perfect so that there is no astigmatism.
BLAAUW wonders why the measurements are only made along one meridian, when they are so comparatively fast and easy to perform.
ESPIARD answers that successive measurements are made at different meridians and that so far, not the slightest astigmatism has been found. Therefore, it is really not necessary to measure more than one meridian.
FEHRENBACH asks about the obtainable accuracy.
ESPIARD mentions that 0.1 micron can be reached when the measurements are made with great care. It demands much of the optician, but many people in the optical shop have already acquired this qualification.

SURFAÇAGE DU MIROIR E.S.O. DE 3.654 METRES DE DIAMETRE RITCHEY-CHRETIEN F/3.

A. Bayle
REOSC

A - TOUR EMPLOYE

Le tour d'optique étudié et construit par nous-mêmes comporte un plateau de 3.50 m de diamètre mû par un moteur à courant continu de 10 CV qui permet une gamme très étendue de vitesses.

Cette machine peut se monter en ébaucheuse au moyen d'une rectifieuse (Fig. 1), ou en polisseuse au moyen de deux excentriques, d'un bras et d'une bielle. Chacun des excentriques est mû par un moteur de 5 CV; un variateur de vitesses relie chaque moteur au réducteur correspondant (Fig. 2).

Les bras s'escamotent facilement au moyen de deux palans pour libérer le miroir lors des contrôles.

B - EBAUCHAGE

1. - Rectification à la meule diamantée de la surface. La rectifieuse est guidée électriquement par un calibre C (Fig. 3).
2. - Rectification du trou central (Fig. 4).
3. - Débordage (Fig. 5).

C - REPARATION D'UN IMPORTANT DEFAUT DE LA MATIERE

La matière présentait un important défaut sous la forme d'un trou irrégulier de 15 cm de profondeur et de 14 cm de dimension latérale maximum (Fig. 6).

Nous avons d'abord creusé dans le miroir une surface concave presque hémisphérique, à la meule diamantée, au moyen d'une rectifieuse spécialement construite. (Fig. 7, 8 et 9)

Nous avons poli cette surface à la teinte plate, contrôlée au calibre interférentiel (Fig. 10).

Nous avons taillé dans la même silice fournie en même temps que le miroir par CORNING un hémisphère convexe, avec la même précision.

Cette pièce convexe s'ajustait dans le miroir avec une précision d'une frange, le contact se faisant au bord. Elle a été collée solidement à la résine synthétique STRATYL dont l'épaisseur après pression n'excédait pas $\frac{1}{100}$ mm.

La surface ainsi reconstituée du miroir n'accuse aucun autre défaut qu'un liseré circulaire microscopique qui apparaît sur les clichés HARTMANN extra-focaux grâce au phénomène de diffraction; l'examen interférentiel de la surface, ainsi que l'examen à la méthode de FOUCAULT, ne révèlent rien. (Fig. 11)

D - DOUCI DE LA SURFACE

La mise en courbure exacte et le douci ont d'abord été effectués avec un outil pleine taille (Ø 3.60 m) rigide et léger en bois de pin, tel que nous les fabriquons couramment, puis avec un outil de diamètre 2.60 m (Fig. 12 et 13).

Nous préférons le bois au métal à cause de la légèreté et de la faible dilatation thermique de ce matériau. La température de la surface de l'outil en contact avec le miroir varie notablement pendant les deux heures que dure environ une séance. Mais pendant ce court laps de temps, les déformations permanentes du bois qui apparaissent en quelques semaines no sont pas gênantes.

L'outil est solidement articulé au bras de la machine au moyen d'un triangle d'acier et de trois poutrelles. Les choses sont organisées de manière que les déformations thermiques de l'acier ne contraignent pas l'outil.

Pour obtenir de bonnes surfaces, nous reglons la pression de l'outil sur le miroir à 10 ou 12 gr au cm^2. L'outil rigide pleine taille avec son support en acier pèse 2.200 kg. Il faut donc déjà l'alléger, ce que nous faisons au moyen d'un cylindre pneumatique relié par un tuyau souple de forte section intérieure à un réservoir de grande capacité (Fig. 14).

Le contrôle de la surface doucie a été effectué suivant notre méthode et nos sphéromètres, que nous décrivons d'autre part.

E - POLISSAGE

Le polissage a été effectué à l'aide d'un outil pleine taille (3.654 m) de souplesse convenable, et toujours construit en bois de pin.

Nous étudions ce type d'outil (Fig. 15 et 16) de manière que sa courbure puisse suivre la courbure asphérique du miroir lors de courses relativement faibles : de l'ordre de 50 cm maximum pour le miroir de 3.654 m. Le centre de l'outil est plus épais que le bord qui présente, d'autre part, un renfort annulaire pour éviter le festonnage de la surface. Un second anneau, au demi-diamètre, permet au bras de la machine de le saisir solidement par l'intermédiaire du dispositif déjà décrit. Le poids de cet outil et de son armature est de 1.200 kg, de sorte que le cylindre pneumatique n'a plus qu'à soulager le poids des bras de la machine.

L'outil est toujours empêché de tourner, au moyen d'un câble de nylon, le miroir tournant lentement en dessous.

La mise en forme exacte de la surface s'obtient en faisant des dégarnis convenables (Fig. 17), axés sur le diamètre dont la translation est la plus faible : 6 à 7 cm maximum, donnés par le second excentrique de la machine.

L'extrême bord (moins de 10 cm de largeur) qui présentait un relevé d'une demi-frange, alors que tout le reste de la surface était bonne, a été corrigé à la main. (Fig. 18)

Les principales étapes de l'évolution de la surface d'onde sont représentées par les courbes (Fig. 19) obtenues par HARTMANN au moyen de l'écran en croix (Fig. 20), qui s'applique exactement sur la surface du miroir. L'analyse de la qualité de la surface telle qu'elle apparaît sur le plateau de la machine est représentée (Fig. 21).

F - TOUR DE CONTROLE

La tour de contrôle construite au-dessus de la machine, comporte une paroi extérieure en maçonnerie, et un cylindre intérieur en acier garni intérieurement d'un revêtement calorifuge. Le cylindre d'acier se continue par une jupe en tissu plastifié (Fig. 22), et qui vient entourer le bord du plateau de la machine lors des contrôles. Cette jupe se relève en quelques instants au moyen d'un treuil (Fig. 23).

Les radiateurs de chauffage, en grand nombre, sont chacun munis d'un régulateur thermique, et réglés de manière que la température augmente régulièrement du bas en haut. Un calcul simple permet de voir qu'un gradient positif de bas en haut et au total de quelques degrés stabilise les couches d'air et ne provoque aucune aberration sphérique gênante.

Des ventilateurs brassent l'air dans le hall et dans chaque étage de la tour, autour du cylindre d'acier.

La jupe est à double paroi et organisée de manière que l'air que l'on souffle continuellement entre les deux parois par le bas en quantité convenable s'élève en suivant une spirale destinée à parfaire l'égalité de température dans chaque plan horizontal.

Le cylindre en acier est de même garni extérieurement d'un tube de nylon à paroi mince, enroulé en spirale, et également parcouru par un léger courant d'air (Fig. 24).

G - TUNNEL DE CONTROLE

L'essai du miroir dans son barillet peut se faire axe vertical dans la tour, et axe horizontal dans le tunnel construit sous l'atelier.

La Fig. 25 montre le miroir et son barillet, axe horizontal, dans notre tunnel de contrôle, et les photos suivantes le transport du miroir dans son barillet, le dégagement du miroir à l'aide d'un anneau de manutention, et son transport sur le plateau de la machine.

NOTE TECHNIQUE SUR LES CRITERES DE PERFORMANCE DU MIROIR CONCAVE DE 3.66 METRES DE DIAMETRE DE L'EUROPEAN SOUTHERN OBSERVATORY

En plus du tracé de la surface d'onde du miroir correspondant à la meilleure sphère de référence, nous avons adopté trois critères supplémentaires pour juger de la qualité de la surface:

1 - Calcul de la valeur relative du maximum central de la tache de diffraction par rapport à la tache d'Airy d'après la méthode du Professeur MARECHAL.

2 - Calcul de la constante de LEHMAN d'après DANJON et COUDER.

3 - Tracé de la concentration de l'énergie dans l'image d'un point en ne tenant compte que des phénomènes géométriques.

---

1 - CALCUL DE LA VALEUR RELATIVE DU MAXIMUM CENTRAL DE LA TACHE DE DIFFRACTION:

Si nous appelons Δ la valeur de l'écart normal de la surface d'onde et de la surface élémentaire du miroir, la valeur relative du maximum central est donnée par:

$$D = 1 - \frac{4\pi^2}{\lambda^2} \left[\iint \Delta^2 \, ds - \left(\iint \Delta \, ds \right)^2 \right]$$

Dans le but de chercher la meilleure mise au point nous faisons varier la valeur du rayon de la sphère de référence de telle manière que la valeur moyenne de Δ que nous appelons $\overline{\Delta_o}$ soit nulle. On détermine une valeur $\overline{\Delta_o^2}$ qui est la différence entre la moyenne des carrés et du carré de la moyenne de Δ , moyenne calculée sur la surface du miroir.

La valeur de D est alors située entre les deux valeurs données par les expressions suivantes:

$$D = 1 - \frac{4\pi^2}{\lambda^2} \overline{\Delta_o^2} \quad \text{et} \quad D = \left(1 - \frac{2\pi^2}{\lambda^2} \overline{\Delta_o^2}\right)^2$$

2 - CALCUL DE LA CONSTANTE DE LEHMAN

Ce calcul fait intervenir les pentes de la surface d'onde dont on optimise les valeurs en cherchant le plan de meilleure mise au point, c'est-à-dire le plan donnant une image dont la dimension géométrique est minimum.

La constante de LEHMAN que nous calculons prend en considération la valeur absolue de chaque pente et nous en faisons une moyenne pondérée, le poids donné à chaque valeur de la pente étant égal à la surface de la couronne du miroir considérée.

Si S_i est la surface de la couronne ayant $|U_i|$ pour pente on a

$T'' = 206.265 \dfrac{\Sigma S_i \, |U_i|}{\Sigma S_i}$; T étant exprimé en seconde d'arc.

3 - CALCUL DE LA CONCENTRATION D'ENERGIE

L'énergie reçue par le miroir est proportionnelle à sa surface et il en est de même pour la surface des couronnes S_i considérée plus haut. L'énergie de chaque couronne est dispersée dans l'angle U_i qui n'est autre que le rayon angulaire de la tache géométrique de diffusion.

Comme nous connaissons pour chaque couronne la valeur correspondante de $|U_i|$ nous pouvons dresser, par valeur croissante, la liste de $|U_i|$ en fonction du rapport $\frac{S_i}{\Sigma S_i}$ qui n'est autre que le pourcentage de la surface du miroir.

En choisissant différents intervalles de classe pour $|U_i|$ on peut tracer une série d'histogrammes de la série statistique par exemple en choisissant un intervalle de classe correspondant à la tolérance demandée, ou un intervalle correspondant à la moitié de la tolérance.

Tous ces calculs sont rapidement effectués sur notre ordinateur OLIVETTI, après avoir mis au point les programmes correspondants.

DISCUSSION

WLERICK would like to have further information on the internal structure of the ESO mirror.
BAYLE informs him that it was made of a rather large number of smaller pieces. There are seven principal hexagons, one of these is in the center, and a number of smaller ones at the edges. So far, there have been no problems because of this structure, but the first disk had a large number of bubbles in the surface and was sent back to Corning. It was then covered with a new silica layer with about 40 small bubbles in the surface.
WILSON asks how much the light concentration will be increased when all small holes etc. have been filled out.
BAYLE estimates an increase of about 1%.
WLERICK asks whether the central hole is filled during the polishing.
BAYLE answers that it is, and that a central support is needed for the sphero-meter.
FEHRENBACH asks whether a Hartmann test has been made with the optical axis in horizontal position.
BAYLE replies that this test is being performed at the moment. It looks as if there is a very good coincidence between the vertical and horizontal measurements. There are still a few minor corrections to be made.
SISSON: Have you some opinion on the thermal stability of the disk? How long do you have to wait after polishing it before you can be sure that your test results will be accurate?
BAYLE answers that when the mirror is placed in the bottom of the test tower (cf. Fig. 22), three to four days must pass before the measurements can start.

The mirror surface is at 22°C and the temperature in the tower is 17 - 18°C, and the temperature gradient must be exceedingly stable. He also estimates a period of three to four days for the mirror to return to equilibrium after being polished.

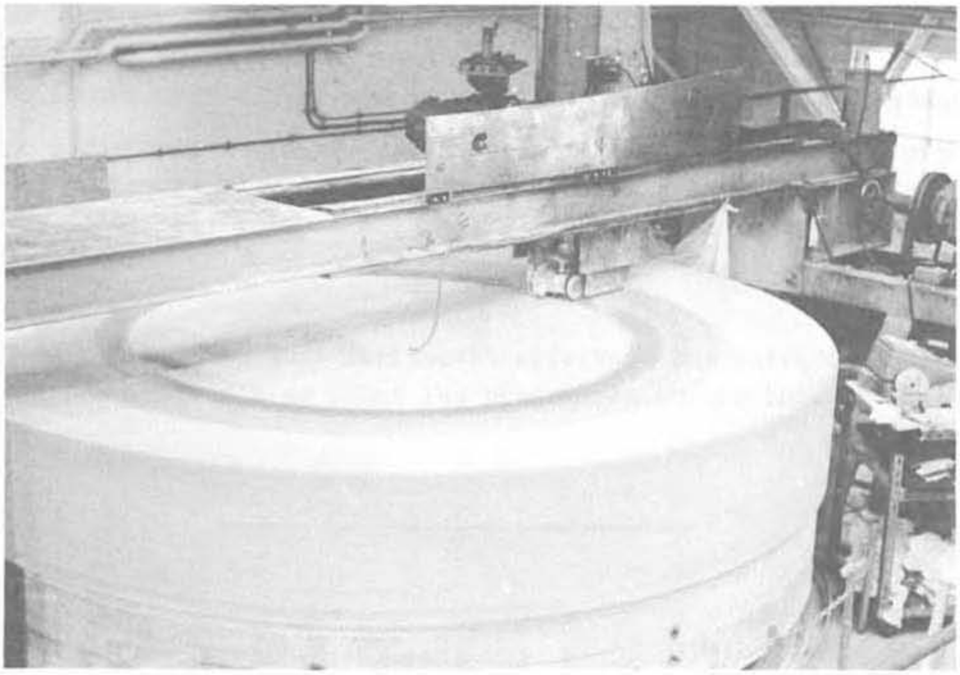


Fig. 1

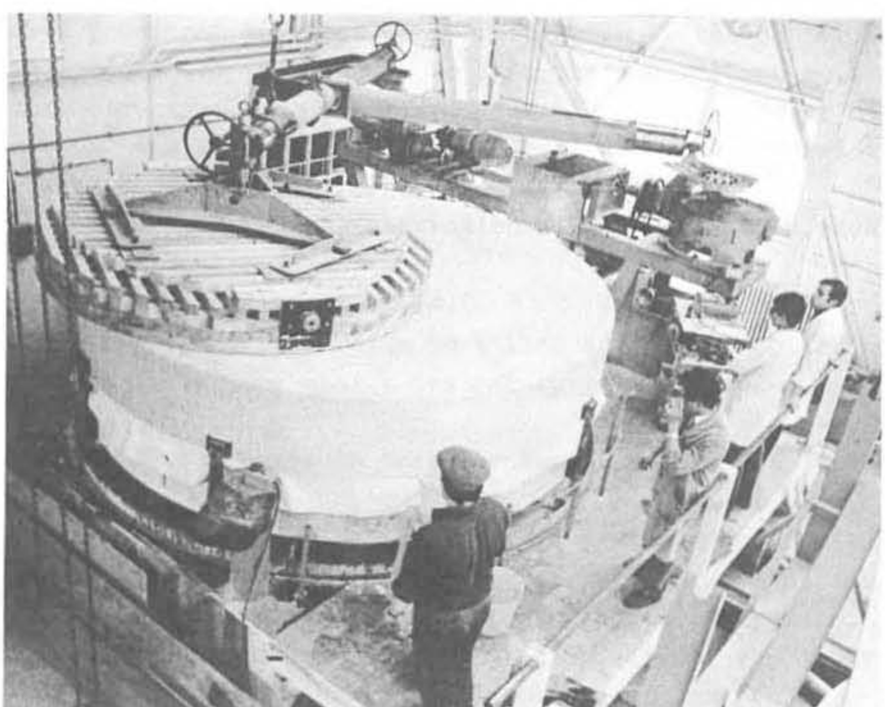


Fig. 2

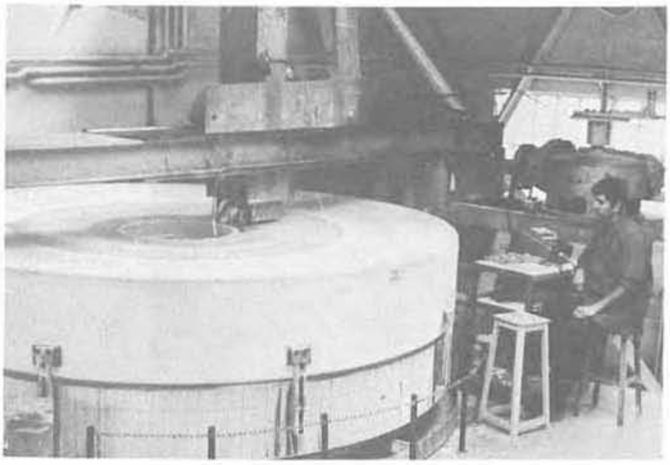
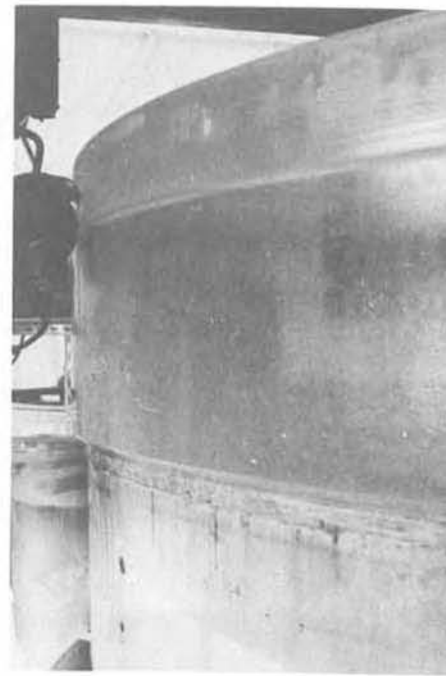


Fig. 3



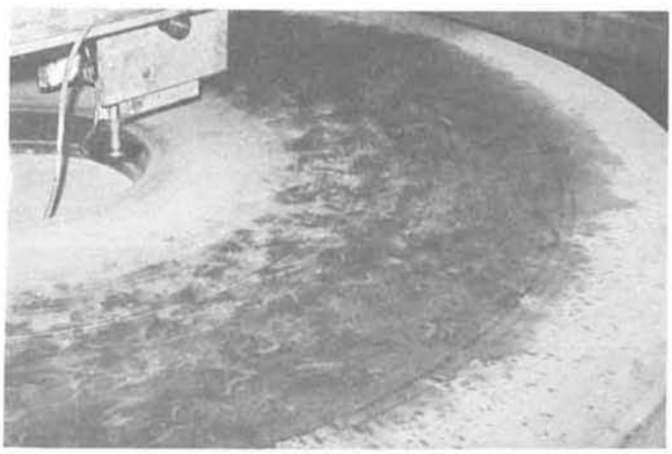


Fig. 5

Fig. 4

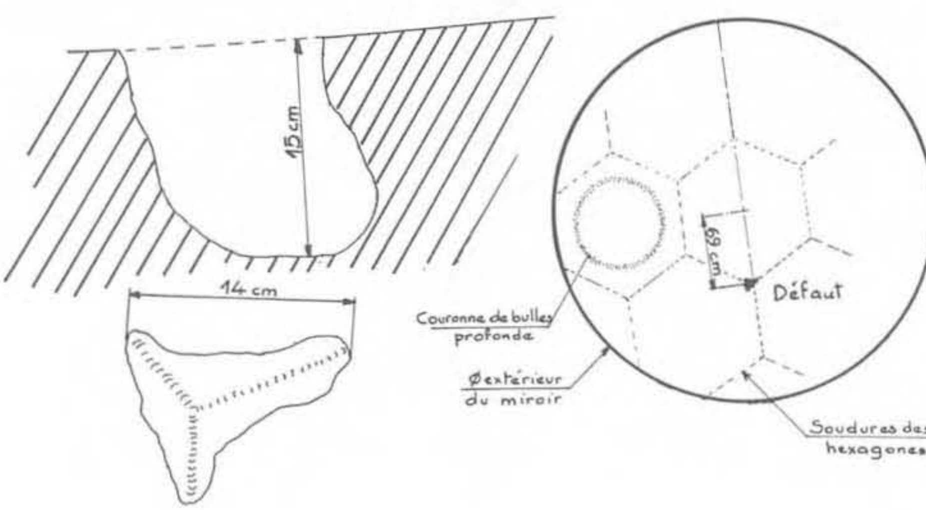


Fig. 6 Forme et position du défaut dans le miroir ESO de 3.6 m.

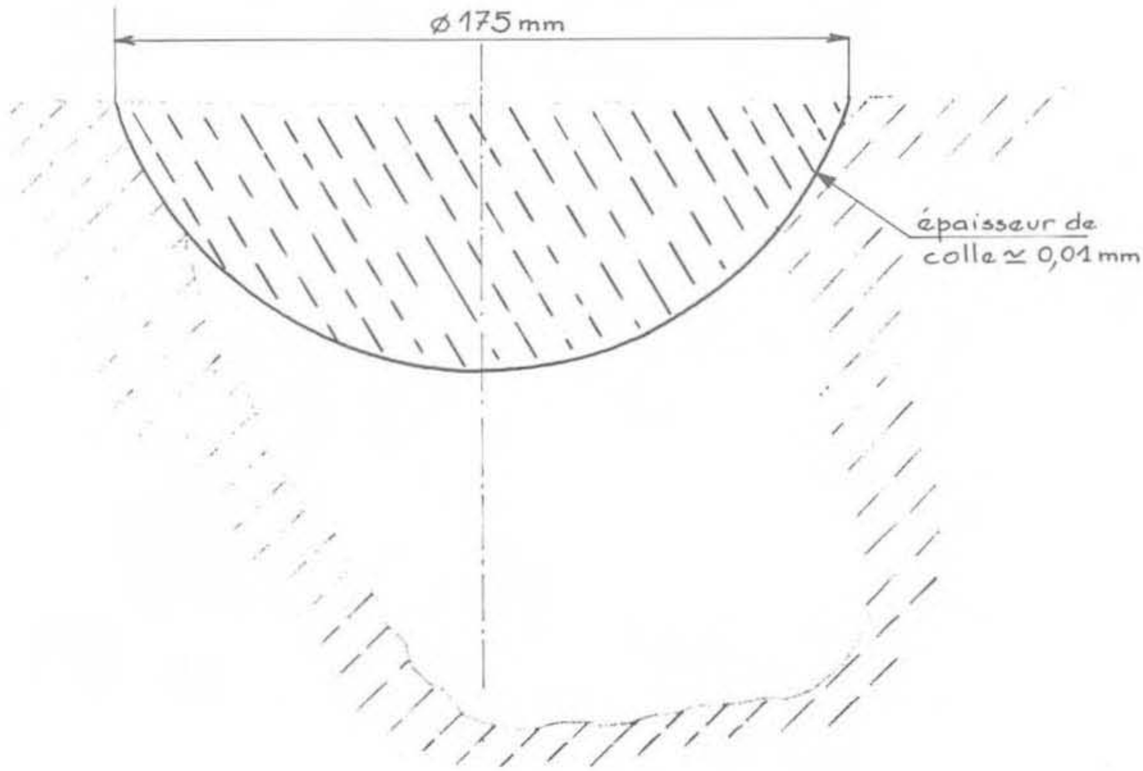


Fig. 7 Rebouchage du défaut du miroir ESO de 3.6 m.

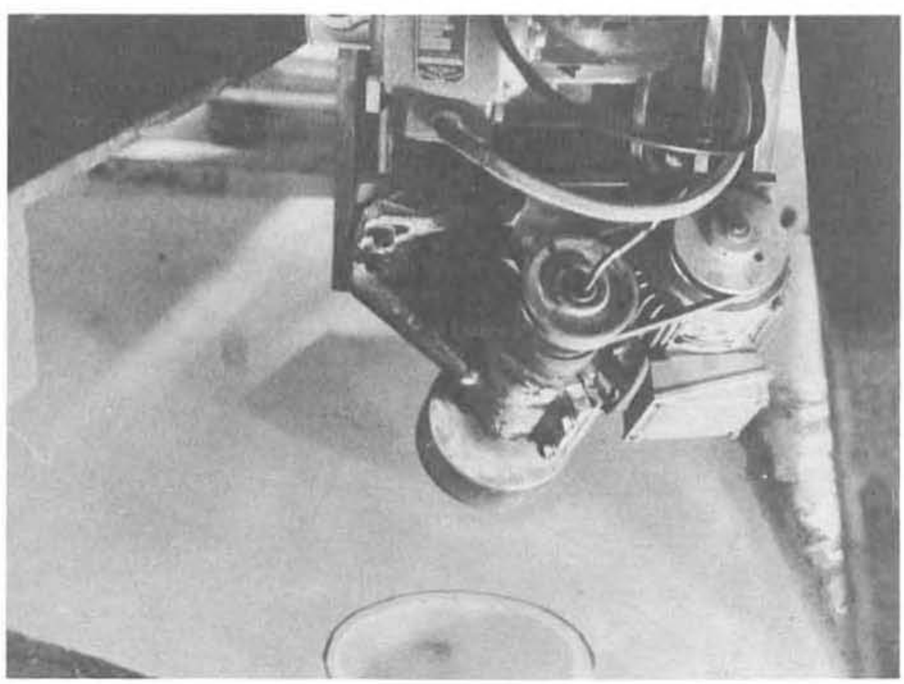


Fig. 8

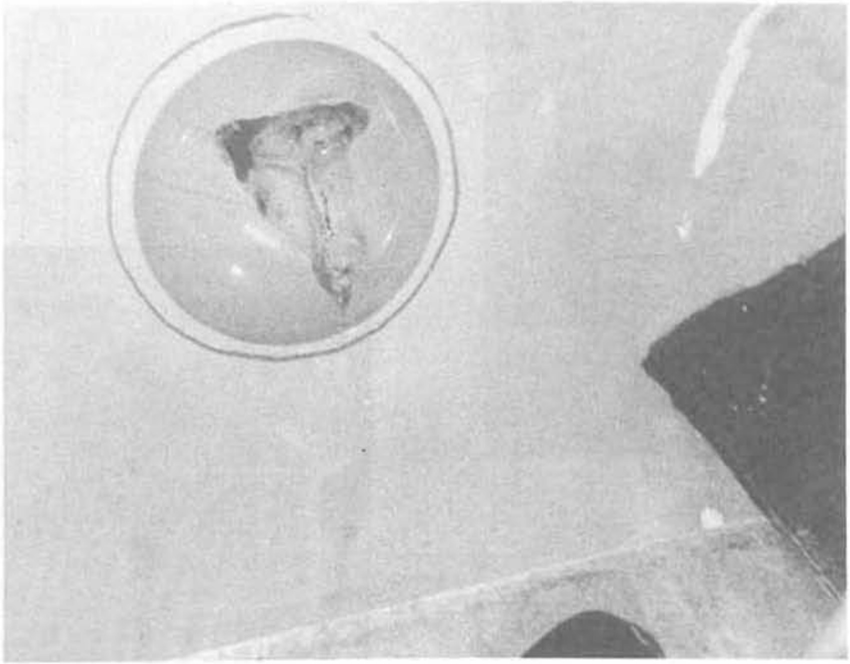
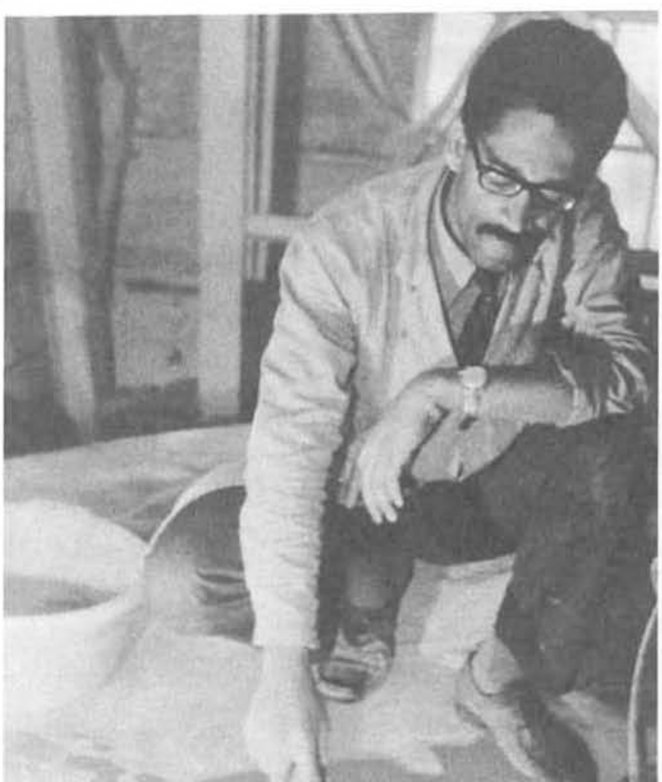


Fig. 9



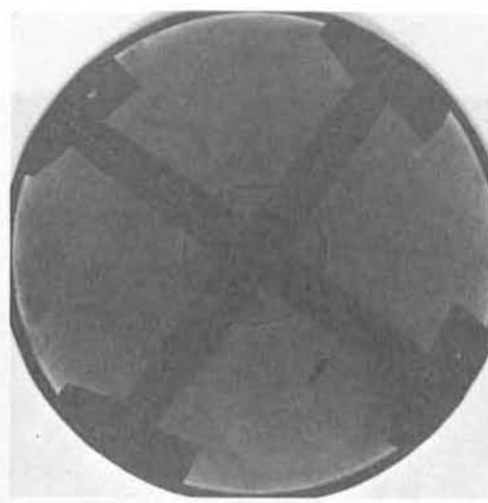


Fig. 11

Fig. 10

Fig. 12

Fig. 13

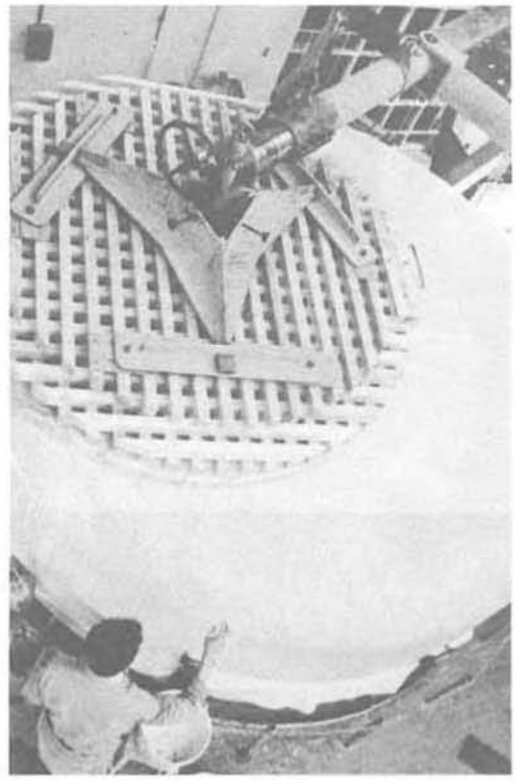
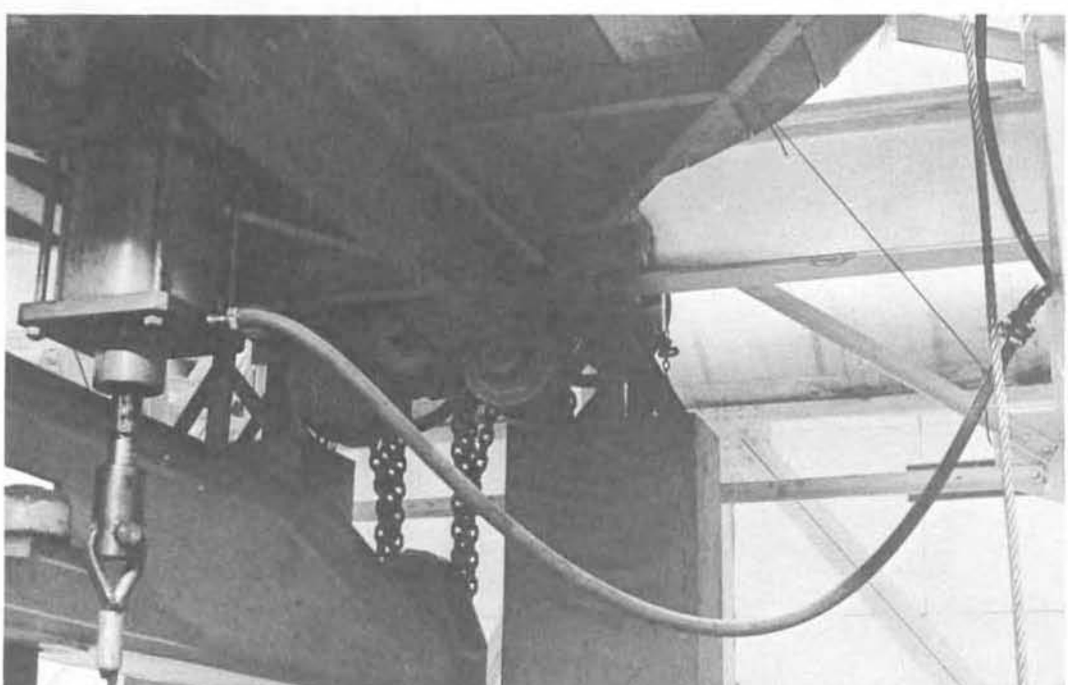


Fig. 14



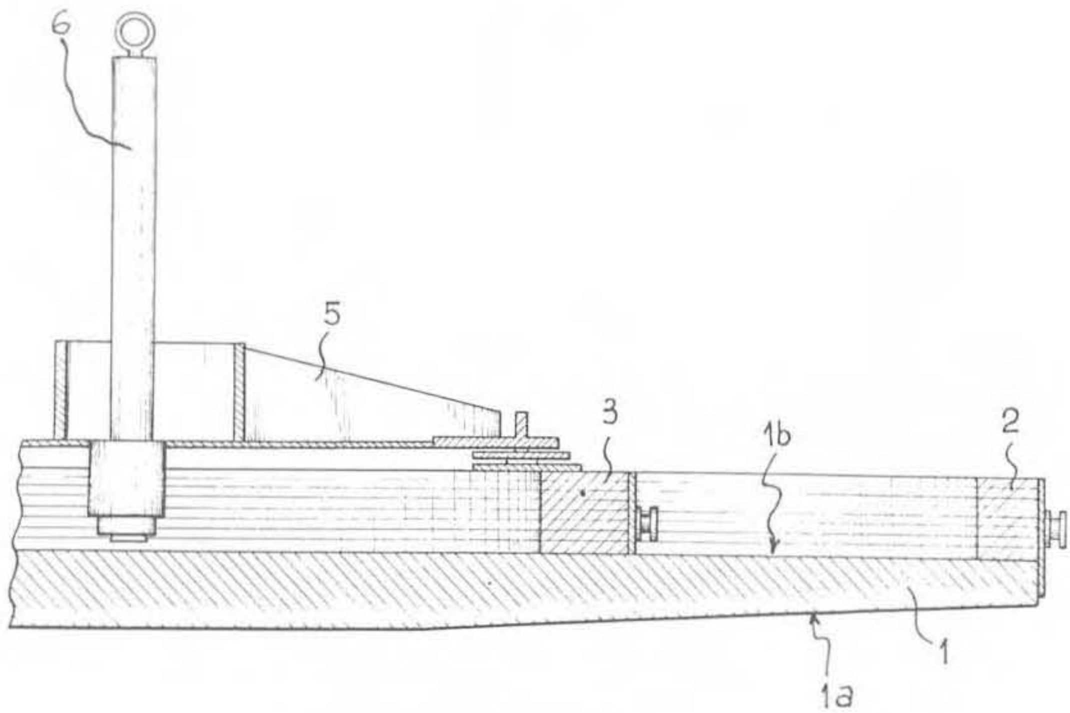
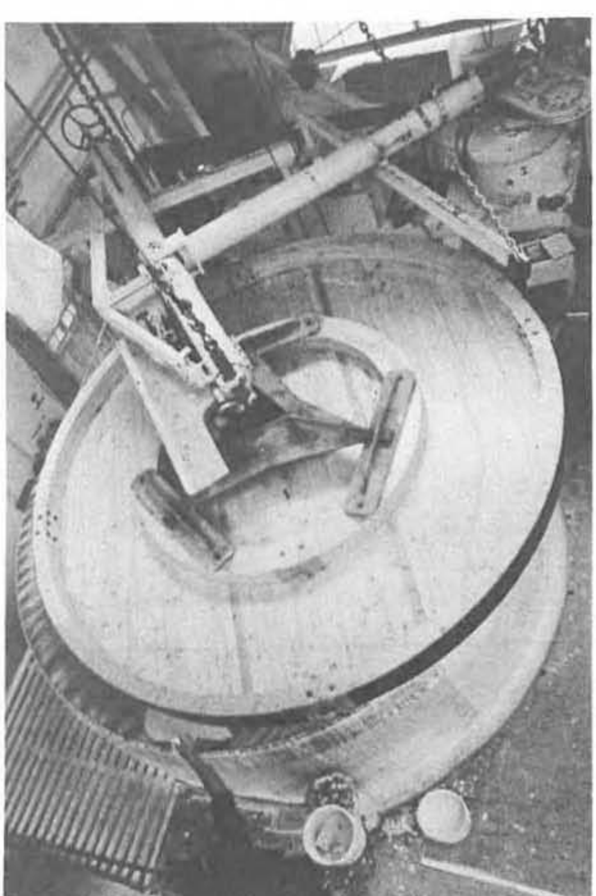
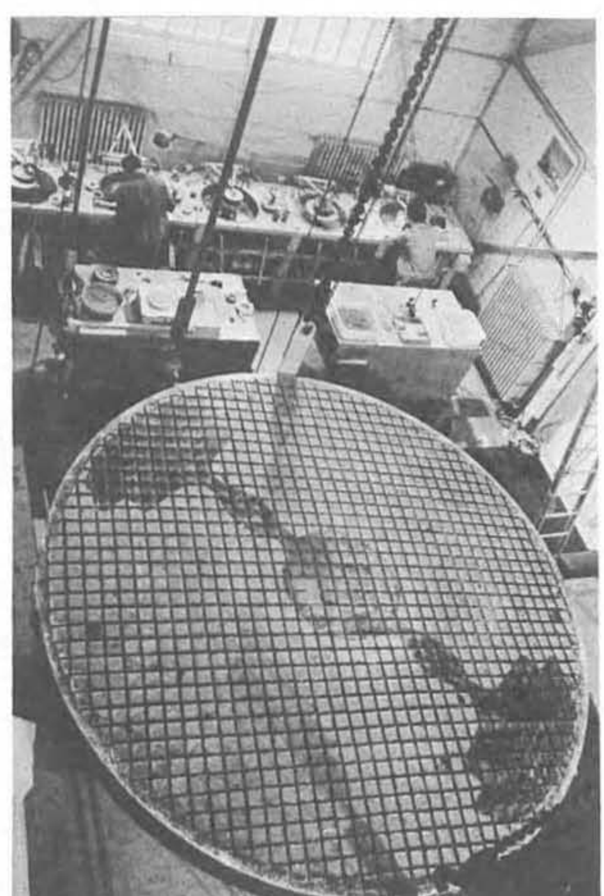


Fig. 15





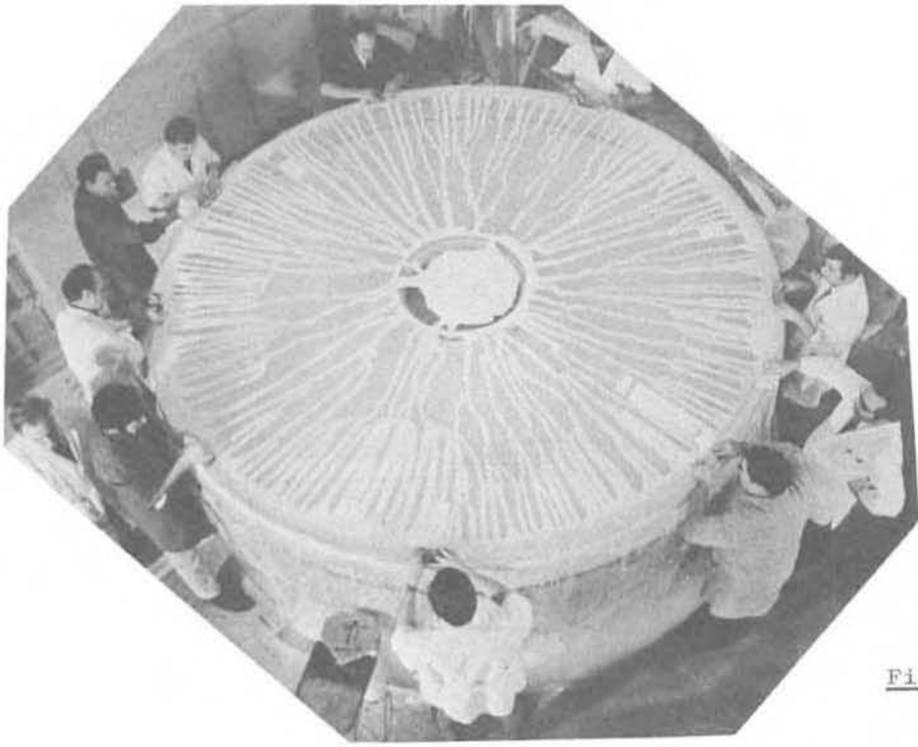


Fig. 18

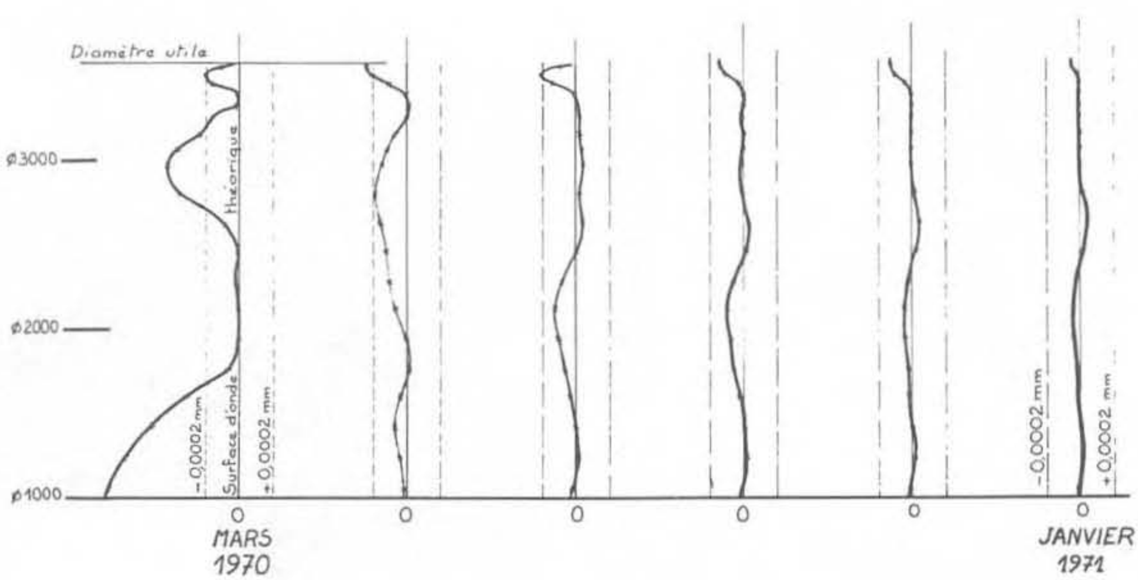


Fig. 19 Evolution de la surface du miroir ESO de 3.6 m.

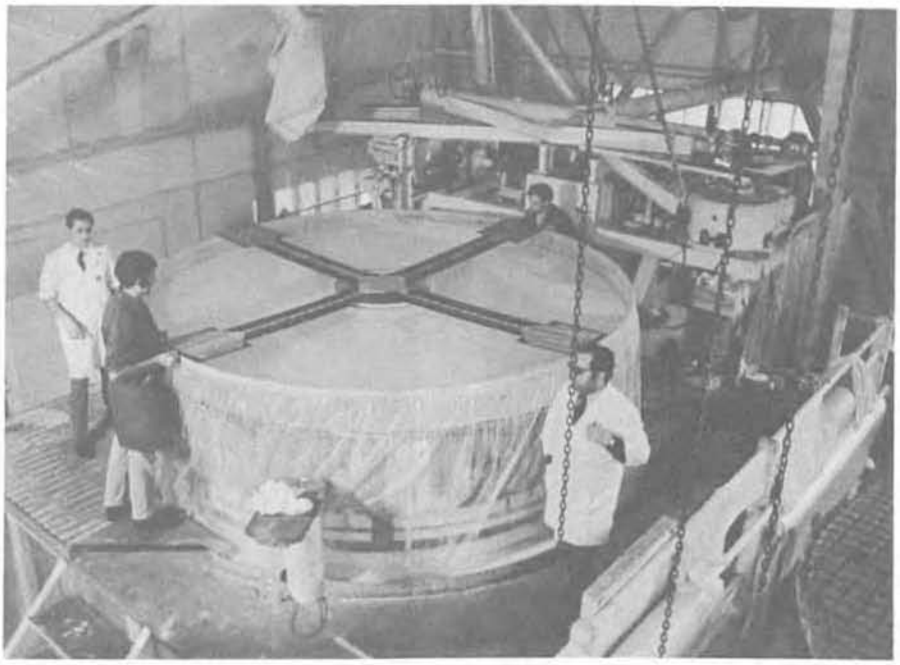


Fig. 20

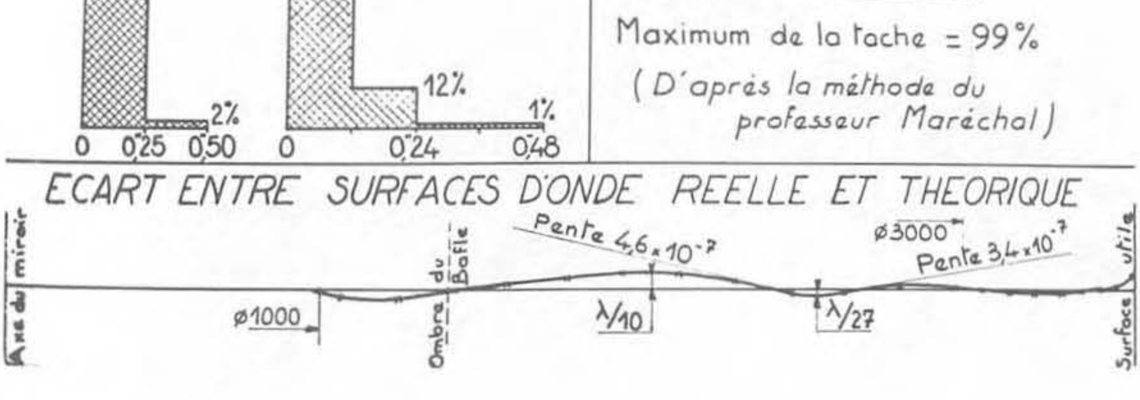


Fig. 21 Miroir ESO de 3.6 m. Critères de qualité de la surface actuelle.

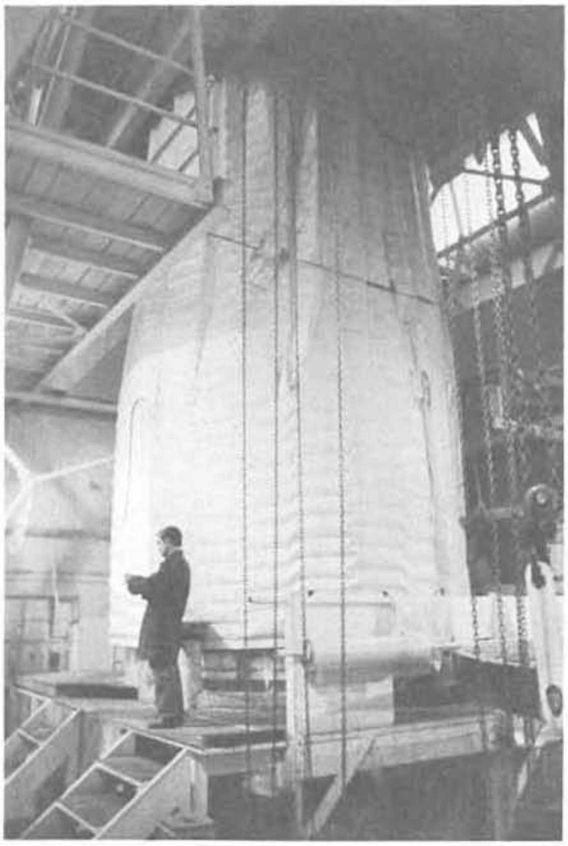


Fig. 22

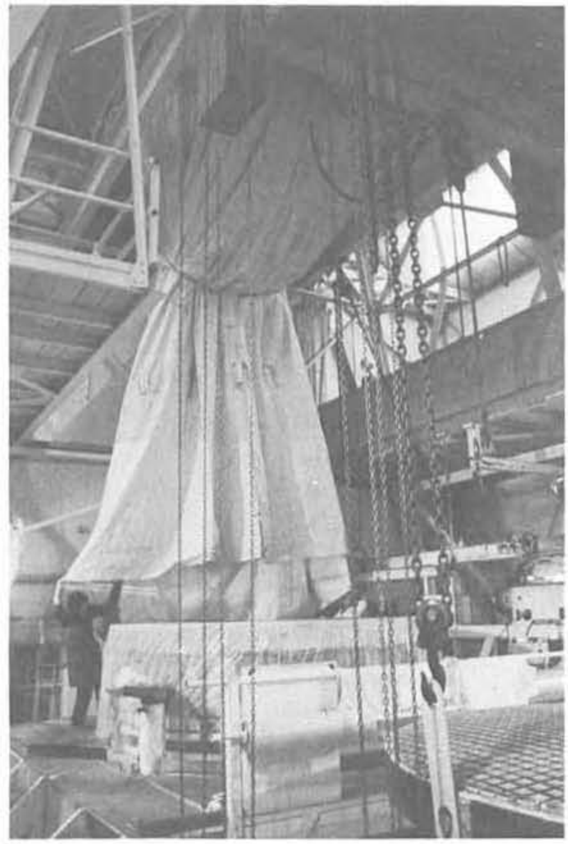


Fig. 23

Fig. 24

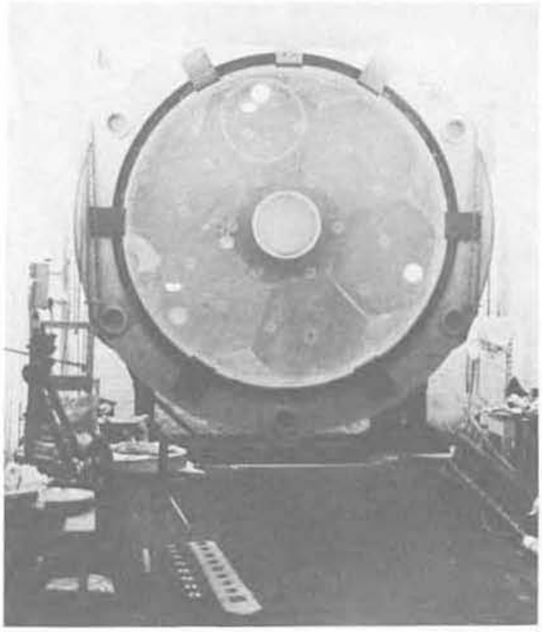


Fig. 25

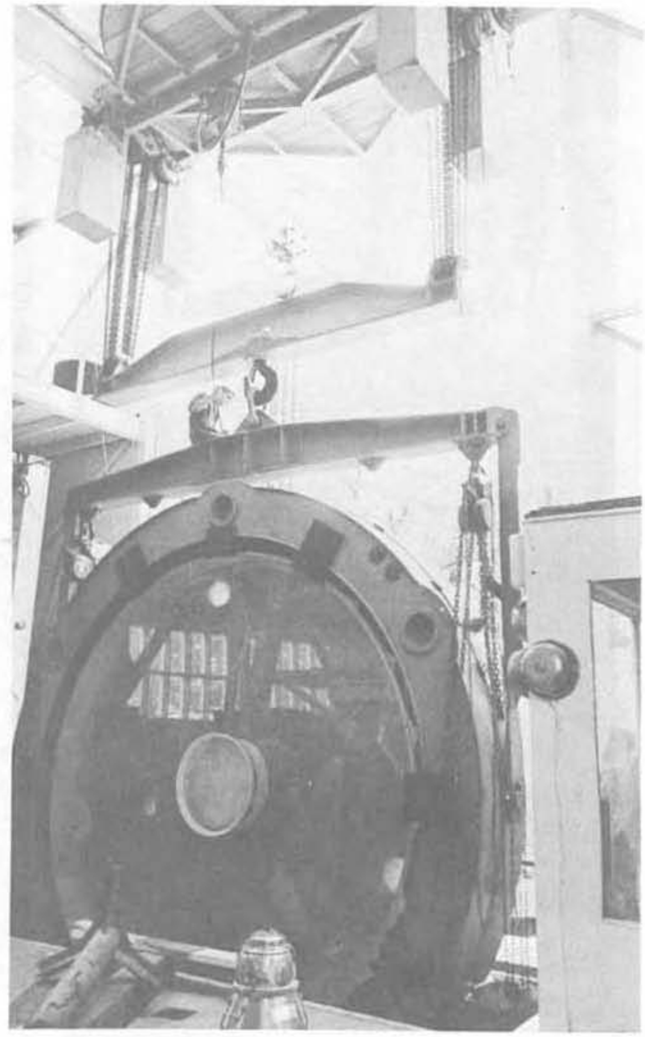


Fig. 26a

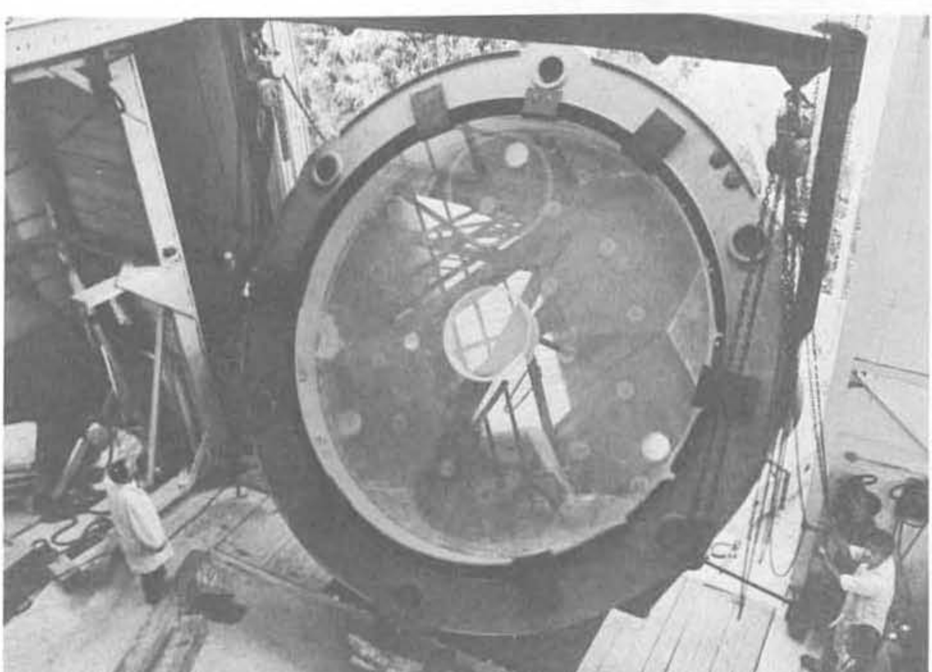


Fig. 26b

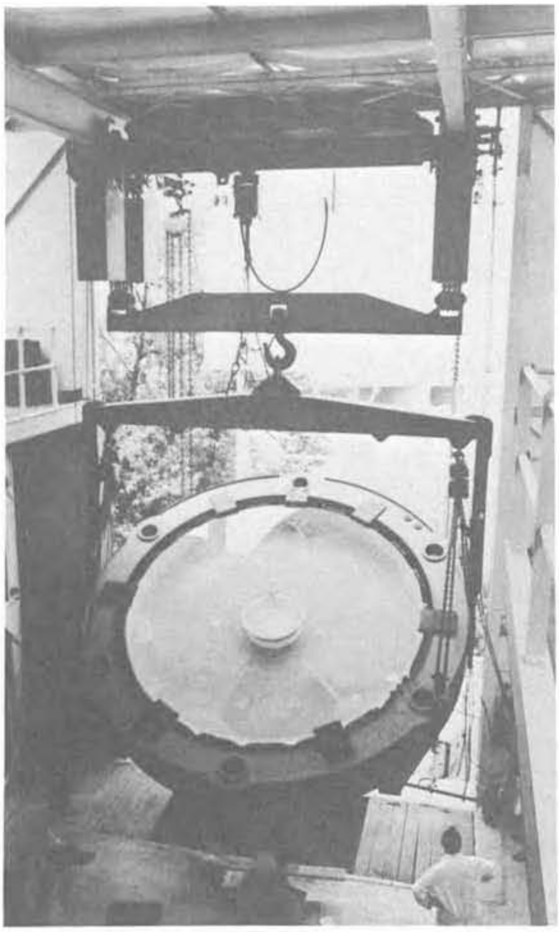


Fig. 26c

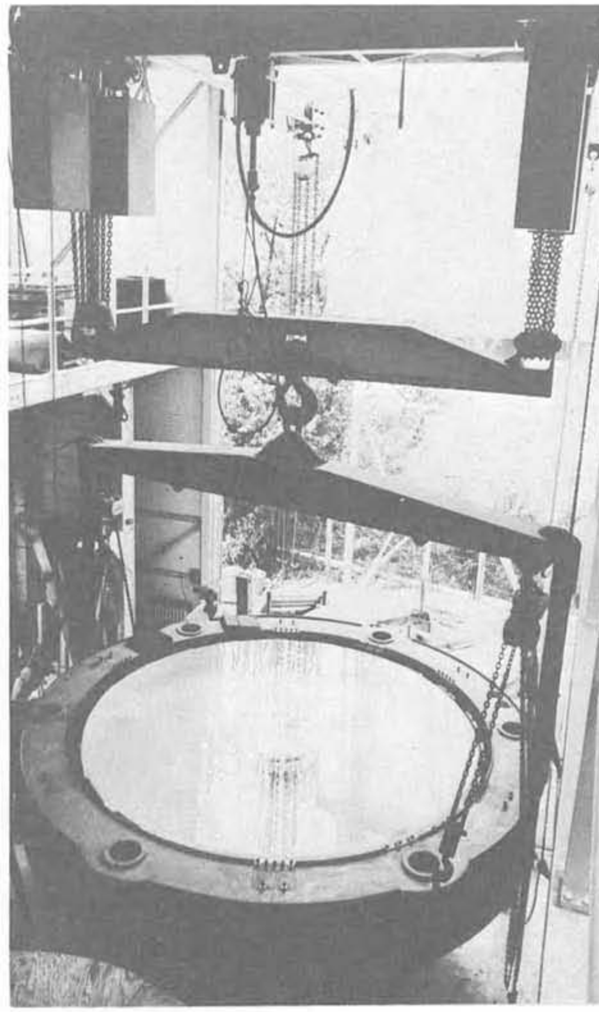


Fig. 26d

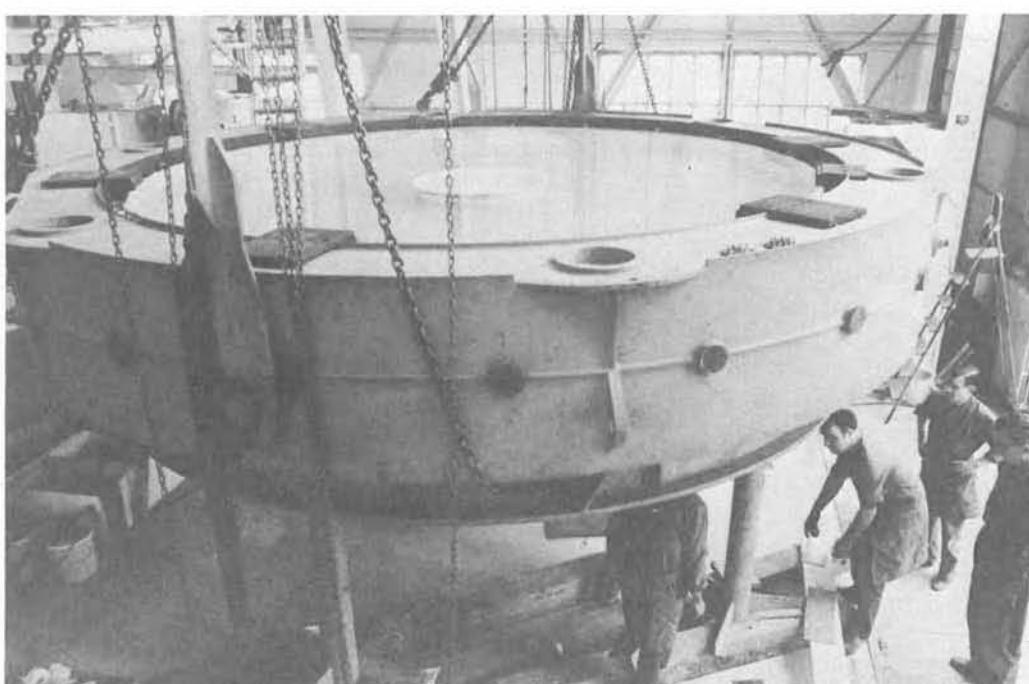


Fig. 27

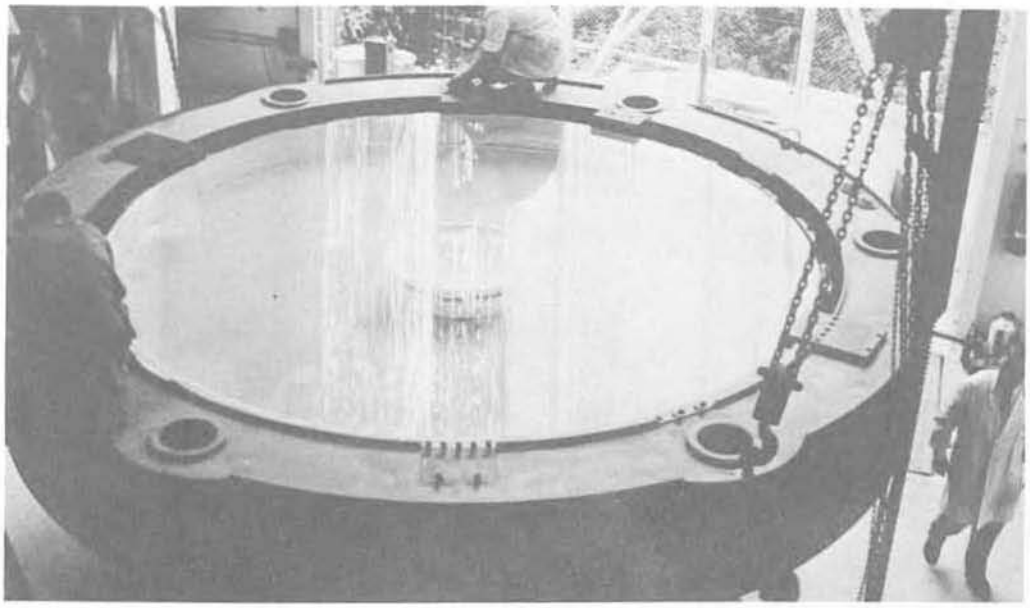
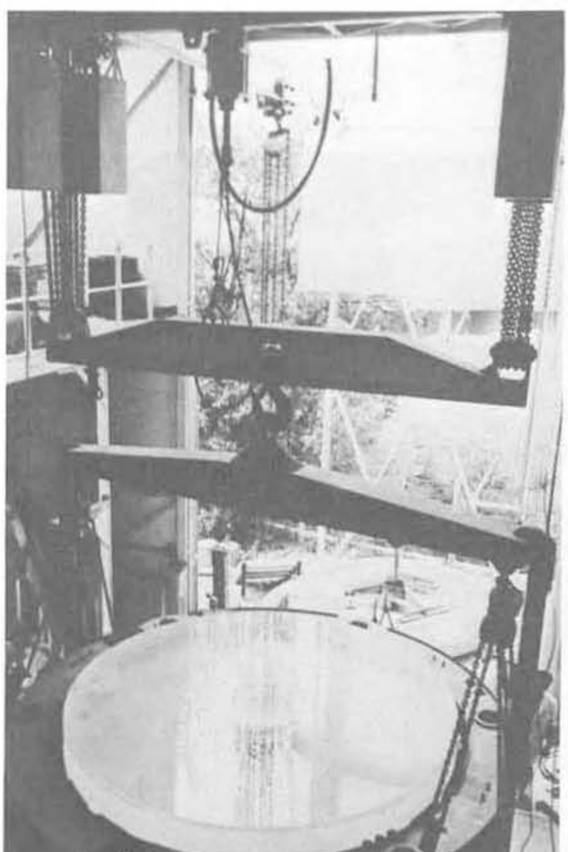


Fig. 28



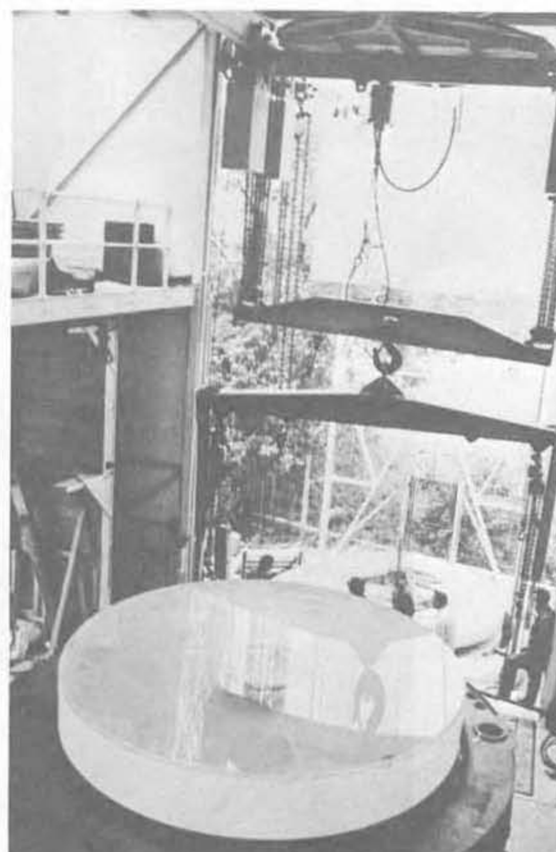


Fig. 29

Fig. 30

Fig. 31

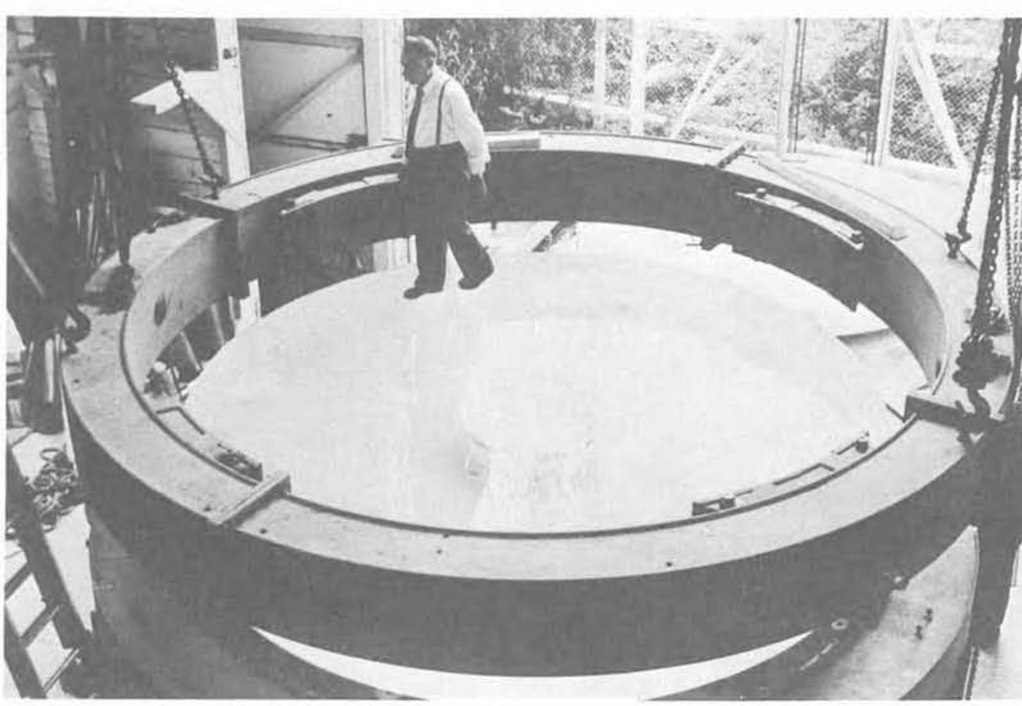


Fig. 32

Fig. 33

Fig. 34

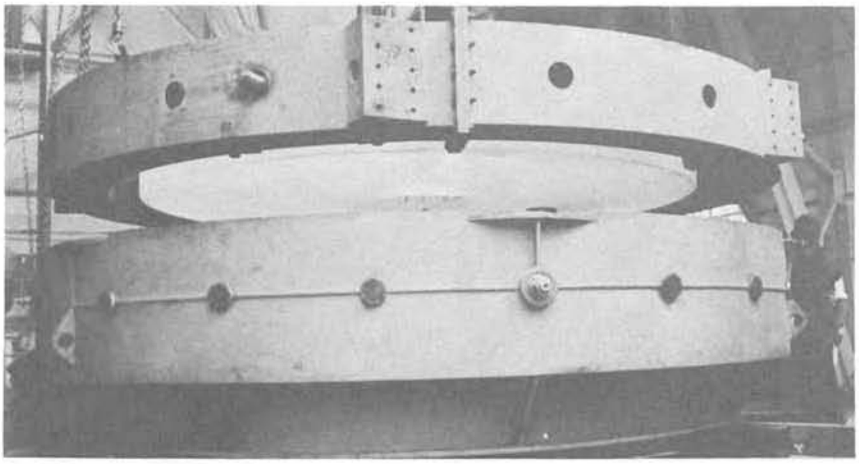


Fig. 35

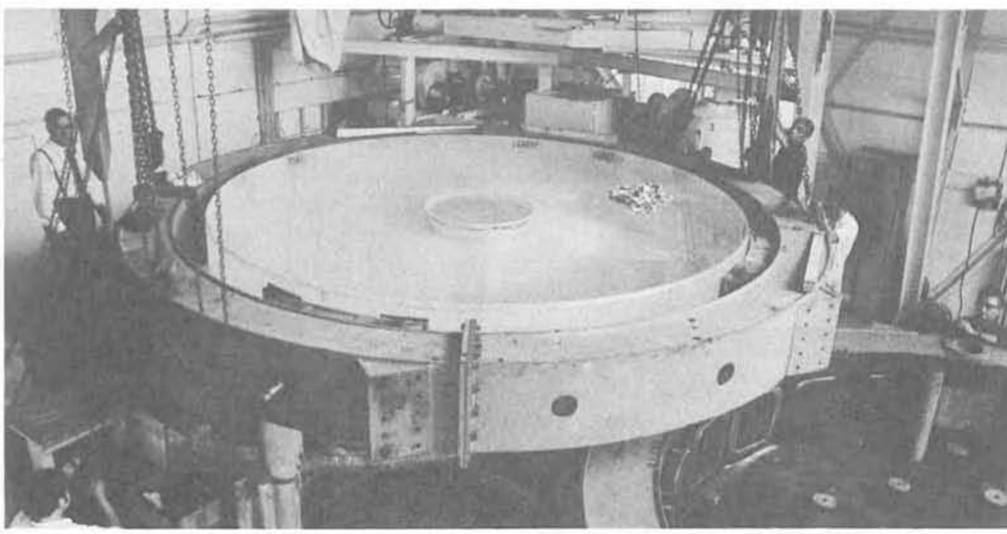


Fig. 36

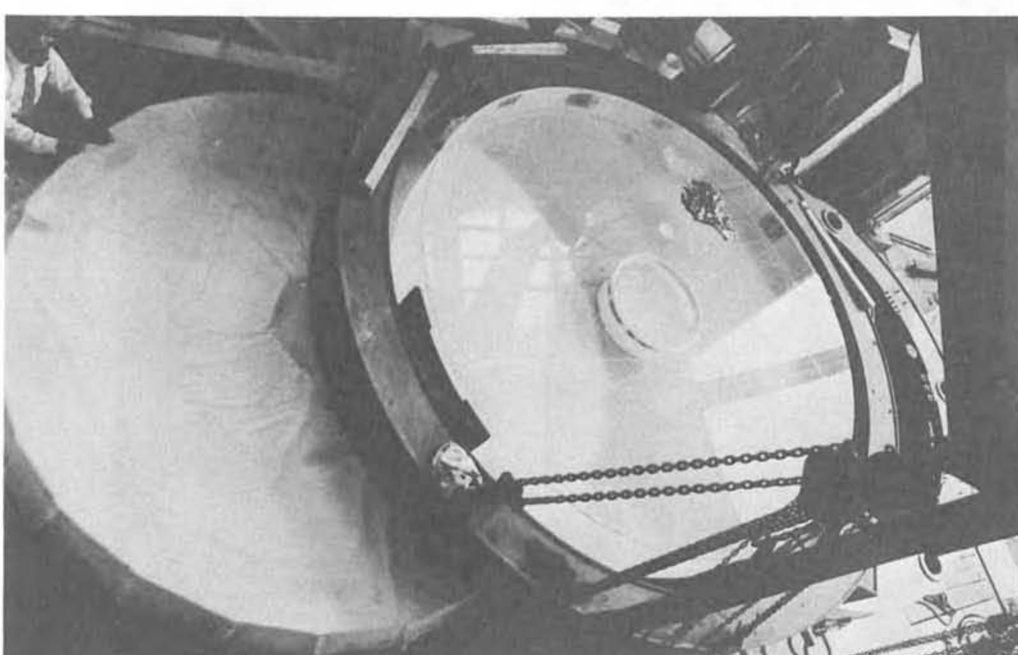


Fig. 37

LUMIERE PARASITE DANS LES CORRECTEURS ET LES RECEPTEURS D'IMAGES

P. Charvin
Observatoire de Paris
et
Institut National d'Astronomie et de Géophysique

avec la collaboration de M. Bourdet
Institut National d'Astronomie et de Géophysique

Une étude de la lumière parasite dans les télescopes a été entreprise dans le cadre de la préparation du projet de télescope français de 3.60 m. Son but principal est d'examiner les conditions à satisfaire par l'ensemble de l'optique utilisée pour pouvoir pleinement profiter de la grande détectivité et de la grande précision photométrique des récepteurs électronographiques du type Lallemand (1936).

L'analyse des sources de lumière parasite et de leurs propriétés, ainsi que l'analyse de leurs effets dans le plan image montrent que l'on peut distinguer la lumière parasite proche (à l'intérieur d'un champ de 10 - 30 secondes d'arc de diamètre) de la lumière parasite lointaine (limite supérieure comprise suivant les cas entre quelques minutes d'arc et quelques degrés). On ne considère ici, pour l'essentiel, que la lumière parasite lointaine produite par l'association d'un récepteur d'images à un correcteur. Quelques chiffres relatifs à la diffusion par les miroirs seront toutefois donnés. Ils ne possèdent généralement qu'un caractère indicatif, l'étude expérimentale correspondante ne faisant que commencer.

Le rôle de la lumière parasite lointaine dans plusieurs types d'observations astronomiques sera ensuite rapidement examiné.

1. Source de lumière parasite lointaine

Une revue des sources de lumière parasite lointaine montre que, dans les meilleures conditions (atmosphère très pure, aluminure fraîchement déposée, absence de poussières), l'essentiel de la lumière diffusée sous grands angles par un miroir provient du micromamelonnage de sa surface. Le meilleur cas est celui des miroirs construits pour des observations coronographiques (ZIRIN et NEWKIRK, 1962; NEWKIRK et BOHLEN, 1965; LEMAIRE, 1965;

HOSTETTER et al., 1968). La lumière diffusée est alors presque uniformément répartie dans le champ. Son taux est de 1 - 2.10^{-4}. Pour des primaires de grands télescopes, 1.10^{-3} paraît un bon ordre de grandeur.

Le secondaire diffuse davantage (TEXEREAU, 1970), surtout s'il est très déformé. Le vieillissement des aluminures, les poussières, augmentent enfin le taux de lumière diffusée et introduisent, joints à de simples effets géométriques, un gradient radial souvent très important. C'est ce gradient de lumière diffusée lointaine qui rend certaines mesures photométriques très difficiles, par exemple dans les amas (JOHNSON et SANDAGE, 1965). Au total, le taux moyen de lumière diffusée lointaine pourrait facilement atteindre 5.10^{-3}, voire 10^{-2} au second foyer d'un télescope de bonne qualité correctement entretenu.

L'ensemble correcteur-récepteur d'images constitue cependant la source la plus importante de lumière parasite, tant à cause de son taux élevé (aisément compris, comme nous le verrons plus loin, entre 3 et 10.10^{-2}) que de sa répartition dans le champ (on perd notamment la symétrie de révolution au centre du champ). Ceci justifie l'étude particulière qui a été faite de la lumière parasite dans l'ensemble correcteur-récepteur d'images.

2. Lumière parasite dans l'ensemble correcteur-récepteur d'images

Les diffusions vraies de chacune des pièces optiques de cet ensemble (auquel s'ajoute souvent un filtre) sont essentiellement des effets de surface, provoqués par les défauts de surfaçage des verres (a priori d'autant plus importants que ceux-ci sont plus déformés), par leurs états de surface, par les imperfections ou les altérations des couches anti-reflets, enfin par les inévitables poussières. Etant donné que les pièces optiques d'un correcteur sont proches du plan de l'image, la lumière diffusée sous grands angles par ces défauts (pratiquement toute la lumière diffusée) va produire dans le plan image des effets comparables à ceux de la lumière diffusée sous des angles petits ou moyens par les miroirs du télescope. Une diffusion à l'intérieur d'un cône de 1° empâtera par exemple l'image d'une étoile jusqu'à une distance de 1 ou 2' de son centre. Comme un correcteur comporte 4, 6 ou 8 surfaces, la diffusion vraie sera importante, par exemple de 1 - 5.10^{-2}. Ces chiffres s'appuient notamment sur les nombreuses mesures faites par l'un de nous avec le coronomètre monochromatique (CHARVIN, 1963) successivement équipé d'un doublet de bonne qualité et d'un objectif de coronographe. Cette lumière diffusée possède, comme celle des miroirs, la symétrie de révolution au centre du champ, et une symétrie approchée ailleurs.

Les réflexions multiples constituent cependant un défaut encore plus gênant. Dans leur étude de la lumière parasite dans la caméra électronique de LALLEMAND et DUCHESNE (1951), WLERICK et GROSSE (1966) ont montré qu'à cause du pouvoir réflecteur élevé des couches photoélectriques (20 à 30%), les réflexions multiples mettant en jeu la photocathode (réflexions multiples "arrière") sont beaucoup plus gênantes que les réflexions multiples "avant" mettant en jeu les rayons incidents. Des précautions appropriées leur ont permis de ramener le taux de lumière diffusée à 10^{-2} environ.

L'effet des réflexions multiples "arrière" sera de même prédominant dans l'association d'un récepteur d'images à un correcteur. C'est naturellement vrai dans le cas de la caméra électronique où les doubles réflexions "par l'arrière" fournissent de 7 à 25 fois plus de lumière que les doubles réflexions "par l'avant" (en prenant R photocathode = 25%, R verre = 1% ou 3.6% suivant qu'il est ou non traité anti-reflets). L'expérience montre que c'est également vrai dans le cas de la plaque photographique dont on connaît l'albédo élevé. Dans le problème traité ici, la plaque photographique se comporte comme une surface ayant un grand pouvoir réflecteur. Un chiffre de 25% sera utilisé dans ce qui suit. Une analyse élémentaire montre qu'au total les réflexions multiples fourniront un supplément de lumière parasite d'environ 2.10^{-2} pour un doublet traité à 1%, d'environ 5.10^{-2} pour un correcteur à 4 verres traités à 1%.

Le calcul de la répartition de cette lumière dans le plan image est un problème pour ordinateur. Il a été effectué pour un correcteur calculé par la C.E.R.C.O. pour le premier foyer d'un Ritchey-Chrétien de 3.60 m de diamètre, ouvert à f/3.75. Ce correcteur est un doublet très semblable à celui calculé par WYNNE (1968) pour le 107 inches de MacDonald. Son champ permet en principe d'utiliser des caméras de grande dimension, telles que celles de 80 à 100 mm de diamètre de photocathode actuellement en cours de développement à l'Observatoire de Paris. Deux méthodes de calcul ont été utilisées conjointement : la première comportant quelques approximations, mais permettant de bien analyser l'effet des diverses réflexions multiples, a été employée par M. BOURDET ; l'autre, plus complète, utilisant 10.000 rayons lumineux répartis au hasard sur le primaire, a été mise au point au Centre d'Etudes de Limeil du C.E.A.

Plusieurs cas ont été traités : celui de la caméra électrostatique de LALLEMAND et DUCHESNE (1951) sans correcteur ; celui de la nouvelle caméra magnétique de LALLEMAND ; celui du correcteur associé à une plaque photographique ; celui du correcteur associé à la caméra électrostatique.

Les répartitions présentées montrent, comme prévu, une série d'anneaux concentriques (l'obstruction centrale est supposée circulaire) dans le cas d'une source ponctuelle placée au centre du champ. Quand cette source s'écarte de l'axe, les anneaux s'ovalisent et glissent l'un par rapport à l'autre le long de l'axe passant par le centre du champ. Une modulation d'intensité apparaît dans plusieurs anneaux. Du fait des dimensions finies du récepteur et du correcteur, le taux de lumière parasite diminue un peu quand on s'écarte du centre du champ. Un correcteur dont une face aurait le centre de courbure au foyer ou proche de celui-ci, montrerait l'un de ces anneaux sous la forme d'une pseudo-image d'aspect stellaire ou nébulaire.

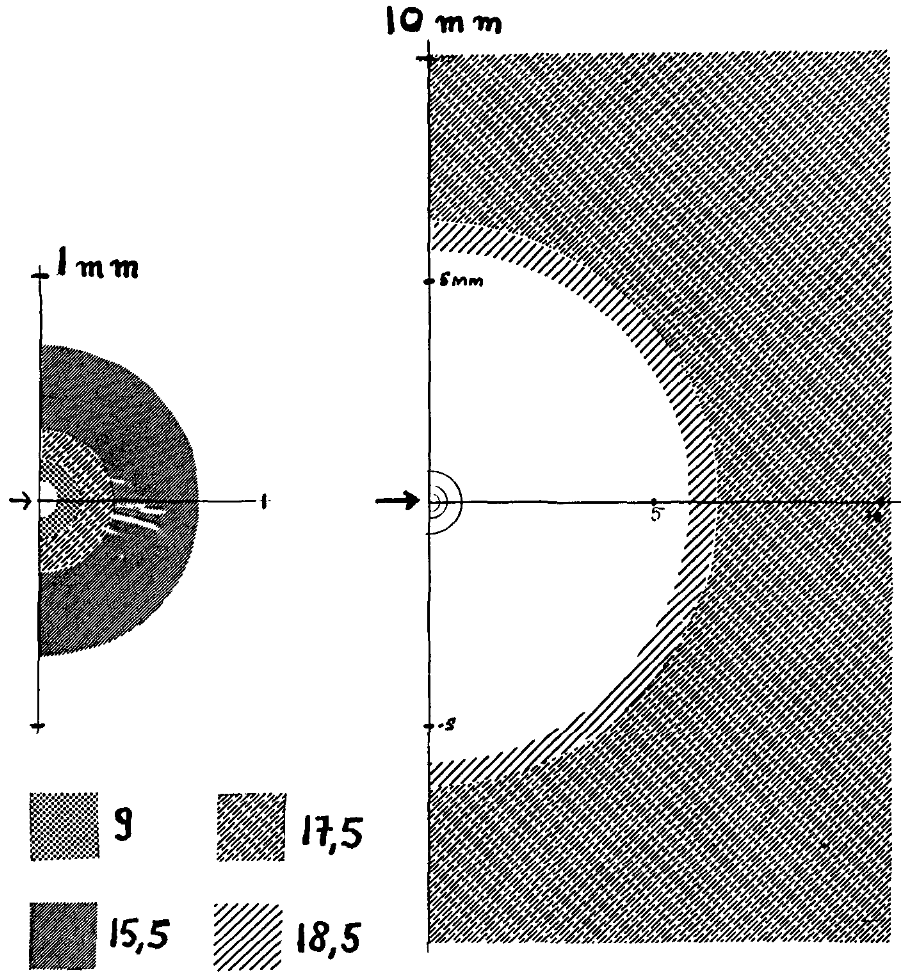


Figure 1a

Figure 1

Répartition de la lumière parasite dans le champ de la caméra électrostatique de LALLEMAND-DUCHESNE, supposée traitée anti-reflets. On a dans la partie de gauche de chaque figure un élargissement du centre du champ.

L'étoile étant supposée de magnitude 0, les diverses teintes de gris fournissent la valeur approchée de la lumière parasite exprimée en magnitude équivalente par seconde d'arc carrée.

1 a : Etoile sur l'axe

1 b : Etoile à 2 minutes d'arc de l'axe.

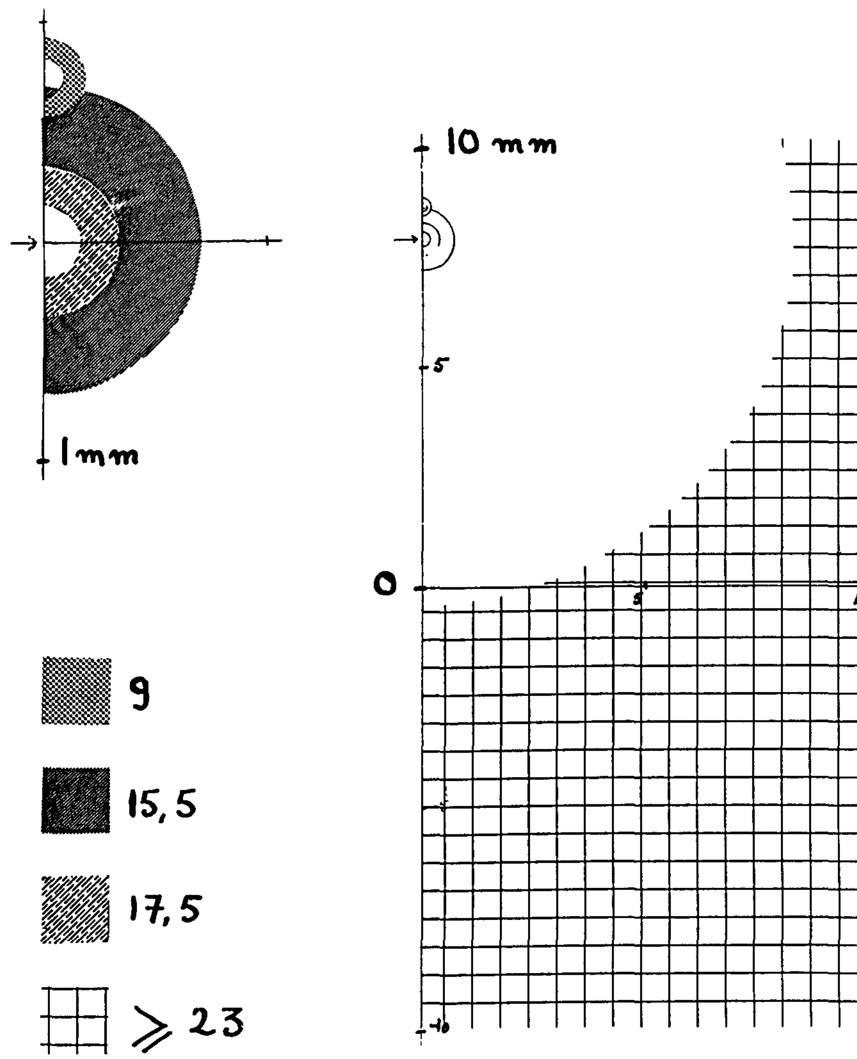


Figure 1b

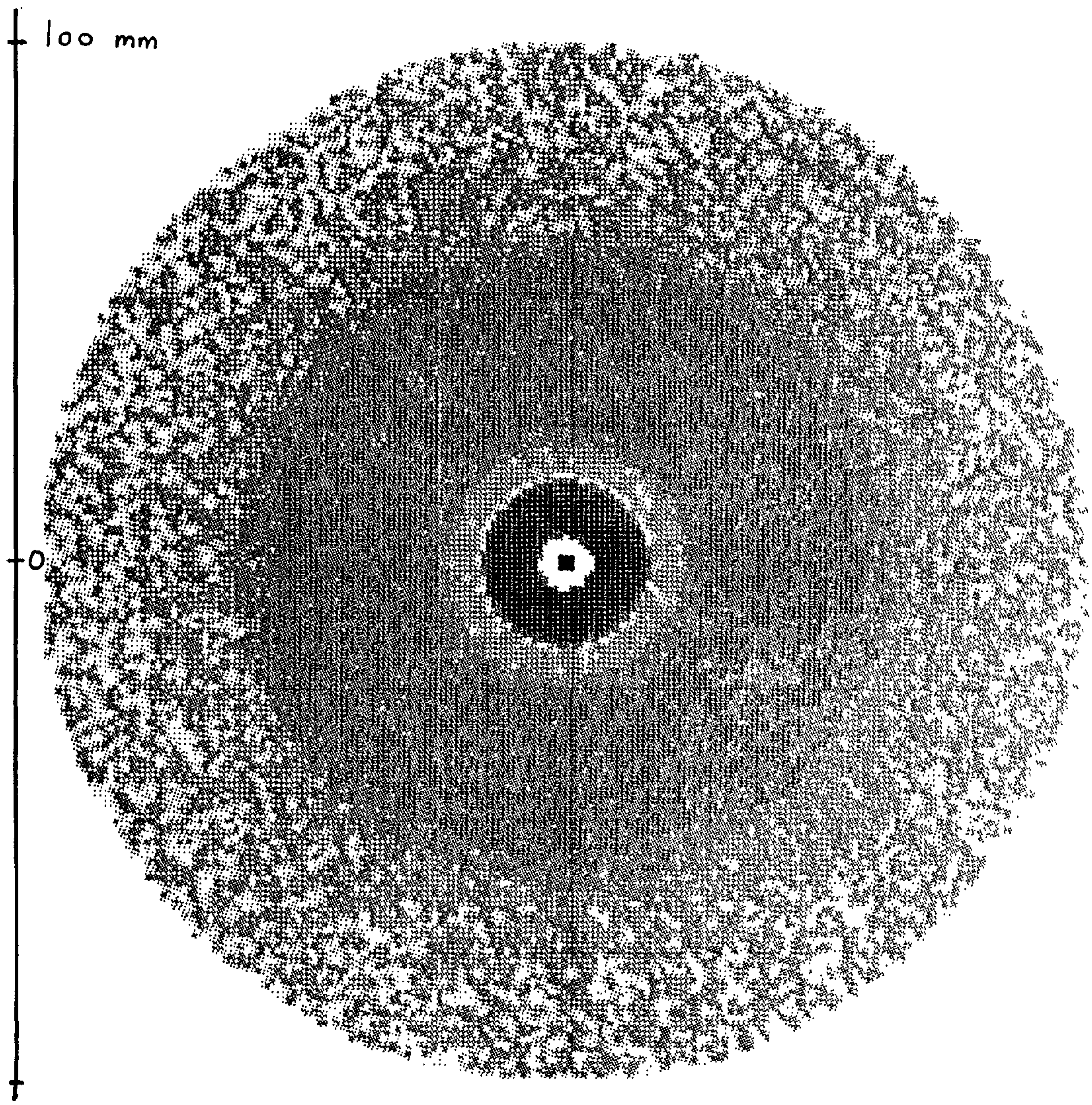


Figure 2a

Figure 2

Répartition de la lumière parasite dans le champ du correcteur C.E.R.C.O. associé à un récepteur ayant un pouvoir réflecteur de 30%. Méthode des 10.000 rayons répartis aléatoirement.

2 a : Etoile sur l'axe

2 b : Etoile à 5 minutes d'arc de l'axe.

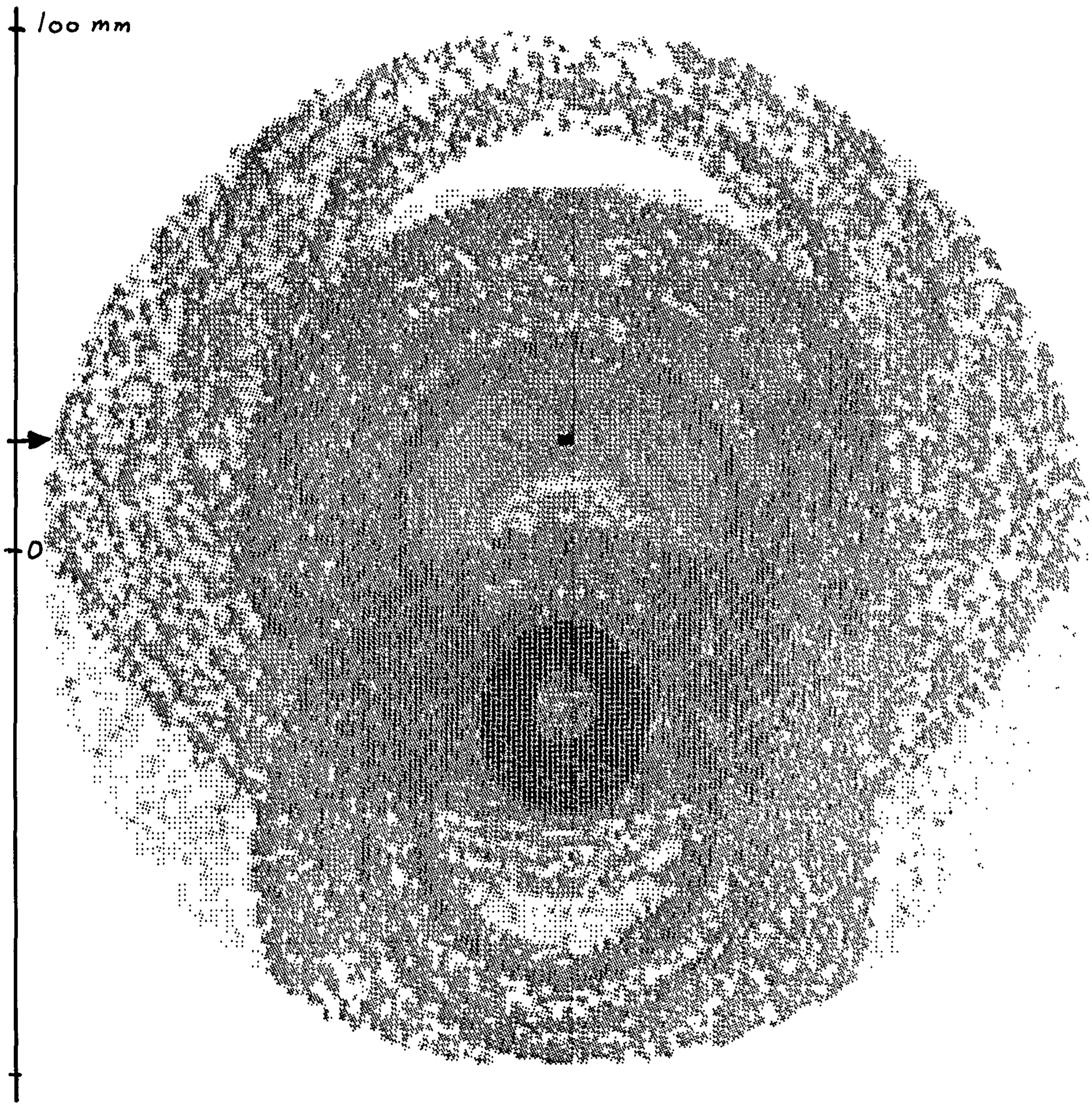


Figure 2b

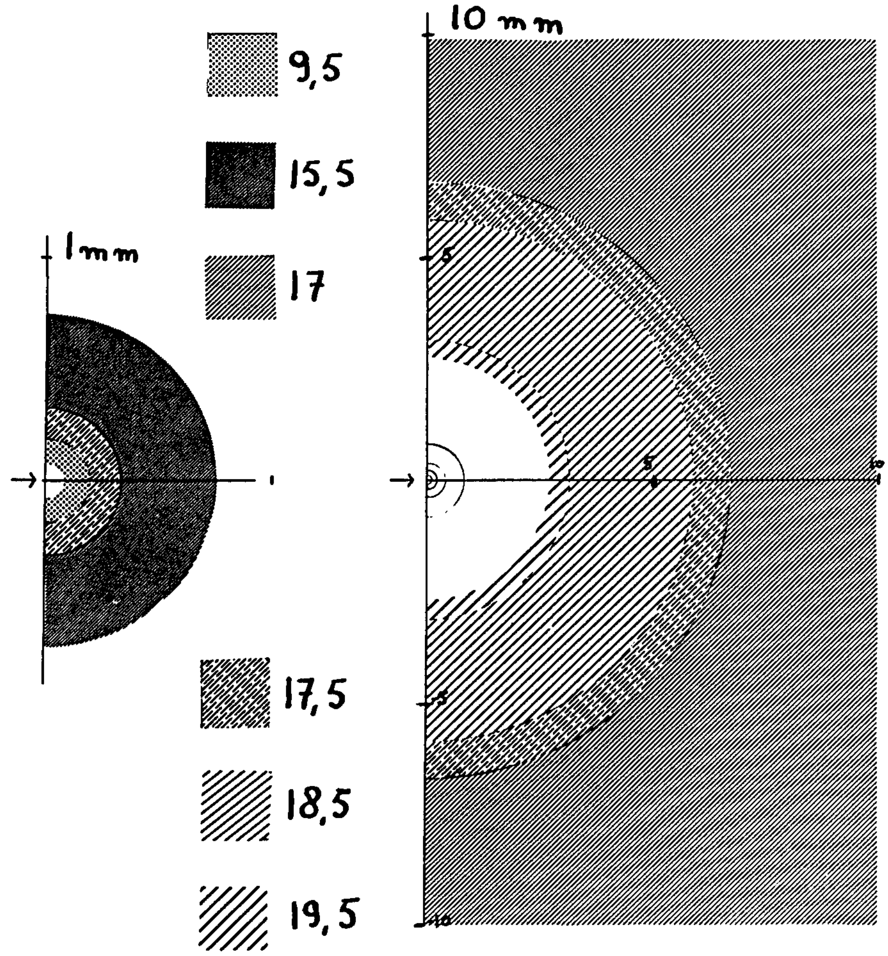


Figure 3a

Figure 3

Répartition de la lumière parasite dans le champ de la caméra électrostatique (supposée traitée anti-reflets) associée au correcteur C.E.R.C.O. (supposé non traité). Mêmes explications que pour la Figure 1.

3 a : Etoile sur l'axe

3 b : Etoile à 2 minutes d'arc de l'axe.

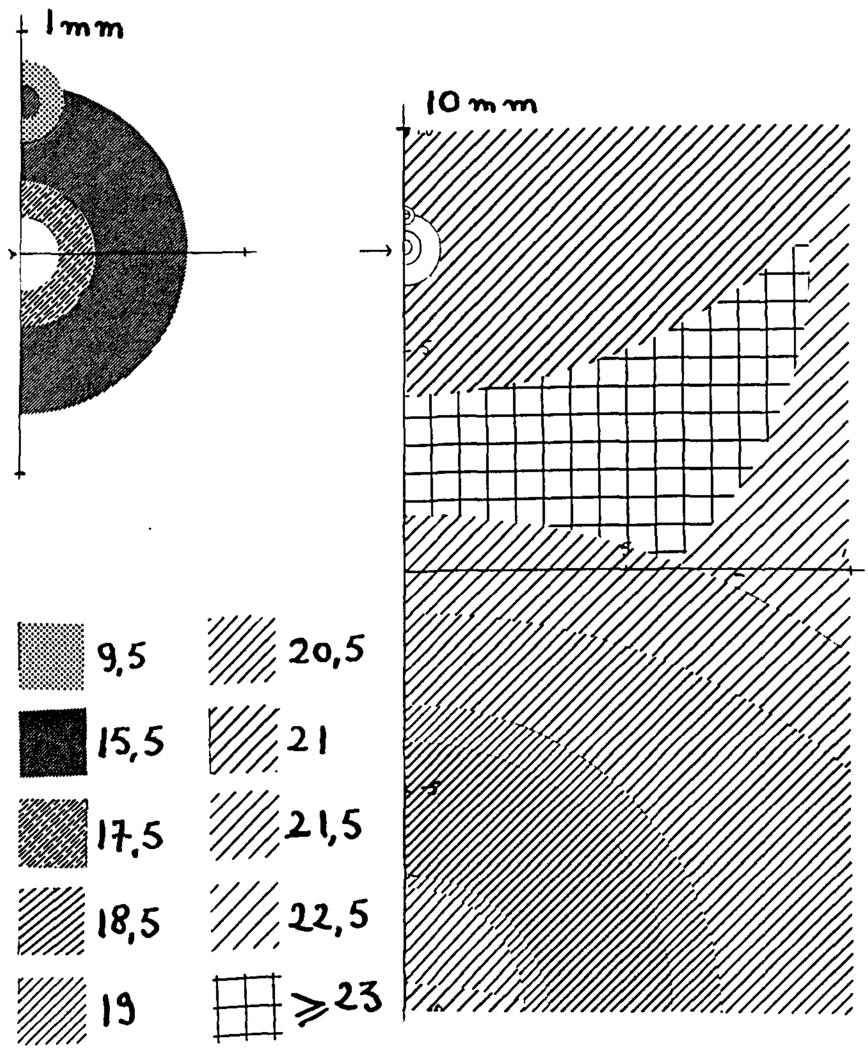


Figure 3b

Des exemples des résultats obtenus sont montrés sur les figures 1 à 3. Leur comparison à des photographies d'astres brillants prises avec des correcteurs montre effectivement plusieurs des images parasites les plus brillantes et confirme l'ordre de grandeur des taux indiqués. Par ailleurs, on voit sur des clichés électroniques présentés par WLERICK (p.265 de ce volume) le premier anneau dû au ménisque des photocathodes de caméras électrostatiques.

3. Influence de la lumière parasite dans quelques observations astronomiques

Les taux de lumière parasite peuvent donc varier autour de 1.10^{-3} au foyer primaire d'un parabolique de bonne qualité fraîchement aluminé (par exemple avec un photomultiplicateur ou dans la partie non perturbée du champ d'une caméra électronique), monter à 2.10^{-3} - 2.10^{-2} au foyer Cassegrain ou Ritchey-Chrétien d'un télescope pas trop ouvert, pour atteindre en moyenne 3 - 10.10^{-2} derrière un correcteur plus ou moins complexe associé à un récepteur d'images.

Ces valeurs données, rappelons-le, à titre indicatif, et dont il serait intéressant de mieux préciser les limites sur plusieurs télescopes, fournissent un premier guide permettant de rechercher la meilleure adaptation d'un récepteur d'images à un télescope chaque fois que la lumière parasite peut constituer une gêne. Quelques problèmes, donnés à titre d'exemple, sont rapidement examinés.

Le premier est celui de la détection d'un astre relativement faible à proximité d'un astre brillant. Ce cas est fréquent dans les systèmes doubles ou multiples. Il peut se poser aussi dans la recherche de radio-sources suffisamment faibles pour que le fond du ciel puisse constituer une gêne particulière. Ainsi, la radiosource 3 C 173 a été identifiée sur un cliché électronique pris au foyer Newton du 193 cm de l'O.H.P. à un objet de magnitude V = 21.3 situé à 10" d'une étoile de magnitude V d'environ 12.6 (WLERICK et al., 1971). On conçoit sans peine que tout élargissement par diffusion de l'astre brillant puisse, dans un tel cas, rendre la détection impossible, ou fortement diminuer la précision photométrique des mesures. Nous pensons d'ailleurs que le recours à des montages du type "coronographe" éliminant une grande partie de la lumière d'un astre brillant, ainsi que la lumière diffractée par l'ouverture du télescope et les araignées peut, dans quelques cas difficiles de recherche de source ponctuelle faible ou d'étude d'objets étendus, permettre de résoudre le problème. Dans de tels cas, il faudrait naturellement se placer à un foyer déjà très pur.

La photométrie d'étoiles faibles dans un amas, essentielle pour prolonger les diagrammes d'amas, est souvent très fortement pénalisée par l'existence du gradient de lumière parasite lointaine due au centre de l'amas (JOHNSON et SANDAGE, 1956). Bien que ce type d'étude paraisse relever, avec un récepteur d'images, des problèmes "à grand champ", l'obligation de ne pas augmenter la valeur du fond général de lumière parasite semble impérative. Il paraît en particulier très important de ne pas perturber la régularité et la symétrie du gradient de lumière diffusée en introduisant les discontinuités et l'asymétrie caractéristiques des correcteurs. Les pseudo-images éventuelles semblent également à proscrire dans des champs dont l'encombrement constitue par ailleurs un problème sérieux.

L'étude de la distribution de brillance des galaxies semble un autre problème type où l'on doit rechercher la solution la moins diffusante.

Pour terminer, on insistera sur le problème des magnitudes limites, car il est absolument spécifique des grands télescopes. VERNIER (1958) a calculé la valeur limite magn. B = 27 en 4 h de pose électronographique au foyer d'un grand télescope, en adoptant un fond de ciel de 22.2 et une turbulence de 1". Des estimations beaucoup plus récentes, basées sur des observations effectives, nous ont été aimablement communiquées par G. WLERICK (1971) *. Celui-ci a mesuré avec G. LELIEVRE, au Newton du 193 de l'O.H.P., dans le champ de 3 C 173, la magnitude limite V 23.6, tandis que la magnitude B était supérieure à 24. Compte tenu des conditions de l'observation, on calcule par la formule de BAUM dans le cas non saturé (1962) que l'on atteindrait avec le même instrument en 3 h 30 de pose et avec un α de 1" : V = 25.25 avec un ciel de 21.6; B = 25.95 avec un ciel de 22.0. Avec un télescope de 3.60 m travaillant avec un ciel très noir, on calcule une magnitude limite B de 27.1.

A ce niveau, la lumière parasite lointaine due à l'ensemble des étoiles du champ (ensemble équivalent en moyenne à 61 étoiles de 10^e magnitude par degré carré, ALLEN (1955)) peut constituer une gêne extrêmement sérieuse si elle ne se répartit pas de façon régulière dans le champ. Nous avons évalué, sur la base des figures de lumière parasite fournies par les correcteurs, le type de fluctuations que l'on trouverait en moyenne dans le champ, ainsi que leur amplitude efficace. On est suffisamment loin d'une distribution poissonnienne pour perturber la fluctuation due au fond du ciel, bien que celui-ci soit beaucoup plus brillant en moyenne. Avec un taux de lumière parasite de 5.10^{-2} dans un champ de 1/5 de degré carré, on augmente considérablement la probabilité de fausses détections, ce qui revient à diminuer le coefficient de certitude k de telle manière que l'on perd en moyenne de 1 à 2 magnitudes. Pour ne pas gêner sensiblement, cette lumière parasite irrégulière doit tomber au dessous de 1.10^{-2}. Ceci exclut le travail à un premier foyer équipé d'un correcteur, et le reporte à un premier foyer de parabolique ou, ce qui paraît nettement moins favorable dans ce type d'étude, à un foyer Cassegrain ou Ritchey-Chrétien. Ceci paraît également nécessiter que l'on abaisse encore un peu le taux de lumière parasite dans les caméras électroniques.

---

* voir par ailleurs dans ce volume p.265

4. Conclusions

Les calculs effectués montrent que, si l'on considère les énergies, la lumière parasite dans un grand télescope associé à un récepteur d'images, peut constituer un "gros phénomène". Les grands télescopes apparaissent de ce point de vue comme potentiellement limités, dans la plus grande partie de leur champ, par la lumière parasite lointaine.

Il est non moins clair que, si l'on considère maintenant l'énergie diffusée par unité d'aire du champ, disons par seconde d'arc carré, la lumière parasite apparaît comme négligeable dans de nombreux problèmes, et notamment si le récepteur utilisé possède un seuil et un voile.

L'astronomie d'hier s'est d'ailleurs faite avec des instruments plus ou moins diffusants (sauf quelques exceptions comme le coronographe et le spectrographe à double passage), et une bonne partie de l'astronomie de demain pourra continuer de s'accommoder de la lumière parasite lointaine. *

Pourtant, nous pensons que des problèmes capitaux de l'astronomie, relatifs par exemple à l'évolution stellaire ou à la cosmologie, exigent qu'un gros effort soit fait pour réduire au maximum la diffusion des instruments. Les progrès des techniques de polissage et de contrôle des miroirs rendent d'ailleurs possible l'obtention de taux de lumière parasite très petits. Nous estimons donc que la réduction de la lumière parasite doit être l'un des éléments importants pris en considération lors de la conception et de la construction d'un grand télescope.

Comme il apparaît fort naturellement, que l'augmentation du nombre des pièces optiques d'une combinaison accroît très rapidement le taux de lumière parasite, en même temps que s'accroît le champ angulaire ou linéaire de bonne définition, l'un des choix importants auquel on doit faire face lors de la définition d'un télescope est le suivant: lumière parasite ou champ?

Il ne nous semble pourtant pas impossible que le dilemne que nous venons d'évoquer puisse aisément se résoudre si l'on considère le nombre croissant des grands télescopes. La perspective d'une certaine spécialisation des grands télescopes, fort difficile à envisager il y a quelques années, nous paraît digne, actuellement, d'être prise en considération. La conception des grands télescopes en serait certainement facilitée, leur coût pourrait être sensiblement plus faible et surtout, l'astronomie y aurait, selon nous, beaucoup à gagner.

---

* Nous tenons à bien souligner que nous ne parlons pas de la diffusion proche pour laquelle l'emploi de télescopes placés hors de l'atmosphère devrait fournir un gain capital de résolution angulaire.

Remerciements

Nous tenons tout particulièrement à remercier Monsieur BRIN, Directeur du Centre d'Etudes de Limeil du C.E.A., et Monsieur GUILLOUD, Chef du Service de Mathématiques Appliquées de ce Centre pour l'aide considérable qu'ils nous ont apportée dans les calculs de figure de lumière parasite.

Nos remerciements vont également à Monsieur G. WLERICK, Astronome à l'Observatoire de Paris, avec qui nous avons eu de fructueuses discussions.

Bibliographie

ALLEN C.W., 1955, Astrophysical quantities, The Athlone Press, Univ. of London.

BAUM W.A., 1962, in Astronomical Technics, ed. W.A. HILTNER, Univ. of Chicago Press, 1.

CHARVIN P., 1963, C.R., 256, 368.

HOSTETTER G.R., PATZ D.L., HILL H.A. et ZANONI C.A., 1968, Appl. Opt., 7, 1382.

JOHNSON H.L. et SANDAGE A.R., 1956, Ap. J., 124, 379.

LALLEMAND A., 1936, C.R., 203, 243 et 990.

LALLEMAND A. et DUCHESNE N., 1951, C.R., 233, 305
1952, C.R., 235, 503.

LALLEMAND A.; DUCHESNE N.; et WLERICK G., 1960, in Advances in Electronics and Electron Physics, 12, 5.

LEMAIRE P., 1965, Thèse de 3e cycle, Paris.

NEWKIRK G. Jr. et BOHLEN J.D., 1965, Ann. d'Astrop, 28, 234.

TEXEREAU J., 1970, Critères de qualité pour grands télescopes (non publié).

VERNIER P., 1958, Thèse de Doctorat, Paris.

WLERICK G. 1971, Communication privée.

WLERICK G. et GROSSE A., 1966, in Advances in Electronics and Electron Physics, 22, 465.

WLERICK G.; LELIEVRE G., et VERON P., 1971, A. and A. (to be published).

WYNNE C.G., 1968, Ap. J., 152, 675.

ZIRIN H. et NEWKIRK G. Jr., 1962, Appl. Opt., 2, 977.

R E S U M E

On présente, dans le cadre d'une étude de la lumière parasite dans les télescopes, des premiers résultats relatifs à la lumière parasite dans les correcteurs et les récepteurs d'images. Les taux de lumière parasite sont élevés à cause du pouvoir réflecteur ou de l'albédo importants des récepteurs d'images. Des exemples de répartition dans le champ sont montrés.

On indique ensuite rapidement les inconvénients de cette lumière parasite dans quelques types d'observations astronomiques réclamant une grande détectivité et une grande précision photométrique. On indique en particulier que la lumière parasite irrégulièrement répartie due à des réflexions multiples doit être inférieure à 1% pour atteindre dans de bonnes conditions les magnitudes limites les plus élevées permises par l'électronographie.

On est conduit en conclusion à recommander l'usage d'un vrai foyer primaire ou de seconds foyers démunis de correcteurs pour toutes les observations à l'aide d'un récepteur d'images requérant un faible taux de lumière parasite. Le choix final peut dépendre du type exact de problème à traiter et du type de récepteur utilisé.

DISCUSSION

VAUGHAN: Apart from the problem of reflection from correctors, I have heard about investigations which show that a star image is surrounded by more or less an inverse-square ring. This ring might be a universal property of telescope mirrors or an atmospheric effect. In any case, it would appear that more than 1% of light, in fact an appreciable amount, is contained just in that part of the image.

CHARVIN agrees that the atmospheric turbulence and small faults in the mirror surface give rise to some parasitic light, but that this is very much concentrated towards the center of the image. The present work does not concern this kind of diffuse light .

MAGNITUDES LIMITES DES ASTRES MESURABLES AVEC LES GRANDS TELESCOPES

Gérard Wlérick
Observatoire de Paris

INTRODUCTION

La caméra électronique utilise l'électronographie. Ce récepteur donnera demain une puissance considérable aux grands télescopes car:

1. Il est efficace. Il comprend deux parties, la photocathode et l'émulsion pour électrons. La photocathode a un rendement quantique élevé, $\geq$ 10% dans le bleu, et le "rendement quantique équivalent" de l'ensemble du récepteur a également un rendement élevé, $\geq$ 8% dans le bleu.

2. Il est linéaire, ce qui est essentiel pour la photométrie. Grâce à la linéarité les mesures sont possibles jusqu'à la limite de détection.

3. Il est propre; c'est le plus propre de tous les récepteurs photoélectriques d'images; c'est celui qui a le moins de lumière diffusée.

Lallemand, Canavaggia et Amyot (1966), puis Walker et Kron (1967) ont montré que l'électronographie est bien adaptée à la photométrie des étoiles très faibles ou des petites galaxies. J'ai utilisé cette propriété pour l'étude des radiosources optiquement faibles.

OBSERVATIONS

A l'observatoire de Haute-Provence, un programme d'identification de la plupart des sources du catalogue de radiosources 3C R a été entrepris. Avec le télescope de 193 cm, treize sources faibles ont déjà été trouvées (Wlérick, Lelièvre, Véron, 1970 et 1971). La photométrie, dans le système U.B.V., de 3C 173 et 3C 190 a été effectuée.

Un dépouillement préliminaire indique que, pour 3C 190, on a, en Novembre 1970, B 20,9 et que les indices de couleur sont les mêmes que pour certains quasars. Le tableau 1 résume les données relatives à 3C 173. Cet objet a les propriétés suivantes:

1. Il est variable: la magnitude B a augmenté de 1.7 magnitude en 13 mois.

2. Fin Novembre 1970, ses indices de couleur sont:

$$B - V = + 0.41 \qquad U - B = - 1.08 .$$

Ces couleurs sont très voisines de celles du quasar 3C 181 (B - V = + 0.43, U - B = - 1.02).

TABLEAU 1

Clichés électroniques de 3C 173

date 1	couleur 2	émulsion Ilford 3	durée en min 4	largeur des images à mi-hauteur 5	magnitude de la radiosource 6	densité optique du fond du ciel 7	magnitude du ciel pour [1"]^2 8	magnitude limite S/B ≥ 4 9	magnitude ultime 10
12.10.69	B	G5	50		20,00±0,15				
12.3.70	B	K5	50		21,02±0,15				
24.11.70	B	K5	110	1,60"±0,15"	21,74±0,10	0,81	21,6	24,1	24,8
26.11.70	V	K5	70	1,10"±0,10"	21,30±0,10	1,04	19,9	23,4	24,1
27.11.70	U	K5	70	1,9" ±0,2"	20,61±0,15	0,25	20,13	21,9	22,6
30.11.70	U	G5	60	1,8" ±0,2"	20,67±0,10	0,59	21,26	22,6	23,3

La figure 1 présente deux clichés de 3C 173, obtenus dans les couleurs V et U en Novembre 1970. La figure 2 représente une série de coupes microphotométriques effectuées dans l'image de la radiosource 3C 173 sur le cliché pris en couleur V.

ASTRES FAIBLES ENREGISTRES

Dans les champs de ces radiosources, on enregistre aussi beaucoup d'astres très faibles. Une façon d'estimer la magnitude limite des clichés consiste à déterminer le rapport signal sur bruit S/B d'étoiles faibles, de magnitude 20 à 22 par exemple, et à calculer pour quelle magnitude le rapport k = S/B a une valeur limite que l'on s'est fixée. On est prudent en prenant $S/B \geq 4$. Ceci conduit aux valeurs de la colonne 9 du tableau 1. Certains auteurs comme Walker vont même plus loin en considérant sans doute, que le signal d'une étoile comprend non seulement le nombre total de traces d'électrons qui forment l'image mais aussi une répartition dans l'espace de ces traces (facteur de forme). On arrive ainsi aux valeurs de la colonne 10.

A titre de vérification, on a mesuré deux astres très faibles sur le cliché obtenu en couleur V; leurs magnitudes V = 23.2 et V = 23.6 montrent qu'en tout cas les valeurs de la colonne 9 ne sont pas surestimées. De même, sur le cliché pris en ultraviolet, on mesure un astre P, (voir figure 1) de magnitude U = 22.4, qui apparaît très en-dessous de la limite.

On peut comparer ces valeurs aux mesures faites avec des photomultiplicateurs. Les astres les plus faibles pour lesquels des magnitudes U.B.V. ont été publiées se trouvent dans des amas globulaires. Les valeurs extrêmes (Sandage 1970) sont relatives à M 15:

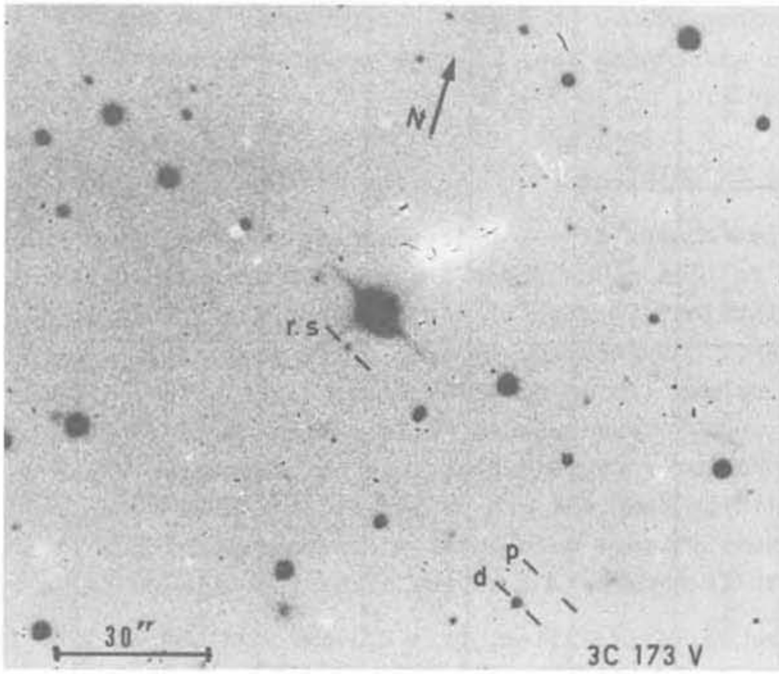
pour l'étoile A 11	V = 22.01
pour l'étoile A 17	B = 22.72
pour l'étoile A 8	U = 22.28

Ainsi on mesure déjà sur les clichés électronographiques, avec un télescope moyen, des astres plus faibles que les astres les plus faibles mesurés avec un photomultiplicateur et un grand télescope. Ceci confirme la prédiction de Walker: l'électronographie fera faire un bond à la photométrie analogue à celui réalisé, il y a vingt ans, grâce à l'emploi des photomultiplicateurs.

Pour mesurer ces astres faibles, il a fallu réunir diverses conditions: bon télescope (optique et mécanique, F/5, F = 9.6 m), télescope propre (aluminure toute fraîche), bon récepteur (bonne cathode, bon lot d'émulsions), qualité des images très bonne dans un cas (couleur V) et acceptable pour les autres clichés. On a eu, par contre, une pénalisation: la luminance du ciel nocturne, particulièrement pour le cliché V.

PREDICTIONS POUR LES GRANDS TELESCOPES

On peut prendre les conditions suivantes:



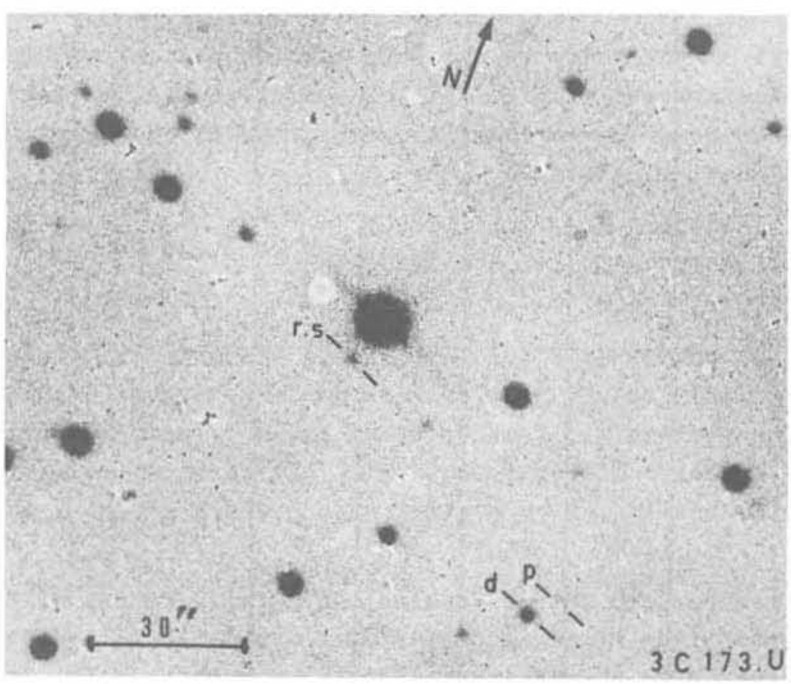


Fig. 1 Photographies électroniques du champ de la radiosource 3C 173. Cliché en couleur V du 26.11.70 et cliché en couleur U du 30.11.70. Les données relatives à ces photographies sont indiquées dans le tableau 1.

- diamètre de 3.5 à 6 mètres
- temps de pose 4 heures
- ciel noir (par seconde carrée, V = 21.6; B = 22.2; U = 21.5)
- images très bonnes: largeur à mi-hauteur 0.6"
- cathode plus sensible que celle utilisée ici: facteur 1.3 pour chaque couleur.

On calcule alors les magnitudes limites suivantes, dans le cas le plus prudent ($k \geq 4$), en utilisant la formule de Baum (1952):

$$V_{lim} \approx 26.8$$

$$B_{lim} \approx 27.5$$

$$U_{lim} \approx 26.1 .$$

On peut majorer ces chiffres de 0.7 si l'on est plus audacieux.

A ces magnitudes limites, on peut estimer qu'on pourra, en dehors de la Voie Lactée, mesurer une centaine d'astres par $(1')^2$, c'est-à-dire plus d'un millier d'astres dans un cercle de 4' de diamètre.

Le contraste des astres limites sera de 0.5 à 1%.

Ainsi des perspectives brillantes sont ouvertes aux grands télescopes mais il ne faut pas sousestimer les difficultés. Je crois qu'il faut ré-analyser en détail l'interaction télescope-récepteur et voir dans quelles conditions l'ensemble des deux travaillera au mieux.

Il faudra aussi faire des progrès sur le récepteur, sur la qualité des photocathodes et sur la lumière diffusée résiduelle dans la caméra électronique.

Il faudra enfin faire des progrès sur les télescopes, travailler avec le moins de miroirs possibles, le plus petit nombre de dioptres possibles, obtenir des surfaces optiques dont le poli se rapproche de celui du coronographe et maintenir l'aluminure parfaitement propre. En particulier les poussières constitueront un très lourd handicap, qu'elles soient situées sur le miroir principal ou sur un filtre coloré devant l'image.

Je ne doute pas que toutes ces difficultés pourront être surmontées.

BIBLIOGRAPHIE

Baum W., 1952, dans "Astronomical Techniques", édité par Miltner, Univ. of Chicago Press, p.1.

Lallemand A., Canavaggia R. et Amiot F., 1966, C.R.Acad. Sci. Paris, 233, 305.

Sandage A., 1970, Astrophys. J., 162, 841.

Walker M. et Kron G., 1967, Pub. Astr. Soc. Pacific, 79, 551.

Wlérick G., Lelièvre G. et Véron P., 1970, Communication au colloque U.A.I.

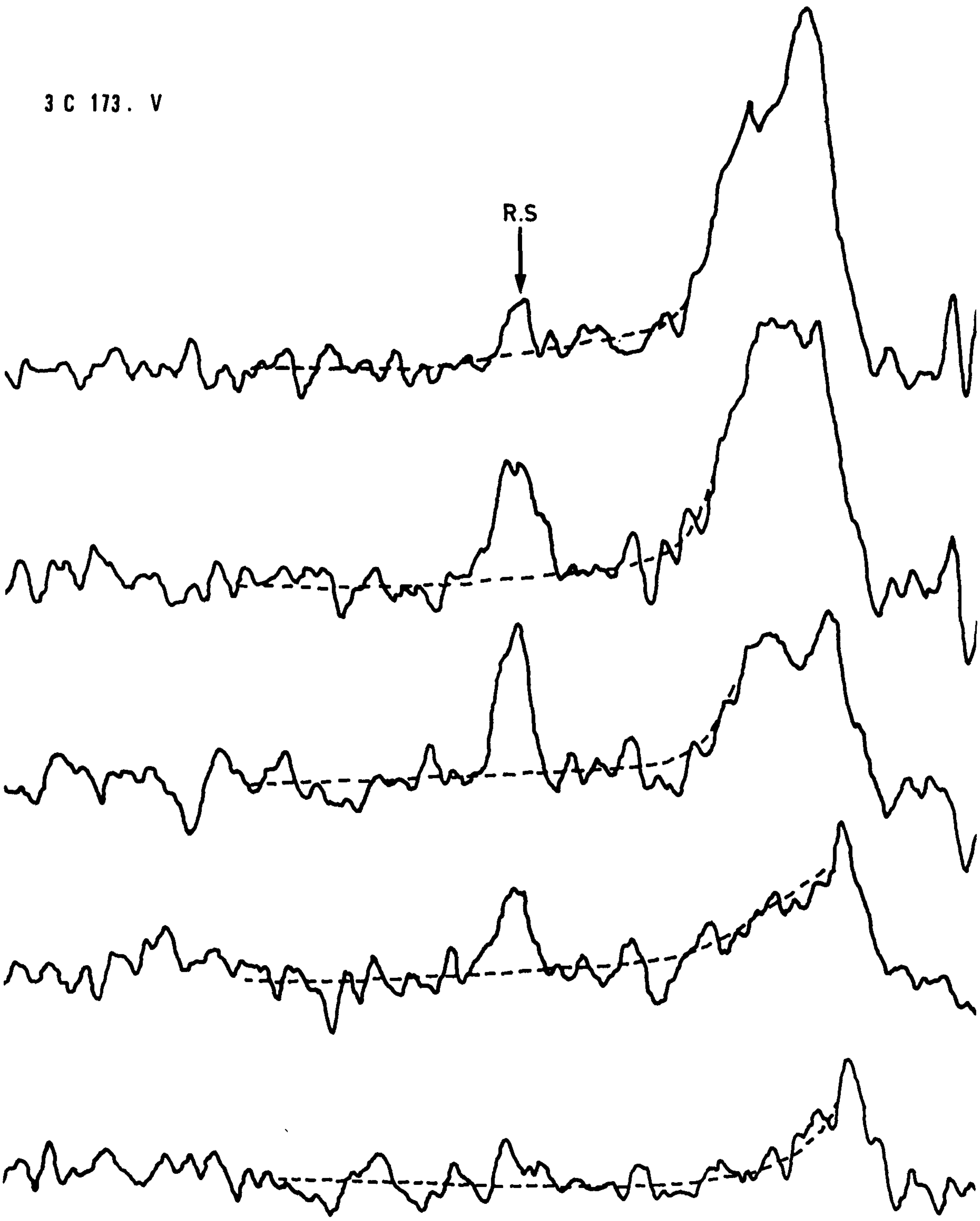


Fig. 2 Série de coupes microphotométriques de l'image de la radiosource 3C 173 sur le cliché V du 26.11.70. La distance entre deux coupes successives est de 25 μm. Elles sont effectuées avec une fente exploratrice carrée de coté 20 μm.

sur les Galaxies, Uppsala, Août 1970, (sous presse).
Wlérick G., Lelièvre G. et Véron P., 1971, Astron. et Astrophys., 11, 142.

DISCUSSION

RICKARD: Suppose you want to integrate for 5 days instead of 4 hours; what problems do you run into then by using an electronic camera?

WLERICK: Well, maybe Prof. Lallemand or Dr. Duchesne could better answer that question, but I may say that Dr. Duchesne has made 12 hour exposures on 12 successive days without any difficulties, and that is extremely important for us, because if we have the slightest noise in the tube, not only will it increase the sky-background, but it might increase it in a non-uniform way and that will degrade the photometry completely.

ROSINO: Which field can you now cover with the electronic camera attached to the 2m telescope of Haute Provence?

WLERICK: We use a field of 20 mm at the present time, corresponding to a field of 7 minutes of arc in diameter. In one of the plates which is outside the Milky Way, we can measure more than 200 objects in the sky. That is what we call an electrostatic camera with an electrostatic focusing. I think within one or two years it will be easy to use a 35 mm photocathode with good electronic resolution, but probably we will not be able to use it at Haute Provence because our connecting instrument between the telescope and the camera will not accommodate a tube of the size of 35 mm. We could, however, use a new connecting system, but for the present time we don't need it as long as we are interested in point objects like radio sources. But there are many other developments at the present time, for instance that by Prof. Lallemand which actually works, and it is already at 9 cm diameter. The electrostatic one by Dr. Duchesne can go up to 10 cm diameter, but the tube has not been built yet. You also have another development of a magnetic camera with a rectangular cathode of 5 x 10 cm by another group at Meudon. The reason for it being rectangular is that they are interested in spectroscopy.

ROSINO: Are the images equally good in all positions on the photocathode?

WLERICK: That is extremely important in photometry, and as long as you have no electronic emission in the tube and no uneven scattered light in the optics, then the photometry looks very encouraging with the electronic camera. What we still have to look at is some localized defect; indeed there are some, but as long as we are at the 23rd magnitude, they are not too bad, because you have 20 times more stars than defects. But it will not be the case any more if you go to fainter objects, and there I think we have some study to make.

From what I have seen this is not a type of defect special for the electron camera; I think you find them in the photocathode of other image tubes as well. Another important thing: we are in the worst case as far as the optics are concerned because we have an optical piece at the image itself. What we need is something like a coronographic polishing, and that would not be too difficult to achieve for such small surfaces. I also think that in the next 5 years progress will be made in the tube that will really permit us to go to the very faint magnitudes that we have quoted.

BERTOLA: How is the extrapolation done down to the 24th magnitude?

WLERICK: Actually I guess these numbers are understatements. Because what we do is the following: we have at the start a profile of the image and look at the maximum contrast. We then compute for a given object like the radio source what we may call the signal-to-noise ratio, and the computation just goes to the moment when the signal-to-noise ratio is still over 4. Many people have now recognized that, may be due to the fact that you have more information than that, you can actually go further. They believe they can go to a factor of 2 and that gives you another 0.7 magnitude. An interesting fact is also that I computed the signal-to-noise ratio theoretically, just assuming some quantum efficiency of the photocathode, and the theoretical and the measured values are of the same order of magnitude. So what we get is what we actually expect. In that sense, we cannot expect much more until the quantum efficiency of the photocathode is increased.

FLORENTIN NIELSEN: You stated earlier that you had no noise in your electronic camera whatsoever. How do you overcome the problem of thermal emission of electrons from the photocathode?

WLERICK: The camera is cooled with liquid air to between -120 and -150°C. It is good to confirm that we have indeed no thermal emission. This is checked by means of a small area on the photocathode on which an opaque silver layer has been deposited. Since the density on the exposed plates is very low inside this area, we conclude that the thermal emission is of no importance.

THE COMPUTER ASSISTED FIGURING OF LARGE MIRRORS

D.S. Brown
Grubb Parsons, Newcastle upon Tyne, England

In the past the figuring of large telescope mirrors has been as much an art as a science, but the ratio of science to art is increasing year by year, and perhaps in the foreseeable future the whole process will be understood and under full control. At present we are an appreciable distance from this goal, but over the last few years we have been able to develop computational techniques which have proved of real use in assisting the figuring process.

In order to use a computer for this purpose, one must first have a mathematical model of the polishing process, but it seemed probable from the start of the project that any simple theory would be quite inadequate. The mathematical model used by the skilled optician is probably rather crude, but still takes into account such variables as polisher size, pressure and movement, and the distribution of pitch on the polishing tool. The skilled optician supplements his theory by observing the way in which the results of an operation differ from his expectations, and uses these observations to improve his predictions. With experience the optician separates these observed differences into three groups, those which occur often which he uses subconciously to refine his mathematical model, those which apply only to work with a specific tool or glass, and a third group of random errors.

Before writing a computer programme using this approach it is in practice essential to restrict the range of techniques to be used, since for any specific set of mirror errors there will be many possible solutions to the problem of removing them. For us this did not present a major difficulty, since for some years we have restricted ourselves to the use of full sized polishing tools wherever possible. We believe that the tendency of a large tool to restore rotation symmetry in the mirror is a valuable asset which should be retained, if possible, throughout the figuring process. The main difficulty in using this approach lies in the design of the full sized tool, which must have sufficient stiffness to aid rotational symmetry and also flex enough to ensure a good contact with the mirror when reasonable polisher movements are employed.

The restriction built into our present programmes is not that the tool must be of any particular size, but that the maximum displacement of the tool from the centre of the mirror is limited to a fairly small fraction of the mirror diameter. The complete programme consists of four sections having separate functions, which operate in succession with inputs from the operator

Computer Assisted Figuring Programme

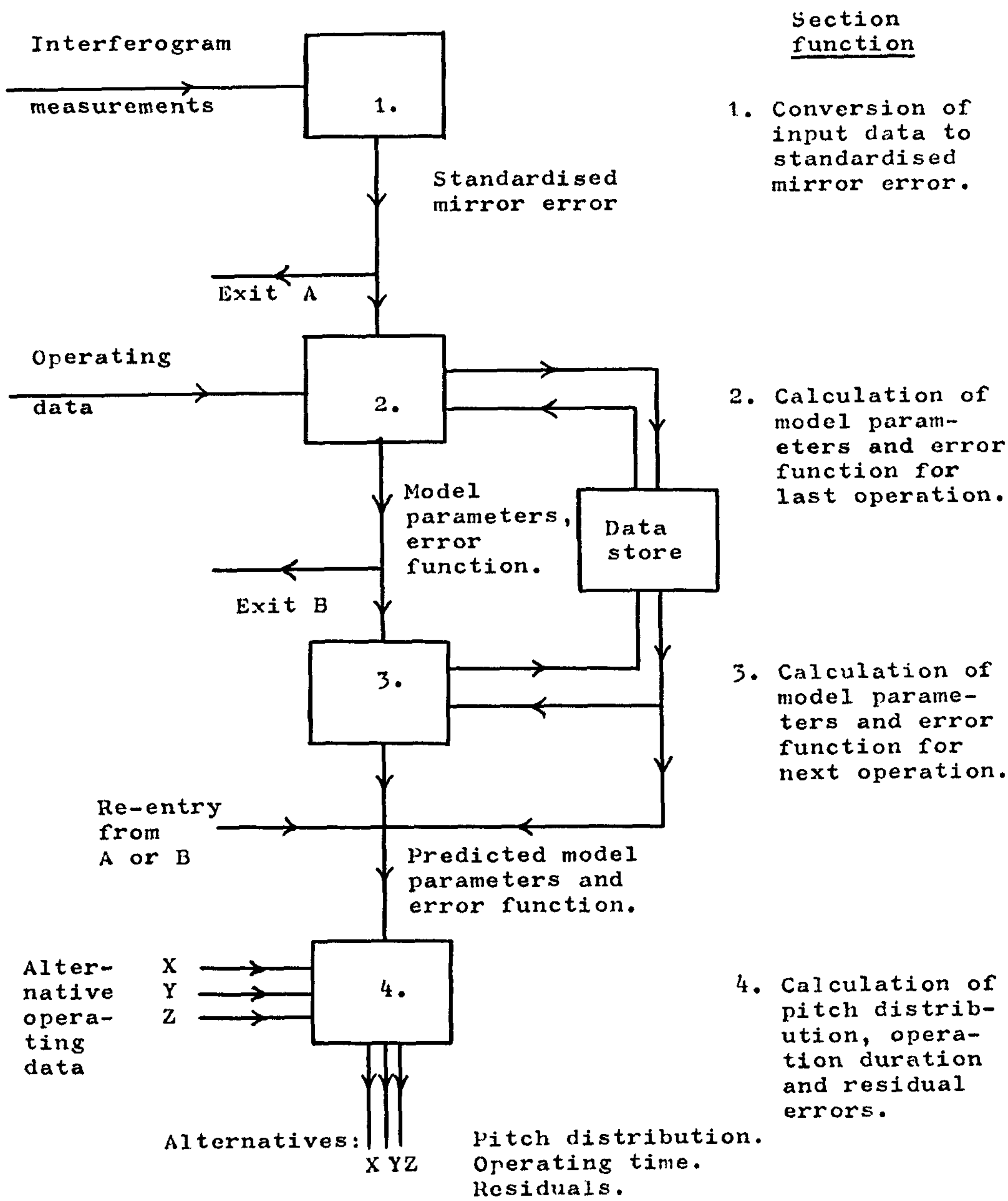


Fig. 1

and from a data store. At present the data store is in the form of punched cards, which is very convenient during the development stage since operator intervention is possible. Originally we had envisaged an internal data store, but the card store has proved so convenient that we do not intend to change in the near future. Fig. 1 is a block diagram of the programme.

The first section accepts data about the mirror shape, and reduces it to a standard reference surface which is everywhere below the real surface, so that all errors are specified by positive numbers representing the material to be removed. In fact we can select any of three alternative input sections, one of which uses data from wavefront shearing interferograms, a second for data from direct reading interferograms, and a third which will process spherometer readings.

The second section of the programme compares the existing mirror errors and those found before the last figuring operation with the operating data, and derives a set of model parameters for the operation, and an error function that describes the lack of fit between the selected model and reality.

The third section examines the model parameters and error function for the operation, relates them to the output data for previous operations, and predicts data for the next operation.

The final section uses this predicted data and the standardized mirror errors to calculate the optimum pitch distribution on the polishing tool, and the time required for removal of the mirror errors for polisher movements specified by the operator. Predicted residuals after the operation are also computed and the results of several different operations may be obtained, and the residualy used as an objective method of determining optimum polisher movement.

When we first started this work, we used an extremely simple model of the polishing process, but since then the error functions obtained have helped us to refine the mathematical model which is now moderately sophisticated. In practice the programmes seem to operate about as well as a good human operator, but we shall need more experience with the programmes before any valid comparison can be made.

DISCUSSION

SCHWESINGER: What is your experience regarding the saving of time with the computer control as compared to the conventional figuring method?

BROWN: Well, so far we are working on a fairly limited sample. We have done two mirrors, a 1.5 and a 1.8 meter, both of them f/3 paraboloids with the computer assistance. Even this sample is not at all uniform because on the

1.8 m we started the figuring operations only two weeks after I managed to get the first sense out of box 2. So we were very much developing the programmes as the figuring progressed. We have sufficient confidence in this approach that we shall be using it on the Anglo-Australian primary and several of the secondaries. The present state is that we save on operating time using the computer programmes, and the total cost is about the same. We are expecting to do significantly better on the next one, simply because the residual outputs which help you to make the decisions are, we believe, very considerably better than they were even two months ago when we last really operated.

FARRELL: Would you prefer to figure a mirror with the plug in the center, and if you also had the choice of the size of the plug, would there be any particular percentage ratio or diameter that you would like to see as a maximum? And if you were to polish without the plug could you predict from your program the motions that are required to prevent removing excess material from the inside edge?

BROWN: First of all I am going to assume that you are talking about largish mirrors, meaning a couple of meters or so. Perhaps I am not the best person to answer as in the 20 years or so that I have been with Grubbs, I can't recall us ever putting the center plug of a large mirror back. The program tells us what is going to happen in the central area and I referred to a sort of hookey type of error near the center. This is related to the presence of the central hole. The program as it is does not tell us what strokes we should use; you tell the program what strokes you are going to try, so there is an area of operator selection. In general the shorter the stroke you use, the less problem you will have in this central area, and the rougher your overall mirror may very well get. But the residual curves we are now getting out of the program do help us to make a fairly sensible choice between the length of stroke and the errors both in the center and at the edge, where you have a similar problem.

DOSSIN: On behalf of Mr. Bayle and Mr. Espiard, I would like to ask if you are able to determine the wear of your pitch, and do you use this as input in your computations?

BROWN: We have tried to feed in amongst the other data a number which relates to the pitch hardness, and this does take care to a limited extent of this problem, but our experience at the moment does not extend to very long runs. All the polishing runs that we have been dealing with with this program have been at a maximum 2 hours duration. I think this problem may become somewhat more acute, for instance when we tackle the Anglo-Australian, we may be facing much longer runs than this. We will then almost certainly break up the run into standard periods of the order of two hours and after each two-hour period the lab. will be restored to its initial condition, as far as we can.

VAUGHAN: I assume you have a machine with a finite number of parameters that you feed into box 2 to describe what was done to the mirror. To what extent is the skill of the optician still required in order to ensure that what he did is what your program thought he did?

BROWN: What we have tried to do is not to dispense with the skill of the optician, but really to re-direct it into thinking which of the polishing movements he should use.

VAUGHAN: It was my impression, although I don't have any experience, that the touch of the optician tells him what is happening to his tool. Is this an important consideration?

BROWN: I have never believed that the touch of the optician was valuable in large work. It certainly is in small work, but we are dealing here with a lab that weighs a ton, and with forces to move it of the order of a ton, and these forces are being supplied by a machine. No, I don't think the touch of the optician has a real place in this particular sort of work. The standardization is extremely important. We have been standardizing such things as pitch and hardness as far as we could for years before we started this operation. Certainly on a job like this the pitch is almost completely standardized, and we measure its hardness. We do in fact put one parameter into the program which relates to the hardness of the pitch, but I don't think this is terribly important. On the other hand I must say that with this sort of fairly complex program, we have now, it is extremely difficult to know quite what the relative importance of different things is. But standardization is really one of the keys. Another one is to restrict the techniques you are using to the one that looks to you to be the most favourable one. We wish to use large tools and we will then give the program the task of really picking pitch distribution as the one thing that it is trying to do.

RIGHINI: What is the upper limit of a piece of optics which require the skill of the optician?

BROWN: Well, we are not trying in this exercise to dispense with skill. Remember this program tells us at its output something about pitch distributions, which are the optimum for particular inputs of polishing movements. And the skill of the optician that we are trying to develop is to choose these intelligently, because for a particular set of mirror errors we can choose from a very wide range. In the past, using the same sort of technique without a computer assistance, our people have been simultaneously trying to tackle the problems of selecting intelligent strokes and for each of them computing the pitch distribution that they should use. But coming to the size of piece at which the skill of the operator is most important, I would guess that when I am trying to deploy our work force to best advantage, I do tend to put our best people onto jobs which are perhaps about one meter, and tasks for example like convex secondary mirrors for the largest telescopes.

ODGERS: What tolerances are you aiming at on the 4 meter Anglo-Australian mirror? What are the specifications set by the astronomers?

BROWN: I think the specification says we have to put 75% into 0ʺ5 or 0ʺ4 and 90% and 98% into some other numbers, but it is a fairly usual sort of specification.

ODGERS: It is tested in the shop in some way, not in the telescope?

BROWN: Yes, we have to demonstrate that the test techniques we employ are adequate, and the test will not initially be made on the support system from the telescope. We will have to separate out any environmental effects that we suspect, such as possible air disturbances and in static air one can have in this size significant air effects. And there is another category which is really the thermal interactions of mirror and cell.

TELESCOPE MOUNTINGS

THURSDAY, MARCH 4

MORNING SESSIONS

Chairman: C. J. Zilverschoon

LARGE TELESCOPE MOUNTS

Bruce H. Rule
Hale Observatories

INTRODUCTION

The increased interest and commitments of astronomy to expanding research problems require an ever larger light gathering area with higher optical efficiency and more stable mounts. New large telescopes include improvements of shorter primary "f" ratios, better optics support systems, stiffer mounts with modern drive components, to take advantage of better "seeing" and site environment conditions now possible at many newly developed good observatory sites throughout the world.

HISTORICAL EVOLUTION

A few words about the important evolutionary trends of large telescopes will help to explain the current and future possible advanced mount technology.

The first major reflecting telescopes were by Herschel, with a 48-inch (1.2 m) in 1789 and by Lord Rosse, with a 72-inch (1.8 m) in 1845. However these reflectors were made with inefficient speculum metal mirrors, so, for a time until large glass blanks became feasible, the astronomers shifted to long focal length refractors such as the Lick 36-inch and the Yerkes 40-inch. After the turn of the century, silver on glass, then later vacuum aluminizing became practical along with grinding techniques for shorter focal lengths, resulting in the development of a series of larger telescopes including the Victoria 72-inch, Mount Wilson 100-inch, Mac Donald 84-inch and others - and finally the Palomar Hale 200-inch in 1948 using low coefficient Pyrex glass and utilizing all possible experience with lightweight mirror blanks, compensating structures, low friction supports, precise drives, and using the best available techniques at that time.

There are now over 220 observatories throughout the world with telescopes of all types. About 15 have mirror diameters of about 36 inches (1 meter). There are now 15 with 48-inch (1.2 meter) up to 60-inch (1.5 meter) similar to the new 60-inch at Palomar. There are only 4 with 100-inch (2.5 meter) or larger, plus the 120-inch (3.0 meter) and 200-inch (5.1 meter) in California. However, we are hearing about at least 6 telescopes in the 150-inch class (3.8 meters) that are being planned or under construction, in addition to the Russian 240-inch (5.8 meters).

PROGRESS IN LARGER SIZE TELESCOPES

Of the presently operating large telescopes, the performance of the Palomar 200-inch has been very successful. The excellence of this instrument has led to a considerable understanding of mount structures, mirror supports, drive technology, and large precise manufacturing capabilities. Especially important also is the recent development of large homogeneous, low stress, low expansion coefficient mirror blanks which provide highly stable optical properties.

The optical quality improvements have consequently required design emphasis and advancement in method of mounting and support systems to keep up with the critical optical systems now planned.

The refractor lens objective was limited in size (aside from optical transmission losses) by the necessity of support at the rim, but the reflector is essentially now unlimited in size, if the surface contour is maintained "gravity free" by low loss supports in areas over the entire back and/or sides of the mirror.

Much information relating to sizes and construction problems has already been reviewed in past telescope symposiums such as I.A.U. #27 in Arizona and California (1965), University of Arizona and Kitt Peak National Observatory (December 1966), NASA Optical Telescope Technology at Alabama (April 1969), together with many recent published reports of design groups at major observatories. The basic telescope requirements have not changed much in scope but rather in quality, accuracy, and observational efficiency. Many variations in telescope mounts have evolved over the years, aided by the ingenuity of designers, application of analytical studies, increased manufacturing finesse and better materials. Until the present period, with several projects of the 150-inch (3.5+ meters) class in process, hardly any have been alike.

It is appropriate therefore to discuss the characteristic criteria of quality designs for large mounts. Other contributors will present more specific details about structural studies and conclusions for current telescope projects.

TELESCOPE MOUNT CHARACTERISTICS

The telescope mount is a rotatable structure to support the optical elements in a fixed relationship with exact collimation to point the optical axis over the sky range and maintain tracking or following a given object to a high degree of accuracy, usually correctable to less than 1/2 arc second to provide resolution of faint star images under best "seeing" conditions. The accuracy factors involve not only the production of high quality optical systems but also control of the gravity deformation, driving smoothness, and environmental effects by integrated structural-mechanical concepts and passive or active servo compensation design features.

Engineering and construction difficulties arise with increased size, areas go up as the square of the aperture, weight goes up as the cube, but the optical and alignment tolerance must be the same or smaller, or about one arc second. The overall design concept is usually a rational compromise between the needs of the optical system, limitations of the mount structure, instrumentation, program operating needs, and the protective dome size. Good technical planning and trade-off of details is required since no ground-based telescope is ever constructed quite satisfactorily with the stability and accuracy that is possible with present optical quality and diverse detectors or photographic instrumentation. The major problem is designing the mount with adequate stiffness and compensation for gravity deformations to meet the optical tolerance.

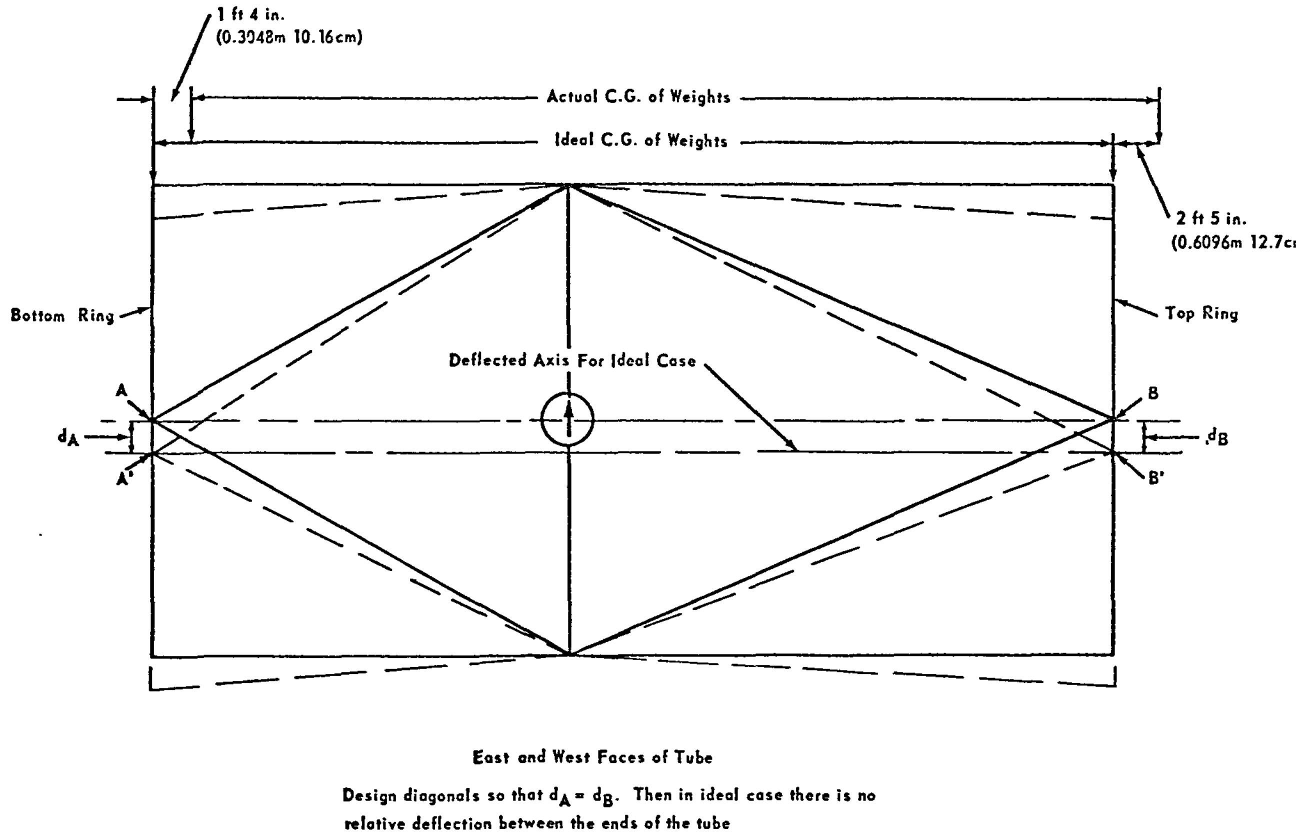
OTHER GENERAL MOUNT REQUIREMENTS

Moreover there are other considerations of efficiency in matters of: cost, fabrication and assembly logistics, ease of operations, and long maintenance life.

Ancient telescopes were hand-held, pivoted about the body axis in azimuth and elevated by the arms. It was recognised very early by Isaac Newton and others that a mount axis parallel to the earth's polar axis to "unwind" the earth's rotation would provide easy, uniform star tracking with an adjustable declination axis for the main optical system. These equatorial or polar axis mounts in various forms have been standard for over two hundred years. They have the advantage of a simple axis system with nearly constant tracking motion about only the polar axis with no rotation of the star field. However with very large telescopes, and particularly with massive radio telescopes, the tilted polar axis becomes excessively difficult and the aperture may be longer than the allowable short polar bearing. The large over-hanging structure becomes unwieldy. Heavy construction may become easier with the alt-azimuth configuration, but at the expense of simple drive and optical field rotation. However, with present availability of computer conversion techniques and precise servo-drive for two axis alt-azimuth motion, star tracking is accomplished with only a small loss of sky area at the zenith "dead zone" of 180 degree rotation of azimuth axis.

For these discussions on the mount, the arguments apply mainly for large equatorial axis arrangement generally preferred up to 200 inches, but apply in general also to large alt-azimuth configurations. The main optical tube structure in either case is the same.

The mount stiffness is relatively easy to accomplish in telescopes, say below 60 inches (1.5 meters) where the practical fabricated member sizes are short with large area sections and total moving weight up to about 10 tons



Deflection-idealized tube.

(9000 kg). However, in the larger telescopes the problems of gravity deformations, thermal expansions, non-uniform loadings, and drive torques increase with such rapidity that only carefully integrated, preferably symmetrical, designed mounts are adequate. Also any excess weight or large off-axis counterweights, or non-symmetrical loading scheme unduly loads the structure, the axis bearings and unbalances drive torques.

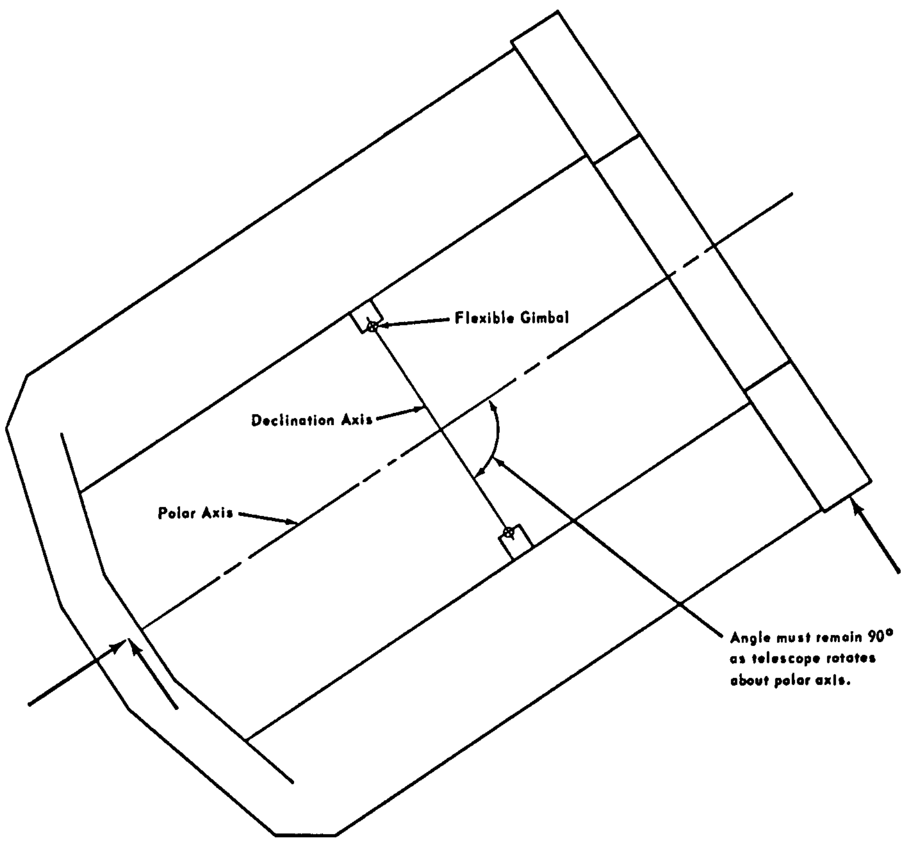
EFFECT OF OPTICAL PARAMETERS ON MOUNT STIFFNESS

One of the first parameters fixed in a new telescope is the optical focal ratio. Lower primary "f" ratio affects the size and overall cost by shortening the main tube, providing less massive structures, shortening the fork or yoke and axis assembly, allowing easier access to Cassegrain or prime focus station, and in particular lowers the size and cost of the dome. Consequently the old traditional f/5 primary for large systems has given way to the smaller values. Since the completion of the Palomar 200-inch with a primary f/3.3, opticians have succeeded in making good deep, large diameter aspherics with f ratios down to f/2.5, but with special efforts and problems in figuring the surfaces.

The desire for large angular photographic fields requires the addition of a corrector lens ahead of the prime focus of Cassegrain focus. The overall optical efficiency is now usually maximized for the easier Cassegrain position where the performance is essentially independent of the primary f ratio (see publication by I.S. Bowen and A.B. Meinel), so that simple mount arrangements are possible that make the complex prime focus position less essential.

The sensitivity of the Cassegrain focal plane to collimation errors is proportional to the collimation error divided by the focal length squared ($e = \frac{\Delta}{F^2}$). However, the decollimation due to gravitational deflection is proportional to distance between optical elements times the cube of the focal length $\Delta = 1F^3$, so that the net decollimation error varies as the length times F^2 for massive structures, but if the secondary is lightweight and a small fraction of the tube mass, the Cassegrain error fraction could be as low as 1 x F, and a compact length for low primary f ratios.

To summarize, the optics of large telescopes usually require primary ratios of about f/3.0, with difficulties in primary optics below f/2.5, with Cassegrain ratios of about f/8 or larger for photographic and detector instruments, and coudé ratio of long focal length to reach the remote stationary coudé room, of about f/30.



Deflection of yoke.

ELEMENTS OF THE TELESCOPE TUBE

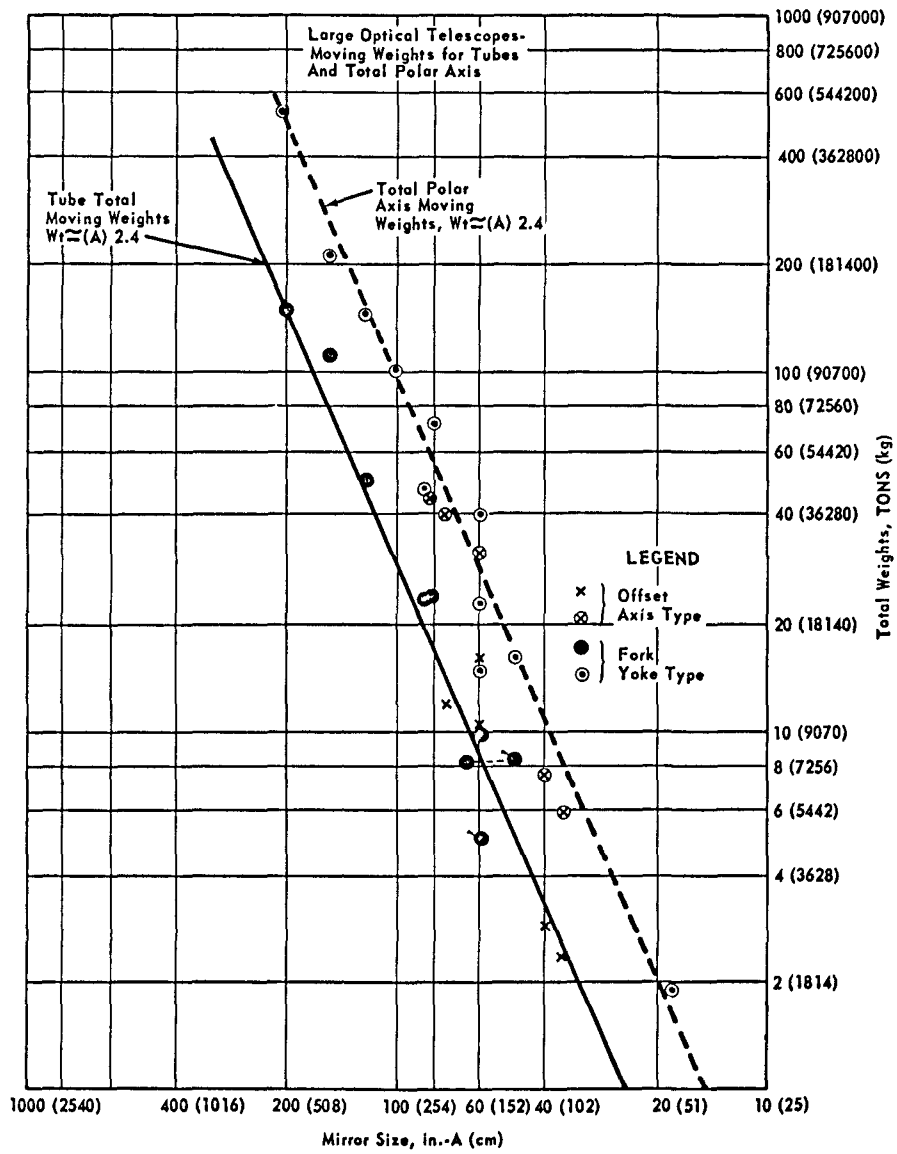
Past discussions and E. Pearson have adequately covered the development of various methods of large gravity compensated mirror supports. These improvements, including precise lever systems, air regulated bags, mercury rings, etc., assure large mirror supports having very low friction, low hysteresis, and defining reactions to less than 1/2 percent. The support applications, together with low coefficient mirror materials, now places the main burden of advancement on the telescope "tube" assembly.

The basic telescope tube must meet critical optical alignment and stable mirror support tolerances. It consists generally of a structural frame balanced about the rotation axis, having at the lower end the cell and support system for the primary mirror, and at the upper end a focusable prime focus or alternate focusable secondary mirrors for Cassegrain or coudé. The tube is symmetrical about the optical axis to provide uniform bending with lowest possible tilting of the ends with various zenith angle positions. In order to minimize these decollimation effects, by far the best tube compensating structure is the four-sided parallelogram type truss (Serrurier truss) which allows reasonably large tube end deflections without end tilt so that the optical collimation axis between primary and secondary is maintained. For example the 200-inch telescope tube weighing 140 tons (137.000 kg) flexes about one centimeter in extreme angles, but the optical axis decollimation is only 1/4 mm. (See slides of 200-inch truss). The upper and lower lengths of this truss are about equal, but subsequent designs have obtained satisfactory compensation with upper to lower length ratios up to about 4.5 to one by designing greater flexure into lower truss members to match the upper deflections.

The base attachment of this compensation truss, or any tube structure, requires special attention to retain the shape at the declination hub and to maintain this precise axis of rotation and transfer the high tube loads without excessive bending and torsion effects to the bearings, which in the case of equatorial mounts forces a change from radial to end axial thrust, or nearly pure radial load in the case of alt-azimuth mount.

The major structural change in this simple tube concept occurs in providing the clearance to bring out the coudé light beam from a third flat mirror at the tube and declination axis intersection. Many coudé examples can be seen in present telescope designs involving slots in the side of the tube for three, four, or five mirror combinations. Other arrangements extend the coudé beam through the declination axis on either the offset or fork type in which the beam is brought down through the hollow fork tine.

This external coudé beam also seriously affects the design of the polar axis structure, which will be discussed further on. There is greater emphasis now on low incidence reflection losses and minimum number of mirrors, so that several schemes for three-mirror systems are proposed. Unfortunately



Weight distribution for large telescopes.

nearly all of these require adequately long and wide unobstructed clearance slots in the main tube structure.

One of the proposals being considered for the Las Campanas, Chile, 100-inch (2.5 meter) Du Pont Telescope involves a 10 degree below horizon, three-mirror coudé system toward the open south pole that uses the slot space between the north or south tube truss members but extends all the way down through the open declination hub to level of the primary mirror. Initial designs indicate the deep slotted hub can be compensating and its flexure relatively independent of the critical optical axis.

It is clear that with larger optics and the more difficult flexure problems in both tube and mount axis, greater design gains are now possible using lightweight mirror blanks, especially for the secondary mirrors. Manufacturing techniques now prevail to fabricate high quality mirror blanks that are less in weight than the solids by amounts up to 60% or more, at reasonable cost increases. By such weight savings, the secondary assembly mass is reduced, tube moments and gravity flexure reduced. They also permit moving the lower primary mirror closer to the declination axis and give more room at the Cassegrain. For each pound saved in the mirror blanks, about three pounds are saved in the overall telescope mount, which may also reduce the net cost by a considerable amount (see also A. Meinel report on 1.8 meter lightweight doubly asymmetric design). In addition the lightweight mirrors reduce the drive and inertia problems.

There are of course other tube accessory requirements to accommodate the lower Cassegrain instrumentation - the central coudé flat, the prime focus cage or flip-over secondary cage, or interchangeable cage rings. Each of these must balance and be safely rigid to meet the optical criteria. There are many examples of manual and automatic mirror change features in current telescope projects.

With the elements of the optical system and telescope tube defined here, the tube weights of most telescopes (except the reductions for lightweight designs) are fairly predictable by some power of the aperture size. A plot of most of the existing known tube moving weights shows the tube weight proportional to about the 2.4 power of the mirror size (see slide of weight distribution). The plot also shows the total polar axis and tube moving weights for all types of offset (asymmetrical class) and all types of fork and yokes (symmetrical class). Here the scatter is broad below the 60-inch size which includes all types, whereas above the 60-inch size most combined weights are for symmetrical fork and yoke type, generally preferred for the largest mounts.

Equatorial telescopes are generally classified either as "symmetrical" such as the fork, yoke, or modified horseshoe type, or as "asymmetrical" such as cross axis or offset fork types.

The asymmetrical class is used quite frequently for the advantages of access to the Cassegrain and polar region, especially in small sizes where the off-axis space, redundant counter-balance and non-concentricity with the dome is not too critical. Examples cover a wide range up to the 82-inch and 108-inch at McDonald Observatory, the 72-inch at Victoria, and the bent fork design of the 98-inch at Mauna Kea, Hawaii. The radial sweep of the Cassegrain station is large and usually requires an elevating floor.

With larger sizes the structural problems become difficult due to the large tube counterweights required, the overhang of the main tube axis, and the off-center orientation with the dome and shutter.

The space limitations of the smaller symmetrical telescope classes diminish as the size increases, the elimination of the extra tube counterweight decreases the structural problems, the fork or yoke provides a more rigid, wider spaced declination axis bearing, and the concentricity with the dome provides better clearance safety and access to observing stations and cages. The lower tube is usually shorter and smaller sweep radius of the Cassegrain focus so that "stand up" operations without elaborate rising platforms are possible, such as represented by Schmidt telescopes and various 36-inch to 60-inch sizes similar to the new 60-inch photometric telescope at Palomar and the 60-year old 60-inch telescope at Mount Wilson.

In the larger sizes of symmetrical classes there are examples of nearly every type from the Lick Observatory 120-inch (3.0 meter) fork type, the Mount Wilson 100-inch (2.5 meter) closed yoke type, the 200-inch (5 meter) open yoke horseshoe, and of course the exceptional 240-inch (6 meter) alt-azimuth Russian type.

Of the current 150 inch (3.8 meter) series under way, all are symmetrical and range from fork, open yoke and horseshoe, and modified short yoke and horseshoe.

In all of these symmetrical classes the axis bearings to maintain a constant angle are either flotation systems (Mount Wilson) or low friction hydrostatic oil pad systems that now permit rotating very large massive mount structures accurately and at low torques; i.e. the 550 ton (500.000kg) weight of the 200 inch rotates with only 50 ft. lbs. torque while tracking with a viscous friction coefficient of 2×10^{-6}.

STRUCTURAL ASPECTS OF LARGE SYMMETRICAL MOUNTS

Two principal structural-mechanical problems must be met for large axis mounts. One is to maintain the polar angle within a few seconds of arc over the range of six hours rotation east or west. With a reasonably long bearing separation the axis can be held differentially by oil pads to less than 0.001 inch (1/40 mm) or about 1/5 of total oil film thickness (or $\pm$ 1 arc second), but the different deflection modes of the yoke or fork at 90° east or west are difficult to design equal due to the asymmetry of the fork or yoke in the two 90° planes. The yoke side members deformation can be similar, but the yoke cross member and/or north horseshoe may produce inequalities that result in optimum deflection errors up to 30 arc seconds over 6 hours of rotation (90°). Structural computer studies are required to reduce this long-period error and the residual must be programmed out by the drive servo system.

Since the deflections go as l^3, the cantilever open fork deflection asymmetry is even more difficult, so that upper feasible limits are usually reached at about the 150-inch size.

The other principal structural-mechanical problem is the declination axis which must be maintained at 90° to the polar axis with rotation of the tube about its own axis as well as with rotation of the yoke about the polar axis. Therefore particular attention must be given to the declination bearing loads and the effects of bending and torsion at this axis and the interaction of this load with the bending and torsion of the yoke or fork bearing housing. The particular bearing design for radial and thrust loads must allow for either free flexure, while maintaining thrust definition free of yoke deformation, or designed as a full moment bearing taking advantage of the bending and/or torsional stiffness of the fork or yoke. In general a good match must be made between the stiffness (spring constant) of the tube hub and the yoke. Careful analysis of the structure and bearing characteristics at this juncture is required in order to provide smooth "zero rate" motion of declination without binding or sliding of ball bearings after motion of the polar axis and consequent yoke deflection.

Another aspect of the yoke design involves sufficiently short and large diameter polar shaft to drive gear to keep torsional "windup" small and prevent oscillation with such large inertia and low friction damping.

As noted above for the optical clearances on the main telescope tube to bring the coudé light beam out, there may be added constriction if the coudé beam is brought through the fork and polar axis.

STRUCTURAL-MECHANICAL ANALYSIS AIDS

As larger telescope designs approach these critical limits for common materials, the small effects of joints, connections, load concentration, and unsymmetrical or nonlinear conditions, that are normally neglected in overdesigned smaller structures, must be included for good performance. The complexity of accounting for the many and redundant members is greatly enhanced with the aid of structural computer programs. The overall structure and most subassemblies are now optimized much more quickly and confidently by such programs.

EXCERPT from an engineering report on the type of mount for the 200-inch Hale Telescope, May 1935. Simple fork type versus yoke type which was recommended for rigidity.

After a good detailed analysis, the report concludes:

Cost of Mount:

The question of cost was touched upon. The figures mentioned naturally varied. We arrived at an approximate cost of 60 cents per lb. for the yoke type of mount and 75 cents per lb. for the heavier fork type, this cost including all machining and assembly. This cost is rather high, but the manufacture must be of the highest quality. These figures give an additional reason against the choice of the fork type. With this differential in price per pound, and with the much greater weight, the fork type will be considerably more expensive.

Recommendations:

a. Choose the yoke type of mount as one being mechanically superior.

b. Build inexpensive scale models (1 inch to 1 foot) of the box and truss type of yokes with the tube in place so as to decide which type has the more pleasing appearance.

c. Strengthen the truss type, which type we prefer, by introducing torque members in the form of rectangular box girders 36" x 36" x 1-1/2". (The final was 16'-6 Ø).

d. After the general design has been chosen, make an exhaustive analysis of the deflections of the mount and tube as a whole.

e. Build a model of the tube and mount properly dimensioned (1/10 to 1/2 full size) to verify and amplify by direct measurement the behaviour of the mechanism for all angles and positions.

f. Build the yoke support of structural steel and rest it on rollers, in order to allow for thermal expansion free from the foundation. (Final : oil-pads).

g. Award the contract for the tube and mount so that the previous experience of the manufacturer in building comparable structures, together with his facilities, personnel, and shipping possibilities are all considered.

h. Specify a manufacturing procedure.

i. Specify that all motors have armatures of superior balance, make provision for vibration absorbing bedplates under all motors driving the various mechanisms on the tube and mount, and also provision for a spring supported stand for the observer, so as to avoid the main vibration effects.

Is this much different from what we are doing today?

DISCUSSION

ELSÄSSER: If you would construct today another 200" telescope, would you again use two worm wheels for the drive?
RULE: I think it would depend on how the encoding would be done. We have not discussed drives today, that is a big subject, but I would like to point out one additional thing about the spur gear. If you use the spur gear for accelerating the telescope, the high efficiency then is also available for the slewing, but the fine motion is to be corrected by a servo system taken somewhere else off the system, for instance off the polar axis. This then changes the whole problem, because in the 200" we were required to take the accuracy readings off the worm which had to be designed for the accelerating load as well as for the indication. So it would depend on the system. If it could be done by a servo loop - which Mr. Dennison says we can do - then I think we would modify the drive.
BORGMAN: You emphasized the desirability to have a low-weight upper end of the telescope. I wonder in this connection whether that does not speak in favour of exchanging the complete upper ends rather than having flip-tops and if so, what is the highest weight at the upper end? Will it be the Ritchey-Chrétien secondary or will it be the primary cage?
RULE: Well, that is a little difficult to answer. This is where the compromise comes in. If it is to be a system of primary cage as well as secondary mirror, then you are going to be hard pressed to get the weight down low enough to get a reasonably high ratio between the top and the bottom. This is one of the reasons which has lead to the philosophy of separate cages, which are interchangeable and do not have to carry the double weight.

Another point which I would like to mention is that for every pound that you save in the secondary mirrors, you save about 3 pounds in the total construction which is not only dollars, but represents quite a change in the flexure and the moments. So the optimum has to be worked out for each case, depending on the size of the secondary. For example, if you have wide-field Cassegrain optics, than you are going to have a secondary mirror which might be 30 - 40% of the aperture; this forces you to go to pretty light-weight mirrors. If on the other hand you use a coudé system of small secondary mirrors, such as has been recommended by Richardson, then there may not be any problem.
BORGMAN: It does answer my question, but I just wondered whether somebody from the ESO team could tell me the difference in weight between the secondary for the Ritchey-Chrétien system and the primary cage?
RICHTER: The Cassegrain and coudé secondary mirrors are the heaviest pieces there. The primary cage will be less heavy so the whole assembly has to be made for the secondaries and dead weights for the primary cage must be put in. Another complication is that the center of gravity is not the same in the two cases, so the dead weights for the primary cage have to be put rather far down

to compensate for this.

ROOSEVELD VAN DER VEN: What is the reason for the top tube ring on the 200"?

RULE: Well, that was to provide a stiff enough cage to take the knife edge forces. There are two sets of knife edges. The lower set carries the mirror cell and the upper set the observer, so it had to be long enough for a two knife edge system.

ROSSEVELD VAN DER VEN: But doesn't it conflict the compensation of the Serrurier system?

RULE: That is right. However, Mr. Pope is going to tell you a little more about the deflection of the top end. In the case of the 200" it was adequately rigid enough for that.

RICHTER: If one leaves out the lower Serrurier system, and replaces it by flexion bars - as is the case for the ESO telescope, where we have 6 flexion bars to carry the mirror cell and an upper Serrurier system which is made out of 4 parts - then you must change over from a 4-point system to a 6-point system in your center section. And then the center section becomes a somewhat weaker piece.

RULE: Well, I am not able to comment on that without seeing the design, but there is a problem going from 4-point to 6-point.

RICHTER: What I wanted to mention is that it is a very important thing in the design of this center section; you need much more stiffness or, if you keep it flexible, then you have to use this flexibility to compensate for instance for the tilt of the secondary mirror. This may well be possible.

FARRELL: What is the stress level in the south beam for the 200" or the deflections of the ends of that beam?

RULE: I think it is of the order of 6 - 8000 PSI at the most. It depends on what part of the beam; the south cross beam has the spherical cap in it, so the loads out on this region are fairly low because it is a 10ft. 6" diameter tube. In the region where the spherical bearings are the stresses go up at 30 - 40.000 PSI, so this had to be stiffened.

CAYREL: Could you comment on the yoke against fork choice according to the latitude of the instrument?

RULE: I think it is obvious that at the higher latitudes the polar axis is such that it is much easier to reach the horizon, whereas at lower latitudes you have difficulties in bringing the tube down on the horizon. Therefore, you have to cut out the fork or the horseshoe. Another comment has to do with the polar axis bearing. At higher latitudes the bearing reactions can be directed towards the center of gravity like the Hamburg-Schmidt - it's a good example of the single spherical bearing and it has a reaction almost exactly at the center of gravity. And then the length of the polar axis is affected because if you are at a very low latitude the polar axis can be quite long. However, that requires a very much larger dome, so it is also related to the size of the dome. So there are always rational compromises between these various parameters, and latitude does have a great deal to do with it.

BAHNER: A question to the astronomers in this context: what is the real elevation above the horizon we need for observing with a large telescope?

RULE: There is quite a lot of difference of opinion. I can only give my own and that of my own group. You pay quite a bit to have to go down to the horizon because of the difficulty I just mentioned and most astronomers are willing to compromise for around 8 - 10° because of refraction and other things. And the other compromise is that with the fork-type or the horse-shoe-type you can always go to the horizon in one direction which is a very necessary requirement for cage changes or collimation.

REDMAN: I am very strongly of the opinion that it is foolish to go below 30° above the horizon in using a large telescope; you only have to look at the refraction.

HERBIG: I have to disagree with that one. Once in a while there is an unusual event of extraordinary importance, which seems to take place at 8^h hour-angle. There is one going on right now in the North American Nebulae, when the object is in conjunction with the sun, and the 120" has a 6^h east hour-angle limit. We went to the limit switches and waited for this star to come up and then turned the drive on when it appeared in the field and followed it up for about 20 minutes before the sun rose. If we had only been able to get down another hour, it would have been worth a great deal. The same thing happens with an occasional bright comet which always occurs at some place which the limits don't want you to obtain. So even though you are not going to encourage routine observations at those positions, I would like to emphasize the option of being able to get there, with some difficulty perhaps, but being able to get there.

REDMAN: If the Almighty is against you, you can't win!

CRAWFORD: I think the answer to the question or comment of Herbig and Redman is that it depends also on your observatory make-up of telescopes. I think that we would be quite willing to compromise on the 150" at Kitt Peak in sky coverage because we have an 84" that will go to the horizon and which will carry almost all the 150" equipment. Without that, then no question, you should have the coverage on the other.

OPTICAL PERFORMANCE CRITERIA

FOR TELESCOPE TUBE DESIGN

J.D. Pope
Anglo-Australian Telescope Project

SUMMARY

This paper describes the types of deformation commonly encountered in the Serrurier truss form of tube used in modern large telescopes. It examines the effects of these deformations on the optical performance of the telescope and shows how parametric equations can be derived which establish rational criteria for the design of tube components.

Examples of deflections calculated for the Anglo-Australian Telescope are given and these have been applied to the parametric equations to show how the design criteria have been met for this telescope.

THE TELESCOPE TUBE

The telescope tube today almost invariably takes the form of an open truss assembly first proposed by M. Serrurier for the 200-inch or 5-metre telescope of the Hale Observatories. This form of tube provides a high stiffness-to-weight ratio and, like a true tube, exhibits substantially the same stiffness in all radial directions. The ideal form of a Serrurier truss telescope tube is shown in figure 1.

The upper and lower trusses are attached to a heavy centre section in the plane of the declination axis. The upper and lower trusses are usually unequal in length and they terminate in the planes containing the centres of gravity of the loads they support. The cross-sectional area of the short lower truss members is less than that of the upper trusses and is chosen so that the deflections of the upper and lower ends are equal. Thus, in the ideal case, as the tube assembly moves from the zenith position towards the horizontal the optical axis moves parallel to itself and introduces neither optical aberrations nor telescope pointing error.

The loads at the ends of the tube act through the apexes of the trusses so that the turning moment is zero and the upper and lower end rings remain parallel to each other as the tube assembly deflects. For this to happen it is of course necessary that the trusses are themselves parallel to each other.

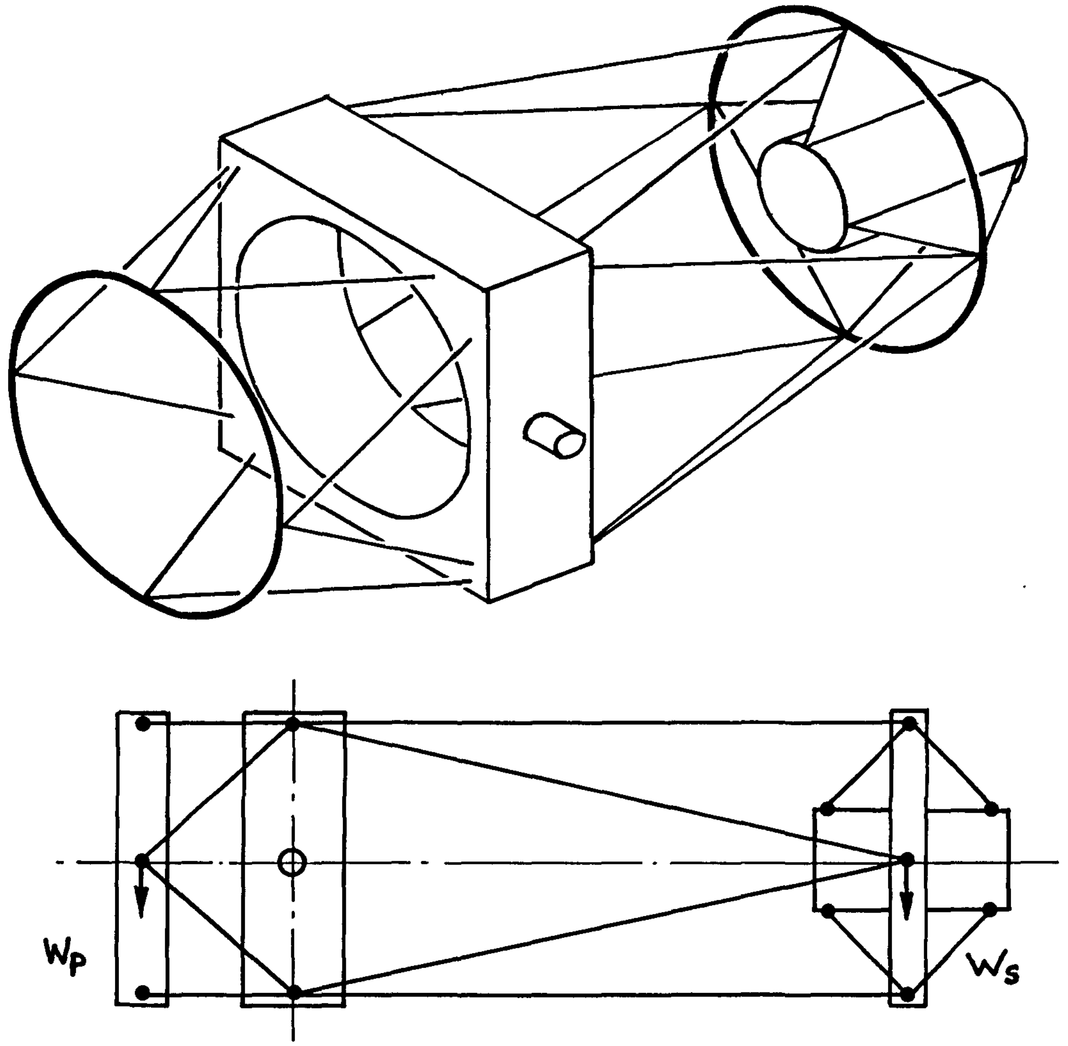


Fig. 1 Ideal Serrurier truss assembly.

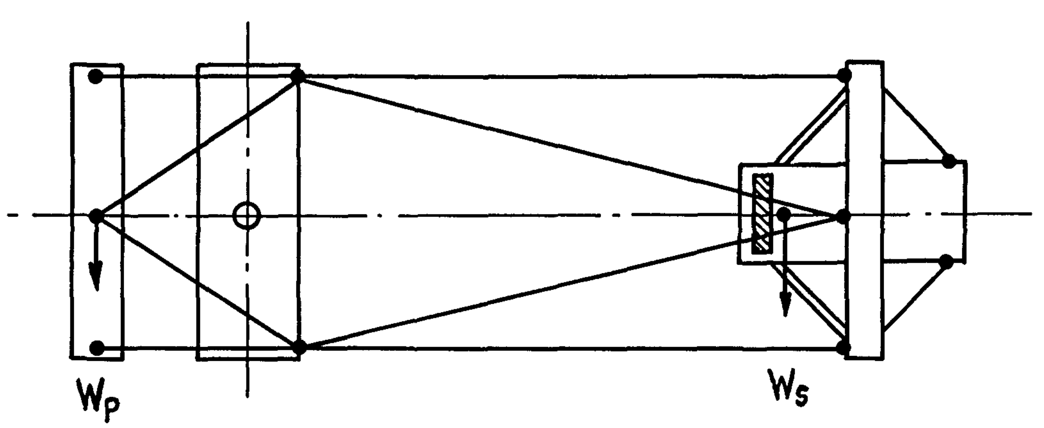


Fig. 2 Serrurier truss assembly in practice.

This then is the ideal case. In practice a telescope tube assembly usually resembles the one shown in figure 2.

With most equatorial mountings there is a requirement to locate the primary mirror as close to the declination axis as possible in order to minimize polar axis structural deflections resulting from long declination axis supports, i.e. , fork tines or horseshoe arms. As a result the length of the lower trusses can be so reduced that it becomes impossible to obtain the same deflection as for the upper trusses without making the cross-sectional area so small that the stresses in the steel become dangerously high. This situation can be eased in practice by connecting the upper and lower trusses together, not in the plane of the declination axis, but at the upper plate of the centre section. With this arrangement the components of the forces acting at the bases of the upper and lower trusses in a direction parallel to the telescope tube axis are no longer equal and opposite. Consequently, the centre section is subjected to additional forces at the points of attachment of the trusses. However, it is not difficult to increase the stiffness of the centre section to withstand these forces and the resultant weight increase is of little consequence as it occurs close to the declination axis.

If the astronomers wish the telescope to be capable of operation at any one of the three focal positions, prime focus, Cassegrain and coudé, and they usually do, then the engineers will have to make provision for mounting the prime focus assembly and the various secondary mirrors at the upper end of the tube. If a composite assembly can be produced containing all the necessary components on hinged arms or rotating mounts then the centre of gravity of the whole can be made to lie in the same plane as the ends of the Serrurier trusses.

However the chosen F ratio for the primary mirror and/or the size of the Cassegrain secondary mirror may not permit the adoption of a composite upper end and the engineers may have to make provision for interchangeable upper end assemblies. One would probably carry the prime focus assembly, another the Cassegrain secondary mirror and a third the coudé secondary mirror perhaps together with another Cassegrain mirror.

It is difficult to arrange for the centres of gravity of three such end rings to lie in the same plane as the ends of the Serrurier trusses. For example, an f/8 secondary mirror working with a primary mirror of 12.5m focal length would have to be positioned about 4m inside focus and the f/35 coudé mirror 2m inside focus. In a case like this the Serrurier trusses would be terminated at a mean position about 2m inside focus. The centre of gravity of the prime focus assembly would then be about 1m beyond the end of the trusses and that of the f/8 secondary mirror assembly a similar distance inside the end of the trusses.

The centres of gravity of these upper end assemblies can be brought

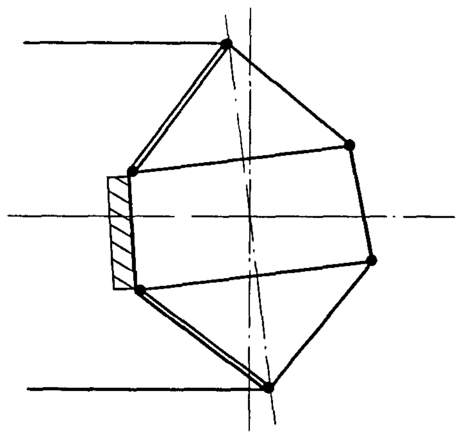


Fig. 3 Deformations of secondary mirror supporting structure.

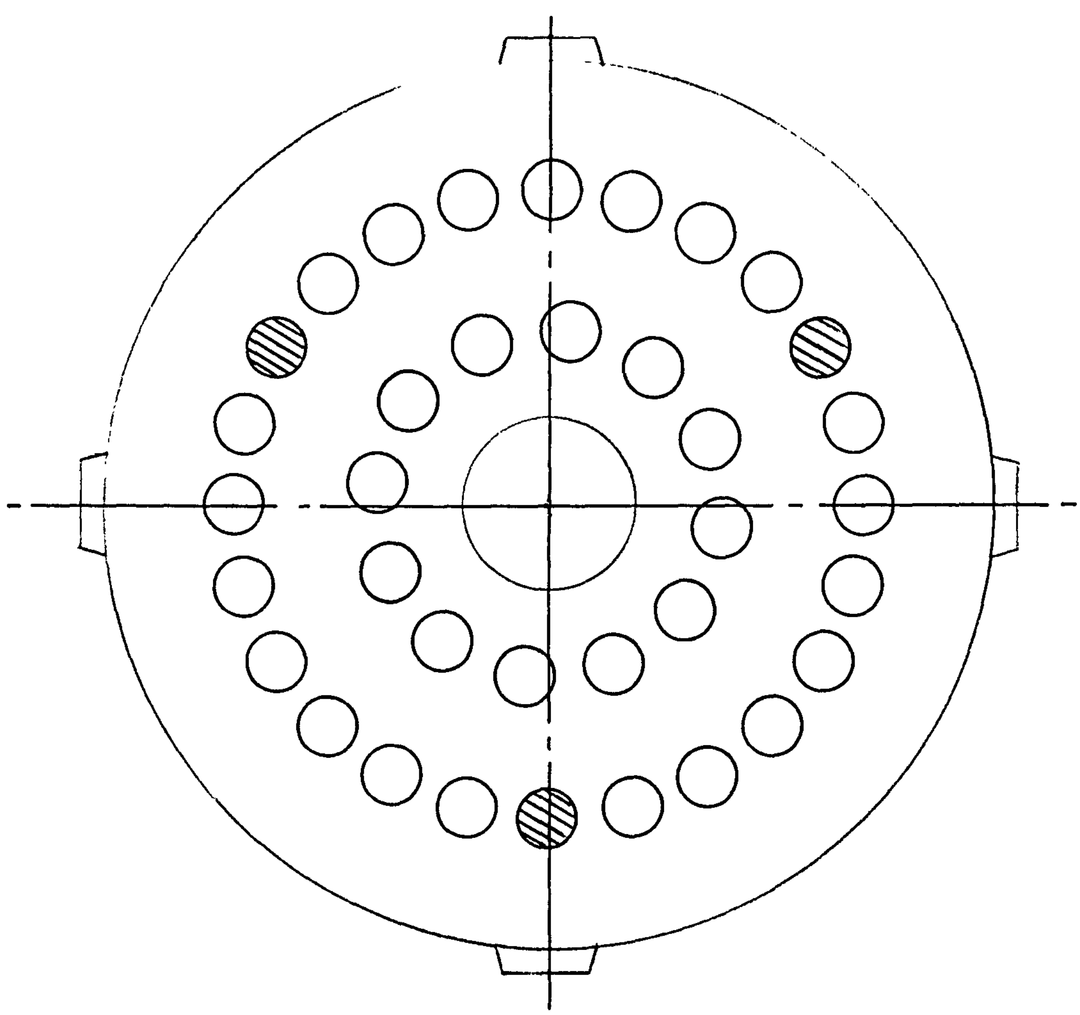


Fig. 4 Position in defining points in primary mirror cell.

into the plane of the truss end ring by adding balance weights, but these are likely to be heavy, perhaps as much as 1.000Kg. Because of the unequal lengths of the upper and lower trusses another 6.000Kg. would be required to balance the tube again. The total increase of 7.000Kg. would appear as an additional load on the declination bearings with an accompanying increase in frictional torque.

The designer will probably prefer to leave the upper end assemblies unbalanced and endeavour to ensure that the rotation or tilt of the end assemblies are made acceptably low. Tilt of the whole upper end assembly results from the axial compliance of the trusses and end connections. Further tilt would result from the unbalanced load within the vane assembly, but it is possible to make the cross-sectional area of the leading and trailing vanes unequal so that the vane assembly deflects in a parallel fashion. The formula for determining the ratio of vane sizes for parallel deflection takes the form:

$$\frac{A_1}{A_2} = \left[\frac{m_2 + a}{m_1 - a}\right] \frac{L_1^3}{L_2^3}$$

where A_1 and A_2 are the cross-sectional areas of the larger and smaller vanes,

m_1 and m_2 are the distances between the central plane of the upper end ring and the points of intersection in space of the larger and smaller vanes on the centre line of the telescope tube axis,

L_1 and L_2 are the lengths of the larger and smaller vanes,

a is the distance between the central plane of the upper end ring and the centre of gravity of the supported central assembly.

In principle it would be possible to choose vane sizes that result in sufficient tilt in the opposite direction to compensate for the tilt of the whole upper end assembly, but in practice this could require the cross-sectional area of the vanes to be so small that buckling becomes a problem.

There is yet another structural deformation that can cause tilt of a secondary mirror and this results from the lack of rigidity of the drum structure within the vanes. With the tube horizontal the upper longitudinal member of the central drum is subject to compressive forces while the lower member is subject to tensile forces. This results in trapezoidal distortion as shown in figure 3 which tilts the secondary mirror in the opposite direction to the tilt experienced by the end ring and so reduces its effect.

These then are some of the structural deformations that can cause rotation or tilt of the prime focus assembly and the secondary mirrors.

It is now necessary to examine the structure supporting the primary mirror to determine whether it causes any rotation of that mirror.

It is not difficult to arrange for the lower trusses to be attached to the primary mirror cell in the plane containing the centre of gravity of mirror and cell so that there is no moment acting on the cell system and parallel deflection takes place.

Although there is no rotation or tilt of the primary mirror cell, rotation of the mirror within its cell does, unfortunately, take place. This results from the use of three defining points to locate the mirror axially within a cell that is itself supported at four points. See figure 4.

The mirror cell deflects under the influence of the near-uniform loading imposed on it by the mirror axial support system and the deflection is greatest along lines midway between the four supporting points. One defining point is normally close to one of these supporting points (north in the diagram) whereas the other two, spaced 120° apart, are away from supporting points and are affected by the cell deflection.

This deflection is at its maximum value when the telescope is in the zenith position and it is assumed that the optical components will be aligned in this position. As the telescope tube moves towards the horizontal the cell relaxes and the two defining points move axially and tilt the mirror top inwards when the tube is directed towards the south and top outwards when the tube is directed towards the north.

From the foregoing it is clear that a Cassegrain telescope will be subject to relative translation of the mirrors (for the truss deflections will not balance exactly) and rotation of both the primary and secondary mirrors.

The design engineer needs to know how much translation and rotation of the tube components can be tolerated and whether he can make use of one type of deflection to compensate in some measure for the effects of another.

It is necessary, therefore, to examine the effect on telescope performance of optical misalignment resulting from a combination of all these tube deformations.

Optical misalignment has two main effects:

a) it produces a telescope pointing error, and
b) it degrades the stellar image by introducing tangential coma.

Comatic aberration is a phenomenon well known to all astronomers and needs no explanation here, but it is necessary to look a little more closely at the matter of pointing error.

Tube pointing error is defined as the angular deviation of the optical axis of the mirror combination relative to the mechanical axis of the telescope tube. These two axes are normally adjusted to be coincident when the telescope is in the zenith position, but they will deviate due to structural deformations as the telescope moves down towards a horizontal position.

Owing to the structural symmetry of the tube and mirror mountings it can be assumed that rotations and translations of the mirrors occurring when the tube is horizontal result in vertical displacements of the star image in the focal plane. These displacements can be evaluated separately and then added to give the total displacement paying due regard to signs.

The direction of the tilt of the primary mirror within its cell actually varies with hour angle, but by taking the situation at 0°HA, when the tilt and the resultant image displacement occur in a vertical plane, the worst case is considered.

EFFECT OF TUBE DEFLECTION ON POINTING ACCURACY

Considering the horizontal two-mirror combination shown in figure 5 with dimensions as indicated:

let η = rotation of the primary mirror taken as positive when the top moves away from the secondary mirror,

ε = rotation of the secondary mirror taken as positive when the top moves away from the primary mirror,

δ = differential translation of the two mirrors taken as positive when the secondary mirror moves downwards with respect to the primary mirror,

f_1 = focal length of primary mirror,

f_2 = back focal length of secondary mirror,

F = focal length of the combination.

The total linear displacement of the star image in the focal plane is the sum of the following displacements:

(i) Displacement due to tilt η of the primary mirror assuming that the secondary mirror is plane

$= 2\eta d + 2\eta S'$

$= 2\eta(d + S')$.

(ii) Displacement due to translation $2\eta d$ of the light ray on the curved surface of the secondary mirror

$= 2\eta d \frac{S'}{f_2}$.

(iii) Displacement due to tilt ε of the secondary mirror

$= 2\varepsilon S'$.

(iv) Displacement due to differential deflection δ causing a further translation of the light ray on the curved surface of the secondary mirror

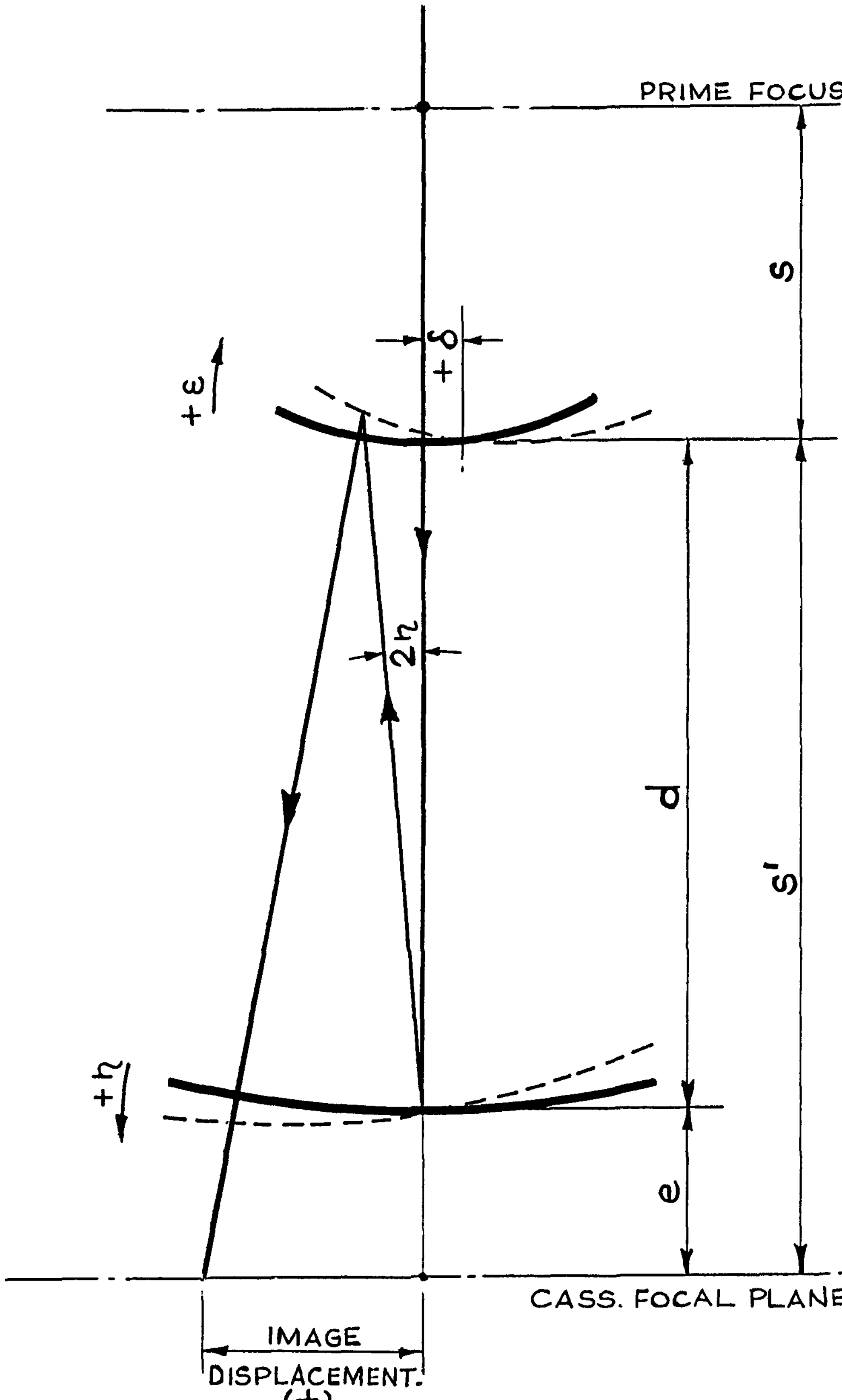

PRIME FOCUS
s
+δ
+ε
2h
d
s'
+h
e
CASS. FOCAL PLANE
IMAGE
DISPLACEMENT
(+)

Fig. 5

$$= \delta \frac{S'}{f_2} .$$

Total displacement is therefore:

$$2\eta (d + S') + 2\eta d \frac{S'}{f_2} + 2\varepsilon S' + \delta \frac{S'}{f_2}$$

$$= 2\eta (d + S' + d \frac{S'}{f_2}) + 2\varepsilon S' + \delta \frac{S'}{f_2} ,$$

but $(d + S' + d \frac{S'}{f_2})$ is the effective focal length of the mirror combination combination = F,

so that total displacement can be written

$$2 F\eta + 2 S'\varepsilon + \frac{S'}{f_2}\delta .$$

$$\text{Pointing Error} = \frac{\text{total displacement}}{F}$$

$$= 2\eta + 2 \frac{S'}{F}\varepsilon + \frac{S'\delta}{f_2 F} \quad \text{radians,}$$

where η and ε are in radians, and δ, F, f_2 and S' are in metres or, alternatively,

$$\text{Pointing Error} = 2\eta + 2 \frac{S'}{F}\varepsilon + 206 \frac{S'}{f_2 F}\delta \text{ arc seconds,}$$

where η and ε are in arc seconds and δ in millimetres. (The number 206 results from converting the tilt from radians to arc seconds and the displacement from metres to millimetres.)

Since $F = \frac{S'}{S} f_1$, the general expression for tube pointing error can be written:

$$\text{Pointing Error} = 2\eta + \frac{2S}{f_1}\varepsilon + 206 \frac{S}{f_1 f_2} \delta \text{ arc seconds.}$$

EFFECT OF ROTATION AND TRANSLATION OF OPTICAL COMPONENTS ON IMAGE QUALITY

For the calculation of tangential coma arising from misalignment of the optical components of a telescope it is convenient to consider the secondary mirror as being rotated with respect to the primary mirror by an angle ϕ about its pole, or by an angle β about its centre of curvature. Optical aberration theory then shows that the coma which arises in these two cases is:

$$\text{coma (angular)} = \frac{3\,\theta^2}{4} (m - 1)^2 (m + 1) \frac{f_2}{F} \phi \quad \ldots\ldots\ldots \quad (1)^*$$

$$\text{or} \quad = \frac{3\,\theta^2}{4} b_2 (m - 1)^3 \frac{f_2}{F} \beta \quad \ldots\ldots\ldots\ldots \quad (2)^*$$

* Equations (1) and (2) supplied by S.C.B.Gascoigne of Mount Stromlo Obs.

where m = magnification $\frac{F}{f_1}$,

$b_2 = -e_2^2$, where e_2 is the eccentricity of the hyperbolic secondary,

θ = the half-angle of the beam (i.e. 1/16 for an f/8 secondary).

A lateral translation Δ of the secondary mirror with respect to the primary axis corresponds to a rotation $\beta = \frac{\Delta}{2f_2}$ plus a rotation $\emptyset = \frac{-\Delta}{2f_2}$.

Substituting in equations (1) and (2) gives the coma due to translation as

$$\frac{3\theta^2}{8F} (m - 1)^2 [m + 1 - b_2 (m - 1)] \Delta \text{ radians}$$

if F and Δ are expressed in metres.
Or alternatively coma in arc seconds due to translation

$$= \frac{3\theta^2}{8F} (m - 1)^2 [m + 1 - b_2 (m - 1)] 206\Delta \quad . . . (3)$$

if F is in metres and Δ is in millimetres.

Δ is the sum of the displacement δ due to tube flexure and the displacement of the primary mirror axis at the secondary mirror due to tilt η of the primary mirror, so that $\Delta = \delta + \frac{d}{206}\eta$ millimetres.

Coma due to rotation

$$= \frac{3\theta^2}{4} (m - 1)^2 (m + 1) \frac{f_2}{F} \emptyset \text{ arc seconds} \quad . . . (1)$$

Where $\emptyset$ is the relative rotation of primary and secondary mirrors $= \eta + \varepsilon$ arc secs.

(1) and (3) are the general expressions for coma in terms of mirror rotations η and ε, and translation δ.

CRITERIA FOR THE ANGLO-AUSTRALIAN 3.9 m TELESCOPE

The use of these general expressions for pointing error and coma can be illustrated by substituting actual numerical values for the optical parameters of the Anglo-Australian Telescope.

	f/8	f/15	f/35
S	4.1	2.6	2.6
S'	10.0	11.6	27.0
f_1	12.5	12.5	12.5
f_2	7.1	3.3	2.8

	f/8	f/15	f/35
F	30	56	132
d	8.4	9.9	9.9
θ	0.065	0.034	0.015
m	2.4	4.5	10.5
e_2	2.92	2.06	1.61
b_2	-8.52	-4.26	-2.61

S, S', f_1, f_2, F and d are given in metres.

Thus for the three mirror combinations:

f/8 Pointing Error = $2\eta + 0.66\varepsilon + 9.6\delta$ arc seconds
f/15 Pointing Error = $2\eta + 0.41\varepsilon + 13\delta$ arc seconds
f/35 Pointing Error = $2\eta + 0.41\varepsilon + 15\delta$ arc seconds.

Substituting the appropriate values in expressions (1) and (3) and adding gives the coma resulting from both rotation and translation:

$$\begin{aligned} \text{f/8 Coma} &= 0.3\Delta + 0.0046\phi \\ &= 0.3(\delta + 0.04\eta) + 0.0046(\eta + \varepsilon) \\ &= 0.017\eta + 0.0046\varepsilon + 0.3\delta \text{ arc secs.} \end{aligned}$$

Similarly for the f/15 combination

f/15 Coma = $0.021\eta + 0.0035\varepsilon + 0.38\delta$ arc secs,

and for the f/35 combination

f/35 Coma = $0.023\eta + 0.004\varepsilon + 0.4\delta$ arc secs.

10 arc seconds is regarded as the acceptable limit for pointing error due to misalignment of the optical components resulting from deformation of the telescope tube, so that the following conditions must be satisfied:

f/8 $2\eta + 0.66\varepsilon + 9.6\delta < 10$
f/15 $2\eta + 0.41\varepsilon + 13\delta < 10$
f/35 $2\eta + 0.41\varepsilon + 15\delta < 10$

The acceptable limit for tangential coma arising from optical misalignment is taken as 0.25 arc seconds which means that the following conditions must also be satisfied:

f/8 $0.017\eta + 0.0046\varepsilon + 0.3\delta < 0.25$
f/15 $0.021\eta + 0.0035\varepsilon + 0.38\delta < 0.25$
f/35 $0.023\eta + 0.004\varepsilon + 0.4\delta < 0.25$

As the acceptable limit for coma is 0.25 arc seconds and that for pointing error 10 arc seconds, multiplication of the coma equations by a factor of 40

TYPICAL DEFLECTIONS CALCULATED BY DILWORTH SECORD AND MEAGHER FOR THE AAT F/8 MIRROR COMBINATION AND APPLIED TO EQUATIONS DEFINING THE ACCEPTABLE LIMITS FOR POINTING ERROR AND COMA

Coefficients are calculated for two positions of the telescope tube; horizontal at 0°HA pointing (a) south (b) north.

Pointing Error Criterion $2\eta + 0.67\varepsilon + 9.6\delta < 10$

Tangential Coma Criterion $0.66\eta + 0.18\varepsilon + 12\delta < 10$

	Primary Mirror Tilt arc secs	Secondary Mirror Tilt arc secs			Tube Deflection millimetres			Calculated Coefficient (max. allowable = 10)	
		Trusses	Vanes	Sum	Upper	Lower	Diff		
	η			ε			δ	Pointing	Coma
Case a	+1.6	-14.5	+3.0	-11.5	1.9	1.7	+0.2	2.7	1.4
Case b	-1.6	-14.5	+3.0	-11.5	1.9	1.7	+0.2	9.0	0.7

Fig. 6

enables a comparison to be made between the two sets of criteria:

	Pointing Error		Coma
f/8	$2\eta + 0.66\varepsilon + 9.6\delta$	< 10 >	$0.66\eta + 0.18\varepsilon + 12\delta$
f/15	$2\eta + 0.41\varepsilon + 13\delta$	< 10 >	$0.86\eta + 0.14\varepsilon + 16\delta$
f/35	$2\eta + 0.41\varepsilon + 15\delta$	< 10 >	$0.92\eta + 0.16\varepsilon + 16\delta$

It is clear from the above table that the conditions for acceptable pointing error are in all cases more stringent than those for acceptable coma, so that if the pointing error is not allowed to exceed 10 arc seconds for each focus than it can safely be assumed that the coma will be within the acceptable limit of 0.25 arc second.

Pointing error resulting from gravity deflections of the telescope tube can be calibrated and compensated for by appropriate corrections fed into the control system of the telescope, leaving only the residual errors of the calibrating and correcting process. On the other hand, coma cannot be similarly improved by feeding corrections into the control system and only corrective positional and rotational adjustments of the primary and secondary mirrors would be effective.

The ability to compensate for pointing error in this way has to be taken into account when deciding upon the acceptable limit. The limit of 10 arc seconds for the uncorrected tube pointing error was chosen for the Anglo-Australian Telescope in the expectation that after calibration and correction the pointing error would be reduced to about 3 arc seconds.

The table of calculated deflections and coefficients for the AAT f/8 mirror combination, figure 6, shows that the conditions for a tube pointing error not exceeding 10 arc seconds have been met, and for the cases quoted the coma is not expected to exceed 0.035 arc second.

Acknowledgements

The writer wishes to thank the Anglo-Australian Telescope Board for permission to publish this paper.

DISCUSSION

ODGERS: Similar equations were worked out last year for the French telescope which has slightly different parameters, assessing the pointing error against coma. I wonder if one of the team would like to comment on the results in that case?

FARRELL: Those equations were worked out by myself and they are based on the work that Mr. Pope has produced right here.

ODGERS: The result is similar then?

FARRELL: The equations are similar, the results are not necessarily so.

RICHTER: Is there a simple explanation why you have this change of sign for the main mirror tilt? It is at first sight a bit surprising.

POPE: I have defined the rotation of the primary mirror as positive when the top moves away from the secondary. Now when the tube is pointing to the north, then a certain point of the mirror is at the bottom, and when it is pointing to the south, the same point is at the top. So on this system you do get a reversal of sign.

CRAWFORD: I think these factors are perfectly acceptable at the horizon, but it is of great interest how they scale with zenith distance.

POPE: The translation and the rotation of the primary will presumably follow a cosine law. The rotation of the secondary, which is a little more complex, may not follow a simple sine or cosine law, but I should not think there is a complicated relationship.

ROOSEVELD VAN DER VEN: What is the maximum deflection and coma for the whole telescope? You only spoke of the tube, but I think astronomers are mostly interested in the whole arrangement.

POPE: Yes, the tube pointing error is only part of the total, but I am afraid I can't yet quote any definitive figures for the maximum error we expect from the mounting as a whole.

ROOSEVELD VAN DER VEN: Is there any possibility to check your calculations before you go into production by means of certain models or computer calculations?

POPE: I think experience has shown that these calculations will be pretty reliable. We are not intending to make any more measurements.

RULE: Would you care to comment on the effect on the tube and balance either from a Cassegrain cage change or the addition of instruments at the Cassegrain on the order of 400 - 500 pounds?

POPE: We will balance additional loads onto the Cassegrain focus by driving weights in the center section outwards. This means that the lower trusses will be subject to a greater deflection, and as the secondary is already deflected more than the primary (δ = + 0.2 mm), any additional weight at the Cassegrain focus is going to reduce and in fact improve the pointing accuracy.

CAYREL: Aren't you perhaps a little pessimistic in thinking that if you have a pointing accuracy of 10", then the overall accuracy after correction of everything by computer will only be improved by a factor of 3?

POPE: I don't want you to pay too much attention to the figures of 2 or 3 that I mentioned. There is bound to be some residual errors from calibration and correction, but whether this error is 1", 2" or 3", I would not like to say.

SCHWESINGER: In order to avoid the rotation of the primary, I wonder if consideration has been given to the possibility of using four defining points instead of three? They would be arranged in the corners of a square and one of the defining points would be clamped elastically, say by spring force to the mirror in order to get a four-fold symmetry corresponding to the symmetry of the Serrurier structure.

POPE: Yes, I did think about having three defining points and some increased force from one of the support pads or an additional spring force to keep the mirror in contact with these three all the time, but as we have achieved our aim and met the requirements for the pointing error to be under 10" we did not feel it was worthwhile making any changes. But certainly one can look at a solution like that if one wants to reduce the pointing error still further.

HERBIG: Are those optical aberrations for a classical Cassegrain system or for a Ritchey-Chrétien or are all possibilities in there somehow?

GASCOIGNE: These are for a Ritchey-Chrétien, but it would tolerate any range of surfaces.

There is another point I would like to mention and that is the tolerance of 0"25 on decentering coma is pretty small. We would think in fact that 0"5 would be quite acceptable; this would make the coma case even less important of course.

HERBIG: I would like to ask a question not necessarily to Mr. Pope, but to those who have considered the mounting problem for these high-resolution, large-scale and large-field reflectors. As you know, if the instrumental pole has the wrong altitude, the field will rotate and the position of the appropriate instrumental pole depends upon the declination I believe. But if you are in the north polar region the pole has to be on the refracted pole. If you are somewhere else on the sky it might be somewhere between the true and the refracted pole. I just wonder whether in these highly precise instruments with the large fields, it is going to be necessary - in order to keep the field from rotating - to have some kind of adjustment of the polar height dependent upon declination. Has this been looked into, or is it negligible, or what is the situation?

OKE: I might comment on this. Dr. Bowen made a thorough study of this question, and he has a couple of papers on it. I think it is not generally a rotation that occurs, except in certain restricted regions of the sky. It is actually a deformation which cannot really be compensated for simply by rotation.

HERBIG: Is it negligible?

OKE: No it is not, particularly in the case of long exposures with these f/8 focal ratios. It is a very serious problem.

REDMAN: In so far as any improvement can be made, we hope to be able to provide a rotation and to guide with two probes, but Dr. Oke is quite right. A good deal of this cannot be corrected; the whole field is distorted.

HANDLING ASPECTS FOR LARGE TELESCOPES

L. D. Barr

AURA, Inc.

There is a class of engineering problems on large telescopes that is called "Handling Problems" because it involves such things as:

A. Handling or moving of large telescope parts, especially the primary mirror.
B. Exchange of instrument, which means handling items of equipment on and off the telescope.
C. Optical changeovers often involving handling of optical elements.

In addition to these procedures, there is another class of problem often called "Human Engineering", which includes consideration of such things as:

A. Usage of observing positions by astronomers. In general more equipment at these positions worsens handling problems.
B. Efficient usage of non-observing time for maintenance, re-aluminizing, etc. It follows that inefficient handling can greatly lengthen maintenance periods.

Strictly speaking, the problems cited above are not problems but are, instead, situations that must be planned for during the design of the telescope and its surroundings. If no planning is done, then problems may arise that seriously diminish the effective utilization of available telescope time.

It is difficult in a short time to discuss the details of planning because solutions will vary from one telescope to the next due to size, astronomer influence, instrumentation needs, etc.

For that reason, this paper will be limited to one example of handling procedure plus a few recommendations. Specifically, this means:

A. The steps involved in removing the Kitt Peak 4-meter primary mirror in preparation for re-aluminizing. The procedure involved is regarded as being rather complex, partly because of the restriction not to remove the mirror from its cell and partly because of design deficiencies.
B. Suggested steps to avoid some of the problems.

The procedure to be described has not yet been tested and may, in fact, still be revised because considerable attention is currently being given to the matter at Kitt Peak. It is frankly acknowledged that attention at an earlier date might have simplified the results.

There is a tendency, however, to postpone "Handling" and "Human Engineering" considerations because these do not directly affect telescope performance. This can be a mistake. Another mistake often made is to underestimate the size and weight of telescope parts.

It is surprising how many parts exceed the weight-lifting capacity of a man. Each of these parts add complexity to the assembly/disassembly procedure.

Turning now to the 4-meter mirror removal procedure, it should first be noted that:

A. The bottom part of the aluminizing chamber also serves as a holding fixture and handling cart for the primary mirror and cell.
B. It is mounted on rails running north-south under the horseshoe.
C. Re-aluminizing is done with the mirror surface horizontal.
D. The primary mirror is re-aluminized without being removed from its cell.

In the re-aluminizing procedure, almost 125,000 lbs. of equipment must be taken from the telescope and re-installed afterward. It is still uncertain how long this will require, but an over-all period of two weeks is considered possible.

The following stages of work will be done during that period and the steps described are greatly condensed from the actual procedure that has been developed.

DIS-ASSEMBLY PROCEDURE

1. Clear away everything from the main floor and the console floor that is not essential. Space is needed for temporary storage of telescope parts.
2. Clean and repair the floors. Mend cracks.
3. Mark off places for work areas and interim storage of large parts.
4. Remove hatches, floor plates, and covers. Install guard rails.

   This operation involves removal and interim storage of 88 individual covers of various kinds, 8 sections of rail track and, finally, crane removal of 6 hatch sections.
5. Bring all special handling equipment to either the main floor or the console floor and place in the assigned position.

   We still do not have everything designed but we know, at least, of the following required items:

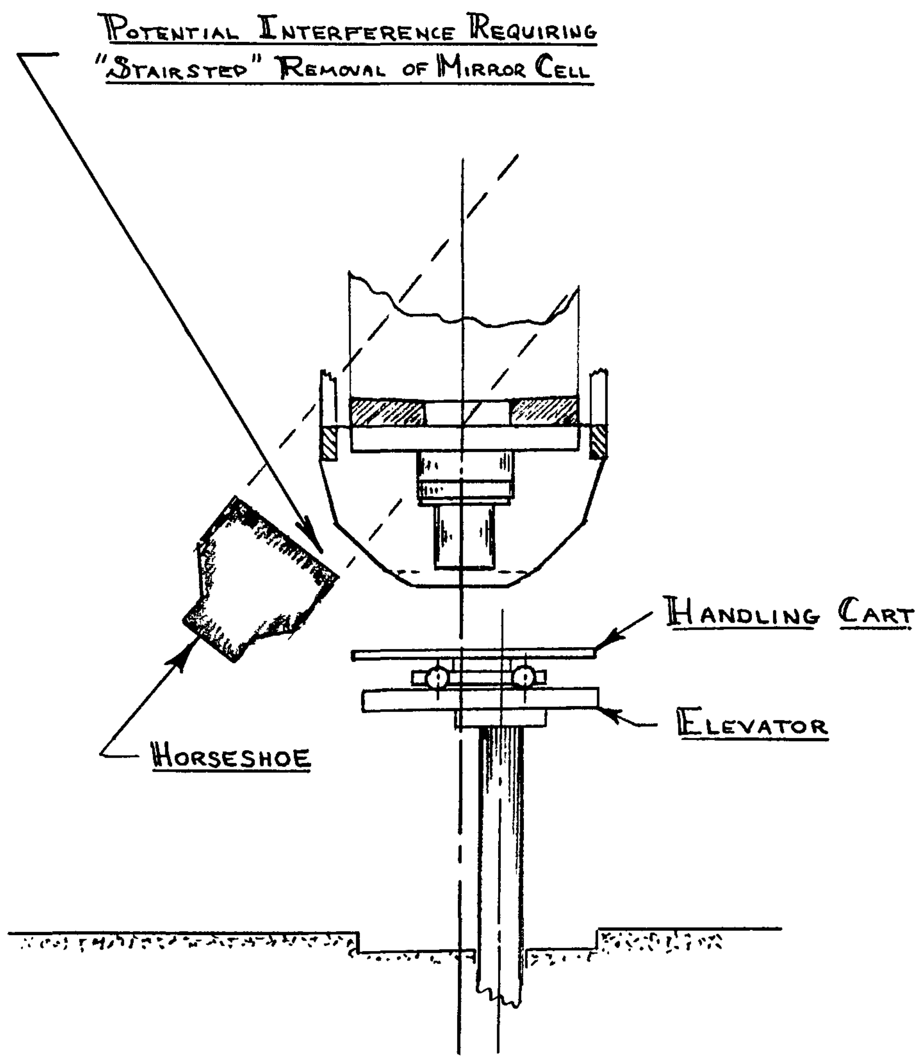

POTENTIAL INTERFERENCE REQUIRING
"STAIRSTEP" REMOVAL OF MIRROR CELL
HANDLING CART
ELEVATOR
HORSESHOE

Fig. 1

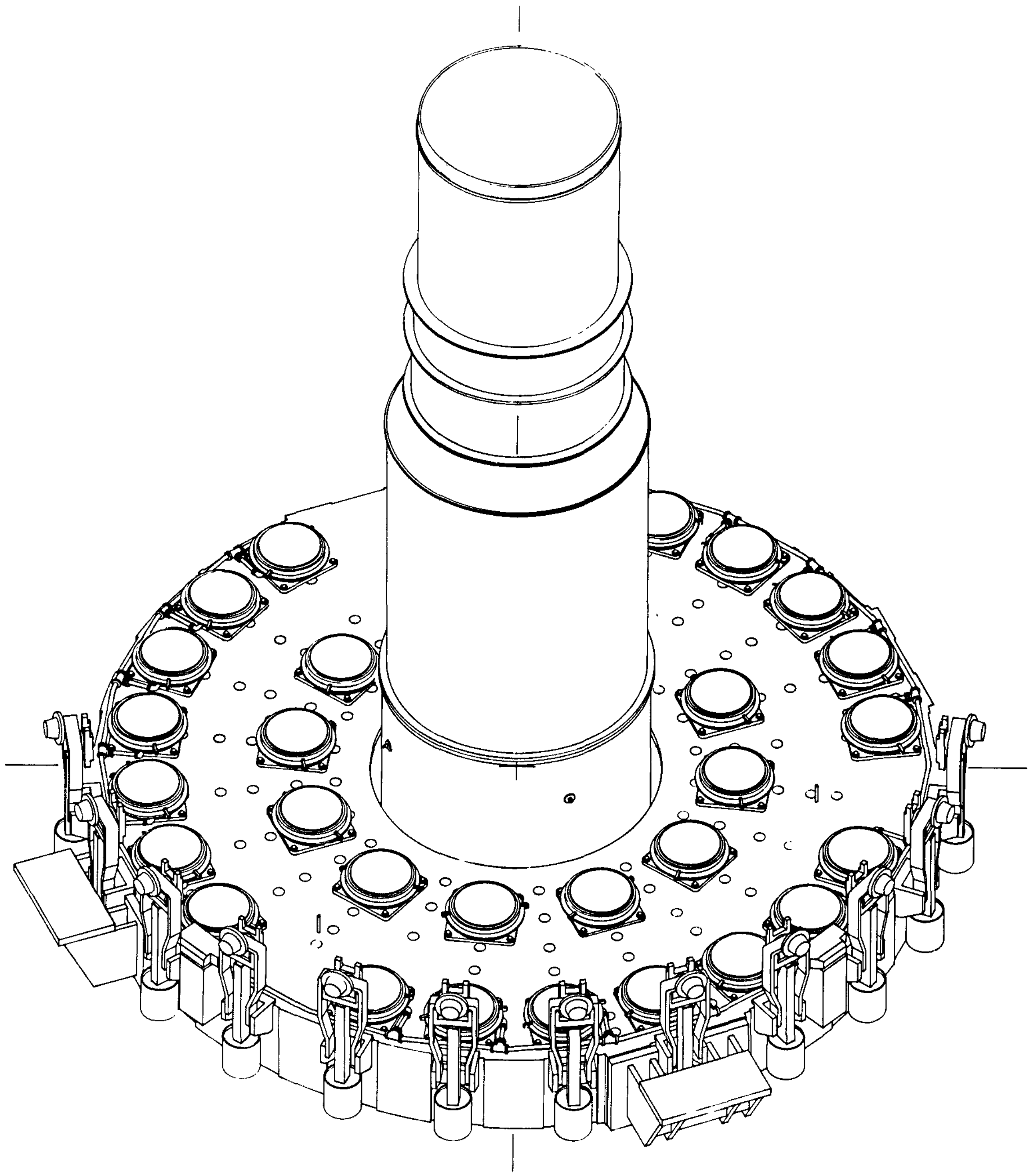


Fig. 2 Mirror cell before dis-assembly.

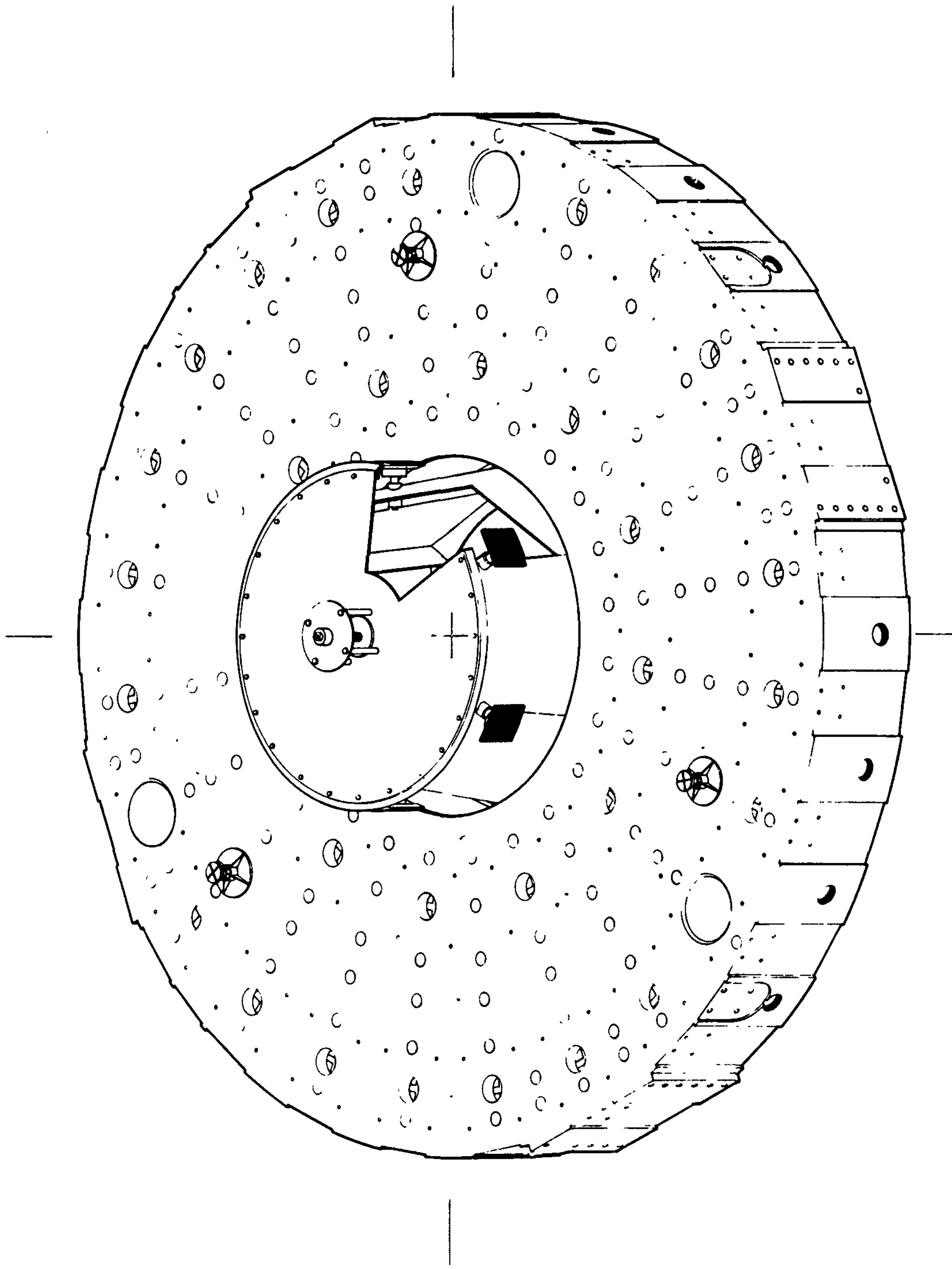


Fig. 3 Mirror cell after dis-assembly.

a) One large handling cart (≈16' x 16').
b) Nine special handling and storage carts.
c) Six major adaptor structures for supporting and removing telescope parts.
d) A center mirror hole plug.
e) A large collection of special tools.
f) Auxiliary work platforms to extend available standing room on the elevator and horseshoe.

This list does not include the mirror carriage that forms the bottom of the vacuum chamber, nor the 5-ton and 50-ton cranes.

6. Bring the aluminizing chamber up from storage to the main floor.

   This is done in stages with the roughing pump section, the control console, and the main aluminizing chamber being raised separately.

7. Replace hatches, covers, etc. and rearrange equipment for best efficiency.

   Note: One or more days may now elapse until the telescope is available for disassembly.

8. With the telescope still powered and balanced, remove various bolts and parts that will be difficult to reach with the telescope in the locked position.

   Note the position of all counterweights and then remove the ramp servicing the Cassegrain cage.

9. Place the tube toward zenith and lock in place with restraining bars. The elevator under the tube now becomes the major disassembly tool.

10. Remove the lower portion of the Cassegrain cage using a special adaptor to fit the cage to a handling carriage. This portion of the cage weighs over 900 pounds and is held in place by forty (40) bolts.

11. Remove instrument - each instrument will have its own handling fixtures.

12. Remove the automatic guider and instrument rotator preferably still bolted together. Combined weight will be about 2000 pounds.

13. Remove the upper cage and place on a special support stand. A special adaptor to fit the handling carriage is required. Approximately 10,000 pounds of weight is involved along with removal of two hundred (200) bolts.

14. Remove the lower support shell assembly using the large handling carriage. 30,000 pounds and 148 bolts are involved in this operation.

   It is also necessary to remove this assembly in a downward, "stair-step" fashion to avoid striking the horseshoe (see Fig. 1). It is necessary to move the carriage to the south away from the horseshoe at the same time the entire assembly is being lowered.

15. Remove items from the center of the mirror such as radial defining pads. Approximately 3600 pounds of equipment will be removed.

16. Remove the inner array of mirror back supports.

    There are twelve of these units weighing forty pounds each and individually piped to the air supply.

17. Jack up the mirror using special jacks, remove the axial defining pads (three of these each weighing 90 pounds) and install support blocks to hold up the mirror during aluminizing.

18. Install the center plug that will stay with the mirror during aluminizing.

19. Remove the mirror cell with the mirror still inside.

    At this point, 55,000 pounds of weight must be lowered in "stair-step" fashion to floor level.

20. Remove the rest of the mirror back supports (21 @ 40 pounds each), the edge supports (24 @ 230 pounds each), safety clamps (4 @ 175 pounds each), and the cell support blocks (4 @ 500 pounds each).

    At this point, the mirror and cell are essentially stripped of hardware that could cause out-gassing problems or that will not fit into the vacuum chamber. Figures 2 and 3 show respectively how the mirror cell was equipped with hardware before stripping and what is left afterward.

    The number of items to be removed is impressive.

21. The last step to be mentioned is cleaning of the mirror before aluminizing. This work is done with the mirror just forward (i.e., north) of the horseshoe so that technicians can work above the mirror from an east-west walkway attached to the north end of the telescope base frame.

    By moving the mirror carriage north or south on the carriage rails it is possible to reach all areas of the mirror from the east-west walkway.

    It is planned to pump water and other cleaning residue from the central hole which will have a plastic film catch basin taped in place beforehand.

From the foregoing, it is apparent that further simplification is desirable. We are continuing our work at Kitt Peak toward this goal, but at this point in time, we are obliged to use many things that have already been manufactured and cannot, therefore, make changes easily.

Our experience to date does lead to a number of recommendations which are listed to follow for designers of large telescopes. Again, it is pertinent to say that solutions to problems will vary widely and the designer is well-advised to use some imagination.

GENERAL RECOMMENDATIONS

1. Investigate the possibility of eliminating the astronomers or the instrumentation, or both, from the moving telescope entirely.

   a) This reduces sharply the number of items requiring special handling.
   b) It enables greater freedom in instrument design.
   c) It will ordinarily reduce cost to build the telescope but may add to complexity of required controls.

   This is basically a recommendation to include handling procedures as one of the criteria for selecting a given mount style.

2. Design for the simplest possible mirror support system to reduce the number of parts that must be removed prior to exposing the mirror to high vacuum.

3. Begin planning at an early stage. Include specific items in the advance planning budget to enable proper study of handling problems. About 10% of the total engineering costs should go for handling.

4. Design for the least number of removable parts. Wherever possible, design the part to either not require removal or to move out of the way without having to be completely removed.

5. Wherever possible, design for vertical dis-assembly from either top or bottom. Horizontal motions usually require a special cart and perhaps special adaptors. Rotating motions are even more difficult to cope with.

6. Be sure that any telescope supporting structure (i.e., the base frame) is made with proper clearances for large parts, carts, elevator platforms, etc. to pass through easily.

7. If an elevator platform is to be used for assembly/disassembly, be sure that it is able to position parts with good precision and speed.

   a) Precision to .010" not unreasonable.
   b) Two-speed operation is desirable.
   c) 5 Ft/min. on heavy items is adequate.

8. Use quick-acting assembly devices wherever possible (i.e. quick-acting clamps). Avoid using small bolts on large bolt circles because of the large number of bolts that will be required.

9. Locate all electrical and utility lines in places that do not require periodic removal.

   Assume that all instruments will require remote control operation (i.e., plan for numerous cable connections).

10. Remember that most telescope instruments now seem to require an electronic rack that is bigger than the instrument itself.

    Try to locate such equipment away from the telescope.

11. Don't try to solve all problems equally well. Only those situations that occur frequently deserve special considerations.

In closing, it is worth re-emphasizing the need to begin planning early. It will pay off well in terms of extra hours and days of usable telescope time.

Discussion follows after next paper

PRACTICAL PROBLEMS
(Summary)*

L. K. Randall

Kitt Peak National Observatory**

A number of recommendations are made to the designers and users of (large) telescopes:

Make changes! Beware of the possibility of making changes, but if you change, then be sure you know what it will do to the whole system.

Aligning the telescope This should not be an astronomer's, but rather the engineers' job.

Balance problems Start checking the balance during the design stage. At Kitt Peak a computer program has been developed for this task. Every time a manufacturer supplies details, weight and c.g. of the various pieces is fed into the computer. This gives always a complete up-to-date picture. It has proved extremely useful for the Kitt Peak 150" projects.

Hydrostatic bearings Bruce Rule's point in planning damping systems is important for telescopes with hydrostatic bearings. Take a careful look at the cavities; even very small cavity sizes can float the telescope. Variable-speed pumps are recommended, at least one variable-speed pump to cover the whole range and one motor pump combination with a step function. Seasonal changes may justify changes in speed. Look after the seals! A duplication of the seals to avoid the risk of having oil all over the telescope is strongly recommended.

Grease The new polymer type grease (97% oil + 3% polymer) holds great promise. It has a long life and might solve many problems.

Mirror covers Especially in the southern hemisphere it is of great importance that dust is kept out to avoid frequent washing and/or realuminizing. Some new covers (e.g. from Zeiss) look promising.

Maintenance problems Let the manufacturer supply a periodic maintenance plan for telescopes. Write maintenance manuals from the point of view that the staff may change.

---

* This summary was prepared by the editor from the tape-recording.

** Operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

DISCUSSION

(relating to the two preceding papers)

FARRELL: You seem to have paid a very high price for not having to lift the mirror out of the cell. On what basis did you make that decision and at what stage of the design was it made?

RANDALL: I think this goes right back to when you look at 30.000 lbs of glass and 30.000 lbs of cell and the piping and all the other little things that go along with it. It does not seem very significant until you have to pull it out of the way, and I honestly think we got trapped into these features. It is now exceedingly difficult to change once you plan how you are going to handle things such as our base carriage and aluminizing tank etc. I still like the philosophy of not lifting a mirror off the cell, but just run it on the carriage to the aluminizing tank without cranes. However, you certainly do have to pay a price in time of disassembly, and I think every group doing a large telescope should look at their own particular problems and the merits of doing it different ways. There are certainly hazards to using overhead cranes for this sort of work. We have had occasions both on the 120" at Lick and on our 84", where we even had fires up in the crane at times when we have had the mirror hanging on them, or parts falling off the cranes. You don't believe it until it happens. We actually go up and check cranes out, sweep and vacuum the platforms, but believe it or not, I stood under the 84" one day and a bolt fell; you never know from where.

The other thing I don't like to do is to tilt the mirror from the horizontal to the vertical, but I have done it on several mirrors of over 2 m size. It's as I said before, a lot of my experience has been in the field, and I just tighten up my stomach muscles and go and do it.

BELLY: How did you solve the problem of washing the mirror in the telescope?

RANDALL: In our case we put the mirror so the axis is horizontal and go in and wash. You have to do some taping and shielding and then it drains out through the center section. It is a workable system. We have done it on some other telescopes, and have some experience with it.

BAHNER: Has anybody any experience with using collodium for washing mirrors?

RICHARDSON: We tried that once at Victoria, but we couldn't get it to peal off properly, so we found it unsuccessful. Perhaps it was our technique that was at fault.

BROWN: There seems to be two different collodium types. I don't have details, but we have used collodium quite successfully on small mirrors; only if you get the wrong sort you will have great difficulty in getting it off. With the right sort, there is no problem - it almost leaps off.

BERTOLA: Did you realize a device in order to avoid the deposit of moisture on the surface of the mirror when there are sudden changes of temperature?

RANDALL: There are some rather interesting techniques coming out of the clean-rooms right now, which I think can be applied to keeping the surfaces of the primary mirrors clean. If you take air in from your building, filter and clean it up with high-efficiency filters, and pump it from the central hole across the surface of the mirror at speeds of no higher than about 1.5 km/h, then you can keep all dust particles that are drifting down into the system in suspension in the moving air, and keep them from ever reaching the surface of the mirror. The moving air also prevents some of the condensation problem. On these big mirrors, even though we don't have a thermal expansion problem, we will probably have a large heat sink that we are going to worry about. I think some of these techniques can make significant contributions as to how long we can go between washing and aluminizing, and how fast you can go into operation in the evening.

HERBIG: When you have been studying all of these questions, have you developed a philosophy of when to realuminize? As the reflectance deteriorates with the years, there must be a point when you think it is the time.

RANDALL: I have been letting the astronomers do the complaining. We have a point when the reflectance goes down to a certain value or when you start seeing sleeks and other things on the surface of the mirror, but the time to realuminize has tended to be chosen by the astronomers. We wash as we see problems with reflectance and scatter and there is finally a point, after usually no more than about 4 washings in that case, when we realuminize. At Kitt Peak we realuminize rather often, every 1-2 years or so and wash every 3-6 months.

RULE: I agree with all the comments that have been made, but between the various sized instruments at Mt. Wilson and Mt. Palomar, the philosophy of aluminizing and handling the mirror is really a case of the two limits. For example for the 200" we do not remove any of the supports. The mirror removal including the removal of the Cassegrain cage and all auxiliaries is done in less than 4 hours. And the only time required out is the actual aluminizing time, so it goes back in the next day within 4 to 6 hours. This is handling 35 tons. On the new designs for the 60" we propose to remove only 4 bolts, to take the whole mirror cell out, and the handling of the mirror will be done with a carriage on a horizontal plane. We don't tip the mirror, nor transport it from level to level. The only improvement we would think of making on the 200" is one that has to do with operating. Mr. Barr mentioned that the time required to prepare the aluminizing tank is a matter of days ahead of time, and perhaps some days afterwards in cleaning up. We therefore prepare for aluminizing while observing runs are on. This means that with aluminizing equipment on the observing floor it does interfere with the observers. On the new 60" we propose to do this at the ground floor level just as we do it at the mezzanine level at the 100" at Mt. Wilson. So this equipment can run while you are actually using the telescope, up to the last minute. The other extreme of not leaving all the supports in, is the case of the 100" and the 60" where the carriage is provided with 3 rams to lift the mirror out of the cell and then with the crane put it in the bottom of the aluminizing tank. This procedure has worked quite well and we will also use it on the new 100".

ELSÄSSER: What range of mirror sizes can you reasonably do within one aluminizing plant? Is it necessary for instance to have one plant for a 3.5 m mirror and another one for a 2.2 m?

RANDALL: If you keep a large plant in position you can run a rather large difference in sizes of mirrors through it as long as you put the surfaces to be aluminized in about the same plane. That means that you must put smaller mirrors up on stands and you have to make adjustments in your filaments. Our chamber for the 4 m telescope is probably the fastest chamber we have got other than the size for 50 cm. It pumps down in less than one hour to $5 \cdot 10^{-5}$ so you have to look mainly at the set-up problem and maybe in some cases at the expense. There is no reason for people who are going to purchase one chamber that they can't do the whole range in mirror sizes. I would do all your coudé mirrors at one time, get some stands and arrange them in the tank. You can get rather even coatings, there is no problem that way, if the filaments are planned properly.

SECORD: For what weight of falling objects should the mirror cover be designed?

RANDALL: I don't know, since I have never seen anything very heavy fall on a mirror cover. I remember to have seen a couple of 2 kg wrenches fall on it, when we have been working up on the top end. It is of course not just weight, but rather kinetic energy, that is important. Most of our mirror covers work rather well; you could drop a fairly heavy body on them and they tend to become unworkable, but they do absorb a great amount of force. We tend to build sandwich-type structures, where we have a double plate with some foam in between. So these are rather rigid, strong structures and if you hit them with something they are forced in and tend to wedge even tighter.

RULE: We did test the mirror cover on the 200" by dropping a 4 lb pointed crowbar 50 feet. The top surface is made for energy absorption and is of aluminium, then comes crumpled foil and a steel plate on the bottom. In these tests we never succeeded in penetrating the bottom plate. During the aluminizing you are really vulnerable because you don't have any protection of this sort.

BAHNER: Mr. Barr mentioned the cable problem for instance for observing stations. Could one imagine a system where one just feeds power and besides this multiplex the commands at the station and get rid of this terrible number of cables?

RANDALL: I think this is certainly worth looking at; it would pay. The thing that we have been trapped into a little bit on the 4 m telescope is that the technology with which we started out several years ago wasn't really advanced in this field. We did not have the knowledge of how to do it, so a lot of the power and the control functions are each using one or more wires, whereas we definitely have a data-link system for the instrumentation. The thing is you don't really win there, we thought we were getting rid of a lot of wires for the instruments, but it turns out now that astronomers would like air and water and high voltage and freon and I have got everything but effluent lines running out of the telescope now so ....

DITTMAR: We are going to this multiplexing approach on the 107" to reduce a lot of the cabling, for instance from the focus and the collimation encoders.

THURSDAY, MARCH 4

AFTERNOON SESSIONS

Chairman: R. O. Redman

THE ENGINEERING DESIGN OF TELESCOPE STRUCTURES

(With Particular Emphasis on the Use of High Speed Digital Computers)

E. Eggmann, J.C. Farrell and L.C. Secord
(read by E. Eggmann)
Dilworth, Secord, Meagher and Associates Limited

To achieve a high performance capability in a large telescope a careful and thorough engineering analysis is necessary. One area in particular where this requirement applies is in the design of the telescope tube and mounting structure. We have found the high speed digital computer to be a helpful tool in assisting the designer in determining structural deflections. This leads to a further step of optimizing the structural concept for the efficient utilization of material.

The computer has been used extensively by our engineers for telescope design over the past five years beginning with the Canadian program for the concept development of the four metre Queen Elizabeth II Telescope. The procedures developed on this program were refined in an application for the structural design of the Anglo-Australian 4 m Telescope. Recent programs include the French (INAG) 3.6 m Telescope and the Italian (O.A.N.) 3.5 m Telescope. Despite this experience, the methods and approaches cannot yet be classed as routine. Each new assignment offers some unique problems and scope for further improvement and economy of technique.

In the design and analysis of a large telescope we normally consider the problem initially segmented into five areas. Each area is individually studied and then the results of the separate studies are integrated to arrive at the overall result. The subdivisions as shown in Figure 1 include:

(i) the basic tube structure,
(ii) the mounting for the tube,
(iii) the tube upper end,
(iv) the tube lower end,
(v) the self-induced deflections of the mirrors.

A brief description of the content of each study is appropriate at this time.

In the analysis of the basic tube structure the internal framework of the upper end, which is supported on flexible spiders, is considered to be rigid and the weight is concentrated at the centre of gravity of the frame. The centre of gravity is normally in line with the apex of the supporting spiders. When the tube is vertical (pointing to the zenith) the spiders are

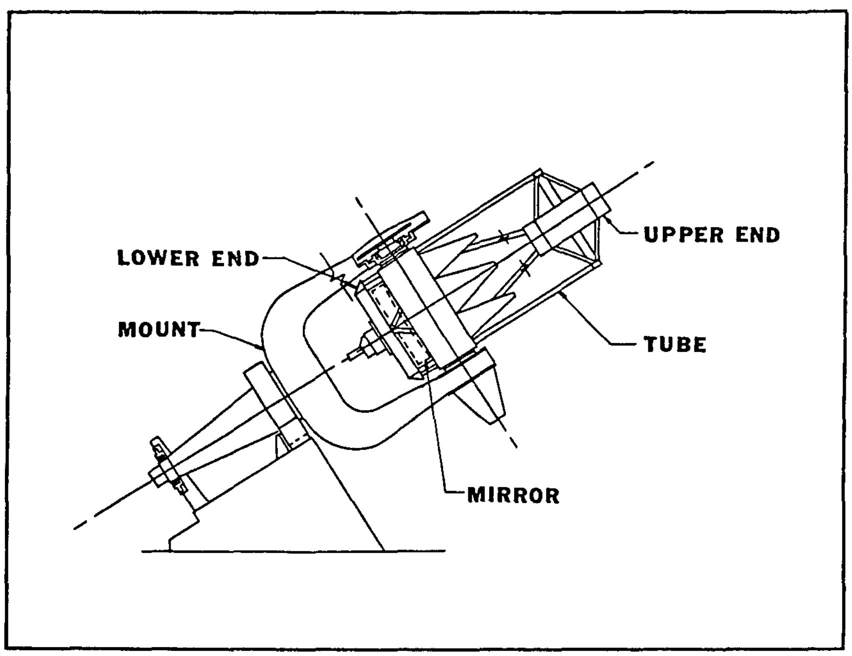


Fig. 1 Analytical segmentation.

equally loaded. When the tube is horizontal the spiders are unequally loaded, their respective loads depend upon their orientation relative to the gravity field. We usually simplify the initial analysis of the tube in the horizontal position by aligning the spider geometry with the vertical and horizontal axis of the Cartesian co-ordinate system.

Similarly the characteristics of the lower end of the tube are simplified by considering the primary mirror cell load distributed to the connections of the lower truss according to the effects of gravity for the relevant tube position. The cell is simulated by a simplified rigid structure.

From the results of the basic tube structure we are able to ascertain the gross rotations and translations of the upper end, the behaviour of the upper end rings, the upper truss (normally of the Serrurier type), and the centre section. Of particular interest in the latter area is the misalignment of the declination trunnions. The results also indicate the gross translation and rotation of the primary mirror cell assembly.

In the analysis of the mounting structure, the tube load is applied at the centre of a beam connecting the declination bearings. The centre section is thus simulated by a cross-connecting member of the appropriate spring constant in line with the declination axis. Other external loads such as balancing weights, Cassegrain cage, coudé first flats, etc. are applied, if present, to the simulated structure. From this study we determine the resulting declination bearing loads (usually seldom equal in magnitude) and the absolute movement of the declination bearing housings. The latter assists in evaluating the relative misalignment of the trunnion with the bearing housing. The analysis also discloses the gross movement of the axis of the tube in space and the local as well as gross rotations and translations of the polar axis mount bearing races. This is of particular interest because of the small film thickness employed in the oil hydrostatic support pads.

The analysis of the upper ends considers the internal structure of the cage or cages (if there are multiple upper ends). The results will indicate the additional deflections leading to the degradation of optical collimation arising from the elasticities of the supporting structure. This area is of particular importance as experience has shown us, because the rotational components in particular can be quite large and even several times greater than the gross structural rotation of the cage itself. Many designers underrate the magnitude of these internal deflections and in so doing overlook an important contributing factor.

The lower end calculations deal with the primary mirror cell deflections, the mirror support deflections and the translations and rotations of the diagonal mirror support as well as the deflections induced by the overhanging diagonal mirror and Cassegrain instrumentation.

The final but not least area of concern is associated with the deflections of the mirrors under the influence of their own weight and the

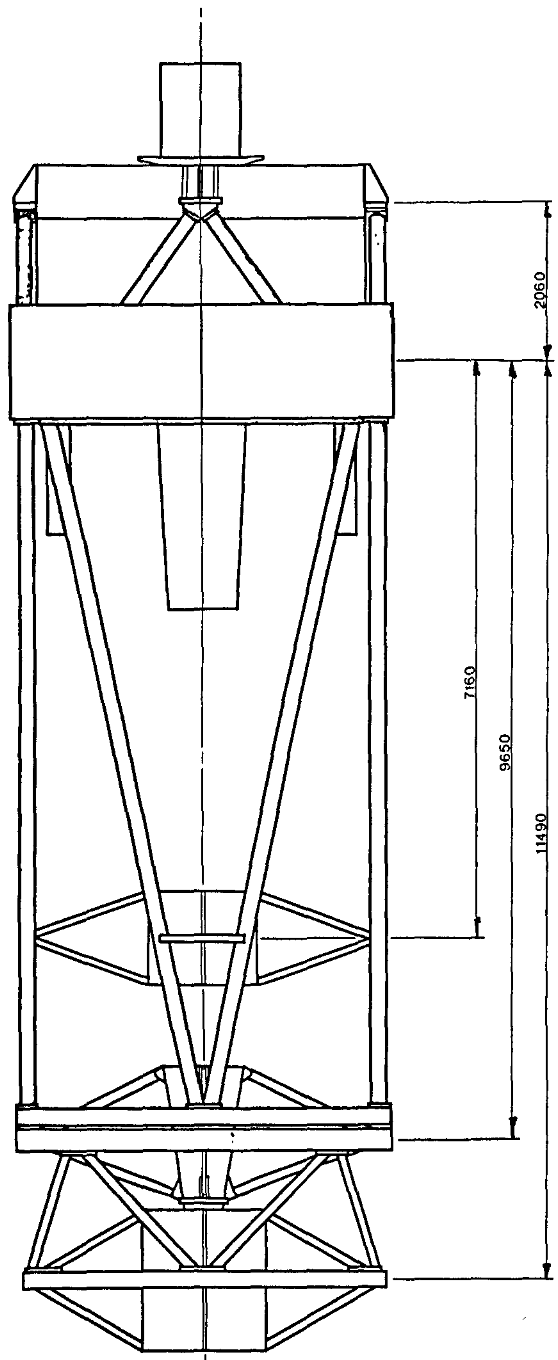


Fig. 2 General tube configuration.

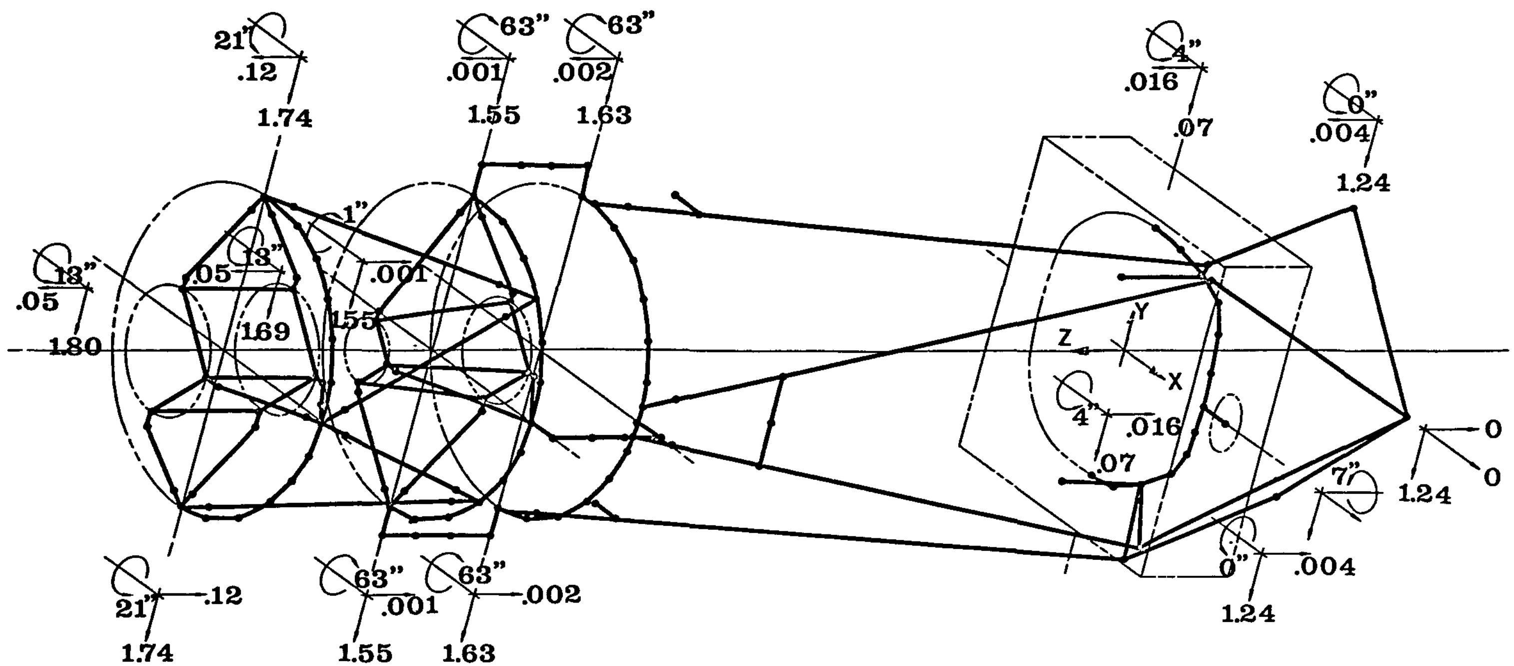


Fig. 3 Analytical model of tube.

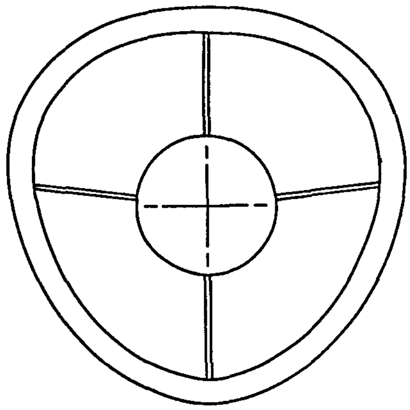


Fig. 4 Distortion of upper end ring.

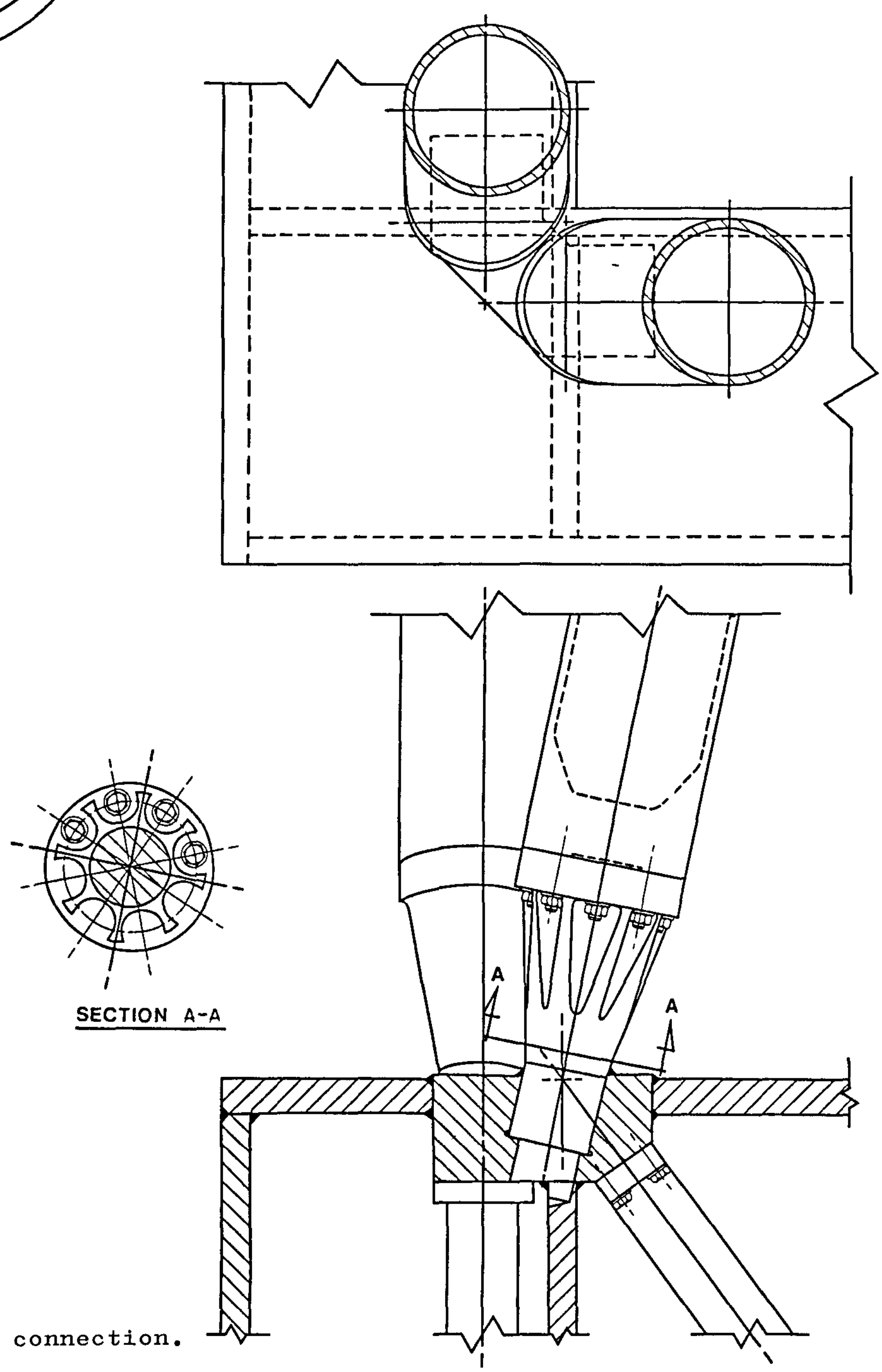


Fig. 5 Serrurier connection.

effect of their supports. This analysis may be carried out for different tube orientations and varying support geometries.

To delve into the details of all five studies would be beyond the scope of this paper and thus we will concentrate on the first two items, the study of the basic tube structure and the mount. The intention is to give the reader some insight into the benefits and usefulness of computer analysis and from this be able to develop some appreciation of the behaviour of a typical telescope structure.

A horseshoe type structure has been selected as an excellent example of the response and interaction of design and analysis. A tube with the conventional Serrurier truss is employed. The tube configuration is shown in Figure 2. Its weight is approximately 84.000 kg with a primary mirror diameter somewhat less than 4 metres. The distance from the declination axis to the upper end is about 10 metres and to the primary mirror cell approximately 2 metres. Figure 3 illustrates the analytical model of a series of lines representing the structural members' neutral axis. The numbers and arrows indicate the deflections of significant structural joints. From the computer printout it is possible to derive the motions of all joints in terms of rotations about an X, Y and Z axis and a translation component in the X, Y or Z direction.

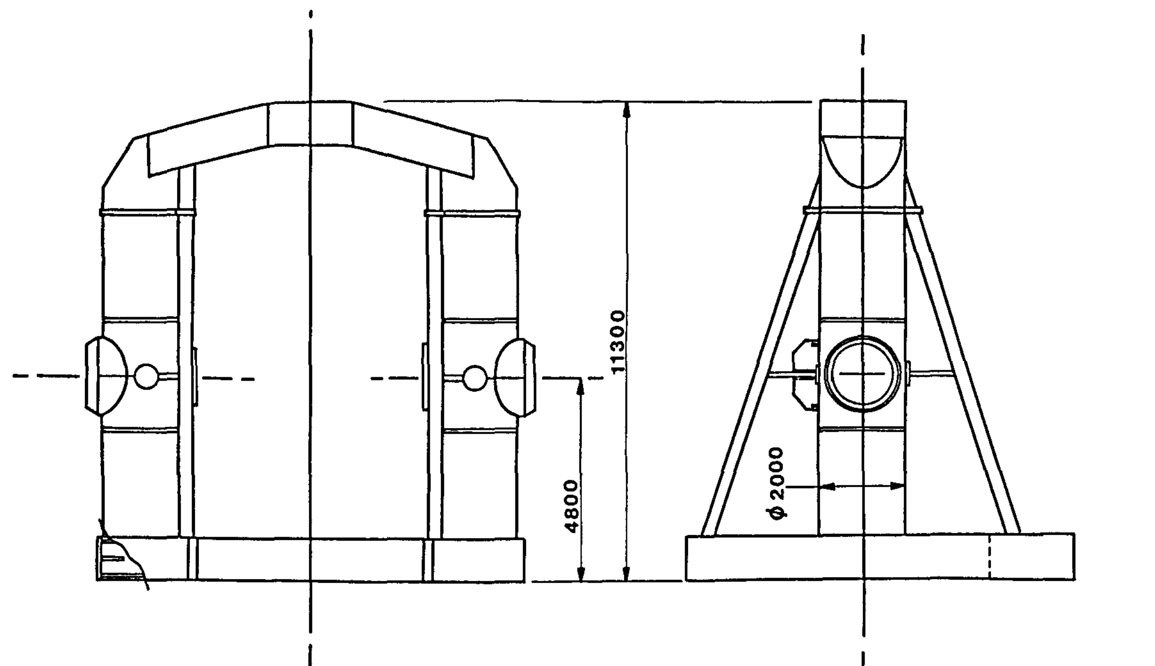
Considering the case of the tube in the horizontal position with the reference axis as follows:

(i) X axis - coincident with the declination axis
(ii) Y axis - in the zenith direction
(iii) Z axis - coincident with the optical axis;

we can see that a local X-rotation of 63 seconds at the upper end of the Serrurier truss at the truss connection point does not significantly influence the overall upper end gross rotation. The overhanging weight of the observer's cage does not result in a significant net rotation of the upper end ring. The extreme upper and lower ring joints have a vertical motion of 1.55 mm. The points on the horizontal diameter move downwards 1.51 mm and thus the ring assumes a slight "eggshape" as portrayed in Figure 4. The cage structure supporting the optics has a vertical translation of 1.55 mm downwards and indicates that there is very little strain induced into the spiders due to the sagging effect. The motion of the cage relative to its original position arises essentially by the bending deflection of the arch of the ring and not by elongation and compression of the spiders.

The observer's cage and its supporting structure is considered fabricated in aluminum. This is permissible since somewhat relatively larger deflections are acceptable due to the isolation from the secondary optics and corrector lens system.

The declination trunnions rotate about 7 seconds in the vertical plane



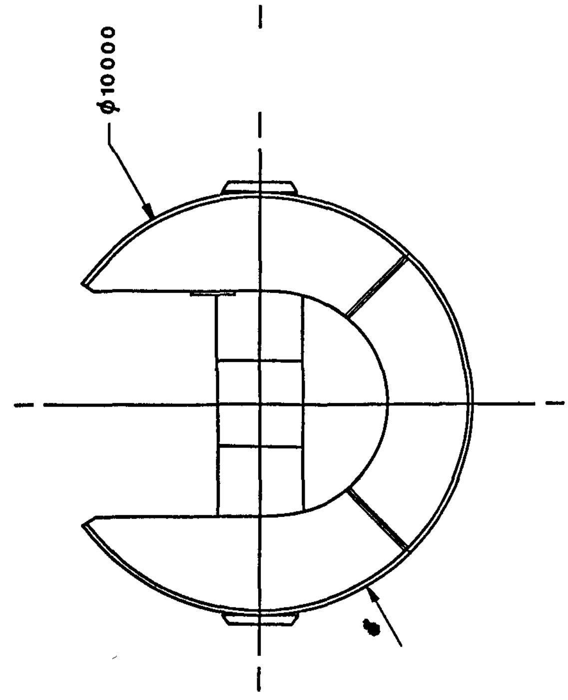


Fig. 6 Yoke mounting.

at the bearing location. For the vertical tube position the trunnion rotation increases to 15 seconds - 12 seconds being contributed by the deformations of the centre section alone.

In the example shown the translation of the lower Serrurier truss does not quite match that of the upper truss. However this may readily be rectified by reducing the cross sectional area of the lower truss. The final tube area to be selected will also depend on the consideration of the further deflections arising from the distortion of the secondary mirror support structure and the local primary mirror cell deflections.

It is essential that the designer of the structure understands the deflection modes and the assumptions made by the analyst in his development of the model. The final design must reflect the characteristics of the model in order to justify the credibility in the predicted performance. As an example, if we consider the Serrurier truss attachment to the centre section we know that the centre lines should meet in the plane of the declination axis. Depending on the overall depth of the centre section it is possible that the centre lines of the upper trusses may be very close together at the point of intersection on the top face of the centre section. In this case it would not be possible to employ a standard flange connection. This is further complicated if the lower trusses are connected to the bottom face of the same plate.

Figure 5 illustrates one possible solution to this problem. The solution appears somewhat sophisticated when compared to a standard flange connection. However a satisfactory standard flange is not entirely feasible as defined by the desired statics. Furthermore the superior rigidity of the solid connection is obvious. It is essential to realize that for the large loads which occur at these joints every 1/100 of 1 mm of local deflection adds one second of rotation to the upper end and hence to the secondary mirror. Thus, if the conditions of the analysis are not met by the design, the telescope will behave differently than expected. Naturally almost any design can be analysed, but if the designer seriously considers the need for minimum deflection he has little choice but to incorporate uniform and straightforward force flow through alignment of the neutral axis of structural members.

Progressing to the mount as shown in Figure 6 we have shown a Palomar yoke type of structure supporting a tube for a 3.6 m mirror. The major dimensions are shown to give perspective to the size of the structure involved. The weight is added as an external load to the declination bearing and the centre section stiffness is represented by an appropriate joining member having an equivalent spring constant (K-value).

Figure 7 shows the neutral axis layout of the structural members and joints. As indicated previously the deflections of any point are available from the computer output. Some of the more important deflections are summarized in Table 1.

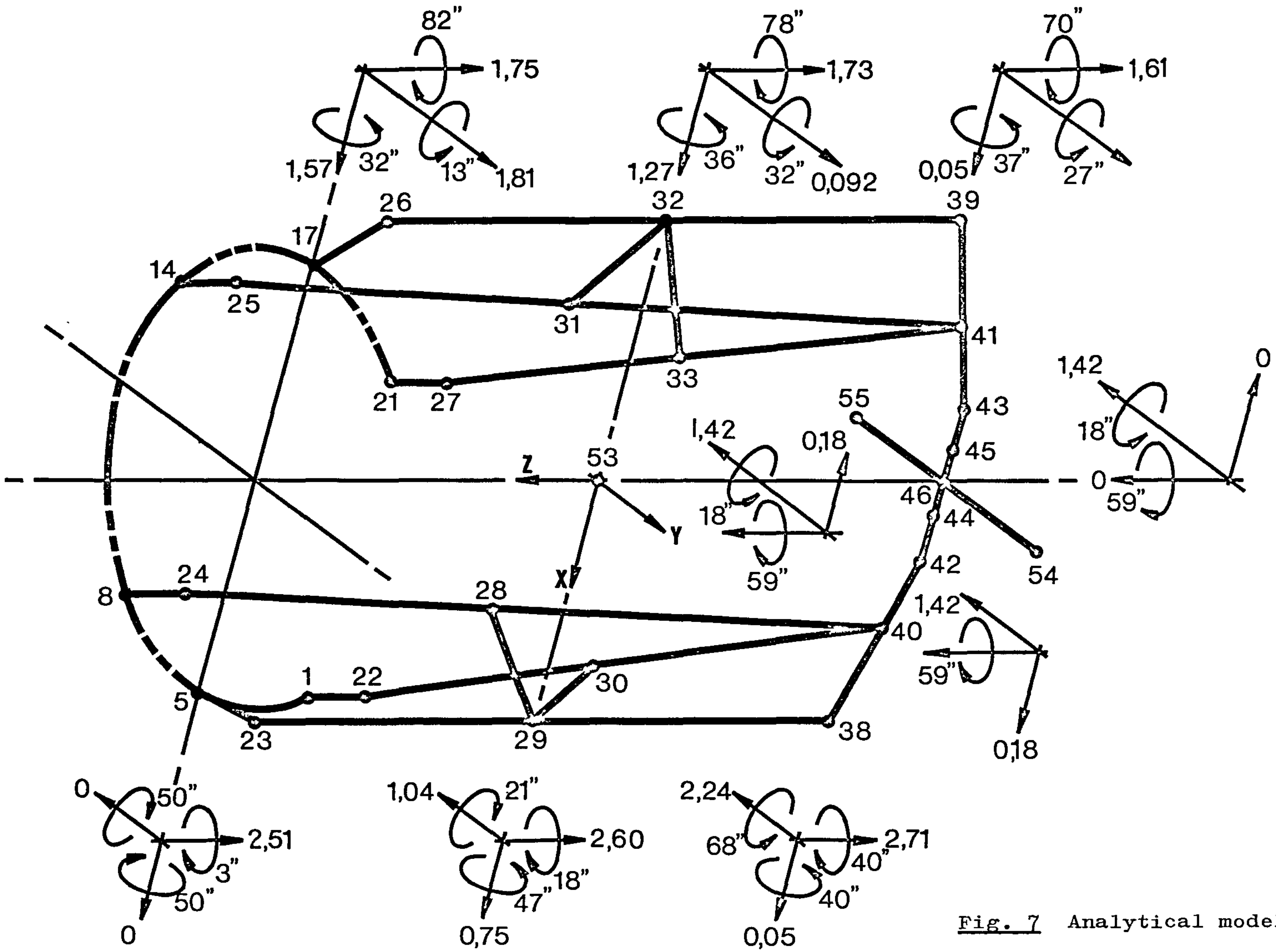


Fig. 7 Analytical model of mounting.

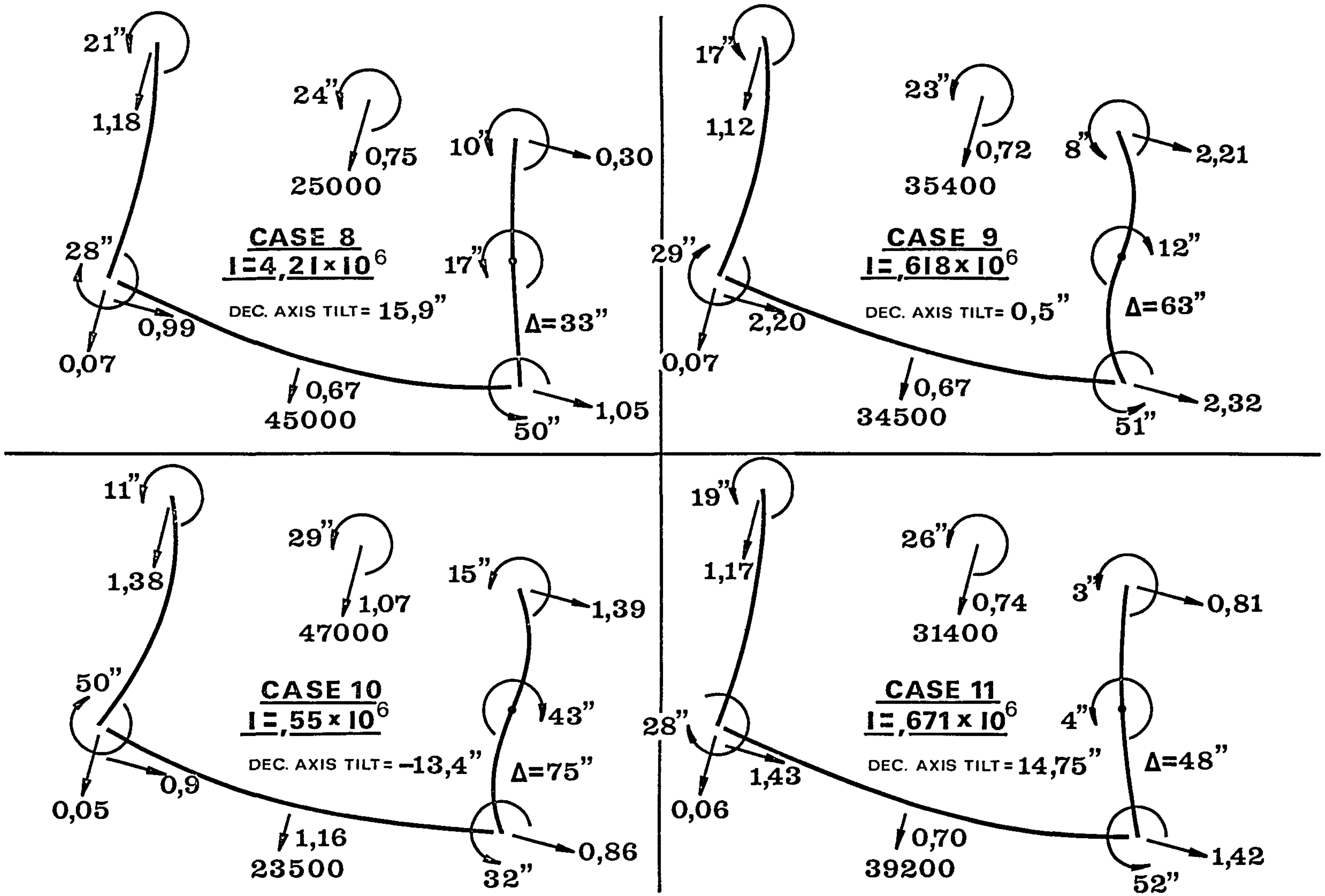
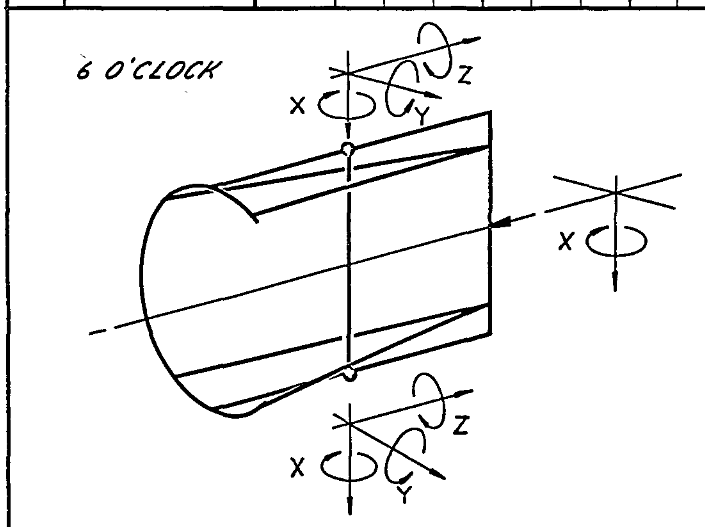
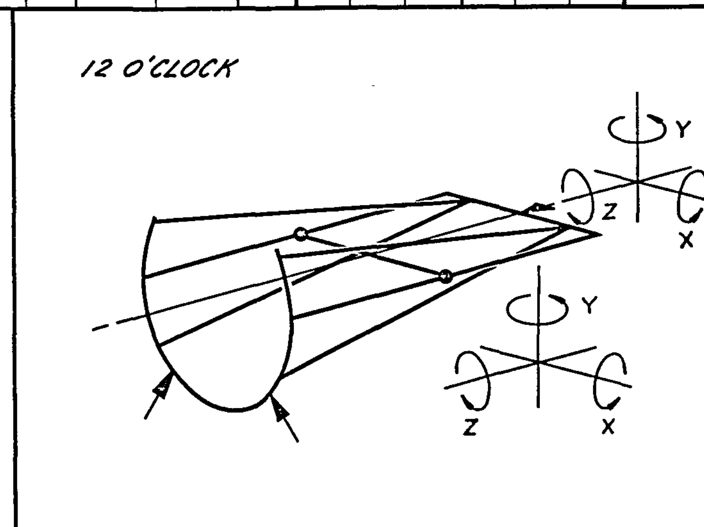


Fig. 8 Frame distortions.

Table 1 Summary of deflections and loads.

CASE	DESCRIPTION	6 O'CLOCK													12 O'CLOCK						NORTH BEARING RACE ROTATION
		TOTAL WEIGHT OF MOUNT	BEARING HOUSING ROTATION UPPER			BEARING HOUSING ROTATION LOWER			ROTATION AT SOUTH PAD			THRUST ON MAIN BEARING		ROT. OF DECL. AXIS	BEARING HOUSING ROTATION			ROTATION AT SOUTH PAD			
			X	Y	Z	X	Y	Z	X	Y	Z	LOWER	UPPER		X	Y	Z	X	Y	Z	△ ROTATION
1	ACCORDING TO DRAWING	94 537	-36"	32"	78"	-47"	-21"	18"	0"	18"	-59"	36 000	34 000	23.27"	-28"	0"	-31"	43"	0"	0"	22"
2	18,5 % SHORTER STRUT	92 987	-9"	29"	65"	-20"	-6"	23"	-15"	39"	-53"	39 400	30 530	35.80"	-8"	4"	-14"	43"	0"	0"	20"
3	SOUTHBEAM I-VALUE DOUBLED	95 620	-9"	27"	65"	-20"	-7"	24"	-14"	41"	-53"	43 400	26 490	36.70"	-9"	6"	-12"	43"	0"	0"	20"
4	ST. SOUTHBEAM ORIGINAL I-VALUE	93 120	-3"	25"	64"	-20"	-6"	22"	-16"	32"	-52"	41 760	28 109	30.00"							
5	HORSESHOE WALL INCREASED 67%	114 917	-7"	27"	61"	-17"	-7"	21"	-15"	29"	47"	38 000	31 800	28.00"							
6	STRUT WALL INCREASED 100%	106 270	-11"	26"	57"	-14"	-4"	17"	-13"	26"	40"	47 315	22 500	24.80"							
7	HORSESHOE & STRUT WALL INCREASED	128 067	-10"	24"	56"	-14"	-3"	15"	-12"	15"	38"	45 000	25 000	20.90"							24"
8	SOUTH BEARING CENTER	128 067	-10"	23"	56"	-12"	-5"	14"	-11"	15"	38"	45 000	25 000	15.90"	-4"	4"	-12"	10"	0"	0"	
9	SOUTHBEAM I-VALUE 0.618 × 10⁶	122 673	-9"	23"	53"	-11"	-5"	12"	-11"	-12"	34"	34 500	35 400	0.50"	-6"	4"	-14"	14"	0"	0"	21"
10	SOUTHBEAM I-VALUE 0550 × 10⁶	123 721	-12"	29"	65"	-14"	-39"	11"	-15"	-44"	44"	4' 003	23 596	13.40"							
11	SOUTHBEAM I-VALUE 0671 × 10⁶	124 186	-10"	26"	55"	-13"	-5"	30"	-12"	4"	37"	31 410	39 190	14.75"							
12	SOUTHBEAM I-VALUE 0329 × 10⁶	121 983	-10"	25"	56"	-11"	-6"	11"	-10"	-4"	28"	31 240	39 000	0.0"	-9"	3"	18"	12"	0"	0"	
13	SOUTHBEAM 9 × 10⁶ RIGID BEARING	130 700	-10"	24"	45"	-12"	-1"	12"	0"	0"	28"	28 224	42 375	8.02"							





Case 1 summarized the deflections of the structure as defined by Figure 6. The second case consideres a shortening of the longitudinal connecting struts by 18-1/2%. It was anticipated that this would result in an improved structure with less gross rotation of the declination axis. This however was not the case. For purposes of comparison and because of the increased torsional stiffness of the shorter strut configuration it was decided to retain this feature for future cases.

Case 3 considers the effects of doubling the moment of inertia (bending stiffness) of the yoke lower cross beam. This resulted in an increased gross declination axis rotation and a greater inequality of the declination bearing loads. The lower bearing carries 43.500 kg and the upper bearing 26.490 kg. In Case 4 the bent lower cross beam was replaced by a straight member having a strength equal to the original beam. As can be seen from comparing this situation with Case 2 the declination bearing rotation has been decreased but the inequality in the bearing loads has been increased. For the following cases it was decided not to change the geometry but rather to operate on the stiffness of selected members.

Case 5 considers the horseshoe wall thickness increased by 67%. This resulted in a small improvement in the reduction of the declination axis tilt, bringing it to 28 seconds, as well as a significant improvement in the distribution of loads on the declination bearings. Case 6 with the original horseshoe and 100% increase in the wall thickness of the struts resulted in an improvement in the declination axis rotation, but the bearing load distribution deteriorated. Considering the increased wall thickness of both the strut and the horseshoe resulted in an improvement in the declination axis tilt with some improvement over Case 6 in the bearing and load distribution. Up to this point the overall weight of the mount had increased by 40% and we concluded that the marginal improvement in performance did not warrant this excessive weight.

One further geometrical modification was considered which involved moving the bearing on the lower cross beam into the centre of the beam to eliminate the effects of the moment introduced by the bearing reactions. For the purposes of comparison the increased wall thickness of the horseshoe and struts was retained. The result was a decreasing in the tilt of the declination axis with no improvement in the bearing load distribution.

All of these various modifications indicated that a more significant modification was required. Case 3 indicated that increasing the south beam I-value made the situation worse. Thus one would suspect that decreasing its value would have the opposite effect. This modification was employed in Case 9 where the south beam's strength was reduced to 1/7th of its original value. The heavier horseshoe and strut were retained. This modification resulted in decreasing the declination axis tilt to practically zero and the bearing loads are nearly equal. The price paid was a significant increase in the beam lateral deflection to a value of 2.31 mm. The stress level in the beam was

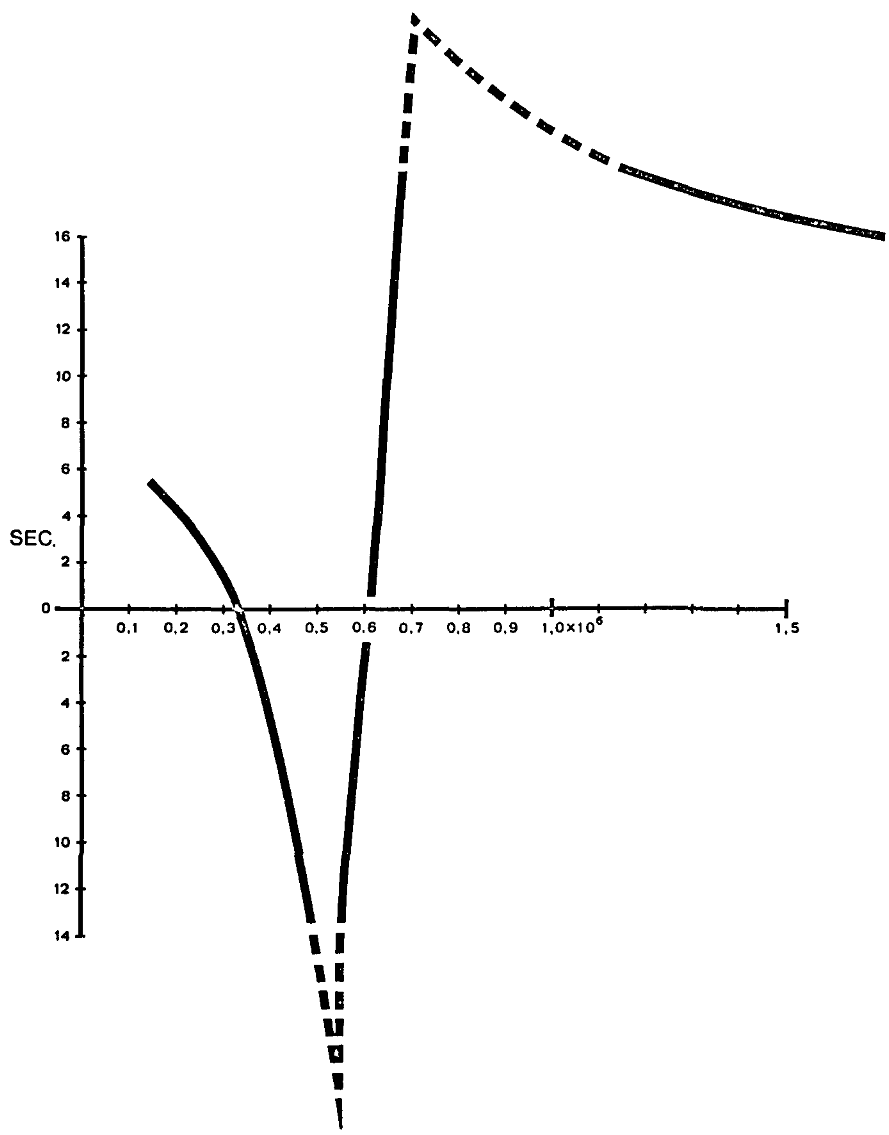


Fig. 9 Tilt angle of declination axis.

700 kg/cm^2 which, although acceptable by normal structural standards, would be considered marginal for telescope structure.

An investigation of the deflected shape of the beam indicated that it had assumed an "S" shaped configuration. This lead to some concern about the deflection mode of this critical member. Further cases, 9a, 10, 11, 12 and 15 were designed to study this problem in detail. The presence of a deflection mode instability in the frame system was confirmed. Figure 8 illustrates the typical frame distortion corresponding to Cases 8, 9, 10 and 11 where only the moment of inertia (I-value) of the lower beam was varied.

Figure 9 gives the tilt of the declination axis as a function of the different I-values for the lower beam when the mount is in the six o'clock position. This reveals a situation that no operator of a telescope would care to cope with. A position of neutral stability exists such that a minor change in the loading situation (for instance the addition of a 600 kg spectrograph) could result in a significant variation on the deflection mode.

The situation in which the lower spherical bearing was replaced by a rigid bearing mounted in a rigid lower beam was considered as a possible solution to the rotation of the declination axis. Case 14 used the high I-value of Case 3 and the results gave a reduced tilt to 8 seconds but the declination bearing load inequality still existed. It was concluded that this feature did not show too much promise.

Up to this point we have considered only two of many parameters upon which the suitability of the structure may be based. In Table 1 we have presented one further parameter in the form of the twisting of the horseshoe with varying hour angle. If a variation of 24 seconds occurs, as it does in some cases, over a six hour range from the zenith position to the six o' clock position and for a pad width of 1 m, this rotation would result in a variation in the oil pad gap of 0.12 mm. This value is of the same order as the dimension of the oil gap. The effects may be seen in Figure 10.

Many more cases were considered but those described above indicate the usefulness of such calculations for designing a telescope structure. There is no simple recipe that the designer may follow to ease the job of designing large precision telescope structures. It is sometimes very frustrating to see how ineffective so-called improvements to the structure really are when their effectiveness is evaluated. The major problem is to overcome factors which lead to rotations of structural elements. To overcome or reduce these problems the designer should adhere to the following guidelines:

(i) maintain axial symmetry of the structure,

(ii) forces must be transferred between members by direct force flow with a minimum of offsets which lead to subsequent bending and rotations,

(iii) maintain a simple and straightforward structural concept,

(iv) maintain determinant and structurally clear details in design of bolted and welded connections, bearings, locking devices, etc.

The subject is not complete without a discussion of the costs involved in such a detailed and extensive engineering analysis. It is true that the greater the work the greater too is the cost. However we believe that an approach of this nature can result in a significant saving in weight for equivalent or better performance. Not only can the telescope be more precise, it will also be a much stiffer and more efficient structure. The saving in weight and the cost associated with this weight, as well as improved performance, help to maintain a proper balance with the additional analysis and engineering involved.

We have dealt with only two of the five topics outlined at the beginning of this paper. Similar analyses are carried out for the upper ends, the mirror cell and mirrors. Many of these calculations occur during the early stages of the design when details are often scanty and few drawings are available. As a result these calculations cannot be considered as final and only become so when a check is made of the detailed design in its finished state. At this latter stage it is possible to combine the upper ends, lower end and the tube structure to eliminate most of the simplifying assumptions that have been made during the preliminary calculations.

We are convinced of the usefulness of a high speed digital computer processing special purpose structural deflection programs that are suited to the complexity of large telescope structures. The designer is able to follow step-by-step the behaviour response of progressive changes without the approximations and guesswork of alternative methods. We are also convinced of the need to become concerned with what were previously classed as secondary deflections. They are often assumed to be small and many of them are. However in this day of greater demands for precision these secondary deflections can no longer be considered as negligible if the higher performance standards are to be met. With the widespread use of the Serrurier truss, oil pad bearings and pneumatic mirror support systems, the emphasis on improving performances has now shifted to the declination bearings and trunnions and to more efficient designs of mounts and internal structures for the supporting of secondary mirrors.

DISCUSSION

CAYREL: I think I am now in a better position to answer the question of Dr. Odgers this morning with regard to the pointing accuracy and the coma requirement for the French design. As you have seen, if you consider not only the tube but the whole structure, you have a deformation of the order of 20" or more. So in fact we have put much stress on the requirement that the coma is not higher than 0."1 for decollimation effects and we have not insisted very much, as the AAT Project has, to have a pointing accuracy of 10", that we are not presently able to reach with this structure.

ROOSEVELD VAN DER VEN: What is the average wall thickness of the beams supporting the declination axis?

EGGMANN: 15 mm.

ODGERS: Is it possible to write optimization programs, Mr. Eggmann?

EGGMANN: Yes, on the French program we did an optimization program of the dimensions and all the little changes which improved the situation.

FARRELL: Mr. Eggmann, I think that what Dr. Odgers may have in mind is that now we have got rid of the observer, the physisist, do we get rid of the engineer too by putting everything into a computer?

REDMAN: You are having a serious effect on Mr. Eggmann! It is quite clear that a lot of work is going into these things nowadays and we are learning a great deal.

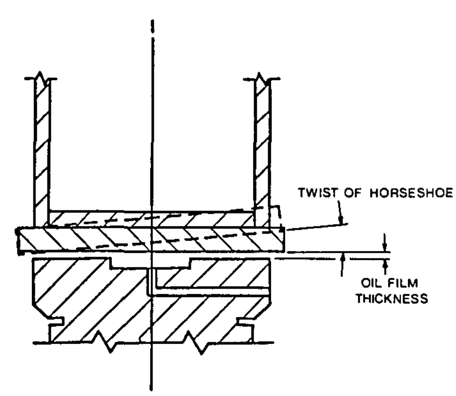


Fig. 10 Tilt of horseshoe.

TELESCOPE BUILDING AND DOME DESIGN

W.W. Baustian
AURA

A telescope building is essentially only a necessary evil in a telescope project, but its cost is generally more than the cost of the mounting itself. Therefore, careful thought and planning should go into the functional layout of the building and into the structural design of the building and dome.

Savings may be made by an awareness that the installation will be in a remote site, and that maximum freedom should be provided for future modifications and updating. It must be kept in mind that telescopes may have expected working lifetimes of 50 years or more.

Domes are specialized structures and all special details of construction should be worked out by the designer and not passed off with the attitude that these are the contractor's problems. The contractors' bids will usually reflect the degree of preciseness and amount of information in the bid drawings.

At the risk of incurring the wrath of the architectural profession, I would recommend that primary design responsibility be given to the structural engineer, and that the architect and mechanical engineer be the associates.

Turning to the building in more detail, one of the first decisions to be made is the height. This will be dependent on local conditions, that is, topography and ground cover effects on seeing. For example, based on micro-thermal tests, the ground influence at Cerro Tololo is much less than at Kitt Peak. The exterior structural wall may be steel or reinforced concrete. Concrete walls will dampen vibrations due to dome rotation to a greater degree than those of steel construction. If slip forming is used for the pier, it would be advantageous to use it for the building wall as well. Uninsulated but standoff ventilated steel decking panels improve the temperature control with concrete wall construction.

For steel construction, metal clad polyurethane foam filled panels make good exterior wall closures. However, it is recommended that the ribbing and architectural details of these panels be kept to a minimum to minimize edge sealing problems.

It has been customary in the past to use aluminum paint for the exterior finish of the domes. However, at Kitt Peak, all exterior building panels and domes have for some time been finished with titanium dioxide paint.

Although there is a super cooling effect with this material, due to night sky radiation, astronomers have not detected any resultant effect on the seeing.

The interior layout of the building is primarily determined by the scientific requirements, such as observing stations, laboratories, and darkrooms. Traffic patterns are very important to keep in mind. This includes the provision of red light illumination in all areas and passageways used by the astronomers during the observing period.

In the past few years several observatories have added coudé feed-ins to large telescopes. These exterior optical systems enable the coudé spectrograph to be used for one object while the telescope is used at the prime or Cassegrain focus for observing another object or field. It would be advantageous to consider this development in the basic design of the building.

All support facilities, such as air conditioning equipment, air compressors, etc., must be vibration isolated and readily accessible for maintenance. For both economy and ease of maintenance, the utilities should have main runs or lines concentrated in one section of the building with all services feeding from a central service shaft. The use of power buss ducts in this shaft will provide good flexibility, as power feeds may be taken off merely by snapping disconnects into the buss wherever desired.

Vibration isolation of the pier may be achieved by mounting the building columns that are near the telescope pier on suitable isolation pads. In addition, these columns can be moved away from the pier, say 10 or 15 feet, and then the floors cantilevered adjacent to the pier.

Since the main or telescope floor must be designed for heavy loading, it will have a rather large thermal inertia, particularly if it is concrete. We have imbedded cooling pipes in this floor to control thermal interference with the seeing in the dome.

It is advantageous to keep the dome weight to the minimum possible, both from a standpoint of cost of the dome itself and of the fact that savings in dome weight result in decreased load requirements for the dome trucks, dome drives, building walls, and decreased seismic loads on these elements. A rational review of some of the design conditions will indicate the following:

A. With the dome trucks attached to the ring girder, all vertical loads are supported directly by the building wall. Therefore, the ring girder need only restrain the horizontal forces and maintain the circularity of the structure. To satisfy interior space considerations, part of the ring girder may extend outside the dome and be incorporated with the outside catwalk.

B. The shutter arch beams, with their structural cross tie at the top, form a relatively stable independent structure.

C. Since the outer skin plates are joined by continuous welds, they should be given their full value as a structural component of the dome. The use of single curvature plates instead of spherical bumped plates is more economical in manufacture, in transportation, and in field installation. With single curvature plates it is recommended the outer flange of the ribs be kept as narrow as possible to maintain minimum separation between this flange and the skin plates at their vertical seams. Vertical butt joints and lapped horizontal joints provide maximum ease of field fit-up of these plates.

D. And finally, the dome should be designed for a moderate dead load deflection, since the dome trucks are not permanently attached to the ring girder until after the structure is complete.

A reappraisal of dome truck design leads me to the conclusion that trucks best be provided with a minimum of spring suspension and that these springs be short and have a high spring constant. The reason is that dome rails are easily leveled to a maximum vertical deviation of 1/16 inch in twenty feet of track length. However, provision must be made for adjustments, during installation, that will accommodate normal structural variations in the ring girder. The cone shaped wheels should be mounted so they can be tilted vertically and horizontally to within several minutes of arc of correct alignment. A mirror fastened magnetically to the inward end of the wheel axle to reflect a laser beam from the center of the building, at track level, back to a target at the laser, makes a fast and convenient alignment control.

Present day domes usually have a multitude of trolley bars under the ring girder to provide power and controls for drives, etc., in the dome. This makes access to the trucks limited for maintenance and almost impossible for removal of a unit. It therefore may be advisable to provide for installation of these trucks down through the ring girder from above. Removal at any future time would be greatly facilitated by this arrangement.

The width of the shutter is usually at least twice the mirror diameter. Less than this increases the requirements for the dome drive and its controls. It increases the complexity of the drive since wide range variable speed units will probably be necessary. Single speed, line start, A.C. motors driving through fluid couplers have been satisfactory for domes with the wider shutter openings. Both brakes and flywheels should be provided on these units. Rubber tired, solid or pneumatic, friction drives have given good service for both large and small domes.

Crane capabilities built into the dome to assemble the mounting are safer and usually cheaper in the long run than hiring mobile cranes of sufficient capacity. This is particularly true of remote installations such as in Chile where such equipment may be hard to find and often in poor condition. The large crane should be supplemented by a smaller crane, say 5 tons or so, for routine service. The problem of obtaining sufficient crane travel does not appear too great in large domes. For one thing, the large modern telescopes will not be of the long fork type mounting, and therefore require service almost to the outer perimeter of the building. Therefore, the heavy lift capability, which can easily be made available in the central half of the building, will be able to handle all the major parts of the mounting. For lighter lifts the service range can be economically increased by an outhaul winch mounted on the back side of the dome. Though standard crane hoist and bridge drive components may be used, the design of the bridge itself should be carefully supervised by the staff engineers to obtain maximum bridge travel.

The choice of shutters, biparting or up and over, it optional. The up and over shutter is approximately one quarter to one third the weight of the biparting shutters. Its loading on the dome remains more concentric and develops less torque in aximuth in the open position during high winds. It does require a larger drive unit and more attention to seal details. The biparting shutter, though heavier, requires a lower powered drive, but develops greater eccentric loads and torsional wind loads on the dome. Both of these factors probably lead to a somewhat heavier dome.

Metal clad polyurethane foam panels are now available for the internal dome surface. Rather simple installation methods have been developed for this type of lining. Caution is urged that fire retardant types of foam are used.

Some thought and design effort are required to develop storm proof ventilation inlets and outlets for the space between the outer and inner skins of the dome. It might be well to plan on installing motorized vent closures for the upper or exhaust vents.

I will close with the observation that there are many details of dome and building design that require very careful engineering study and systems design. In particular, it can not be emphasized too much that the correlation and integration of building, dome and mounting design be a staff responsibility. I have been through several large telescope programs and I am still finding many changing problems, most of which are best resolved in the staff stage of planning.

DISCUSSION

HERBIG: I wonder if you would like to comment on the extensive use of titanium dioxide on the hemispherical part of the dome? I think people approve of it on the cylindrical part below the ring girder where all that cold air can drain away to no-one's harm, but titanium dioxide radiates to the cool sky all night and the hemispherical part gets terribly cold. Do you think of this as a good thing or a bad thing with respect to dome conditions?

BAUSTIAN: I think most of the colder drainage would be down off the dome and usually away from the seeing, but I would like to refer to Dr. Crawford who may have more observational experience on this.

CRAWFORD: Dr. Hoag on our staff is an extremely critical observer as I think most of you know, and he worried about the exact point. Our 84" dome with an up and over shutter is titanium dioxide painted and Hoag has made extensive tests looking at the actual telescope image under varying conditions of wind and temperature when the seeing has been very good. To this date he has not been able to detect any adverse effect due to the titanium paint on the dome. His personal belief is that the advantage gained in restricting heat loads etc. far more than make up for any disadvantages which so far he has been unable to detect.

SECORD: When you use titanium dioxide you have an internal design temperature which is 2 - 3°C lower than the mean outdoor temperature.

HERBIG: There is another problem of course with titanium dioxide and that is snow. Snow turns to ice and the ice melts very slowly after a storm and this may be a problem. Does anyone care to comment on that?

REDMAN: Go to a warmer climate.

CRAWFORD: Well, that is probably what we have done, but at our site with titanium based paints some years now we only had one night with problems, and we would probably have had the problems with aluminium painted domes too that night.

DESIGN OF CASSEGRAIN CAGES*

J. B. Oke

Hale Observatories
California Institute of Technology
Carnegie Institution of Washington

Since I am one of the few people at this Conference who actually observes regularly in the Cassegrain cage of a large telescope, it seems worth while to discuss some of my experiences with such a cage. I might begin by describing briefly the Cassegrain cage which now exists on the 200-inch telescope.

This cage is used with major auxiliary instruments, some of which are as complex as any instrument which is likely to be designed and used in the near future. Therefore, the provisions required in our cage are, perhaps, typical of what will be required generally of large telescopes.

The cage at the Cassegrain of the 200-inch telescope is approximately 17 feet in diameter, and has a height of somewhat less than 6 feet. Because of restrictions caused by the design of the telescope itself, the cage has a floor which is sloping on one side but flat on the other. In addition, an insert provides a flat floor in the area immediately below the instrument which has been mounted at the Cassegrain focus. The cage has a chair with a large number of degrees of freedom, the major ones of which are motorized for easy operation in the dark while observing.

The walls of the cage on the south side are vertical and are designed to accommodate the large number of electronic chasses required. These electronic components can be put into the cage together in a single rack which is approximately 4 feet high. This permits extensive changes in electronics relatively quickly with, at most, changes in a few electrical cables.

One of the questions which has been discussed at this Conference is that of access to the cage. Our experience has been that access is only necessary when the telescope is at the zenith, and this access is primarily for installation and checkout of the instrument during the day. In this case, the existence of a flat floor beneath the instrument is extremely useful, since it permits workers to get around easily to the various sides of the instruments for the installation and checkout procedures which are standard.

----

* Ed.note: This paper was read on Friday Afternoon (Chairman: A. Lallemand), but has been moved to its natural place in these proceedings.

It is also our experience that access at night during observing is really not very important except when the telescope is at the zenith. This, of course, very much simplifies the problems of access stairways, etc. and does not create problems of safety during the night. It should be emphasized that almost all work at the Cassegrain is done during the dark of the moon and on objects which are very faint. Therefore, the observer must remain dark-adapted at all times during the night, i.e., he cannot really roam about the dome with a bright flashlight, and he also cannot go into any rooms which are lighted - for example the data room - since when he comes out, it requires 15 or 20 minutes to become dark-adapted again. As a concequence, if the observer is riding in the cage, he will want to stay there continously for extended periods of time.

Dr. Dennison has described some of the new TV guiding systems which are under development at the present time. If these prove as successful as we expect they will, then the need for an observer in the cage will have almost completely disappeared. There will be exceptions, of course, for special programs which require special equipment, or special techniques, in which an observer in the cage will still be necessary.

Even without requiring an observer in the cage, it would appear desirable to still have a cage on the telescope, since this very much facilitates the installation and checkout of the instrument before observing actually begins. Performing these two operations from hoists on platforms might be highly uncomfortable and somewhat dangerous.

It also has been indicated in this Conference that not very much thought has yet been given to the comfort of the observer as he is riding in the cage. I would put in a very strong plea that the facilities for the comfort of the observer be the best that can possibly be provided. While an observer is in the cage, he has a great many things which he must do, such as setting up the instrument parameters, checking the telescope guiding, handling finder field charts, and many other tasks as well. It is important that the number of things which he has to do be kept to an absolute minimum in order that the observer not become overly tired and careless. The best way to achieve the maximum possible observing efficiency under these circumstances is to provide the observer with a comfortable chair which can be moved sufficiently so that he can nearly always sit in a comfortable position no matter what orientation the telescope takes. This chair should have available various pockets and slots for the storing of finder field charts, lists of coordinates, and numerous other things. An observer can only do very good astronomy if he is comfortable and relaxed, and spending all of his time thinking about the observing problems at hand.

DISCUSSION

BARR: I would just like to clarify my comment about pillows. We are not really anti-astronomers, it was simply that at Kitt Peak we have divided opinions on chairs v. pillows, and it is easier to put pillows in than chairs right now.

OKE: This is certainly true, pillows are also much cheaper.

RANDALL: You said that your chair had some degrees of freedom. Is it free to move around in the cage?

OKE: This particular chair we have designed with motions such that the standard observer's head remains moderately close to the eyepiece; in other words there are rotational motions around a point, which is very close to the eyepiece. There are three motions of this sort: an azimuthal motion, a swing away from or towards the instrument, which takes account of the altitude of the telescope largely, and finally a circular motion in the other direction. One further motion, which is needed, particularly for comfort, is the height of the chair; this has to allow for the different heights of observers. This is not done with motors, but the observer adjusts it for his own particular run.

RANDALL: Do you have to move around to reach the telescope controls?

OKE: No, everything can be reached from the chair. All of the controls that are needed will eventually be on the arms of the chair. The instrument controls are also right in front of the observer, so normally there is no necessity to get out of the chair at all during observation.

RANDALL: I am not sure I should be asking you, maybe I should ask Bruce, but what is the balance sensitivity of the 200" to movements in the cage?

RULE: It is balanced to about the corresponding weight of the man at the Cassegrain focus, which would be around 800 ft lbs. It can be balanced to 50 ft lbs, however, but this is ridiculously small. Unbalances up to the weight of two men don't seem to produce any large deflections, although this has not been tried during an actual critical run.

LAUSTSEN: I should like to have a little more advice on the dimensions in the cage. Could you state the range of acceptable dimensions for two measures: from the back side of the main mirror cell to the focus, and from the focus to the bottom of the cage?

OKE: The focus in the 200" is about 20 cm from the lower edge of the mirror cell. The distance from the focus to the bottom of the cage is about 1.60 m, so the total height available is around 1.80 m.

LAUSTSEN: Those are ideal measurements?

OKE: No, they are not ideal, it is all the space we had available. The problem with the 200" is that when you go south, then the cage comes up against the inner surface of the horseshoe. It would have been nice if they had given us about 2 more feet.

LAUSTSEN: In the present design of the ESO 3.50 m telescope the distance from the focus to the bottom of the cage is 120 cm, and the distance from the back side of the cell to the focus is about 50 cm. The focus can be changed inwards towards the cell or even inside the cell.

OKE: The zenith distance is 170 cm?

LAUSTSEN: Yes.

OKE: Well, ours is 180 cm.

BLAAUW: May I ask a practical question? How comfortably or uncomfortably can Maarten Schmidt work in this cage?

OKE: He doesn't complain.

BLAAUW: What would he like?

OKE: He would like a little bit more headroom, I think.

BLAAUW: That's what I thought, but can he work comfortably?

OKE: Yes, he doesn't complain bitterly to anybody. I can work quite comfortably, but he is about 3 or 4 inches taller than I am.

DENNISON: I just want to acknowledge that Dr. Joe Wampler at the Lick Observatory has pioneered a TV system and that at the Lick Observatory they are trying to operate the system without a cage, and without an observer on the telescope. I think it will be a year or so before we really know whether this is satisfactory or not, but at least they are trying the experiment.

FARRELL: What is the total weight of the cage on the 200" and what is the desirable distance between the back of the cell and the focal plane?

RULE: The cage is supported from the outer rim of the cell and weighs around 2500 - 3000 lbs. Concerning the distance below the cell we were, as Dr. Oke pointed out, limited by the dimensions built into the telescope years ago, but it would be desirable to have a head distance of the order of 25 cm because of the angle of the body. I think that would be about minimum. Usually it is difficult to get more because of the Cassegrain optical system. Maarten Schmidt works uncomplaining because he wears a tin hat, and Ed Dennison complains a bit because he doesn't wear a tin hat.

BELLY: Could you comment on the respective virtues of a cage v. a platform?

OKE: I have almost never observed with the platform which moves on the floor with the 200", and the real problem is that the bottom of the 200" travels about 10 cm/min or more. If you try to observe a star there and keep adjusting the device on the floor, then you find that you are moving all the time. I would also be very afraid of getting pinned between the device and the telescope.

CONTROL AND DRIVE SYSTEMS

COMPUTER CONTROL OF LARGE TELESCOPES

Edwin W. Dennison

Astro-Electronics Laboratory, Hale Observatories
Las Campanas Observatory of the Carnegie Institute of Washington
Pasadena, California, U.S.A.

The telescope computer systems which will be described here have been developed for operation on the telescopes of the Hale Observatories. As of this time the hardware has been completed and the software or computer programming is nearly complete, although none of the systems have been used for astronomical observations. At this time it is anticipated that a similar system will be designed and constructed for the 100" Du Pont telescope of the Las Campanas Observatory.

SYSTEM DEVELOPMENT

When this project was started approximately three years ago, we attempted to design a computer system which would have all of the advantages of the older hard-wired data systems plus the advantages which are obtainable with a computer. Our initial concept was to develop a system which centered around a relatively inexpensive mini-computer which was capable of handling a large number of custom made peripheral devices designed to serve the specific needs of astronomical observations. We wanted to have a system which would be able to control the telescope and all of its various functions as well as collecting, displaying, and recording observational data. The design had to provide the observer and the night assistant with adequately flexible controls over the entire system. Still another criterion which we felt important was that our system should be capable of having new peripheral devices added without disturbing any of the previously constructed hardware or software drivers. With the older hard-wired data systems we had encountered the problem that when a new device was added, the data system had to be taken out of operation. After the old circuits were modified or removed and the new circuits added and thoroughly debugged, the system could again become operational. With the philosophy of our new computer systems we wanted to be able to add new peripheral hardware devices by connecting them with new plugs and cables. These devices could be tested without disturbing any of the older hardware. In addition, if one of these new devices did not function correctly, it could be removed for further testing without any

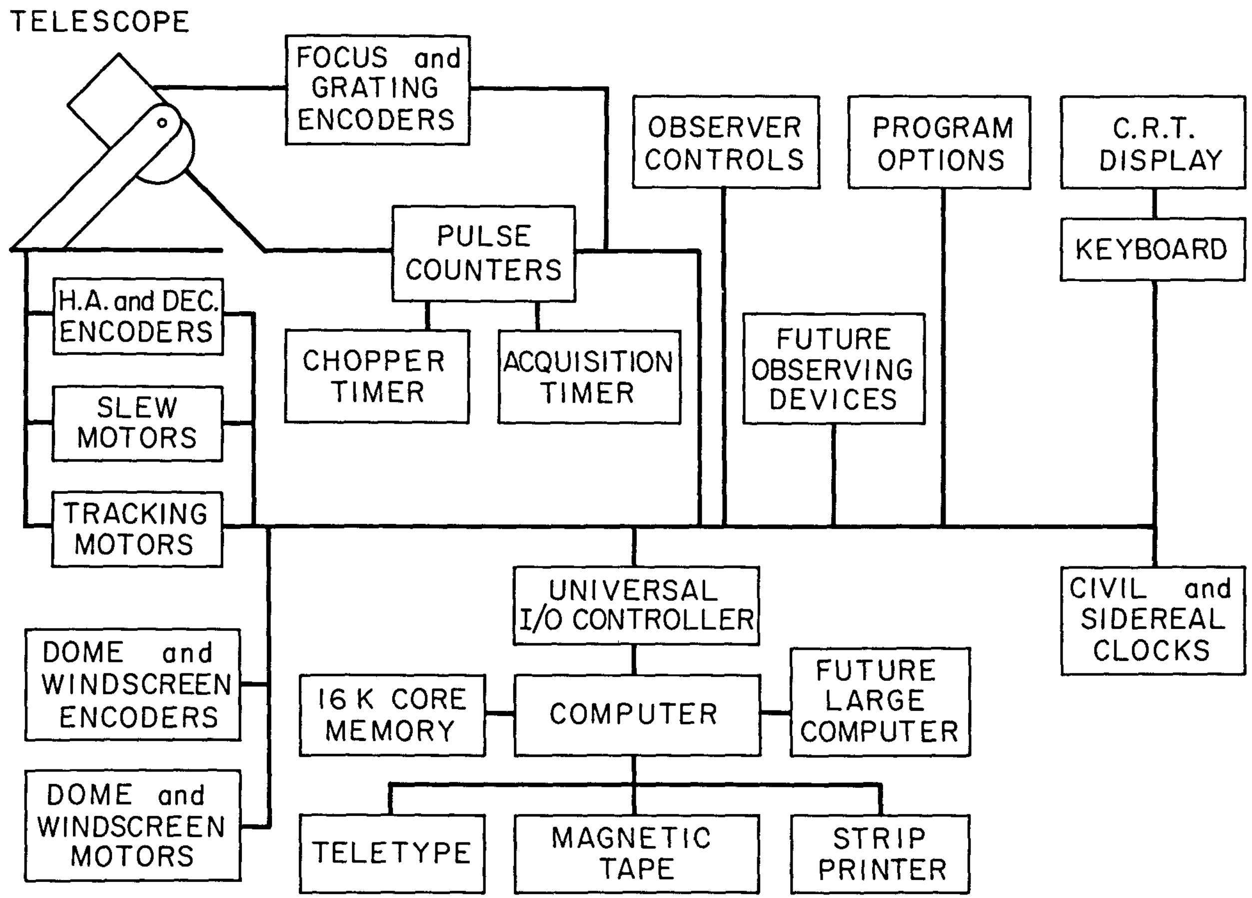


Fig. 1 Block diagram for a typical Hale Observatories computer system with provisions for data collection and telescope control.

disruption of the system operation. With each new hardware device, new computer software drivers would be necessary, but here also the development of the new software did not disturb the previously functioning software. This means that the check out and debugging operations of a new system could be accomplished during the daytime and each evening the system could be returned to its older configuration for the night's operation.

The block diagram for the system which we finally developed is shown in figure 1. The heart of the system is a Raytheon 703 computer with 16,000 words of core memory, a standard ASR 33 teletype printer with a paper tape punch and reader, a 9 track magnetic tape recorder, and a strip printer. Because the basic mini-computer is a 16 bit machine, it is anticipated that at some time in the future we will add a large computer which is designed specifically for arithmetic operations. This machine will probably be a 24 bit machine. The computer communicates with the other peripheral devices by means of a universal input/output controller.

DATA SYSTEM

Because accurate civil and sidereal time is fundamental to both data acquisition and telescope control, we developed a digital clock which is accurate to 1 part in 10^8 and can be set to an accuracy of 1/10 second of time for both civil and sidereal times. Because of the fundamental importance of this unit it has a separate display which is independent of the computer.

At the present time photometric data is collected in a dual pulse counter unit which is related to a chopper timer unit for use with mechanical or electronic star/sky choppers. One of these counters can be used as a preset counter. This unit also contains an acquisition timer to determine the length of time required to make a specific observation. All of these devices are addressable and controllable by the computer.

The observer communicates with the system by means of three units: the first is an observer control box which enables him to control the data gathering cycle; the second unit provides the observer or night assistant with the option of choosing various program functions which have been built into the software system (this is similar to a computer sense switch control); the third unit consists of a Cathode Ray tube display and keyboard. The CRT character generator unit has a composite video signal output which can be displayed on a standard television monitor. All of the data which is important to the observational process is displayed on this unit both to the night assistant and the observer at the telescope. The keyboard unit is used to enter fixed data into the computer system and also to control various computer functions such as the acquisition time, preset counter, telescope tracking rates, etc. By using these units to control the system it is not necessary for the night assistant or the observer to manipulate the computer directly. This ensures that the basic computer program will not be disturbed accidentally and also that the computer can check for inconsistant or erroneous operational commands.

Absolute position digital encoders are used to read out the position of the secondary-focus mirror, the grating angle of spectrum scanners, the hour angle, and the declination of the telescope. Other peripheral devices control the slewing, tracking and instrument stepping motors. The dome and windscreen positions are also encoded and the computer controls the dome and windscreen motor drives.

The most important element in the entire system is the universal input/output controller. This device can be connected by means of a serial cable to 250 different devices. Each device has its own designation and can be addressed by the computer. Once addressed by the computer, it can be issued up to 256 different commands. In turn each device has the possibility of generating an interrupt signal which informs the computer that data is ready to be transmitted by that particular device. The availability and status of each device can be sensed by the computer. All data to and from the devices is transmitted 8 bits or one byte at a time in a parallel presentation.

For a typical observing operation, the observer or the night assistant will select the program options which are applicable to that particular observation, and then by means of a keyboard enter into the computer the various pertinent adjustable parameters, such as, the acquisition time for a pulse counting photometric observation and the name of the object. When the observer centers on the star which he wishes to measure, he presses a button on the control console which starts the counters into operation. After the acquisition timer has reached its pre-determined value the data counters are shut off and the computer is informed by means of the interrupt circuit. The next step is for the computer to interrogate all of the various encoders, clocks, and other devices and gather the data into an output buffer. The computer then starts the strip printer and magnetic tape recorder to permanently record the data. The strip printer serves not only as a redundant data channel but also as a convenient means by which the observer can review the data which was collected earlier during the observing period.

While the data collection process is in operation, the computer periodically refreshes the image on the CRT display with the most recent clock and encoder information. The computer also interrogates the dome and windscreen encoders and compares their position with those calculated from the telescope coordinates. If needed the computer operates the dome and windscreen motors. The tracking rate for the telescope is also automatically computed from the telescopes coordinates and sent to the tracking rate generator.

CONTROL SYSTEM

All control systems consist of three elements: the first is an input device; the second is a decision circuit or device; and the third is an output or controlling device. In conventional systems these three elements are combined in one unit. In the case of our system, the input device is either the clock unit, the encoders, or the keyboard which handles the information from the observer or night assistant. The computer program determines what action is required in order to respond to the input information, and the output devices are peripheral circuits attached to the I/O controller.

The greatest advantage to using a computer as the decision component in a control system is that it permits the relationship between the various control elements to be highly flexible and sophisticated. These relationships can be changed easily as new requirements are generated by the needs of the observers. An on-line computer controlled system has some disadvantages and dangers. Although the error rate in a properly functioning computer is infinitesimally small, the program can be destroyed by means of an erroneous program instruction or the failure of a computer component. For this reason, all controlled devices must have absolute limit circuits which are independent of any electronic components and all devices must have provisions for manual override. Because the computer time shares between the data and control functions, special attention must be paid to program timing. Software costs are not insignificant and adequate budgets must be made for programming. Although our experience in this area has been limited, we feel that the potential power of this computer-oriented control system is very great and we expect to see a large increase in telescope effectiveness in the near future as a result of this approach.

We felt that the output circuits required special investigation because of the problems inherent in linking computer type signal circuits with power circuits. We have paid special attention to developing and using isolation circuits which will not permit electrical noise to cause circuit interaction. Such devices are now commercially available. In most cases the actual power control is handled by silicon control rectifier type devices. To reduce line transients and electrical noise we have chosen circuits which turn on the AC power at the instant the voltage is zero and turn off the power when the current is zero. To control devices which require DC, we use an AC supply and a silicon rectifier.

When a device which is being controlled requires a simple on/off action, the circuit is relatively straight forward, but when controlling large DC motors, the circuits become more complex. We have developed a circuit which will start the motor with a low armature current and then advance the current through eight or sixteen steps to full current. If a proportional type control is required or if the motor is required to operate at less than full torque the computer can achieve this by appropriate instructions.

We have designed a number of stepping motor circuits with varying degrees of sophistication as required by the particular application. The most complex design, so far, is one which allows the computer to specify the stepping motor speed up to 2,000 steps per second and the total number of steps required as well as the direction of the motor. This unit will include some circuitry of our own design and some furnished by the stepping motor manufacturer.

For tracking motors we have used a synchronous motor for the hour angle and a stepping motor for declination. Both of these motors are driven by a computer-controllable preset counter working from our standard 5 MhZ crystal oscillator. Once the computer has set the preset counter value, the output rate remains constant until a new instruction is issued by the computer. We have made provision for manual control of the rate generator for special operations or computer failure.

There are cases of telescope control where it appears unnecessary and even undesirable to use a computer as the control decision element. In these cases we have used standard high voltage digital logic. These all solid state control systems should have the advantage of low maintenance and minimum power switching transients.

SUMMARY

We have been developing a comprehensive data and control system which is based on a small computer. We have also developed all solid state control techniques. Most of these devices are just now going into operation and we can report that we see no major difficulties and there is every reason to believe that these techniques will result in very substantial increases in astronomical observing effectiveness.

DISCUSSION

RICHARDSON: Approximately how much does it cost to convert to this system?

DENNISON: These systems initially are very expensive. The system for our 60" which of course includes a great deal of one-time engineering has cost us something in excess of $ 150.000. The software costs are running about 15 - 20% of the total hardware costs for the system. People now warn me that you in budgeting should even allow as much as 100% for software costs. The second system will obviously cost somewhat less but that is the general sort of price tag that this system will have.

ELSÄSSER: Could you comment on the expected gain in efficiency compared to a conventional drive system?

DENNISON: Well, that's hard to say. The sort of goal I have set for myself, particularly for large telescopes like the 200", is to be able to achieve something like 10 - 20% increase in efficiency for all control operations. This sounds like a relatively small percentage, but even this much time saved on a very large telescope is certainly worth the effort. Now I must also emphasize that these systems do the data handling simultaneously with the control. Therefore we get gains of a factor of 2 and 4 and more in our data handling operations by the use of the computer so the real gold is in the data operations. But since this conference is not about data systems, I didn't say that.

FLORENTIN NIELSEN: You are using the same computer for telescope drive and for data acquisition. Do you really find this is a good thing to do?

DENNISON: Yes, we think it is a good approach. Again we all love our own approaches, but this is the way that we think is best because we feel that so many of the functions are common to both data collection and telescope control. We are afraid we will get into trouble when we do sophisticated long numerical data reduction operations and for these we will have to have a second computer. But for the moment we have not run into this limitation.

REDMAN: You are contemplating on-line reduction of data?

DENNISON: Yes, as much as possible. We feel that the observer can perform better if he gets the reduced data in a form that he can readily understand.

SCHARNWEBER: How much time have you spent on computer task specification?

DENNISON: The design time? Well, the total project has been going for about 3 years. A good share of that time it has been one or two men. At times of peak production we have had 3 or 4 men in total on it, so it has not been large in the way of numbers of man-hours.

REDMAN: 6 man-years?

DENNISON: Something of that order, yes.

REDMAN: You have not yet included automatic guiding?

DENNISON: Not yet. Our philosophy has been to do every step the best that we can; for example we are making the tracking rates automatically compensated for refraction and thereby minimizing the amount of guiding that has to be done when we add a guider on top of that.

BAUSTIAN: Could you use the guide frequency as a superimposed frequency on top of your tracking rate? We have used this on our so called manual system on our 60" in Chile.

DENNISON: It is entirely possible. It is simply a matter of looking at the economics of whether it is cheaper to have the automatic guider put out pulses to the second guide motor which after all has sufficient resolution. On the other hand there is certainly no reason technically why you can't go directly to the computer, have it alter the rate slightly and even take account of accumulated errors and therefore alter the rate too. It's just that this gets to be a fairly elaborate program and this may be more expensive than the other approach, but it is perfectly possible.

REDDISH: Do I understand that you have adopted a general policy of closing your digital servo loops outside the computer and restricting the computer to essentially a management function?

DENNISON: No, what I meant was that in the case of slewing the telescope to some preset coordinates, one enters the data into the CRT display. The data then goes into the computer and is compared with an encoder on the telescope and from that the signal is generated to direct the slew motors until the desired setting and the encoder setting are equal. So the loop is closed through the computer itself.

SCHARNWEBER: I assume that you have a special software program to accelerate the telescope. How does it work? How do you accelerate the telescope?

DENNISON: That is an operational problem that we have not met and handled yet. We think that with this kind of drive with the dominant inertia in the flywheel on the slew motor we will be able to accelerate in a relatively simple way; in fact by simply putting on the full power command, since the DC motors start with a low armature current and step up through the 8 steps in about $0^s.5$ - $1^s.0$ per step. This is then actually built into the hardware, and similarly with deceleration it will step down through the same chain. We think that this will work very smoothly.

ROOSEVELD VAN DER VEN: In case you have to drive with spur gears, you have to compensate for the tooth errors. Can you do that with a similar system or do you need some more components?

DENNISON: Obviously we don't have that problem with this system. For the spur gear drive system, I don't see any problem at all with the compensation, you only have to make sure that you have sufficient resolution in the encoder that reads the gear. You simply have a look-up table in the computer which gives the correction or perhaps you can put it in some other form. It must be a resolution of I would think $0''.25$ or better. Even though your accuracy won't be that good, but that's what you must do.

MALM: I see you have α and δ displayed on the small screen only. Do you find it sufficient for the observers and the night assistants just to have the small digits or have you some additional displays in large figures? Furthermore if the computer takes a vacation, have you any display possibility or are you just out?

DENNISON: To answer your last question. Yes, we have a mechanical back-up system, a simple dial on the telescope. I would recommend that if budgets would allow, it would be better to have a simple synchro system as a back-up. But in any case one does need some back-up system. As to how the observers and night assistants will respond we really don't know. We have had some preliminary tests and there seems to be no problem in reading the television screens. It perhaps looked a little worse to you on the slide than it is in real life, but if this proves to be a problem we will simply add another peripheral terminal. We felt we would rather invest in the television system and put as much as possible there, and if we absolutely have to, we will go

back to other forms of display. But we think it is going to work very well.
BAHNER: That would mean that the poor guys who are 50 years and older would have to change their glasses when reading the screen with the tiny numbers on it?

DENNISON: No, we can put television sets wherever you want. If one of our observers wants to have a television set across the room, then we use a large screen television, and if another wants a smaller one nearby, we can also provide it. By using TV with a composite video output the displays are very cheap and you can just simply put them wherever you wish.

REDMAN: Would Dr. Crawford like to say anything about the Kitt Peak plans?

CRAWFORD: This system is obviously far more advanced than our 150" system. We reviewed it very extensively with Ed and he could comment on it more than I.

REDMAN: What does the older generation say, Dr. Heckmann?

HECKMANN: I am quite satisfied if I see the possibility to handle all this by hand!

DENNISON: We haven't forgotten you!

HECKMANN: I am very thankful to the young technicians if they provide this possibility. I am willing to work with all the electronics and all the automation but in case they fail I want to switch immediately over to the old-fashioned system. That's my philosophy.

DENNISON: And this is an extremely important point. I think that at this stage in the development of computer systems, one really must have this kind of back-up, there is no alternative.

BAHNER: On Tuesday I introduced telescopes as essentially optical instruments, now we may become a little bit afraid that we end up with a telescope that is a big computer with a large optical analog-input at its periphery.

REDMAN: Here is another representative of the older generation.

TELESCOPE CONTROL BY ON-LINE COMPUTERS

S. Laustsen
B. Malm

European Southern Observatory

First of all we should state that the control of the ESO 3.6 m telescope is still in the design stage. For some parts the design is advanced; for others we have just an idea of the conception. Nothing has been built so far, but one experiment has been made with a view to its application on the 3.6 m telescope. This is the development and construction of a new type of control for an ESO 50 cm telescope. Later this afternoon Mr. Florentin-Nielsen will report on this work.

Our principal aim when designing the control and when including a computer as an integral part of this control is to achieve:

1. Optimal performance of the instrument
2. Possibility of carrying out complicated and difficult control functions giving simple instructions.

The second point might need some explanation. Firstly, what is meant by "simple instructions"? Examples are:

- go to next star
- correct to equinox of actual date
- correct for refraction
- correct for field rotation
- correct for gear errors
- drive coudé mirror 5 according to motion of telescope
- rotate the dome when necessary

Complex control tasks of this type can best be performed by applying the complex electronic units called computers. This is shown as a simplified block diagram in Figure 1. The computer receives the instructions, executes the computations required and sends appropriate commands to the object to be controlled. Furthermore, it receives information back from the controlled object on how the instructions have been performed and gives new instructions when required.

In the example shown, the simple instructions may consists of information on the next star and orders to make all necessary corrections. The computer reads the actual position of the telescope from the position encoder

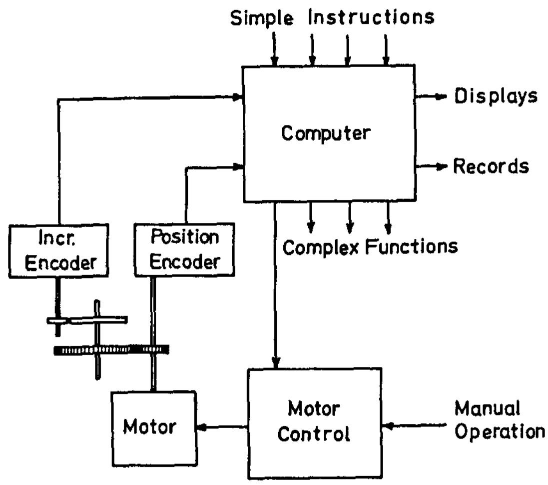


Fig. 1 Example of computer control of complex functions.

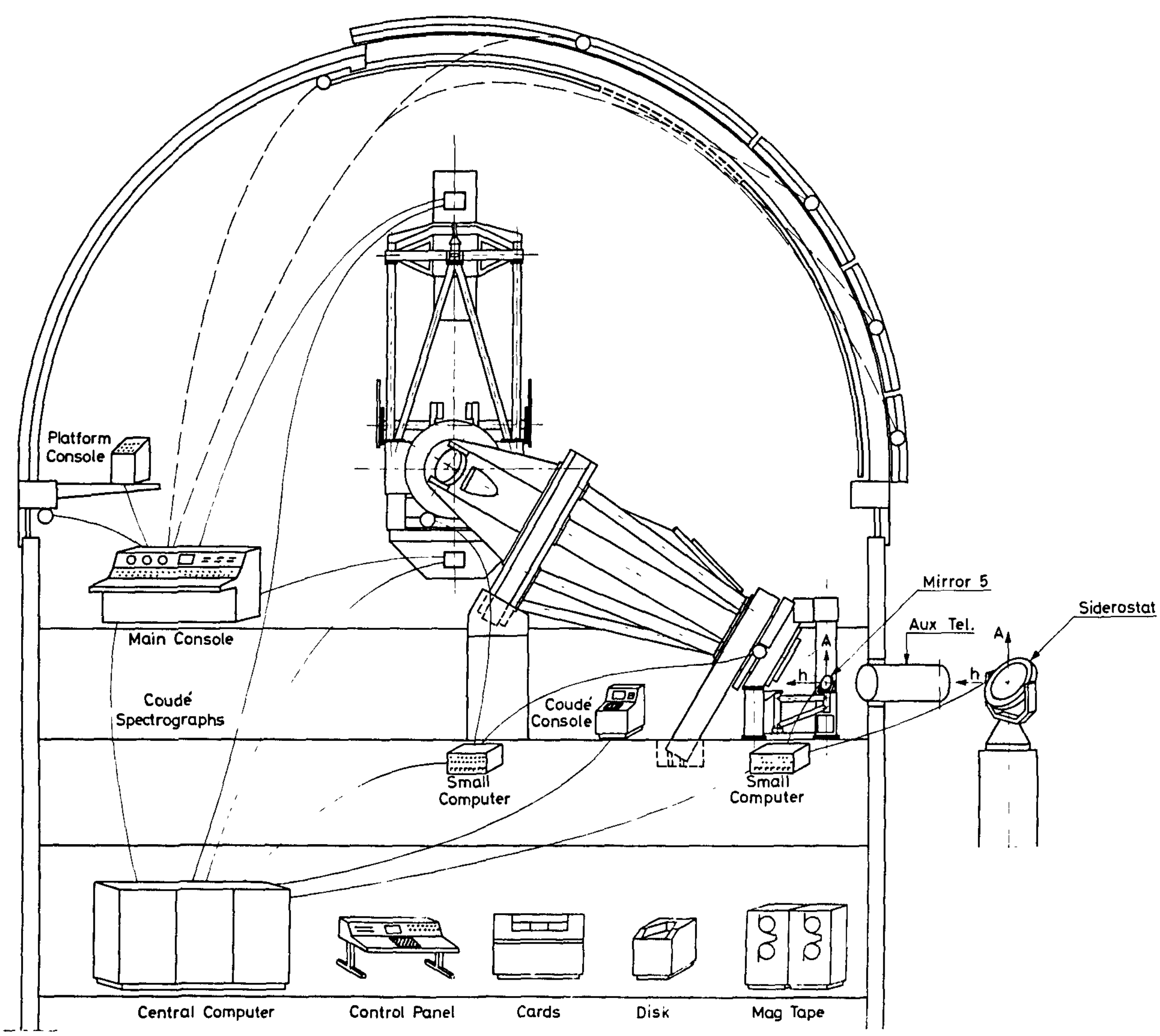


Fig. 2 Principal control lay-out.

and computes how the telescope should be moved. The incremental encoder feeds back information on how the telescope behaves and the computer compares this with the orders given. For the observer's convenience the computer displays and provides records of information of interest.

Now, it might be valuable to make a list of the most important control functions we have to consider, and to show in this list what modes of operation we intend to include. Three modes of operation have to be considered:

1.	Manual	The most simple one. Example: push-button motor control.
2.	Computer controlled	The most complex control mode, where influences and instructions from many sides can be combined. The observer can, in many ways, intervene in the control.
3.	Automatic	Fully automatic control without any possibility of interfering with the procedure except for switching off.

List of the Various Control Functions with the Proposed Operation Modes

CONTROL FUNCTION	OPERATION MODE		
	Manual	Computer Controlled	Automatic
α, δ drive	(+)	+	
Mirror 5		+	
Siderostat		+	
Focusing	+	+	+
Guiding - local or whole telescope	+		+
Top unit		+	
Top unit control	+	+	
Dome and Windscreen	+	+	
Mirror support			+
Monitoring		+	+
Telescope Analysis		+	

Some brief explanations of the control functions follow. The α and δ drives will be treated in more detail later.

Mirror 5 and the siderostat will be controlled in very much the same way as the large telescope. In addition coordinate transformation has to be made from the equatorial to the alt-azimuth system. These two mirrors can therefore only be used under computer control.

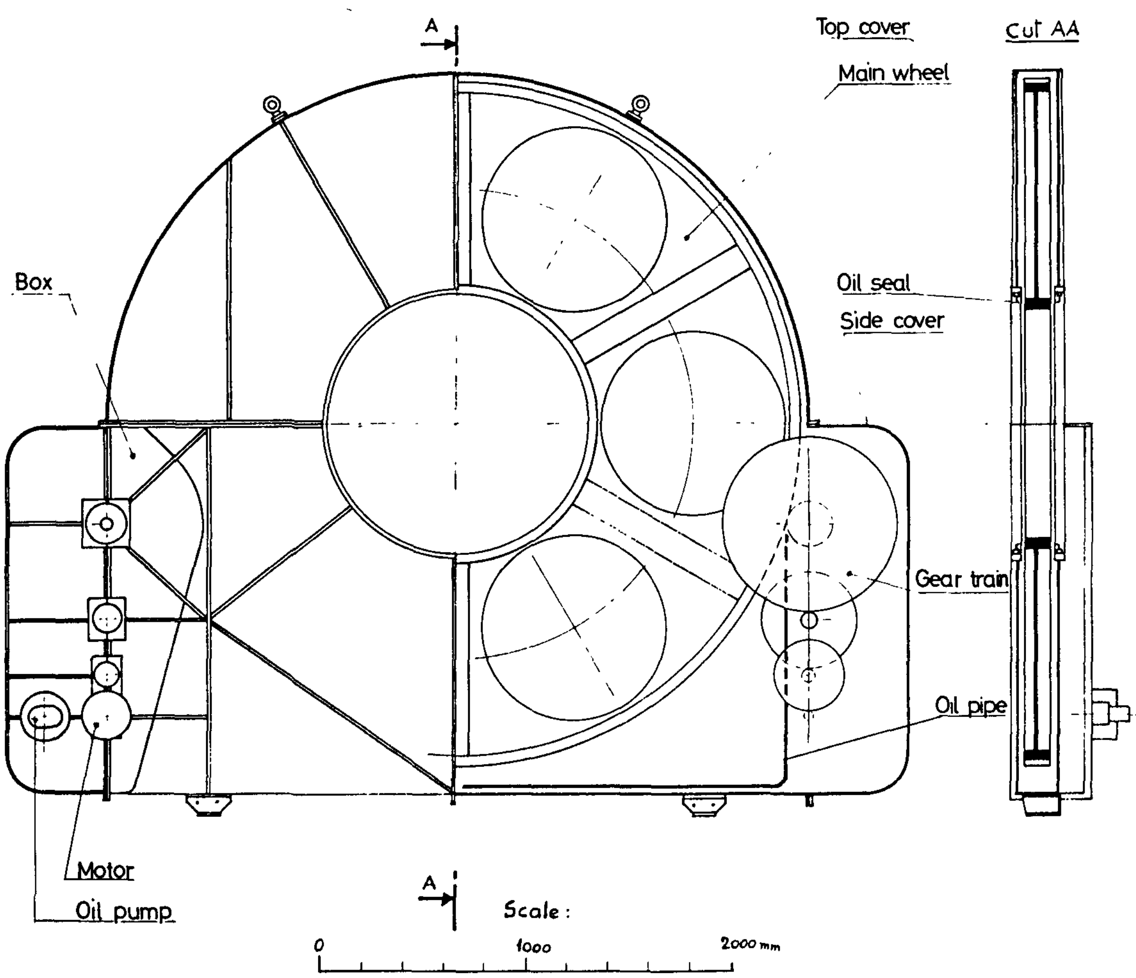


Fig. 3 Right ascension drive.

Focusing can of course be made manually but also computer controlled for compensation of temperature effects and deflections of telescope parts. In a completely automatic mode a laser interferometer system could measure the actual distances between the optical components, and these could be automatically adjusted into the correct position.

Automatic guiding can be performed with local guiders giving fast and accurate guiding. By feeding information on the guiding operations performed to the computer, tracking speed and position corrections can be made in order to avoid the photographic plate or other detectors being driven too much off the optical axis.

The top units of the telescope have been given a simplified mechanical design, still including all the desired degrees of freedom. This has been possible by making the necessary non-linear adjustments by computer control.

The dome and windscreen have to be operated in an alt-azimuth system. In order to optimize the use of the four dome shutters, the computer will also take care of this procedure.

In the mirror cell design the lateral support system consists of 18 pneumatic pads. The air pressure for each pad has to be calculated depending upon the tilt angle of the tube, and the corresponding valve control has to be carried out. This is performed by a mechanical controller, but it could be made by the computer as well.

By monitoring is understood all types of supervision and log-book-keeping. The log-book should contain all interesting information about the telescope itself, the environmental conditions (meteorology), the auxiliary instrumentation, the observation programme, etc.

The telescope analysis will be mentioned at the end of this paper.

Figure 2 shows how the entire control system could be arranged with the central computer and the two smaller ones for the special drive control purpose The control consoles serve for the manual control and as the link between the observer and the computers.

The following is a brief review of the main characteristics of the α and δ drives as an introductory explanation for a more detailed description of the drive control.

The drives for the two axes are very similar. The right ascension drive is shown in Figure 3. They are both double spur gear drives with printed circuit torque motors. This symmetrical system with one driving and one braking motor is free of backlash and can easily reverse the drive direction. The gear chains have reductions 1:12.000. The big gears are 3.4 m in diameter with 468 teeth. The width is 15 cm and a helix angle of 16° gives the contact ratio 2.0.

The motors are of 1 kW and 3 kW for the δ and α drives respectively. The total speed range is about 1:3000. As the slewing speed is 1°/sec, this

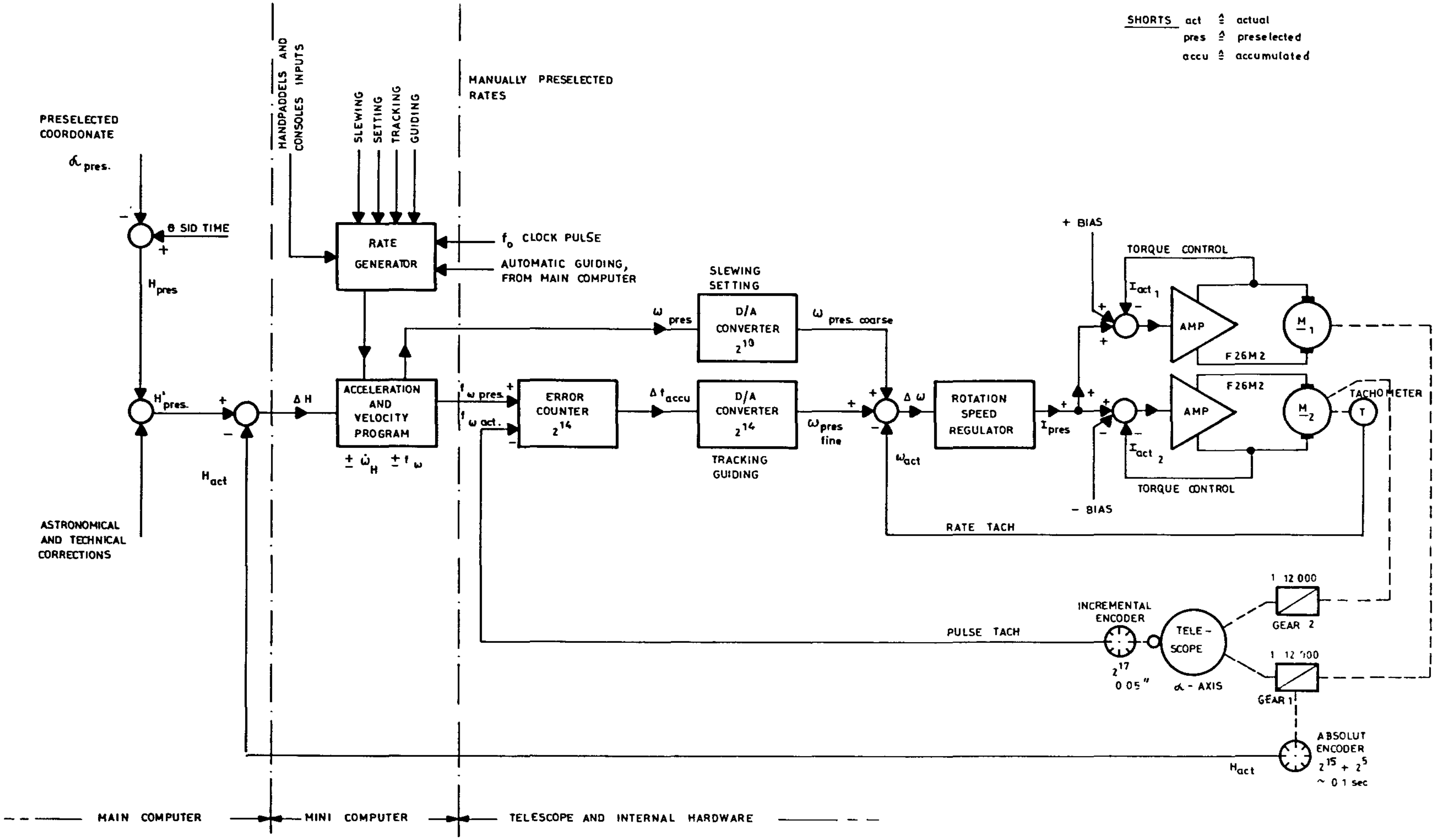


Fig. 4 Block diagram of right ascension drive control.

means that the lowest continuous speed will be 1.2"/sec. Below this speed, tracking in δ has to be done in a stepping mode of operation.

The following table gives a summary of speeds and accuracies.

	Right ascension		Declination	
Speed	Range	Accuracy	Range	Accuracy
Slewing	1°/sec	5 %	1°/sec	5 %
Setting	120"/sec	5 %	120"/sec	5 %
Guiding	±(0-5)"/sec	0.1"/sec	±(0-5)"/sec	0.1"/sec
Tracking	15±(0-5)"/sec	0.001"/sec	±(0-5)"/sec	*

* The accuracy will be set by the smallest steps mechanically achievable.

Encoding will tentatively be performed in the following way. Absolute position encoding will be made either by 20-bit encoders directly on the axes or by two encoders of 2^{15} and 2^5 bits geared together and driven from the last drive pinion. This gives a resolution of between 1 and 2 seconds of arc. Incremental feedback encoders will be driven by friction rollers from cylindrical tracks on the gears or on similar disks. The resolution will be about 0".05.

Figure 4 shows a simplified diagram of the drive control.

The actual coordinates of the telescope are given by the absolute encoders. These coordinates are compared with the preselected corrected coordinates, and the difference directs the telescope to the desired position. The acceleration phase will be controlled by the computer up to a specified upper speed limit (slewing). It will, at chosen intervals (e.g. 100 msec), compute the desired speed according to the regulation curve or equation given to the computer. The acceleration time will be about 4-5 sec and the slewing speed 1°/sec.

In order to measure what happens to the telescope and the motors, four feedbacks of different orders are provided. The one of highest order is the position feedback from the absolute encoder mentioned above. The next two are speed feedbacks; for the low speeds from the incremental encoder and for the high speeds from the tachometer. The latter feeds back a voltage, proportional to its rotation rate, ω_{act}, for comparison with the voltage demanded for the desired speed, ω_{pres}. This primarily gives a damping effect. The pulses from the incremental encoder, $f\,\omega_{act}$, are counted with negative sign and the pulses from the "acceleration and velocity program" output, f ω_{pres}, with positive sign in an up/down "error counter". The accumulated count, Δf_{accu}, gives via a DAC, a control voltage proportional to the desired speed, ω_{pres}. This feedback becomes important for the low speed ranges, which are below the sensitivity range of the tachometer. Parallel to this DAC, another one is provided for the high speeds. It is directly controlled by the "acceleration and velocity program".

The fourth feedback is for control of the motor torque. The actual current through the motor, I_{act}, is measured and fed back to provide a current controlled amplification. The "bias" is introduced in order to provide an appropriate amount of preload for the anti-backlash motor.

There will also be a possibility to make manual selection of desired speeds as input to the "rate generator". The output from the rate generator can be manually activated from push-buttons on the control panels or on the astronomers' hand-paddles. Also, the automatic guiders can feed their commands for speed corrections (via the main computer) to the rate generator.

Especially in the case of the right ascension and declination motor control, the computer solution seems to be a convenient one. In comparison with the special analog hardware for two coordinates, the computer solution gives a much less extensive hardware. Besides, the reliability should be higher. By using a special small-computer for this task, and having a spare computer, any long break downs should be entirely avoided.

As our last point we should like to bring forward one somewhat outside what has been described so far. This is the possibility of making a thorough and detailed Telescope Analysis.

The wish of astronomers is always to have a telescope built in no time at all, and afterwards to ask the designers to stay away as long as the instrument is running well. We think the time has come when we should offer our collaborators - the telescope designers - the chance to thoroughly investigate their products during its operation.

From the first days of operation a special computer program could analyse in detail the behaviour of the whole telescope. It would have to be a separate program with no interference possibility on the control program. Each setting process would be supervised and some data be stored. Guiding of any type would be under continuous supervision, and so forth.

A huge amount of data would result from such supervision, but we do think it is worthwhile performing the analysis. As a reward for the work, we should achieve the following:

1. Improved performance of the telescope being analysed, as in course of time the accumulated experience could make possible an efficient compensation for instrumental errors.

2. Accumulation of quantitative experience to be available for the design work of future telescopes.

In connection with this last point, we would even propose a close collaboration between the handful of computer controlled telescopes to be put into operation soon, with the aim of making the analyses comparable. And especially if the one large telescope with alt-azimuth mounting could be included in this collaboration, 10 years from now we would certainly have a much better knowledge of telescopes and their behaviour than we have today.

DISCUSSION

REDMAN: I particularly appreciated the last point, that there should be kept if possible - and this is where the computer might do the work - a record of the progress of performance for the benefit of the designers. If there is anything weak in the present system, it is that you build a telescope and thereafter you never get the users to admit in public that there is anything wrong with it. It is a "perfect instrument", and this goes on for at least 20 or 30 years, and then at last the news gets around; "Well you know, there is a certain amount of backlash here, and it does let us down when we do such and such a thing", and "Such and such a control was never very satisfactory and the windscreen occasionally falls down" etc. Well if this could now all be put in a computer and studied by the designer of the next telescope, we should all go along much faster than we do now. However, some of you may have some better remarks to make.

DENNISON: I just wanted to emphasize also the self-checking aspects of computers. The fact that a computer can perform not only a diagnostic test on its own operations and its own memory, but also on the various peripheral devices, is one of the great assets in using a computer and one of the things that contributes to the very high reliability that we will see with the computer systems.

RULE: Having the problem of going back and looking up the records of the 100" at Mt. Wilson for about sixty years, I am keenly aware of the problem of logging data. There are logs but they sometimes don't log the mistakes. I was wondering in the electronic SNOOPY which we will have taking place here, will these records be kept so they can be used by the maintenance people?

DENNISON: Let me add that at least our current formats are such that every time the identification record is printed out, the right ascension and declination encoders accurate to about 1" will also be recorded along with the time and other fixed information. This is recorded on magnetic tape and the observer is not even aware of the fact that he has someone looking over his shoulder to check up on these things. So these records will become readily available.

REDMAN: Big Brother is watching you.

DENNISON: Right.

RICKARD: I would like to point out that you can use this technique in the daytime also. You don't have to wait until night when the astronomer is using the telescope. You can do functional tests during the day, and essentially double the rate at which you can accumulate data and sooner detect maintenance problems.

LAUSTSEN: That is certainly true. Many of those things could be done during the daytime, but not everything, for instance not the check of the setting and guiding accuracy. This and several other things will have to be done during the night.

SECORD: Since your declination encoder is not on the declination axis, will you have in the computer memory the errors in the gear train to the encoder?

LAUSTSEN: If you are thinking about the position encoder, yes. But maybe Malm would like to answer this question?

MALM: That is correct. For this purpose we will give the computer a table of the wheel errors.

RULE: Does that encoder-position correction include the run-out of the declination oil pad bearing?

MALM: Frankly, we have not been thinking about that, perhaps due to the fact that the oil bearings are quite new in our design. That is a point we should think about.

FLORENTIN-NIELSEN: I would like to appreciate your definition of a small computer just being "a small piece of electronics", meaning that this comparison also goes for the reliability. I think one could simply consider a small computer as being a piece of electronics which has been thoroughly tested and which is a most reliable thing.

REDMAN: And does not cost very much money.

LAUSTSEN: And for which you have spare parts.

PRESENT STATUS OF TELESCOPE DRIVES AND CONTROLS AT MCDONALD OBSERVATORY

D. N. Dittmar
J. E. Floyd

Department of Astronomy, University of Texas

INTRODUCTION

There are four optical telescopes at McDonald, all equatorially mounted. The 107", 82" and 30" telescopes are cross axis and the 36" is fork mounted. The 30" and 36" are conventional small models with synchronous motor-worm gear tracking drives referenced by a sidereal oscillator. Discussion will center about the tracking drives of the larger telescopes. The 82" is an older telescope that has recently been rewired and modernized. The 107" telescope is an example of a large new telescope with a computerized direct drive system. Due to worm gear problems, a spur gear drive, providing full feedback control, is being built. Modifications and improvements are being made in the readout systems and the computer complex. The problems and circumstances that motivated the changes are detailed. Finally, several successful mechanical features of the 107" telescope are noted.

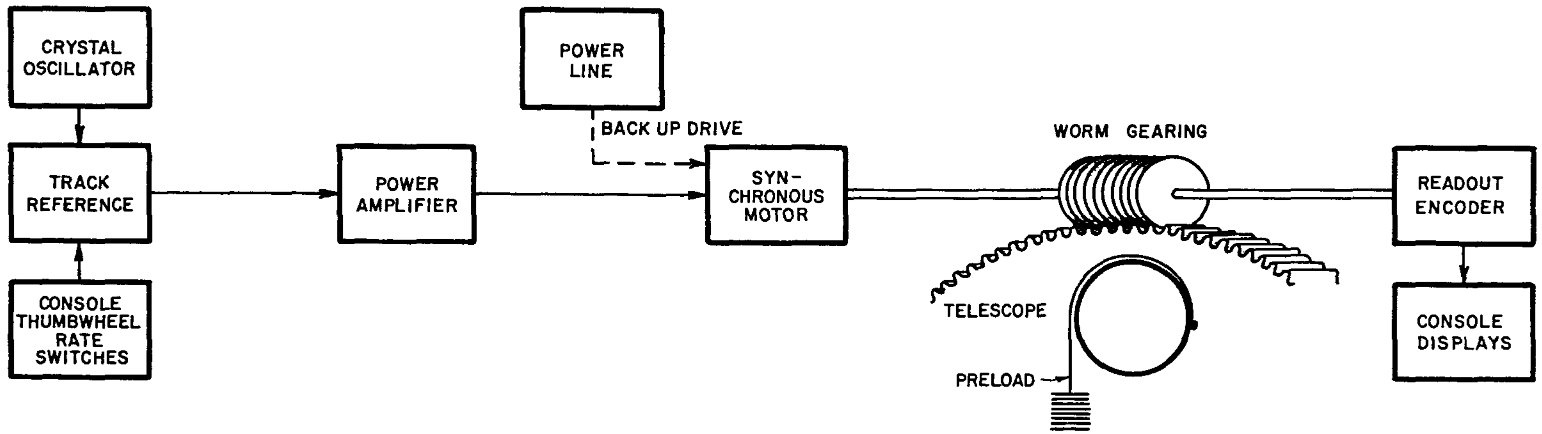
OLDER DRIVE APPROACHES

The 82" telescope's polar axis is driven at the sidereal tracking rate by a synchronous motor through an ingenious gear train. When referenced to the 60 Hertz line frequency, the motor runs at 1800 RPM, and operates worm gears having ratios of 57:1, 63:1, and 360:1. This gives a 1.0025•• revolutions per day ratio, compared to the 1.00273•• ratio required by the sidereal interval. Refraction effects tend to make the ratio reasonably effective, however, when referencing the motor to the 60 Hz powerline. This backup mode of operation is easily incorporated in case of failure in the primary track reference.

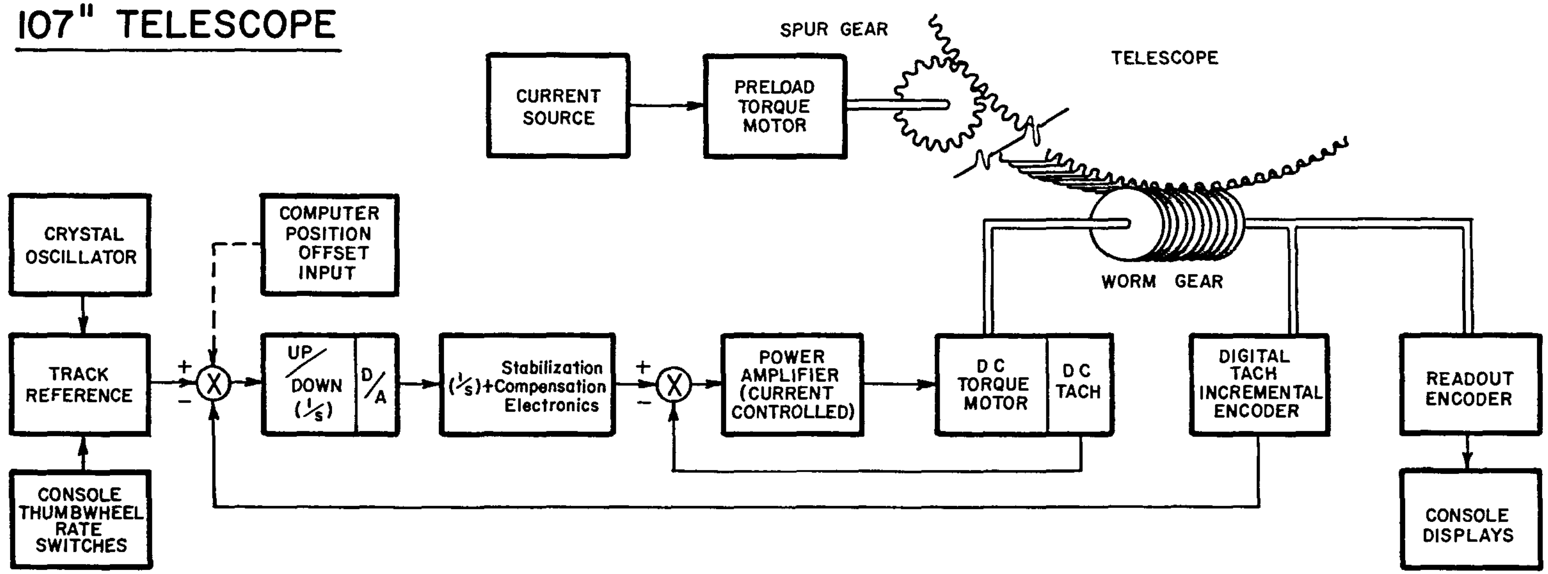
In 1970 the control system was rebuilt to provide a linear control of polar axis tracking rates over a range of about ±30% by variation of the frequency applied to the synchronous motor. The rate resolution provided was 0.1 arc sec./minute, or .0016•• arc sec./sec. More appropriate guide and trail rates were made available, and provision was made for computer control of certain rates. Regrettably, however, the desirability of a position control system was not appreciated at the time the control system was designed.

82" TELESCOPE

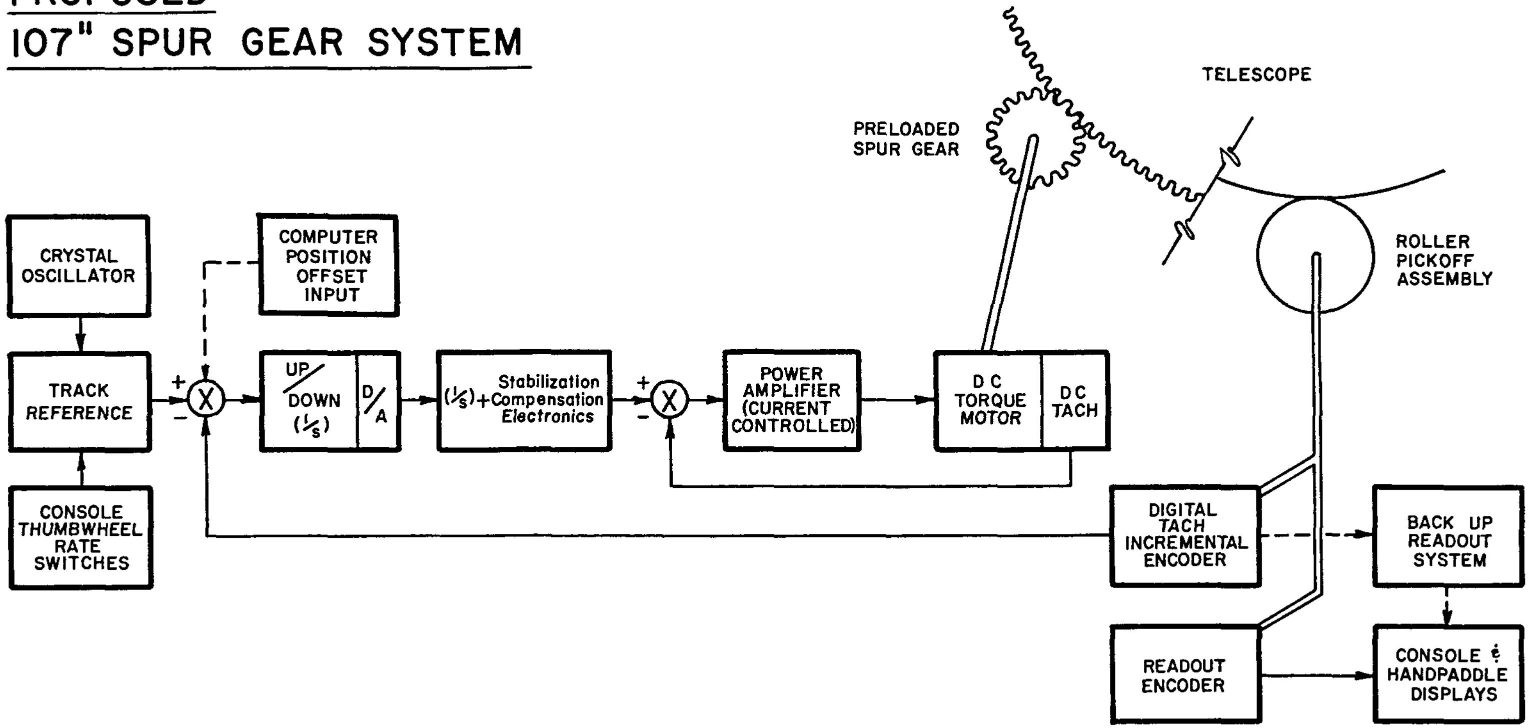
PRESENT SYSTEMS



107" TELESCOPE



PROPOSED
107" SPUR GEAR SYSTEM



Position control or "zero position error" control means that the control system is capable of moving the telescope in response to a reference input an exact distance or angular position. After transients have settled there must be an error no greater than the resolution of the system, even in the presence of a constant rate. Relatively sophisticated control techniques must be used to obtain a "zero position error" system, compared to that required to obtain a "zero velocity error" system. It can be seen intuitively that, with little natural damping, a position loop will be oscillatory because of the required integrations. The significance of position control lies in direct computer position compatibility, where one pulse may equal a tenth arc second of telescope motion in an offset from a known and observable object to a blind position, for example. Compatibility with position sensing devices for automatic guiding is another example.

The 82" declination drive was also designed with only rate control taken into consideration. However, the drive motor selected was a stepping motor for the low range of speeds. The advantage of the stepping motor system is the simplicity and digital nature of the drive amplifier for position controllability. Disadvantages are limited dynamic range and the "open loop" character, where telescope position accuracy depends upon the accuracy of the drive gearing. On the 82" declination system, a slew drive with the attendant clutches and brakes was already present, making the limited dynamic range of the stepping motor acceptable. Also, the existing worm gearing was adequately precise to provide acceptable accuracy. Thus, with only minor modification to the control electronics and the addition of preload, a good position control could be obtained for the 82" declination axis.

THE 107" TELESCOPE

The initial version of the 107"·RA tracking system was designed by David Edison of Westinghouse Electric Corp. The concept had been proven on the 84" at Kitt Peak and others. It uses a DC torque motor operating with a high resolution digital tachometer to drive the worm gear directly. There were significant advantages to the approach. Because of the wide dynamic range of the torque motor, it allowed a single motor and worm-worm gear combination to perform all the drive functions from track to slew in each axis, an enormous simplification. It allowed a highly responsive "zero position error" control, compared to the "zero velocity error" control obtainable with the synchronous motor approach. A side advantage was the ease of telescope balancing, since the necessary drive torque is directly related to the current required by the torque motor, an easily measured quantity.

As experience was gained in the operation of the 107" telescope, two things became apparent. First, the resolution of desired rates was not adequate. 0.01 arc sec per second was the value provided. 0.001 arc sec/sec was required to prevent frequent guiding corrections. Secondly, the arrival of the lunar laser ranging experiment demanded declination tracking capability and full computer position compatibility for very accurate offsets in both axes to blind areas from known points on the moon.

Integrated circuits had invaded the market and were revolutionizing digital design and packaging. It was possible to build a new track reference containing both axes, extra resolution, and extra up/down counter capacity or memory, in about one/sixth the size and complexity of the previous unit designed only 2 years earlier. Parts count and interconnections were greatly reduced. The digital portions were primarily designed by Robert Nelson of Tracor in Austin, Texas, and the new track reference was built in only six weeks, while the laser station was being installed. Using McDonald Observatory's newly obtained IBM 1800 computer for control system simulations, we designed the necessary servo electronics to convert the declination axis to a zero position error servo loop. Computer control for offsetting and setting up was made a simple matter of providing pulses onto one line at a value of 1 pulse equals 1/20 arc second of position, and a high or low voltage on another line to indicate the required direction for each of the two axes. The computer position offset pulses add to the pulses already being provided by the track reference system to give the correct tracking rates in each axis. This nearly trivial control function leaves nearly all the computer time and capacity to be devoted to the functions of data acquisition and storage.

The success of the new drive system was clouded by problems with the worm gears. Consideration of alternatives led to a new approach to large telescope drives.

GEAR PROBLEMS

One of the most troublesome areas of telescope design in years past has been the design and construction of adequately accurate and sturdy worm gears. Telescope drive rate and position accuracy has depended completely upon this component's ability to transfer the motions of a "controllable" shaft to a telescope. Even the new concept of a torque motor-digital tachometer servo loop operated only on the shaft driving the worm gear and thus the telescope was not included "in the servo loop". Actual telescope accuracy still was dependent upon the worm gear's ability to average errors over a large number of teeth, and the precision of the bearings.

The 107" gears proved to be no exception to the troubles often experienced with large worm gears. Due to several factors - poor initial alignment, marginal compatibility between gear materials, questionable gear geometry, and possibly presence of metal particles in the contact area - the worms and worm gears were heavily damaged during installation.

In the reclamation period that followed, the problems were isolated, and the gears hand-worked back to usable status, except for about a third of the worm gear on the polar axis which was damaged beyond repair. This portion of the gear was oriented to allow telescope operation over the full range of -6 to +6 hours of hour angle, but with the telescope tube on only one side of the polar axis. The gear is operating marginally. Weekly inspections sometimes reveal small new scratches, which are immediately repaired to prevent catastrophic damage.

SPUR GEARS

For preload the 107" telescope contains a separate large spur gear coaxial on each axis to the worm gear. Driving the spur gears are DC torque motors having the function of providing steady torque regardless of the speed or direction of motion over the low speed range of tracking, guiding and setting motions. Obviously, the torque motors are required to have adequate torque to provide prime motion of the telescope, since in one direction the worm retreats and furnishes only the restraint necessary for control.

The concept of combining coarse spur gearing to provide prime motion and accurate high resolution sensing of telescope position with encoders into a feedback servo system, which includes the telescope in the servo loop, has long been recognized as feasible. None had yet been built, however, although tentative plans for several of the new telescopes included the possible use of the approach. Dr. Mortara of Kitt Peak was well into computer simulations being made for their 150" telescope, for example.

The combination of circumstances - a search for acceptable alternative to the extremely expensive replacement of the damaged worm gears, the availability already on the telescope of spur gear sets with acceptable torque motors for drive, and digital tachometer encoders for feedback - allowed an actual test to be made on the 107" telescope to prove the concept. An accurate 720:1 roller mechanism was built to drive the encoder off the edge of the gear facing. The servo drive electronics were modified to accommodate the new gear ratio, efficiency and motor characteristics. The worm gear was removed from mesh on the polar axis, and in a test run it was demonstrated that telescope motion while tracking, measured from the encoder feedback compared to the track reference input, could be controlled to within $\pm$1/10 arc second about this axis. This was judged satisfactory, and the decision was made to proceed with development of an operational system for the 107" telescope.

The approach includes a mechanical preloading mechanism comparable to the spring loaded, split gear idea, and the very accurate roller mechanism used to drive the feedback encoder at the 720:1 ratio previously provided by the worm gear. A disadvantage of the approach is the lack of an absolute reference such as would be obtained with gearing. This is considered acceptable, however, since the very high accuracy requirements are over relatively short arcs, referenced to known objects. Another factor to be considered strongly with a wide dynamic range system is safety. The accidental removal of feedback, for example, could result in loss of control with disastrous results due to the wide dynamic range of the system. Several automatic failure sensing and braking devices are being included in the spur gear design.

READOUTS

On the 82" and 107" telescopes, absolute optical encoders are attached to the final worms of the drive trains, except for the 82" hour angle encoder, which is mounted directly to the polar axis. Resolution on the 107" hour angle readout encoder is 0.1 seconds of time (= 1.5 arc seconds). Declination resolution is 1.0 arc second. The translation is made from the encoder grey code into binary coded decimal (BCD) for the hours, minutes, seconds, and tenth seconds of hour angle and degrees, minutes, and seconds of declination. The hour angle is delivered to the McDonald time standard, a digital clock developing both sidereal and solar time bases from a single 1 MHz oscillator, for a continual parallel binary addition to sidereal time. This gives the right ascension coordinate, having resolution, as in hour angle, of 0.1 seconds of time, equal to 1.5 arc seconds. The focus position is also read out in a 5 digit decimal format. Presently, data are displayed on console mounted "Nixie" displays. There has been some difficulty experienced with electrical noise produced by the variable pulse width dimming circuitry used with the Nixie displays.

The 82" declination readout is the same as the 107" system, but the directly coupled 82" hour angle encoder provides only one second of time, or 15 seconds of arc resolution. The 82" right ascension coordinate is developed by the parallel addition technique used at the 107" telescope, except the resolution, limited by the hour angle encoder, is 15 seconds of arc.

Presently, the 107" telescope coordinates are available to the IBM 1800 computer. The typical setup procedure is to manually slew the telescope to within a degree or so of the desired position before transferring control to the computer. The computer compares the encoder information to ephemeris data, adds corrections for refraction and telescope deflection, and outputs pulses to drive the telescope in each axis at a rate of 50 arc seconds per second. With the installation of the spur gear drive, higher rates will be made available to the computer with profiling or ramping of rates to maintain position integrity.

The problems experienced with the readouts have been mostly associated with lightning effects. The most serious effect is induced transients from very near strikes. The low operating voltages associated with integrated circuits make them highly vulnerable to damage when they are attached to long lines. All data lines between domes are presently protected with resistor-zener diode networks. This is effective, but expensive. Damage occasionally occurs even within the domes, however, and this, along with the consideration of reduction of cabling complexity, has motivated the development of a serial data transfer technique. The conversion of data links from parallel to serial is proceeding, with the restriction that telescope operation is not to be disrupted. Only about a tenth of the former number of wires will be required, making fairly elaborate protection of the serial lines feasible.

Since an underground power distribution system was installed, equipment has been relatively invulnerable to lightning damage through the power lines. Considerable inconvenience results from momentary outages from strikes on the lines as much as a hundred miles distant, however. The clock system is maintained by batteries, but the computers and telescope controls initiate automatic shutdown sequences and must be manually restarted. The possibility of installing battery-inverter units for selected loads is being considered to deal with this problem.

Another new readout approach involves the displays. The serialized data will be routed to a special handpaddle containing, in addition to the standard telescope controls, light emitting diode alphanumeric displays. The displays are about 1/4" high and emit a red colour. They operate at low voltage and current levels, and are easily dimmable without the electrical noise problems associated with the Nixie displays. Being encapsulated in epoxy and "solid-state" in operation, the displays are extremely rugged and long-lived. Its use will be extended to other observing stations at the 107" telescope, as well as to the other telescopes.

A new system being developed presently as a backup to the primary readout system on the 107" telescope uses the incremental encoders of the control system for position inputs. With new integrated circuit up/down counters, the pulses coming from the encoders are counted, and the totals are displayed in the appropriate format for HA and Dec. For RA the sidereal clock pulses are added to the HA pulses with the appropriate sign. With the serial data links, the data will be displayed on the same readouts as the primary system. To protect the memory in case of power failure, the system is maintained on batteries. Fiducial lines will be provided on each axis for position reference checking.

COMPUTER COMPLEX

The IBM 1800 is increasingly maintained off-line for non-process programs, high quantity data storage, and observer assistance through the teletype multiplexer (MUX) system. Up to sixteen teletypes can be accommodated simultaneously through the MUX. Other available accessories to the 1800 are a card punch, card reader, a plotter, removable disc packs, digital to analog converter, a high speed paper punch and a low speed printer terminal. Through dataphone connection, access is also available to the IBM 6600 computer at the University of Texas at Austin.

For on-line observing work, smaller peripheral computers are used extensively. These provide various control functions, and store and display limited amounts of data for later high speed transfer to the 1800 through the MUX. A Varian performs timing and data acquisition functions on the laser project. A Data General NOVA controls a scanning spectrograph for the planetary project. A NOVA and a NOVA 1200 are used in pulsar and occultation work. The goal is to provide computer stations at each of the telescope observing positions with an adequate selection of cables and connectors, and patchboard type cards for any signal conditioning that may be required on input or output lines. A new high speed data link for data transfer between computers will also be a part of the station.

OTHER NOTABLE FEATURES OF THE 107" TELESCOPE

Several successful mechanical features of the 107" design are: 1) Stable, trouble free oil pad bearings for the polar axis. 2) Smooth operating, heavily preloaded declination bearings of a closely spaced, angular contact type. 3) A torsionally rigid cross-axis structure. 4) Very low friction mirror support systems throughout, utilizing "flex pivots". 5) An easily adjustable horizontal spectrograph having good temperature stability, and kinematically supported on the telescope piers for reduction of coupling disturbances.

Some deficiencies are: 1) Insufficient radial support for the primary. Adding pivoted supports to the existing three fixed supports would be an improvement. 2) A crowded slit room. A large room for housing several fixed experiments in the slit area is highly desirable.

It is perhaps most notable that approximately 2700 hours per year of observing time has been recorded on the 107" telescope.

DISCUSSION

VAUGHAN: You indicate that the astronomer puts plug boards in, but it seems to me that as a general practice this is an unwise procedure. Perhaps there is some special reason for it in your case, but I would hope that in general the astronomer does not have to do that kind of work on a major scale, and that he can expect that the system will be maintained professionally by a team of electronics designers and engineers.

DITTMAR: Most of our astronomers have their own teams of electrical technicians that come with them, but we are more and more getting astronomers who are able to do this sort of thing and actually are building their own electronics. We only try to protect ourselves by buffering very carefully with throw-away buffers and then let the astronomers play. If they want to develop the experiment with our aid, then we bid on it just like an outside contractor would. Only when they turn over the experiment to the McDonald Observatory for our maintenance and usage do we actually take charge of it. But they are all entitled to our help whenever they wish.

FLORENTIN NIELSEN: What kind of gear protection have you in case of a sudden electronic failure? Suppose full power is applied to the motor, how do you protect the gears then?

DITTMAR: Well, in the first place we are current limited on the output of the amplifier. Secondly we have emergency stop buttons all over the place. Whenever it happens, the motor lines are forcibly ripped from the amplifier by a big relay and a dynamic brake, i.e. a resistor is put on to dissipate the energy.

FLORENTIN NIELSEN: Yes, but by that time you may very well have had a disastrous torque pulse into the gears even if it lasts for only a fraction of a second.

DITTMAR: There is enough inertia in the components of the drive that is effectively a flywheel.

FRIDAY, MARCH 5

MORNING SESSIONS

Chairman: G. Wlérick

DRIVING THE FRENCH 2 m AND 3.60 m TELESCOPES FROM THE HORSESHOE

B. Bertin

I.N.A.G. Technical Division

1. INTRODUCTION

This paper deals with the strictly mechanical aspects of the drive; the control aspects will not be considered herein.

In our view the mechanical components of the drive should be designed, produced and mounted in such a way as to provide the best possible mechanical precision for the telescope drive. In other words, the quality of the drive should never be subordinated to that of the servo system; the latter should serve as a means of improving the mechanical performances of a basically good drive, not as a palliative for an intrinsically poor drive.

This philosophy leads, on one hand, to elevated costs due to the need for high precision gears, but on the other hand to an instrument which can perform satisfactorily without complex electronic devices, the reliability of which is most likely to be inferior to that of the mechanical components.

This philosophy explains why we have not considered the friction drive, whose performance depends too greatly on the control system.

This point of view finds additional justification in the fact that less than top grade gears may in some cases pose insurmountable problems for the servo people.

2. RATIONALE OF DRIVING YOKE MOUNT TELESCOPES FROM THE HORSESHOE

One relatively new drive requirement stems from the rapid development of photoelectric guiding systems which brings hope for the correction of high frequency excursion of the seeing image, wind action, observer movements, vibration due to the drive, etc.

To be able to do this, the entire telescope should have a natural frequency as high as possible. Because of the succession of telescope components (tube, declination drive and bearings, mount, polar axis drive, gear box, motor amplifier), each of which tends to reduce the natural frequency of the whole, it is essential to locate the polar axis drive at the point where it causes least harm.

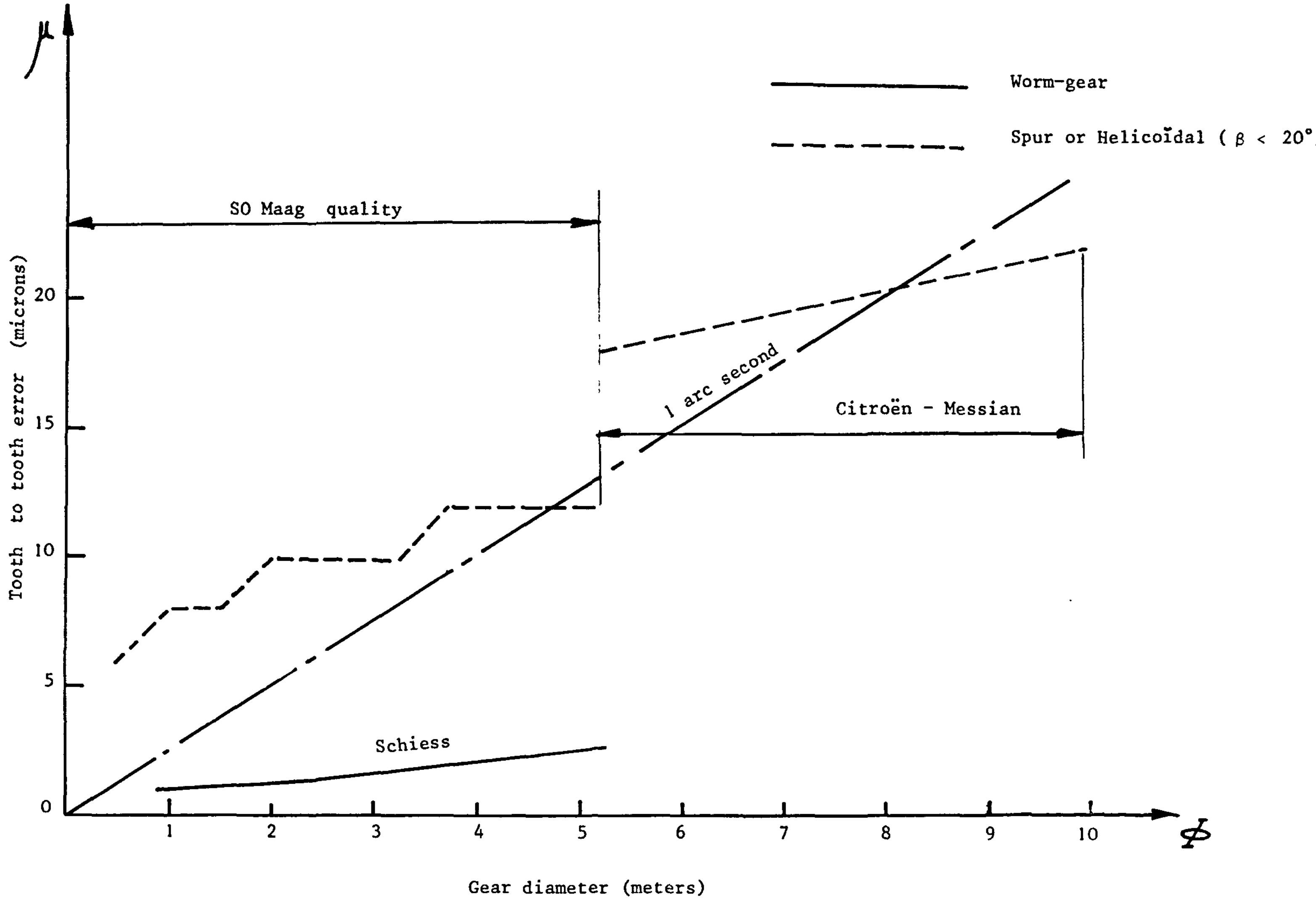
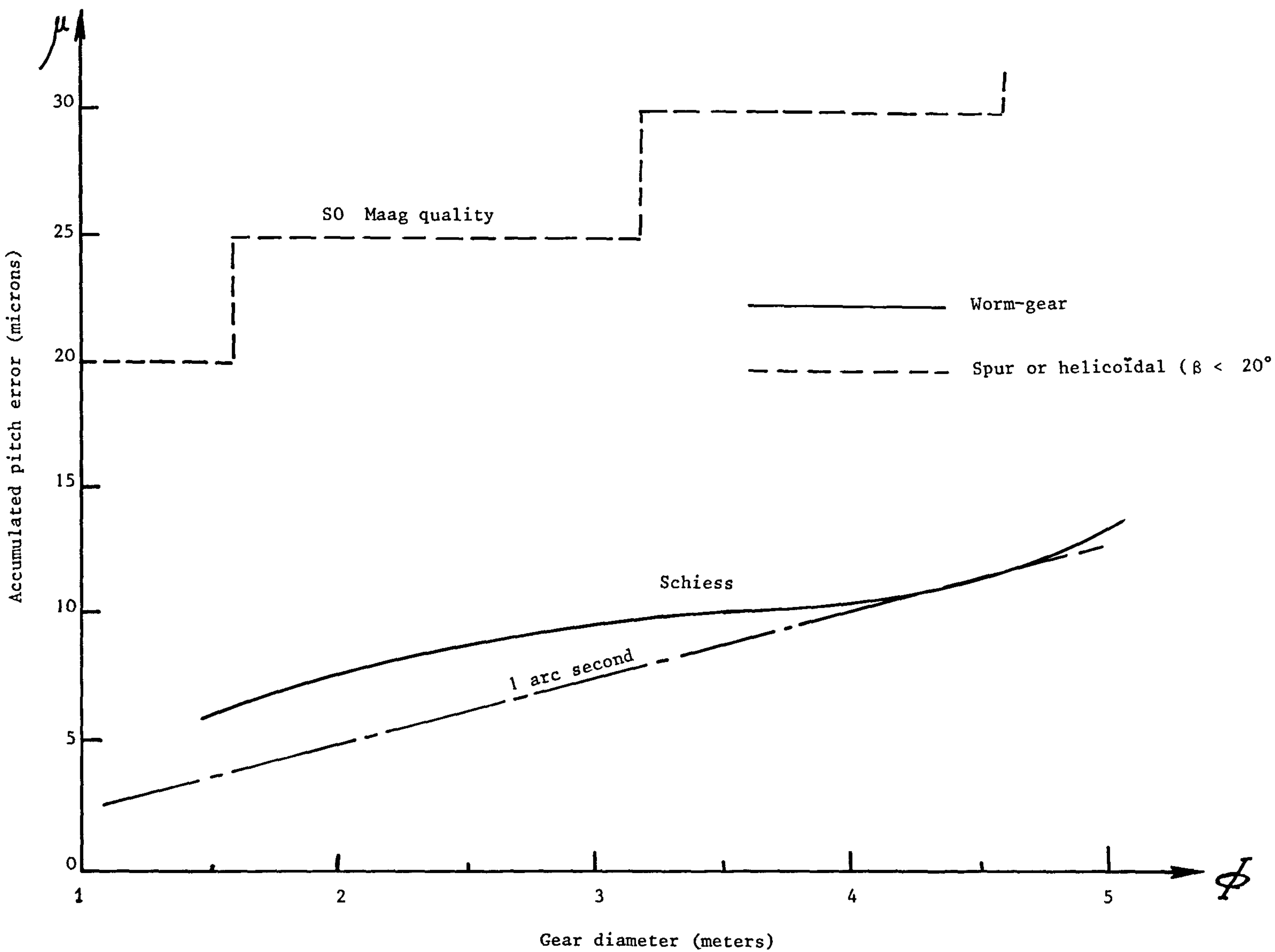
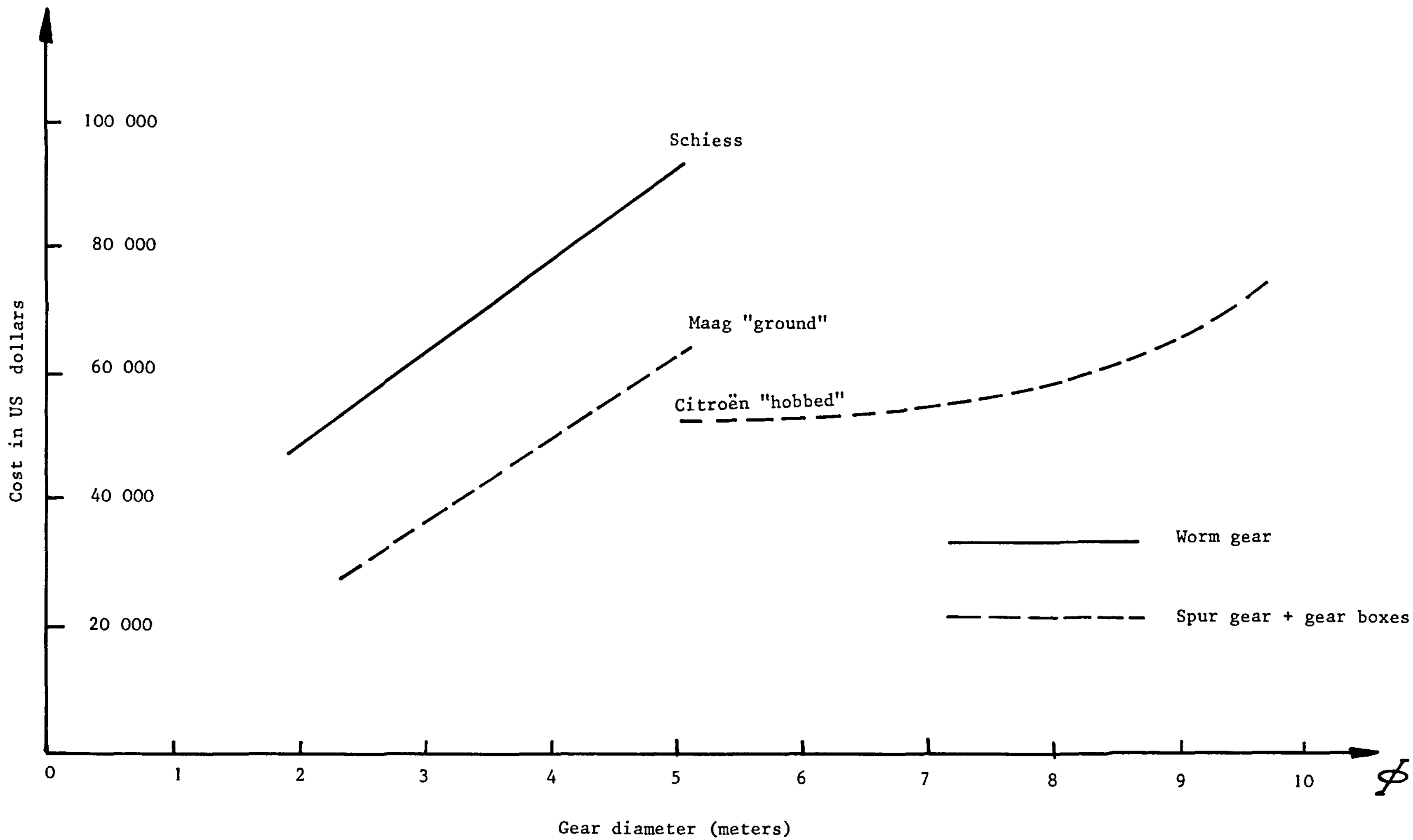


Fig. 1 Tooth to tooth error. (Tooth to tooth error + profile error).



<u>Fig. 2</u> Accumulated pitch error.



<u>Fig. 3</u> Cost of gear tutting.

As we will demonstrate, the best solution is to put the drive on the horseshoe instead of the traditional location on the south end of the telescope.

For the calculation of the natural torsional frequency of the mount, one may consider that the built-in end of the mount is the right ascension drive. Figure 4 shows the schematic representation of a north hemisphere telescope driven,

a) from the South end,
b) from the horseshoe.

Let J be the polar moment of inertia of the constant section shaft equivalent to the mount, C the modulus of elasticity in torsion, I_1 and I_2 the moment of inertia of the telescope tube and of the horseshoe, l_1, l_2, and l_3 the distances defined in Figure 4.

The natural frequency in torsion is given by:

$$f = \frac{1}{2\pi}\sqrt{\frac{CJ}{I_1 l_1 + I_2 (l_1 + l_2)}} \qquad \text{for solution a)}$$

$$f = \frac{1}{2\pi}\sqrt{\frac{CJ}{I_1 (l_2 + l_3) + I_2 l_3}} \qquad \text{for solution b)}$$

Very roughly the horseshoe and the tube each represent about 1/3 of the total mass of the rotating part of the telescope. It can thus be easily seen that solution b) is much more advantageous because $l_2 + l_3 < l_1$, but mainly because $l_3 \ll l_1 + l_2$.

The advantage is evidently of greater significance as l_2 becomes smaller with respect to l_1, i.e. when the declination axis is closer to the horseshoe.

Using formulae derived from the above expressions, we have obtained the following values for our 3.6 m and 2 m telescopes.

<u>3.6 m telescope</u>:

Drive at the south end: 8.6 Hz
Drive on the horseshoe: 17.2 Hz

<u>2 m telescope</u>:

Drive at the south end: 13.9 Hz
Drive on the horseshoe: 26.3 Hz

Because of the simplification used, the above frequencies have no absolute values. More refined calculations give lower values, but what is important is the factor of two found in each case between the two solutions.

As we have previously stated, this improvement is of paramount importance for fulfilling the ambitions of large modern telescopes; at the same time the mechanical engineer views the new solution with great interest:

1. The considerable increase in diameter noticeably reduces the tangential force on the teeth,
2. this will permit a reduction in module, that is, an increase in the number of teeth of the main gear,
3. as a consequence, it will allow an increase in the reduction ratio which in turn will facilitate the design of high stiffness gear boxes when required,
4. the reduced tangential force diminishes the risk of wear; it also reduces the force on the bearing of the worm or pinion depending on the type of gear used,
5. for a given encoder resolution, an encoder mounted on the worm or pinion will have a better resolution as measured on the polar axis,
6. the space available for the drive auxiliary equipment is no longer limited,
7. access to this equipment is very easy,
8. there is no risk of interference with the coudé beam.

The disadvantages of the new solution are few:

1. expansion and distorsion are admittedly greater than those of the south end,
2. the gear has no rigidity in itself. Its stiffness is entirely dependant upon the horseshoe,
3. the gear is subject to deformation when the sector corresponding to the opening of the horseshoe is cut,
4. the large diameter of the gear requires exceptionally large-sized cutting machines and therefore cost is relatively higher and the number of possible competitors in industry is limited.

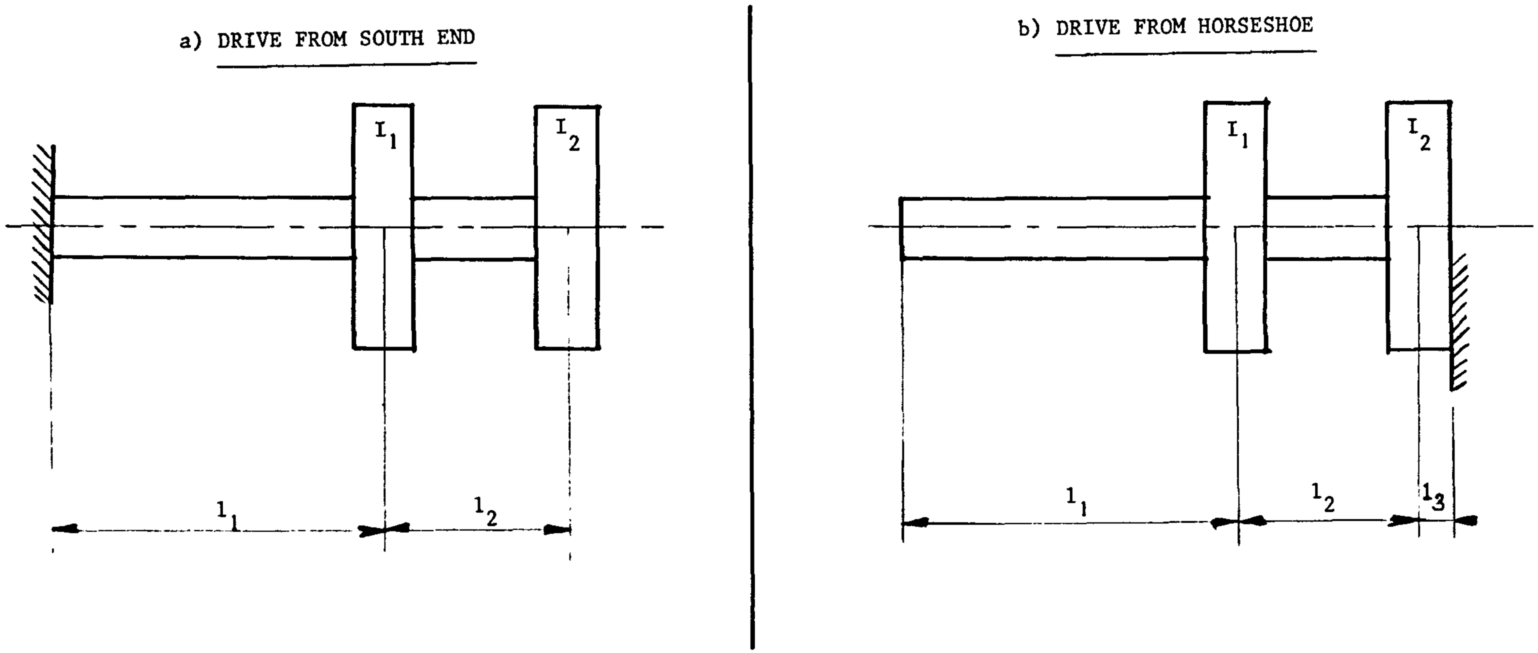
Let us examine these points in detail:

<u>1. Greater deformation</u>

The situation is not drastically different from that at the south end. In both cases, compensation is required to remedy expansion or deformation of the mount; only the scale is different.

<u>2. Lack of gear rigidity</u>

Deformation of the horseshoe in its plane during a 0 to 6 hr rotation leads to a movement of the center of the horseshoe and thus to a movement of the instrumental pole. Such a movement produces a tracking speed error. This error can be programmed out by the control. Another solution



$$f = \frac{1}{2\pi}\sqrt{\frac{CJ}{\Sigma\, I.l}}$$

8,6 Hz ←	3.6 meters telescope	→ 17,2 Hz
13,9 Hz ←	2.0 meters telescope	→ 26,3 Hz

Fig. 4

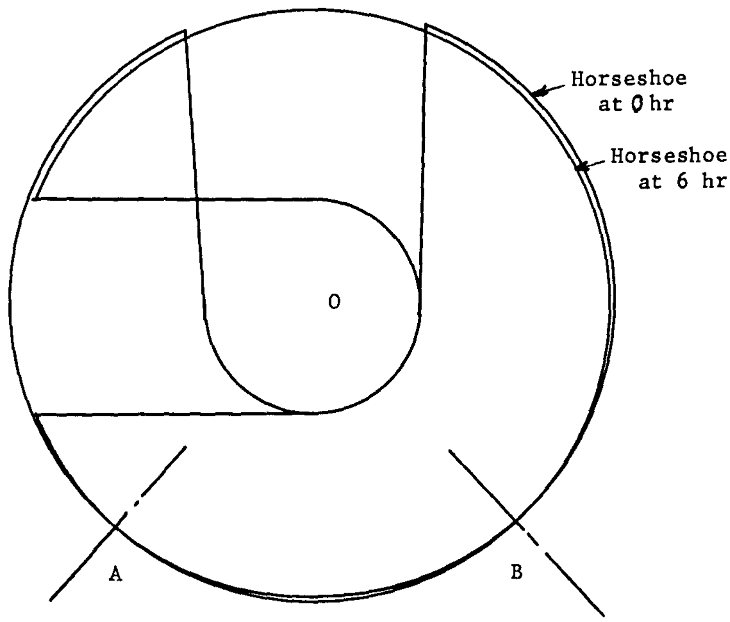


Fig. 5

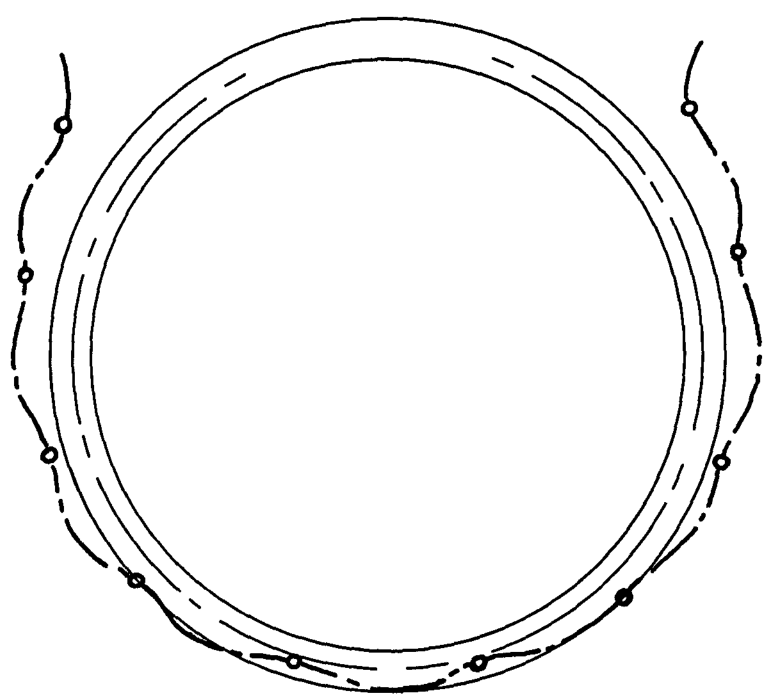


Fig. 6

consists of the annulation of the movement of the center of the horseshoe by selecting a proper geometry for the horseshoe race (this is what was done on the Palomar 200 inch: the horseshoe was machined circular but in a preload condition so as to have the desired geometry when preload is removed). It is always possible to find a loading pattern during machining so that the triangle OAB remains identical to itself during 0 to 6 hr rotation (see Figure 5). Thus by locating the gear boxes at the hydrostatic pads, OA and OB remain constant, so that the accuracy of the gear mesh is not affected by the general deformation of the horseshoe. If no preload is applied during machining, the variations in OA and OB lengths will result in a 24-hr period tracking error which can be programmed out by the control, just as well as that due to the movement of the instrumental pole.

3. Deformation of the gear when the upper sector is cut

The gear is composed of a series of individually shaped and stress-relieved sectors. After tooth cutting, the upper sector corresponding to the opening of the horseshoe is removed. This results in a deformation of the gear which can be minimized by keeping the distance between the fixation bolts small (200 mm maximum). Figure 7 explains how the gear is machined and then installed on the horseshoe: during machining the gear is fitted on a rigid ring (B on Fig. 7) using bolts at the exact location of the bolts to be used for final installation on the horseshoe. After tooth cutting, ring B is discarded and the gear attached to the horseshoe. Provided the above operations are carefully and accurately carried out, the assembling of the various gear elements on the horseshoe should not introduce any additional error.

4. Need for large-sized gear cutting machines

In western continental Europe there appear to be no more than three firms capable of machining large diameter precision gears:

- worm-gears up to 5.2 meters can be supplied by Schiess in Germany,
- ground cylindrical gears up to 4.2 meters in one piece, or up to 6 meters in several sectors, can be supplied by MAAG in Switzerland,
- hobbed cylindrical gears can be supplied by Citroën Messian in France up to 10 meters.

In conclusion, as none of the above disadvantages seems insurmountable, and in view of the important benefits to be gained, we have decided to put the hour angle drive on the horseshoe of our 3.6 and 2 meter telescopes.

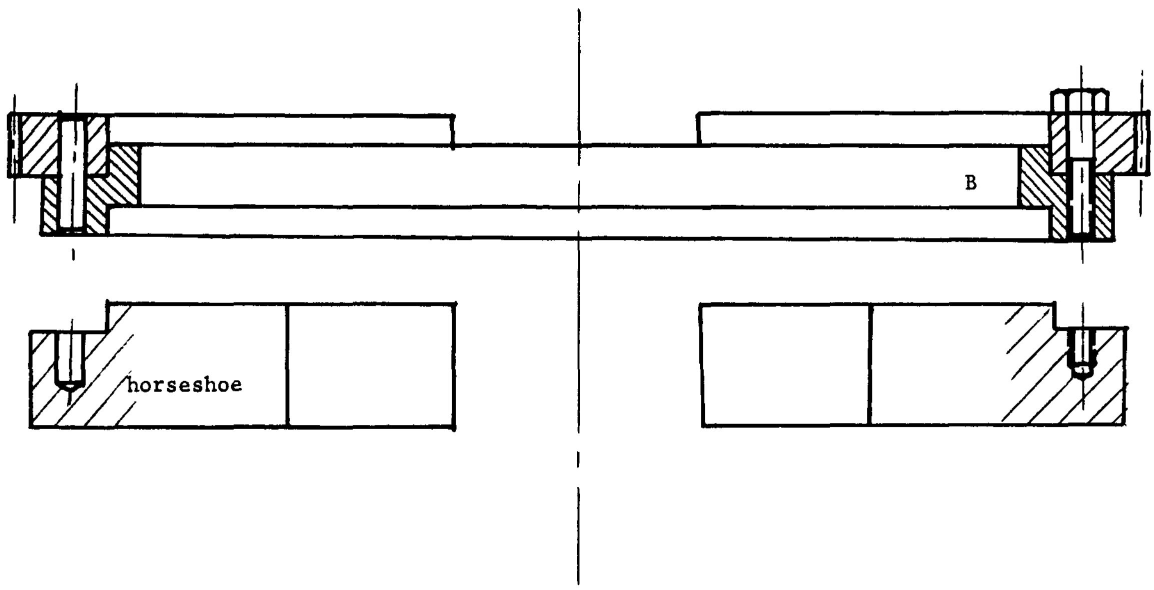


Fig. 7

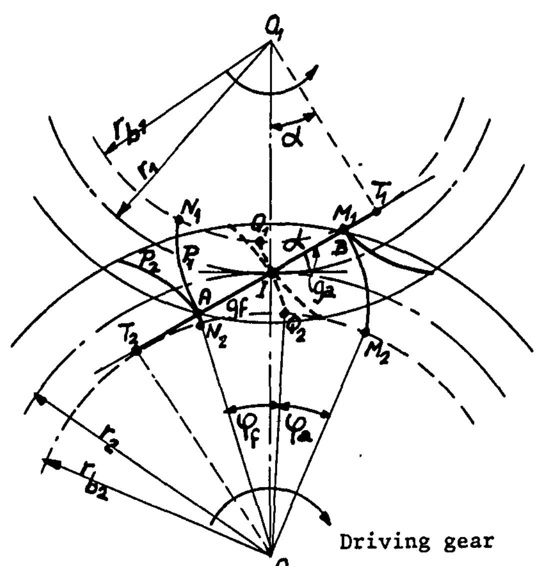


Fig. 8

3. IN DEFENSE OF THE WORM-GEAR DRIVE

The worm-gear drive has been up to now universally used on large and medium sized telescopes regardless of their type of mounting. Recently this practice has been questioned, for a certain number of inconveniences arise when attempts are made to improve the basic performance of the worm-gear by the addition of sophisticated control systems.

The major disadvantages of this type of drive are the following:

Poor efficiency

For the standard gear ratio of 1/720 efficiency is between 10% and 15%. With traditional motors the only inconvenience of their increased size was heat generation which could add to local air turbulence. With modern motors and especially when a single worm-gear is used both for tracking and slewing, poor efficiency is a major problem in the design of the control amplifiers.

Irreversibility

of the worm gear makes it impossible for the servo to compensate for angular deviations caused by structural deflections, wind action on the tube, observer movements, etc... since the farthest upstream the servo loop can be closed is the worm. In addition, power failure and temporary unbalance of the telescope due to focus changeover or disturbing torques are directly absorbed by the gear teeth, and may be detrimental to the drive accuracy. When the worm-gear is used both for slewing and tracking, this danger can be prevented by using a flywheel which leads to further increase in motor size, or by a worm carriage which slides whenever the tangential force is too high. This last solution renders the carriage extremely complex, diminishes the rigidity of the drive and is difficult to adjust. As an alternate, one may use the worm-gear only for tracking and a different drive for slewing. This solution avoids the above mentioned danger by the use of clutches which act as torque limitors. The major drawbacks of this solution, however, are higher cost and clutches that are large, complex and poorly accessible.

Precise alignment

of the worm with respect to the gear is required. This alignment must be maintained regardless of structure deflection or thermal expansion, variation in oil pad film thickness and gear excentricity or wobbling. The solution which consists of a worm carriage rigidly fixed to the telescope base and a gear with web having high torsional rigidity but great flexibility in its plane is not completely satisfactory since it compensates only for the axial movement. A better solution is found in the use of a "floating" worm carriage guided by rollers moving along races machined onto the gear during gear cutting. An even better solution is to use hydrostatic pads instead of rollers: friction is reduced and errors due to roller excentricity are avoided. It is advisable to keep the oil thickness below 30 microns in order to maintain sufficient "rigidity". As can be seen from the preceding discussion, solutions to the alignment problem can be found but they are expensive, complex and difficult to maintain.

Difference in elastic tooth deflection

If a worm gear is used for the declination guiding, tooth deflection will not be the same in both directions of rotation due to the existence of the preload: in one direction tooth deflection results from the sum of friction and preload torque while in the opposite direction it results from their difference. This effect is not negligible since friction and therefore preload are usually high in declination because of the use of ball bearings. It leads to a small error in declination which is not taken into account by the control loop. Naturally this is not true of the polar axis drive where the direction of rotation is always the same.

Wear

is a particular problem with the worm gear drive. The IBM zero-wear theory* shows that wear is a function of the ratio between the maximum shear stress in the contact zone (τ_{max}) and the shear yield point (τ_y). In a worm-gear system the worm is usually made of hardened high strength steel and therefore does not pose any problem, but the gear is cut in a hoop of bronze or mechenite, which have shear yield points two to three times lower than that of steel. Moreover τ_{max} is substantially higher than in any other type of gear due to the hoop shear stresses. Our calculations show that if the worm-gear is used for slewing as well as for tracking, and is installed at the south end of the mounting, it is impossible to reach the condition of zero-wear. Wear is exacerbated by the fact that the gear is permanently fixed to the mounting and thus subjected to wear primarily over the section close to the meridian (this uneven wear wouldn't occur if the gear were used only for tracking since the position of the gear with respect to the mounting is statistically distributed uniformly over 360^o. One must also note that good lubrification is almost impossible since tooth profiles slide over one another rather than rolling, thus rendering the formation of hydrodynamic lubricant film impossible.

All these disadvantages have led the engineers involved in the design of the AURA and AAT 150-inch telescopes to abandon this type of drive in favor of spur or helicoidal gears. We are endebted to these engineers, our colleagues, for their invaluable "pathfinding".

----

* An engineering model for zero wear and its application to design, by A.R. WAYSON, R.G. BAYER and T.C. KU. IB19 System Development Division. 89th ASME Winter Annual Meeting.

However, while many opinions unite to condemn the worm-gear drive we feel it important to reexamine the intrinsic good qualities which have made the worm-gear drive such a long-time favorite.

Accuracy

is unquestionably the greatest virtue of the worm-gear drive. It is possible in Europe to cut worm-gears with much greater precision than cylindrical gears. According to the British Standard BS 1498 - 1954 a 3.6 meter Class A worm gear has a tooth to tooth tolerance of 2 microns (Fig. 1). This tolerance can be guaranteed by the Schiess Co. in Düsseldorf. For cylindrical gears, on the other hand, the MAAG gear book indicates that a 3.6 meter class SO gear (equivalent to DIN 2 or AGMA 15) has a maximum tooth error of 5 microns. As for the accumulated pitch error, its value is 10 microns for the worm gear as compared to 25 microns for the cylindrical gear. One can thus see that there is a factor of 2.5 for these two errors when comparing worm and cylindrical gears. The corresponding angular errors are respectively 0.22 and 1.0 arc second for the worm gear and 0.55 and 2.5 arc second for the cylindrical gear. This difference can be easily explained by the fact that the worm gear teeth are generated by the envelope method, the gear cutting tool being identical to the worm. These errors are themselves smoothed out because several teeth are engaged at the same time. The Duplex type worm in which the pressure angle and the pitch vary from one end of the worm to the other further improves this smoothing effect by increasing the length of contact. One can then be sure that the drive cannot generate any low-period error of amplitude greater than a few hundredths of arc second. Provided that the motor drives the worm directly, the only mechanical error is due to the worm. This error which is sinusoidal (with a 2 mm period when a speed ratio of 1/720 is used) can be restricted to less than 0.5 second of arc. As this error is completely reproducible , it can be easily corrected for mechanically with cams, or programmed out by the control system.

The worm gear drive permits one to obtain the largest speed ratio in a single pair. The speed reduction does not compensate for the low efficiency of the drive (a worm gear with a ratio of 1/720 is only equivalent to a cylindrical pair of gears of 100% efficiency having a speed ratio of 1/720 X 0.15 = 1/110), but the speed reduction is acquired under the best possible conditions:

Drive rigidity

is greater than that for cylindrical gears due to the necessity of gear boxes in the latter case, and there is no additional error in the drive, unlike the cylindrical gear assembly in which each gear pair of the gear box introduces periodic errors.

In conclusion, we do not think that the worm gear drive should be rejected a priori. Provided that it is well designed, its accuracy will surpass that of any other kind of gear system, with no more than traditional controls. Almost immune to sudden errors, its performance will be higher than that which one might expect to attain with the combination of cylindrical gears and sophisticated servo systems, which cannot compensate for sudden errors.

Recalling our basic philosophy that accuracy of the drive should not primarily depend on the servo control, we are inclined to adopt, whenever possible, the type of gear offering the greatest accuracy, that is to say the worm gear, although we fully realize that as a consequence we will have to cultivate the patience necessary to live with its shortcomings.

As we have seen, European gear manufacturers cannot supply worm gears larger than 5.2 meters in diameter. This corresponds approximately to the usable diameter of the horseshoe of a 2 meter telescope yoke mount. The high performance desired from the new 2 meter telescope to be installed at the Pic du Midi in France justifies this choice.

As for our 3.6 meter telescope which has a horseshoe of approximately 10 meters in diameter, we are obliged to turn to cylindrical gears.

4. EXAMINATION OF CYLINDRICAL GEARS

Gear standards define the following errors:

F_β : Total tooth alignment error over a 100 mm length
Δf_p : Difference between adjacent pitches
F_f : Total profile error
F_p : Maximum accumulated pitch error
f_r : Radial run out
$F_{i''}$: Total composite error
$f_{i''}$: Radial tooth-to-tooth composite error.

The accumulated error is the sum of F_p and f_r, where f_r is sinusoidal and has a 24 hour period, in the case of the last mesh. F_p can have a shorter period.

In the case of the last gear mesh, the accumulated error, of long period, can be easily corrected.

One must, on the other hand, be cautious about the accumulated error of the preceding gear meshes, whose periods, divided by the reduction ratio, cannot always be neglected.

The tangential tooth-to-tooth composite error ($f_{i'}$) is much more serious especially on the last gear mesh. Theoretically it is equal to the algebraic sum of F_β, Δf_p and F_f. It is virtually impossible to foresee what the tangential tooth-to-tooth error will be, since one cannot know how F_β, Δf_p and F_f are distributed on a single pinion, not to speak of the case where two meshes are involved. The MAAG specialists are mute on the subject:

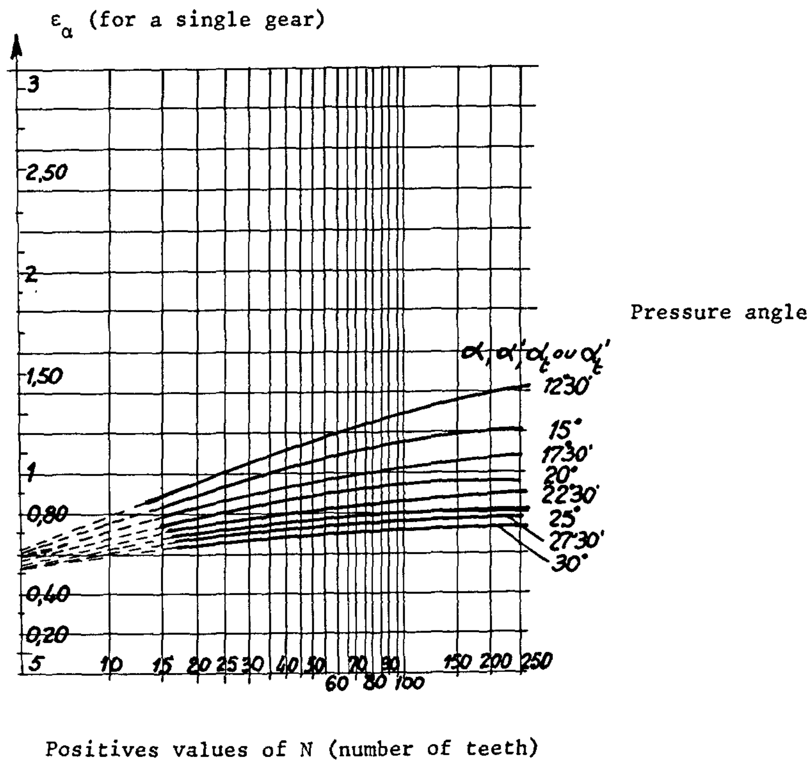


Fig. 9 Cylindrical gear (spur). Addendum module.

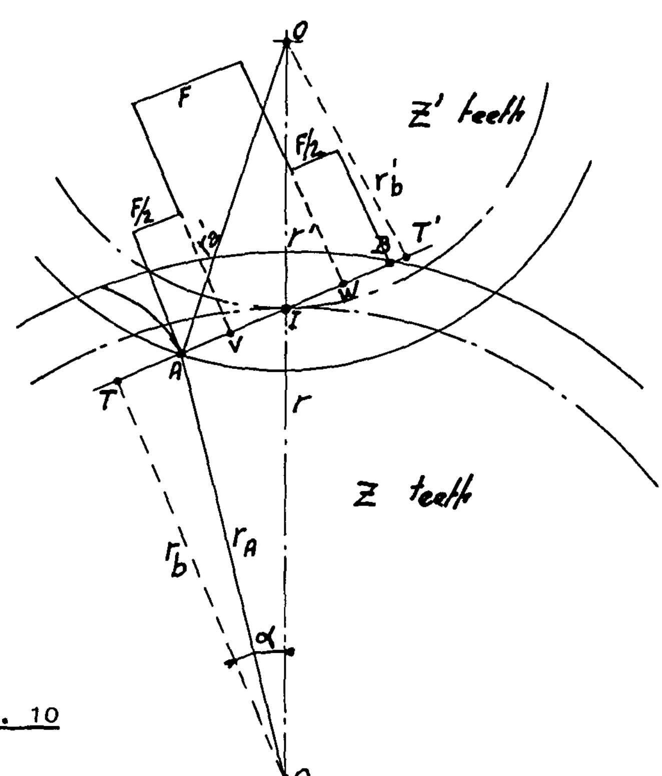


Fig. 10

the measure of $f_{i'}$, tangential tooth-to-tooth composite error, is veritably impossible. Authoritative works indicate that:

$$f_{i'} = \Delta f_p + F_f$$

an error which cannot be neglected even in top grade gears (Class S 1 of MAAG, DIN 3 or AGMA 15), since it corresponds to 2" angular error on the main gear plus 1.4" on the pinion. This means that if only one tooth is in contact, a 3.4" tangential jump could occur on the polar axis while using top grade gears and a main gear of 3.2 meter in diameter.

This error is of course minimized when the number of teeth in contact at the same time is increased, or in other words when the contact ratio is increased. L.D. MARTIN has indicated in an article published in Machinery 1967, that the composite error is reduced by 95% at a contact ratio of 2.6. This is the only experimental evidence upon which one may rely.

For <u>spur gears</u> the contact ratio is defined as:

$$\varepsilon_\alpha = \frac{\text{path of contact (AB)}}{\text{transverse base pitch}}$$

ε_α is a function of the pressure angle, of the number of teeth and of the addendum.

Figure 9 shows that with a pressure angle of 20°, ε_α is maximum for a contact ratio of 2.0, that is to say inferior to the optimum value given by L.D. MARTIN.

Moreover it is preferable that ε_α be an integer in order to remain constant during rotation. For example with $\varepsilon_\alpha = 2$ the load is constantly distributed over two teeth; with $\varepsilon_\alpha = 2.5$ the load will be distributed over two or three teeth (Figure 10) which means that the deflection of the teeth will not be constant.

Once the number of teeth has been determined, it is advantageous for gear reversibility to select a standard tooth profile with the addendum equal to the module. There is only one parameter left which we can play with to increase the contact ratio: the pressure angle. Figure 9 shows that with an extremely small pressure angle (12°30') ε_α would be only 2.9. It is thus impossible to reach the value 3.0 with spur gears. Although the value of 2.9 is high enough to be found on the asymptotic part of L.D. MARTIN's curve, there is no guarantee that the residual error (± 5% of 3.4", i.e. 0.35") cannot give a tangential jump.

The risk of tangential jump disappears only with much higher contact ratios, 6 at minimum, 8 if possible, which can only be obtained with helicoidal gears.

For <u>helicoidal gears</u>, the total contact ratio, ε_γ, is equal to the sum of ε_α which has been previously defined, and of ε_β, the overlap ratio which is defined as:

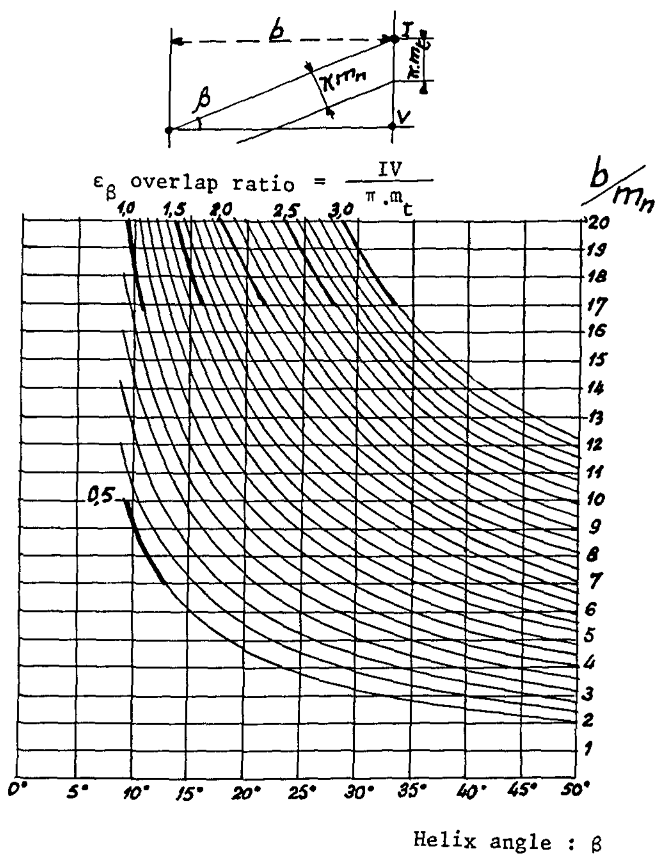

b
I
π.mt
π.mn
β
V
εβ overlap ratio = IV / π.mt
b/mn
1,0
1,5
2,0
2,5
3,0
0,5
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0°
5°
10°
15°
20°
25°
30°
35°
40°
45°
50°
Helix angle : β

Fig. 11

$$\frac{b \times tg\beta}{\pi \times m_t}$$

where b is the gear facewidth, β the helix angle and m_t the apparent module.

The number of teeth on the main gear is limited by the capacity of tooth cutting machines; the number of teeth on the pinion cannot be less than 50 which corresponds to the minimum possible pressure angle (15^o). Then ε_α is virtually determined. High contact ratios can then only be obtained by increasing the value of ε_β.

In order to keep the bearing loads low, and the tangential displacement due to excentricity small, it is recommended to select a value of β less than 20^o. One can then see that ε_β and finally ε_γ will depend only on the gear facewidth, b (Fig. 11).

In view of their higher contact ratios, we have adopted helical gears for the main mesh of our 3.6 meter telescope hour angle drive. Its characteristics are as follows:

	Main gear		Pinion
Number of teeth	2 000		50
Diameter	10 000 mm		250 mm
Actual module		4.70	
Apparent module		5.0	
Facewidth		175 mm	
Helix angle		20^o	
Actual pressure angle		15^o	
Reduction ratio		1/40	
Contact ratio ε_α		2.21	
Overlap ratio ε_β		3.81	
Total contact ratio ε_γ		6.02	
Tooth to tooth error		22 microns (DIN 4)	
Maximum tangential jump		1 micron i.e. 1/25 arc second	

The above figures were recommended by Citroën Messian after actual tests on a 5.76 m diameter gear, module 30, using a Schiess tooth cutting machine.

Two gear boxes will mesh with the main gear, each of them being driven by a bidirectional torque motor. During slewing the two motors act in the same direction, but during tracking only one motor will drive the gear while the other exerts a restraining force to avoid backlash. The value of the normal backlash is given by:

$$j_n = 0.05 + (0.0025 \text{ to } 0.1)m$$

i.e. 175 microns (7 arc seconds) to 550 microns (22 arc seconds) for the last mesh.

The two gearboxes will be installed at the oil pad location in order to maintain the main gear center to pinion gear center distance as constant as possible.

The horseshoe/gear concentricity error, the hydrostatic pad film thickness variation and local deformations due to hydrostatic pads will result in a variation of the main gear center to pinion center distance.

Axial displacement of the mount with respect to the base will result in a rotational speed variation due to the helix angle.

The tracking speed error which results from axial and radial displacements can be corrected by the control system provided that the encoder is driven directly by the horseshoe.

The horseshoe deflections have an amplitude defined by the value of j_r (radial play) and by j_t (tangential play) with:

$$j_r = \frac{j_n}{2 \sin\alpha} \quad \text{i.e. 340 to 1060 microns for } \alpha = 15^\circ$$

$$j_t = \frac{j_n}{\cos\alpha \ \cos\beta} \quad \text{i.e. 192 to 600 microns for } \alpha = 15^\circ.$$

If one fixes the value of j_n as a function of horseshoe deformations or vice-versa, it is possible to avoid the use of "floating" gearboxes which would significantly reduce the stiffness of the drive.

ACKNOWLEDGEMENTS

We are indebted to our colleagues of the AURA and AAT 150-inch telescopes for pointing the way in new drive concepts and making all their studies available to us, to SCHIESS, MAAG and CITROËN MESSIAN engineers for their gear performances assessment, to Sally for making this translation poetic and finally to Bruce RULE, in whose philosophy we are happy to plant our roots.

DISCUSSION

BARR: Where do you plan to sense the motion of the gear? What system are you using to drive your encoders?
BERTIN answers that two gear systems on the horseshoe have been foreseen so that when slewing they work together but when tracking they work against each other in order to suppress the backlash. The encoder will be mounted at the horseshoe and be driven directly by friction.

(Some discussion between ROOSEVELD VAN DER VEN and BERTIN about MAAG and SCHIESS gears.)

FLORENTIN NIELSEN: When using a precision pick-up roller for the encoder, wouldn't this in itself give precision in the telescope drive system? Could you then not consider using friction rollers for the drive itself?

BERTIN informs that it has been the philosophy to have a mechanical transmission, although a friction drive might give an almost equal performance. But maybe the accuracy of the friction drive is not high enough for a large telescope.

BARR: This causes me to ask another question. When you say the friction drive is not accurate enough, are you referring to position accuracy on the telescope over a long period of time, or accuracy during a tracking period? It is my impression that friction drive is inherently more accurate than a gear drive, but it has a tendency to creep over a period of time and it puts the encoding system in error.

BERTIN agrees to this. Furthermore, beside the constant creep, there is a certain random creep which is due to mechanical imperfections in the friction drive setup. This is why the friction drive can not sufficiently guarantee stability for this task.

A DIGITAL TELESCOPE DRIVE SYSTEM

R. Florentin Nielsen

Copenhagen University Observatory, Brorfelde

A telescope drive system has been designed for an ESO 50 cm reflecting telescope intended for general photoelectric observations. This telescope is provisionally mounted at the Observatory of Brorfelde near Copenhagen. Here, a rather extensive series of test observations and reliability tests of the telescope drive system have been carried out. The reliability tests have been very successful in the sense that a number of imperfections in hardware as well as in software and even actual errors have been detected and corrected. So now we are very close to an entirely satisfactory solution. Also several ESO staff members have had the opportunity to handle the telescope drive system during test observations.

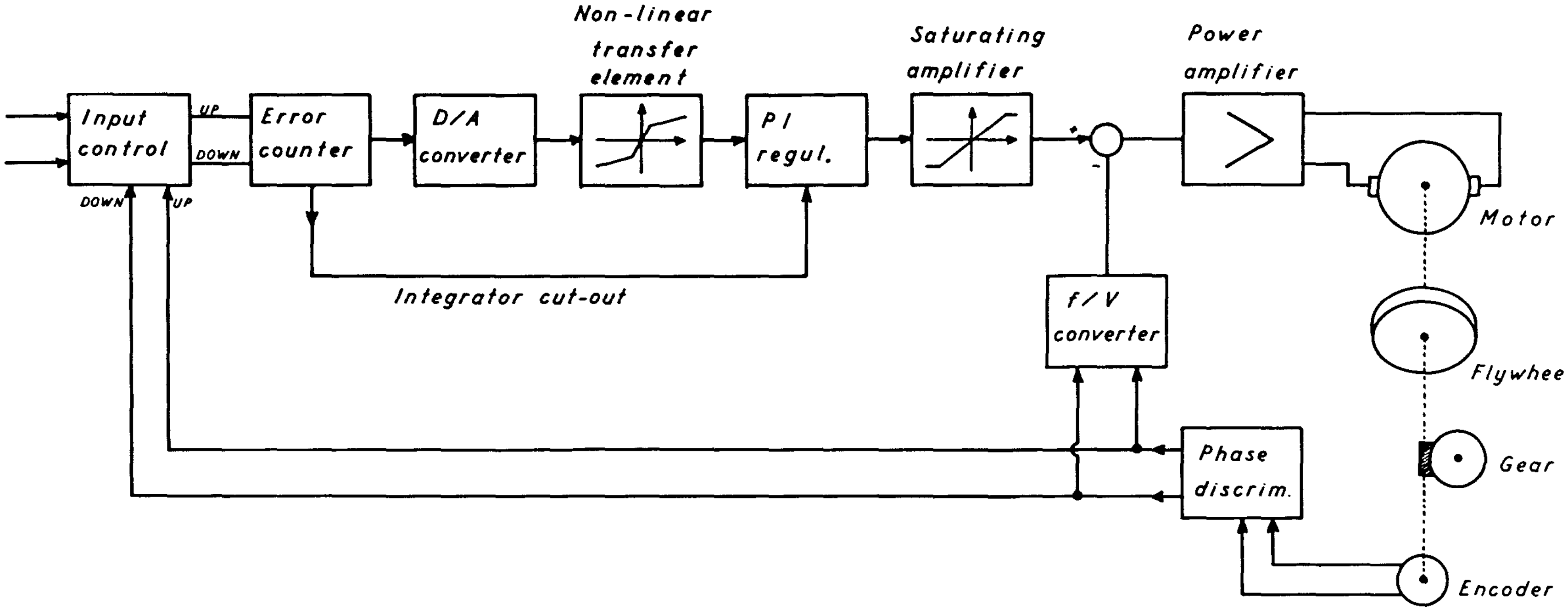
I shall now proceed to describe the system in some detail.

Single printed circuit d.c. motors or torque motors, one for hour angle and one for declination, drive the telescope over the entire range of speed, from slewing and down to tracking and guiding.

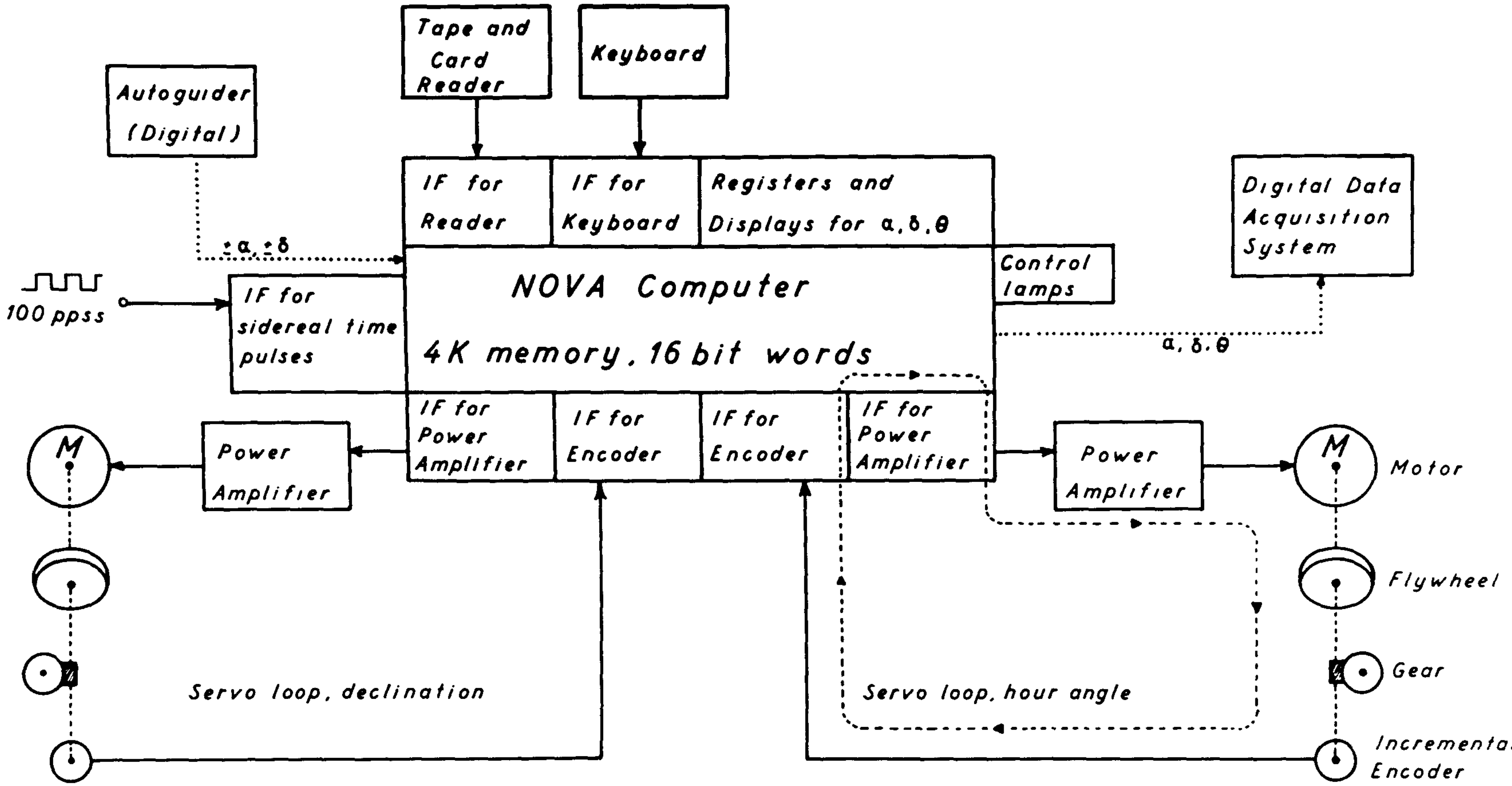
Each of the two motors are incorporated in a servo loop. This servo loop also contains an incremental encoder for position and velocity reference.

Figure 1 shows a traditional approach to such a servo loop. It consists of a digital part including the position reference feed-back and a reversible error counter. A digital-to-analogue converter and a frequency-to-voltage converter interfaces the digital units to the rest of the servo loop which consists solely of analogue units such as operational amplifiers having various feed-backs causing specific, generally non-linear transfer functions.

Figure 2 is a block diagram for the entire computer controlled telescope drive system developed for the ESO 50 cm telescope. In this figure the servo loop for one of the motors is shown as a dashed curve. Notice that the number of peripheral units in the loop is very much reduced in this solution. This is achieved as the analogue functions of various units of the servo loop and are taken care of by the computer programme itself. Hence, the characteristics of the analogue functions can be altered simply by writing other parameters into the programme. Also the reduced number of individual units helps to increase the reliability of the overall system.



<u>Fig. 1</u> Typical servo loop for a telescope drive system.



<u>Fig. 2</u> Telescope drive system, block diagram.

The computer controls the motor current and consequently the motor torque by outputting to the computer interface a binary number representation of the motor current. The interface converts the binary number to an ON/OFF ratio of a 10 kHz switching signal. Therefore the power amplifier works in a pulse width modulated switching mode, which yields extremely high power efficiency. Thus the amplifier can deliver half a kilowatt of power to the motor and yet have a power loss, i.e. a heat dissipation of a few watts in the amplifier.

A flywheel on the motor axis and very tightly coupled to the motor serves two purposes.

1. During acceleration and deceleration the flywheel is the predominant load of the motor, since the moment of inertia of the whole telescope referred to the motor axis is by far smaller than that of the flywheel. As a result the angular acceleration is effectively limited to the maximum torque which can be produced by the motor divided by the moment of inertia of the flywheel

$$\left[\frac{d\omega}{dt}\right]_{max} = \frac{\Gamma_{max}}{J}$$

   Therefore the gear is protected against high torque pulses which might occur in case of a sudden electronic failure, and also a constant and well defined acceleration is ensured, e.g. when starting up from a stand still to slewing motion.

2. The flywheel helps to filter out the unit steps of torque pulses during tracking and guiding.

The incremental encoder is coupled directly to the motor axis. Thus there is no compensation for mechanical inaccuracies in the gear. On the other hand, a stiff and well behaved servo loop is obtained.

The sidereal time and the diurnal movement of the telescope is derived from an externally generated reference of 100 pulses per sidereal second.

Preparations have been made for incorporating an autoguider having a digital output and for feeding the information of the actual right ascension, declination and sidereal time to a digital data acquisition system.

Figure 3 shows the control panel of the system. The actual and the preset coordinates as well as the sidereal time are displayed. Right ascension in hours, minutes and seconds and declination in degrees, minutes of arc and tenths of minutes of arc. The control buttons and signal lamps are strictly functional in the sense that they all have specific astronomical relevance. There are no confusing extra buttons for computer manipulations. This means that the observer does not even realize that he is operating a computer.

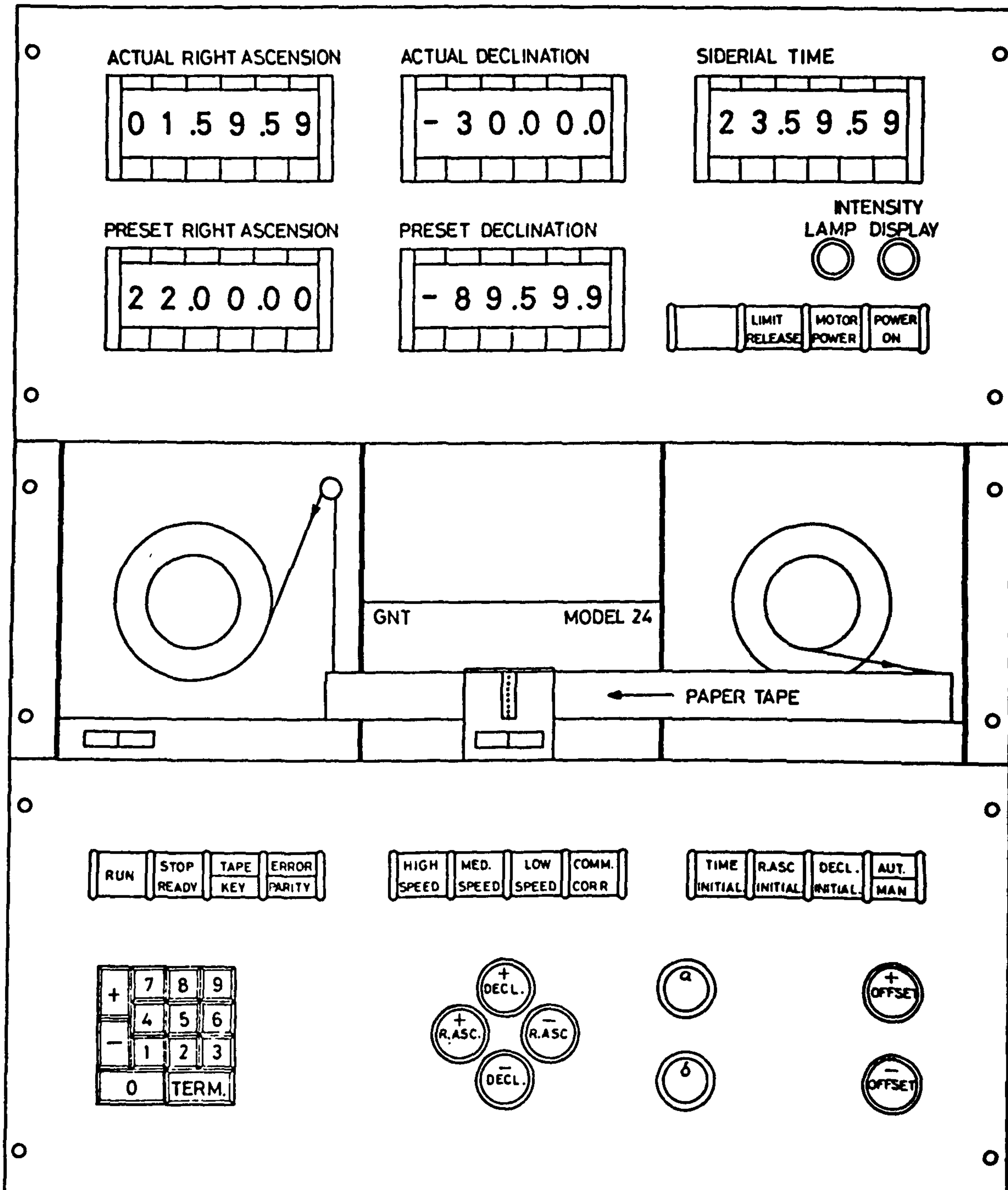


Fig. 3 Control Panel.

One group of contacts concerns the initiation of sidereal time, right ascension and declination at the beginning of a night's observations.

Another group is used for driving the telescope manually. Speed and direction of the movement in the two coordinates can be selected. The speeds are named: High, Medium and Low. The low speed can be varied in six octave steps independently in right ascension and declination.

Also in this manual mode of operation there are provisions for minor shifts of the (α, δ) - reference system and for offsetting the telescope by multiples of $\pm 0\overset{'}{.}8$ enabling the observer to bring the star in and out of a photometer's diaphragm.

Finally a group of contacts including a numerical keyboard serves for presetting the telescope. The preset coordinates can be entered either by the keyboard or via a reader for paper tape and edge punched cards.

The telescope is provided with limit switches for minimum height and maximum hour angle. Besides this the computer contains a program which at any time supervises that the position of the telescope is within permitted intervals. If a run is requested to a preset position which is forbidden, the computer looks ahead, displays an error signal and does not at all attempt to drive the telescope to this position.

In the provisional set-up in Brorfelde the overall setting accuracy is $0\overset{'}{.}2$ over limited intervals of the sky. The sources of inaccuracy is gear errors and any imperfection in the setting of the polar axis. I must point out that in the final set-up the telescope will be preloaded to minimize backlash in gears and worm-to-wormwheel transmission, whereas in the present set-up the preloading is not feasible. Therefore, in the end the setting accuracy is expected to become somewhat better than the figure just stated, since the inaccuracy caused by the electronics, working in unit steps is completely insignificant.

DISCUSSION

DENNISON: I think this is an excellent example of the use of a small computer for a control system, and your control and operator philosophy are very good and are guaranteed to be very satisfactory to the operators. But you would probably want to go to a little more resolution in your encoders, even if your accuracy is not that good, particularly because this will give you experience with a high resolution system which you will need for a large telescope.

FLORENTIN NIELSEN: Yes, this is perfectly true. In fact the resolution is

0".1, but this is not displayed because we found it would not be worth while displaying figures that were not really significant to us. We have just chosen the last displayed digit to be the one which is comparable to the obtainable accuracy, but in fact the computer itself deals with a much higher resolution.

BAHNER: You could use the higher resolution for differential offsetting, which might come in quite handy at times.

FLORENTIN NIELSEN: You mean that we ought to have more digits in the display?

BAHNER: Well, at least some means of getting a differential offsetting of higher accuracy.

FLORENTIN NIELSEN: Yes, but it is not a general offset device. It is a simple means when doing single star photometry to take the star out of the diaphragm and bring it back. It comes back within 0".1, although this is not completely true since we still have some backlash in the gears, but they are high precision gears and worm wheel.

DITTMAR: I agree that this is a very clever system. It is a very good example of the proper usage of a small computer. I noticed that you only have a siderial reference to 100 pulses per sec. What type of reference is this and how do you get the rates commanded into the two axes?

FLORENTIN NIELSEN: The slewing motion, for example, is determined by a velocity feedback. The signals from the incremental encoder is differentiated and taken as a velocity reference; that means that the actual accuracy of our slewing and setting speed is no more than say 5%, but we are not too much concerned about that.

DITTMAR: How do you set very small differential tracking rates and what is your reference? Do you have a crystal oscillator?

FLORENTIN NIELSEN: No, it is a very simple internal generator, for which the accuracy is not that high. We did not intend to make it very accurate because we did not see any use of it.

DITTMAR: Is it variable? If the observer has to make continual guiding corrections, can he then vary the speeds?

FLORENTIN NIELSEN: Yes, it is switchable in octave steps, and you can guide up to as much as 20"/sec.

DENNISON: You have a system here which is capable of being modified to include all of these variations, that is to say that you could include offset accuracies to 0".1 if that proved to be necessary. I think I can understand perhaps the reasons why you want to have that kind of accuracy because it implies that you can come back with that sort of precision. This is potentially possible with this system. Another thing is that as far as the siderial rate is concerned, again you have the possibility of putting a high resolution preset counter for your siderial rates, so that this can be external for the computer and this is something you can add at a later time if it proved to be a necessity.

FLORENTIN NIELSEN: Yes, this is a drive system which can be considered almost a pre-study, and we did not want to put too much money into it for such a small telescope. It can easily be extended, for instance an automatic guider could be added, but I don't think we will use this for such a small telescope. Of the 4K memory there is still 1K vacant for doing extra jobs. You may change your system or you may add to it as much as you like; if it doesn't work out very well, then you just take the old program and run it into it and you have got your old system running again.

COMPUTER CONTROL OF THE 2.2 m - TELESCOPES

J. Solf

Max-Planck-Institut für Astronomie, Heidelberg-Königstuhl

In the control systems of the 2.2 m telescopes, now under construction at C. Zeiss, Oberkochen, small digital computers will be integrated. This contribution summarizes the design of our future telescope-computer systems, as far as driving problems are concerned.

TELESCOPE DRIVE HARDWARE

The driving systems for both axes consist of single worm wheels, used for both tracking and slewing. The right ascension and declination drives are functionally identical. Oil-pad bearings are foreseen for the hour axis as well as for the declination axis.

The figure shows the rough operational scheme of the right ascension drive. Only one motor will be used for slewing, setting, tracking and guiding purposes. This motor is essentially a d.c. motor. However, its integrated electronics allows to operate it as a d.c. motor as well as a "stepping motor". The development of these electronics is done at C. Zeiss. The general functions may be summarized as follows.

Three different input devices of the motor are foreseen:

a) The analog input

provides for slewing (100°/min) and setting (2°/min), controlling the acceleration phases;

b) The frequency input

allows the superposition of several independent frequencies; each pulse given to this input is followed by one step, corresponding to $0\overset{''}{.}1$ in telescope position;

c) The binary input

is connected to the frequency input; a binary coded integer number given to this device will cause an equal number of steps to be performed at a rate exactly proportional to the given number. So, the time interval, needed for execution of these additional steps, is independent of the number.

This time interval is chosen to be equal to 0.02 sec, the sampling cycle of the computer control.

TELESCOPE OPERATIONS INDEPENDENT OF THE COMPUTER

The design of the telescope-computer system provides the possibility of giving instructions to the telescope without involving computer operations. In case of a computer break down, a simpler mode of telescope operations is possible. Operations independent of the computer are surrounded by dashed lines in the diagram. Slewing and setting can be done by pushbuttons connected to the analog input of the motor. Tracking at sidereal rate is performed by feeding the corresponding frequency, controlled by the digital clock, into the frequency input. For guiding purposes the same input device allows the superposition of a lower frequency (rate: 2"/sec) or single pulses (step: $0\overset{''}{.}1$), controlled by pushbuttons.

CONCEPT OF THE COMPUTER CONTROL

The basic element of the software operation system will be one cycle of a sampling frequency. At a rate of 50 Hz the computer gets an interrupt signal from the digital clock. Once the absolute time, binary coded, has been read from the clock, the computer may generate several time measures at each moment. Other cycling subroutines can be triggered at proper rates less than 50 Hz. This makes possible a software organization most versatile and powerful. The following examples may demonstrate the system in more details.

DISPLAY CONTROL

At a certain rate the computer reads data from the encoders attached to the worms. This binary information is converted to Hour Angle (or Right Ascension) and Declination, corrected for refraction, flexure, decollimation and circle errors. We hope that the error of the corrected position will be less than 10". Transformations of H.A. and Dec. to Altitude and Azimuth can be done easily. The corrected or transformed coordinates and the different time scales will be given cyclicly to the display unit.

POSITIONING UNDER PROGRAM CONTROL

After the operator has given the coordinates to the preset unit (card reader or switches), the computer will drive the telescope, dome and windscreen to the desired position, if this is an allowed one. The coordinates will be corrected for precession and the instrumental position for refraction, flexure, pole deviation, circle errors etc., using parameters

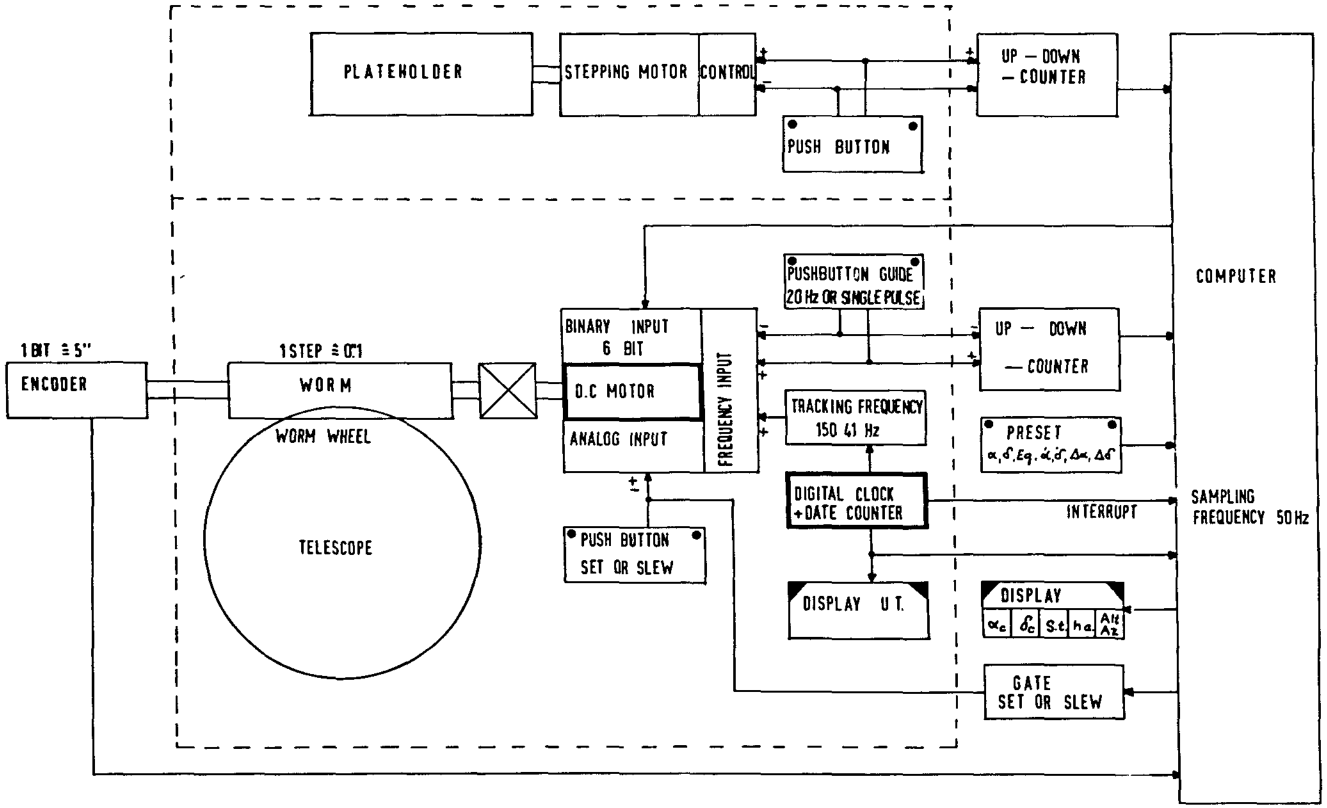


Fig. 1 Operational scheme of the right ascension drive.

derived empirically. The slewing and setting gates, connected to the analog input of the motor, are controlled by cyclic comparison of the actual coordinates from the encoders to the given ones. At the end of the setting phase, the tracking frequency from the clock drives the telescope at sidereal rate. The residual deviations from the desired position are derived from encoder data. The corresponding number of steps of $0\overset{''}{.}1$ will be given ratewise to the binary input of the motor, until the total number has been executed.

The same procedure of differential positioning can be used in the tracking mode if the computer is instructed via the preset unit, to perform a well-defined displacement in the telescope position with a high degree of accuracy.

CONTROL OF ADDITIONAL ANGULAR RATES

The sidereal tracking rate in H.A. and zero tracking rate in Dec. have to be modified for several reasons. The binary input device of the motor is used to solve this problem in a very simple manner. To any angular rate $\dot{\alpha}$ or $\dot{\delta}$ corresponds a certain number of steps to be performed during each sampling cycle of 0.02 sec. By cyclicly giving the corresponding integer to the binary input, the computer drives the telescope at any required rate in addition to the clock controlled sidereal rate.

In this way, modifications of the track rate due to changing refraction, flexure etc. can be performed under program control, using constants derived empirically. Or, via the preset unit, angular rates can be fed in, to track objects with significant apparent motions as well as for drifting and scanning purposes.

During tracking, pointing corrections can be done by hand or star sensor, feeding a lower frequency or single pulses into the frequency input device of the motor. All these correction pulses are counted by up-down-counters connected to the computer. By cyclic inspection (rate: 1..2 min) the computer derives from the counters the net number of steps in the prevailing directions. From this, for the next cycle, the corrected number is calculated that will be transmitted at the sampling rate to the binary input of the motor. In other words, the <u>uniform</u> rate for the new cycle corresponds to the <u>average</u> rate - including hand corrections - of the last one.

If the pointing corrections are performed at the plateholder a similar procedure has been provided. The plateholder is moved by stepping motors in X-Y coordinates and the steps are counted by up-down-counters. From the effective number of steps performed during the last cycle, the computer calculates the corresponding corrections to be given to the telescope drive during the next cycle.

FURTHER FACILITIES PROVIDED

Of the facilities further provided we mention only the following four:

- control of the optimal plateholder rotation due to refraction and instrumental errors;
- control of refocusing due to thermal and mechanical change of the tubus length;
- control of scanning operations etc.;
- writing a logbook of telescope operations.

DISCUSSION

DOSSIN: I have a question which relates also to the paper of Mr. Florentin Nielsen. Are you not afraid to use the worm gear for slewing motion when this gear is probably made especially for the tracking? It seems dangerous to me to drive this worm gear at high speeds.

SOLF: I would like to pass this question over to the Zeiss people.

KÜHNE: I think that this is not very dangerous, but naturally you have to make some protections against the forces which will arise between the teeth of the worm wheel and the worm itself. We have made this in such a way that the worm will be shifted in axial direction by a certain limited force, so that the forces cannot increase beyond a certain limit.

FLORENTIN NIELSEN: We have no fear whatsoever in doing so; in fact we have had telescopes using the same worm wheel transmission for slewing, tracking and guiding for several years.

BARR: One comment with respect to the use of a worm gear for both slew and tracking operations. As long as you don't overload the teeth of the gear, as Dr. Kühne has pointed out, the operation of a worm gear will be superior at high speed, because you have better lubrication. At a high speed you develop a hydrodynamic oil film which you don't usually have at tracking operation. It is actually worse for the gear to operate at tracking speed than it is at slewing speed. The wear is much greater.

RULE: In all of the Hale telescopes the worm is used for both low and high speeds. The only thing different about the 200" is that there is a separate worm for tracking and slewing; in fact the situation is such that we think we will convert it to both tracking and slewing. We have had no problems at all in tracking and slewing with the same worm.

FLORENTIN NIELSEN: You still have the encoder on the worm? I have become convinced by Dittmar that one should rather use a pick-off roller on the telescope itself. What is your opinion about that?

SOLF: We don't feel the need to take the telescope into the loop because the precision of the worm gears is so good that we think we can get this resolution and speed.

BAHNER: These are just points of view working against each other. Of course you want to put your servo pickup as far upstream as possible, that stands to reason. On the other hand the demands on resolution and the encoder are getting higher, so you have to compromise somewhere. We think we can develop the compromise of the Zeiss people.

A HIGH SENSITIVITY TV SYSTEM AS A VISUAL AID FOR OBSERVERS

Edwin W. Dennison

Astro-electronics Laboratory
Hale Observatories

This project had its beginning something over three years ago when Mr. John Lowrance of the Princeton University Observatory came to Mount Wilson to make preliminary tests on the 60-inch telescope with two high sensitivity television tubes. One tube was a Westinghouse Secon without intensifier and the other was an R.C.A. Image Isocon. By good fortune, there was a heavy fog over the Los Angeles basin during the period of testing, which enabled the system to be tested with a fairly dark sky background. After the moon rose that night the system was also tested with a bright sky background. With both TV tubes we were able to record stars which were approximately 2.5 magnitudes, a factor of 10, fainter than could be seen by experienced observers who were fully dark adapted.

As a result of these tests, we initiated a project to provide the observers with a device to locate and display stars which were fainter than could be seen with the unaided eye. The need for such a device was the result of the fact that image tube spectrographs and chopping-type spectrophotometers could measure objects which were too faint to be seen directly. For such measurements it is always possible to use the traditional method of blind offsets, but these methods are very expensive, both in man hours and in telescope hours, due to the large amount of time required to take plates and set the telescope to the correct offset position. It also occurred to us that if such a system were successful it would be possible for the observer to make his observations without being directly at the telescope.

The system consists of an image intensifier and a SEC Westinghouse television tube coupled together with fiber optic face plates. The intensifier has a gain of roughly 40, and the gain at the SEC target is about 100, thus the total gain is approximately 4,000. In addition to the usual video amplifiers and sweep circuits, the system has an automatic feedback system for controlling the high voltage in the intensifier and the front end of the SEC tube, two storage tubes, digital controls for integration time and other related circuitry and controls.

The system is physically packaged in four separate units. The first is a camera unit, which is approximately 14 inches long and 5 inches square, with a weight of about 10 pounds. This unit is compact enough to be mounted on a telescope of moderate size. The second unit is within 10 feet of the camera head. This unit contains electronics which must physically close to the camera tube but not necessarily mounted in its immediate vicinity. The third unit is mounted at a distance of up to 30 feet from the second unit and contains more of the electronic circuitry. Units one, two and three contain all of the circuitry to operate the system as an independent non-integrating television system. The fourth unit is mounted separately from the telescope and can be located at a distance of up to 400 feet from the third unit. This fourth unit has the storage tubes and all of the necessary remote controls to operate the system from our data room. The output of the final unit is to a series of television monitors which can be mounted both in the data room and on the telescope near the observer.

In one of the modes of operation the system runs at the standard frame rate, which for the American television system means one full frame every 30th of a second, and one field every 60th of a second, using an interlaced field pattern. A second mode of operation is used when the signal on the target is integrated for a predetermined period of time. This integration time can be from 0.1 seconds up to 99.9 seconds in 0.1 second steps. Our tests so far indicate that there is no appreciable improvement in signal beyond approximately 30 seconds of integration time. This is probably the result of the fact that the system does not shut off the filament of the electron gun in the camera tube and, therefore, there is a small amount of light leaking from the filament to the photocathode causing an increase in background exposure.

The gain of this system over the unaided eye is not the result of higher efficiency or sensitivity but rather that the eye cannot integrate for a period of time much longer than approximately one or two tenths of a second. Our preliminary estimates indicate that we will achieve sufficient sensitivity with an integration time of approximately three seconds.

The storage tubes which we use are Lithocon type tubes. These tubes have a silicon diode target very similar to the silicon diode target used in vidicon tubes. The picture is written with an electron beam and also read with the same beam. We had to use two tubes because the erase cycle for the storage tube is approximately one second and we felt that this was too long a flicker time for the observer to tolerate easily. We read the integrated picture onto one tube while the other tube is being erased and prepared for the next cycle. After the end of the next integration period, the second tube receives the television image and the first tube is erased and prepared for the subsequent cycle. During each integration time the system reads out the picture from the storage tube at standard frame rates so that the observer sees a flicker free picture which changes every time a new integration cycle is completed. When a static video image is read from the SEC target in an interlaced pattern, most of the signal is contained in the first field. To avoid the flicker, which would result from this effect, we read the image in a non-interlaced pattern when using the tube in an integrating mode. We also have provision for storing up to 10 integrated frames on each storage tube. This feature enables us to take advantage of the fact that the storage tube has a larger dynamic range than the camera tube. Our experience so far indicated that storing up to five or six frames appears to be optimum.

We have not as yet conducted exhaustive resolution tests on the system but our preliminary tests indicate that the camera tube has a resolution of approximately 450 television lines. When the picture from the camera tube is placed on the storage tube the final system resolution appears to be approximately 350 television lines. This image degradation is a result of the finite camera tube resolution combined with the finite storage tube resolution. We feel that this resolution is adequate and that even if the star images are slightly enlarged due to this limited resolution, there will be no problem in identifying the star fields. It is interesting to note that the camera deflection system is stable enough to permit several frames to be recorded on the storage tube without any further loss in resolution.

One of the intrinsic limitations of the SEC tube is that if it is exposed to a very bright light for too long a period of time the excess number of electrons flowing onto the target will cause damage. This kind of damage could occur with the 200-inch telescope when looking at a star as faint as the 10th magnitude. When our system is in the repetitive frame operation, the high voltage in the intensifier sections is controlled by an automatic gain control circuit which limits the amount of current which can flow onto the SEC target. This automatic gain control system is designed to detect peak signals rather than average signals in order to detect the presence of a star which may be too bright for the system. One of the advantages of electrostatic intensifier tubes is that the voltage can be changed without any substantial change in focus or image rotation. This automatic feedback system appears to work very well and we hope that it will be possible to leave the television system turned on when slewing the telescope from one field to another.

We have been unable to determine the system noise in terms of photocathode photoelectrons. Various estimates indicate that the noise level is anywhere from 3 to 10 photoelectrons. Most of the information indicates that it is at the higher figure. It is interesting to note that when looking at a faint image the noise level in bright parts of the test pattern is apparently higher than amplifier noise, that is, the number of bright spots increases as the light level increases. If one had a system which could detect individual photoelectrons one would expect to see an effect of this type.

The system was built by the Quantex Corporation in Mountain View, California and will be delivered to our laboratory in a week or two. At that time we will initiate a series of tests under laboratory conditions. One of these tests will be to expose the system to a known flux level as determined by a photomultiplier which has been calibrated at the telescope. The preliminary tests at the Quantex factory indicated the system is working extremely well, and we have every reason to believe the system will work as we had hoped.

DISCUSSION

BAHNER: How much did you pay for it?

DENNISON: The contract for the developmental system was about $ 46.000; I don't know what a second unit would cost, probably somewhat less. We did have to pay a little bit more than that, because the documentation supplied by the manufacturer was not up to our standards and we felt that this was necessary for maintenance.

RICKARD: Could you comment why you choose the storage-tube assembly rather than a storage oscilloscope and built up the integration on the oscilloscope?

DENNISON: The reason was that we wanted to be able to have a wide variety of monitors and to be very flexible with the output video-signal, for instance to put it on tape recorders, and we felt that this system gave us more flexibility than using a storage scope directly. I think that would have been possible, although most of the storage scopes, as I understand them, have a rather limited dynamic range; they tend to be on/off devices. Now, that is all right looking at stars but if you want to look at a part of a galaxy or nebula, then that would not be satisfactory.

Let me also anticipate the question as to why we use a storage tube rather than a video disc. The problem is that when you read off the first field of an interlaced system you take most of the energy off of the target. As a result, when you read the next field, there is very little image, you get a great deal of flicker, and it is very hard to handle this on a disc recorder. Here we were able to have the electronics worked out so that it reads the image in a non-interlaced fashion onto the storage tube, and then it reads from the storage tube onto the monitor in an interlaced fashion. Therefore you satisfy both the requirements of the camera and of the operator.

RICHARDSON: If one were to use a three-stage fibre-optic image-intensifier tube giving a gain of, say, 100.000, could one then get reasonable results with an inexpensive closed circuit TV system?

DENNISON: No, that is the trap that one has to avoid. The gain is, as I said, because of the integrating characteristic, not because of the sensitivity, so you would only see a very noisy image. You would see the individual photon events very brightly, but because you didn't have the integrating capability, you would not be able to improve your signal to noise ratio. With a photon limited system you must improve that signal to noise ratio by integration; that is the only way.

CAYREL: What is the integration time that must be used to achieve a $2^{m}.5$ gain over the unaided eye?

DENNISON: We think it will be somewhere around 2 sec, but we will know better. This is based on experiments that Westinghouse and Mount Wilson have made with a tube without an intensifier, and in that case it took something like 30-60 sec to get a sufficient image.

DOSSIN: I don't quite see where the loop is for your high-voltage control.

DENNISON: The signal for this comes from the video signal and essentially it is a peak detector, so whenever there is a sharp peak, then that peak value is used to determine what the high voltage should be. Commercial systems use the average value and this makes for a very nice studio or commercial type system.

BORGMAN: Could you describe what happens once you have acquired a field, but not yet the star on the cross-hair or the slit of the spectrograph and you therefore have to move that image? While moving you certainly do not gain $2^{m}.5$ any more, it must be perhaps even below what you see with the eye.

DENNISON: That is correct. What one will do is to point the telescope near the object, say a 20^{m} star, and then put it into the integration mode. You will then see the star, perhaps off of the entrance aperture of your photometer. Now you must move slowly, because you only get a new image every 2 sec or so. I suspect one will try varying the integration time so that you have just enough integration to be able to see the object and then you must move the telescope slowly as you track it over to your photometer slit. I see no way around this. It is saving half an hour as compared with a blind offset, but it is not instantaneous.

BORGMAN: Is it not possible to put some sophistication in your circuits so that you, just as the human eye, can follow the moving object with the integration, and don't loose the superior limiting magnitude that you have? I think it is a little bit awkward to see the picture disappear while you move the telescope, and that you have to wait 2 sec to find out again where you are. Could you elaborate a little bit on this possibility?

DENNISON: First of all, with this system it is not possible, because the image that you put on will stay there for 20-30 min, even at continous read-out, and if you stop the read-out, it will stay there for ever essentially. You have no decay of your image on the storage target, and that is what is really necessary for the sort of thing that you are talking about. If on the other hand one had gone for a long persistence phosphor in the display monitor, and if you had a long enough display time, so that now the phosphor acts as the integration source, then presumably you could have something that would ooze around. My own judgement is that the observer would not find that very satisfactory and would become quite irritated and agitated by something that was that oozy, and that he would much prefer to have clean fresh images each time.

BAHNER: Would not that be one more reason for easy, differential offsets for the telescope? You could read the distance of your object from the slit in both coordinates, put in these numbers by some switches, push your oscilloscope button, and the telescope centers automatically on the object.

DENNISON: That is to say that you electronically put a box around the star image, press the button and say "Now lock on that box", and then with some wheels or some other device you can move this box around and the star field will move with it. Yes, that is entirely possible. It takes some more sophistication in the circuitry.

BELLY: Is the resolution good enough for guiding?

DENNISON: I think so, but that is a subjective judgement; I have not made any experiments. In many guiders you simply balance the two halves of an image of a star and you can get a precision in locating the center, which is much smaller than the diameter of the object that you are looking at. In fact it can be quite defocused if you have a scheme that really balances the two halves of the image. I think the resolution of even 100 lines would be sufficient to make a guider which would be accurate to at least one thousandth of the picture. I know this to be a fact as far as guiders are concerned, but we have not been using the present system for guiding.

FLORENTIN NIELSEN: I find this a magnificent system. I would like to know whether you would consider using a similar set-up for large-scale area photometry, although with a somewhat moderate accuracy?

DENNISON: Yes, I would consider it, and we are looking forward to making many experiments with this system. We want to find out how close it is to the photon limit; we want to put another intensifier on to see if we really can see the photopulses. We also want to look into the possibility of using it as a kind of photometer. Other people have reported using vidicons as very excellent photometers. There are many possible applications, but remember, our first goal was simply to enable us to observe these very faint objects.

REDMAN: I was recently at Mt. Stromlo and Dr. Rodgers there showed me what I believe must be identically the same apparatus, and I can confirm everything that Dr. Dennison has said. I can add that the tube according to Dr. Rodgers is about as sensitive as the human eye in the blue, but is more and more sensitive than the eye as you go to the red.

DOSSIN: Did you investigate the geometrical characteristics? Do you have some geometrical distortion?

DENNISON: As we saw the tube in the manufacturers facility it did have some distortion, more than I think we can tolerate, but with all video systems you have to spend quite a bit of time adjusting the various sweep circuits to get things to be relatively free of distortion. I would think that the kind of precision we can go for is certainly better than 5% on distortion, possibly towards 1%. I don't think getting better than 1% is very practical.

WLERICK: What do you mean by 10 photoelectrons of noise?

DENNISON: If you have 10 photoelectrons for each individual picture element, then you will be able to just see it as being twice the background, i.e. the amplifier noise. The problem with all such vidicon systems is that you are limited by the amplifier noise rather than the noise of the target.

COMPUTER SUBSYSTEM OF THE ANGLO-AUSTRALIAN 150-INCH TELESCOPE*

G.W. Bothwell

AAT Project Office

1. INTRODUCTION

The computer subsystem will form an integral part of the Anglo-Australian Telescope, and is concerned with both telescope control and astronomical instrumentation. In this paper these two computer applications will be introduced and the proposed computer configuration will be described.

2. TELESCOPE CONTROL

The following subsections describe the application of the computer to activities associated with control of the telescope.

2.1 Drive System Applications

Figure 1 shows the principal interfaces between the computer and the various telescope control subsystems. These fall into three broad categories, (a) main drives, (b) autoguider, and (c) dome and windscreen, which are described below.

(a) Telescope Main Drives

The telescope R.A. and Dec. drive motions can be controlled either manually from thumb switch inputs, or from the computer. In the latter case (shown in Figure 1) the computer will be used to apply corrections for atmospheric refraction, structural misalignment, structural flexure, and encoder gear errors. These corrections will be applied both during telescope tracking and in correcting apparent star positions during slewing and setting. Regarding the interface for each axis of the telescope the computer presents a rate demand to a rate generator (which generates the clock pulses for driving the telescope). This interface is in B.C.D. since the rate generator uses a decimally orientated rate multiplier principle in order to simplify input processing from thumbswitches when under manual control. The rate generator resolution is 0.001 arcsecond/second, and the cycle time for one

----

* not read at the conference

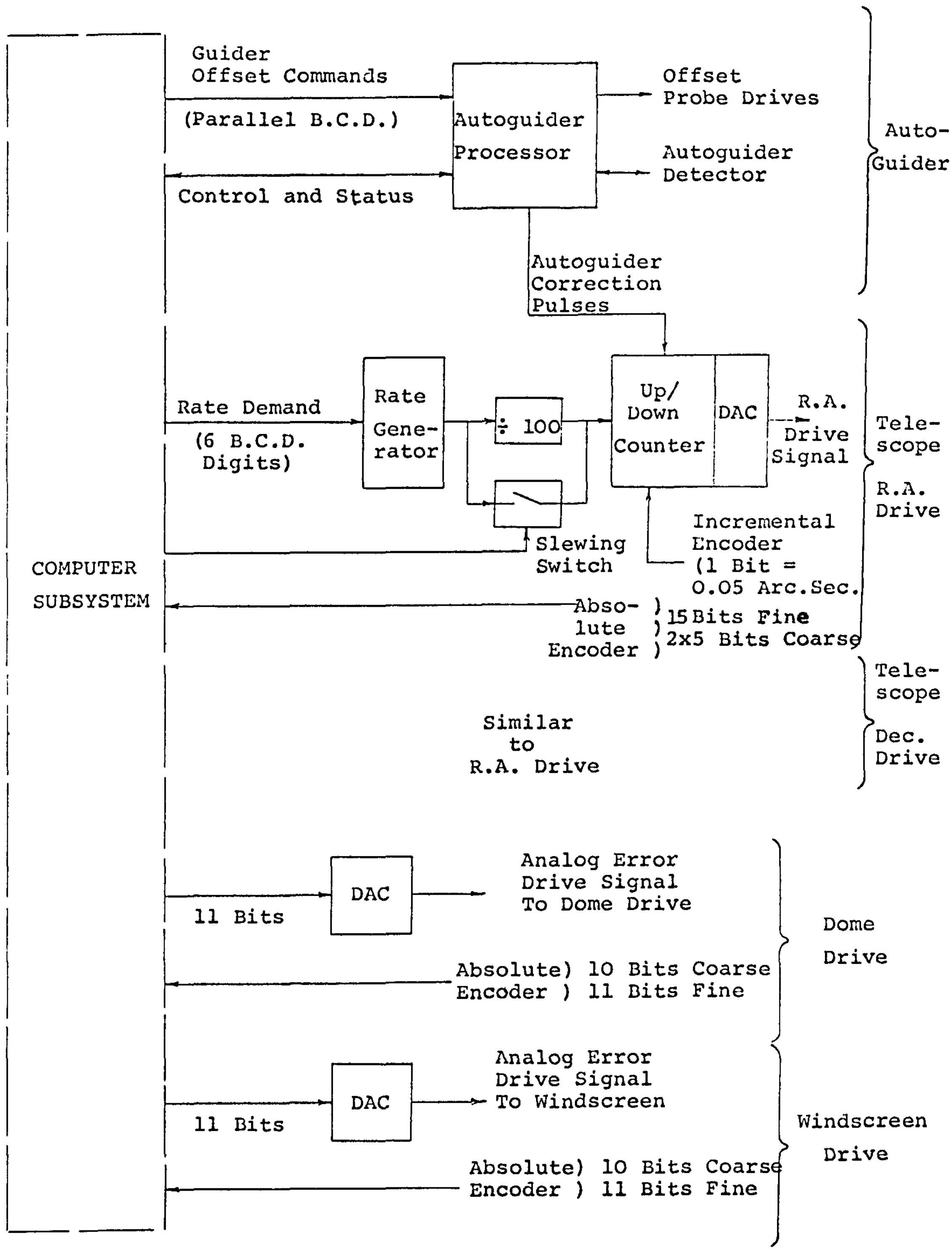


Fig. 1 Principal computer interfaces to drive & control subsystem.

complete parallel-to-serial conversion is 1/20 second. The computer interface to the rate generator is synchronized so that servicing can be at up to 20 times per second without any loss of resolution. During slewing the computer switches out a times-100 divider in the output stages of the rate generator in order to achieve the required slewing rates.

The telescope encoders are in coarse and fine sections, and the selection of the correct coarse encoder, together with the conversion from gray code to binary, are done by the computer. The encoder readings will be processed and displayed at 1 second intervals.

(b) Autoguider

Details of the autoguider are as yet not complete, but the current conception is that shown in Figure 1. The autoguider processing equipment feeds correction signals directly into the telescope drive system. All operations carried out by the autoguider are supervised by the computer, which, for example, outputs demand positions for the offset guider probes, checks guider error signals, controls the guider processing in general, and carries out associated background computations.

(c) Dome and Windscreen

Both the dome and the windscreen are controlled via a position loop in which the computer outputs a scaled position error to a digital-to-analog converter, as shown in Figure 1. Sampling and processing is carried out at 30 second intervals while tracking, and this is reduced to 4 second intervals when slewing. A special positioning algorithm will be employed to avoid the potentially high dome velocities when the telescope tracks in the immediate vicinity of the zenith. The normal algorithm for calculation of the dome and windscreen positions is considerably more complex than the straightforward equatorial to alt-az coordinate conversion. This arises because the telescope axes are not coincident (by an amount of 3'-6") and also because the centre of the dome is offset from both of the telescope axes (a vertical distance of 5'-0" above the closest axis).

2.2 Monitoring

There are three basic categories of routines concerned with monitoring.

(a) Interlocks and Software Limits

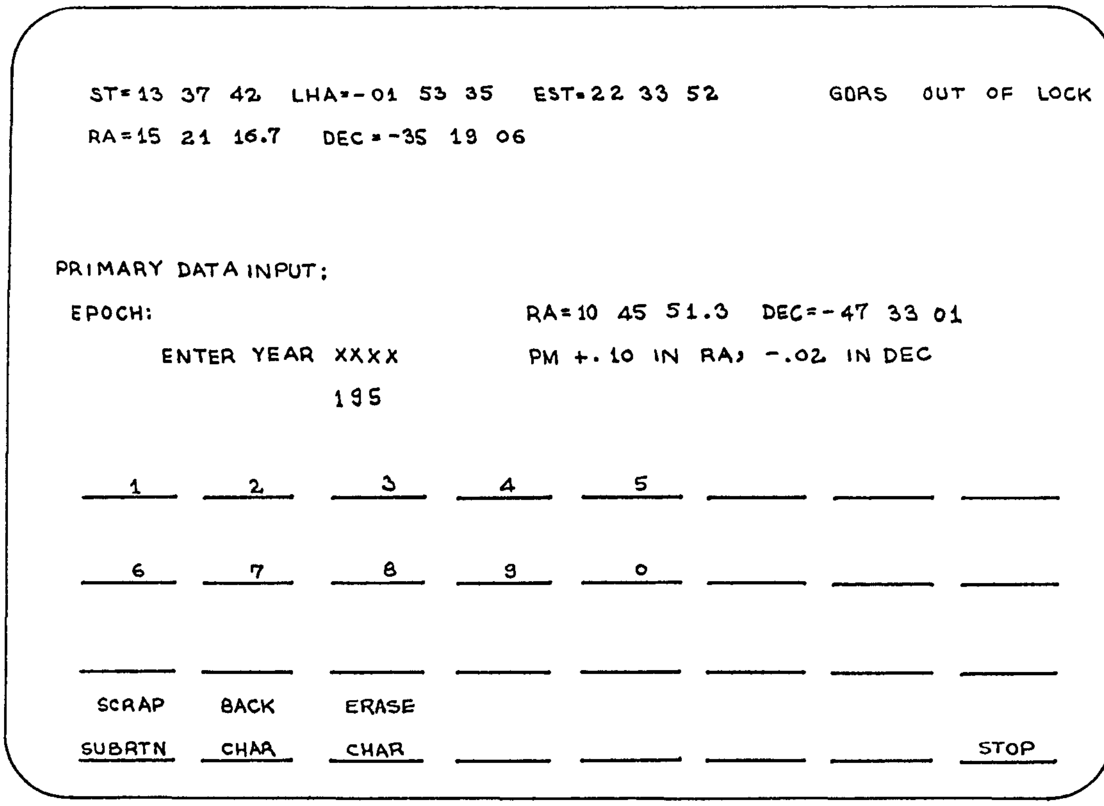
All interlocks associated with the various engineering subsystems are available to the computer and will be checked once per second for alarm conditions. Software checks on servo errors in the telescope, dome and autoguider subsystems will also be made.

(b) Sequence of Events

All operations initiated by the software will be logged if required.

(c) Meteorological Instruments

Instruments to monitor temperature, humidity, wind, and precipitation



Note: 1. The diagram shows 32 touchwires, although a smaller number in a different arrangement might also be suitable.

2. Touchwires not labelled would be ignored if touched.

3. The fine wires connecting to each touchwire are effectively not visible.

4. The diagram is purely an illustration of the touchwire principle and is not intended to indicate details of any particular application.

Fig. 2 Entering data using video display with touchwires.

will be monitored regularly or upon demand. Excess wind or the detection of rain will initiate closing of the dome shutter and the termination of operations.

2.3 Operations Terminal

It is planned in general that all operator control be done by way of a video display terminal. To optimize the man-machine interface the operator input during video display operations will be via a touchwire unit. This device consists of a clear perspex mask over the CRT, in which are embedded a number of horizontal wires connected to bridge circuits and thence to the computer. The operator executes control by touching the wire appropriately labelled by the video display. One example of how a video display and touchwire system might appear during a data inputting sequence while tracking, is shown in Figure 2.

3. INSTRUMENTATION

Since the astronomical instruments to be used on the telescope will originate from a number of observatories and laboratories, the prime need at this stage is for a standardized and modular instrumentation interface. To this end it is proposed to employ the Camac instrumentation system developed by the ESONE committee of the European Atomic Energy Community. Camac interfaces will be provided at the various telescope foci and in the main control room. A serial communication system is planned in order to extend the Camac highway over the distance between the control room and the Cassegrain cage.

A set of standard assembly language subroutines are proposed in order that instrumentation control software might generally be written in a high language such as Fortran.

A limited amount of real-time data processing is being catered for, and a graphical plotter and display will be available for this purpose.

4. COMPUTER SYSTEM CONFIGURATION

A block schematic of the system proposed for the initial installation is shown in Figure 3. It is envisaged that in time this will be expanded along the lines of the system shown in Figure 4.

The initial system will be suitable for telescope control together with control and data recording for those astronomical instruments currently being developed for the telescope. Both activities will be carried out in the one computer. The development of more complex instruments will undoubtedly lead to the eventual acquisition of a second processor, and also the use of individual computers for some special instruments. In these cases, the Camac instrumentation interfacing can readily be disconnected from the

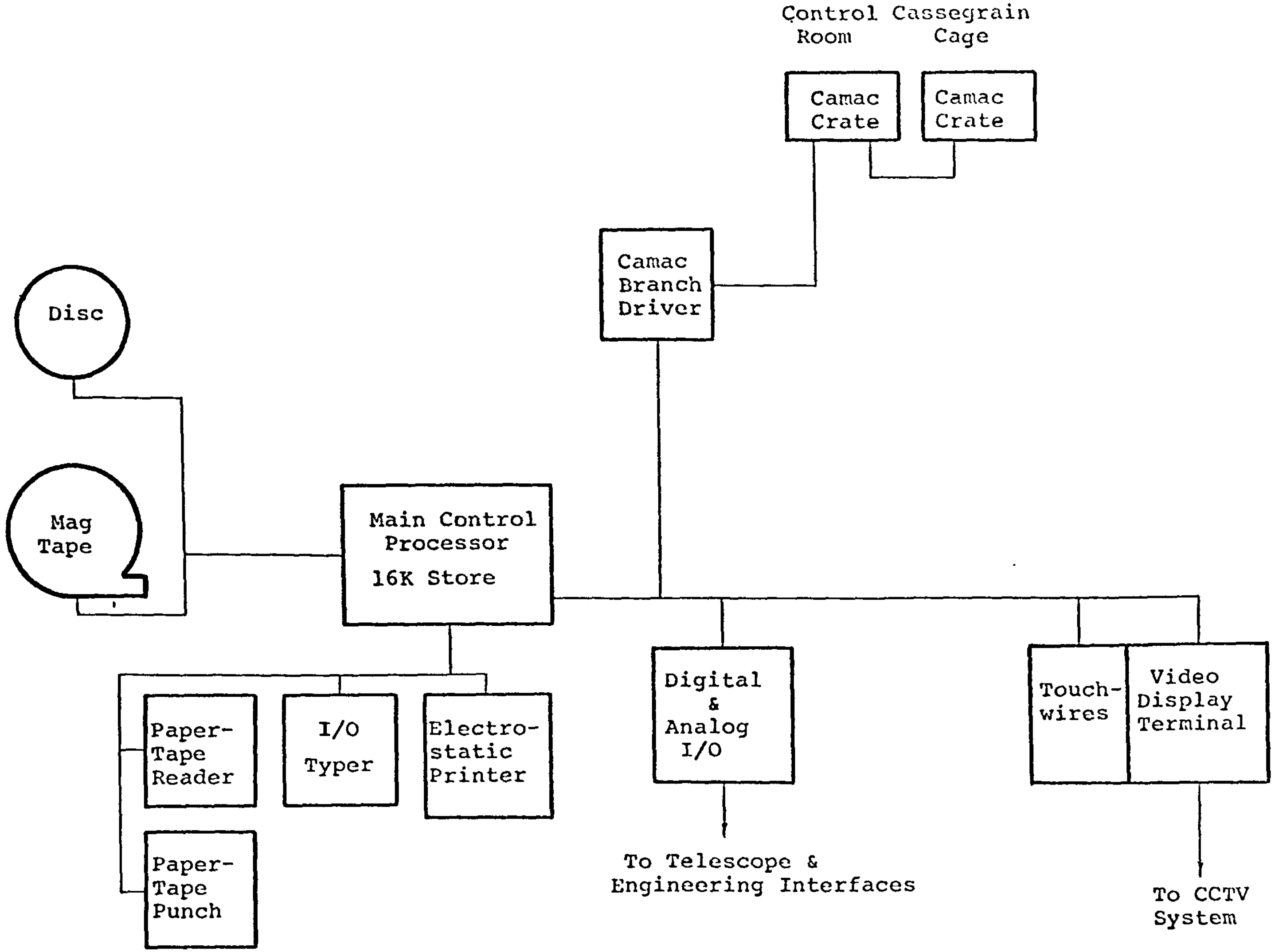


Fig. 3 Initial configuration of computer system.

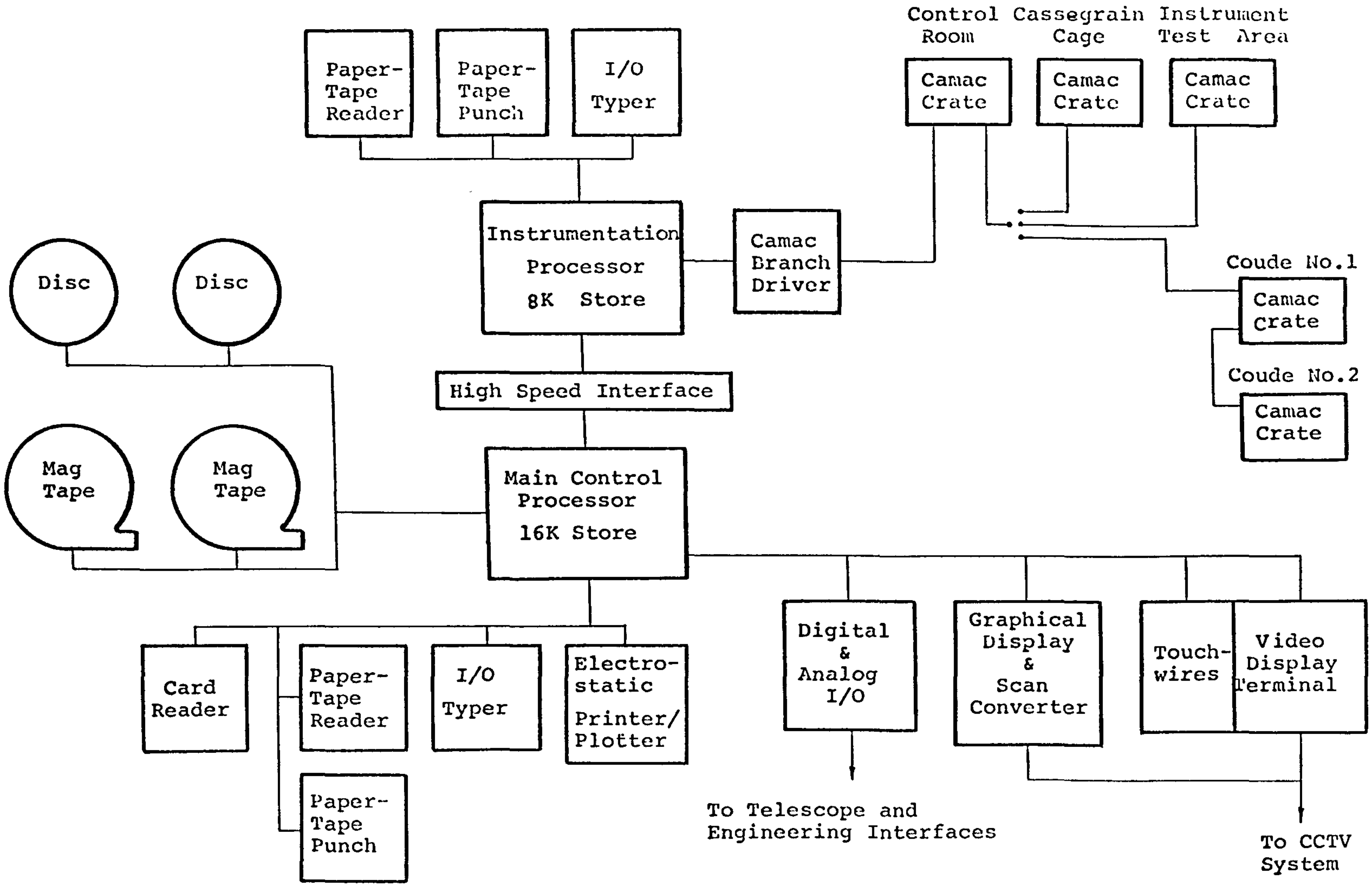


Fig. 4 Proposed eventual configuration of computer system.

main control computer and coupled to the satellite processor.

The computer will initially have approximately 16K words of core store, the exact figure depending upon the processor chosen, owing to the variation in core store overheads required by the executive/operating systems of the various computers under consideration for the task. The executive/operating software will supervise all core and disc operations, the disc being used for storing programs and tables, as well as being a buffer for astronomical data. An electrostatic printer is under consideration for both graphical output and high-speed printing.

There are also some economies inherent in the initial configuration. For example, the single magnetic tape for data recording and the single disc/drum ($\simeq$ 200K words), which will later be expanded to dual units to enhance flexibility and backup. Also, the Camac instrumentation facility will initially be available in only the Cassegrain cage and the control room. However, facilities to suit all initial astronomical and control requirements will be present and future expansion should be readily accommodated.

Final specification of the system is presently being completed and it is expected that a supplier will be chosen by October of this year.

ACKNOWLEDGEMENT

The writer wishes to thank the Anglo-Australian Telescope Board for permission to publish this paper.

ANGLO-AUSTRALIAN TELESCOPE
PROPOSED DRIVE AND CONTROL SYSTEM*

J. Rothwell

AAT Project Office

The following proposals for the drive and control system of the Anglo-Australian Telescope result from studies of existing or proposed drives for large optical telescopes which formed the basis of a design study carried out commercially on behalf of the Anglo-Australian Telescope Project.

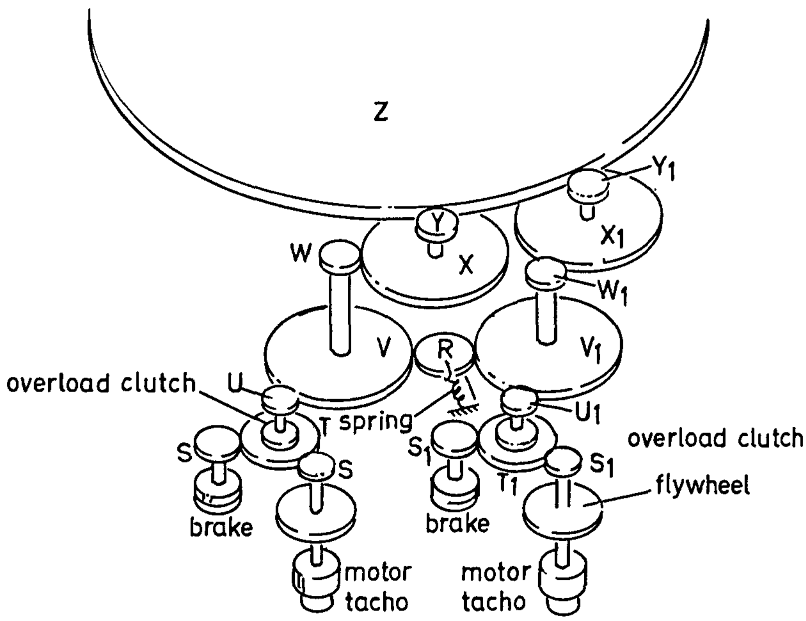
The telescope's hour angle and declination axes are to be driven by trains of spur gears with identical ratios. The final gear wheel will be 3.6 m diameter and will have 600 teeth which will be ground extremely accurately. Several factors determined the selection of spur gears rather than the conventional worm drives. Among these are the avoidance of control problems caused by non-reversability of worm drives, stiffer wheel because axial movements can be ignored, and simplification of arrangements for slewing, preloading and balance measurement. Each axis will be driven by two motors and two gear trains which will be independent of each other except for a spring-loaded idler pinion which will mesh with both trains to provide a preload which will eliminate backlash from the final meshes. This method of preloading ensures that the pinions share the drive torque equally thus effectively doubling the mechanical stiffness of the gearbox and also requires less motor power compared with other systems since only the additional friction torque introduced by the preload has to be supplied by the motor and not the preload torque itself. To further increase the gearbox stiffness and to avoid drive discontinuities, it will be arranged that each final drive mesh will have a contact ratio of at least 2 thus producing a total effective contact ratio for each axis of 4.

Two 19 cm printed circuit motors, each capable of producing 3.18 Newton metres torque will be used to drive the telescope through an overall gear ratio of 20,300:1. These motors have the advantages of smooth low-speed operation and minimum brush sparking due to the very low inductance of the armature. It has been estimated that the brush life of the motors will be about 15 years.

A torque-limiting clutch will be included in each drive train to avoid gear damage in the event of seismic shocks or accidental collisions.

----

* not read at the conference



gear	number of teeth	DP or module	nominal PCD	gear ratio	
Z	600	6 mm	141·73	24:1	20,300:1
Y	25	6 mm	5·906		
X	188	10	18·8	7·835:1	
W	24	10	2·4		
V	240	12	20	12:1	
U	20	12	1·667		
T	180	16	11·25	9:1	
S	20	16	1·25		
R	34	12	2·83		

Fig. 1 Schematic layout of power drives.

(See figure 1.)

Because of the low friction torque of the hydrostatic bearings, it is possible that load disturbances, due to, say, movements of an observer at the prime focus, will cause the structure to resonate for prolonged periods. To guard against this it is proposed to make provision for a friction-driven damping motor and tacho-generator at the horseshoe. Accelerations of the load will be sensed by the tacho-generator and its amplified output signal will then be used to cause the motor to generate a damping torque.

Independent gearboxes with drive pinions meshing also with the 3.6 m diameter drive wheels will be provided on each axis to drive encoders and synchros, (see figure 2). A 15-bit fine absolute encoder will be geared up from the axis by 1:40 making each bit approximately equal to 1 arc sec. A 5-bit coarse absolute encoder will be geared down by 32:1 from the fine encoder thus providing a total unambigous range of 288^{o} for each axis.

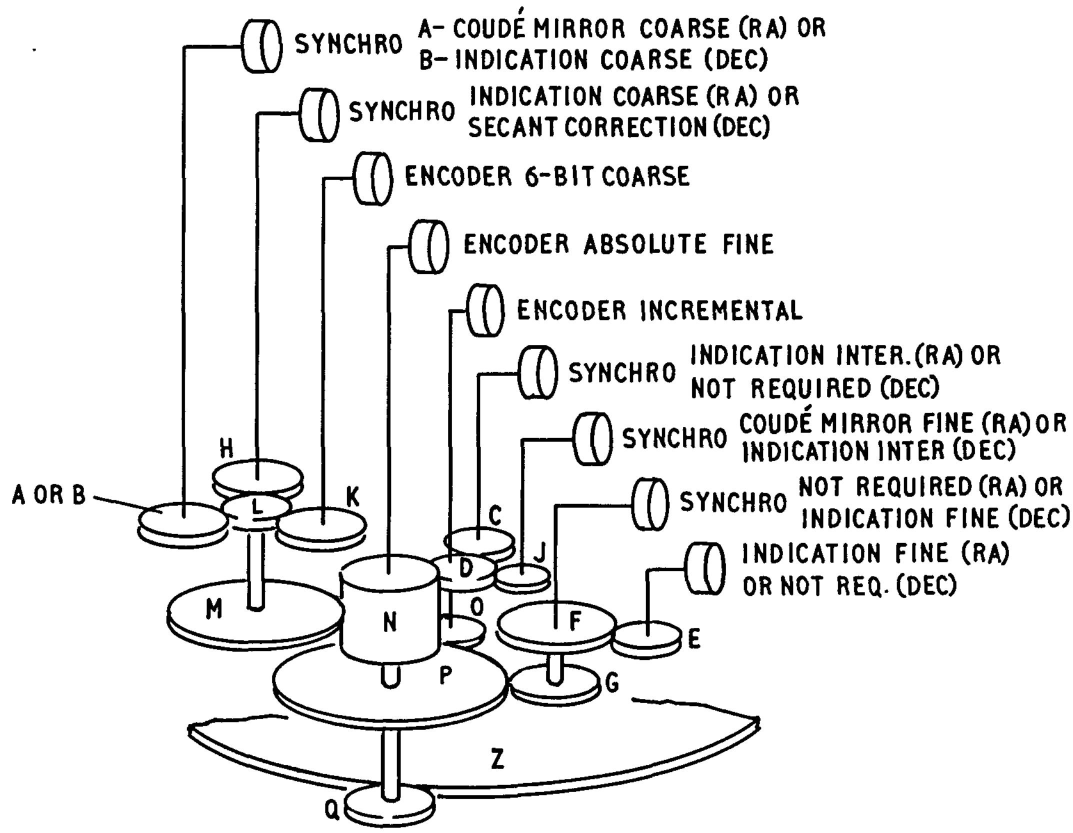
A 48,000 count per turn incremental encoder will be geared up by 1:13.5 from the fine absolute encoder thus having a ratio of 540:1 relative to the telescope axis, i.e., each count represents exactly 0.05 arc sec at the telescope axis.

Synchros will be used to drive back-up analogue indicators (normal indication will be digital, derived from the absolute encoder outputs) and also in the case of the hour angle axis to control the position of the drive mechanism for the coudé No. 5 mirror and the case of declination for correction of the hour angle gain according to the secant of the declination angle.

A thyristor bridge amplifier has been chosen as the power amplifier which will drive the two motors of each axis connected in series. This type of amplifier produces a d.c. current output with a small saw tooth component of about 1 Khz frequency superimposed. The response of this amplifier is extremely fast compared with conventional machine-set power amplifiers or mains-commutated thyristor amplifiers. It also has the advantage that variations in back e.m.f. and brush contact resistance have virtually no effect on the output current, thus again ensuring smooth drive at slow speeds.

A rate generator will be used to produce drive signals in the form of a train of pulses whose pulse repetition frequency determines the drive rate for the appropriate telescope axis. This rate generator will consist basically of a decimal rate multiplier and will have the capability of direct control by the computer or of being controlled manually to produce a composite output determined by the required track, set, guide and trail demands.

The output pulses of the rate generator will be combined in an up/down counter with the output pulses of the incremental encoder in such a manner that the output of the counter will be zero when the telescope is faithfully following the demand signal with zero error. Each error count will represent exactly 0.05 arc sec at the telescope axis, (see figure 3).



	gear	teeth	PCD	ratio to load	element R.A.	element DEC.
24 DP	A	120	5·0	1	Coudé mirror coarse synchro	
	B	60	2·5	2		indication coarse synchro
	C	45	1·875	24	indication inter synchro	not required
	D	78	3·25			
	E	18	·75	1440	indication fine synchro	not required
	F	72	3·0			
	G	30	1·25		not required	indication fine synchro
	H	120	5·1	1	indication coarse synchro	secant correction synchro
	J	30	1·25	36	Coudé mirror fine synchro	indication inter synchro
	K	96	4·0	1·25	6-bit coarse encoder	
	L	24	1·0			
	M	216	9·0			
	N	27	1·5			
	O	20	·833	540	incremental encoder	
	P	270	11·25			
6mm	Q	15	3·543	40	absolute fine encoder	
6mm	Z	600	141·732	rack		

Fig. 2 Schematic layout of encoder drives.

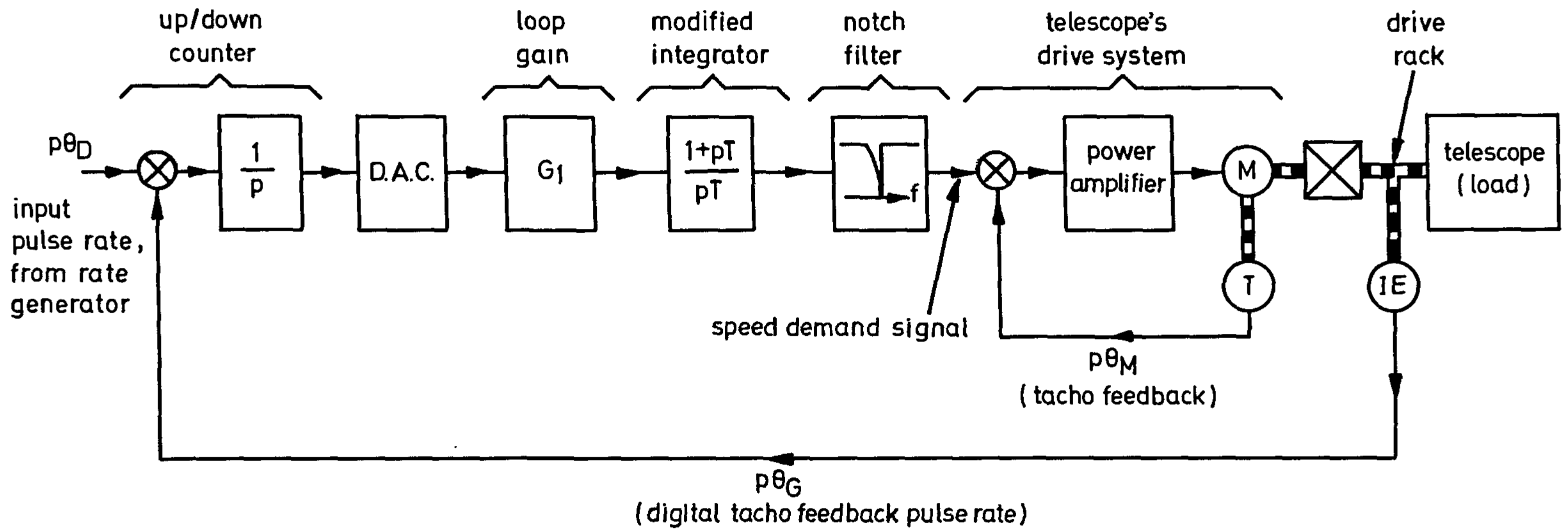


Fig. 3 Digital tacho-generator loop.

The digital error output from the up/down counter will then be converted to an equivalent analogue signal after which the error signal will be processed by integrators, filters, etc. to ensure the stability of the control loop. The resultant analogue signal will then be used to control a velocity loop formed by feeding back a signal, derived from an analogue tacho-generator mounted integrally on the motor shaft, over the output stages of the amplifier. Alternative processing will be provided in the amplifier to optimise the different modes of control, i.e., computer, auto-guider, etc. It is anticipated that the maximum bandwidth of the system will be about 0.8 Hz.

It is intended that systematic errors due to refraction, gearing (lower frequency), structural alignment and structural flexure will be corrected by the computer which will control the output of the rate generator in such a way as to overcome these errors. The residual random and higher frequency errors will be dealt with by the auto-guider to the limit of its capability.

The computer will also be used for controlling the positions of the dome and windscreen. After performing the necessary coordinate conversions, the computer will compare these demanded positions with the positions of encoders driven by re-transmission servos, producing any necessary error signals to cause the encoders to be driven to the demanded position. Synchros, also driven by the re-transmission servos, will then be used, in conjunction with synchros coupled to the dome and windscreen, to control the power servos which will drive the dome and windscreen to the demanded position. This approach reduces the slip-ring requirement and also simplifies manual control and position indication.

Although, at this stage, these are only proposals, it is envisaged that the final design will not deviate in principle but only in details.

Thanks are due to the Anglo-Australian Telescope Board for permission to prepare and publish this paper.

FRIDAY, MARCH 5

AFTERNOON SESSIONS

Chairman: A. Lallemand

ON DRIVE CONTROLS FOR ALTAZIMUTH MOUNTINGS

C. Kühne

Carl Zeiss, Oberkochen

The difficulties encountered in the use of altazimuth mountings are essentially due to three causes:

1. The singularity of the zenith for azimuth motion;
2. The nonlinear drive rates required for the two telescope axes;
3. The nonlinear rotation of the stellar field in relation to the tube.

The singularity of the zenith is peculiar to altazimuth mountings and thus unavoidable.

The nonlinear drive rates required in the telescope are in itself no simple problem. Still, it can be solved satisfactorily with the technical means available today, as is borne out by the outstanding accuracy of some radio telescopes.

In the following, I shall primarily deal with the difficulties encountered in the observation of stellar fields due to field rotation.

The situation is best explained if we picture what an observer has to do to keep a star on the optical axis of the telescope.

Assuming that a computer is employed to determine the drive rates for the telescope axes and control the drive motors - as will be indispensable for altazimuth mounts - the first operation to be performed by the operator is to set the telescope for the star. After starting, he will correct the position and drive rate and check the tracking motion of the instrument at more or less frequent intervals. The difference between this procedure for the equatorial and the altazimuth mounting is a quantitative one, rather than one of principle. This is due to the fact that the non-linearity of the drive rates of the two axes will result in a position error much more quickly than in the case of an equatorial mounting.

The rotation of the stellar field, however, is quite a new element that becomes particularly evident in stellar photography, but also in photometric and spectrographic work when the observer has to rely on off-set guiding.

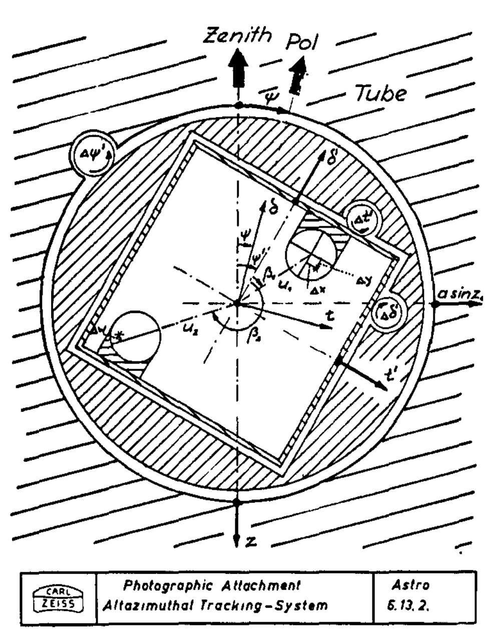
It appears logical first to stick to the known principle and only to extend the intermittent checking of stellar position to two off-axis guide stars. However, I believe an observer would be overtaxed if he were required to make the necessary corrections with the aid of the two guide stars. This is due to the fact that an operator cannot readily decide whether a deviation or combination of two deviations is the result of a tracking error in azimuth, zenith distance or rotation. The correlation between deviation and correction is a complicate function of the position of the telescope and the relative location of the guide stars.

I therefore believe that the difficulty can be overcome only if the observer is replaced by photoelectric star sensors. These should link onto the two guide stars from the original field by means of suitable prism systems and continuously monitor their position. The monitor signals generated by the star sensors can then be used for tracking via a control network or a computer.

However, this would be solving the problem only in principle. In addition, we have to take into account that the mounting itself is a very heavy body which will follow any acceleration only with a certain inertia. It will therefore only be able to compensate with a certain delay the positional errors of the optical axis that are unavoidable due to mechanical mounting and drive tolerances as well as spontaneous displacements of optical elements. This makes it advisable to use a light and rapid control system in front of the heavy and slow control system of the telescope.

This method can best be explained with the aid of the Photographic Attachment (Fig. 1).

Fig. 1



A plate holder carrier is rotatably mounted in the telescope tube at the primary, Cassegrain or Nasmyth focus. In this carrier the plate holder can be shifted in two mutually perpendicular directions as in a compound slide. The rotation is represented by the angle ψ', shifts by the coordinates t', δ' and $\Delta t'$, $\Delta\delta'$, respectively. The plate holder is rigidly connected to two star sensors, one of which is designed as a quadrant sensor, the other as an edge sensor. The former measures the deviation of a guide star in the Δx and Δy components, the latter only in the Δw component. The problem now consists in moving the rotatable carrier and the movable plate holder so that the deviation signals Δx, Δy and Δw are continuously kept to zero. The kinematic degrees of freedom of the plate holder (ψ', t' , δ') apparently suffice to do this.

However, it will be noted right away that this is possible only within the limited motion range of the compound slide, i.e. only within a certain position difference between telescope and central star. In order to avoid the plate holder reaching the end of its motion range, the displacements $\Delta t'$, $\Delta\delta'$ and ψ' are picked up and used to correct the motion of the telescope. The resulting control will guide the tube in azimuth and zenith angle so that $\Delta t'$ and $\Delta\delta'$ are kept to zero.

The following properties can be predicted for a tracking system of this type:

1. Follow-up in ψ', t' and δ' will be relatively fast, since the rotary carrier and the plate holder can be made fairly light. Fast in this sense would be a control that regains balance within 1 sec after a single exterior disturbance.
2. The control of the overall telescope may be relatively slow. A certain amount of inertia is even necessary because rapid response of the telescope would have an undesirable effect on the plate holder control. The time constants of the telescope control should therefore at least be one power of ten greater than the time constants of the plate holder control. Towards higher values, the time constants are only limited by the maximum admissible position difference of the telescope, which is limited by the motion range of the plate holder.
3. Rotation of the different coordinate systems as a function of time suggests that the overall control will be a widely intermeshing system whose stability can by no means be taken for granted and should therefore be the subject of further study.

Before making a few remarks on the quantitative investigation of the control problem it should be said that this method is, of course, not restricted to photography. An off-set guiding system of equivalent characteristics for photometric or similar work look roughly like Fig. 2.

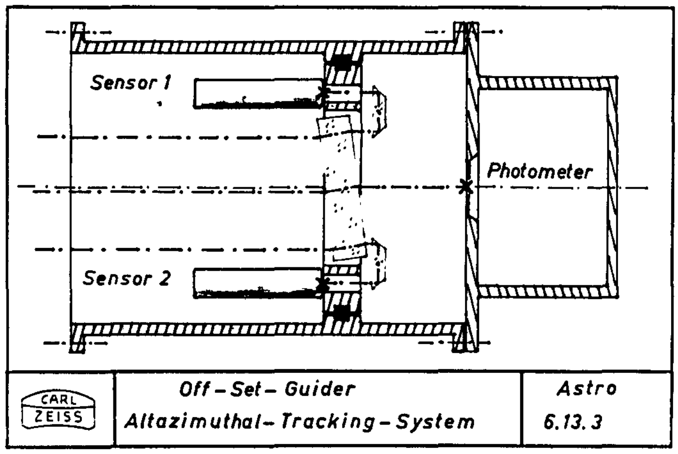

Sensor 1
Photometer
Sensor 2
CARL ZEISS
Off-Set-Guider
Altazimuthal-Tracking-System
Astro
6.13.3

Fig. 2

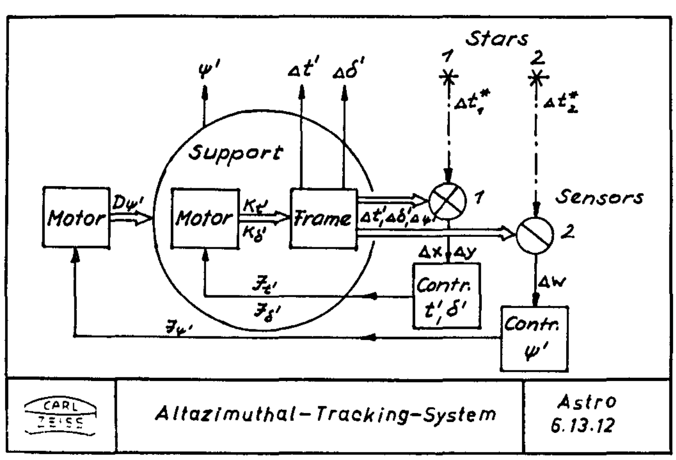

Stars
Support
Motor
Motor
Frame
Sensors
Contr.
t', δ'
Contr.
ψ'
CARL ZEISS
Altazimuthal-Tracking-System
Astro
6.13.12

Fig. 3

As in the plate holder system, the field is rotated by a suitable support. In this case, however, the function of the plate holder is transferred to a plane-parallel plate which can be tilted in two components.

For better understanding of the following remarks I should like to explain the coordinate systems used.

Star	$t^*, \delta^* \Leftrightarrow a^*, z^*, \psi^*$
Telescope	a, z, ψ
Plate Holder	t', δ', ψ'
Sensor 1	$\Delta x, \Delta y$
Sensor 2	Δw

The coordinates of the star, hour angle, declination and azimuth, zenith angle and angle of rotation have been marked with an asterisk. This also avoids confusion with the physical time t .

Let us first of all take a look at the control circuit of the plate holder alone. This control system can be schematically explained as Fig. 3.

The input of the control circuit is the motion of the stars 1 and 2. Via the controllers t', δ' and ψ' and the servo-motors, the error signals Δx, Δy and Δw cause the support and the plate holder to move so that $\Delta x, \Delta y$ and Δw are always kept as close to zero as possible. The required motions $\Delta\psi'$, $\Delta t'$ and $\Delta\delta'$ of the plate holder are measured as electrical signals and transmitted to the outside. However, they are of interest only in connection with the telescope control system.

The behaviour of the plate holder control is described by the equilibrium of forces acting on the plate holder and the equilibrium of moments acting on the plate holder carrier.

$$(1) \qquad M\Delta\ddot{t}' + R\Delta\dot{t}' = K_{t'} = cJ_{t'} = a\Delta x + b\Delta\dot{x}$$

$$(2) \qquad M\Delta\ddot{\delta}' + R\Delta\dot{\delta}' = K_{\delta'} = cJ_{\delta'} = a\Delta y + b\Delta\dot{y}$$

$$(3) \qquad \Theta\Delta\ddot{\psi}' + F\Delta\dot{\psi}' = D_{\psi'} = c'J_{\psi'} = k\Delta w + j\Delta\dot{w} + i\int_0^t \Delta w\, dt$$

where M is the mass of the plate holder, R the friction coefficient of the bearing, K the force which the motor exerts on the plate holder and J the motor current. For the $\Delta t'$ and $\Delta\delta'$ components we may assume these magnitudes to be approximately equal. The third equation (3) contains the equivalent torque equilibrium for the rotation $\Delta\psi'$.

An explanation may be helpful in connection with the coefficient of friction R and F respectively. The formulation making the frictional force ($R\cdot\Delta\dot{t}'$) proportional to the speed $\Delta\dot{t}'$ is not quite correct. Normally, one should also make allowance for a component whose value is constant and whose sign changes with the sign of $\Delta t'$.

However, this component is non-linear and would considerably complicate analytical treatment. It can be shown, on the other hand, that this non-linear component can be replaced by an increase in the linear coefficient R insofar as the damping behaviour and the maximum control variation are then roughly equal. And since the exact variation with time is of relatively little interest, provided that the control variation and time constant are comparable, I think this simplification is admissible.

The right-hand side of the equation contains the formulation I have chosen for the controllers. For the components $\Delta t'$ and $\Delta\delta'$ it includes a PD control with a combination of Δx and $\Delta\dot{x}$ or Δy and $\Delta\dot{y}$ for each of them, whereas for rotation I have chosen a PID control which in addition to the proportional and differential component also includes an integral component. This is necessary because with a pure PD control a residual deviation remains that is proportional to the drive error of the telescope. While this error can be compensated by the telescope control system as regards azimuth and zenith distance, it cannot be compensated with respect to field rotation. It is thus necessary that the rotation be reduced to zero by the plate holder alone, and this is possible only if the control circuit includes an integral component.

The control quantities are rather complex functions of stellar motion and of the locus of the two guide stars in the field:

$$\Delta x = \sin z_0 \cos\psi_0 \int_0^t (\dot{a}^* - \dot{a})dt + \sin\psi_0 \int_0^t (\dot{z}^* - \dot{z})dt + u_1 \cos\beta_1 \int_0^t \dot{\psi}^* dt - \Delta t' - u_1 \cos\beta_1 \Delta\psi' \tag{4}$$

$$\Delta y = \sin z_0 \sin\psi_0 \int_0^t (\dot{a}^* - \dot{a})dt - \cos\psi_0 \int_0^t (\dot{z}^* - \dot{z})dt - u_1 \sin\beta_1 \int_0^t \dot{\psi}^* dt - \Delta\delta' + u_1 \sin\beta_1 \Delta\psi' \tag{5}$$

$$\Delta w = \sin z_0 \cos(\psi_0 + \beta_2) \int_0^t (\dot{a}^* - \dot{a})dt + \sin(\psi_0 + \beta_2) \int_0^t (\dot{z}^* - \dot{z})dt + u_2 \int_0^t \dot{\psi}^* dt - \cos\beta_2 \Delta t' + \sin\beta_2 \Delta\delta' - u_2 \Delta\psi' \tag{6}$$

where the quantities z_0 , ψ_0 refer to the central star at the initial time t = 0. (The other notations see Fig. 1)

This extremely complicated function is fortunately greatly simplified if we take into account that the periods involved in plate holder control are so short that the speeds $\dot{a}^*$, $\dot{a}$, $\dot{z}^*$, $\dot{z}$ and $\dot{\psi}^*$ remain practically unchanged.

We then have the following approximation:

$$\left.\begin{array}{ll}(7) & \dot{a}^*(t) - \dot{a}(t) \approx \Delta\dot{a}(0) = const. \\ (8) & \dot{z}^*(t) - \dot{z}(t) \approx \Delta\dot{z}(0) = const. \\ (9) & \dot{\psi}^*(t) \approx \dot{\psi}^*(0) = const.\end{array}\right\} \text{for short intervals}$$

where $\Delta\dot{a}(o)$ and $\Delta\dot{z}(o)$ are residual errors remaining in the computation by the digital computer and in the transmission to the telescope drives at the beginning of observation.

In the following I should like to be somewhat more specific and consider a certain position of the guide stars in the field, because general treatment of the subject would become too confusing within the scope of this paper.

$$(10) \qquad u_1 = u_2 = u$$

$$(11) \qquad \beta_2 = \beta_1 + \pi$$

$$(12) \qquad \beta_1 = \pi/4 = 45^\circ$$

(10) and (11) mean, the two guide stars face each other in the field at equal distances while in (12) $\beta_1 = 45^\circ$ has been chosen. This is, of course, arbitrary, but an admissible simplification.

With these simplifications we obtain from (4), (5), (6)

$$(13) \qquad \Delta x = \Delta A \cdot t \quad - \Delta t' - \frac{u}{\sqrt{2}} \Delta\psi'$$

$$(14) \qquad \Delta y = \Delta B \cdot t \quad - \Delta\delta' + \frac{u}{\sqrt{2}} \Delta\psi'$$

$$(15) \qquad \Delta w = \Delta C \cdot t \quad + \frac{1}{\sqrt{2}} \Delta t' - \frac{1}{\sqrt{2}} \Delta\delta' - u \Delta\psi'$$

where ΔA, ΔB and ΔC are replacing the constant expressions

$$(16) \qquad \Delta A = \sin z_0 \cos\psi_0 \Delta\dot{a}(0) + \sin\psi_0 \Delta\dot{z}(0) + \frac{u}{\sqrt{2}} \dot{\psi}^*(0)$$

$$(17) \qquad \Delta B = \sin z_0 \sin\psi_0 \Delta\dot{a}(0) - \cos\psi_0 \Delta\dot{z}(0) - \frac{u}{\sqrt{2}} \dot{\psi}^*(0)$$

$$(18) \qquad \Delta C = -\frac{1}{2}(\Delta A - \Delta B) + 2u\dot{\psi}^*(0)$$

Now we can carry the time functions $\Delta t'$, $\Delta\delta'$ and $\Delta\psi'$ from (1), (2), (3) into the Laplace transform. Using the notations and the initial values as follows

$$(19) \qquad \mathcal{L}\{\Delta t'(t)\} = f(s) \qquad \Delta t'(0) = \Delta\dot{t}'(0) = 0$$

$$(20) \qquad \mathcal{L}\{\Delta\delta'(t)\} = g(s) \qquad \Delta\delta'(0) = \Delta\dot{\delta}'(0) = 0$$

(21) $\mathcal{L}\{\Delta\psi'(t)\} = h(s) \qquad \Delta\psi'(0) = \Delta\dot{\psi}'(0) = 0$

we obtain the transformations

(22) $$f(s) = \frac{P_3}{2s^2}\left[\frac{\Delta A + \Delta B}{P_1} + \frac{P_2(\Delta A - \Delta B) - \sqrt{2}\,P_4\,\Delta C}{P_1P_2 + P_3P_4}\right]$$

(23) $$g(s) = \frac{P_3}{2s^2}\left[\frac{\Delta A + \Delta B}{P_1} - \frac{P_2(\Delta A - \Delta B) - \sqrt{2}\,P_4\,\Delta C}{P_1P_2 + P_3P_4}\right]$$

(24) $$h(s) = \frac{P_4}{u\sqrt{2}\,s^2} \cdot \frac{P_3(\Delta A - \Delta B) + \sqrt{2}\,P_1\,\Delta C}{P_1P_2 + P_3P_4}$$

with

(25) $P_1 = Ms^2 + Rs + P_3$

(26) $P_2 = \Theta s^3 + Fs^2 + P_4$

(27) $P_3 = bs + a$

(28) $P_4 = u(js^2 + ks + i)$

Unfortunately, the limited time available here does not permit a more detailed discussion of the system of equations. May I therefore restrict myself to two numerical examples, using the estimated dimensions of a 30 x 30 cm plate holder and arbitrary proportionality factors for the controllers.

(29)

$M =$	120 kg	$\Theta =$	1,2 kgm²
$R =$	1800 kg/sec	$F =$	36 kgm²/sec
$b =$	3000 kg/sec	$uj =$	12 kgm²/sec
$a =$	48 000 kg/sec²	$uk =$	480 kgm²/sec²
		$ui =$	4800 kgm²/sec³

The first example

(30) $\Delta\dot{a}(0) = \Delta\dot{z}(0) = 0 \qquad \dot{\psi}^*(0) = \text{const}$

is based on the assumption that the telescope is driven at the correct rates and that only field rotation has to be compensated by the plate holder. The second example,

(31) $\Delta\dot{a}(0) = \text{const} \qquad \Delta\dot{z}(0) = \dot{\psi}^*(0) = 0$

taken alone, is not realistic because in general there is always some rotation of the field. However, the results of example 2 and of a further example in which only $\Delta\dot{z}$ is constant can be superimposed on those of example 1 in order to study the conditions in all practical cases.

We thus obtain in example 1 the time functions

$$\left.\begin{matrix}\Delta x \\ -\Delta y\end{matrix}\right\} = u\dot{\psi}^* \Big[-0.0551(1-4.28t)e^{-20t} + 0.0221 e^{-26.9t} + 0.033(\cos 16t + 0.342 \sin 16t)e^{-6.55t}\Big] \tag{32}$$

$$\Delta W = u\dot{\psi}^* \Big[0.0780(1-4.28t)e^{-20t} - 0.0221 e^{-26.9t} + 0.0559(\cos 16t - 2.165 \sin 16t)e^{-6.55t}\Big] \tag{33}$$

If we plot Δx, Δy and ΔW graphically, we obtain Fig. 4.

It is obvious that the error signals generated by the star sensors have completely died down after about 500 milliseconds. In other words, the star field now is practically being fixed in relation to the plate holder. In our numerical example, which applies to a polar altitude of 30° and star transit in the direct vicinity of the zenith, the amplitudes of Δx, Δy and ΔW are so small that they can be neglected.

The time functions of the plate holder movements $\Delta t'$, $\Delta \delta'$ and $\Delta \psi'$, not plotted here, are a combination of sensor functions Δx, Δy, ΔW. In addition, there is merely a uniform speed of the specified value $\dot{\psi}^*$ which is superimposed on the rotation only.

The second case is similar, although the time functions are more complex.

$$\Delta x + \Delta y = (\cos\psi_0 + \sin\psi_0)\sin z_0 \Delta\dot{a}(0)\Big[0.0375 - 0.0375(1-6.67t)e^{-20t}\Big] \tag{34}$$

$$\Delta x - \Delta y = (\cos\psi_0 - \sin\psi_0)\sin z_0 \Delta\dot{a}(0)\Big[0.0375 - 0.0778(1-4.28t)e^{-20t} + 0.0445 e^{-26.9t} - 0.0042(\cos 16t - 4.2 \sin 16t)e^{-6.55t}\Big] \tag{35}$$

$$\Delta W = (\cos\psi_0 - \sin\psi_0)\sin z_0 \Delta\dot{a}(0) \cdot \Big[0.0551(1-4.28t)e^{-20t} - 0.0221 e^{-26.9t} - 0.033(\cos 16t + 0.342 \sin 16t)e^{-6.55t}\Big] \tag{36}$$

Since, moreover, the amplitude is a more complicated function of the rotational position of the stellar field, I have calculated the example in which ψ_0 is zero and the star is just crossing the meridian. Then the graphical representation is as Fig. 5.

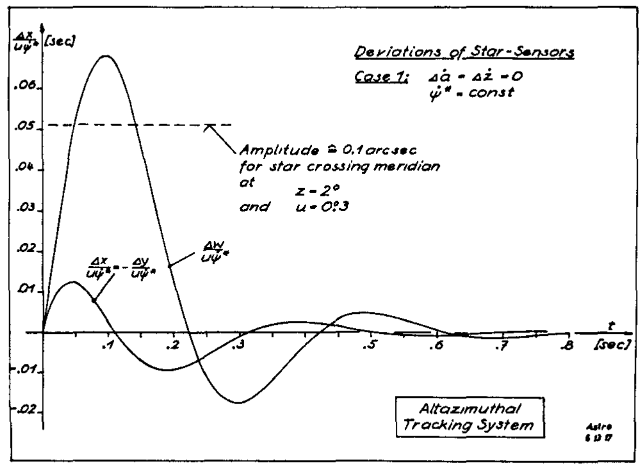

Deviations of Star-Sensors
Case 1: $\Delta\dot{a} = \Delta\dot{z} = 0$
$\dot{\psi}^* = const$
Amplitude ≙ 0.1 arcsec
for star crossing meridian
at z = 2°
and u = 0°3
Altazimuthal
Tracking System
[sec]
t [sec]

Fig. 4

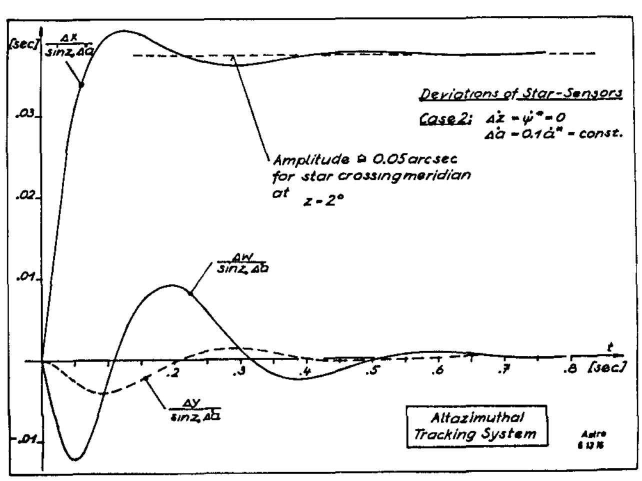

Deviations of Star-Sensors
Case 2: $\Delta\dot{z} = \dot{\psi}^* = 0$
$\Delta\dot{a} = 0.1\dot{a}^* = const.$
Amplitude ≙ 0.05 arcsec
for star crossing meridian
at z = 2°
Altazimuthal
Tracking System
[sec]
t [sec]

Fig. 5

Here also I have chosen the unfavorable case of transit near the zenith for the numerical example. The function ΔX asymptotically approaches a constant value which is essentially determined by the error of the telescope drive rate in azimuth. The deviations Δy and Δw disappear. The amplitudes are similar as in Example 1 and can be tolerated.

The corresponding time functions of $\Delta t'$, $\Delta\delta'$ and $\Delta\psi'$ are the result of a superposition of the functions Δx, Δy and Δw plus a uniform motion of speed proportional to the error in the drive rate.

As a result of a closer study, which unfortunately I cannot describe in greater detail here, we find that the control values Δx and Δy asymptotically approach a constant which is only a function of the errors of the telescope drive rates, without any dependence on field rotation. By analogy, this applies to the plate holder motions, and we can state

$$
(37)\qquad
\left.\begin{array}{l}\Delta x\\ \Delta y\end{array}\right\} \rightarrow const.(\Delta\dot{a}(0), \Delta\dot{z}(0), \dot{\psi}^{*}(0))
$$
$$
\Delta w \rightarrow 0 \qquad\qquad \text{for}
$$
$$
\left.\begin{array}{l}\Delta t'\\ \Delta\delta'\end{array}\right\} \rightarrow const.(\Delta\dot{a}(0), \Delta\dot{z}(0), \dot{\psi}^{*}(0))\cdot t \qquad t > 0.5\,\text{sec}
$$
$$
\Delta\psi' \rightarrow \dot{\psi}^{*} t
$$

In addition, the asymptotic state is reached in less than 1 sec. The telescope control need then only compensate for the original errors $\Delta\dot{a}(0)$ and $\Delta\dot{z}(0)$. To perform this compensation, the telescope control has relatively much time, namely just as much as the motion range of the plate holder is capable of absorbing.

At least theoretically, the solution of the telescope control problem is relatively easy. The control circuit looks roughly as in Fig. 6.

The little box marked "support" replaces the entire plate holder control mentioned above. The equilibrium of torques at the telescope axes is:

$$
(38)\qquad \Theta_{TA}\ddot{a} + F_{TA}\dot{a} = D_A = c_A \mathcal{I}_A = P_A\Delta\xi + Q_A\Delta\dot{\xi} + V_A\int_0^t \Delta\xi\, dt
$$

$$
(39)\qquad \Theta_{TZ}\ddot{z} + F_{TZ}\dot{z} = D_Z = c_Z \mathcal{I}_Z = P_Z\Delta\eta + Q_Z\Delta\dot{\eta} + V_Z\int_0^t \Delta\eta\, dt
$$

The controllers necessitately are PID-controllers. The notated control quantities $\Delta\xi$ and $\Delta\eta$ are formed from the plate holder coordinates $\Delta t'$, $\Delta\delta'$ and ψ' with the aid of the converter as follows:

(40) $$\Delta\xi = \frac{1}{\sin z}(\cos\psi'\Delta t' + \sin\psi'\Delta\delta')$$

(41) $$\Delta\eta = -\sin\psi'\Delta t' + \cos\psi'\Delta\delta'$$

The computer contributes the zenith distance z. The accuracy of this coordinate transformation need not to be very high. However, it does contain the only truly critical point in the control loop due to the occurrence of sin z in the denominator of $\Delta\xi$. $\Delta\xi$ must therefore be additionally limited, so that the control will work worse in a certain area near the zenith. But this is known and unavoidable.

As for the rest, I shall be brief. Once the plate holder has reached its state of equilibrium, $\Delta\xi$ and $\Delta\eta$ approach

(42) $$\Delta\xi \approx \Delta a(t) = a^*(t) - a(t)$$

(43) $$\Delta\eta \approx \Delta z(t) = z^*(t) - z(t).$$

For control, e.g. in azimuth, it may be p(s), the Laplace transform of the time function $\Delta a(t)$. Then we obtain with the initial values

(44) $$\Delta a(o) = 0$$

(45) $$\Delta\dot{a}(o) = \dot{a}^*(o) - \dot{a}(o)$$

the Laplace transform

(46) $$\{\Theta s^2 + (F+Q)s + P + V\tfrac{1}{s}\} = -\Theta\dot{a}(o) - -(\Theta s + F)a^*(0) + s(\Theta s + F)\mathcal{L}\{a^*(t)\}.$$

For greater simplicity I have omitted the indices. An analogous equation applies to the zenith angle. If we choose the parameters P, Q, V of the control so that the following relations apply

(47) $$V = \frac{FQ^2}{4\Theta} \qquad P = \frac{Q}{\Theta}\left(F + \frac{Q}{4}\right)$$

then the behaviour is essentially determined by two time constants T_1 and T_2

(48) $$T_1 = \frac{\Theta}{F} \qquad T_2 = \frac{2\Theta}{Q}$$

Of these time constants, T_2 can be chosen practically arbitrarily and is therefore well suited for optimization, while T_1 is essentially a function of the coefficient of friction so that it can be influenced only from the design. The Laplace transform $\Delta a(t)$ is then the following:

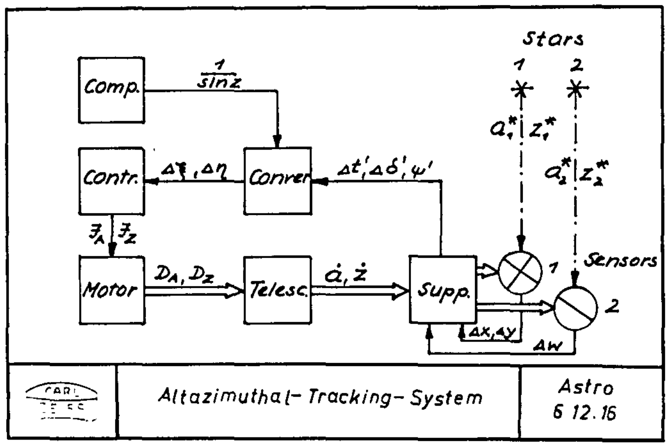

Stars
1
2
Comp.
1/sinz
Contr.
Conver
Motor
Telesc.
Supp.
Sensors
Altazimuthal- Tracking- System
Astro
6 12.16

Fig. 6

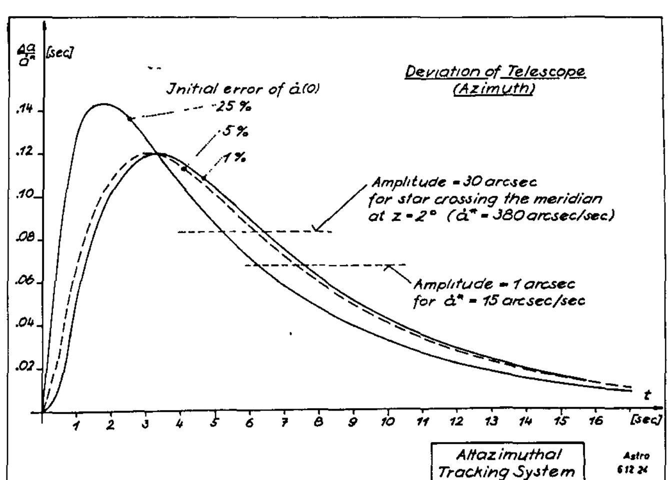

Deviation of Telescope
(Azimuth)
Initial error of ȧ(0)
25 %
5 %
1 %
Amplitude = 30 arcsec
for star crossing the meridian
at z = 2° (ȧ* = 380 arcsec/sec)
Amplitude = 1 arcsec
for ȧ* = 15 arcsec/sec
Altazimuthal
Tracking System
Astro

Fig. 7

(49) $$p(s) = -\frac{T_1 T_2^2 s}{(1+T_1 s)(1+T_2 s)^2}\dot{a}(0) - \frac{T_2^2 s}{(1+T_2 s)^2}a^*(0) + \left\{1 - \frac{1+2T_2 s}{(1+T_2 s)^2}\right\}\mathcal{L}\{a^*(t)\}$$

On the right hand side we still have in a general form the Laplace transform of a*(t) so that the retransformation to the time function a(t) contains a convolution integral. We then obtain

(50) $$\Delta a(t) = \frac{T_1 T_2^2}{(T_2 - T_1)^2}\left[e^{-\frac{t}{T_1}} - \left\{1 - \frac{T_2 - T_1}{T_2^2}t\right\}e^{-\frac{t}{T_2}}\right]\dot{a}(0) + a^*(t) + \left\{\frac{t}{T_2} - 1\right\}a^*(0)e^{-\frac{t}{T_2}} + \frac{1}{T_2}\int_0^t a^*(\tau)\left\{\frac{t-\tau}{T_2} - 2\right\}e^{-\frac{t-\tau}{T_2}}d\tau$$

The complicated expression can be simplified if the convolution integral is partially integrated. a* is then replaced by the drive rate $\dot{a}^*$, and it follows

(51) $$\Delta a(t) = \frac{T_1 T_2^2}{(T_2 - T_1)^2}\left[e^{-\frac{t}{T_1}} - \left\{1 - \frac{T_2 - T_1}{T_2^2}t\right\}e^{-\frac{t}{T_2}}\right]\dot{a}(0) - \int_0^t \dot{a}^*(\tau)\left\{\frac{t-\tau}{T_2} - 1\right\}e^{-\frac{t-\tau}{T_2}}d\tau$$

For further evaluation $\dot{a}^*(t)$ would have to be known. However, here also we may assume $\dot{a}^*$ to be practically constant. Although the control circuit of the telescope is slow referred to the servocontrol of the plate holder, the time constants T_1 and T_2 can still be kept to less than 10 sec and within these periods $\dot{a}^*$ will change only very little.

For a numerical example I have chosen the following data of the dimensions of a 2,2 m - telescope, in order not to rely too heavily on estimations

(52) $$\begin{aligned} \Theta_A &= 200 \cdot 10^3 \ kg\,m^2 \\ F_A &= 40 \cdot 10^3 \ kg\,m^2/sec \\ Q_A &= 400 \cdot 10^3 \ kg\,m^2/sec \\ P_A &= 280 \cdot 10^3 \ kg\,m^2/sec^2 \\ V_A &= 40 \cdot 10^3 \ kg\,m^2/sec^3 \end{aligned}$$

(53) $$T_1 = 5 \text{ sec} \qquad T_2 = 1 \text{ sec}$$

Graphically we obtain the time function $\Delta a(t)$ as Fig. 7.

May I finally mention that these remarks can, of course, not cover all the difficulties of the control aspect in altazimuth mountings. The problem discussed here is undoubtedly only one of many and has certainly not been optimized under all technical aspects. Many parameters were chosen more or less arbitrarily, frequently only with the aim of making the problem accessible to analytical solution. I have, however, tried to choose the parameters within limits that appear technically feasible.

The result justifies my personal opinion that there is a possibility that already in the near future altazimuth mounts will be considered or used not only for giant telescopes. Besides these difficulties in fine guiding the other well known advantages of altazimuth mountings are so great that their use should be considered also for smaller diameters.

The studies on which the present article is based have been supported by the Bundesminister für Bildung und Wissenschaft within the Technology Programme.

DISCUSSION

DITTMAR: That was an excellent analysis; I might say that a simpler one which is very applicable and is considerably easier to mechanize could be used also for standard mountings. Your idea of a high-response plateholder is very good. We are presently using this on one interferometer, where we transmit the information to the computer, which corrects the telescope up to the center of the plate holder again, only when the limits are reached in the two axes of the plate holder. It is a very successful automatic guiding technique.

KÜHNE: Thank you very much.

HERBIG: May I ask you a more general question about the advantages of altazimuth mountings? I understand that you have the advantage of a mirror support system which has to work only in one coordinate, a simplification in the bearing problem, a simplification in the structure and perhaps others. As one goes to larger-size telescopes, which of these advantages increases most quickly in importance? That is, which one of these difficulties does one encounter first?

KÜHNE: I think the increasing difficulty comes first in the support system of the mirror, and secondly in the mechanical parts of the mounting itself, in the driving system and so on, whereas the electrical circuits to drive the telescope are nearly the same for all diameters. You need the same control circuit for a 1.5 meter and for a 6 meter telescope.

ODGERS: Dr. Kühne, a similar analysis to yours must have been made for the Russian 6 m telescope. Has this been published or have you had any access to the details of the Russian control system?

KÜHNE: I am sure that the Russians have made this analysis too, but I never read about it. Maybe Dr. Kopylov could make some remarks about it?

KOPYLOV: In our 6 meter telescope the problem of compensation of the field rotation is realized by some kind of rotating tables in each focus. These rotating tables are operated by the computer, which gives to the tables two signals, namely the position and the speed of rotation. In each focus we have also some kind of manual guide in order to compensate for the possible errors of these devices. The theoretical details of such a problem have not yet been published in detail, but we have decided to publish in the near future - it may be in one or two years - a set of papers about the details of our system for compensation of the field rotation.

BORGMAN: I understand from Dr. Kopylov's explanation that the Russians are not using two star centers in order to drive the rotation of the plates, whereas you want to extract the information from two stars in the field directly. I wonder how you can do such a thing in practice, because from field to field the two stars must be in quite a different configuration? And what would you accept for a limiting magnitude of the stars in case of for instance the 2.2 m MPI telescope? Earlier in this week Dr. Elsässer described a system, which will possibly be used for the rotation of the plate holder.

KÜHNE: The star guider is a cylindrical equipment, 50 mm ∅ x 250 mm, and we can put the star sensors in the original field you want to photograph by means of a prism, or in the offset guiding system. With the star guider, that we have developed, we have reached $7^{m}.5$ with a 15 cm telescope, and the residual error of the motion is of the order of $0''.4$. This has been done in the very poor atmospheric conditions in Oberkochen. If you extrapolate, you find that the 2.2 m telescope will reach approximately $13^{m}.5$.

RULE: Are the mechanical errors of the plate holder and guider included in this analysis? Is the plate holder accurate to $0''.4$?

KÜHNE: No, this was for the whole instrument; it was a position error. In this test we did not use a plate holder. We connected the star sensors directly to the driving system of the small instrument.

SOLF: If you are making observations at large zenith angles you have considerable distortion of the star field because of differential refraction. This distortion changes with time, and I think you will have trouble with a system involving two star centers.

KÜHNE: Naturally, but since you cannot reduce this field distortion anyhow, you cannot photograph in this large zenith angle.

REDMAN: Is it possible to correct the rotation entirely by computation, and leave the guiding to a xy-correction, or will this not be sufficiently accurate?

KÜHNE: I think it depends very much on the angle of field that you like to photograph.

REDMAN: Say 1^{o}?

KÜHNE: It might be possible, but I am not sure you can have very long exposure times.

REDMAN: We have to settle it by experiment, I am afraid.

NEW ASPECTS

SOME ASPECTS OF DAYTIME OPERATIONS OF LARGE TELESCOPES

J. Borgman

University of Groningen

A telescope can be used with reason in the daytime for a variety of purposes. The classical studies of Antoniadi of surface details on the planet Mercury are one example; other examples could be given. This introduction will be restricted to an analysis of the possibilities and problems connected with daytime operation of telescopes in the field of infrared astronomy.

1. THE ATMOSPHERE AND INFRARED RADIATION

The diagrams and the numbers on atmospheric radiation, as given in this section, are largely based on the work of Bell, Eisner, Young and Oetjen (JOSA 50, 1313, 1960).

The visible radiance of the daytime sky is produced by scattering of the sun's radiation. An approximate upper value for this radiation can be derived from the simple model that all of the solar radiation is diffusely scattered downward. In this way the solar radiance is reduced to the atmospheric radiance by a factor 2×10^{-5}. This upper limit might be expected from a bright cloud (Figure 1). For a clear sky the near-infrared scattering is probably around 10% ($\approx$ extinction coefficient) of this upper value.

In addition to the "visible" radiance of the sky comes the thermal emission. The atmosphere, unfortunately, is only more or less transparent in a number of infrared windows; as a first approximation we shall assume a black body model for the radiation, characterized by a temperature of 300°K. As is illustrated in Figure 1 the combined total daytime radiation in this simplified model can be divided in two components: the scattered sunlight for $\lambda < 4\mu$ and the thermal emission for $\lambda < 4\mu$, with the minimum radiance occuring at 4μ.

The scattered sunlight, which is dominant in the region $\lambda < 4\mu$, disappears at Sunset. However, the thermal emission in the infrared is with us, day and night. This emission is the largest single problem source for observations beyond 5μ. To simplify, one may say that as far as the infrared detector is concerned there is no difference between day and night for $\lambda < 5\mu$.

TABLE 1

Atmospheric windows

$\lambda(\mu)$	$\Delta\lambda(\mu)$	radiation mechanism*	absorption features	
			1.9	H_2O
2.2	0.4	S		
			2.7	H_2O
3.6	0.6	S+E		
			4.3	CO_2
5	0.5	E+S		
			6.3	H_2O
10	5	E	9.6	O_3
			15	CO_2
20	6	E	>17	H_2O

* S = scattering
E = emission

TABLE 2

Radiance data (units 10^{-15} W cm^{-2} μ^{-1})

2400 m altitude, 15°C, zenith, 10" ∅ diaphragm

$\lambda(\mu)$	day	night	black body	gal.centre	R Mon
2.2	60	< 0.2	0.3		
3.6	20	4:	80		0.5
5	40:	10	400		0.4
10	160	160	1600	2	
20	300	300	600	3	

Fortunately, the blackbody model with unit emissivity for the infrared radiation of the sky is not correct. There are a number of windows, which have been identified in Table 1 (starting with the 2.2μ window), together with the important absorption features in which the sky is opaque and behaves as a black body.*

The dominant factors which determine the infrared thermal emission of the sky are connected with the lower level of the atmosphere: the amount of precipitable water, the atmospheric pressure and the temperature. It follows that the optimum site for a ground-based infrared telescope is a dry, high and cold observatory. In connection with daytime operation the temperature is of some importance; blackbody emission near the peak of the Planck curve (300^{o}K, 10μ) is strongly temperature dependent. The residual thermal radiation of the atmosphere in the windows is expected to show approximately the same variation with temperature. In practice, this is found back as a slight deterioration of signal to noise ratio during the day.

It is instructive to take a look at the absolute radiance values in Table 2. The data have been normalized for a circular diaphragm of 10 seconds of arc, 2400 m altitude and 15^{o}C ambient temperature. In the case of the daytime sky data in the 2.2, 3.6 and 5μ windows the sun has been assumed to be at least 90^{o} away from the field. The sky data in Table 2 should be regarded with caution; they have been compiled from data on atmospheric radiance under a large variety of conditions. However, they are sufficiently accurate to illustrate once again the statement that daytime operation in the 10μ and 20μ windows is not fundamentally inferior to nighttime work; the same applies probably to the 5μ window.

2. NIGHTTIME INFRARED OBSERVATIONS

Before enlarging on daytime operation something should be said on those aspects of infrared telescope design which are important for nighttime work as well.

A large telescope is required for light collection (as in the visible); however, the infrared observer has an extra need for a large telescope: the large diameter is required for spatial resolution. The resolving power of a 350-cm telescope at 20μ is 1.5 seconds of arc, nicely compatible with the seeing disturbances; a diaphragm of 10 seconds of arc diameter will just about include the first order aberration ring, which is a requirement for

---

* Actually, the picture is much more complicated. In the windows there are more absorption lines than O_3 = 9.6μ, whereas in the dark regions there are mini-windows, restricting or allowing sometimes the detection of non-telluric spectral lines as has been demonstrated, a.o., in the high resolution work of Connes. For the purpose of this introduction I have restricted myself to a discussion of the coarse window-model; the discussion, therefore, has a direct bearing on integrated photometry in each of the windows.

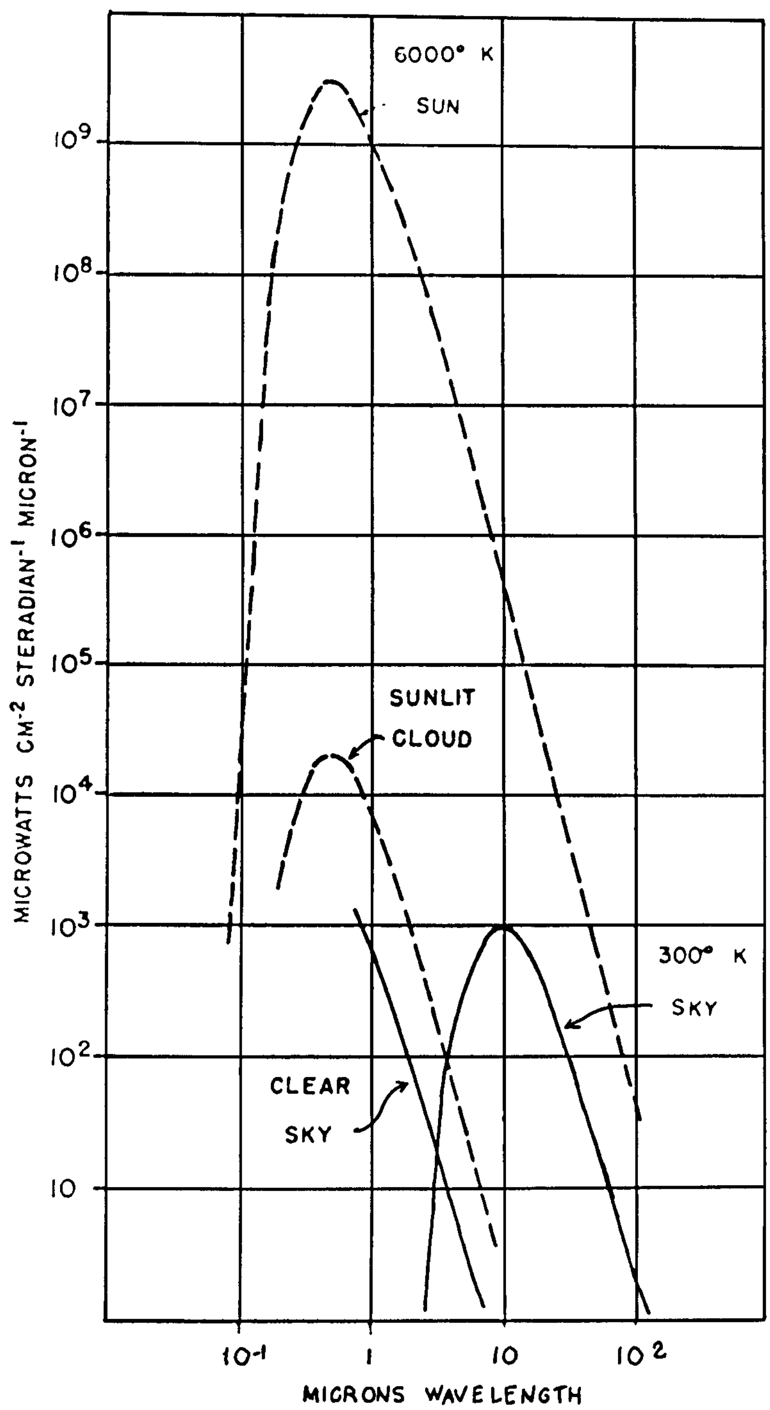


Fig. 1 An idealized spectral radiance of the sun, emitting atmosphere, sunlit cloud, and sunlight-scattering clear sky.

reasonably accurate spectrophotometry. A 350-cm telescope is required to provide spatial infrared detail which is compatible with the details that can be studied in the visible.

The data on sky radiance, together with the blackbody values and the observations of two relatively bright objects (Table 2) clearly illustrate the desirability of a highly efficient chopping mechanism to reject the sky contribution. Equally important is the reduction of radiation from telescope parts, which can produce a large (and in any case noisy) offset signal that consumes a large portion of the dynamic range of the detector system. This radiation may be considerable. Unavoidable is the emission of the mirrors; two reflecting surfaces with an emissivity of 2% each will give rise to a radiance of 70 units in the 10μ window (units of Table 2). The same size contributions can be expected from obscurations in the lightpath with a projected surface of 4% of the surface of the primary mirror. In order to reject this type of radiation elaborate chopping systems have been designed, which help to suppress unwanted differential detector signals.

Neugebauer and associates have wobbled an entire 60-inch lightweight primary mirror at 30 cps, others have wobbled secondary mirrors at even higher frequences. In any case, it is wise to keep black body pollution inside the telescope tube down to the minimum. These considerations point to a thin spider, to support a clean secondary assembly with a facility to wobble the secondary mirror.

3. DAYTIME INFRARED OBSERVATIONS

As argued in section 1, daytime observations in the 10 and 20μ windows (and possibly the 5μ window as well) are perfectly possible. The requirements for nighttime work (section 2) apply also to daytime operations. In addition, a new requirement has to be imposed. At night, pointing errors of the telescope are, as a matter of routine, corrected on the basis of visual inspection of the field. Invisible infrared objects are centered by offsetting from nearby stars. During the day one must rely on the pointing accuracy of the telescope system as a closed loop system, without opening the loop for object-derived position information. With some reluctance I put the requirement of the pointing error at 1 second of arc. This requirement is compatible with the usable diaphragm size of 10 seconds of arc while observing a pointlike object with a 350-cm telescope, even at 20μ.

The requirement on the pointing error applies after correction for refraction (which depends on atmospheric conditions and wavelength), flexure, aberration and encoding errors. It is obvious that this calls for computer controlled drive and a highly reproducible mechanical behaviour of the telescope system. This is one reason why a well-engineered conventional telescope is required for general daytime infrared work.

Is it permissible to open the dome for daytime operation? Of course some boundary conditions must be observed and some specifications for the construction of the building may be helpful to extend the period of daytime operation, without unduly damaging the nighttime seeing. In this connection one may think of keeping the sun from directly shining into the dome, both by an adapted observing program and by screening the slit. It may be necessary to close down for some hours around noon. It would probably help to have a floor with a low thermal inertia or to cool the floor artificially.

Personally I believe that one should not a priori rule out daytime operation because of the potential danger to nighttime seeing.

Large telescopes have been used in the daytime. Possibly we can hear in the discussion what the experience with this type of operation has been.

Discussion follows after next paper

DAYTIME AND OTHER UNANTICIPATED USES OF TELESCOPES

G. H. Herbig

Lick Observatory, University of California

I begin on the assumption that the designers of the large telescopes to be built in the 1970's have already incorporated in their instruments the obvious technical improvements of the past two decades: better telescope structures and controls, improved optical materials and designs, automatic guiding throughout, computer control of telescope, dome, instruments, etc. Beyond these, I think that there are some astronomical requirements that were not envisaged 20 years ago, and that now are having to be provided - sometimes rather awkwardly - at those last-generation telescopes. Clearly these should be considered for incorporation from the beginning in the new designs.

1. DAYTIME OPERATIONS

In the past, large telescopes have been used occasionally during twilight and even during the day for special tasks such as planetary observations, or on the occasion of a very bright comet. Now that infrared spectroscopy and broad-band photometry is becoming widespread, and at wavelengths where the clear daytime sky is quite dark, one can anticipate that the infrared observers will want to use the telescope all through the day. During the year 1970, the Lick 120-inch was in fact scheduled for such operations on about 70 days. The traditional objection to such operations has been that if the dome is open all day, especially with full sunlight streaming directly in, the internal seeing or the telescope performance on the following night would be worsened. No such effects have been detected at Mt. Hamilton, so far as I know. It is possible that at Lick these difficulties are minimized by the rather small day-to-night temperature range, and that problems would appear at other sites. But even if that were so, I think that one must balance the scientific gains against losses: that is, whether the astronomical results lost by a short period of poor internal seeing at the beginning of the night would overshadow the astronomical results gained by a full day's infrared work. On the basis of our experience, I am very doubtful that a convincing scientific case could be made for the exclusion of daytime operations.

If daytime work is to be undertaken seriously, then of course there is no need to invest in an expensive air-conditioning plant for dome cooling. And one must not forget to include in the dome-control computer program an instruction, in case that direct sunlight is allowed to fall on the primary mirror, that the solar image thus formed does not reach on any part of the inner dome surface that might be damaged by the heat.

If one is to work in the daytime, he must be able to see his objects. Under ordinary conditions, one can see 4th or 5th magnitude stars without difficulty against the day sky, but these are not usually the objects that the infrared observers are interested in. It is very desirable therefore to provide for image-converter viewing of the field in near-infrared light. We are already doing this at night, to make possible the detection of visually very faint infrared stars. In fact in this way one can readily "see" objects on the coudé slit such as NML Cygnus and the Leo object IRC +10216 that are utterly invisible visually with the same telescope. If the daytime sky brightness is controlled by pure Rayleigh scattering, then at 1μ the sky is about 3 magnitudes darker than it is visually, with a corresponding advantage in detection of faint stars. Such an image can then be transferred to another station by TV, and then it occurs to one: why is it necessary for the observer to be there at the prime focus, or at the cassegrain focus at all?

2. REMOTE CONTROL

It is traditional to think of the observer, often heavily dressed for protection from the cold, sitting (often uncomfortably) at an eyepiece, doing elementary tasks with knobs or pushbuttons while he peers at a star image. It has been so for centuries, but one asks if, with today's technologies, it is still an acceptable way for a scientist to perform his science. Certainly the human mechanism can operate more efficiently in a warm, well-lighted room, watching the field and the guide star on a TV screen, changing plates or filters (or whatever) by remote control, and going out to the cold telescope only for those occasional tasks (such as changing gratings or optical elements) that are not worthwhile to automatize or to carry out remotely.

For these reasons, I believe that the effort being given to provide for a human passenger in the Cassegrain cage of a new telescope is effort misplaced. I appreciate the conservative wait-and-see philosophy expressed by Dr. Oke. But I feel strongly that if one has the advantage to be 'starting from scratch', provision should be made for complete remote control and TV monitoring of Cassegrain operations from the very first. As Dr. Dennison has told you, this is being done at Lick by the group headed by Dr. E. J. Wampler. They have had several years' experience with TV guiding and with disc storage and stacking of TV images. Completely remote operation is of course more expensive in terms of hardware alone, but not if one allows for the lessened wear-and-tear on the astronomer, who after all is also a very expensive institutional investment. It seems that the only serious question could be whether it is practical to service such a complicated system at a remote site. But this is a general problem as every kind of astronomical instrument becomes more complicated, and I cannot accept it as a valid objection to remote operations.

3. COUDE AUXILIARY TELESCOPES

The principle now seems to be widely accepted that it is undesirable to allow an expensive and powerful coudé laboratory, or coudé spectrograph, to sit idle for the half or more of the month that the telescope itself is being used at one of the other foci. There are many problems for which the full aperture is not required, and for which a beam of the proper f-ratio from a smaller telescope would enable much good work to be done, not to speak of instrument tests and speculative experiments. But there is still a further interesting possibility here, namely that this smaller instrument can be built as a completely off-axis system with no central obstruction or mirror support vanes in the aperture at all. This would not always be of significance for conventional coudé spectroscopy, where the central region of the collimated beam is often obstructed by on-axis plateholders. But it would be a major advantage for infrared observers, who suffer greatly from the thermal emission from secondary cells and support vanes. For some problems, they might well consider this to be a superior instrument to the main telescope.

In looking ahead at this new generation of telescopes, one should quite properly try to profit from past experience. But let us not hold to too conservative a philosophy, and be accused like the generals, of always planning to wage the next war with the weapons that won the last.

I want to acknowledge that most of the developments discussed here arose from the work or the suggestions of others, and must mention particularly the contributions of Drs. G.W. Preston, D.H. Rank and E.J. Wampler.

DISCUSSION

(This discussion relates to the two preceding papers)

CONNES: I want to support the view that much interesting work can be done in daytime. My experience extends only to the near infrared windows, namely 1 - 2.5 microns, and this is a fortunate region in the way that both thermal sky emission and Rayleigh scattering are practically negligible. All our

Venus spectra and some of our stellar spectra have been made in daytime with no trouble at all. On the point of spoiling the seeing for the night observer, I have a very simple, non-technical solution: you only have to grant to the infrared observer both the daytime observing period and the night after, and he won't complain!

<u>BORGMAN</u>: That's an interesting suggestion, Dr. Connes! We have been assigned on such a basis three weeks in succession on one occasion in Chile, and I think it is implicit in your suggestion that it is really tiring to be on a 24 hours observing scheme during three weeks.

<u>HERBIG</u>: I would say the same thing. The infrared people at Lick work 24 hours for 2 days, and then they collapse exhausted. 24 hours later they come back and do it for two more 24-hour periods. That seems to be within the limit of human endurance, but 3 weeks around the clock is asking a lot of any enthusiastic astronomer.

<u>FEHRENBACH</u>: I agree completely with you, that it is very important to have infrared astronomical work made in the daytime. I also agree completely with Connes that if you have a telescope which is working at the limit for astronomical work in the night, then it is impossible to have daytime work before. You will have a deterioration of the image, and if you want to have resolving power of $0\overset{''}{.}1$, $0\overset{''}{.}2$ or $0\overset{''}{.}3$ - and that is what we need for going to the limiting magnitude - then you cannot observe in the daytime. At La Silla the thermal variation during the day is of the order of $5^{o}C$, and in the evening you will have a certain temperature that remains almost constant during the night. If you open the dome, even if you are very careful not to let the sun in the dome, you will have air exchange from the inside to the outside and the temperature of the mirror will increase, probably not symmetrically. So in the evening you will not have the good figure for which we ask. Surely you can work, you will have an image of 1" to 2" - you have very often an image of that size - but you will miss the nights with very good images.

<u>HERBIG</u>: How many nights per year do you expect the seeing, even under nighttime operations, to be $0\overset{''}{.}2$?

<u>FEHRENBACH</u>: I don't know exactly, but it would be very important to use those nights.

<u>HERBIG</u>: I think we could agree, let's not close any doors to these possibilities in the construction of the telescope until these matters can actually be investigated with the telescope at your site.

<u>FEHRENBACH</u>: My impression is that we have to be very cautious in the future. It is not so seldom that you have an image of $0\overset{''}{.}5$ or $0\overset{''}{.}8$, but I think the fact that you now have quartz mirrors instead of glass, will make it much easier to obtain this performance. It seems to me that up to now we never used all the possibilities of the large telescopes in the optical sense.

<u>HERBIG</u> to <u>BORGMAN</u>: Would you like to respond?

<u>BORGMAN</u>: Yes, I wondered just a bit whether those observers who really are going to need the $0\overset{''}{.}3$ very rare resolution of the sky, are really also

scheduled on those nights or whether they are scheduled for those nights when you just have average seeing? Or do you expect that all observers who are scheduled for nighttime observation are going to benefit from the exquisite seeing that very rarely occurs?

FEHRENBACH: You see, that is the problem in Chile of scheduling observations. If you have one, two or three nights with very good observing conditions, then it is difficult for an astronomer in an observatory with many people to get this observing time, but remember the work done by Baade during those good nights on the resolution of the center of the Andromeda Nebula. You have other problems, say the globular clusters in the Magellanic Clouds, for which you need the very best images. Do remember that the limiting magnitude of a telescope depends not only on the diameter of the mirror, but that divided by the image size. If you have 0".5 and three meters you are just as well off as with 1" and six meters. You can obtain sometimes the best documents for the whole work in one or two nights of the year and you should not spoil this.

RICKARD: From the observing experience we have in Chile you can predict that during the winter months of June, July and August you will not have seeing less than 1".5 - 2".0 for periods of 10 or 20 days. The Magellanic Clouds are not visible at this time of year and most of the infrared observers are interested in the Galaxy, which happens to be straight overhead at that time. So I think that during those sections of the year quite easily the infrared observer could be scheduled to use his equipment efficiently.

BORGMAN: The bad season coincides with the cold weather which is another interesting asset that the infrared observer requires. If it also coincides with the bad seeing conditions and with the availability of the Milky Way, then really it is a very nice combination.

BLAAUW: Let us assume that we would work on a 24 hour schedule for infrared observations, thereby preserving the possibilities for the best kind of work in the optical area on the night after that. Could perhaps Dr. Borgman comment on how you want to preserve the possibilities for the infrared people in the telescope design? What would it mean in things to think of in the design stage? You have already mentioned the question of the influence of the spider and that you have to make it as thin as possible.

BORGMAN: Yes, I could mention a few things. What I termed earlier in my introduction as black-body pollution inside the telescope is something that must be avoided at all costs. It is not so much because of the radiation itself as how to reject it in the chopped signal, since it is very difficult to make the detector see the same black-body configuration in the two opposite portions of one complete chop. That may consume a major portion of the dynamic range of the detector system because it gives an offset signal which will in any case be rather noisy. It is a little bit difficult to say how much deterioration you can expect without knowing exactly the figures and the amount of obscuration. To contradict one suggestion immediately: sometimes people think that you can get rid of all problems by polishing all these black-body surfaces or aluminizing them etc. That helps of course a great deal to remove the black-body radiation of these surfaces, but they reflect unwanted radiations of other things moving around in the dome and people lighting cigarettes and so on; this is of course much more serious than the constant radiation which in principle at least gives only a noisy signal.

Secondly I would say that it is very nice to have a wobbling secondary mirror and in that connection it is advantageous to be completely free in the future to put up new secondary assemblies. A flip type arrangement - like I understand that they have in the Kitt Peak design - is associated with a rather large portion of black-body radiation, because the wobbling mirror would be one of the smaller ones, which is not going to obscure the ring that has to support the other mirrors as well. If a wobbling secondary has to be changed, one would like to do so quickly, because if the daytime observer is ever going to share the 24 hours with the night-time observer, then it is very unlikely that the latter wants this wobbling mirror. Instead of a flip top arrangement the best would be to change the complete top units, so that you can optimize them for infrared work and any other type of operation.

In the design of the ESO telescope it is only foreseen to change the mirror on some carriage that will be loaded right in the center of a spider that is always there. I think there would be a slight deterioration as compared to the optimum infrared requirements; it would work well because you have there the possibility to enter a small wobbling secondary mirror, although you must accept the black-body radiation of the assembly that is too large to be obscured by that mirror. I always say small, wobbling mirror because you would like to wobble these things, even the larger ones. You would prefer an f/15 beam, which would still require in the case of the ESO telescope something like a 60 cm secondary mirror and (I hesitate to say that) you would like to wobble that up to frequencies to 400 Hz. Now this looks a little bit prohibitive, but I mean by wobbling a harmonic motion to change from two adjacent circular fields with a minimum diameter of 10", because otherwise it is probably impossible. It is much nicer of course to have a rectangular drive, resulting in a very short period for the transition but that is probably impossible for these large sizes.

I think that these are my first thoughts, if you ask the question as you put it.

BLAAUW: Has it been considered at all to cool those parts of the telescope which are most in sight of the sun? For instance could you cool the spider?

BORGMAN: Yes, I think you could do that, but you would probably end up with a very big spider because it would grow with ice around it. In principle it would be nice, but as far as I know no project has ever been engineered from such a conception.

BLAAUW: One must be the first.

BORGMAN: Yes, I would not like to specify it.
HECKMANN: Would Dr. Borgman be kind enough to describe to us a telescope which is completely specified only for infrared observations and does not interfere in any way with optical observations?
BORGMAN: If you had a completely free hand and could find a sponsor for making such an instrument, then I think that the 1".5 resolution with 3.5 m diameter at 20 microns would probably not be acceptable to Prof. Fehrenbach, because he would also like to benefit from the available 0".5-nights! Well, that would then call for a telescope with a diameter of 10 m, that should have a figure compatible with this resolution. And this very huge instrument should then have pointing capabilities in the 1" class; you would of course not like to scan the sky to find your objects, because then you could only study the very bright ones. And it should also have an aluminized surface - it is not very easy to polish this thing of course right into metal - so it would require also a huge aluminizing chamber. It is not a very realistic proposition I think!
BLAAUW: Would it cost less than the 3 1/2 m normal telescope?
BORGMAN: I think it would be much, much more expensive.
RICHARDSON: Concerning the problem of black-body radiation entering the infrared detector, would it be feasible to have near the focus a mask which is cooled in dry air, that does not cause seeing disturbances being so close to the focus?

And a comment about secondary mirrors: presumably there is no advantage to having the secondary mirror smaller than the hole in the primary, so a large telescope would be restricted that way.
BORGMAN: Right. Starting with the last comment I think it is correct for infrared work that you must also consider the black-body radiation that comes from the hole in the primary mirror. When you image the aperture on the detector there is no point in making the secondary mirror smaller than the hole. That was your point? OK.

The first question: most of these detectors at 10 and 20 microns are now helium cooled and they require to be accommodated in a helium-Dewar, where the detector is hanging underneath a bracket or something. The usual arrangement is that we have somewhere in front of it a field lens and finally there is a cooled diaphragm which is necessary, because otherwise it would radiate and flood the detector with black-body radiation.

Now take a close look at the image of the aperture right on the detector. One sees the primary mirror, a spider and probably the portion of the rim around the secondary mirror and there may be other things. What you would like to have just in front of the detector is a mask that simply transmits the light from the mirror only. Nobody, as far as I know, has ever done it, but in principle that would be an arrangement to avoid the major portion of all these radiating surfaces. One should not be too pessimistic of course. The total cross section of these things may go up to 4% of the area before it radiates as much as the surfaces of the mirrors themselves anyhow do. So as long as you are staying below 4% projected black-body area, then you are not going to have a significant contribution to the total black-body radiation that reaches the detector. On the other hand, as I pointed out, it is much more difficult to cancel this radiation by a chopper because it is very likely that the detector sees different configurations when looking at the two opposite sides of one chopping cycle. But in principle I would agree with you that it would be very nice to have such a mask just in front of the detector.

RICHARDSON: I had really in mind the possibility of putting it somewhat further back, maybe a meter or so before the focus, where the beam is still quite large so that it might be easier to make the mask.

BORGMAN: I wonder if that is a very feasible thing to do. I would have to think about it.

RICKARD: Would you care to comment on the fact that many of your problems would disappear if you optimized your infrared experiments for the prime focus and not for the Cassegrain?

BORGMAN: Yes, I think that in the prime focus you have to deal always with an obscuration that you cannot easily shield off. If you want to avoid the black-body problems, then you would like to operate only in the prime cage for observations in the 2.2 and 3.6 micron windows. At 5, 10 or 20 microns the cage is certainly going to give a very significant contribution to the radiation from the sky that is already there, both at night and day.

RICKARD: I don't mean the standard optical cage, I mean your own special infrared prime-focus cage.

BORGMAN: I still would like to sit in it then.

RICKARD: Why? You can't see it anyway!

BORGMAN: Well, it needs some service now and then, although I must admit that that would not be a very strong requirement. Refilling with liquid helium might be done once every 5 hours or so, but the equipment is yet rather experimental and it still requires, let's say, more or less an artist's approach. You would not like to do all that on remote control yet. If it is completely standardized and if somebody takes over all the engineering that is necessary to do it remotely controlled, yes, then I would be happy to sit in this well-lighted and warm room also, but for the time being I would say that this is a little bit out of the question. So I would have to specify then a prime cage that is large and contributes significantly to the black-body problems.

RICKARD: I believe that the Neugebauer-survey was done at the prime focus. That is why I asked the question.

BORGMAN: Now you are speaking of an instrument of 1.5 m diameter with Neugebauer standing right beside it, within reach of the detectors.

VAUGHAN: Is the background that you described fluctuating and to what extent is this the same from day to night?

Another question has a bearing on Dr. Blaauws request for guidance in constructing telescopes. Would you expect infrared observers in the future to have their own special truck load of instrumentation and would it therefore be desirable to provide what we call a data room with convenient cable connections to the telescope, so that if a day and night observer are working together they do not get in each other's way?

BORGMAN: Please notice that I specified the normalized data for 15°C. The radiance is very sensitive to temperature, and you may easily have differences between days and nights. A night temperature that is 5 - 6°C lower will certainly help a great deal in suppressing the radiance of the sky. However, that is not so extremely important, because this is a random signal that is chopped away. The noise depends also on the fluctuations of temperature that you have within a wide-aperture beam; I just could not say how big the effect is, but from the discussion with Low I understand that the difference between day- and nighttime observations in terms of noise is very slight.

Concerning the second question, I think there will be a time when a considerable fraction of the observing time is given to people with standardized equipment. But always there are those who try to have experimental equipment on the telescope, and for them it would be a real big help if indeed there were, let's say, well standardized data-transmission lines from the Cassegrain cage. Coming back to what was said earlier this week, I think that it would be very recommendable to put up a number of multiplex lines so that you can really get out an enormous amount of data without being limited by the number of cables. About a separate room near the telescope to locate your recording equipment, I agree when this equipment is running without anybody interfering with its operation. But I think there is quite an amount of equipment which you want to run with short cables to the Cassegrain equipment, and where you really want to handle the knobs on the front panels. Judging from my experience with infrared equipment I would say that as the technique now stands, this is a major portion of the equipment.

LARGE INFRARED LIGHT COLLECTORS
(Summary)

P. Connes

C.N.R.S., Observatoire de Meudon

Light collectors have already been built for the detection of infrared objects and for infrared photometry (1). However, high resolution spectral analysis by the technique of Fourier spectroscopy (2) has different requirement; very large light collectors will be needed to extend the already collected results to fainter stars. The accuracy requirements, the already proposed techniques, and the work of different groups are described in (3,4). At the Meudon Observatory a 4.2 m light collector, designed mainly for the near infrared and making use of 36 servo controlled elements, is being built; the extension to larger sizes is discussed.

1) Johnson, H.C. and Richards, W.L., Astrophys. Journ. 160, L 111, 1970

2) Connes, P., Ann. Rev. Astr. Astrophys., 8, 209, 1970

3) Fellgett, P.B., Optical Instruments and Techniques 1970, 475 (Oriel Press)

4) Mertz, L., Optical Instruments and Techniques, 1970, 507 (Oriel Press)

DISCUSSION

BELLY: What was the cost of the Meudon telescope?

CONNES: Our overall budget is in the order of 100.000 $ for telescope, building, workshop, machine tools - everything.

SWINGS: Can the new instrument be used for comet observations?

CONNES: Since the new instrument I am proposing would have a non-negligible field, it could in principle be used on comets or large objects, provided one did get the facility of offset guiding. But with the Meudon telescope it would be hopeless. You would need an exceptional comet, just to see it.

HECKMANN: Why is this type of telescope limited to the near infrared?

CONNES: I think it is at optimum for the near infrared. Infrared is an extremely wide field, and from the start one has to bear in mind that it is perfectly hopeless to design an optimum system to work from 1 to 1000 microns. Radio astronomers do nothing of the kind. They build centimeter-waves, decimeter-waves or meter-waves radio-telescopes. On top of that you have an important crossover point close to about 3-4 microns. Below that wavelength thermal emission from the sky, thermal emission from the telescope, and especially thermal fluctuations from the sky are negligible. Above that they become extremely important phenomena. I think that the construction of a telescope using discrete elements, which are not faced, is feasible only for the near infrared, simply because the diffraction pattern at 10 or 20 microns or above gets too big. Then the elements have to be made very large, but if you want them to be correct for near infrared, then they have to be made very good, which means that they become too expensive. So this design is primarily aimed at the near infrared. Other people have made proposals for longer wavelengths.

BORGMAN: The construction of such a telescope as you have undertaken might hold big promise in the 0.3 mm field in order to get the theoretical resolution that you can achieve there. Of course you can only realize this if you face the individual elements. I wonder whether it is feasible once you go to the 0.3 mm atmospheric window?

CONNES: I think at 0.3 mm there is really not much point in still using discrete, faced elements. You can certainly get your required accuracy from a machined metal surface and it will be much simpler. In the near infrared we do have to use optically polished glass or possibly metal surfaces, and they can't be made very big, or we will have hopeless transportation problems, for instance. And they can't be very well made on the spot, so one has to resort to the mosaic principle.

ODGERS: How far towards the visible do you think it is feasible to push your Fourier-transform spectroscopy?

CONNES: Presently we are beginning to record laboratory visible spectra. The only point is that no appreciable gain in signal to noise ratio can be expected compared to the classical slit spectrograph. What you can gain is higher resolution in the case you have very sharp lines and relatively bright sources. You will also gain increased accuracy in the wave-number measurements and good linearity which you don't get from the spectrograph, but no basic gain in signal to noise ratio. And then of course Fourier spectroscopy would be distinctly inferior to image tubes, electron cameras and such instruments, so the advantages are rather different. One could for instance produce improved spectral atlases of the Sun and relatively bright stars by Fourier spectroscopy, but without the spectacular gain in signal to noise ratio one has obtained in the infrared.

RICKARD: Using a Fourier transformer device such as the type that you have built, could you comment on the computer needs? In some of the large telescope designs you notice that computers have been included as part of the telescope. One of the functions of the computers would be data reduction, but I believe that the enormous amount of data that you are handling necessitates computers of quite expensive sizes.

CONNES: The present situation, as far as computing goes, is that the very large transforms - in the present case up to 10^6 samples, which also means 10^6 samples in the spectrum and that is a lot of information - can be computed only on large computers. We are for instance using an IBM 360/75, and in this case the computing time is only of the order of 8 mins. We have also built our own real-time computer, which can take any amount of input samples, that is to say which can work at any resolution, but it cannot compute the full spectrum, only a window in it. Therefore, while taking many samples and having an extremely complex and extended spectrum, we can look at a small slice of it and see the resolution increase and check we are not wasting telescope time. Some people have done the same thing by programming small computers, which can also compute a spectrum in real time, but then they are much slower than our special purpose instrument. Also they can do this only from low-resolution interferograms, meaning a small number of points; this would be adequate in the case of faint objects, but not bright objects.

SWINGS: What are the sizes of the Michelson plates that you use in your instrument?

CONNES: In the relatively small interferometer for astronomical purposes we have used 5 cm maximum travel which means 10 cm maximum path-difference and 0.1 cm^{-1} resolution; the size of the beam was very small, about 2 cm diameter. We have now built new instruments which can accept an 8 cm beam and have 1 m travel, which means 0.005 cm^{-1} resolution. One of these will be used with the Meudon telescope.

SWINGS: Do these plates require a very high accuracy?

CONNES: No, they are not plates at all, because we never use the classical Michelson design, which is too sensitive for adjustment. The optical surface accuracy you require is of the order of $\lambda/4$, which is the same you need in any two-beam interferometer and which has nothing to do with the accuracy you require of Fabry-Perot plates. And in any case you can demonstrate that in Fourier spectroscopy your final instrumental line-shape is independent of all optical surface imperfections.

COMMENTS ON A COUDÉ LABORATORY TELESCOPE

L.D. Barr
AURA

During the preceding sessions of this conference there has been much discussion on automation and methods for allowing the astronomer to remain away from the telescope during observing runs. With this in mind, it may be of interest to briefly mention a project now in progress at AURA which is called the Coudé Laboratory Telescope.

The basic intent is to provide a good laboratory set-up for more than one experiment and somehow bring the light beam to stationary experiments with the least number of reflections. This serves the useful purpose of maximizing experimental efficiency but does require a different approach to telescope mount design.

Two possibilities now being considered are shown in Figure 1 and Figure 2 that are called the Alt-Alt and the Az-Alt styles because of the motions involved. Based on preliminary study, it appears that the Alt-Alt style will be less expensive, especially if more than one telescope is considered.

One aspect of our planning is to consider feasibility of feeding more than one light beam into the laboratory even though the initial plan involves just one telescope.

The telescope will be optimized for planetary work, which means reduction of scattered light, long primary mirror f-ratio, and a small field. Aperture will be around 100 inches (2.5 meters) and a sun shield will be needed to shade the dome opening for daytime usage. The drive systems will be computer controlled.

It is not intended here, however, to discuss telescope details but rather to point out some of the advantages of having the astronomer off the telescope. A few of these are:

1. The ability to optimize experimental equipment without major regard for size, weight, or mobility.
2. The ability to run concurrent experiments. A minimum of six horizontal and one or more vertical experiment platforms are planned.
3. Simplification of telescope design and reduction in dome size. The dome needs only to provide wind and thermal protection.
4. Reduction in cost for both mount and dome. Laboratory costs, of course, are extra but the laboratory building is conventional construction and, hence, less costly than most dome

Coudé laboratory and telescope concept

Fig. 1

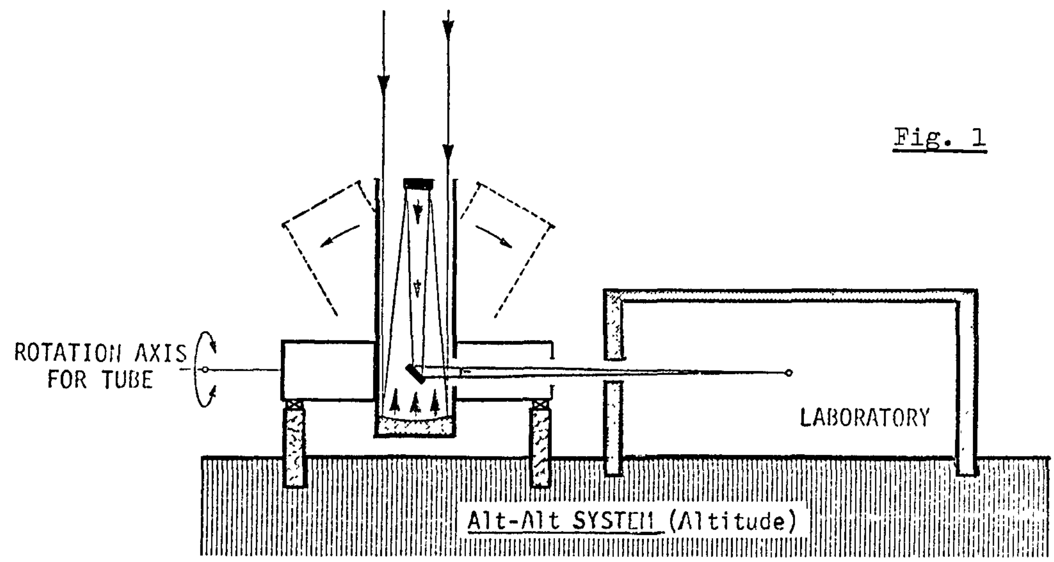
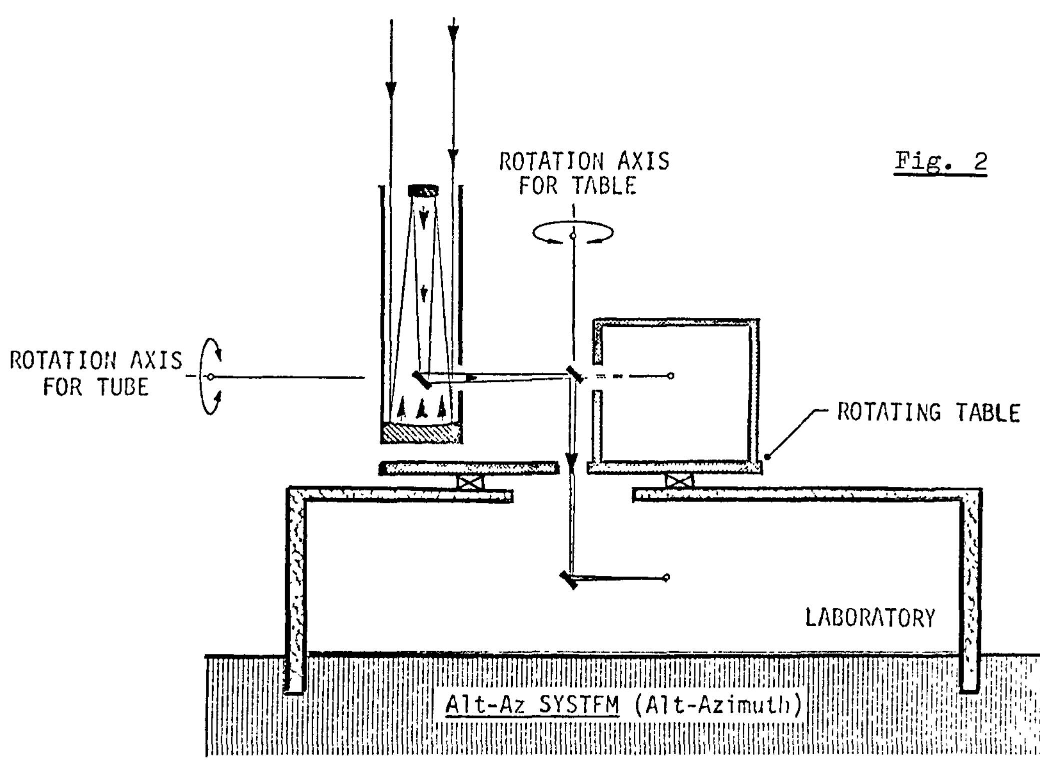


Fig. 2



buildings.

5. Simplified maintenance and handling procedures.

Further work at AURA will serve to amplify these comments in the future, but for the present we invite all astronomers present to seriously consider the merits of working in the comfort of a stationary, well-equipped laboratory compared to riding around in a cage or on a platform at the rear of the telescope. We think the technology now exists to accomplish such a goal without sacrifice in performance, but a new design philosophy is obviously required.

DISCUSSION

WLERICK: What do you mean by low scattered light?

BARR: Low scattered light is intended to mean a reduction of stray light from any portion of the telescope. In practical terms it means that we are considering the use of a very well made spherical primary mirror, antireflection coating on all the other mirrors, and a closed tube construction with the ability to control the flow of air in the tube, so that we keep out dust particles. It also includes, although it doesn't show in the sketches, the ability to shield the opening of the dome by means of an external sunshield, which is tracked through the sky to maintain a constant shadow on the dome opening.

BELLY: What will be the size of the primary mirror?

BARR: Approximately 2.5 m. One additional feature is that the secondary mirror is expected to be very small, as small as we can make it, maybe even 10 inches. It will probably be a wobbly secondary for the purpose of image stabilisation rather than for any other reason. The field size will be very small, of the order of 1'.

A PHOTON COUNTING IMAGE RECORDER

Edwin W. Dennison

Astro-electronics Laboratory
Hale Observatories

This is a brief report on the plans for a project which grew out of our previous work on television systems. It appeared to us that if the television systems for viewing faint star fields were nearly photon limited, then it should be possible with some slight additional gain, to have a system which would be actually photon limited. Such a system could be connected to an all digital memory to make a digital image recorder. The concepts and ideas which I am about to discuss are certainly not unique with our group and they are being worked on by several other groups throughout the world. We have all been working on the problem of building a two dimensional photon detector for some time, but it is only recently that television and image intensifier developments, as well as solid state digital technology, have made this project practical.

The first requirement of such a system is that the noise should be entirely determined by statistical photon fluctuations in the image. Other requirements are that it should be linear, have a wide dynamic range, and be capable of storing a large number of information bits per picture element. We also wanted to have a system which could handle a wide variety of exposure times and particularly a series of short exposures in rapid succession. We also felt it would be advantageous to be able to change the scanned area from a square for direct images to a narrow rectangular array for spectroscopic images. Finally, we wanted the recorded information to be available to a computer for further analysis.

With the exception of the last three requirements, there is nothing which this system can do which has not been done by the Lallemand Camera, which has been available for many years. We will feel very satisfied if we can approach the same degree of success, but at the moment our project is speculative and there is still a real chance that we will be unable to achieve our goal. Nevertheless, we have been encouraged by the success of the new television camera systems.

If we have a television camera system with a SEC camera tube and two intensifiers our overall gain will be approximately 160,000. This should be more than enough gain to see individual photoelectrons. We can get approximately the same overall gain if we use one silicon target vidicon, with a target gain of 4,000, and a single stage intensifier in front with a gain of approximately 40.

If the target is considered to be divided into a series of picture elements, roughly 500 picture elements long by 500 picture elements wide, and we scan over the entire frame once every 33 ms, the time per picture element will be approximately 130 ns. Modern electronics can easily handle information at this rate. Every time we scan over an image we expect to find that some of the picture elements will have been struck by photoelectrons and, therefore, will generate an electron pulse. To insure that we have sufficient accuracy and do not loose too much information because one picture element has received a photoelectron twice during each scanning frame, we plan to use this system at flux rates which will give an average of 0.1 of a photoelectron event per picture element per frame. Most of the time we expect to find each cell empty. As we scan over the target we use the electronic scanning circuits to generate the coordinate location of the pulse which is detected. This coordinate information is used to address the mass memory and determine which memory cells should be incremented as a result of receiving the photoelectron pulse. It is possible to use either disc memories or the new all solid state memories. The latter appear to be more attractive at this time.

To better understand this concept, assume that as the camera reading beam sweeps over the target at each point in time, the memory word which corresponds to the location of the reading beam has been brought out and made available in a small buffer register. If an electron pulse has been detected at that particular point, the buffer register content is increased by one count. The memory word is again restored to the memory and the register continues to circulate onto the next element.

The time constants required for this operation are somewhat higher than can be easily handled by disc memories; and because the cost of solid state memories has now been reduced to approximately 0.8 of a cent per bit, it should be possible to buy the memory components for about $ 32,000. Clearly, the entire project will cost a great deal more, but the memory cost is reasonable.

With 16 bit binary words we can store up to 65,000 pulses per memory word. This provides us with the wide dynamic range. Initially we will attempt to get a photometric accuracy of one percent which corresponds to 10,000 photoelectron events per picture element.

Another factor which made us feel this entire project was possible was that Tom Janssens, of the Aero-Space Corporation in Los Angeles, has constructed a similar system using a disc recorder. For his system he uses an 8 bit digitizer to convert the analog signal into digital form. During each frame cycle he can add an 8 bit number to each of his 16 bit memory words. Because of the limitations on disc memory recording rates, he has had to slow his frame rate down to one frame every 15th of a second. His system does work extremely well and gives us confidence that this project is feasible.

We estimate that with the 200-inch telescope, if we use a scale size that will make one picture element correspond to 0.5 seconds of arc, the average photon rate for a reasonable band-pass filter will correspond to approximately 0.16 events per frame per picture element. With this system we should be able to detect stars of the 27th magnitude. This limit is similar to that which Gerard Wlérick has discussed earlier in this meeting. We will have to expose for approximately 60,000 frames or about 2,000 seconds.

In addition to looking for very faint stars it will also be possible to look at the faint outer extensions of galaxies. Because we are using a computer to record the data on magnetic tape, it will be possible to move rapidly from one field to another and thereby collect an enormous amount of information per night. We hope to use the computer to perform preliminary analysis on the data. We will construct the system so that it will generate a video display as the data is being gathered. It may even be possible to use the computer to generate a contour video display for the observer.

Information from bright stars will be lost in the center of the stellar image due to system overload. Bright stars will be displayed as circles which are totally filled in. It should be possible to measure these stellar magnitudes as one does with an Iris photometer on photographic plates.

The system also will be designed to scan over a spectroscopic image and record the spectrum in a similar manner. It should be possible to gather both star and sky background information simultaneously and process these data for immediate display to the observer.

In summary, we feel that it is possible now to construct a digital image recorder using currently available electronic techniques. This project will be underway within the next year and we hope that, if successful, it will contribute substantially to increasing the capability of all large telescopes.

DISCUSSION

WLERICK: Will you have an analog display?
DENNISON: Since you know the coordinates of the spot that you are looking at, you can take the value of the corresponding word, run it through a D/A converter and generate a video signal for a video display. You can also play other tricks by taking section of lines, etc.
WLERICK: How far will you reach in magnitude on this video display?

DENNISON: I really can't answer, because clearly the very faint stars will simply show up as small brightnesses against the background, and the brighter stars will look as discs with ever increasing sizes for the brighter stars.

RICHARDSON: Walker at the University of British Columbia has a working system which is somewhat similar in principle, but which is designed for scanning spectra. The resolution is about 100 microns. Would your system be suitable for work with a coudé spectrograph?

DENNISON: The system can be used for spectra, although you are then not taking advantage of its two-dimensional characteristics. I don't think we can improve the resolution much for this kind of video system, but on the other hand there are many other concepts. The ones that Joe Wampler and many others have used with image disectors are now going for 1000 resolution elements. There are other devices which one could use on a simple one-dimensional spectrum that probably are more simple than this approach.

BORGMAN: Do you intend to drive the scanning electron beam digitally?

DENNISON: Yes, it seems to be the simplest way. One will have a generator which generates the address for the memory and then, also, by means of a D/A converter, generates the scanning voltages for the camera. That would seem to be the most logical way.

BORGMAN: What happens with star images that fall halfway on the edge of the cells?

DENNISON: They are not star images now, but photon pulses. When they fall on several adjacent cells is one of the serious problems. It is possible that there will be effects that will essentially pull the charge from the other parts of the target, considering the fact that the scanning beam is always very large. If this does not prove to be the case, then we simply have to digitally make a series of boxes and compare on successive scan lines. If there are photons in contiguous boxes then we count them as one pulse instead of several. This is a principle that I believe Dr. Boxenberg is working on at the University of London. If we have to, we will go to this kind of complexity, but we are planning to try with a simple concept initially.

RICKARD: Most of the ordinary commercial computers that you can buy off the shelf have microsecond cycletimes. Now, if you are on each spot for only a tenth of a microsecond, I don't see how you can have time to address, add, and then put it back in the memory?

DENNISON: Well, the virtue of these solid-state shift-registered type memories is that they can be driven at these speeds. The disc memory goes at about half that speed. The bit rate is just under 4 MHz from a disc or drum memory and with the solid state memories it looks like it can go about twice as fast. It is a relatively new development that these high-speed solid-state memories have become cheap enough to be practical for this sort of system.

CHARVIN: Could you say a few words about the electronic noise in such a system?

DENNISON: We are just on the edge of being able to see photon pulses, and we think that the noise will now be entirely limited by photon statistics and that the amplifier noise will be well below that. Obviously one must have a discriminator which cuts off the lower noise and accepts only the higher pulses. But we think it will be essentially noiseless, as far as the information is concerned.

61

ACHEVÉ D'IMPRIMER
LE 30 JUIN 1971
SUR LES PRESSES DU COURRIER DE GENÈVE