The Prediction of Seeing and Other Relevant Climatological Conditions

Marc Sarazin

European Southern Observatory, Karl-Schwarzschild-Str. 2, D-85748 Garching.

Fionn Murtagh

Space Telescope – European Coordinating Facility, Karl-Schwarzschild-Str. 2, D-85748 Garching. Affiliated to Astrophysics Div., Space Sci. Dept., European Space Agency.

Abstract. The aim of flexible scheduling is to improve the quality of observations and to guarantee efficient use of telescope time. Flexible scheduling implies the necessity of accurate forecasts and nowcasts (the latter term, widely used in aviation, implies near real-time analysis).

The Astronomical Site Monitor (ASM) will constitute an interface between the VLT observer and the local environment. Seeing and meteorological data are continually collected at ESO's observational sites, and external meteorological data is being assessed. The climatological quantities of greatest importance for flexible scheduling are seeing (at approximately one hour timescales) and water vapor and cloudiness (at approximately 24 hour timescales).

A comprehensive range of ongoing studies are concerned with modeling and prediction. We will describe work carried out, and activities which are being pursued. These include: nowcasting of seeing using statistical and neural network methods; cloud cover and water vapor prediction using observational satellite data; and the development of a meteorological local area model (LAM). The neural network approach even allows policy decisions relating to seeing quality to be incorporated.

A number of papers, and further information, can be found at URL http://http.hq.eso.org/seeing-meteo/meteo.html

1. Introduction: Space-Borne versus Earth-Based Observation Scheduling

Ground-based scheduling issues are reviewed in Chavan et al. (1995). Here we will briefly list some of the issues which make space-based observing different, using the Hubble Space Telescope (HST) case.

HST scheduling is complex. Its low-earth orbit leads to rapidly changing viewing, background and straylight. Its slow slewing ability, with earth occultation, limit its versatility. Its solar panels must be kept in a more-or-less fixed orientation towards the sun. HST's orbit slowly changes due to atmospheric drag. On-board data recording, for subsequent down-loading, imposes limitations on data gathering abilities. The telecommunications satellites which play an intermediary role in getting the data to the ground may not always be available. Proposers may specify 'special requirements', e.g. conditional observations, time separation, non-interruptibility, and early acquisitions. Parallel observations are desirable, for efficiency reasons, but instrument combinations are restricted. Targets of opportunity may be of importance, even if in principle the HST schedule is pre-planned.

Faced with such a range of interacting operational, spacecraft and environmental constrains, a stochastic optimization approach which incorporates fuzzy reasoning was developed by Johnston and Adorf (Adorf, 1990; Johnston, 1989).

Such aspects of space-borne observing have necessitated automated scheduling from the earliest stages. Ground-based observing is learning from this experience. Among the motivations for ground-based observing following the same evolutionary path are: multi-instrument systems, and interferometric modes of observation, which require optimization to make efficient use of observing time; and an increasing physical dissociation of observer and instrument, which was always the case with space instrumentation and is now becoming more widespread with increasing complexity of ground-based observing facilities.

To these reasons can now be added one related to the work we describe in this article: satisfactory prediction of environmental conditions. We have already seen how occultation and other concerns play a major role in HST's observing. Knowing the upcoming meteorological and other climatic conditions provides important information for ground-based installations. We will describe the ongoing state of our research into the forecasting of all aspects relating to seeing.

2. The VLT Astronomical Site Monitor

2.1. Description

The VLT Astronomical Site Monitor (ASM) is an automatic unit operated 24 hours a day to gather information about the environment of the VLT observatory. It includes a large number of stand-alone sensors and two expert systems which deal with modelling and prediction tasks.

The sensing unit includes all local meteorological and atmospheric sensors with their interfaces to the local control unit. A communication link with the outside world also allows data to be collected from non-local sensors, i.e. satellite data, radiosondes, professional synopsis bulletins, etc.

The modelling unit filters the input flow of information and produces an accurate picture of the current environmental status. In particular, it computes secondary parameters such as water vapour, isoplanatic angle, lifetime, etc., according to specific user requirements.

The predicting unit takes care of the short-term predictions of the variables for which local predicting models are available. It also handles the incoming external global forecasts.

The ASM is interfaced locally to expert systems composing the *Observatory Operation Control and Command* with several levels of capabilities among which are: (a) the display and archival of information; (b) the direct command of some telescope functions (e.g. thermal control of the enclosures, light ducts and primary mirror, with a prediction of the air temperature of the next night/hour); (c) the definition of the optimal set-up, to help tuning of the observations with the particular constraints of the environment at the telescope (e.g. wind load, enclosure management, adaptive optics reference star and bandwidth selection) and at the instrument; and (d) the definition of the optimal observing schedule (e.g. to be able to benefit from the optimal atmospheric conditions when they occur).

2.2. The VLT ASM Sensing Unit

The ASM sensing unit is composed of independent subsystems including complex instruments developed during the site evaluation campaign which led to the selection of Cerro Paranal for the VLT observatory. The site survey database which is currently used for the prediction mode is being continuously extended during the VLT construction phase. New monitoring instruments are currently under development. The ASM will reach a final state when the VLT starts operating. It will then include the following elements:
• **Seeing and Coherence Monitor**: measuring seeing with the differential image motion method. In the coherence mode, it monitors optical wavefront temporal characteristics defined as average velocity, average direction and dispersion velocity. In this mode, the index of scintillation is also available.
• **Sky Monitor**: determines the cloud map of the night sky (photometric or otherwise), measures infrared emissivity at zenith at several representative wavelengths and monitors the atmospheric extinction index. Monitoring OH is also being considered.
• **Ground Meteorological Station**: measuring classical meteorological parameters (wind speed and direction, ground and air temperature, relative humidity, pressure) and monitoring the airborne particle density (cleanliness class) of the site. Monitoring microseismicity is also considered.
• **External Data Sources**: consisting of all available information from meteorological institutes in terms of meteorological forecasts and satellite charts.

2.3. The VLT ASM Prediction Unit

The prediction unit is a software item detailed in Fig. 1 where the distinction is made between long-term forecasts obtained at least one day in advance and short-term forecasts from half a day to one hour in advance. It is assumed that long-term or global forecasts are provided by specialized meteorological institutes. Because the observatory lies in a part of the globe poorly covered by ground stations, the spatial grid used for such forecasts will be of the order of tens of kilometers and will allow sharp temperature gradients, wind storms and large scale cloud banks to be foreseen.

Short term or local forecasts might ideally rely on physical models trained on the site orography for the micrometeorological variables (current activity at ESO is described in Section 6.). Astronomical seeing has escaped all models up to now as it depends on the vertical distribution of several parameters which do not belong to the same spatial scales. It was shown by Sarazin (1992) that advance information could be obtained, using 3D wind and turbulence vertical profiles

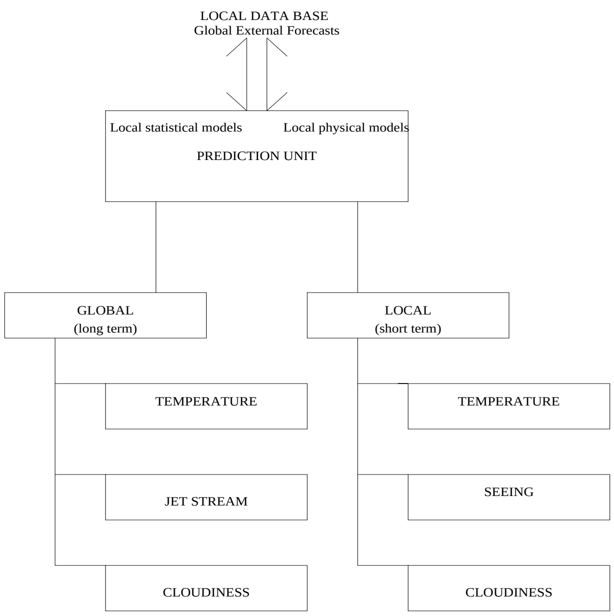

Figure 1. ASM Prediction functional Diagram.

delivered by an acoustic sounder placed at a distance of a few kilometers upwind. However this method is more adapted to sites of passable quality, dominated by low-level turbulence carried by the nocturnal atmospheric boundary layer.

For the higher atmosphere the first steps have been taken towards an identification of the relevant parameters (VanZandt et al., 1976; Coulman et al., 1986). Such models were applied to commercially available radiosonding in the ASM database. In agreement with Bély (1987), even in absence of dome seeing, it was concluded that the high altitude data sampling was grossly insufficient to capture thin horizontal atmospheric temperature gradient sheets. A joint project involving several institutes is underway to apply a meteorological numerical simulation model to a deterministic prediction of the seeing. Such a MESO-NH model, taking into account non-hydrostatic situations, needs to be initiated with an upstream vertical profile of the thermodynamic condition of the atmosphere. Promising results were obtained by Bougeault et al. (1995).

Faced with the difficulties and incompleteness of the physical model approach, purely mathematical methods were investigated. The following sections describe two novel methods for producing local forecasts solely based on the statistical analysis of a large local database.

3. Forecasting Telescope Thermal Environment

Accurate temperature forecasts were obtained in Murtagh et al. (1992). 24-hour ahead predictions were carried out, based on temperatures at 0 (current time), 24 and 48 hours previously, and pressures at 0 and 24 hours previously. A nearest neighbor method was used.

The data used in this assessment relate to over 18000 observations carried out in austral summer 1989-1990. Many missing values, and the relative utility of the different variables, required extensive initial exploration in order to arrive at data-sets on which to carry out assessments. The number of tuples used in the results below, with no values missing, was 5260.

The following sets of tuples were derived from this data, for temperature prediction:

$$t_n, t_{n-1}, t_{n-2}, t_{n-3}, p_{n-1}, p_{n-2}$$

where

- t_n is the temperature value to be predicted;
- $t_{n-1}, t_{n-2}, t_{n-3}$ are temperature values at $n-24$, $n-48$, and $n-72$ hours;
- p_{n-1}, p_{n-2} are pressure values at $n-24$ and $n-48$ hours.

The sequence of temperatures is used in order to capture contemporary trend. Pressure is used for its information on quickly changing weather conditions, such as incoming weather fronts.

For production use, a characteristic of the data to be borne in mind is that it is constantly growing. The forecasting approach implemented must be able to cope with such a dynamic data set.

Temperature prediction was carried out using a 1-nearest neighbor method. I.e. the best matching, chronologically prior, tuple was sought. The matching was carried out on the five independent variables in the tuple, i.e. t_{n-1}, t_{n-2}, t_{n-3}, p_{n-1}, p_{n-2}, each variable having been range-normalized to the interval $[0, 1]$, and using Euclidean distance. A new five-valued tuple was matched against all chronologically prior prototypes. The value of t_n corresponding to the best-matching prototype provided the forecast.

Results using a multilayer perceptron approach, and results based on autoregressive modeling with exogenous inputs, were both compared with the preferred forecasting method. "Carbon-copy" prediction of temperature (i.e. using the previous value) within half a degree centigrade of the actual temperature value was obtained in 20.5% of cases. The forecasting method employed by us found predictability within half a degree to be 62.3%. If the accuracy of prediction was relaxed to 2 degrees, then a correct temperature forecast was obtained in 85.1% of cases.

4. Statistical Forecasting of Seeing: Methods and Results

4.1. Seasonally-Referenced Nowcasting

Extensive seeing and accompanying meteorological data have been collected at ESO observatory sites over many years. Careful consideration was given to the appropriate analysis tools for exploring this data, and for achieving the goal of a seeing prediction engine. A range of novel methods have been developed in order to do this. These will be summarized here (see Murtagh and Sarazin, 1993; Murtagh et al., 1995).

Given a high-frequency signal, i.e. the seeing, and seeking to chart its association with a number of low-frequency signals (windspeed, ambient temperature, pressure, etc.) we found that a nowcasting was appropriate. Nowcasting, or near real-time forecasting, is widely used in fields such as aviation and meteorology.

In a decision-making context, a fuzzy algebraic framework may be of particular help. Instead of empirical probabilities, we formulate the problem in terms of seasonally-referenced "low" and "high" seeing, and we obtain possibilities (rather than probabilities) of acceptable and desirable outcomes under various circumstances. Following comprehensive exploratory data analysis, in which we found various dependencies between seeing and other meteorological variables, we employed two complementary techniques. Other than trivial baseline prediction results, each of these methods served to validate the other. The principle nowcasting methods used were a k-nearest neighbor method, and a recurrent dynamic connectionist network. Both are nonlinear mapping methods. Theoretical and implementation-oriented background on these methods may be found in many articles available at the URL mentioned in the Abstract.

Denoting good (low-valued) seeing by `seeL`, and similarly for bad (high-valued) and moderate (respectively, `seeH` and `seeM`), then possibility, a scalar bounded by 0 and 1, is a notion like probability but subject to different composition laws. The possibility of good seeing will be denoted by `poss(seeL)`. The possibility of good seeing, given that bad seeing was predicted is `poss(seeL|seeH)`. A measure of relevance is provided by `poss(seeL)`; and a measure of prediction quality, subject to a relevant ambiance, is given by `poss(seeL|seeL)`.

The next section (Section 4.2) discusses nowcasting of one-hour averaged seeing, during the observing night, between October 1988 and January 1992, at ESO's observing sites at La Silla and Paranal. Section 4.3 discusses nowcasting of nightly median seeing values in the same time-period and at the same observing sites.

The coding used had an important difference in the two cases. For the hourly study, some variables (windspeed, windspeed standard deviation, wind direction, and seeing) were globally recoded relative to quantile values at either La Silla or at Paranal. This allowed for the different environmental conditions at the two sites, but did not seek to take time into account (i.e. we assumed the meaningfulness of such non-time-varying quantile values). Other variables – humidity and temperature – were additionally seasonally-referenced, at the two observing sites. Again, the time-line was not used for this coding.

In the case of the nightly study, we sought to move closer to an operational framework. At a given time-point, a window covering the notional season up to that time-point was used to provide the reference quantile values. About 90 nights were aimed at, to provide such a notional season. But we found that roughly 40 records contained missing values in any sequence of 90 nights. For this reason, we took 49 nights instead as a notional season, with the 50th night being the one for which an estimate of seeing was required.

4.2. One-Hour Seeing Nowcasts

Exploratory data analysis was followed by removal of missing values (a record at a given time-point was removed if any meteorological value was missing) and coding into "low", "moderate" and "high" categories. Approximately 3500 records were available for Paranal, and approximately 2700 records for La Silla. We considered all possible unique environmental "constellations" or patterns, and we based the nowcast on the database of historical records. To provide acceptable tests, the pattern of meteorological values, whose close-matching historical records were sought to provide an estimated value of seeing, were of course not themselves used. Further details of this work may be found in (Murtagh and Sarazin, 1993).

Up to 100 cases ("up to" since some random selections were replicated) were withheld from the remaining cases, and on the basis of the latter only, unique historical meteorological configurations were determined. Then, exact matches of the 100 cases were sought, among these unique configurations. If no such match was found, or if the unique combination was associated with too few cases, then we decided that no prediction was possible.

The seeing values associated with the best match cases were used to estimate seeing. Given, however, that a certain number of good, bad and intermediate seeing values are associated with the best match cases, A *confidence* coefficient was defined to guide our choice of estimate.

Next, to simplify the assessment of results obtained, we fuzzified this confidence coefficient: a value less than $\frac{1}{3}$ signified a high (i.e. bad) seeing estimate; a value between $\frac{1}{3}$ and $\frac{2}{3}$ inclusive signified an intermediate seeing estimate; and a value above $\frac{2}{3}$ signified a low (i.e. good) seeing estimate. Knowing the seeing value of the withheld test case then allowed a comparison. The contingency tables shown in Tables 4.2. and 4.2. display the results obtained. Each contingency table is based on five runs, in each of which up to 100 cases were withheld; then estimates of seeing were obtained and compared with the known seeing.

Various measures such as hit rate and completeness, or recall and precision, can be derived from these contingency tables. One can see that, for La Silla, when our system stated that good seeing was expected, then this was in fact the case in 29 cases, with 11 intermediate cases, and 3 errors (i.e. good seeing predicted, and bad seeing actually happening). This would appear quite good, and the table of Paranal results indicates a similar outcome. On the other hand, note that many actual cases of good seeing were "lost" by our system: in the case of Paranal, 41 (or, depending on usage of such data, 41 + 62) cases of misleading estimates were provided by our system. There is always a trade-

estimated actual	bad	moderate	good
bad	90	63	41
moderate	39	67	62
good	2	4	19

Table 1. Paranal. One-hour nowcasts.

estimated actual	bad	moderate	good
bad	69	62	21
moderate	38	67	70
good	3	11	29

Table 2. La Silla. One-hour nowcasts.

off in such systems between hit accuracy, on the one hand, and completeness, on the other. The onus is on the user to state how the system should be used: conservatively or optimistically. Should one attempt to benefit from any possible foreseeable good seeing potential, or should one attempt to avoid anything other than good seeing at all costs? In the study described in the next section, an automated way of incorporating such a value judgement will be used.

If we look at the reliability of our system as indicated by how many times good seeing actually happens, relative to how many times our system estimated that good seeing should happen, we find values of 76% for Paranal and 64% for La Silla (i.e., with reference to Tables 1 and 2, respectively 19/(19+4+2) and 29/(29+11+3)). We may note that there is higher predictability at La Silla (29/(29+70+21) compared to 19/(19+62+41) at Paranal) and this points to the fact that seeing is more determined, there, by local near-ground effects.

4.3. Median Nightly Seeing: Fuzzy-Neural Results

A connectionist system was used, which incorporated a cost policy: an a priori judgement of what is important and what should be prioritized in regard to predicted versus actual scenarios.

Various performance measures, based on cost policies, may be proposed so as to meet the observers' requirements. With a view to presenting the performance of the connectionist model with the above objective in mind, three pairs of thresholds were used, related to the following performance measures of interest:

Policy 1: maximum hit rate, when actual and estimated seeing are in the same category: `poss(seeL|seeL)` + `poss(seeM|seeM)` + `poss(seeH|seeH)`.

Policy 2: maximum conditional possibility to have good seeing when good seeing was predicted: `poss(seeL|seeL)`.

Policy 3: minimum of the cost function given by Table 3.

Table 3 expresses user-oriented utility, or the wish to diminish the number of "false alarms" (e.g. bad seeing, when good is expected). Positive and negative values express success and failure, respectively. Observing time is lost when an observation requiring good seeing is scheduled during an actual bad or moderate seeing night. Conversely, observing time is inefficiently used when an observation with no specific seeing requirements is scheduled during a good seeing night.

Beyond the quest for reliable forecasts, the use of cost tables can allow optimization of scheduling. The observation time assignment procedure would be based on an optimal thresholding, based on the judgements of what is important, as expressed by the cost policy table.

The results shown in Tables 4 and 5 are typical for two-season experiments. These Tables summarize the important values. The upper left value, for example, shows that in cases of good seeing (`seeL`), our neural network approach will output "good seeing" in 66.7% of cases.

We can also attempt to minimize incorrect results, setting weights and threshold values in the connectionist network in order to seek 0% incorrect results, but this is very much at the cost of the relevance of such a result. Further discussion of such results can be obtained in Aussem et al. (1994).

The results confirm that Paranal is less predictable than Cerro NTT, a lower summit close to Paranal more subject to ground effects.

estimated \ actual seeing	bad	moderate	good
bad	1/4	−1/4	−1/2
moderate	−1/4	0	−1/2
good	−1	−1	+1

Table 3. Costs associated with each possibility.

Policy	`poss(seeL|seeL)`	`poss(seeH|seeL)`	`poss(seeL)`
1	80.0%	6.7%	28.6%
2	87.0%	4.3%	21.9%
3	85.7%	3.6%	26.7%

Table 4. Conditional possibilities, Winter 1992 – Spring 1992 (Cerro NTT)

5. Cloud-Cover and Water Vapour Forecast from Satellite Images

Weather satellites provide continuous coverage of remote areas where conventional meteorological observation methods are absent. These satellites measure meteorological parameters by passive remote sensing at different electromagnetic wavelengths. ESO is currently performing a feasibility study (A. Erasmus, University of Northern Colorado) of the detection and forecasting of cloudiness and water vapour above the observatories from the analysis of satellite images. It is proposed to use Meteosat-3 and Goes-8 observations, at 6.7 μm for water vapour and to combine visible, 11.1 μm and 3.7 μm channels for the detection of clouds, in particular of thin cirrus. The 6.7 μm images reflect water vapour emissions from the layer between 700 mb and 300 mb, thus corresponding roughly to the air column above our observatory.

The representativity of the detection methods is being checked against surface data collected during the past years at Paranal, consisting of visual observation of the night sky for cloud detection and infrared emissivity recording with one of the Kitt Peak Water Vapour Monitors (Morse, 1982).

6. Meteorological Forecasts in Chile

ESO is currently performing a feasibility study (R. Benzi, CRS4, Sardinia) of meteorological forecasting over Chile. The problem is to find the most efficient way to obtain 48 to 72 hour forecasts of the atmospheric conditions at the Chilean installations of La Silla and Paranal. There are several centres in the

Policy	`poss(seeL|seeL)`	`poss(seeH|seeL)`	`poss(seeL)`
1	66.7%	20.0%	28.6%
2	72.7%	18.2%	10.5%
3	70.4%	14.8%	25.7%

Table 5. Conditional possibilities, Spring 1989 – Summer 1989 (Paranal)

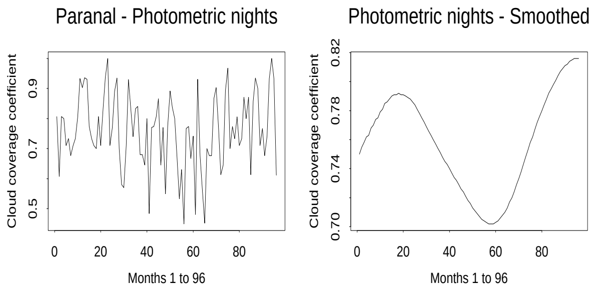

Figure 2. Paranal monthly percentage of photometric nights January 1987-December 1994.

world (in Europe, ECMWF) which provide operationally short- and medium-range (up to 10 days) forecasts on a global scale. Such information is available on a regular grid of about 100 km at the mid-latitudes. The idea of the project is to understand whether the medium-range forecast correctly predicts the observed meteorological situation at the observatories so as to use it as a boundary condition for an operational Limited Area Model (LAM) providing a forecast on a regular grid of about 20 km. In the case of success, a software tool would be developed to handle automatically the meteorological service and permanently update the local forecast.

7. Long-Term Forecasting

It is often stated that a site turns out of poorer quality at the time the telescope starts operation, compared to what it was during the preceding site survey. What appears as bad fate is in fact due to site surveys, in essence, picking out the sites in a favourable situation with regard to large-scale climatic trends. The site surveys seldom long enough to sample the latter. As shown on Fig. 2, the cloudiness at Paranal seems to follow a 40-month half cycle. A prediction of such climatic trends would be of interest (a) for the development of the scheduling tools, since different overall conditions may lead to choose different policies, and (b) for scheduling major technical work in the least favourable periods. Research is currently underway to gather external data – such as sea surface temperature, high-altitude wind velocity (jetstream) – and compare it to our local measurements of seeing and cloud cover.

8. Conclusion

This work has described a wide range of strategies for tackling the problem of predicting observing conditions, in the frame of the VLT Astronomical Site Monitor. Clear recommendations follow in many cases. The feasibility of building a prediction engine based on this work is evident. Some results have been shown to be worthy of interest, while others are excellent. Our contribution has been to achieve such predictability, and to do so we have had to develop a range of innovative methods. In addition, an interdisciplinary approach is necessary, including the fields of meteorology and earth observation, to develop the tools modern scheduling schemes require.

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