AN ASTRONOMICAL SITE MONITOR FOR THE ESO VERY LARGE TELESCOPE

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Abstract

A comprehensive system is currently being developed at the European Southern Observatory for the monitoring and prediction of astronomical observing conditions at the Very Large Telescope Observatory at Paranal in Northern Chile. The purpose is to provide a permanently updated database depicting current and foreseen external environmental parameters relevant for the various astronomical observing modes.

Several remote sensing instruments were designed or tested for that purpose over the past years. This paper describes the functional specifications of the VLT Astronomical Site Monitoring Unit, planned to start operating in 1996. It covers in particular the monitoring of the spatio-temporal characteristics of nocturnal atmospheric turbulence using an acoustic sounder in parallel with optical monitors.

The prediction of observing conditions for the following night, or the trend in image quality one hour in advance, allows higher efficiency in scheduling telescope operation. The current state of the art is summarized for statistical prediction methods trained on a large database fed by ground-based meteorological sensors and atmospheric soundings.

1 The VLT Astronomical Site Monitor

1.1 Introduction

The VLT Astronomical Site Monitor is an automatic unit operated 24 hours a day to gather information about the environment of the VLT observatory. It includes a sensing unit composed of a large number of stand-alone sensors described in section 1.2 and two expert systems in charge of modeling and prediction tasks.

The modeling unit filters the input flow of information and produces an accurate picture of the current environmental status. It uses physical correspondence laws between measured parameters and the related astronomical variable (e.g: SODAR backscattered echo and seeing).

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 which are, by order of complexity and priority: the display and archival of information, the direct command of telescope thermal control, the definition of the optimal instrumental set-up and the definition of the optimal observing schedule. The latter function, named flexible scheduling, is derived from space applications and aims at increasing observing efficiency by choosing the type of observing mode best adapted to foreseen atmospheric conditions.

1.2 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 [Sarazin 90]. The site survey database to be used for statistical prediction purposes (Section 3) is being continuously extended, even during the current VLT construction phase. New monitoring instruments are still under development. The ASM will reach a final state when the VLT starts operating in 1997. It will then include:

1. Seeing and Coherence Monitor: measuring seeing with the differential image motion method. In the coherence mode, it monitors the temporal characteristics of the optical wavefront: average velocity, average direction and dispersion velocity. In this mode, the index of scintillation is also available.

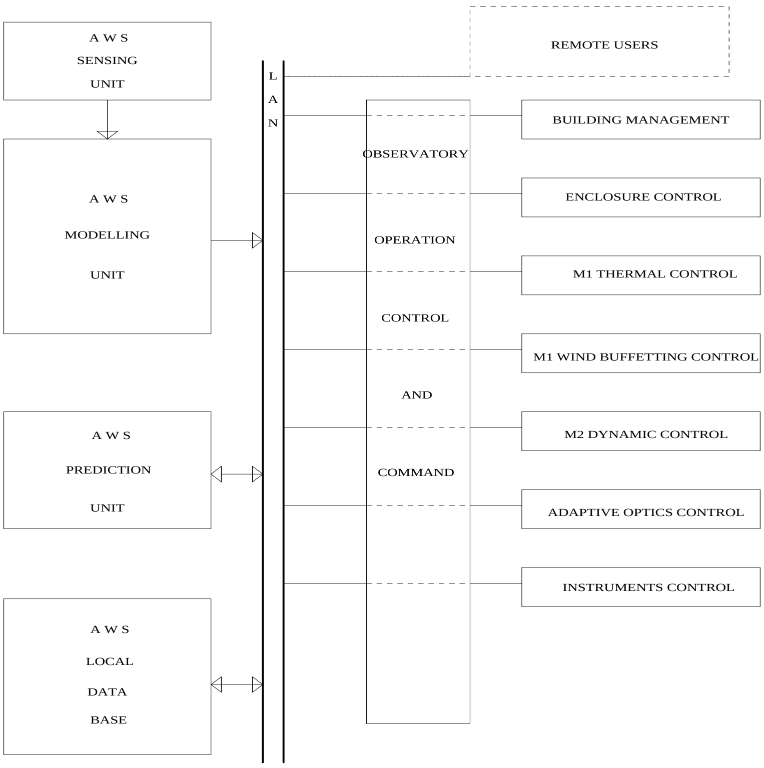

Figure 1: The function of the ASM in the VLT Observatory.

2. Acoustic Sounder: measuring the 3D wind pattern (horizontal velocity and direction, vertical velocity) as a function of height above ground from 50 m up to several hundred meters. It delivers also information on the vertical profile of thermal turbulence ($C_T^2(h)$).

3. Sky Monitor: determines the cloud map of the night sky (photometric or otherwise), measures infrared emissivity as well as the atmospheric extinction coefficient at several representative wavelengths.

4. 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.

1.3 The VLT ASM Prediction Unit

The prediction unit is a software item where the distinction is made between between long term forecasts obtained at least one day to half a 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 including cloudiness and water vapour are provided by specialized meteorological institutes using models with a resolution of several tens of kilometers.

Short term or local forecasts might ideally rely on physical models trained on the site orography for the micrometeorological variables. Unfortunately no such model exists, in particular for astronomical seeing which has escaped all attempts up to now. Image quality depends indeed on the vertical distribution of several parameters which do not belong to the same spatial scales. The thermal turbulence in the surface layer is now well understood [de Baas 91] but the thermal structure of the troposphere is still debated, in particular with regards to the size of the outer scale of turbulence [Coulman 88, Dalaudier 94]. Experiments are conducted to determine wether vertical profiles delivered by an acoustic sounder could be used to predict the behavior of the nocturnal atmospheric boundary layer, as described in Section 2.

Faced with the difficulties and incompleteness of the physical model approach, purely mathematical methods are also investigated. Section 3 describes a novel method for producing local forecasts solely based on the statistical analysis of a large local database.

2 The use of the SODAR for predicting observing conditions in astronomical observatories

2.1 Introduction

Seeing and stellar scintillation have been monitored simultaneously with identical instruments during several nights at two astronomical observatories in Chile: Las Campanas and La Silla, distant of 30 kilometers in the direction of the prevailing wind. The good correlation of the signals shows that turbulence in the atmosphere conserves its features over long distances . The analysis of their relative time of occurrence permits to determine the direction and speed of propagation of the turbulence layers either in the atmospheric boundary layer or in the higher troposphere [Sarazin 92].

These properties may be used for predicting, a few hours in advance, observing conditions at modern ground based astronomical observatories as an input to a knowledge based telescope scheduler during flexible operation. A feasibility study is underway at ESO, as part of the development of the VLT Astronomical Weather Station (ASM), using a Remtech 3D Acoustic sounder.

2.2 The physical meaning of astronomical seeing

Seeing is defined as the Full Width at Half Maximum of a long exposure image obtained at the focus of a large telescope limited by the atmosphere. For a given zenith angle γ, it can be written as a function of the refractive index structure coefficient along the path:

$$FWHM = 0.976\frac{\lambda}{r_0} = 5.345\lambda^{-1/5}\left[(\cos\gamma)^{-1}\int C_n^2(z)\,dz\right]^{3/5} \; ; radians \tag{1}$$

The index of refraction n of the atmosphere, restricted to the contributions of the continuum, for a wavelength λ, pressure P, absolute temperature T, and water vapor pressure e is, at visible wavelengths:

$$n - 1 \;=\; 77.6\,10^{-6}(1 + 7.52\,10^{-3}\lambda^{-2})(P + 4810\,e/T)/T \tag{2}$$

The fluctuations of the refractivity may be expressed as a function of the fluctuations in potential temperature, pressure and humidity along:

$$dn(T,P,e) = \left[\frac{\partial n}{\partial T}\right]_{(P,e)} dT + \left[\frac{\partial n}{\partial P}\right]_{(T,e)} dP + \left[\frac{\partial n}{\partial e}\right]_{(T,P)} de \tag{3}$$

The local variations of the index n are responsible for the perturbations induced on the optical wavefront. Most authors agree to neglect humidity fluctuations for optical wavelength [Andreas 88]. Considering local statistics only (i.e: at fixed height over land), pressure fluctuations may also be neglected and absolute temperature may be used in lieu of potential temperature. One may then define the local structure parameter for the index of refraction at $\lambda = 0.5\,\mu$m:

$$C_n^2 \approx \left(80 \cdot 10^{-6}\frac{P}{T^2}\right)^2 \; C_T^2 \; ; m^{-2/3} \tag{4}$$

where C_T^2 is the local isotropic temperature structure parameter defined as:

$$C_T^2(r) = \frac{< (T(r) - T(r+\Delta r))^2 >}{\Delta r^{2/3}} \; ; {}^oC^2 m^{-2/3} \tag{5}$$

2.3 SODAR calibration

In the theory of atmospheric turbulence one often uses the hypothesis that the turbulence moves with the wind without modification of its statistical properties along the path (frozen turbulence). In presence of a layered vertical structure, the determination of the average and dispersion velocities of the turbulence is of interest for optimizing interferometric techniques ([Lopez 91]).

height	C_n^2 , 10^{17} $m^{-2/3}$			
(m)	day mean	day rms	night mean	night rms
10	5470	5150	158	205
30	1670	2410	129	160
50	*	*	303	280
90	804	644	208	307
130	586	574	142	241
170	452	535	100	144
210	349	466	83	116
250	277	390	71	90
290	219	270	58	78
330	189	256	45	59
370	159	221	39	60
410	138	197	33	50
450	125	219	33	67
490	105	192	27	60
530	81	140	20	50
570	70	135	21	50
610	58	132	18	56
650	48	105	16	53
690	37	86	12	46
730	33	83	15	57
770	25	71	13	52
810	18	62	9	37

Table 1: Statistical summary of C_n^2 data in function of altitude : average profiles obtained during two weeks on 40 m high slices centered from 50 m to 810 m in altitude. The 10 m and 30 m levels are given by independent microthermal sensors on a mast. The mean is an arithmetic average of 15 mn samples. The rms is the arithmetic average of the 15 mn standard deviations. The received level exceeded saturation limit in the layers indicated with an asterisk

The acoustic sounder or SODAR is in principle the best tool for boundary layer monitoring. The SODAR qualitative output for turbulence and wind velocity has no equivalent in terms of amount of information delivered per unit of time. Yet, in astronomical observatories, accurate absolute data are necessary to retrieve the complete vertical profile $C_n^2(h)$.

This is in theory possible since the acoustic backscattering cross-section is proportional to the temperature structure coefficient of the atmosphere:

$$\sigma = 0.0075\lambda^{-1/3}\frac{C_T^2}{T^2} \tag{6}$$

The need for absolute data has prompted many studies worldwide both in meteorology [Neff 75, Haugen 75] and in astronomy [Dubosclard 84, Forbes 85, Barker 87] but attempts to calibrate the instruments showed very cumbersome. A large scale site monitoring campaign took place at the La Silla observatory in 1986 and permitted to calibrate a monostatic acoustic sounder against optical methods during nighttime. The same calibration law was then used to retrieve the turbulence profile also in daytime.

The results over two weeks of continuous measurements, given in Table 2.3, show that microthermal sensors cannot be used in all cases to calibrate the SODAR output. In daytime convective pluming, microthermal measurements and SODAR can be modelized by a single power law. On the othe hand, the nighttime profile shows a discontinuity between 30 m and 50 m which is not predictable if the height of the nocturnal inversion cannot be accurately determined by other means. This problem was also studied by [Gur'Yanov 91] who come to a different conclusion using time dependent calibration factors.

Furthermore, high dryness increases the absorption of our SODAR acoustic frequency during its propagation through air, part of the acoustic energy being transferred into molecular excitation. This effect is the main limitation to the performances of acoustic sounders when the vertical profiles of humidity and temperature are not simultaneously available.

The prospect of a quantitative application of SODAR data to optical propagation matters in mountain areas remain thus uncertain. Current work is now focused to depict the temporal evolution of the spatial structure of the atmosphere above the observatory so as to predict trends rather than exact profiles.

3 Nowcasting Seeing

The principle of the work more extensively described in [Murtagh 93] is to predict temperature, humidity, and the other meteorological variables at a few time steps into the future; and then to use the predicted environmental configuration to determine, or nowcast, the seeing.

The method used for nowcasting is *nearest neighbor regression*, where the closest historical (or archived) meteorological configuration is checked out. The corresponding seeing value is used as an estimate of the seeing (assumed unknown) associated with a given meteorological configuration. Using similar conditions which prevailed in the past is a very intuitive approach. Variables used were the following:

- `s1`: Wind velocity (ms^{-1}) at 10m above ground.
- `s1d`: Standard deviation of the wind speed during the averaging period (20 minutes).
- `d1`: Wind direction (degrees) at 10m above ground.
- `rh`: Relative humidity (percent) at 2m above ground.
- `t1`: Air temperature (degrees) at 2m above ground.
- `see`: The seeing is measured at 5m above ground and is defined as the full-width at half-maximum of a stellar image observed with a perfect large telescope, at $0.5\mu m$ wavelength and at zenith. One-hour averaged seeing values are used.

Among the initial data treatment steps undertaken, cases (i.e. meteorological variable, and seeing, values at a given point in time) were selected so that no measurements were missing. This reduced the many tens of thousands of cases of the two year database to a few thousand.

A categorical coding of the measurements was carried out: we used the fuzzy coding of a variable into "high", "low" and "intermediate". "High" was coded 1, 0. "Low" was coded 0, 1. "Intermediate" was coded x, y, such that $x + y = 1$, and such that x was linearly interpolated between 1 and 0, necessitating y to be similarly linearly interpolated between 0 and 1. The division points, used to define these three categories, were the 33rd and 67th quantiles.

Variables `s1`, `s1d`, `d1` and seeing were recoded in this way, on the basis of all cases. Finally, variables `rh` and `t1` were recoded with reference to seasonally-related quantile values.

To quantify associations of interest, the first measure used is the conditional possibility of good seeing on one or more meteorological variables. This is a fuzzy success rate, given a particular environment. A second measure is the possibility of these meteorological variables arising in practice.

To come closer to a production system, we tested the nowcasting ability of our system in the following way. Up to 100 test cases were withheld from the training set, and on the basis of the latter only, the unique configurations were determined. Knowing the seeing value of the withheld test case then allowed a comparison. The contingency table shown in Table 2 displays the results obtained.

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 (i.e., with reference to Table 2: 19/(19+4+2)).

Paranal		Actual Seeing		
		bad	intermediate	good
Estimated	bad	90	63	41
Seeing	intermediate	39	67	62
	good	2	4	19

Table 2: Contingency table exemplifying estimated versus actual low, intermediate and high seeing values.

References

[Andreas 88] Edgar L. Andreas; *Estimating C_n^2 over snow and sea ice from meteorological data*;J. Opt. Soc. Am. A **5**, n^o 4, Apr. 1988.

[de Baas 91] A.F. de Baas, M. Sarazin; *The Temperature Stucture Fonction for Complex Terrain*; Eight Symposium on Turbulent Shear Flows, Munich, September 9-11, 1991.

[Barker 87] E.S. Barker; *Site testing with an acoustic sounder at McDonald Observatory*; Proc. of the Int. Conf. on "Identification, Optimization, and Protection of Optical Sites", Flagstaff, Arizona (May 22-23, 1986). R.L. Millis et al., edit., Lowell Observatory, Flagstaff (1987) p. 58.

[Coulman 88] C.E. Coulman, J. Vernin, Y.Coqueugniot and J.L. Caccia, *Outer scale of turbulence appropriate to modeling refractive-index structure profiles*; App. Opt. Vol.27, n^o1, January 88.

[Dalaudier 94] F. Dalaudier, C. Sidi, M. Crochet, J. Vernin; *Direct Evidence of "sheets" in the Atmospheric Temperature Field*; J. of the Atm. Sci., Vol. 51, 2, 15 Jan. 1994.

[Dubosclard 84] G. Dubosclard, H. Hecquet, G. Coupinot, and H. Sauvageot; *Forecasting and optimizing astronomic image quality using acoustic sounding*; Astron. Astrophys. 273 (1984)

[Forbes 85] F.F. Forbes, E.S. Barker, K.R. Peterman, D.D. Cudaback, D.A. Morse; *High Altitude Acoustic Soundings*; East 85, SPIE symp., Arlington, VA, Apr. 1985.

[Gur'Yanov 91] A.E. Gur'Yanov, S.D. Danilov, M.A. Kallistratova, I.V. Petenko; *Intercomparison of fast response microthermometers and acoustic sounder at Mt. Maydanak*; Starnberg Astronomical Institute pre-print **18**, 1991.

[Haugen 75] D. A. Haugen, J. C. Kaimal, J.T. Newman; *The use of an Acoustic Echo Sounder for Optical Tracking Applications*; Air Force Cambridge Research Lab. (LYB), Report n^oAFCRL-TR-75-0454, Aug. 21, 1975.

[Lopez 91] B. Lopez, M. Sarazin; *Optimum exposure times for interferometry*; Proc. ESO-Conf. on High Resolution Imaging by Interferometry II; Garching, Oct 14-18, 1991.

[Murtagh 93] F. Murtagh, M. Sarazin; *Nowcasting Astronomical Seeing: A Study of ESO La Silla and Paranal*; P.A.S.P **105**; 932-939, 1993 September.

[Neff 75] W. D. Neff; *Quantitative Evaluation of Acoustic Echoes from the Planetary Boundary Layer*; Report NOAA TR ERL 322-WPL 38, June 75.

[Sarazin 90] M. Sarazin, *E.S.O Site Evaluation for the V.L.T*; XI IAU ERAM, Teneriffe, in *New Windows to the Universe*, Vol. 1, p435-449, Ed. F.Sanchez and M. Vazquez, Cambridge Univ. Press. 1990.

[Sarazin 92] M. Sarazin; *The use of the large spatial coherence of turbulence patterns for predicting observing conditions in astronomical observatories*; Scintillation, Intern. Meeting for wave propagation in random media; Aug. 3-7, 1992; Seattle, Wa. *and* Atmos. Oceanic Opt. **5**, 12, Dec. 1992 (translated from Russian).