Automated Seeing Monitoring For Queue Scheduled Astronomical Observations

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ABSTRACT

Large and expensive astronomical facilities are now planning operation of their multi-instruments telescopes under queue scheduling mode. The main idea is to boost the efficiency of astronomical observing making a better use of available dark time. The choice of a given observing program would be driven by environmental constraints which have therefore to be reliably and accurately monitored.

Atmospheric seeing is one of those and earlier site survey oriented monitors have now to be upgraded towards unattended continuous operation. Differential Image Motion (DIMM) Seeing Monitoring is now a common feature of a growing number of observatories worldwide because of a straightforward theory and of its robustness to instrumental errors. However, basic rules have to be respected in particular to reduce the sensitivity of such systems to site dependent parameters such as short wavefront coherence time and finite outer scale of the turbulence.

In the light of several years of automated seeing monitoring at the La Silla Observatory and as part of the development of the VLT Astronomical Site Monitor, the criteria for designing such instruments are reviewed and results are presented.

Keywords: astronomical imaging, atmospheric seeing, queue scheduling

1. INTRODUCTION

Planning a modern astronomical facility requires to find an adequation between the future needs of the user community and the perspectives offered by existing or promising sites. A major project needs several years of development and is expected to deliver at least an equivalent amount of operation time at a ground based facility. These considerations impose two constraints on site surveys, first enough data should be accumulated on the candidate sites before the final choice can take place, and secondly guaranties should be obtained that the site parameters will not significantly change (at least not in the wrong direction) as long as the facility will remain in operation. The best (although unfortunate) example of the second condition not being fulfilled can be found in most observatories of the first half of the century, slowly surrounded by rampant urban lights.

If human expansion is a parameter now rather well modelized, climate variation prediction is still open to speculation and also not always relevant for astronomy. Astronomers have defined a set of environmental variables which affect observing quality at ground based facilities. The term *astroclimate* is often used for this set of parameters related to atmospheric constituents (clouds, water vapour, air glow, volcanic and desert dust) as well as to atmospheric thermal turbulence (seeing, scintillation, wavefront velocity). These are precisely the links between this *astroclimate* and meteorology which one would like to investigate, and it is proposed here to use recent experience gained during the ESO-VLT site survey and the database gathered for the monitoring of ESO sites in Chile to illustrate the amplitude and length of climatic trends for astroclimatic variables such as cloud cover and seeing.

The site survey database which is also currently used for the development of prediction algorithms has been continuously extended during the VLT construction phase. New monitoring instruments are currently under development to constitute the so-called VLT Astronomical Site Monitor (ASM). The ASM should be fully operational when the first VLT instruments are offered to the community. 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

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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 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 serving as inputs to dedicated forecast models.

2. SEEING MONITORING

2.1. Generalities

The Differential Image Motion (DIMM) Method was developed in the mid-eighties during the NNTT and VLT site surveys ([1]) and is nowadays used in ongoing site surveys (Australia, South Africa, China, India, Central Asia) and in operating observatories as well (La Palma, La Silla). The main advantage of the method is to be independent of telescope vibrations inevitably induced by wind shake or tracking errors. Building a DIMM has now become more affordable thanks to the rapid development of good quality CCD detectors poduced for the market of amateur astronomy. However, some important remarks have to be kept in mind at design stage: the exposure time τ and the geometric arrangements of the sub-pupils (Diameter d and separation s) have to be chosen in order to minimize the errors due to time averaging and to the effect of a finite outer-scale of the turbulence.

2.2. Time averaging

The sensitivity to the speed of motion of the atmosphere has been accurately modelized in the early years ([2]) and more recently demonstrated on a real instrument ([3]). A too long exposure time can artificially reduce the apparent turbulence induced image motion and lead to over-optimistic results. Some sites dominated by turbulence borne at high wind velocity are very difficult to monitor correctly because the small exposure time required to freeze the wavefront is either not technically achievable, or drastically reduces the number of available stellar objects. A signal to noise ratio analysis shows that there are limitation to the design of a DIMM fast enough to cope with all extreme situations all year round. In particular, the exposure time averaging is variable with the relative orientation of the apertures with respect to the direction of the frozen motion and may reach a factor of 2 in inferred to true image size ratio ([2]). Our proposed turnaround is to interlace time series taken with two different exposure times τ_1 and τ_2 (eg. $\tau_1 = 10$ ms and $\tau_2 = 20$ ms). The comparison of the corresponding signal variance ($\sigma^2_{\tau_2} \leq \sigma^2_{\tau_1}$) allows to immediately detect time averaging effects. When intercalibrating two instruments of different design described on Table 1, it was found that the assumption of a linear attenuation with exposure time was adequate up to 2 arcsec seeing in 95% of the cases. The exposure time corrected variance is then obtained in each direction (longitudinal and transverse) along:

$$\sigma^2_{\tau_0} = \sigma^2_{\tau_1} \frac{\sigma^2_{\tau_1}}{\sigma^2_{\tau_2}} \tag{1}$$

The results of the interlaced exposure time method are shown on Figure 1 over several night of intercalibration of the La Silla reference DIMM with electromechanical shutter and ICCD (DIMM2) and some cheaper portable version (DIMM4) using an electronic shutter (CCD frame transfer) limited to 10 ms minimum exposure time. Although the correction method increases the statistical noise, it is found to be acceptable to assess the average quality of remote sites with a light and unexpensive transportable system. The results presented in Section 4.are composed of DIMM2 measurements only.

2.3. Outer Scale Effects

It has been shown ([4]) that the assumption of an infinite spatial-coherence outer scale for the turbulence may lead to an overestimation of the inferred seeing when the actual outer scale is of the order of a few meters. Although the statistics on this parameter is currently very poor, available data tend to converge to an average outer scale of a few tens of meter. Such values would then only affect DIMM technique applied to widely separated sub-pupils, and leave standard site monitors on the safe side. Moreover, variable separation DIMM measurements such as available

Table 1.

Monitor	Exposure Time ms	Pupil diameter (cm)	Pupil separation (cm)	$\frac{d}{\tau}$ m/s
DIMM2 (standard)	8	12	25	15
DIMM4 (standard)	10	8	20	8
DIMM4 (interlaced)	20	8	20	4

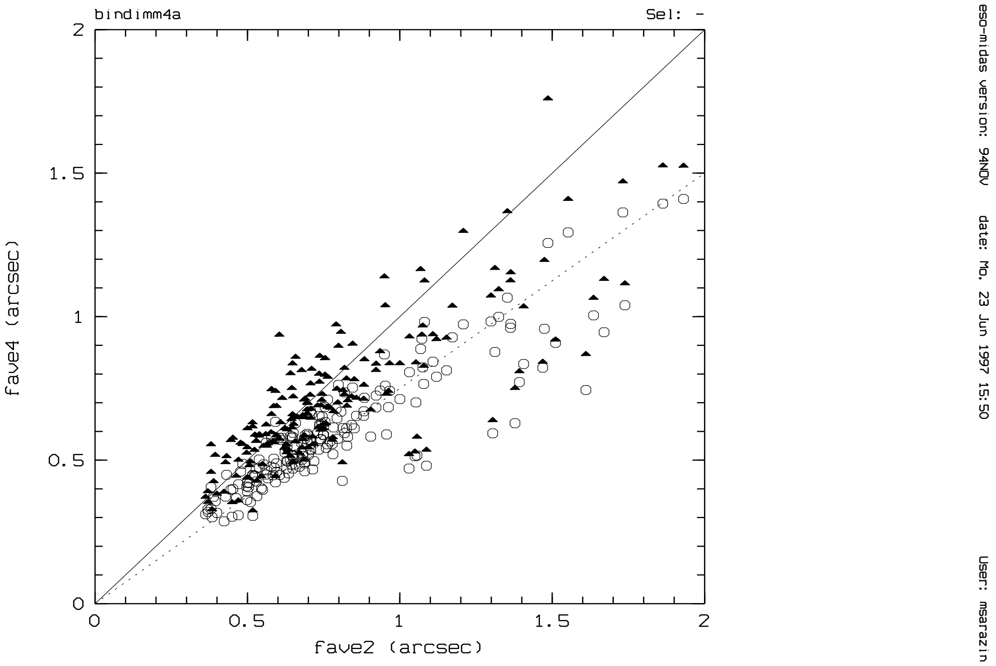

Figure 1. Comparison of the 15 m/s DIMM2 and the 8 m/s DIMM4 before (open circles) and after (filled triangles) correction of exposure time averaging using the interlaced mode method. The linear regression is moved from a 1.25 slope (dotted line) to 1.0 (full line). Only 5% of the DIMM4 data remain out of the expected range (linear attenuation assumption not valid).

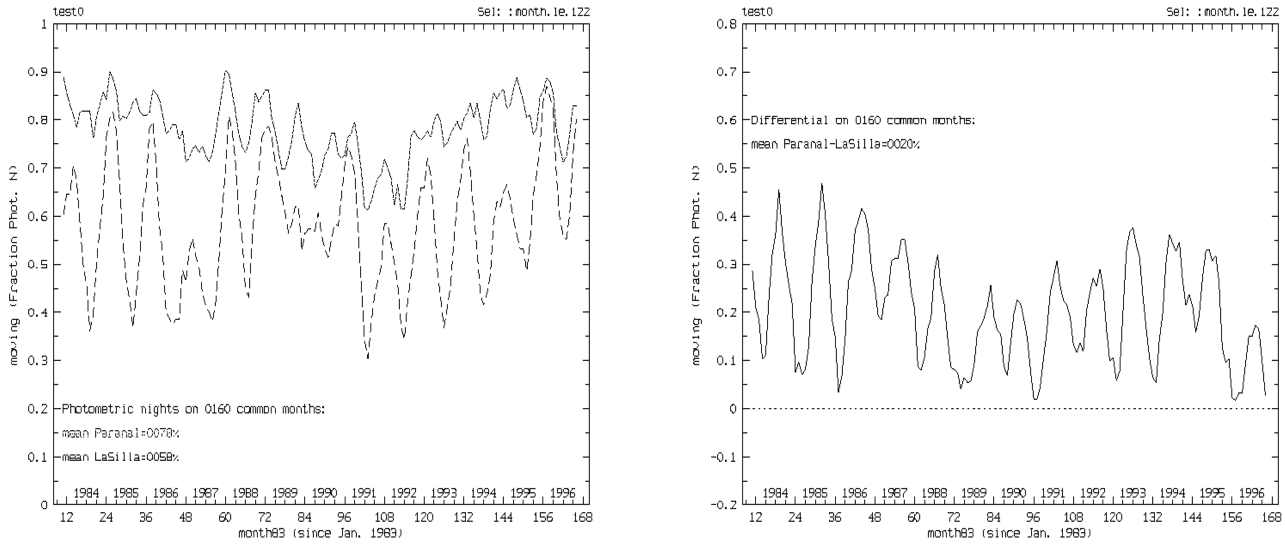

Figure 2. Monthly percentage of photometric nights (left) and Monthly differential of photometric nights (right), filtered with a 5 month wide window from 1983 to 1996 at Paranal and La Silla

from Shack-Hartmann wavefront sensors of adaptive optics systems, were proposed as a tool for monitoring the outer scale.

3. CLOUDINESS STATISTICS

Both ESO sites, La Silla (289.3E, 29.26S, 2400 m) and Paranal (289.6E, 24.62S, 2636 m) are located in the Atacama desert of Northern Chile. Cerro Paranal, where the Very Large Telescope is currently under construction, is nearer to the tropics and closer to the coast (10 km inland versus 40 km). Although the Atacama area benefits from a very stable climate, the vegetation shows that considerable changes took place in the far past. Middle term cycles are also noticeable at ESO observatories with regards to cloud cover as shown on Figure 2. From this database, a 40 months half cycle has been estimated for Paranal ([5]) with an amplitude as high as 10 % (or 36 nights) between the best and worst years. Attempts to correlate with local variables such as sea surface temperature at nearby harbors or 200 mB wind were not successful, which tends to indicate a relation to a more global circulation pattern.

However, the lower amplitude of the climatic fluctuations at Paranal with respect to La Silla agrees with the initial assumption of a better stability of the Northern Atacama area. Nevertheless, although the global figures did not change compared to 10 years ago, the differential performance presented on Figure 2 shows that a shorter site survey conducted at a non-representative period (1988-1990) would have led to a 50% underestimate of the superiority of Paranal with respect to La Silla.

In the frame of the development of a prediction scheme for the VLT observatory, an attempt was made to compare geostationary satellite images in the 6.7 μm channel at 10 km pixel resolution to visual observations of cloud cover made at Paranal over the past years. The ongoing feasibility study ([6]) involving Paranal ground measurements, Antofagasta radiosoundings, ECMWF (European Center for Medium Range Forecast) analyses and Meteosat images provided confidence that such a method applied both to cloudiness and to precipitable water vapour could also be useful to extend backwards the database of ongoing site surveys (Millimeter Array, Large Southern Array) in the area. Because of the satellite sensitivity to the altitude of the radiating components the availability of a limited ground based observation database is recommended for the initial calibration when such a method is applied to other parts of the world.

4. SEEING STATISTICS

4.1. Long Term Behavior

For the first time a longterm database of natural seeing is available. This is an opportunity to scrutinize the behavior of this parameter. Seeing is defined as the path integral of the index of refraction structure coefficient (C_n^2) as seen through a large telescope of perfect optics observing at 0.5 μm wavelength at zenith. Seeing has thus obviously some relationship with the status of the atmosphere, but thermal turbulence is produced at much smaller scales than all that global models (ECMWF) can provide. Modelization at mesoscale level (500 m to 1000 m terrain resolution) could possibly improve seeing predictability ([7]) at the cost of a high computing time which currently limits the area of analysis to a few tens of kilometers.

As can be seen on Figure 3, none of the ESO sites presents a cyclic variation of seeing as was found for cloudiness. Seasonal trends are virtually nonexistent at Paranal. At La Silla, they are washed out by the strong uprise of 1993 for which no explanation has feen found up to now. The initialization and duration of this event are unfortunately inaccurate due to a failure of the monitoring system, almost entirely destroyed by a lightning in 1992.

These monthly averages hide much larger variations from night to night and even the course of a given night. The distributions of 20 mn average seeing over several years (Figure 4) are perfectly log-normal. However the monthly data sets sometimes deviate from log-normality, in particular when unusually bad seeing occur during several nights in a row. This was the case at Paranal in March/April 1996, with wavelike oscillations possibly linked to a climatic anomaly: unusually warm weather in northwestern Argentina while torrential rains (80 to 250 mm) were drenching most of northeastern Argentina. So the log-normality of the distribution is a good test of the representativity of a limited sample.

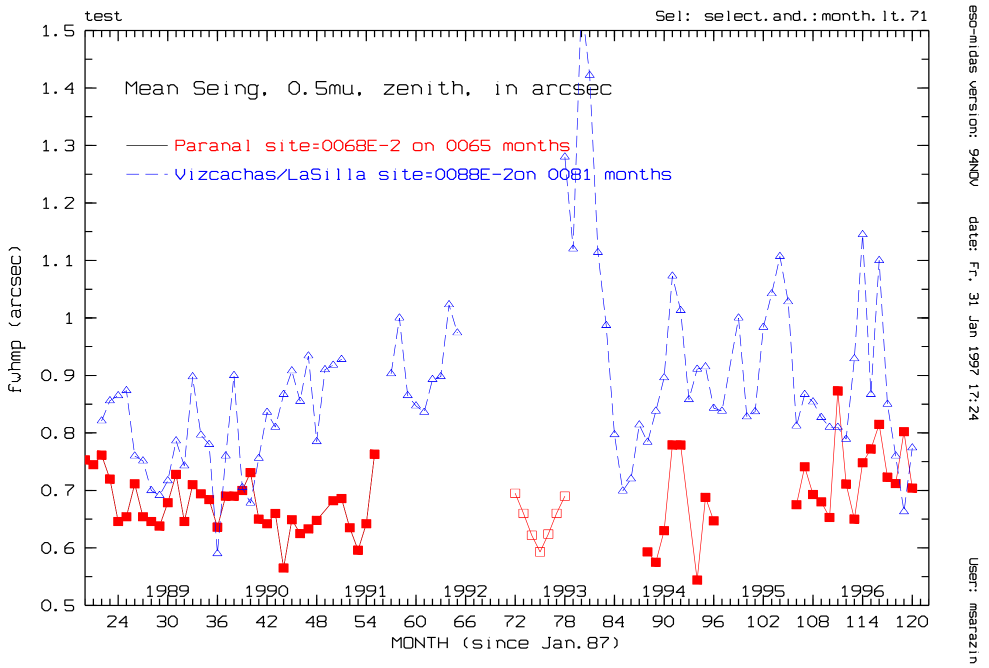

Figure 3. Monthly average seeing at Paranal (filled squares) and La Silla (triangles) from 1989 to 1996. Measurement are taken at 5 m above ground. A void period in 1991-1993 corresponds to leveling work of the Paranal summit. The period after 1995 corresponds to the start of the erection of the VLT enclosure and reflects the strong increase of human activity on the site.

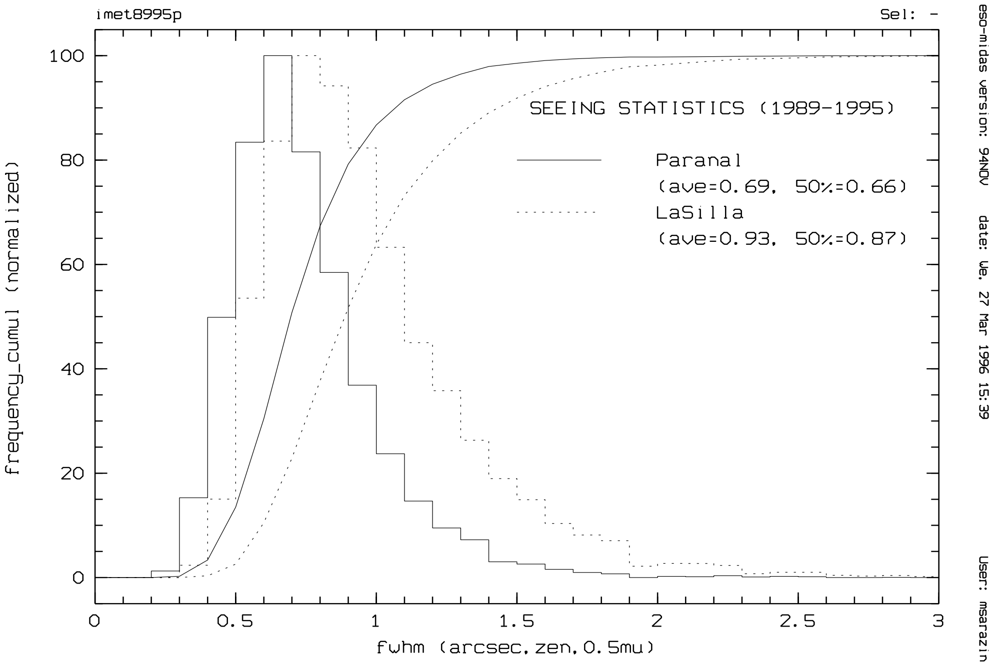

Figure 4. Statistical distribution of reconstructed 20 mn exposure seeing at Paranal and La Silla from 1989 to 1995

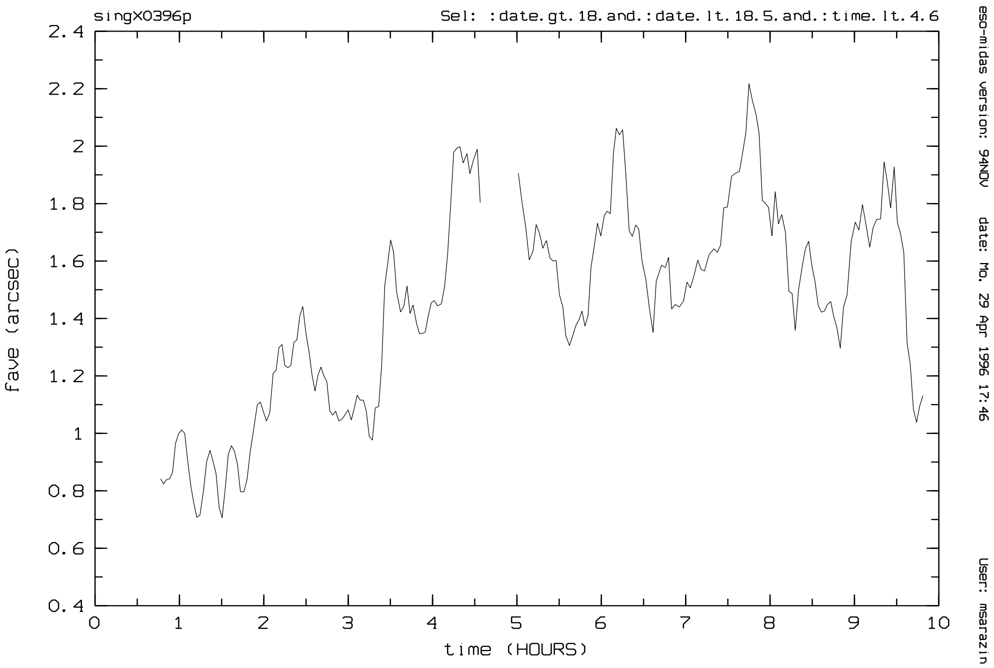

Figure 5. Wavelike structure of seeing at Paranal during an atypical climatic anomaly on March 17 to 18, 1996: possibly linked to unusually warm weather in northwestern Argentina while torrential rains (80 to 250 mm) were drenching most of northeastern Argentina

4.2. Short Term Temporal Stability

The short term temporal stability of seeing is a rather new parameter of interest to adaptive optics users aiming at observation micro-scheduling. Other authors recently discussed this parameters using different mathematical tools which we tried on the ESO database. Then we propose another approach allowing to estimate the final strehl ratio of a long exposure assisted by adaptive optics.

In order to analyze the free atmosphere turbulence above Mauna Kea ([9]), the fractional seeing change over a time interval Δt was defined as a function of seeing $\omega(t)$ along:

$$f(\Delta t) \propto \frac{\mid \omega(t+\Delta t) - \omega(t) \mid}{\omega(t+\Delta t) + \omega(t)} \tag{2}$$

For comparison with the data given in ([9]), the result $< f(\Delta t) >$ of this calculation for the Paranal database is presented on Figure 6.

A second way of characterizing short term seeing stability was proposed in ([8]) during the analysis of the DIMM data set from the Observatorio del Roque de los Muchachos. In that paper, the temporal behaviour of seeing is characterized by an average autocorrelation function:

$$C_\omega(\Delta t) =< \frac{< \omega(t)\omega(t+\Delta t) >_i - < \omega >_i^2}{< \omega >_i^2} > \tag{3}$$

where i refers to individual nights. The result of a similar computation is presented Figure 6 where the normalized autocorrelation of the centered seeing as been calculated along:

$$C_\omega(\Delta t) = \frac{< (\omega(t) - < \omega >_i)(\omega(t+\Delta t) - < \omega >_i) >_i}{< (\omega(t) - < \omega >_i)^2 >_i} \tag{4}$$

It is interesting to note that the function proposed for La Palma in ([8]):

$$C_\omega(\Delta t) = \exp \frac{-\Delta t}{T} \tag{5}$$

agrees rather well with the Paranal data set with the same exponential decay $T = 1.2$ hour. The saturation of the correlation function (when measurements are independent from each other) occurs after 2 hours: this confirm the absence of daily cycle or specific trends in the course of the observing nights.

Finally, we computed the seeing stability as a function of exposure time at Paranal as the rms seeing variation during the exposure. The computation was done a second time restricting the database to the lowest 50 percentile at beginning of exposure. Figure 7 shows that exposures starting with good seeing is 20 % more stable with an average rms of about 0.1 arcsec for exposures longer than one hour.

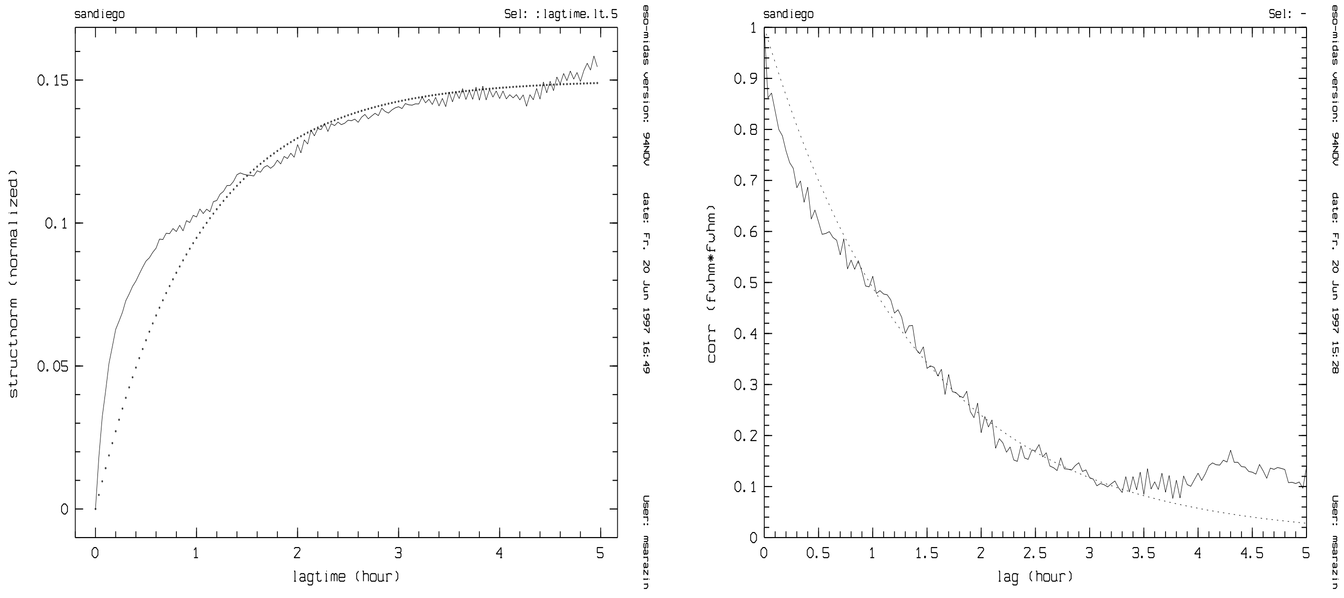

Figure 6. Short Term Temporal Stability of seeing at Paranal, the database time resolution is 2 mn and contains 5000 samples. Left graph: Temporal structure function of seeing as described in ([9]), the dotted line corresponds to $0.15(1 - exp(\Delta t)$. Right graph: Decorrelation of seeing samples as a function of their distance in time. The dotted line corresponds to the 1.2-hour exponential decay proposed in ([8]).

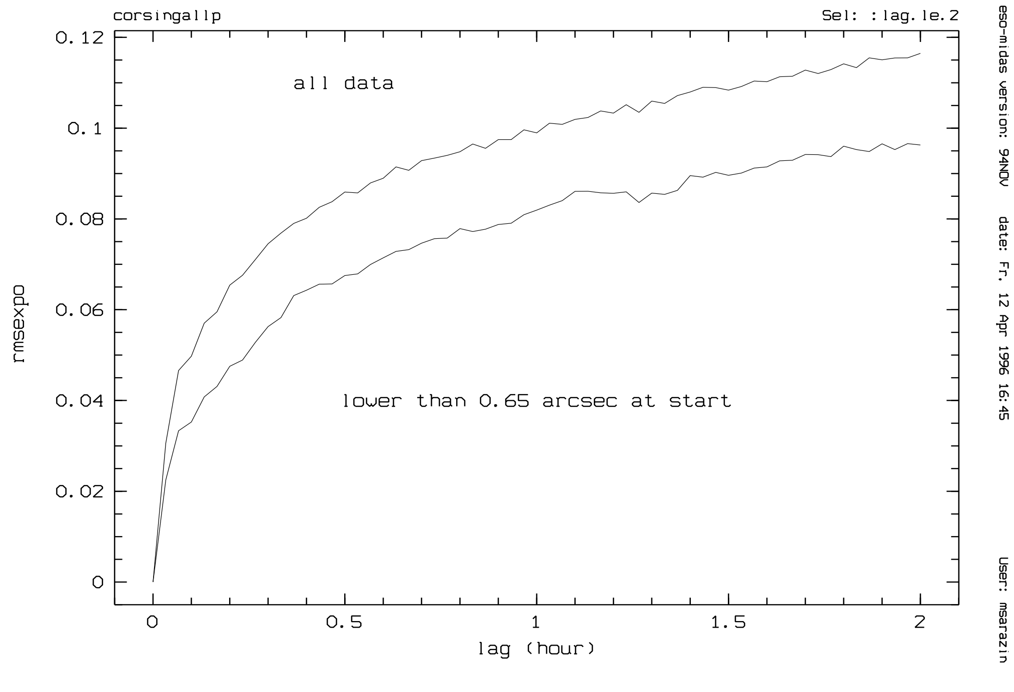

Figure 7. RMS variation of zenith seeing in arcsec as a function of exposure duration at Paranal for 2 classes of initial conditions. The database time resolution is 2 mn and contains 5000 samples.

5. CONCLUSION

Astroclimate parameters have different characteristic time scales which are either linked to long term climate change (cloudiness), large scale weather circulation (cloudiness and water vapour) or to more local 3D patterns (seeing). Forecasting cloudiness can be achieved using input data covering a wide area such as satellite images. Forecasting seeing requires a tool capable of representing orographic waves (gravity waves, lee waves) such as a high resolution (mesoscale) 3D model. A detailed analysis of the Paranal seeing database does not reveal temporal structures longer than 2 hours.

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