# Generalized Seeing Monitor (GSM) : a dedicated monitor for wavefront optical parameters measurement.

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## ABSTRACT

The Generalized Seeing Monitor (GSM) is a new instrument for the monitoring of the atmospheric optical parameters (AOP) like the spatial-coherence outer scale $\mathcal{L}_0$, the seeing $\epsilon_0$ and the isoplanatic angle $\theta_0$. This instrument, equipped with 4 identical modules, works like a Shack-Hartman sensor and allows the analysis of the perturbed wavefront (observation of the angle-of-arrival fluctuations) at four points. Different measurement campaigns have been done at different sites over the world: Cerro Paranal, La Silla, Cerro Pachon (Chili) , Oukaïmeden (Morocco) and Maydanak (Uzbekistan). The main results of the AOP parameters ( $\mathcal{L}_0$, $\epsilon_0$ , $\theta_0$) obtained during those missions are presented and discussed. The whole of these measurements provides an important data bank allowing the analysis of the temporal variability of these parameters.

**Keywords:** atmospheric turbulence, seeing, outer scale, isoplanatic angle, adaptive optics, interferometry

## 1. INTRODUCTION

The atmospheric turbulence limits severely the ground-based astronomical observations. In order to acheive the limit diffraction resolution, the High Angular Resolution (HAR) observing techniques have been developed, namely long baseline interferometry (LBI) and adaptive optics (AO). But the performance of these HAR methods requires a better understanding of the behavior of wavefronts perturbed by the atmospheric turbulence. More exactly a better knowledge of atmospheric optical parameters (AOP). Among these parameters the well known Fried coherence size $r_0$ which is related to the seeing ($\epsilon_0 = 0.98\lambda/r_0$), the spatial coherence outer scale $\mathcal{L}_0$, the isoplanatic angle $\theta_0$ and the wavefront coherence time $\tau_0$. It is well known that the performance of an AO system (PSF) depends upon the seeing conditions. On the other hand, for passive LBI the outer scale $\mathcal{L}_0$ is of interest because its value provides the spectral bandwidth optimizing the signal-to-noise ratio.[1] In addition, the $\mathcal{L}_0$ remains also a critical parameter for co-phasing an interferometer.[2] In the case of large telescope equipped with AO system, the residual error after a tip-tilt correction grows for small $\mathcal{L}_0$ values.[3] On the other hand, the choice of the AO reference star has to be done by taking into account the constraints related to the isoplanatic angle. And the knowledge of the wavefront coherence time $\tau_0$ is of intersest to optimize the exposure time. Indeed, a compromise is to be found between the flux, as a function of increasing exposure time, and the degradation image quality.

Thus, the whole of these reasons we developed an instrument for monitoring all of these optical parameters and especially the outer scale $\mathcal{L}_0$. This instrument is the Generalized Seeing Monitor which is succuntly described in Sect.2.1 and data reduction procedures. Then in Sect. 2.2 we go over all the methods in GSM processing for AOP estimation. Finally, in Sect.3 the summary of the measurement campaigns made with GSM at five observatories over the word are presented. And a particular attention is directed to the temporal variability of the AOP data.

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## 2. GENERALIZED SEEING MONITOR (GSM)

### 2.1. GSM instrument

The GSM instrument consists of evaluating the optical parameters of the perturbed wavefront by measuring Angle of Arrival (AA) fluctuations. Indeed, GSM uses the same principle than a Shack-Hartmann, i.e., measuring AA at different points of the wavefront and doing AA spatio-temporal correlations lead to estimations of the seeing $\epsilon_0$, outer scale $\mathcal{L}_0$, isoplanatic angle $\theta_0$ and coherence time $\tau_0$. The instrument consists of four 10-cm telescopes on equatorial mountings (Fig. 1) equipped with a detection modules measuring the AA fluctuations and interfaced to a computer PC managing simultaneously the 4 modules. Each telescope, pointing the same star, measures the AA fluctuations by means of flux modulation which is produced by a star displacement over a Ronchi grating. Two telescopes are installed on a common mounting on a central pier and working as a differential image motion monitor (DIMM)with a 25 cm baseline. Two other telescopes have different mountings on separate piers, located 0.8 m to the south and 1 m to the east from the central pier, thus forming an L-shaped configuration (Fig. 1). This configuation has been chosen for more sensitivity to the outer scale.

The AA fluctuations are measured with 5 ms time resolution during 2 minutes acquisition. Data are processed immediately after each acquisition, allowing a quasi real-time monitoring of the AOP. The data acquisition is repeated typically every 4 minutes.

The AA covariances are computed for each baseline (six baselines for the 4 modules) and an outer scale $\mathcal{L}_0$ is deduced. Final value of $\mathcal{L}_0$ is taken as a median of the six individual values. The seeing $\epsilon_0$ is calculated from the differential variance given with the coupled modules 1 and 2, as in the DIMM instrument.[4] The isoplanatic angle is estimated from the scintillation index as suggested by Loos and Hogge.[5] In the next section, a review of these methods is presented.

A quantification of the different GSM noises has been done and hence corrections of photon and scintillation noises are done before data processing. Another correction for finite exposure time is also done; it consists of computing AA variance (or covariance) for 5 ms and 10 ms and extrapolating linerarily to the 0 ms exposure time. Finally, the statistical errors of the computed variances and covariances are estimated and finally the errors of the measured AOP with GSM are provided.

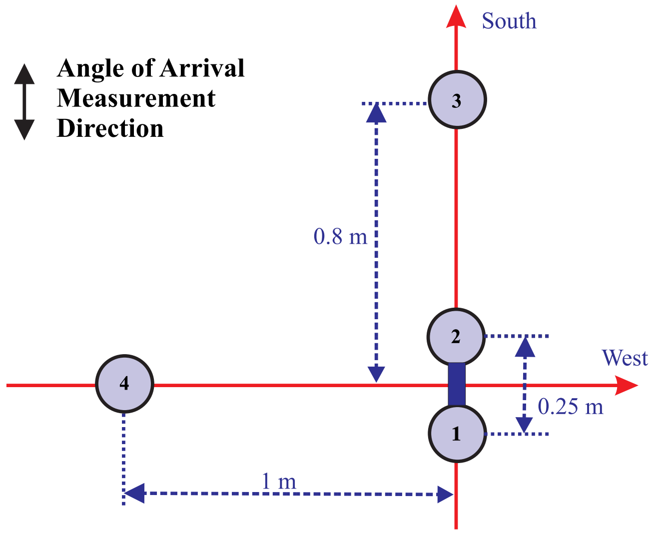


**Figure 1.** The GSM modules configuration.

### 2.2. Atmospheric optical parameters (AOP) estimation methods

Here we present the processing methods used by the GSM for estimating the AOP ($\mathcal{L}_0$,$\epsilon_0$,$\theta_0$) from the the AA fluctuations statistics.

#### 2.2.1. The outer scale $\mathcal{L}_0$

The 2-D AA covariance may be obtained from the Fourier Transform of the AA power spectrum. In the case of the Von Karman model, the expression of AA covariance for two pupils of diameter D separed by a baseline B is given by[6]:

$$\begin{aligned} \mathcal{C}_\alpha\left(B,\gamma,D,\mathcal{L}_0\right) &= 0.0716\ \lambda^2 r_0^{-5/3} \int_0^{+\infty} df\ f^{\ 3} \left(f^{\ 2} + \frac{1}{\mathcal{L}_0^2}\right)^{-11/6} \\ & \times \left[J_0\left(2\pi f B\right) - \cos\left(2\gamma\right)\ J_2\left(2\pi f B\right)\right] \left[2\frac{J_1\left(\pi D f\right)}{\pi D f}\right]^2 \end{aligned} \tag{1}$$

where $\gamma$ is the angle between the x-axis and baseline, $f$ is the spatial frequency and $\lambda$ the wavelenght. This covariance presents a strong sentitivity to the outer scale $\mathcal{L}_0$ for small values of the baseline. In order to avoid the Fried parameter $r_0$ term dependence, the expression 1 is normalized by a differential variance (Eq. 3) which is less sensitive to $\mathcal{L}_0$.[7] The AA covariances normalized by the differential variance are compared to the theoretical normalized covariances which are stored in a file for a grid of baseline coordinates $(x, y)$ and a logarithmic grid of outer scale values. For each baseline its projection onto the sky is calculated, using the star and site coordinates. Then the theoretical covariances as a function of $\mathcal{L}_0$ are found by interpolating the grid to the projected baseline. Finally, the appropriate $\mathcal{L}_0$ for each baseline is determined. The adopted value of the outer scale is taken as a median of the 6 individual values corresponding to each baseline. The error of the final $\mathcal{L}_0$ is computed taking into account all the GSM noise sources.

#### 2.2.2. The seeing $\epsilon_0$

The seeing is related to the Fried parameter $r_0$ called also coherence size ($\epsilon_0 = 0.98\lambda/r_0$) which can be deduced from the longitudinal AA differential variance defined by[8]:

$$\begin{aligned} \sigma^2_{dif}(D,B,\mathcal{L}_0) &\simeq 0.179\lambda^2 r_0^{-5/3}[D^{-1/3}\{1 - 1.525\,(\frac{D}{\mathcal{L}_0})^{1/3} + 5.568\,(\frac{D}{\mathcal{L}_0})^2\ \} - \\ & 0.57\ B^{-1/3}\{1 - 2.675\,(\frac{B}{\mathcal{L}_0})^{1/3} + 47.417\,(\frac{B}{\mathcal{L}_0})^2\}] \end{aligned} \tag{2}$$

In the case of GSM ($D = 0.1m$ and $B = 0.25m$) and typical oute scale $\mathcal{L}_0 > 10m$, this equation can be reduced to:

$$\sigma^2_{dif}(D,B) \simeq 0.179\lambda^2 r_0^{-5/3}[D^{-1/3} - 0.57\ B^{-1/3}] \tag{3}$$

One can remark that the effect of the outer scale disappeared in this approximation. That's why this technique is used in the case of DIMM measuremnt.[4] But, the sensitivity to the $\mathcal{L}_0$ appears for metric values of the outer scale.[7] In addition, this differential method eliminates the errors due to the guiding vibrations.

On the other hand, the seeing can be also deduced from the AA variance but it remains dependent of the outer scale value. Indeed, from Eq. 1 and putting B=0 one can obtain the AA variance which can be expressed at the first order as:

$$\sigma^2(D,\mathcal{L}_0) \simeq 0.179\lambda^2 r_0^{-5/3}(D^{-1/3} - 1.525\,\mathcal{L}_0{}^{-1/3}) \tag{4}$$

Generally, telescopes are sensitive to the guiding errors that can hardly distinguished from atmospheric fluctuations. From this consideration the differential variance (Eq. 3) is in a better position for $r_0$ estimation. This remark is used to check the GSM modules vibrations due to the wind. Indeed, the $r_0$ deduced from Eq. 4 which used the estimated $\mathcal{L}_0$ is compared to $r_0$ provided by the differential technique (Eq.3). The difference between those $r_0$ estimations gives us informations about wind effect on the GSM modules. From the data a good agreement is found for ground wind speed less than 10 m/s, showing that telescope vibrations were not significant.

### 2.2.3. isoplanatic angle $\theta_0$

The GSM provides scintillation index $\sigma_I^2$ measurements which can be used to estimate of the isoplanatic angle as suggested by Loos & Hogge.[5] The isoplanatic angle $\theta_0$ as defined by Fried[9] is proportional to $C_N^2(h)$ profile with $h^{5/3}$ weighting.

The scintillation index $\sigma_I^2$ is defined as the normalized variance of received light flux I. It is related to the turbulence profile as:

$$\sigma_I^2 = 9.62\lambda^{-2} \int dh C_N^2(h) W(h), \tag{5}$$

where the weighting function $W(h)$ is given by:

$$W(h) = \int_0^{+\infty} df\, f^{-8/3} \sin^2(\pi\lambda h f^2) P(f) \tag{6}$$

where $f$ is the modulus of the spatial frequency and P(f) is the aperture transmission function which is defined in the case of an aperture of diameter $D$ with a central obscuration $\varepsilon$ as:

$$P(f) = \frac{1}{(1-\varepsilon^2)^2} \left[ \frac{2J_1(\pi D f)}{\pi D f} - \varepsilon^2 \left( \frac{2J_1(\varepsilon\pi D f)}{\varepsilon\pi D f} \right) \right]^2 \tag{7}$$

$J_1$ is the first order Bessel function. The scintillation in an intermediate aperture (close to GSM one $D = 10cm$) for a thin turbulent layer at an altitude h is proportional to $h^{5/3}$. Thus, The isoplanatic angle $\theta_0$ can be deduced from the scintillation index at a zenith distance $\gamma$ as:

$$\theta_0 = K\, (\sigma_I^2)^{-0.6}\, (sec\gamma)^{1.6} \tag{8}$$

where the coefficient $K$ depends on the wavelength and also on the ratio $W(h)/h^{5/3}$. For the GSM condition this ratio is fixed for $h = 10Km$ and $\lambda = 500nm$ which give a coefficient $K \sim 0.2$.

The scintillation index is computed with a resolution time of $5ms$ which is not sufficient to integrate high frequencies of the scintillation spectrum. Thus, we corrected $\sigma_I^2$ for time averaging in the same manner as for the AA variance (Sect. 2.1). Then using Eq. 8 one can provide the isoplanatic angle $\theta_0$ from scintillation index.

## 3. DATA RESULTS

The Standard data acquisition sequence consisted of 2 minutes integration time repeated every 4 minutes continuously during the night, with some gaps due to the star change, clouds passages,etc. The data have been obtained for the configuration presented in Fig.1. The observed stellar sources have been selected from a list of single bright stars that pass close the zenith. Typically, the selected star is observed one hour before meridian (due to technical limitations) and 2-3 hours after meridian. Thus, observations were obtained at zenith angles from 0° to 45°.

Since 2 years, several site testing campaigns have been made with GSM over the world (La Silla (Chili), Oukaïmeden (Morocco), Maydanak (Uzbekistan), Cerro Pachon and Paranal (Chili)). The dates of these missions are summarized in Table 1. During these campaigns additinal data on the main meteorological parameters have been provided namely ground wind speed and direction, temperature and relative humidity.

Except Oukaïmeden site, data on seeing measured by ESO DIMM were available for comparison with GSM measurements. During La Silla mission independent measurements of outer scale and seeing were obtained with the ADONIS adaptive optics system on the ESO 3.6 m telescope during 1 hour on the night of August 29/30. A good general agreement with GSM was noted.[10]

Fig. 2 to 6 show the whole main data corresponding of the different campaigns done with GSM. The AOP estimations ($\mathcal{L}_0$,$\epsilon_0$,$\theta_0$) are plotted in the same frame. The reported points represent the median value of each night measurements and the bars correspond to the rms dispersion. A first remark is that the all AOP have a slow temporal variability. Contrary, during one night a rapid variation of the $\mathcal{L}_0$ is usually observed as well as isolated 'bursts'. All of the AOP follow log-normal distributions and as is shown in table 1 a rather similar median values of $\mathcal{L}_0$ are observed at all GSM campaigns (from 22 to 32m) but with different rms dispersions.

On the other hand, the reputation of sites having good seeing conditions, has been confirmed except La Silla which gives a poor seeing ($\sim 1.7''$) due to the jet stream conditions prevailed during this mission. From Table 1 one can remark that the correlation between outer scale and seeing is not significant but a high correlation exists between the seeing and the isoplanatic angle $\theta_0$ (or scintillation). This is due to the high turbulent layers ($10\,km$, $20\,km, ...$) which are responsible of scintillation and contribute to the seeing degradation. The presence of weak scintillation (good $\theta_0$) suggests that the overall seeing was dominated by the boundary layer ($\sim 1\,km$).

## 4. TEMPORAL VARIALITY OF THE AOP

Now, the experimental results being presented, one has to ask about their temporal stability. Indeed, this question is of interest because in the AO framework the PSF calibration error is related to the temporal seeing variation between science observation and PSF calibration.[11] This question has been raised by Racine[12] for seeing prediction and for scheduling astronomical programs. To analyze this temporal variality he suggested to use the normalized difference (ND) of two measured AOP separated with $\Delta t$[12]:

$$ND_X(\Delta t) = \frac{|X(t+\Delta t) - X(t)|}{(X(t+\Delta t) + X(t))} \tag{9}$$

Fig. 7 presents this $ND$ in the case of AOP measured at La Silla observatory. As described in the previous section all of these are well fitted by log-normal distributions and the median values are reported on Table 1. The first remark is that the amplitude of this relative difference is more important in the case of the outer scale $\mathcal{L}_0$ comparatively to the seeing $\epsilon_0$ and to the isoplanatic angle $\theta_0$. On the other hand, the $\mathcal{L}_0$ and $\theta_0$ saturate more rapidly than the seeing $\epsilon_0$. Indeed, the saturated ND-curves in Fig. 7 could be fitted by an appropriate function defined by[12]: $ND_X(\Delta t) = ND_s(1 - exp(\Delta t/\tau))$; where $ND_s$ is the saturation value of $ND_X$ and is $\tau$ is the e-folding time. This function was used to fit the data by least squares minimization and as is shown in Fig. 7 it was found for the $\mathcal{L}_0$ a $\tau = 6.1mn$, for the seeing $\tau = 17.2mn$ and finally for the isoplanatic angle $\tau = 8.9mn$. If an error of 5% ($\simeq$ statistical error on DIMM seeing measurements) is bearable the corresponding change time is 1.54 minutes for $\mathcal{L}_0$, 9.2 minutes for the seeing $\epsilon_0$ and 4.2 minutes for the isoplanatic angle $\theta_0$.

## 5. CONCLUSION

The results presented here show the potentialities of the measurements that can be carried out with the GSM. Indeed, for the first time the wavefront outer scale $\mathcal{L}_0$ was monitored continuously for several nights at different astronomical sites over the world. The GSM instrument provides also measurements on the seeing $\epsilon_0$, the isoplanatic angle $\theta_0$ and the wind speed of turbulent layers to deduce the wavefront constant time $\tau_0$. Thus, the GSM instrument is the first minitor providing a complete characterisation of astronomical sites in regard of HAR techniques (AO,LBI) optimization.

From the outer scale $\mathcal{L}_0$ data provided by GSM at different sites over the world, this parameter is well fitted by an log-normal distribution with similar median values but with different rms dispersions. On the other hand, the $\mathcal{L}_0$ measurements during one night present a strong temporal variability as well as isolated 'bursts' are obeserved which lead to a parallel monitoring with HAR observations. Not significant correlation exist between the $\mathcal{L}_0$ and the seeing but there is one between the seeing and the isoplanatic angle $\theta_0$ which is due to the high turbulent layers contribution.

The GSM instrument produced an important database of the major astronomical sites over the world: La Silla, Cerro Paranal, Cerro Pachon (Chili); Oukaïmeden (Morocco) and Maydanak (Uzbekistan). Thus, all these data are studied to analyze the temporal evolution of the main optical parameters ($\mathcal{L}_0$,$\epsilon_0$,$\theta_0$) for AO and LBI optimization and the possibility of their prediction via a modelization.

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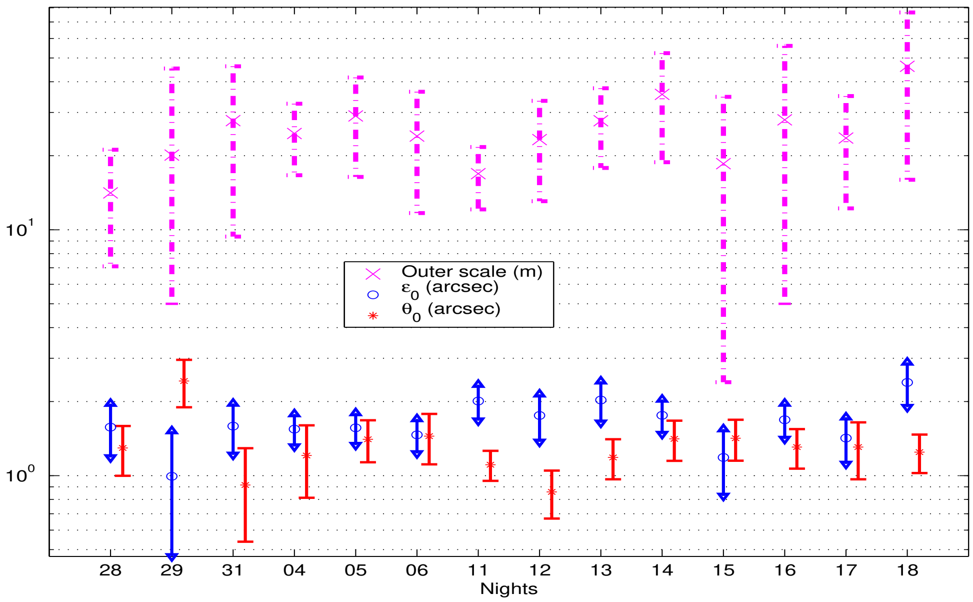


**Figure 2.** Summary of the atmospheric optical parameters ($\mathcal{L}_0$,$\epsilon_0$,$\theta_0$) statistics at La Silla observatory. The reported points represent the median value of each night measurements. The variation ranges indicated by bars correspond to the rms dispersion of the parameter measurements during one night.

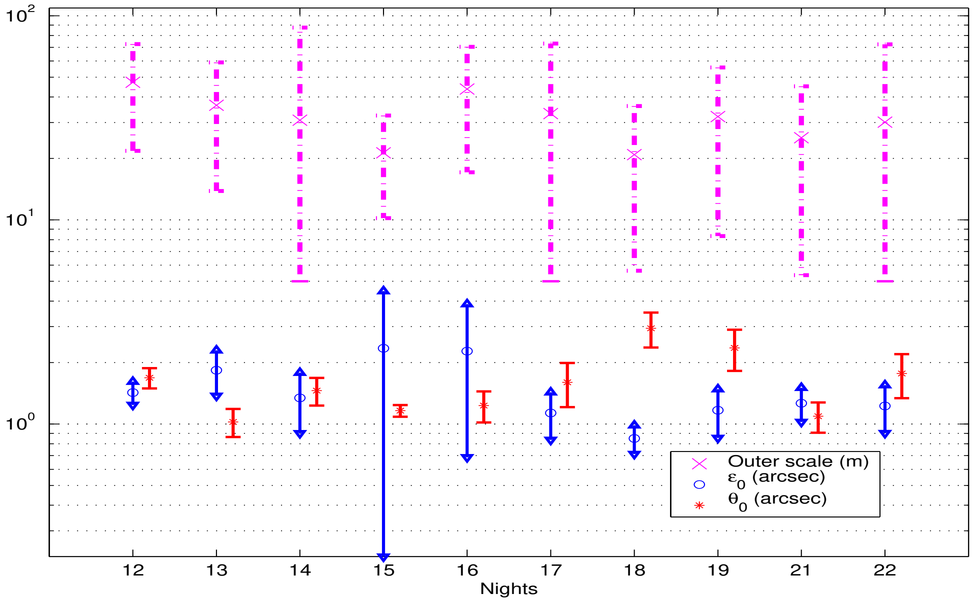


**Figure 3.** Same legend than Fig. 2 for the Oukaïmeden (Morocco) site.

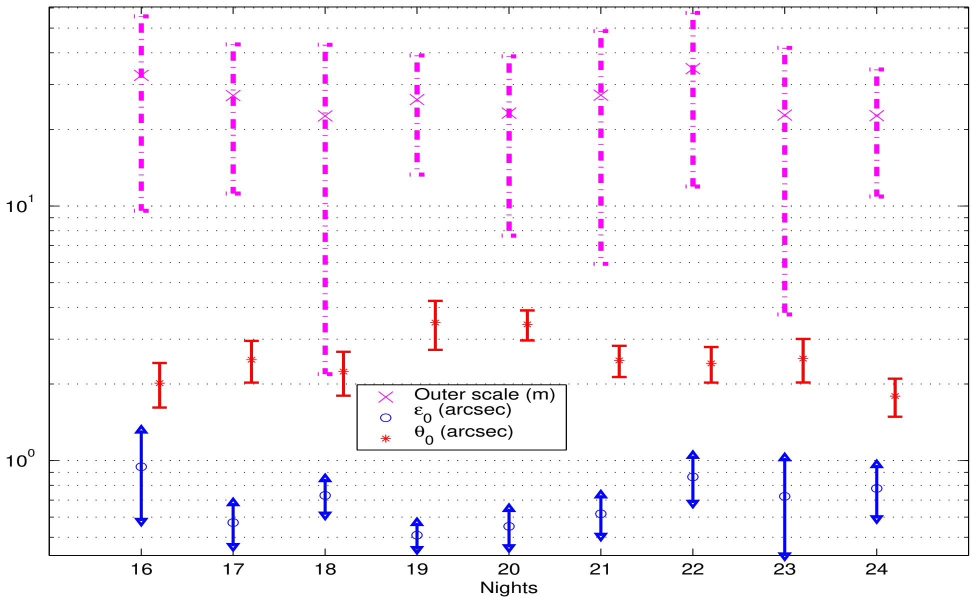


**Figure 4.** Same legend than Fig. 2 for the Maydanak (Uzbekistan) observatory.

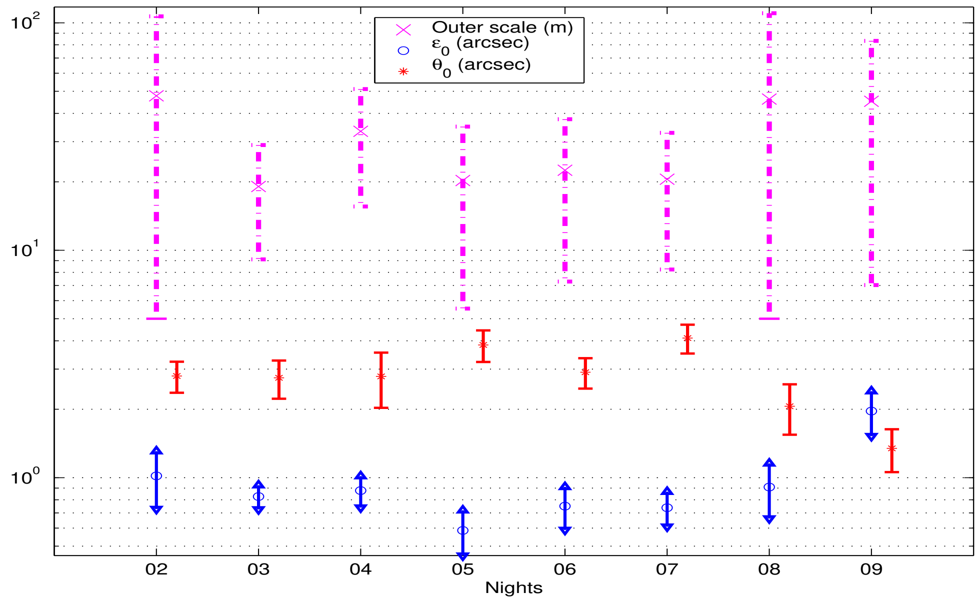


**Figure 5.** Same legend than Fig. 2 for the Cerro Pachon (Chili) site.

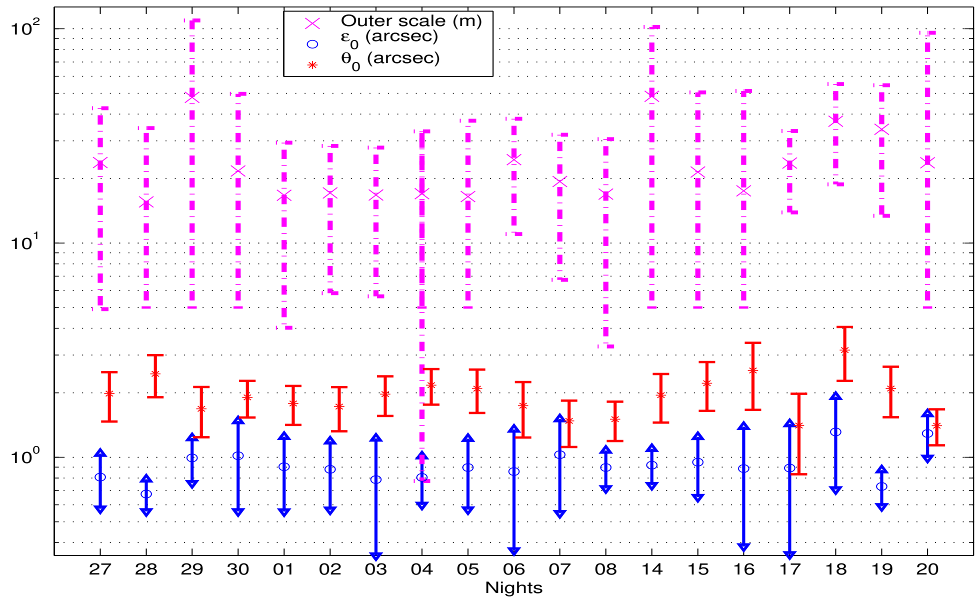


**Figure 6.** Same legend than Fig. 2 for Cerro Paranal (Chili) observatory.

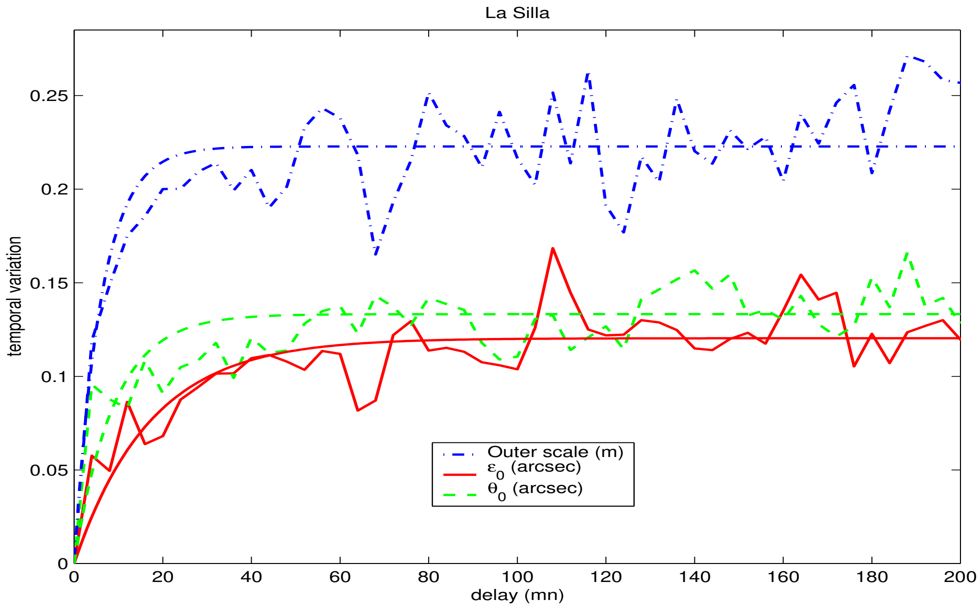


**Figure 7.** The temporal normalized difference $ND$ of the measured optical parameters ($\mathcal{L}_0$,$\epsilon_0$,$\theta_0$) obtained with GSM at La Silla observatory.

| Site | Date | *Seeing* $\varepsilon_0$ $(as)$ | *Outerscale* $\mathcal{L}_0$ $(m)$ | *Isoplanatic angle* $\theta_0$ $(as)$ |
|---|---|---|---|---|
| La Silla | 08/26/97 09/20/97 | 1.68 ± 0.47 | 24.8 ± 19.3 | 1.26 ± 0.42 |
| Oukaïmeden | 04/10/98 04/25/98 | 1.33 ± 0.90 | 31.1 ± 34.8 | 1.50 ± 0.69 |
| Maydanak | 07/16/98 07/25/98 | 0.66 ± 0.25 | 25.9 ± 19.0 | 2.48 ± 0.70 |
| Cerro Pachon | 10/02/98 10/09/98 | 0.83 ± 0.46 | 26.7 ± 33.5 | 2.82 ± 097 |
| Cerro Paranal | 11/27/98 12/20/98 | 0.88 ± 0.40 | 22.1 ± 33.9 | 1.90 ± 0.69 |

**Table 1.** Data summary of the sites visited by GSM.