RevMexAA (Serie de Conferencias), **19**, 31–36 (2003)

WAVEFRONT OUTER SCALE MEASUREMENTS AT SAN PEDRO MÁRTIR OBSERVATORY. ITS IMPACT ON ADAPTIVE OPTICS PERFORMANCES

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RESUMEN

Se presentan las primeras mediciones de la escala externa de coherencia espacial $\mathcal{L}_0$ en el Observatorio Astronómico Nacional de San Pedro Mártir, México. Dicho parámetro fue medido con el monitor generalizado de seeing de la Universidad de Niza, Francia. Se encuentra una distribución log-normal con valor mediano de 27.0 m. La importancia de $\mathcal{L}_0$ en la derivación del desempeño de la óptica adaptativa (OA) es analizada. Se demuestra que valores bajos de $\mathcal{L}_0$ incrementan las habilidades correctoras de la OA de bajo orden, pero no tienen prácticamente ningún efecto en OA de alto orden.

ABSTRACT

The first measurements of the spatial coherence outer scale $\mathcal{L}_0$ at the Observatorio Astronómico Nacional at San Pedro Mártir, Mexico, are reported. This parameter was measured with the Generalized Seeing Monitor of Nice University, France. A log–normal distribution is found with a median value of 27.0 m. The importance of $\mathcal{L}_0$ in the derivation of adaptive optics (AO) performances is discussed. It is shown that low $\mathcal{L}_0$ values boost the corrective ability of low–order AO, but have almost no effect on high–order AO performances.

Key Words: **ATMOSPHERIC EFFECTS — TURBULENCE — SITE TESTING — TECHNIQUES: HIGH ANGULAR RESOLUTION — INSTRUMENTATION: ADAPTIVE OPTICS**

San Pedro Mártir: Astronomical Site Evaluation (México, D. F. and Ensenada, B. C., México, April 3-4, 2003)
Editors: Irene Cruz-González, Remy Avila & Mauricio Tapia

1. INTRODUCTION

In recent years, astronomical High Angular Resolution (HAR) facilities have seen a fast improvement and deployment. The two leading techniques which are Adaptive Optics (AO) and long baseline interferometry benefit from a better modeling and knowledge of the optical effects of atmospheric turbulence (Avila & Vernin 1998; Masciadri, Avila, & Sánchez 2002; Masciadri, Vernin, & Bougeault 2001; Masciadri & Garfias 2001). Several atmospheric parameters are monitored to still improve existing models for the design of HAR facilities. Among them, we can cite the turbulence profile $C_\mathrm{n}^2(z)$ (Avila 1998; Avila, Vernin, , & Masciadri 1997; Avila, Vernin, & Cuevas 1998; Avila, Vernin, & Sánchez 2001), the Fried's parameter r_0 (Fried 1966), the wavefront outer scale $\mathcal{L}_0$, the isoplanatic angle (Fried 1976; Roddier, Gilli, & Vernin 1982), and the atmosphere coherence time (Roddier, Gilli, & Lund 1982).

Here we present, in § 2, the first measurements of the outer scale $\mathcal{L}_0$ at the Observatorio Astronómico Nacional at San Pedro Mártir (OAN–SPM), Baja California, México, held by the Instituto de Astronomía of the Universidad Nacional Autónoma de México (IA-UNAM). The results have been reported in a previous paper by Conan et al. (2002). The measurements of $\mathcal{L}_0$ were obtained with the Generalized Seeing Monitor (GSM) of the Laboratoire Astrophysique Universitaire de Nice (LUAN). This instrument has been utilized for similar studies at several observatories around the world: ESO La Silla (Chile), ESO Paranal (Chile), Oukaïmeden (Morocco), Maidanak (Uzbekistan), Cerro Pachón (Chile), Mauna Kea (Hawaii, USA).

$\mathcal{L}_0$ has a strong impact on the performances of HAR instrumentation (Conan 2000; Conan et al. 2000). In § 3, the effects of $\mathcal{L}_0$ for imaging with Extremely Large Telescopes with or without an AO system are emphasized.

2. THE MEASUREMENT CAMPAIGN

2.1. *The Generalized Seeing Monitor*

This instrument was developed at the LUAN, France. Several articles provide extensive descriptions of the GSM since its early development until its last missions. The initial version of GSM is presented by Martin et al. (1994). Avila (1998), Martin et al. (1998b), and Tokovinin et al. (1998b) describe

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the instrument used for the measurements reported here. A detailed description of the instrument and an analysis of its performances are given by Ziad et al. (2000). We also refer the interested reader to the reports on the previous GSM missions (Martin et al. 1998b; Tokovinin et al. 1998a; Martin et al. 1998a).

At the OAN-SPM, the GSM modules and their mounts were installed on top of 3 concrete pillars, the telescopes being 1.5 m above ground. A wind-protective enclosure consisting of 2-m-high-nets was installed, covering South, East and West sides around the instrument. The angle of arrival fluctuations are measured for two integration times, 5 ms and 10 ms, and their variance is extrapolated to an integration time of 0 ms (Ziad et al. 2000). The angle of arrival fluctuations are recorded during two minutes and processed to provide the Fried's parameter r_0, the wavefront outer scale $\mathcal{L}_0$ and the isoplanatic angle θ_0. The GSM worked 8 nights from 3 - 13 December 2000, gathering a total of 556 measurements of each of these parameters.

2.2. *The wavefront outer scale*

The median value of $\mathcal{L}_0$ measured in the whole observing campaign is equal to 27.0 m. The histogram of $\mathcal{L}_0$, given in Fig. 1, shows a log–normal statistics.

An example of typical variations of $\mathcal{L}_0$ during one night is given in Fig. 3. The median value for this night is 20 m with a standard deviation of 16 m. At the beginning of the night, a sudden high $\mathcal{L}_0$ value has been measured. This kind of large isolated values have been already noticed in previous campaigns of the GSM and have been called "bursts".

The former monitoring of $\mathcal{L}_0$ made with the GSM, in other astronomical sites, gave also log–normal distributions. The median values obtained at the different sites are very similar to each other, ranging from 24 to 31 m and in every case the dispersion of $\log(\mathcal{L}_0)$ is about 0.23.

The histogram of r_0 measured by the GSM for a wavelength of 2.2 μm is shown in Fig. 2. These values along with those of $\mathcal{L}_0$ will be used for the statistical analysis of the AO performances in §3.2.

3. OUTER SCALE IMPACT ON AO PERFORMANCES

3.1. *A theoretical point of view*

Here some theoretical results are presented emphasizing the importance of $\mathcal{L}_0$ in imaging through turbulence. Accent is put on the Extremely Large Telescopes (ELT) performances for both cases with and without AO.

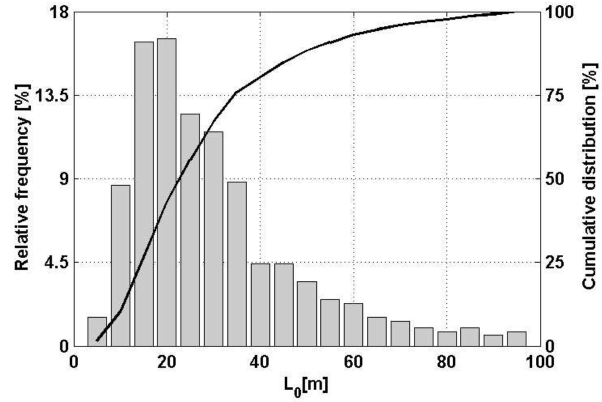

Fig. 1. Histogram of $\mathcal{L}_0$ values for the whole GSM campaign.

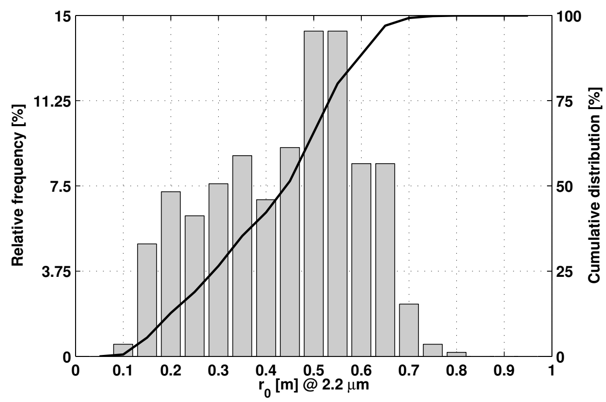

Fig. 2. Histogram of r_0 values in K (2.2 μm) for the whole GSM campaign.

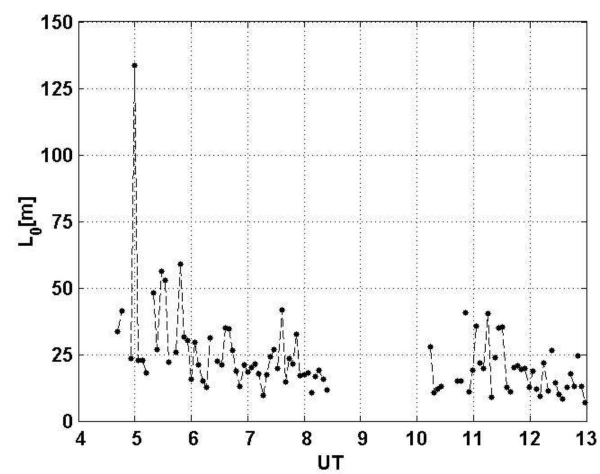

Fig. 3. $\mathcal{L}_0$ values measured by the GSM during the night of 2000 December 8th to 9th.

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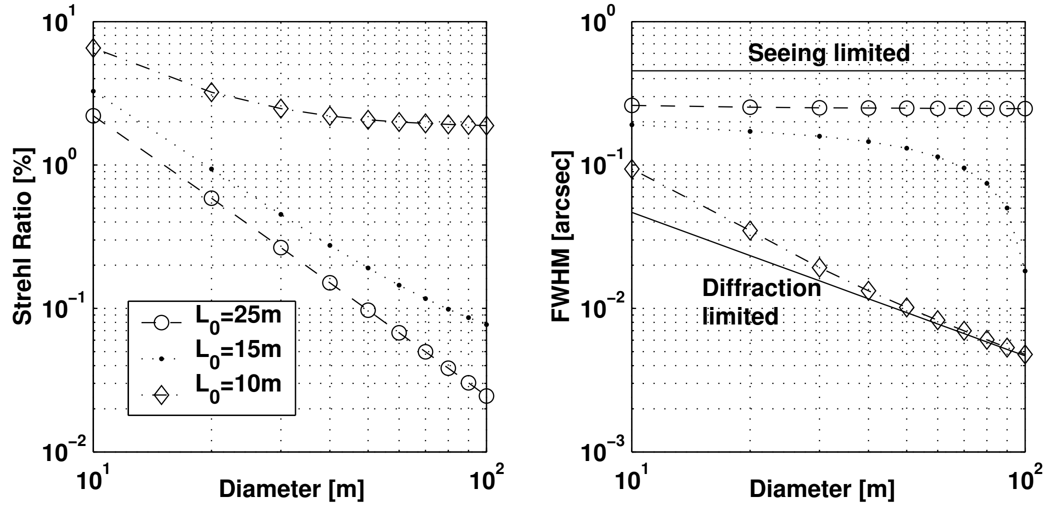

Fig. 4. Strehl ratio (left panel) and full width at half the maximum (FWHM) (right panel) plotted versus the telescope diameter for $\mathcal{L}_0$ values of 10 m, 15 m and 25 m and a single r_0 value of 1 m in K(2.2 μm). On the right panel, the full lines give the diffraction limited and seeing limited FWHM bounds.

The point–spread function (PSF) at the focus of a telescope after propagation of the astrophysical wave through the Earth turbulent atmosphere can be characterized with two parameters: the Strehl ratio (SR) and the full width at half maximum (FWHM). In Fig. 4, these parameters are plotted versus the telescope diameter. On each panel, three curves are shown corresponding to three $\mathcal{L}_0$ values, 10, 15 and 25 m. The r_0 value is fixed to 1 m. On the right panel the FWHM variation laws are represented and the diffraction and seeing FWHM limits are indicated.

Surprisingly, when $\mathcal{L}_0$ becomes very small compared to the telescope diameter, the FWHM of the turbulent PSF reaches the diffraction limited PSF (Fig. 4 right panel). The SR remains small (lower than 10%) but higher than for the larger $\mathcal{L}_0$. The SR values vary from 6% to 2%.

Such an effect can be understood looking at Fig. 5 where the modal expansion of the wave–front phase is plotted as a function of the Karhunen–Loeve modes (Cannon 1996). The cases for the telescopes like the Very Large Telescope (VLT) and the Overwhelmingly Large telescope (OWL) are shown, each for $\mathcal{L}_0$ values of 25 m and 500 m and an r_0 value of 1 m at K.

At first glance, we see that the integrals over the modes of the modal expansions decrease when $\mathcal{L}_0$ decreases with respect to the diameter. These integrals correspond to the total wavefront phase variance. As the SR varies inversely with respect to the variance, it increases when $\mathcal{L}_0$ decreases with respect to D. This is what we see on the left panel of Fig. 4: a global improvement of the SR when $\mathcal{L}_0$ is smaller than the diameter.

On Fig. 5, we see also that for each of the telescope–types considered, the loss in the phase energy when $\mathcal{L}_0$ decreases affects first the low order modes, the very first ones (piston, tip and tilt) being the most attenuated. Remembering that the enlargement of the turbulent PSF due to the wandering of the stellar image at the telescope focus is mainly the result of the fluctuations of the tip–tilt mode, if these ones are considerably reduced only a tiny motion remains giving a long–exposure image with a core width close to the diffraction–limited–PSF FWHM. This is what is shown on the left panel of Fig. 4: a tendency to reach diffraction limited FWHM when $\mathcal{L}_0$ decreases with respect to the diameter.

Figure 6 is an illustrative example of the former remarks in the case of OWL restricted to a full aperture of 100 m diameter. It shows the diffraction limited PSF in the rightmost graph and from left to right, the turbulent PSFs corresponding to four decreasing $\mathcal{L}_0$ values (1000 m, 25 m, 15 m and 10 m) and an r_0 value of 80 cm. Again, this peculiar behavior due to the constraint added by $\mathcal{L}_0$ on the phase total energy and on the phase spectrum is put in evidence.

3.2. *An experimental point of view*

After having presented the theory, a similar analysis can be followed using the measurements of $\mathcal{L}_0$ and r_0 obtained with the GSM during the campaign at the OAN–SPM.

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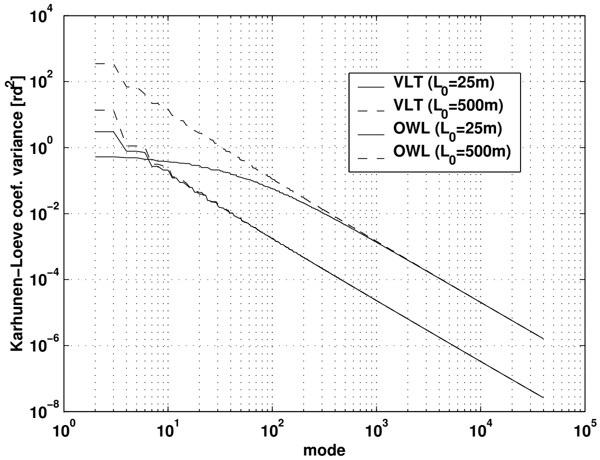

Fig. 5. Modal spectrum of the wave front phase when this one is expanded on a Karhunen–Loeve basis of 40.10^3 modes. Two kind of telescopes are compared: the VLT with a diameter of 8 m and a central obscuration ratio of 0.14 and OWL with a diameter of 100 m and a central obscuration ratio of 1/3. Full and dashed lines correspond respectively to outer scales of 25 m and 500 m. The r_0 value has been fixed to 1 m at K(2.2 μm).

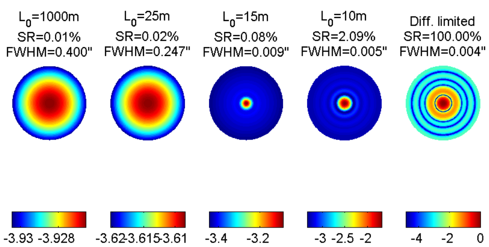

Fig. 6. OWL (full 100m–diameter aperture) PSFs. The rightmost graph gives the diffraction limited case. From left to right, four PSFs are plotted for $\mathcal{L}_0$ values of 1000 m, 25 m, 15 m and 10 m, respectively. All the PSFs are computed in the K band (2.2 μm). The r_0 value is 80 cm and no AO correction is emulated for the computation of the PSFs.

The goal of this section is to show the distribution of the expected values of some parameters relevant for imaging with and without AO, at the OAN–SPM. These parameters are computed for every couple of values $[r_0(t), \mathcal{L}_0(t)]$ in the K-band obtained during the observing campaign, using theoretical formulas (Conan 2000; Voitsekhovich & Cuevas 1995; Voitsekhovitch, Orlov, & Avila 1998; Voitsekhovich 1995; Orlov, Voitsekhovich, & Cuevas 1998; Wang & Markey 1978; Whiteley, Roggemann, & Welsh 1998; Dai 1996). Four telescope diameters are considered: 10 m, 30 m, 50 m and 100 m.

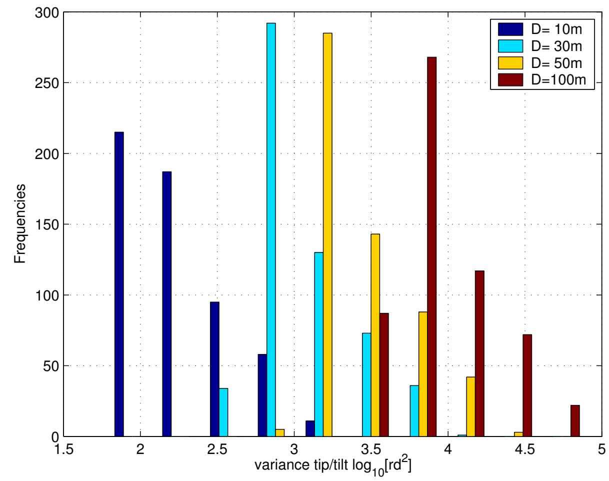

Fig. 7. Histograms of the tip–tilt variance calculated using r_0 values measured at SPM but an infinite outer scale. The histograms are computed for telescope diameters of 10, 30, 50 and 100 m.

In § 3.1, the importance of the tip–tilt mode in image formation with ELTs has been demonstrated. The histograms in Figs. 7 and 8 show the distribution of the tip–tilt variance for the four telescope diameters. Fig. 7 corresponds to an infinite outer scale and in Fig. 8 the measured $\mathcal{L}_0$ values are used. From these histograms, two things can be noticed. First, the range of values of the tip–tilt variance obtained with the measured $\mathcal{L}_0$ values is much smaller than in the case of an infinite outer scale. Second, the mean tip–tilt variance increases with the diameter when $\mathcal{L}_0$ is infinite and it is the contrary for the measured $\mathcal{L}_0$. This is a very significant impact of the outer scale values on the tip–tilt energy and consequently on the long exposure image patterns.

The histograms in Figs. 9 and 10 illustrate the effect of $\mathcal{L}_0$ in a high–order AO system. These histograms show the distributions of the variance of the residual phase that remains uncorrected when the first 136 Zernike polynomials are perfectly removed from the original wavefront using an ideal noise–free AO system. Fig. 9 corresponds to an infinite outer scale and in Fig. 10 the measured values are used.

There is very little difference between Figs. 9 and 10. This result – expected from the theoretical result on Fig. 5 – demonstrates that almost no performance gain results from small $\mathcal{L}_0$ values for high–order AO. This is because a small $\mathcal{L}_0$ value reduces first the low order modes and once these are perfectly corrected, there only remains the high order modes which are approximately the same for every telescope diameter.

So, small $\mathcal{L}_0$ values with respect to the telescope

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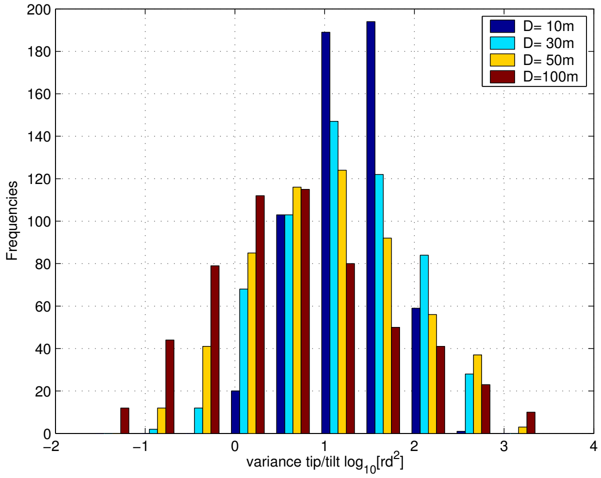

Fig. 8. Similar to Fig. 7 but for $\mathcal{L}_0$ values measured at the OAN-SPM.

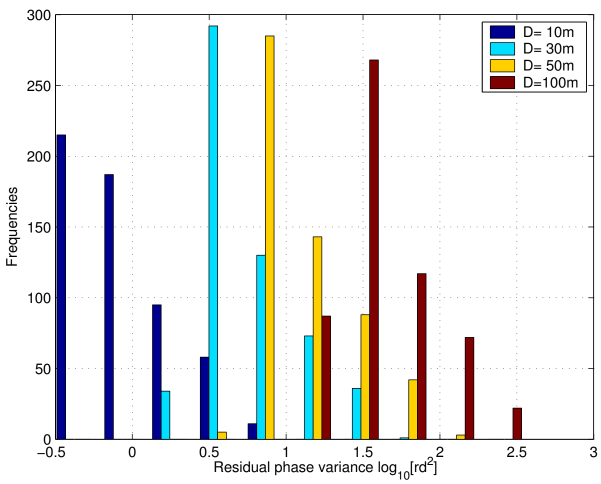

Fig. 9. Histograms of the variance of the residual phase after perfect correction of the first 136 Zernike polynomials. The variances are computed using r_0 values measured at SPM but an infinite outer scale. The histograms are computed for telescope diameters of 10, 30, 50 and 100 m.

diameter bring a huge improvement of the performances of low–order AO but almost none for high–order AO. If $\mathcal{L}_0$ is much smaller than the telescope diameter, the low-order modes of the wavefront may have extremely low energy.

4. CONCLUSIONS

Measurements of $\mathcal{L}_0$ at the OAN-SPM performed with the GSM have been presented. A median value of 27 m has been found along with a log–normal statistics. Sporadic $\mathcal{L}_0$ bursts appear on some nights.

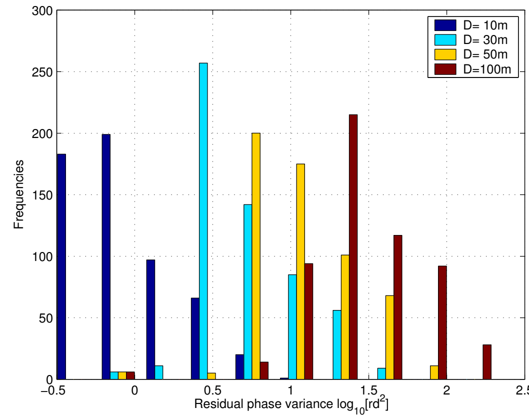

Fig. 10. Similar to Fig. 9 but for $\mathcal{L}_0$ values measured at the OAN-SPM.

Very similar results have been obtained at other astronomical sites.

The impact of $\mathcal{L}_0$ values on AO performances has been studied theoretically. We show that the SR and FWHM of the PSF improve when $\mathcal{L}_0$ is much smaller than the telescope diameter. In such favorable conditions, the lowest mode of the phase expansion is very strongly attenuated. This would allow to obtain near–diffraction–limited images with ELTs without AO or with low–order AO. However, when high–order AO are needed, like for coronagraphy, the effects of $\mathcal{L}_0$ on the performances of such AO devices are negligible.

The GSM campaign at the OAN–SPM gives only a snapshot of $\mathcal{L}_0$ values at the site. Longer missions performed in different periods of the year during a few years would bring valuable information concerning the temporal/seasonal variation of this parameter. As an example, the favorable turbulence conditions for ELTs are those when there is coincidence of high r_0 and small $\mathcal{L}_0$ values. During the GSM campaign at the OAN–SPM, in 2% of the data the values of r_0 and $\mathcal{L}_0$ were above 70 cm (K band) and below 15 m simultaneously. To reach the highest gain in AO systems for ELTs, the values of r_0 and $\mathcal{L}_0$ must be higher than 80 cm (K band) and lower than 10 m, respectively. 4% of $\mathcal{L}_0$ values obtained in the campaign were below 10 m, but these values did not occur when r_0 was larger than 80 cm. GSM measurements during other periods of the year, particularly in summer time, may give more optimistic results.

Anyway, the OAN-SPM has $\mathcal{L}_0$ values in the range of those measured on others sites (e.g. Cerro Paranal, Mauna Kea) and from this point of view it can be envisaged as a serious host observatory for future ELTs.

We are grateful to the OAN–SPM staff for their valuable support. This work was done in the framework of a collaboration between the Instituto de Astronomía of the Universidad Nacional Autónoma de México and the UMR 6525 Astrophysique, Université de Nice–Sophia Antipolis (France), supported by ECOS–ANUIES grant M97U01. Funding was also provided by the grants J32412E from CONACyT, IN118199 from DGAPA–UNAM, and the TIM project (IA-UNAM).

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