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A site-testing campaign at the Calar Alto Observatory with GSM and DIMM instruments

A. Ziad,[1⋆] R. Gredel,[2⋆] J. Aceituno,[3] J. Borgnino,[1] F. Hoyo,[3] A. Irbah,[4] F. Martin,[1] U. Thiele[3] and S. Pedraz[3]

[1]*Laboratoire Universitaire d'Astrophysique de Nice – UMR 6525, Université de Nice–Sophia Antipolis, Parc Valrose, 06108 Nice Cedex 2, France*
[2]*Max-Planck-Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany*
[3]*Centro Astronómico Hispano Alemán, Jesús Durbán Remón, E-04004 Almería, Spain*
[4]*Service d'Aéronomie – CNRS, BP-63, 91371 Verrières le Buisson Cedex, France*

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ABSTRACT

The main atmospheric optical parameters have been measured at the Calar Alto Observatory simultaneously using the Generalized Seeing Monitor (GSM) and a Differential Image Motion Monitor (DIMM) during several nights in 2002 May. The temporal evolution of the seeing, the outer scale, the isoplanatic angle and the coherence time have been analysed. There is excellent agreement between the seeing measurements provided by the two instruments, particularly when the turbulence is slow. Indeed, the GSM measurements are corrected from the exposure time when the DIMM data were recorded for at least 5 ms. From almost three years of DIMM (at 5 m height above ground) data, a seeing of 0.92 arcsec with a standard deviation of 0.31 arcsec has been obtained for this site. The outer scale $\mathcal{L}_0$, the isoplanatic angle θ_0 and the coherence time τ_0 measured with the GSM are well fitted with log-normal distributions with median values of 22.9 m, 2.27 arcsec and 3.7 ms, respectively.

Key words: atmospheric effects – site testing.

1 INTRODUCTION

Since the 1970s, various techniques have been developed to achieve diffraction-limited resolution of observing instruments, namely speckle and long-baseline interferometry as well as adaptive optics (AO). In order to maximize the performance of the high angular resolution (HAR) methods, a deep understanding of the behaviour of wavefronts perturbed by atmospheric turbulence is required. The wavefronts are described in terms of atmospheric optical parameters (AOP). Among these parameters are the Fried coherence size r_0, which is related directly to the seeing ϵ_0 (Dierickx 1992), the spatial coherence outer scale $\mathcal{L}_0$, the isoplanatic angle θ_0 and the wavefront coherence time τ_0. The performance of an AO system depends critically upon the seeing conditions. Indeed, the power in the lowest Zernike aberration modes (e.g. tip and tilt) (Winker 1991; Conan 2000) and the overall stroke required for an AO system (Le Louarn et al. 2000) can be much reduced for small $\mathcal{L}_0$. A finite outer scale has implications for interferometry as well. The outer scale $\mathcal{L}_0$ is a critical parameter for co-phasing an interferometer (Mariotti 1994). With the current interest in the design of extremely large ground-based optical and infrared telescopes (Nelson 2002; Dierickx et al. 2002), reliable estimates of the true size of the outer scale have assumed considerable importance. On the other hand, the choice of the AO reference star must take into account constraints related to the isoplanatic angle. Finally, knowledge of the wavefront coherence time τ_0 is of interest to optimize the exposure time. Indeed, the total accumulated number of photons increases with exposure time τ, while the image quality degrades.

The optical parameters of the perturbed wavefront can be measured by observing angle of arrival (AA) fluctuations. The Generalized Seeing Monitor (GSM) has been developed by the Laboratoire d'Astrophysique of Nice University and is designed to measure the AA fluctuations. The instrument uses the same principle as a Shack–Hartmann, i.e. measuring AA at different points of the wavefront and computing AA spatiotemporal correlations leads to estimates of the whole AOP ϵ_0, $\mathcal{L}_0$, θ_0 and τ_0. Since 1997, the GSM has been used for the evaluation of major astronomical sites all over the world, and has thus become a reference instrument for site testing.

The present paper describes the results of an observing campaign of the GSM at the Calar Alto Observatory [Centro Astronómico Hispano Alemán (CAHA)] in 2002 May. CAHA is located at an altitude of 2168 m in the Sierra de Los Filabres, Andalucia, Spain (longitude 02° 32′ 48″ west; latitude 37° 13′ 16″ north). It provides three telescopes with apertures of 1.23, 2.2 and 3.5 m. A 1.5-m telescope is operated under the control of the Observatory of Madrid. Calar Alto was chosen in 1970 as the site for the observatory after several years of site testing in the Mediterranean area. An initial agreement for

⋆E-mail: ziad@unice.fr (AZ); gredel@caha.es (RG)

30 yr was signed in 1973 between the Max-Planck Society and the Comisión Nacional de Astronomía (CNA) for the operation of the observatory. Construction work on Calar Alto started in the summer of 1973 and 2 yr later the 1.2-m telescope was installed, which at the time was the biggest telescope of the Federal Republic of Germany. In the years to follow, an 0.8-m Schmidt telescope, and the 2.2-m and 3.5-m telescopes were installed by the Max-Planck Society. A 1.5-m telescope operated by the Observatorio Astronómico Nacional of Madrid and a fully robotic 0.5-m telescope operated by the Instituto Nacional de Tecnica Aerospatial (INTA) Madrid complement the CAHA instruments. In 2004, a new agreement was signed between the Max-Planck Society and the Spanish Consejo Superior de Investigaciones Cientificos (CSIC) which secures the operation of CAHA for the next 10 yr. The new agreement replaces the CNA as partner. CAHA is now jointly operated by the Max-Planck-Institut für Astronomie in Heidelberg (MPIA) and the Instituto de Astrofísica de Andalucía in Granada (IAA).

Since 2001, a commercially acquired Differential Image Motion Monitor (DIMM) from LHESA Electronique, Paris, has been used for seeing measurements at Calar Alto. While the Calar Alto DIMM only measures the seeing, the GSM allows the measurement of all the atmospheric optical parameters. The present paper describes the results of the joint GSM and CAHA-DIMM campaign of 2002 May. The two instruments are described in detail in Section 2. Section 3 summarizes the measurement campaign, and a discussion is given in Section 4.

2 THE CALAR ALTO CAMPAIGN INSTRUMENTS

2.1 The GSM instrument

The GSM consists of four 10-cm telescopes on equatorial mounts (Fig. 1) equipped with detection modules measuring the AA fluctuations and interfaced to a PC managing the four modules simultaneously. Each telescope, pointing at the same star, measures the AA fluctuations by means of flux modulation, which is produced by the displacement of the star image over a Ronchi grating. The flux transmitted through the grating is detected by a photomultiplier working in the photon-counting mode. Two telescopes are installed on a common mount on a central pier (Fig. 1) working as a DIMM with a 25 cm baseline. The other two telescopes have different mounts on separate piers, located 0.8 m to the south and 1 m to the east of the central pier, thus forming an L-shaped configuration, which has been chosen for more sensitivity to the outer scale. The telescopes were situated 1.7 m above the ground.

Figure 1. The DIMM and GSM configuration at the Calar Alto site in 2002 May.

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

The AA covariances are computed for each baseline (six baselines with four GSM modules) and normalized by the differential variance of AA on the 25-cm baseline. They are compared to Von Kàrmàn theoretical normalized covariances and the appropriate $\mathcal{L}_0$ is found for each baseline. The final value of $\mathcal{L}_0$ is taken as the median of the six individual $\mathcal{L}_0$ values and its error is estimated. The seeing ϵ_0 is calculated from the differential variance given by the coupled modules as in the DIMM instrument (Sarazin & Roddier 1990). The scintillation index σ_I^2 is computed during data reduction, from which estimate of the isoplanatic angle is deduced (Ziad et al. 2000).

We also employ here a new method for estimating the AA coherence time $\tau_{0,\mathrm{AA}}$ in real time as described by Ziad et al. (2004). This method consists of processing the AA temporal structure function. The AA fluctuations are measured at regular time intervals τ (multiples of 5 ms) with the GSM module. This temporal structure function $\sigma_\alpha^2(r, \tau)$ saturates for large values of τ; the point at which the structure function reaches 1/e of this maximum corresponds to the AA coherence time. In order to distinguish this parameter from τ_0, which is deduced from the wavefront phase structure function (Roddier 1999), we will denote the GSM coherence time as $\tau_{0,\mathrm{AA}}$.

A quantification of the various noise in the GSM has been performed, and hence corrections for photon and scintillation noise are done before data processing. The exposure time correction is also performed, which consists of a linear extrapolation from 5-ms and 10-ms measurements to the 0-ms exposure time. Finally, the statistical errors of the computed variances and covariances are estimated, and consequently the errors of the AOP measured with GSM are provided.

In order to check the wind shake effect, r_0 is computed from absolute image motion in each telescope, corrected for finite $\mathcal{L}_0$ and compared to r_0 provided by the differential technique. Good agreement is found for ground wind speed less than 10 m s^{-1}, showing that telescope vibrations are not significant.

A complete description of the GSM instrument is given by Ziad et al. (2000).

2.2 The Calar Alto DIMM

The Calar Alto DIMM is a two-aperture Differential Image Motion Monitor from LHESA Electronique, very similar to the one described by Vernin & Muñoz-Tuñón (1995). Mainly, the system consists in a C8 Schmidt–Cassegrain telescope from Celestron on a motorized German equatorial mount (GTO-400, Astro-Physics) with automatic guiding capabilities. The telescope is equipped at its entrance pupil with a diaphragm having two 60-mm sub-apertures separated by 140 mm and a wedge prism (30 arcsec deviation angle) placed on one of them, producing a twin image of the same star. This information is captured by an intensified camera (LH-760, LHESA Electronique) and send to the PC via a framegrabber (Matrox Meteor-II). The total focal length of the system is increased to 3 m with a single eyepiece to match the pixel size of 0.5 arcsec.

The PC computes the variance of the differential motion of the two images of the star in two directions, perpendicular and parallel with respect to apertures, giving two independent values for r_0, and consequently two values for the classical astronomical seeing. A detailed description of the algorithm used by the Calar Alto DIMM is given by Sarazin & Roddier (1990). The advantage of the differential method is that problems arising from DIMM tracking and wind shake will cancel out. The two seeing values derived from the two motion directions should be identical. However, during strong winds, the longitudinal and perpendicular values may differ (Martin 1987). The differences can be minimized if the exposure time is decreased, and disappear when the exposure time effect is corrected (Tokovinin 2002). The CAHA-DIMM is operated with an exposure time of 5 ms. Seeing values are referred to zenith, taking into account the airmass correction, and using a zenith angle smaller than 30°. The standard deviation of the wavefront tilt differences in both directions is calculated on 300 such short exposures. This corresponds to a seeing estimation approximately every 30 s.

2.3 GSM-DIMM configuration at the site

The on-site mission preparation on Calar Alto consisted in the building of three piers to support the different GSM modules. These piers were built on a platform at 20 m in the north-west direction from the office building on Calar Alto. The piers had a compact L-shaped configuration, as described in Section 2.1. The DIMM instrument has been installed at the same place and at the same level from the ground for direct comparison to the GSM (Fig. 1) .

Observations were carried out remotely from the office building. With a prevailing wind from the north-north-west, these instruments were supposed to be free from the locally generated turbulence, and the building was not troublesome either. On the other hand, with a south-east wind, the GSM and DIMM were in the turbulent lee created by the building.

A star was selected from a list of single bright stars of 2–3 mag and passing close to zenith at the Calar Alto site during this season. Owing to the limitation of the possible hour angles (in the GSM configuration adopted the telescopes could not be pointed at hour angles less than 1 h after meridian because they touched the piers), the selected star was usually some 30–40 min after meridian at the end, and 2–3 h before meridian at the start of its observations (depending on the availability of a more suitable source). Thus, observations were obtained at zenith angles from 0° to 45°. The DIMM used the same targets for a direct comparison to the GSM.

After pointing to the source, the GSM telescopes were focused by maximizing the modulation contrast. Then, the acquisition sequence was started, interrupted every 30–40 min for re-centring of the star in the field of view. The signal was normally recorded for 2 min, and these acquisitions were repeated every 4 min. Occasionally, longer or shorter acquisition times were used for exploratory purposes. Immediately after each acquisition the data were transferred to the hard disk and processed.

3 RESULTS OF THE CALAR ALTO CAMPAIGN

A summary of the different results obtained with the GSM is presented in Fig. 2 and Table 1. We can see the night-by-night evolution of $\mathcal{L}_0, \epsilon_0, \theta_0$ and $\tau_{0,\mathrm{AA}}$ measurements obtained at this site in 2002 May. Each measurement corresponds to 2 min acquisition time and obtained every 4 min. All atmospheric parameters are calculated for the wavelength $\lambda = 0.5$ μm. We remark that the number of data N (Table 1) recorded during one night depends on the meteorological conditions (cloud passages, strong wind, ...), on the observed star change and on technical problems of the instrument. Despite this, for this campaign the mean measuring time was more than 4 h per night, providing a high number of measurements of the seeing, outer scale, isoplanatic angle and coherence time. We also note that the mean values of the outer scale $\mathcal{L}_0$ obtained at the Calar Alto Observatory is rather similar compared to other sites (Ziad et al. 2000). However, as shown in Table 1, for some nights $\mathcal{L}_0$ presents small median values. The distributions of the AOP $\epsilon_0, \mathcal{L}_0, \theta_0$ and $\tau_{0,\mathrm{AA}}$ are well fitted by a log-normal law as shown in Fig. 3.

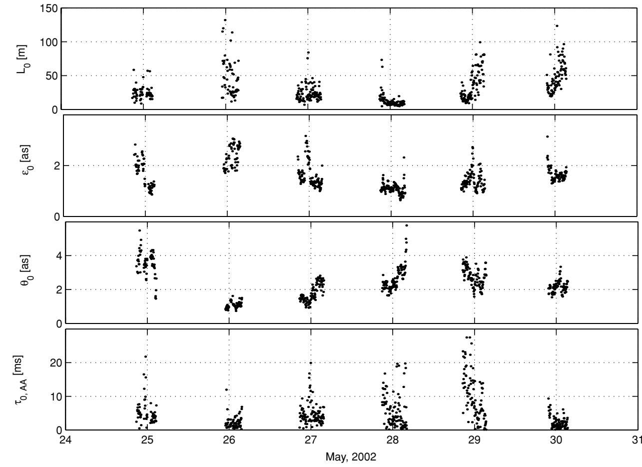

Figure 2. Summary of the AOP data measured during six nights at the Calar Alto site in 2002 May.

Table 1. The night-by-night evolution of the GSM results obtained during the campaign at the Calar Alto Observatory in 2002 May. N is the number of data values, where each one is recorded during 4 min (not necessarily consecutively).

Date (2002 May)	N	ϵ_0 (arcsec)	L_0 (m)	θ_0 (arcsec)	$\tau_{0,\mathrm{AA}}$ (ms)
25	60	1.68	22.3	3.54	4.32
26	59	2.30	36.0	1.05	1.89
27	95	1.43	21.5	1.66	4.00
28	100	1.09	9.0	2.42	3.77
29	95	1.34	27.9	2.71	8.11
30	78	1.58	45.2	2.16	1.79

One can remark that, when the seeing conditions are stable (night of May 28 in Fig. 1), the $\tau_{0,\mathrm{AA}}$ values are large. At the time-scale of one night the $\mathcal{L}_0$ presents decametre values (Fig. 2) with a log-normal distribution and some bursts corresponding to newly generated turbulence (Ziad et al. 2000). These bursts have been noticed at all visited sites and typically last for a few minutes. The $\mathcal{L}_0$ is highly variable (Ziad et al. 1999), which means that it would be desirable to monitor this parameter for the optimization of adaptive optics systems and of long-baseline interferometry observations. Indeed, this question is of interest because in the AO framework the point spread function (PSF) calibration error is related to the temporal seeing variations between science observation and PSF calibration (Rigaut & Sarazin 1999).

No significant correlation exists between outer scale and seeing, but for the period of May 25–28, as illustrated in Fig. 2 and Table 1, there is a correlation between seeing and isoplanatic angle. Indeed, when the seeing increases (decreases), the isoplanatic angle decreases (increases). This correlation is due to the contribution of high turbulent layers on the seeing degradation.

Figs 4 and 5 show a comparison between GSM and DIMM seeing data. All the GSM results are corrected from the exposure time

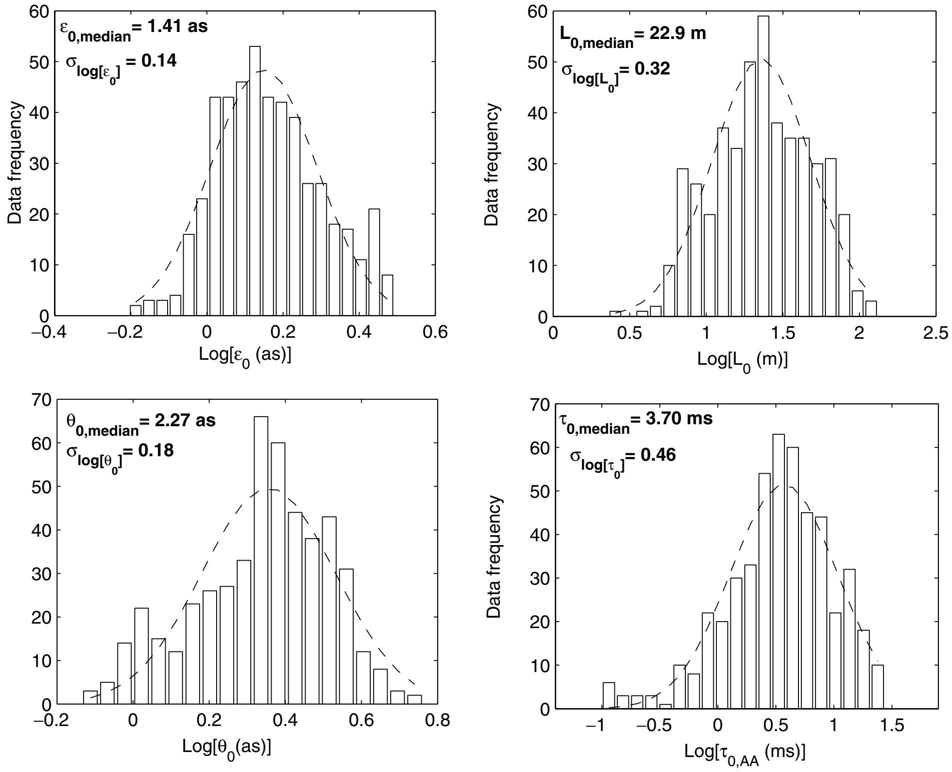

Figure 3. Histograms of the AOP measured with GSM during several nights at the Calar Alto site in 2002 May. All these parameters are well fitted with log-normal distributions (dashed line).

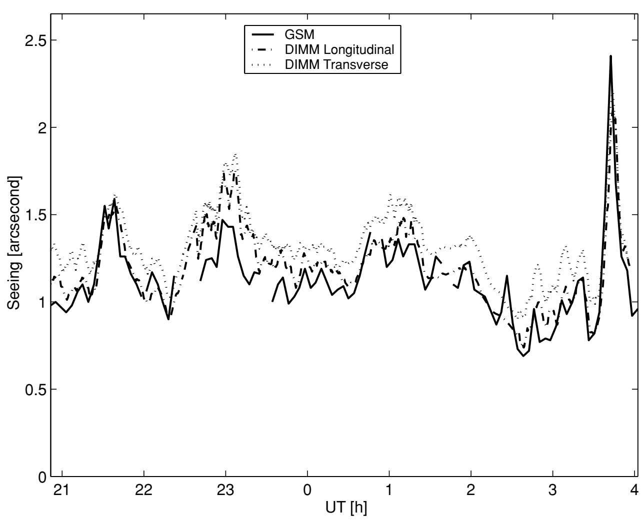

Figure 4. Comparison of the GSM and DIMM seeing data obtained during the night of 2002 May 28, at the Calar Alto site. The seeing data correspond to 0.5 μm wavelength.

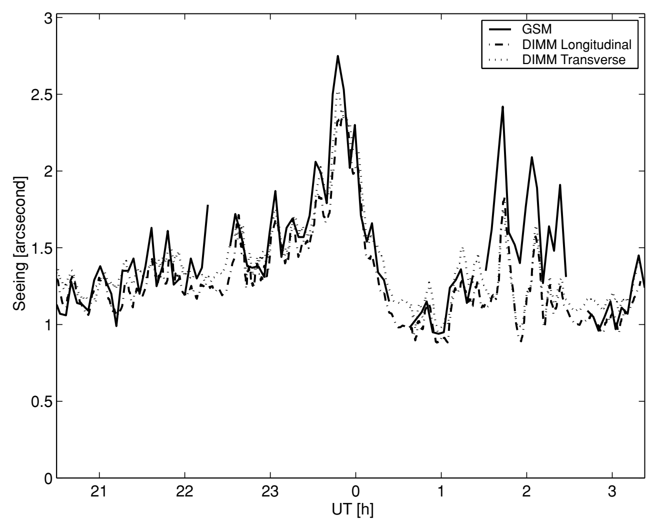

Figure 5. Comparison of the GSM and DIMM seeing data obtained during the night of 2002 May 29, at the Calar Alto site. The seeing data correspond to 0.5 μm wavelength.

as explained in Section 2.1. This is not the case for the DIMM data. Indeed, the seeing has been measured with 5 ms exposure time. When the turbulence conditions are not fast, the exposure time effect on the seeing is reduced and so excellent agreement is found between GSM and DIMM. This behaviour is also accompanied by a small difference between longitudinal and transverse seeing measurements (Figs 4 and 5).

4 DISCUSSION AND CONCLUSION

For the first time the seeing ϵ_0, the outer scale $\mathcal{L}_0$, the isoplanatic angle θ_0 and the coherence time $\tau_{0,\mathrm{AA}}$ were monitored continuously during several nights at the Calar Alto site.

The simultaneous measurements resulted in excellent agreement between the GSM and DIMM instruments, particularly when the turbulence is less rapid. Note that the GSM data are corrected for

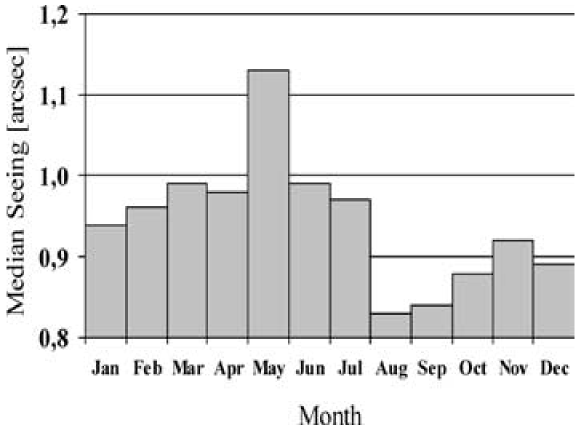

Figure 6. Monthly variation of the seeing on Calar Alto obtained during the period 2001 June–2004 May.

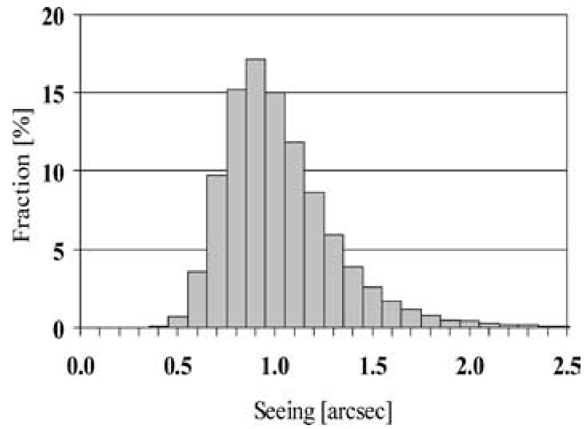

Figure 7. Calar Alto seeing distribution obtained during the period 2001 June–2004 May.

the exposure time effect when the DIMM used 5 ms charge-coupled device (CCD) exposures.

The outer scale $\mathcal{L}_0$ and the isoplanatic angle θ_0 data provided by GSM show that these parameters are well fitted by log-normal distributions with rather similar median values compared to other sites visited by the GSM (Ziad et al. 2000). The seeing data present some nights with values comparable to the La Silla Observatory (Fig. 2). The monthly DIMM statistics shown in Fig. 6 show, however, that the GSM campaign was not carried out during very good seeing.

The DIMM measurements obtained in the 2001 June–2004 May period show that the median seeing on Calar Alto is 0.92 arcsec, with a dispersion of 0.31 arcsec (Fig. 7). During this period, the DIMM was installed at 5 m height above ground. The median seeing on Calar Alto compares well with the seeing at other continental sites. In 2000 October, a dome ventilation system was installed at the 3.5-m telescope, which now allows a very efficient air exchange at the beginning of the observations. For many years, the mirror cell has been cooled during daytime by cold air. Data obtained with imaging instruments such as the prime focus imager LAICA or the focal reducer MOSCA show that, in general, the image quality measured on the detector is within 0.1–0.2 arcsec to the external seeing. Poor image quality is now limited to rapid temperature drops, which in some 10–20 nights per year cause the primary mirror to be at a temperature of 2°C or more above the ambient air temperature.

Since 2004 July, Calar Alto has been operating a new robotic seeing monitor. Its design is very similar to that of the commercial seeing monitor from LHESA. The new RoboDIMM has, however, a significantly improved mode of operation, mostly due to experience gathered at the IAA and on Calar Alto. A detailed description of the new instrument is available via the Calar Alto Newsletter.[1]

[1] http://www.caha.es/newsletter/protada.html

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