European Extremely Large Telescope Site Characterization. II. High Angular Resolution Parameters

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ABSTRACT. This is the second article of a series devoted to European Extremely Large Telescope (E-ELT) site characterization. In this article we present the main properties of the parameters involved in high angular resolution observations from the data collected in the site testing campaign of the E-ELT during the design study (DS) phase. Observations were made in 2008 and 2009, in the four sites selected to shelter the future E-ELT (characterized under the ELT-DS contract): Aklim mountain in Morocco, Observatorio del Roque de los Muchachos (ORM) in Spain, Macón range in Argentina, and Cerro Ventarrones in Chile. The same techniques, instruments, and acquisition procedures were taken on each site. A multiple aperture scintillation sensor (MASS) and a differential image motion monitor (DIMM) were installed at each site. Global statistics of the integrated seeing, the free atmosphere seeing, the boundary layer seeing, and the isoplanatic angle were studied for each site, and the results are presented here. In order to estimate other important parameters, such as the coherence time of the wavefront and the overall parameter “coherence étendue,” additional information of vertical profiles of the wind speed was needed. Data were retrieved from the National Oceanic and Atmospheric Administration (NOAA) archive. Ground wind speed was measured by automatic weather stations (AWS). More aspects of the turbulence parameters, such as their seasonal trend, their nightly evolution, and their temporal stability, were also obtained and analyzed.

Online material: color figures

1. INTRODUCTION

The site selection for the future large European telescope is a fundamental issue and was undertaken within the E-ELT Design Study (DS) proposal funded by the European Community. First meetings and contacts to define the site selection project started in 2003. Possible interested partners and institutions were approached, and a first version of design and plans was submitted to the European Commission in February 2004. After revision using the committee feedback, the final proposal was accepted at the end of 2004. The site selection work started formally in 2005 and ended in May 2009. In a previous paper (Vernin et al. 2011, hereafter Paper I), we presented an overview of the campaign. In the present work, the statistics of the parameters relevant to high angular resolution (HAR) astronomy of such a large telescope are presented and discussed in detail. Results were obtained after the analysis of about one year of atmospheric turbulence observations with the same instrumentation (MASS-DIMM, see Kornilov et al. [2007]) in four different sites: Aklim (in Morocco), Macón (in Argentina), Observatorio del Roque de los Muchachos (ORM) (in Spain), and Ventarrones (in Chile). This study is similar to the site characterization produced by the Thirty Meter Telescope (TMT) team: its first article from Schöck et al. (2009) focused on the statistics of the seeing, the second on the isoplanatic angle (Skidmore et al. 2009), and the third on the coherence time (Travouillon et al. 2009).

The paper is organized as follows: first, the overall observing configuration at each site is detailed in § 1.1, and the definitions of the parameters under study are introduced in § 1.2. The employed instruments and the data provided by them are described in § 2.1, while § 2.2 is devoted to the archives used...
in order to obtain the complete vertical wind profiles at each site, which are needed to compute some of the parameters. The main global statistics of the sites are covered in § 3. Seasonal behavior, the evolution during an averaged observing night, and the stability of the studied atmospheric parameters are addressed, respectively, in § 4, 5, and 6. Finally, the main results are summarized in § 7.

1.1. Observing Configuration

Our aim was to monitor the atmospheric turbulence at the four candidate sites using well-known, reliable, and as homogeneous instrumentation as possible. All the MASS-DIMM instruments were installed on 5 m high towers. This was determined based on previous studies of the surface layer thickness (see Vernin Muñoz-Tuñón [1992]). The instrument setup was as follows:

1. Four identical MASS-DIMM instruments.
2. Four identical telescopes Celestron C11 (11 inches).
3. Four identical fast read-out CCDs for DIMM devices: the PCO PixelFly VGA.  
4. Each MASS device contains four photo-multipliers (Kornilov et al. 2007).
5. Four towers in order to observe at 5 m above ground level.
6. Three robotic mounts (ASTELCO NTM-500) installed at ORM, Macón, and Ventarrones, and one automatic (Losmandy Gemini) installed at Aklim.
7. Four automatic weather stations (AWS) at a few meters above ground level (see Paper I for details).

The observations taken at Aklim and ORM sites were carried out regularly by observers (in particular, at ORM site observations took place five nights per week; at Aklim, observations were less regular due to strong difficulties accessing the mountainous site), while those taken at Macón and Ventarrones sites were obtained robotically every night. More details about the duty cycle of the MASS-DIMM instrument at each site was already given in Figure 1 of Paper I.

Concerning the observation itself, the configuration adopted in each site is summarized in Tables 1 and 2. The measurements taken with both instruments, DIMM and MASS, are filtered according to well defined criteria stated in § 2.1.4. After filtering, one obtains the total number of accepted data $N_{\text{acc}}$ and the percentage of rejected data $N_{\text{rej}}$. These parameters, together with the total number of exposures per measurement, $N_{\text{exp}}$, the exposure time, $t_{\text{exp}}$, and the median sampling time, $\Delta t$, are given in Tables 1 and 2 for the DIMM and the MASS, respectively.

![Table 1: Synthesis of DIMM Data Acquisition](image)

| Site       | $N_{\text{acc}}$ | $N_{\text{rej}}$ (%) | $t_{\text{exp}}$ (ms) | $\Delta t$ (s) | $N_{\text{exp}}$ |
|------------|------------------|---------------------|------------------------|----------------|-----------------|
| Aklim      | 10992            | 21.4                | 5                      | 42             | 200             |
| Macón      | 29723            | 24.4                | 5                      | 100            | 400             |
| ORM        | 47328            | 11.3                | 5                      | 47             | 200             |
| Ventarrones | 56547            | 8.8                 | 5                      | 101            | 400             |

**Note.**—The number of accepted data, $N_{\text{acc}}$, the percentage of rejected from the total, $N_{\text{rej}}$ (%), the exposure time $t_{\text{exp}}$, the median time interval between measurements, $\Delta t$, and the number of exposures per measurement, $N_{\text{exp}}$, are shown.

1.2. Parameters

The major parameters relevant to HAR (imaging, adaptive optics, interferometry) have been grouped into two classes: “integrated” parameters and “profiles”. The later class is represented by optical turbulence profiles, $C_N^2(h)$, and wind speed profiles, $V(h)$. It is well known that integrated parameters, such as seeing or Fried’s radius, isoplanatic angle, and coherence time, can be deduced from both of the above-mentioned profiles (see equation (1)–(4), where the light wavelength is $\lambda = 0.5 \mu m$ and all the measurements are referred to zero zenith angle).

$$r_0 = 0.185 \lambda^{6/5} \left( \int_0^\infty C_N^2(h) dh \right)^{-3/5}.$$  

$$\varepsilon_{\text{fwhm}} = 0.98 \frac{\lambda}{r_0} = 5.25 \lambda^{-1/5} \left( \int_0^\infty C_N^2(h) dh \right)^{3/5}.$$  

$$\theta_0 = 0.058 \lambda^{6/5} \left( \int_0^\infty h^{5/3} C_N^2(h) dh \right)^{-3/5}.$$  

$$\tau_0 = 0.058 \lambda^{6/5} \left( \int_0^\infty |V(h)|^{5/3} C_N^2(h) dh \right)^{-3/5},$$

Table 2: Synthesis of MASS Data Acquisition

| Site       | $N_{\text{acc}}$ | $N_{\text{rej}}$ (%) | $t_{\text{exp}}$ (ms) | $\Delta t$ (s) |
|------------|------------------|---------------------|------------------------|----------------|
| Aklim      | 13763            | 25.2                | 1                      | 63             |
| Macón      | 94623            | 5.3                 | 1                      | 63             |
| ORM        | 35962            | 15.4                | 1                      | 63             |
| Ventarrones | 83273            | 1.9                 | 1                      | 63             |

**Note.**—The number of accepted data, $N_{\text{acc}}$, the percentage of rejected from the total, $N_{\text{rej}}$ (%), the exposure time $t_{\text{exp}}$, and the median time interval between measurements, $\Delta t$, are shown.

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9 See http://www.pco.de/sensitive-cameras/pixelfly-vga/

10 See http://www.astelco.com/products/ntm/ntm.htm

11 See http://www.losmandy.com/losmandygto/gotospecs.html
are also used to compute some figure of merit, as already discussed in Paper I, depending upon the HAR technique employed. A more general approach is given by Lloyd (2004), who defines the “coherence étendue” $G_0$, in which a photon remains coherent. $G_0$ takes into account a combination of Fried’s radius, isoplanatic angle, and coherence time:

$$G_0 = r_0^2 \tau_0 \theta_0^2.$$  

(5)

This new formulation shows a strong dependence of $G_0$ with $r_0$ and $\theta_0$, and less with $\tau_0$. $G_0$ is computed with $r_0$, $\tau_0$, and $\theta_0$, expressed in m$^2$, ms, and arcsec$^2$, respectively.

2. MASS-DIMM AND COMPLEMENTARY NOAA DATA

2.1. MASS-DIMM

MASS and DIMM devices are attached to the same equatorial mount and track the same star, but each instrument has its own setup.

2.1.1. Differential Image Motion Monitor (DIMM)

DIMM provides accurate, absolute, and reproducible integrated seeing data, although systematic control tests on the focus or saturation are, however, important (see, e.g., Tokovinin 2002; Varela et al. 2004). The instrument description is given in Sarazin Roddier (1990) and Vernin Muñoz-Tuñón (1995). Since the early nineties, DIMMs have become very popular and have been used at different observatories. DIMMs are now auxiliary instruments for telescope operation and complement adaptive optics (AO) experiments. For site selection, having accurate statistics is an important issue. Extensive results have been recorded in large databases (Muñoz-Tuñón et al. 1997; Ehgamberdiev et al. 2000). For example, in Ehgamberdiev et al. (2000), seeing values at Paranal and La Palma were analyzed and compared for more than two years. From this analysis, the excellent behavior of the two sites is clear and reinforces their preselection for hosting the future E-ELT. The DIMM, however, provides only the seeing, and a $C_N^2(h)$ profile is needed to access the isoplanatic angle (eq. [3]).

2.1.2. Multi-Aperture Scintillation Sensor (MASS)

This instrument detects fast intensity variations of light in four concentric apertures using photo-multipliers. Every minute, the accumulated photon counts obtained with microexposures of 1 ms are converted to four normal scintillation indices and to six differential indices for each pair of apertures. This set of 10 numbers is fitted by a model of six thin turbulent layers at predefined altitudes, $h_i = 0.5, 1, 2, 4, 8,$ and 16 km above the site altitude (Komilov et al. 2003). Another model of three layers at floating altitudes is fitted as well. The set of integrals of the refractive index structure constant,

$$J_i = \int_{\text{th layer}} C_N^2(h) dh,$$

(6)

in these six (or three) layers represents the optical turbulence profiles measured by MASS (see Tokovinin et al. [2003] for details on MASS weighting functions). Turbulence near the ground does not produce any scintillation: MASS is blind to it and can only measure the seeing in the free atmosphere.

MASS has been cross-compared with the Generalized SCIntillation Detection And Ranging (G-SCIDAR) optical turbulence profiler (Avila et al. 1997) during a campaign performed at Mauna Kea (Tokovinin et al. 2005), showing very good agreement. SCIDAR has proved to be the most efficient and reliable technique to accurately measure the optical vertical structure of the atmospheric turbulence strength from ground level, although it requires a one-meter class telescope to perform the observations. A more recent study carried out at Paranal Observatory (Dali Ali et al. 2010) also produced consistent results. Similar comparisons between the parameters provided by the MASS-DIMM instrument and the G-SCIDAR, made at ORM, will be addressed in the forthcoming issue within the present series which will be devoted to the G-SCIDAR profiles.

Assuming that the optical turbulence profile remains constant within each slab defined by the MASS, one can deduce the isoplanatic angle (eq. [3]). The coherence time (eq. [4]) still requires the knowledge of the wind speed profile, which is not delivered by the MASS, but will be retrieved from meteorological archives, as explained in § 2.2.

2.1.3. Cross-Calibration of the DIMM Device

This section describes the comparison made between the seeing values obtained with one of the DIMM devices employed during the E-ELT site characterization project (the DIMM part of the MASS-DIMM instrument) and with an existing stable seeing monitor at ORM (hereafter called IAC-DIMM, see Vernin Muñoz-Tuñón [1995]). An online report is available$^{12}$ with detailed information on the systems setup and on data analysis that is not included in this section.

The campaign took place for four nights in September 2007, a few months before the starting of the turbulence monitoring runs, with both instruments, the E-ELT and IAC DIMMs, located at ground level and at a distance of four meters from each other.

Although the telescope apertures are not the same (the IAC-DIMM is 8” while the other is 11”) the combination of telescope and CCD gave rise to a very similar pixel scale, around 0.8” pixel$^{-1}$. They were empirically measured through the observation of a double star with known angular separation. So, similar performances of both systems were expected. The study was restricted to the observation of the same stars by both

$^{12}$See http://www.iac.es/proyectos/sitetesting/index.php?option=com_content&task=view&id=75&Itemid=71.
instruments and at the same time. The targets were selected to be as close as possible to the zenith.

Both seeing time series followed a similar behavior. The differences between the seeing values measured by the E-ELT DIMM and those of the IAC-DIMM, represented as \( \varepsilon_{\text{ELT-DS}} - \varepsilon_{\text{IAC-DIMM}} \), had a mean value of 0.035\(^\circ\), a median of 0.037\(^\circ\), and a standard deviation of 0.099\(^\circ\).

As a result, seeing values provided by the E-ELT site characterization DIMM device are in good agreement with those of IAC-DIMM within the measured range: from \( \varepsilon \approx 0.3'' \) to \( \varepsilon \approx 1.1'' \). This is shown in Figure 1, where the IAC-DIMM data are plotted versus those acquired by the ELT-DS DIMM. A linear fit, \( y = Bx + A \) with the condition \( A = 0 \), yields a slope very close to the unity, \( B = 1.01 \pm 0.01 \). Unfortunately, bad seeing values (those worse than 1\(^\circ\)) were scarce and therefore were not well sampled during that four nights of cross-calibration.

2.1.4. Data Rejection

Raw data provided by each instrument are validated and filtered following standard criteria. In the case of DIMM device, following Muñoz-Tuñón et al. (1997), the longitudinal FWHM and the transverse FWHM, seeing are compared so that only data fulfilling equation (7) are taken into account:

\[
0.8 < \frac{\text{FWHM}_l}{\text{FWHM}_t} < 1.2. \tag{7}
\]

The reason for rejection comes from the physics bases of the DIMM technique (see the study on its uncertainties and errors made by Vernin Muñoz-Tuñón [1995]) and ensures the reliability of the measurements. For the MASS device, several parameters, such as the removal of vignette data and the correction of MASS overshoot, are taken into account. All of them are inspired by the work of Kornilov et al. (2007). The flux recorded by the MASS D channel \( F_D \) and its background signal \( B_{F_D} \) are used to check the signal-to-noise ratio. The uncertainty of the free atmosphere seeing \( \varepsilon_{\text{fa}} \) provided by the MASS software is also used as test value. Finally, the \( \chi^2 \) corresponding to the restoration of the \( C_N^2(h) \) profile is also taken into account. The adopted criteria for MASS accepted measurements are the following: \( B_{F_D} < 3\% \) and \( F_D > 100 \) pulses/m (prevents too faint stars or clouds); relative \( F_D \) error \( \leq 0.03 \) (prevents too bright sky); \( \sigma_{\text{fa}} < 0.15'' \); and \( \chi^2 < 100 \) (prevents bad profile restoration, from the restored \( C_N^2(h) \) profile).

2.1.5. Boundary Layer Contribution

The boundary layer seeing \( \varepsilon_{\text{bl}} \), here defined as the integrated turbulence between \( h = 5 \) m and \( h = 500 \) m, is evaluated from combined MASS-DIMM observations, as follows:

\[
\varepsilon_{\text{bl}}^{5/3} = \varepsilon^{5/3} - \varepsilon_{\text{fa}}^{5/3}, \tag{8}
\]

where \( \varepsilon \) is the value provided by the DIMM, and \( \varepsilon_{\text{fa}} \) is gathered by integrating the MASS profiles. Due to noise, it may happen that when doing the subtraction in equation (8) the boundary layer seeing is negative, and it is withdrawn from the statistics. We estimated that, so doing, any possible bias is almost negligible because it happened very seldom at ORM (2.8% of the whole data set), Aklim (3.8%) and Ventarrones (7.8%). However, at Macón this happened more often (17.6%), mainly during the southern winter (from August to November) coinciding with very strong wind regimes. It turned out that the percentage of this anomaly increases with the free atmosphere seeing, so rejecting those data means biasing to lower \( \varepsilon_{\text{fa}} \). Around the southern summertime, when the wind speed was lower than in winter but still higher compared with the other three sites, the percentages of these occurrences falls from more than 25% to around 13% of the total data acquired. See the next forthcoming issue of this series of papers, which will be devoted to ground meteorology, for a more detailed discussion.

2.2. Complementary Wind Speed Data

As expressed in § 1.2 and equation (4), wind speed profiles are necessary to access the coherence time, and MASS-DIMM cannot provide these missing data. Travouillon et al. (2009) wrote a long discussion about the possibility to retrieve \( \tau_0 \) with the MASS only, according to a Tokovinin document, but still leading to uncertainties of up to 20%.

In order to retrieve the missing wind speed profiles necessary to solve equation (4), we extracted them from Air Resources Laboratory (ARL) of the National Oceanic and Atmospheric Laboratory (NOAA) ARL Atmospheric
TABLE 3

STATISTICS OF $\varepsilon$, $\theta_0$, $\tau_0$, and $G_0$ OBTAINED FROM APRIL 2008 TO MAY 2009

|        | med | mean | $\sigma$ | 5% | 25% | 75% | 95% | $N_{\text{acc}}$ | % rej | $t_{\text{obs}}$ (h) |
|--------|-----|------|----------|----|-----|-----|-----|-----------------|------|-------------------|
| $\varepsilon$ (arcsec) |     |      |          |    |     |     |     |                 |      |                   |
| Aklim  | 1.00| 1.09 | 0.45     | 0.61| 0.81| 1.28| 1.82| 10992          | 21.4 | 250               |
| ORM    | 0.87| 0.91 | 0.26     | 0.57| 0.74| 1.05| 1.38| 29723          | 24.4 | 1246              |
| ORM    | 0.80| 0.94 | 0.55     | 0.46| 0.62| 1.06| 2.00| 47328          | 11.3 | 790               |
| Ventarrones | 0.91| 0.96 | 0.29     | 0.58| 0.76| 1.10| 1.50| 56547          | 8.8  | 2214              |
| $\theta_0$ (arcsec) |     |      |          |    |     |     |     |                 |      |                   |
| Aklim  | 1.29| 1.43 | 0.75     | 2.66| 1.79| 0.96| 0.55| 13763          | 25.2 | 296               |
| ORM    | 1.37| 1.51 | 0.77     | 2.81| 1.85| 1.01| 0.66| 94623          | 5.3  | 1705              |
| ORM    | 1.93| 2.02 | 0.77     | 3.41| 2.44| 1.48| 0.87| 35962          | 15.4 | 669               |
| Ventarrones | 1.96| 2.18 | 1.92     | 3.97| 2.56| 1.47| 0.84| 83273          | 1.9  | 2626              |
| $\tau_0$ (ms) |     |      |          |    |     |     |     |                 |      |                   |
| Aklim  | 3.53| 5.64 | 4.98     | 15.87| 7.46| 2.34| 1.59| 1004           | 0.0  | 80                |
| Macón  | 3.37| 3.95 | 2.67     | 8.58| 4.99| 2.20| 1.28| 69376          | 1.5  | 1227              |
| ORM    | 5.58| 6.51 | 4.14     | 14.24| 8.26| 3.70| 1.82| 36802          | 0.0  | 619               |
| Ventarrones | 4.90| 5.65 | 4.38     | 11.77| 7.13| 3.27| 1.58| 103782         | 1.0  | 1807              |
| $G_0$ (m$^2$ ms arcsec$^{-2}$) |     |      |          |    |     |     |     |                 |      |                   |
| Aklim  | 0.05| 0.32 | 0.66     | 1.71| 0.31| 0.02| 0.01| 1004           | 0.0  | 80                |
| ORM    | 0.10| 0.35 | 1.20     | 1.49| 0.30| 0.03| 0.01| 69376          | 1.5  | 1227              |
| ORM    | 0.38| 1.02 | 1.80     | 4.24| 1.16| 0.11| 0.01| 36794          | 0.0  | 619               |
| Ventarrones | 0.26| 0.68 | 1.42     | 2.58| 0.68| 0.09| 0.01| 103782         | 1.0  | 1807              |

Note.—The median, the mean, the standard deviation of the mean, four percentiles, the number of accepted data, and the % of rejected data and the total observing time are shown.

3. GLOBAL STATISTICS

In this section, the statistics of seeing ($\varepsilon$), isoplanatic angle ($\theta_0$), coherence time ($\tau_0$), coherence étendue ($G_0$), Fried’s radius ($r_0$), free atmosphere seeing ($\varepsilon_{fa}$), and boundary layer seeing ($\varepsilon_{bl}$) at each of the four sites (Aklim, Macón, ORM, and Ventarrones) is presented.

Data processing software has been implemented by the IAC team, and we made it available to all institutions who take care of data gathering and analysis at the different sites (see Paper I). Statistics of the parameters mentioned above are obtained from the whole data set and in accordance with the previous remarks concerning the turbulence within the boundary layer and the wind profiles. From the probability distribution of each parameter, the cumulative distribution and four percentiles (0.05, 0.25, 0.75, and 0.95) were computed together with the mean, the standard deviation of the mean, and the median (0.50 percentile) of the corresponding data subset.

Many properties of these parameters might be analyzed depending on each possible purpose, such as the trend of the parameters along a year (§ 4), their typical behavior during the night (§ 5) and their temporal stability (§ 6). The global statistics only takes into account the valid data (those that fulfill the criteria mentioned in § 2.1.4) as a whole, regardless of any temporal consideration. The global statistics of the parameters $\varepsilon$, $\theta_0$, $\tau_0$, $G_0$, $r_0$, $\varepsilon_{fa}$, and $\varepsilon_{bl}$ are presented in Tables 3 and 4 over the whole observing campaign at the four sites. Both tables show the median, the mean, the standard deviation of the mean, $\sigma$, four percentiles, $5\%$, $25\%$, $75\%$, and $95\%$, the number of accepted data $N_{\text{acc}}$, as

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14 See http://www.arl.noaa.gov/REAlYamet.php.
cept Mauna Kea, which benefits from a better isoplanatic angle comparable to most of those found in the TMT candidate sites, except Macón et al. 1997). The best median isoplanatic angle was very similar to those obtained at ORM and, while for the other three sites their sampling rate is per minute, at Aklim only one measurement is recorded every five minutes. This led to the aforementioned poorer statistics.

The summary of the best achieved values of the different parameters at the different sites is the following:

During the extent of the E-ELT site campaign, the lowest median integrated seeing was obtained at ORM ($\varepsilon = 0.80\arcsec$). If this particular value is compared with the results of the TMT site testing campaign, it is found to be around 0.1" higher than those obtained at the TMT candidate sites showing the best total seeing statistics (see Skidmore et al. 2009). However, in the particular case of the ORM, for instance, previous studies have proven that they are very similar (see, e.g., Muñoz-Tuñón 1994). The best median isoplanatic angle was very similar both at Ventarrones and at ORM ($\theta_0 \approx 2^\circ$), and they are comparable to most of those found in the TMT candidate sites, except Mauna Kea, which benefits from a better isoplanatic angle ($\theta_0 = 2.69^\circ$) (Skidmore et al. 2009). The best (highest) median coherence time was measured at ORM ($\tau_0 = 5.58$ ms), closely followed by Ventarrones; both of them were better ($\tau_0 \geq 5$ ms) than Aklim and Macón ($\tau_0 \approx 3.5$ ms). The $\tau_0$ values at ORM and Ventarrones are also comparable to those of the candidate sites of the TMT with highest coherence time, $\tau_0$ better than 5 ms (see Travouillon et al. 2009). Finally, the combined parameter $G_0$ defined in equation (5) was clearly higher at ORM ($G_0 = 0.4$ m$^2$ ms arcsec$^2$) and Ventarrones ($G_0 = 0.3$ m$^2$ ms arcsec$^2$) than at Macón and Aklim ($G_0 \approx 0.1$ m$^2$ ms arcsec$^2$).

The smallest contribution of the free atmosphere measured by the MASS instrument was obtained again at ORM ($\varepsilon_{fa} = 0.31\arcsec$), although the median contribution of the boundary layer measured was lower at Macón ($\varepsilon_{bl} = 0.51\arcsec$) and at Ventarrones ($\varepsilon_{bl} = 0.60\arcsec$) than at ORM ($\varepsilon_{bl} = 0.65\arcsec$). The relative contribution of the ground layer and the free atmosphere to the total seeing at each site is shown in Table 5. In this regard, a turbulence profile showing a higher proportion of boundary layer turbulence, with a relatively clear free atmosphere, will be much more tractable for an AO system than one with, for example, strong jet stream related turbulence in the tropopause (see, e.g., Marks 2002; Vernin Muñoz-Tuñón 1994).

In Figures 2–7, the histogram as well as the cumulative distribution of seeing ($\varepsilon$), isoplanatic angle ($\theta_0$), coherence time ($\tau_0$), coherence étendue ($G_0$), free atmosphere seeing ($\varepsilon_{fa}$), and boundary layer seeing ($\varepsilon_{bl}$), again at each of the four sites, are plotted. As is well known, the conditions, in terms of atmospheric turbulence, are more favorable when some parameters are small: seeing (integrated, free atmosphere and boundary layer) and/or when they are large: isoplanatic angle, coherence time, Fried’s radius, and coherence étendue. In the last cases ($\theta_0$, $\tau_0$, $G_0$, and $\varepsilon_{fa}$), instead of estimating the cumulative distribution, the complementary cumulative distribution is calculated, which equals 1 minus the cumulative distribution. The four percentiles and the median are indicated by dotted lines, while the mean is marked with a dashed one in each of the figures.

As a summary, the cumulative distributions of the four candidate sites were put together in a plot for each parameter in

### TABLE 4

| Site   | $\tau_0$ (ms) | $\varepsilon_{fa}$ (arcsec) | $\varepsilon_{bl}$ (arcsec) | $G_0$ (m$^2$ ms arcsec$^2$) | $N_{acc}$ (h) | $\%$ rej | $t_{obs}$ (h) |
|--------|---------------|-----------------------------|-----------------------------|-----------------------------|--------------|---------|-------------|
| Aklim  | 10.10         | 0.60                        | 0.51                        | 0.68                        | 13561        | 13.4    | 625         |
| ORM    | 11.56         | 0.80                        | 0.75                        | 0.85                        | 13623        | 13.6    | 450         |
| Macón  | 12.71         | 0.31                        | 0.66                        | 0.88                        | 13762        | 13.7    | 420         |
| Ventarrones | 11.12       | 0.41                        | 0.65                        | 0.73                        | 13821        | 13.8    | 400         |

Note.—The median, the mean, the standard deviation of the mean, four percentiles, the number of accepted data, the % of rejected data and the total observing time are shown.
Figure 8. From these cumulative distributions at the different sites, it is concluded that ORM shows the best behavior in all the values $\varepsilon$, $\theta_0$, $\tau_0$, and $G_0$, closely followed by Ventarrones.

4. SEASONAL EVOLUTION

Although the length of the Framework Program VI (FP6) campaign is only slightly longer than a year, the monthly variations of the quantities under consideration are shown in Figures 9 and 10; in particular, the statistics of the parameters $\varepsilon$, $\theta_0$, $\tau_0$, $G_0$, $\varepsilon_{fa}$, and $\varepsilon_{bl}$ are presented for each month during the whole observing campaign at the four sites. Surprisingly, the seeing seems better (lower) during 2008 May–August and 2009 January–August in both hemispheres, when one would expect an inverse trend depending on the hemisphere. In large database studies, e.g., at ORM, the seasonal trend is more remarked, with summer being the best period (Muñoz-Tuñón et al. 1997). We conclude that this one year is not enough for study the seasonal evolution.

5. EVOLUTION DURING THE NIGHT

Nightly evolution of $\varepsilon$, $\theta_0$, $\tau_0$, $G_0$, $\varepsilon_{fa}$, and $\varepsilon_{bl}$ at each of the four sites over the whole campaign is plotted in Figures 11–16. Midlines represent the middle of the astronomical night (the middle point between sunset and sunrise). Due to the fact that the length of the night varies during the year, the beginning and the end of the figures are more poorly sampled than around the astronomical midnight (this is shown with a black curve in the plots). Every quarter of an hour, before and after midnight, all the data have been averaged in order to put into evidence any trend during the night. No clear nightly trend is visible except perhaps at Macón site, where the conditions are poor at the beginning of the night (large seeing, low isoplanatic angle, small coherence time, and thus low coherence étendue) and they get gradually better during the night until the sunrise. This behavior is highly correlated with the evolution of wind speed at Macón, being high at the sunset and decreasing along the night. This issue will be discussed in more detail in the next paper dedicated to meteorological statistics.

6. TEMPORAL STABILITY

Figure 17 shows the “stability” of each of the following parameters: $\varepsilon$, $\theta_0$, $\tau_0$, $G_0$, $\varepsilon_{fa}$, and $\varepsilon_{bl}$. Stability means the average of the time interval during which a parameter, say seeing, remains “better” than a given value. This means, in some cases, remaining lower than the given value (integrated seeing, free atmosphere seeing, and boundary layer seeing), and in other cases remaining higher (isoplanatic angle, coherence time, and coherence étendue). The stability plots were built assuming a threshold of 4 minute in order to decide whether two consecutive data points of the time series are considered as belonging to the same time interval, or whether the continuity has been broken. The time intervals during which each parameter remains below (or above) a given value were averaged. This procedure leads to the smooth curves shown in Figure 17.

This concept is important in order to get an idea of how many times the atmospheric conditions would remain stable in order to carry out a particular observation that may imply a specific adaptive optics configuration. As an overall result, the ORM site seems to exhibit higher stability than the other three sites, except with respect to isoplanatic angle.

7. SUMMARY

The FP6 site testing campaign for the E-ELT measurements started in April 2008 and finished in May 2009. Four sites were characterized: Aklim (in Morocco), Macón (in Argentina), ORM (in Spain), and Ventarrones (in Chile). The observations were made under almost identical instrumentation and setup for data analysis homogeneity. The main statistical properties of the parameters were discussed here. The study is limited to the observations made during the FP6 contract.

In this sense, it is clear that a longer campaign would have been desirable in order to get rid of any bias produced by peculiar conditions during particular periods of time within the observations. A longer campaign would have made the conclusions of this study more robust. Unfortunately, the time spent on the setup of the systems in the four sites and the time constraints naturally associated with the ELT-DS work package resulted in a campaign slightly longer than one year. In any case, detailed and valuable information on these sites is provided here. Data and results from the E-ELT site study can be put in a more general context by making use of longer databases, when available, at the different sites.

The parameters relevant for performing HAR observations were obtained employing several instruments (MASS-DIMM and AWS installed in each of the four candidate sites) and the NOAA/ARL wind profile database (needed to determine the coherence time). Data coming from the MASS-DIMM instruments was carefully filtered by means of standard and well-known criteria in order to get rid of spurious data. The DIMM instrument measurements were compared with a stable IAC

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Table 5: Relative Contribution of the Boundary Layer and the Free Atmosphere to the Total Seeing

| Site      | $\varepsilon_{bl}$ (arcsec) | %     | $\varepsilon_{fa}$ (arcsec) | %     | total $\varepsilon$ (arcsec) |
|-----------|-----------------------------|-------|-----------------------------|-------|-----------------------------|
| Aklim     | 0.77                        | 65    | 0.52                        | 34    | 1.00                        |
| Macón     | 0.51                        | 41    | 0.66                        | 63    | 0.87                        |
| ORM       | 0.65                        | 71    | 0.31                        | 21    | 0.80                        |
| Ventarrones | 0.60                      | 50    | 0.55                        | 43    | 0.91                        |

Note.—Data shown at the different sites (obtained using the median values also shown in the table). Sampling period from April 2008 to May 2009.
Fig. 2.—Histogram and cumulative distribution of the seeing at each of the four sites. See the electronic edition of the PASP for a color version of this figure.

Fig. 3.—Histogram and cumulative distribution of the isoplanatic angle at each of the four sites. See the electronic edition of the PASP for a color version of this figure.
FIG. 4.—Histogram and cumulative distribution of the coherence time at each of the four sites. See the electronic edition of the PASP for a color version of this figure.

FIG. 5.—Histogram and cumulative distribution of the coherence étendue at each of the four sites. See the electronic edition of the PASP for a color version of this figure.
Fig. 6.—Histogram and cumulative distribution of the free atmosphere seeing at each of the four sites. See the electronic edition of the PASP for a color version of this figure.

Fig. 7.—Histogram and cumulative distribution of the boundary layer seeing at each of the four sites. See the electronic edition of the PASP for a color version of this figure.
DIMM at ORM for several nights, with a satisfactory correlation found between them.

In the case of the reference sites, ORM and Ventarrones (some kilometers away from Paranal Observatory), large records of atmospheric turbulence conditions already exist, although the discussion here is limited to the results of the FP6 contract campaign. However, it is worth noting that the present work represent the first results obtained at the new sites Aklim and Macón.

The global statistics of the HAR parameters were studied as well as their seasonal trend, their evolution during a typical night, and their time stability.

Concerning pure statistics, the following are the ranges of the median values taken by the studied parameters during the campaign: the integrated seeing, $\varepsilon$, from 0.80″ (ORM) to 1.00″ (Aklim); the isoplanatic angle, $\theta_0$, from 1.29″ (Aklim) to $\theta_0 \approx 2$″ (Ventarrones and ORM); the coherence time, $\tau_0$, from 3.37 ms (Macón) to 5.58 ms (ORM); the coherence étendue, $G_0$, from...
0.05 m² ms arcsec² (Aklim) to 0.38 m² ms arcsec² (ORM); the Fried’s radius, \( r_0 \), from 10.1 cm (Aklim) to 12.7 cm (ORM); the free atmosphere seeing, \( \varepsilon_{fa} \), from 0.31” (ORM) to 0.66” (Macón); and the boundary layer seeing \( \varepsilon_{bl} \), from 0.51” (Macón) to 0.77” (Aklim). Moreover, the percentages of the contribution of the boundary layer seeing to the total atmosphere seeing were 71% (ORM), 65% (Aklim), 50% (Ventarrones) and 41% (Macón). Both reference sites, ORM and Ventarrones, presented significantly higher median values of the global parameter, \( G_0 = 0.4 \) m² ms arcsec² and \( G_0 = 0.3 \) m² ms arcsec², respectively, than those found at Aklim and Macón, with \( G_0 \approx 0.1 \) m² ms arcsec².

The site testing campaign lasted for around a year, so although the monthly values of every parameter were estimated in order to study their behavior over the course of the year, more observations would obviously be needed to make conclusions about seasonal trends of the sites under consideration.

Regarding the trend of the parameters averaged over all observation nights, it is found that they are very stable in ORM and Ventarrones sites. Aklim also showed good stability along the night, although most of the parameters seem to behave slightly better during the second half of the night than during the first half. A systematic variation was identified at Macón site, where the observing conditions are poor at the beginning and they get gradually better, being this phenomenon correlated with strong winds at the beginning getting weaker to sunset.

The temporal stability of the parameters was also investigated. ORM showed generally better stability than the other three
FIG. 11.—Nightly evolution of the seeing deduced from all the nights during the whole observing campaign at the four sites. The median (squares) and the mean (diamonds) of each time interval are shown together with the standard deviation of the mean (error bars) and the number of data (solid line). See the electronic edition of the PASP for a color version of this figure.

FIG. 12.—Nightly evolution of the isoplanatic angle deduced from all the nights during the whole observing campaign at the four sites. The median (squares) and the mean (diamonds) of each time interval are shown together with the standard deviation of the mean (error bars) and the number of data (solid line). See the electronic edition of the PASP for a color version of this figure.
FIG. 13.—Nightly evolution of the coherence time deduced from all the nights during the whole observing campaign at the four sites. The median (squares) and the mean (diamonds) of each time interval are shown together with the standard deviation of the mean (error bars) and the number of data (solid lines). See the electronic edition of the PASP for a color version of this figure.

FIG. 14.—Nightly evolution of the coherence étendue deduced from all the nights during the whole observing campaign at the four sites. The median (squares) and the mean (diamonds) of each time interval are shown together with the standard deviation of the mean (error bars) and the number of data (solid lines). See the electronic edition of the PASP for a color version of this figure.
Fig. 15.—Nightly evolution of the free atmosphere seeing deduced from all the nights during the whole observing campaign at the four sites. The median (squares) and the mean (diamonds) of each time interval are shown together with the standard deviation of the mean (error bars) and the number of data (solid lines). See the electronic edition of the PASP for a color version of this figure.

Fig. 16.—Nightly evolution of the boundary layer seeing deduced from all the nights during the whole observing campaign at the four sites. The median (squares) and the mean (diamonds) of each time interval are shown together with the standard deviation of the mean (error bars) and the number of data (solid lines). See the electronic edition of the PASP for a color version of this figure.
sites. As an example, the total seeing remained below 1″, the free atmosphere seeing below 0.5″, the isoplanatic angle was higher than 1.5″, and the coherence time was higher than 5 ms for an hour, on average, at ORM (all these parameters are considered separately; i.e., these conditions are not necessarily occurring at the same time).

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Fig. 17.—Mean time interval during which seeings (total, free and boundary layer) are better (lower) than a given value, and during which isoplanatic angle, coherence time, and coherence étendue is better (higher) than a given value. See the electronic edition of the PASP for a color version of this figure.
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