Optical turbulence vertical distribution with standard and high resolution at Mt Graham

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ABSTRACT
A characterization of the optical turbulence vertical distribution ($C_N^2$ profiles) and all the main integrated astroclimatic parameters derived from the $C_N^2$ and the wind speed profiles above the site of the Large Binocular Telescope (LBT) (Mt Graham, Arizona, USA) is presented. The statistics include measurements related to 43 nights done with a Generalized SCIDAR (GS) used in standard configuration with a vertical resolution $\Delta H/\Delta H \sim 1$ km on the whole 20 km and with the new technique (High Vertical Resolution GS) in the first kilometre. The latter achieves a resolution $\Delta H \sim 20–30$ m in this region of the atmosphere. Measurements done in different periods of the year permit us to provide a seasonal variation analysis of the $C_N^2$. A discretized distribution of $C_N^2$, useful for the Ground Layer Adaptive Optics (GLAO) simulations, is provided and a specific analysis for the LBT Laser Guide Star system ARGOS (running in GLAO configuration) case is done including the calculation of the ‘grey zones’ for J, H and K bands. Mt Graham is confirmed to be an excellent site with median values of the seeing without dome contribution $\varepsilon = 0.72$ arcsec, the isoplanatic angle $\theta_0 = 2.5$ arcsec and the wavefront coherence time $\tau_0 = 4.8$ ms. We find that the OT vertical distribution decreases in a much sharper way than what has been believed so far in the proximity of the ground above astronomical sites. We find that 50 per cent of the whole turbulence develops in the first $80 \pm 15$ m from the ground. We finally prove that the error in the normalization of the scintillation that has been recently demonstrated in the principle of the GS technique affects these measurements by an absolutely negligible quantity (0.04 arcsec).

Key words: turbulence – atmospheric effects – site testing.

1 INTRODUCTION
The Mt Graham International Observatory (MGIO) is located on Mt Graham (32°42′05″N, 109°53′31″W), Arizona (USA), and hosts three telescopes: the Vatican Advanced Technological Telescope (VATT – pupil size $D = 1.83$ m), the Heinrich Hertz Submillimeter Telescope (SMT – $D = 10$ m) and the Large Binocular Telescope (LBT – two $D = 8.4$ m dishes that, when working in an interferometric configuration, can achieve the resolution of a telescope with a 23 m pupil size). The study and characterization of the optical turbulence (OT) distribution in space and time are fundamental for ground-based astronomy in the visible up to the near-infrared range to design adaptive optics systems and to optimize their performances. The vertical distribution of the OT (i.e. the $C_N^2$ profiles) is the parameter from which all the integrated astroclimatic parameters derive.

In this paper, we present a study based on measurements of the $C_N^2$ profiles related to 43 nights and obtained with a Generalized SCIDAR (GS) placed at the focus of the VATT on the Mt Graham summit, around 250 m from the LBT. Fig. 4 in Egner & Masciadri (2007) shows the relative position of the two telescopes. It is worth noting that the primary mirror of the LBT is located $\sim 35$ m above the dome of the VATT.

The scientific motivations for such a long-term site testing campaign are as follows.

(i) To collect as rich as possible a statistical sample of OT vertical distribution ($C_N^2$ profiles) to be compared with simulations obtained with the atmospheric mesoscale model Meso-Nh with the aim of validating the model above Mt Graham. This is a key milestone for the ForOT project1 whose final goal is to predict the OT above astronomical sites (Masciadri 2006). The measurements from a vertical profiler such as a GS are crucial for the validation

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of such a kind of model. It is our interest to collect a heterogeneous sample of measurements taken in different periods of the year and different turbulence conditions in such a way as to better control the model behaviours under different conditions and to better validate the model itself. The atmospheric models have been used for the first time to reconstruct and characterize the $C_n^2$ profiles by Masiadri, Vernin & Bougeault (1999a,b). Since then, much progress has been achieved by our group: the model has been applied to different astronomical sites in a simple monomodel configuration (Masiadri, Vernin & Bougeault 2001; Masiadri & Garfias 2001) and more recently in a grid-nesting configuration (Lascaux et al. 2009), a new calibration technique has been proposed (Masiadri & JBouille 2001) and statistically validated (Masiadri, Avila & Sanchez 2004) and the first application of the Meso-Nh model as a tool of turbulence characterization has been presented (Masiadri & Egner 2006). However, so far we could always access GS measurements concentrated in a well-defined period of time. This series of site testing campaigns with a GS at Mt Graham aimed to comply with the necessity to diversify the measurement sample.

(ii) To provide a characterization of all the most important integrated astrometric parameters above the site of the LBT and verify if any evident changes are observed with respect to previous results obtained on a three times smaller sample (Egner, Masiadri & McKenna 2007). This study can therefore be important to confirm/reject/refine those conclusions. We remind that the GS is a manually operated instrument and the statistical richness of GS measurements cannot be compared to that of monitors such as the Differential Image Motion Monitor (DIMM) and the Multi Aperture Scintillation Sensor (MASS) that are routinely run above many observatories. However, these monitors can provide only integrated values (as is the case for the DIMM) or turbulence distribution with very low vertical resolution $\Delta H \sim h/2$ (as is the case for the MASS). The GS remains therefore a unique instrument for a detailed analysis of the vertical distribution of the OT in the whole troposphere.

(iii) To provide as rich as possible a statistical sample of the high-resolution vertical distribution ($\Delta H = 200$--250 m and 25--30 m) of the OT in the first hundreds of metres up to 1 km to support the feasibility studies of new generation instruments for the LBT, such as the LBT Laser Guide Stars system ARGOS (Raben et al. 2008), that, in its first baseline, is planned to work with a Ground Layer Adaptive Optics (GLAO) configuration. The GLAO efficiency, indeed, strongly depends on the turbulence distribution and strength near the ground. The study we intend to perform can be achieved, thanks to a new technique that has been recently proposed, called High Vertical Resolution Generalized SCIDAR (HVR-GS; Egner & Masiadri 2007), which aims to reconstruct the OT vertical distribution in the first kilometre above the ground with a resolution up to 10 times higher than what has been achieved so far with standard vertical profilers such as the GS (typically $\Delta H \sim 1$ km). In Egner & Masiadri (2007), the validity of this technique has been proved and it is now our intention to characterize the turbulence distribution in statistical terms, to verify how the turbulence decreases in the first hundreds of metres above the ground and provide inputs to test the ARGOS performances.

In Section 2, we briefly review the principle of the GS and HVR-GS techniques. In Section 3, we present the site testing campaign data set that has been analysed and presented in a preliminary form in Stoesz et al. (2008). In Section 4, we present an exhaustive statistical analysis of all the most important integrated astrometric parameters derived from the $C_n^2$ profiles and characterizing Mt Graham. In Section 5, we quantitatively discuss the turbulence distribution of the OT in the whole troposphere in application to the adaptive optics. We provide a composite profile distribution on the whole troposphere with the vertical resolution required for the characterization of the LBT-LGS system running in the GLAO configuration (ARGOS), i.e. $\Delta H \sim 200$ m in the first kilometre and $\Delta H \sim 1$ km above 1 km. In Section 6, we characterize the $C_n^2$ profiles at standard and high vertical resolution and their seasonal variation. Section 7 summarizes the conclusions. In Appendices A and B, we briefly show that the error in the normalization of the scintillation of the GS technique, demonstrated by Johnston et al. (2002) and Avila & Cuevas (2009), produces absolutely negligible effects on these measurements. From a general point of view, we will show that GS measurements obtained with a pupil size $D \geq 1.5$ m and a binary separation $\theta \leq 8$ arcsec are affected by this error for less than a few hundredths of an arcsec.

2 INSTRUMENTS: GS AND HVR-GS

Two instruments have been used for this study: the GS and the HVR-GS. We used the GS as developed by McKenna et al. (2003). The SCIDAR technique has been originally proposed by Rocca, Roddier & Vernin (1974) and Vernin & Azouit (1983) and relies on the analysis of the scintillation images generated by a binary in the pupil plane of a telescope. The SCIDAR technique (called Classic SCIDAR) is insensitive to the turbulence near the ground. More recently, Fuchs, Tallon & Vernin (1998) proposed a generalized version of the SCIDAR (called GS) in which the detector is virtually conjugated below the ground permitting extension of the measurement range to the whole atmosphere (~20--25 km). The GS principle has been later put into practice by several authors above different astronomical sites (Avila, Vernin & Masiadri 1997; Kluczeckers et al. 1998; McKenna et al. 2003; Avila et al. 2004; Fuensalida et al. 2004; Egner et al. 2007; Garcia-Lorenzo et al. 2009). The GS is based on the observation of binaries with a typical separation $\theta$ within 3--10 arcsec, binary magnitude $m_1, m_2 \leq 5$ mag and $\Delta(m_{1,2}) \leq 1$ mag. When two plane wavefronts propagating from a binary meet a turbulence layer located at a height $h$ from the ground, they produce on the detector plan, optically placed below the ground at about $h_{gs} = 3$ km, two scintillation maps made by a set of characteristic shadows appearing in couples separated by a distance $\delta d$ that is geometrically related to the position of the turbulence layer as $\delta d = \theta (h + h_{gs})$. The calculation of the autocorrelation (AC) of the scintillation map produces the so called ‘triplet’. The central peak is located in the centre of the AC frame; the lateral peaks are located at a symmetric distance $d$ from the centre. The amplitude of the later peaks is proportional to the strength of the turbulence of the layer located at the height $h$ weighted by the scintillation that such a layer produces on the detector.

In a multilayer atmosphere, different turbulent layers produce triplets with lateral peaks located at a different distance $d'$ from the centre of the AC frame. To monitor the whole troposphere, the pupil size needs to be large enough ($D \geq 1.5$ m) to avoid one of the shadows that form a couple (or both of them) falling outside the pupil of the telescope. In the AC frame, the triplets are all placed along the direction of conjunction of the binary. To retrieve the $C_n^2$ profile, the central peak of the triplet, in which some sources of noise such as the photon noise are present, is first eliminated. Finally, the $C_n^2$ is obtained by inverting the Fredholm equation which, in the LBT-GS, is done by using the conjugated gradient Egner et al. (2007) algorithm. The vertical resolution $\Delta H(h)$ of the GS technique depends on our ability in discriminating two different later peaks and it is
proportional to the Fresnel Zone (FZ) (Vernin & Azouit 1983):
\[
\Delta H(h) = \frac{0.78 \sqrt{\lambda h}}{\theta} = \frac{0.78 \times \text{FZ}}{\theta}.
\]
(1)

For typical values of the observable binaries with a standard GS, the
typical vertical resolution is \(\Delta H(0) \sim 1\) km.

The HVR-GS technique has been introduced recently (Egner & Masciadri 2007) and
aims to measure the \(C_N^2\) profiles with a high vertical resolution (\(\Delta H \sim 25–30\) m) in the first kilometre above the
ground. We briefly summarize here the main concepts on which
this technique is based. If we abandon the idea of monitoring the
whole 20 km and we limit our attention to the first kilometre, we
can easily increase the vertical resolution of a GS up to a factor
of 4 using the standard GS technique based on the calculation of
the AC obtained from the scintillation maps of binary stars having
a separation \(\theta\) around four times larger than the typical separation
used for the standard GS technique. This is not enough, however,
to achieve resolution of the order of 25–30 m because we are funda-
mentally limited by the FZ size. However, if we use simultaneously
the AC and the cross-correlation (CC) maps taken with 20–40 ms
time lag, the triplets in the CC frames are not aligned anymore
along the same direction identified by the binary separation, but
the central peak of each triplet is located in the direction of the wind
speed of each turbulent layer distributed in the troposphere and the
distance from the centre of the CC frame is proportional to the wind
speed of the same turbulent layer. Under this assumption, it is
possible to prove (Egner & Masciadri 2007) that the vertical resolu-
tion \(\Delta h_{\text{pix}}\) is finally limited by the accuracy with which we can
estimate the position of the lateral peaks in the CC frames that are
smaller than the pixel size projected on the pupil (\(\Delta x_{\text{pix}}\)), and it is
equal to
\[
\Delta h_{\text{pix}} = 0.56 \frac{\Delta x_{\text{pix}}}{\theta}.
\]
(2)

For \(\theta = 30\) arcsec and \(\Delta x_{\text{pix}} = 7\) mm, we retrieve a typical
vertical resolution \(\Delta h_{\text{pix}} \sim 25–30\) m. In conclusion, the main HVR-
GS concept consists of (i) taking a wide binary of the order of
30–35 arcsec, monitoring the first kilometre and (ii) treating simulta-
neously the AC and CC frames. From a practical point of view,
the \(C_N^2\) retrieved from the AC frames is characterized by an energy
that is redistributed in a set of thinner layers within the first kilo-
metre whose vertical resolution is of the order of 25 m. The AC frames
are fundamental to renormalize the total energy in the first kilo-
metre. The final high vertical resolution \(C_N^2\) profile is retrieved from
\[
\int_{-\Delta h_{\text{max}}(0)/2}^{\Delta h_{\text{max}}(0)/2} C_{N,\text{AC}}(h) dh = f_{\text{scale}} \sum_i C_{N,\text{CC}}(h_i),
\]
(3)
where \(h_{\text{max}}\) is the height of the highest detected layer; the infe-
rior limit of the integral \(\Delta h_{\text{max}}(0)/2\) takes into account the vertical
resolution at \(h = 0\). \(f_{\text{scale}}\) is a factor that takes into account the decorrela-
tion of the central peak of the triplets having \(V > 0\) \(\Delta V\)
(\(\Delta V = 0.2–0.8\) m s\(^{-1}\)) with respect to the zero velocity triplet. It
has been measured (Egner & Masciadri 2007) that \(f_{\text{scale}}\) in the range
\(\Delta H = 1\) km can be considered the same for all the thin turbulent
layers. We note that, using the HVR-GS, we have to consider a rate
of rejection of frames because of the wind fluctuations that can
produce a spreading of the central peak of the triplets. The rate
of rejection can be more or less conservative, depending on the con-
straints that the user wishes to introduce in this analysis. Anyway,
in Egner & Masciadri (2007), it has been proved that no bias in
the measurements is introduced if we reduce the statistic sample.

This can be explained with the fact that the conditions that facilitate
the spreading of the central peaks are not necessarily correlated to
typical bad or good seeing. We refer the reader to that paper for
further details. We highlight that two slightly different approaches
have been proposed recently in the literature to increase the vertical
resolution near the ground: the HVR-GS (Egner & Masciadri 2007)
and the Low Layers SCIDAR (LOLAS) (Avila et al. 2008; Avila
& Chun 2004). The main difference from the point of view of the
principle is the following: the HVR-GS uses a known instrument
(the GS) but with a new technique. LOLAS uses a new instrument
but with the same technique of the GS. The reader can find in
the corresponding papers the details (and technicalities) related to both.

3 SITE TESTING CAMPAIGNS: DATA SET STATISTICS

So far we have collected and analysed observations related to 43
nights (Table 1). As already noted, the GS is manually operated
and therefore the site testing campaigns have been scheduled respecting
the periods in which the VATT was shut down (July and August)
and trying to cover as many different periods of the year. Table 2
shows the code used to identify the typology of the data set: ‘GS’
indicates the standard GS measurements extended on \(\sim 20\) km (43
nights), ‘WB’ indicates the \(C_N^2\) retrieved from the AC frames as-
associated with wide binaries (\(\Delta H \sim 200–250\) m) (15 nights) and
‘HVR-GS’ indicates the \(C_N^2\) obtained with high vertical resolution
(\(\Delta H \sim 25–30\) m) (15 nights) in which both the AC and CC frames
have been treated. The samples of the three categories have differ-
ent richness because we started to use the HVR-GS more recently
and this new technique has a higher rate of measurement rejection.
We note that, to avoid biases in the estimates in the HVR-GS, it
has been decided to discard from the statistics all doubtful cases
characterized by the presence of clouds or cirrus. A method that
we called ‘normalization’ (it will be described later) has been ap-
plied to the sample of high-resolution measurements (15 nights).
Among other advantages, it permits us to provide a turbulence bud-
get representative of the whole sample of 43 nights. Basically, the
morphology of the turbulence energy distribution (shape of the \(C_N^2\)

### Table 1. Observing runs at Mt Graham.

| Observing runs | Nights |
|----------------|--------|
| 2005 April 27  | 1      |
| 2005 May 19–24 | 6      |
| 2005 December 6–15 | 5   |
| 2007 May 27 to 2007 June 3 | 8      |
| 2007 October 16–28 | 13     |
| 2008 February 23 - 2008 March 3 | 10     |

### Table 2. Classification of the GS campaign measurements. ‘GS’: \(C_N^2\) profiles retrieved from the standard GS. ‘WB’: \(C_N^2\) profiles retrieved from the AC frames of the GS measurements obtained with wide binaries. ‘HVR-
GS’: \(C_N^2\) profiles retrieved from the wide binaries autocorrelation (AC) and
cross-correlation (CC) frames following the technique described in Egner
& Masciadri (2007).

| Sample   | Nights | Measurements | Hours | Resolution |
|----------|--------|--------------|-------|------------|
| ‘GS’     | 43     | 16 657       | 163   | \(\Delta H(0) \sim 1\) km |
| ‘WB’     | 15     | 36 569       | 6.2   | \(\Delta H(0) \sim 200\) m |
| ‘HVR-GS’ | 15     | 28 122       | 5.1   | \(\Delta H(0) \sim 25\) m |
versus the height) is retrieved from the observation of wide binaries for 15 nights and with the ‘normalization’ procedure the turbulence energy of the first kilometre detected with the standard GS is redistributed in thin turbulent layers according to the profile morphology reconstructed with the CC frames. The selected binary stars for the standard GS and HVR-GS techniques are reported in Table 3. They are substantially the same as indicated in Egner et al. (2007) and Egner & Masiadi (2007), but we eliminated from the sample those binaries with magnitude larger than 6 mag (i.e. 118 Tau has been discarded) to avoid potential biases due to a too weak intensity.

### 4 INTEGRATED ASTROCLIMATIC PARAMETERS

The seeing, the isoplanatic angle $\theta_0$, the wavefront coherence time $\tau_0$ and the equivalent velocity $V_0$ are defined as

$$ r_0 = \left[ \frac{2 \pi}{\lambda} \right]^2 \int_0^\infty C_n^2(h) \, dh \right]^{-3/5}, $$  \tag{4}  

$$ \varepsilon = 0.98 \frac{\lambda}{r_0}, $$  \tag{5}  

$$ \theta_0 = 0.057 \lambda^{6/5} \left[ \int_0^\infty h^{5/3} C_n^2(h) \, dh \right]^{-3/5}, $$  \tag{6}  

$$ V_0 = \left[ \int_0^\infty \frac{V(h) h^{5/3} C_n^2(h) \, dh}{\int_0^\infty C_n^2(h) \, dh} \right]^{3/5}, $$  \tag{7}  

$$ \tau_0 = 0.31 \frac{r_0}{V_0}. $$  \tag{8}  

Fig. 1 shows the cumulative distribution of the astroclimatic parameters (seeing, seeing in the free atmosphere calculated for $h > 1$ km, isoplanatic angle and wavefront coherence time) calculated for the total 43 nights and for the April–September and October–March periods which we will simply call summer and winter.\(^2\) Table 4 summarizes the median (50th), first (25th) and third (75th) quartiles for the three main integrated astroclimatic parameters calculated for the following groups: the whole sample of 43 nights, the summer and the winter time.

A composite wind speed profile has been used to calculate the median wavefront coherence time $\tau_0$. Below 2 km the wind speed retrieved from the GS has been used; above 2 km the wind speed profile retrieved from the European Centre for Medium-Range Weather Forecast (ECMWF) analyses extracted at the nearest grid point (32.75° N, 110.00° W)\(^3\) to Mt Graham (∼11.5 km north-west of the summit). Due to the fact that the wind speed vertical profiles retrieved from the ECMWF analyses are calculated at the synoptic hours (00:00, 06:00, 12:00, 18:00), a temporal interpolation of wind speed from adjacent synoptic hours has been performed to better represent the wind speed in the local temporal range in which $C_n^2$ measurements have been done. It has already been shown (Egner et al. 2007) that this is the best method to treat the wind speed to calculate a reliable $\tau_0$. The ECMWF analyses do not reconstruct well the orographic effects produced on the atmospheric flow at the top of the summit. Moreover, the ECMWF grid points spaced by 0.25° correspond to locations with lower altitudes than the summit altitude $H_0$, and, as a consequence, the ECMWF wind speed calculated at a height equal to $H_0$ is, in general, larger than the wind speed measured on the summit. On the other hand, measurements of the wind speed with GS imply a great number of rejected frames and it is frequently difficult to retrieve a profile extended on the whole troposphere. The composition method for the wind speed is revealed, therefore, to be the best solution for the calculation of $\tau_0$ (Egner et al. 2007).

Looking at Fig. 1 and Table 4, a clear seasonal variation appears evident for all the integrated astroclimatic parameters. In 2005 May and 2007 May, in both years, 10–15 days of extremely good seeing and large isoplanatic angle features have been observed. Such a long time of extremely good conditions in the same period of the year indicates that this is, highly probably, among the best periods of the year for turbulence conditions at Mt Graham. This result is coherent with the typical weather conditions at synoptic scales in this region and in this season that are characterized by weaker wind speed in the high troposphere. A low probability to trigger OT in the high atmosphere confirmed by a weaker $C_n^2$ strength (see Section 6) is coherent with a large median $\theta_0$ and a small median seeing in the free atmosphere (Fig. 1) in the summer seasons. If we also take into account the typical weaker equivalent wind speed (equation 4) in summer with respect to winter time (see Table 4 and Section 6), we can explain the typical larger value of the median $\tau_0$ in this season (see equation 8).

Finally, to quantify the contribution of the seeing provided only by the atmosphere, the dome seeing ($\varepsilon_d$), calculated with the method described in Egner et al. (2007) and Avila, Vernin & Sanchez (2001), has been subtracted from the total seeing ($\varepsilon$). The method consists of discriminating the triplets located at the ground [$H = H(0) \pm \Delta H$] with a velocity $V = 0 \pm \Delta V$ from those located at the same height and having a velocity different from zero ($V > \Delta V$). The velocity resolution $\Delta V$ of our system is 0.8 to 0.2 m s$^{-1}$ per pixel with time lags within the range 10 to 40 ms. Fig. 2 shows the cumulative distribution of the dome seeing calculated for the whole sample and the two seasons. The median value of the ‘dome seeing’ is $\varepsilon_d = 0.52$ arcsec (Fig. 2). For the first time, an interesting seasonal

\(^2\) As shown in Table 1, measurements do not cover all the months of the year with an exact uniform distribution. For example, there are no measurements in the July–September period. However, we are interested in demonstrating macroscopic differences between the two extreme seasons and we observed that the morphology of the average $C_n^2$ profile and the turbulence strength was substantially the same when including or not including the data related to the month of October. We therefore decided on this division instead of a more reductive April–June and December–March division that would have implied the study of a less statistically representative sample.

\(^3\) It is worth highlighting that the analyses from the ECMWF are available, at present, with a horizontal resolution of 0.25°. Calculations done by Egner et al. (2007) have been obtained with data extracted at latitude 33° N and a horizontal resolution of 0.5°.
**Figure 1.** Cumulative distributions of four integrated astroclimatic parameters. Top left: the total seeing (including the dome contribution). Top right: the seeing in the free atmosphere ($h > 1$ km). Bottom left: the isoplanatic angle ($\theta_0$). Bottom right: the wavefront coherence time ($\tau_0$). Thick lines: the whole sample. Dotted lines: summer time. Thin lines: winter time.

**Table 4.** Median, first and third quartile values of the main integrated astroclimatic parameters above Mt Graham (43 nights): seeing in the total troposphere, isoplanatic angle, wavefront coherence time, integrated equivalent wind speed.

| Parameter       | 25th | 50th | 75th | 25th | 50th | 75th | 25th | 50th | 75th |
|-----------------|------|------|------|------|------|------|------|------|------|
| $\varepsilon$ (arcsec) | 0.65 | 0.95 | 1.34 | 0.53 | 0.61 | 0.72 | 0.89 | 1.19 | 1.50 |
| $\theta_0$ (arcsec)  | 1.6  | 2.5  | 3.6  | 3.1  | 3.8  | 4.5  | 1.4  | 2.0  | 2.7  |
| $\tau_0$ (ms)        | 2.7  | 4.8  | 8.7  | 6.4  | 10.1 | 14.6 | 2.5  | 3.8  | 6.2  |
| $V_0$ (ms$^{-1}$)    | 5.1  | 7.2  | 9.3  | 3.7  | 5.1  | 7.8  | 5.9  | 7.7  | 9.6  |

**Figure 2.** Cumulative distribution of the dome seeing for all of the 43 nights (thick line), the summer (dotted line) and winter (thin line) period.

trend has been observed in the dome contribution that certainly deserves a careful investigation in the future. Knowing that the median seeing in the whole atmosphere (including the dome seeing) is $\varepsilon = 0.95$ arcsec and that $\varepsilon_d = 0.52$ arcsec, it follows that the median seeing related to the whole atmosphere, without the dome contribution for the richest statistics we collected so far (43 nights), is $\varepsilon_{\text{tot}} = 0.72$ arcsec.

Table 5 reports the difference in the median estimates of the principal integrated astroclimatic parameters obtained above Mt Graham with samples that have different richness by a factor of $\sim 3$. No major differences can be highlighted with the exception of $\tau_0$ that appears larger, by about 1 ms, with respect to the paper of Egner et al. (2007).

To complete the analysis of the integrated astroclimatic parameters, it is worth reminding that, in the context of GLAO systems

**Table 5.** Comparison of values obtained in the study of Egner et al. (2007) (16 nights) and Masciadri et al. (2009) (43 nights). Seeing (with and without dome contribution) and $\theta_0$ are in arcsec, the $\tau_0$ in ms.

| Parameter | Egner et al. (2007) | Masciadri et al. (2009) |
|-----------|---------------------|-------------------------|
| $\varepsilon$ included dome | 0.80 | 0.95 |
| $\varepsilon$ without dome | 0.68 | 0.72 |
| $\theta_0$ | 2.71 | 2.5 |
| $\tau_0$ | 3.6 | 4.8 |
(Tokovinin 2004), the atmosphere can be divided into three vertical slabs: a region near the ground \( (h < H_{\text{min}}) \) in which the turbulence is totally corrected, an intermediate region \( (H_{\text{min}} < h < H_{\text{max}}) \), called the grey zone, in which the turbulence is partially corrected, and a region that covers the rest of the troposphere \( (h > H_{\text{max}}) \) in which the turbulence is not corrected any more. The values of \( H_{\text{min}} \) and \( H_{\text{max}} \) depend on the wavelength, the field of view, the turbulence conditions and the pitch size of the adaptive optics system. A more detailed discussion on that will be presented later but it is, of course, evident that it can be very useful for the GLAO applications (i) to know the budget of turbulence energy developed in the high part of the atmosphere, i.e. how much turbulence remains not corrected by a GLAO system, and (ii) to better estimate the size of the grey zone and the vertical distribution of the turbulence inside the grey zone. The gain of a GLAO system depends, indeed, mainly on these two issues. From the standard GS measurements it is trivial to calculate the cumulative distribution of \( \varepsilon_{FA} \) for \( h > 1 \) km (Fig. 1). The same calculation is done for the whole year, the summer and winter time. We calculated a median value \( \varepsilon_{FA} = 0.39 \) arcsec for \( h > 1 \) km \( (\varepsilon_{FA, \text{sum}} = 0.31 \) arcsec, \( \varepsilon_{FA, \text{win}} = 0.44 \) arcsec). For those cases in which \( H_{\text{max}} = 1 \) km, the \( \varepsilon_{FA} \) represents the portion of turbulence that is not corrected at all. In the next section, we will deal with the portion of turbulence developed above \( X \) m, where \( X < 1 \) km is extremely important for GLAO applications.

5 COMPOSITE PROFILES FOR ADAPTIVE OPTICS APPLICATIONS

The ‘composite profiles’ are used to represent efficiently and in statistical terms the vertical distribution of the OT in a discretized number of layers particularly suitable for AO simulations. The method is commonly used by many authors in the field (Tokovinin & Travoillon 2006; Egner et al. 2007; Stoesz et al. 2008; Masciadri et al. 2009; Chun et al. 2009) and it consists of identifying a finite number of vertical slabs covering the whole troposphere \( (~20 \) km) with their corresponding value of seeing \( (\Delta J_i \) or \( J_i) \) so that the total turbulence integrated on the troposphere is conserved. \( J \) is defined as

\[
J = \int_{0}^{\infty} C_{\beta}^2(h)dh \tag{9}
\]

and it is related to the seeing as

\[
J = 9 \times 10^{-11} \times \lambda^{1/3} \times \varepsilon^{5/3}, \tag{10}
\]

where \( \lambda \) is expressed in metres, \( \varepsilon \) in arcsec and \( J \) in \( m^{1/3} \). The turbulence in the free atmosphere \( (h > 1 \) km) and in the boundary layer \( (h \leq 1 \) km) is treated in an independent way to permit the study of different combinations of probabilities for the OT vertical distribution. Table 6 reports the \( \Delta J_i \) values in the range \( h > 1 \) km calculated at different heights and obtained from the \( C_{\beta}^2 \) associated with the \( r_0 \) related to 20–30 per cent of its cumulative distribution \( (‘good’ \) case), to 45–55 per cent \( (‘typical’ \) case) and to 70–80 per cent \( (‘bad’ \) case). Measurements from the sample ‘GS’ (see Table 2) are used.

The \( C_{\beta}^2 \) profiles retrieved from the ‘WB’ sample characterized by a \( \Delta h \sim 200 \) m near the ground \( (H < 1 \) km) have a suitable vertical resolution to calculate the composite profiles in this vertical range for applications to ARGOS (field of view \( \theta = 4 \) arcmin) because the turbulence developed below \( H_{\text{min}} = \Delta X/(2\theta) \sim 200 \) m \( (\Delta X = 0.5 \) m is the pitch size, i.e. the projection of the actuator of the deformable mirror on the pupil of the telescope) is resolved by the instrument. Basically, we do not need a higher vertical resolution for this application. We therefore first calculated a similar distribution to Table 6 for \( h \leq 1 \) km and obtain a temporary table that we call Table T similar to Table 6. As already anticipated in Stoesz et al. (2008) and Masciadri et al. (2009), to take into account the different statistics obtained with the standard ‘GS’ and wide binary sample ‘WB’ and to take into account the quantitative information of the turbulence present in the first kilometre provided by the whole sample of 43 nights, each number of this temporary Table T has to be multiplied by the correction factor \( f_{\beta} \).

\[
f_{\beta} = \left( \frac{\theta_0}{\theta_{\beta}} \right)^{5/3}, \tag{11}
\]

reported in Table 7 to finally obtain the composite distribution for \( h \leq 1 \) km (Table 8). The numerator of \( f_{\beta} \) is the seeing measured in the first kilometre from the ground from the ‘GS’ sample. The denominator is the seeing measured in the first kilometre from the ground from the ‘WB’ sample. Table 8 reports the composite profiles for \( h < 1 \) km equivalent to 43 nights. It includes the dome contribution frequently preferable for AO simulations. In the last row, the \( J \) values in the case in which the dome contribution is subtracted are reported. The multiplication by the \( f_{\beta} \) factor (the method that we call normalization) offers a great advantage to retrieve the spatial distribution of the turbulence in the first kilometre using the HVR-GS technique (or the ‘WB’ as is this case) and to use the quantitative turbulence energetic budget of data extracted from the standard GS technique which can be done on a richer statistical sample (43 nights). We overcome therefore the intrinsic limitation of a high number of rejected frames typical of the CC technique. This method also is completely insensitive to any bias potentially

| Bins (m) | ‘Good’ \( J (m^{1/3}) \) | ‘Typical’ \( J (m^{1/3}) \) | ‘Bad’ \( J (m^{1/3}) \) |
|----------|----------------|----------------|----------------|
| 14 000–20 000 | 7.61e-15 | 1.02e-14 | 1.91e-14 |
| 12 000–14 000 | 5.10e-15 | 9.65e-15 | 1.57e-14 |
| 10 000–12 000 | 7.24e-15 | 1.27e-14 | 2.09e-14 |
| 8 000–10 000 | 8.52e-15 | 1.72e-14 | 3.22e-14 |
| 6 000–8 000 | 6.45e-15 | 1.05e-14 | 1.77e-14 |
| 4 000–6 000 | 9.50e-15 | 1.23e-14 | 2.10e-14 |
| 3 000–4 000 | 9.18e-15 | 1.14e-14 | 1.45e-14 |
| 2 000–3 000 | 1.97e-14 | 3.39e-14 | 4.02e-14 |
| 1 500–2 000 | 6.98e-15 | 1.52e-14 | 2.86e-14 |
| 1 000–1 500 | 5.28e-15 | 1.50e-14 | 2.86e-14 |

| Ground layer seeing | ‘Good’ | ‘Typical’ | ‘Bad’ |
|---------------------|-------|----------|-------|
| GS                  | 0.55  | 0.81     | 1.16  |
| WB                  | 0.62  | 0.75     | 0.88  |
| \( f_{\beta} \)     | 0.82  | 1.1      | 1.6   |

\[^{4}\text{We note that the median seeing of Table 4 is not exactly the same as the seeing retrieved by the composite profiles because the former treats a set of individual seeing values that are proportional to } J^{5/3}.\]
Table 8. Composite profiles for $h < 1$ km after the ‘normalization’ for the $f_{gl}$ factor. These composite profiles are statistically representative for 43 nights. In the last line are reported the $J$ values obtained without the dome contribution (median values: $e_d,25 = 0.35$ arcsec, $e_d,40 = 0.52$ arcsec, $e_d,75 = 0.70$ arcsec).

| Bins (m) | 'Good' $J$ (m$^{1/3}$) | 'Typical' $J$ (m$^{1/3}$) | 'Bad' $J$ (m$^{1/3}$) |
|---------|-------------------------|--------------------------|---------------------|
| 900–1000 | 4.35e-15 | 7.06e-15 | 1.33e-14 |
| 800–900 | 2.48e-15 | 3.53e-15 | 6.29e-15 |
| 700–800 | 3.30e-15 | 6.04e-15 | 1.04e-14 |
| 600–700 | 7.72e-15 | 1.09e-14 | 2.05e-14 |
| 500–600 | 4.30e-15 | 7.70e-15 | 1.38e-14 |
| 400–500 | 4.21e-15 | 9.60e-15 | 1.86e-14 |
| 300–400 | 2.05e-14 | 4.26e-14 | 8.26e-14 |
| 200–300 | 6.15e-15 | 1.14e-14 | 2.53e-14 |
| 100–200 | 2.03e-14 | 4.14e-14 | 8.11e-14 |
| 0–100 | 1.79e-13 | 3.27e-13 | 6.17e-13 |
| 0–100 | 3.4e-14 | 8.5e-14 | 2.20e-13 |

Table 9. Dome seeing included. Left: percentage of turbulence developed above the height $h$ with respect to the turbulence developed in the whole troposphere. Right: percentage of turbulence developed between the ground and the height $h$ with respect to the turbulence developed in the whole troposphere. The second and fourth columns are obviously complementary.

| $h$ (m) | $J_{[0,h]}/J_{tot}$ (per cent) | $h$ (m) | $J_{[0,h]}/J_{tot}$ (per cent) |
|---------|-------------------------------|---------|-------------------------------|
| 1000 | 25 | 1000 | 75 |
| 800 | 26 | 800 | 74 |
| 600 | 29 | 600 | 71 |
| 400 | 31 | 400 | 69 |
| 300 | 38 | 300 | 62 |
| 200 | 40 | 200 | 60 |
| 100 | 47 | 100 | 53 |

we deduce that the ‘grey zone’ extends in the 200–378 m range and assumes its smallest value when we observe in $J$ band and we consider the ‘bad’–‘bad’ case (75 per cent case). It extends in the 200–3777 m range and assumes its largest value when we observe in $K$ band and we consider the ‘good’–‘good’ case (25 per cent case). Fig. 3 shows the values of $H_{max}$ (blue, red and yellow) for different fields of view and for the residual wavefront coherence size FWHM of GLAO simulations (Table 11, column 5) obtained using, as inputs, the central columns of Tables 6 and 8.

6 OPTICAL TURBULENCE VERTICAL DISTRIBUTION: $C_N^2$

6.1 GS: vertical distribution in the whole troposphere

Fig. 4 shows the median $C_N^2$ profile obtained with the whole data set of 43 nights, the summer and the winter periods. The morphology of the vertical distribution of the OT ($C_N^2$ profile) shows that the greatest turbulence contribution develops in the first kilometre above the ground. Between 1 and 10 km, we observe a set of minor peaks changing their position and strength during the year. At around 10 km, we observe the typical secondary $C_N^2$ peak developed at the jet-stream level. Concerning the seasonal variation, we observe that the ground layer bump, responsible for most of the turbulence budget, shows a clear seasonal trend indicating larger turbulence strength in winter than in the summer period. In the free atmosphere, we observe the interesting effect of the secondary $C_N^2$ peak located at 10 km in the winter which shifts to greater heights (∼14 km) and is characterized by a weaker strength in summer. This effect (which we call the ‘α effect’) has been discovered for the first time by Masciadri & Egner (2006) above a different site (San Pedro Mártir) with simulations provided by a mesoscale atmospheric model. Above Mt Graham, the jet-stream $C_N^2$ peak appears to have a similar shift of ∼4 km towards greater heights in summer and the $C_N^2$ peak is located at roughly the same absolute height from the ground with respect to San Pedro Mártir (Masciadri & Egner 2006). At that time, we had no measurements extended to different periods of the year above San Pedro Mártir to retrieve a seasonal trend. Avila et al. (2004) referred just to the spring and therefore they could not demonstrate any seasonal trend. It is worth noting that this was, to our knowledge, the first time that an atmospheric model could demonstrate new insights before measurements showing that simulations can be a valuable tool to investigate the nature of the turbulence by itself.
The FWHM values are obtained with the GLAO simulations using as inputs Tables 6 and 8. \( H_{\text{max}} = \Delta X/2\theta \sim 200 \text{ m} \) for all the wavelengths.

| 75 per cent | FWHM (arcsec) | \( H_{\text{max}} \) (m) | 50 per cent | FWHM (arcsec) | \( H_{\text{max}} \) (m) | 25 per cent | FWHM (arcsec) | \( H_{\text{max}} \) (m) |
|-------------|---------------|------------------------|-------------|---------------|------------------------|-------------|---------------|------------------------|
| \( J \)     | 0.43          | 378                    | \( J \)     | 0.30          | 567                    | \( J \)     | 0.18          | 945                    |
| \( H \)     | 0.37          | 606                    | \( H \)     | 0.20          | 1123                   | \( H \)     | 0.11          | 2042                   |
| \( K \)     | 0.25          | 1208                   | \( K \)     | 0.13          | 2324                   | \( K \)     | 0.08          | 3777                   |

Figure 3. Extent of the ‘grey zone’, i.e. \( H_{\text{max}} < h < H_{\text{max}} \) for different fields of view and wavelengths in the case of the median turbulence distribution (50 per cent). \( H_{\text{max}} \) (coloured lines) is calculated for \( J \) (blue), \( H \) (red) and \( K \) (yellow) bands. \( H_{\text{min}} \) (black line) is the same for all the wavelengths. The pupil size is \( D = 8 \text{ m} \) and the pitch size \( \Delta X = 0.5 \text{ m} \). The FWHM is equivalent to \( r \), i.e. the residual wavefront coherence size after correction.

More recently (Els et al. 2009), MASS measurements done above San Pedro Mártir and extended on a yearly time-scale have been published as part of the Thirty Meter Telescope (TMT) site testing project (Schoeck et al. 2009). The MASS vertical resolution is much lower than the GS one, but some information, useful in this context, can be retrieved. The layer at 8 km (the nearest to the jet-stream level) is unfortunately not perfectly centred on the jet-stream, and considering a resolution of 4 km at this height, the absolute values of the peak-to-peak seasonal variation can be smoothed out. However, if we do not take care about the absolute estimate of the amplitude peak-to-peak variation for which the MASS is not the most suitable instrument, we can say, in any case, that the MASS 8 km layer can provide a qualitative seasonal trend near the jet-stream level. In fig. 5 of Els et al. (2009), we can observe above San Pedro Mártir a seasonal effect of the turbulence strength similar to what has been obtained above the same site with simulations performed with atmospheric models (Masciadri & Egner 2006) and to what has been observed above Mt Graham, i.e. an increase of the turbulence strength in summer. This fact might therefore play a role in the mechanism producing the shift towards greater heights of the jet-stream. This fact might therefore play a role in the mechanism producing the shift towards greater heights of the jet-stream.

This instrument cannot resolve seasonal variations since its vertical resolution is \( \sim 8 \text{ km} \) at \( h = 16 \text{ km} \). We conclude therefore that results obtained at San Pedro Mártir with an atmospheric model and at Mt Graham with a GS are evidence that the ‘\( \alpha \) effect’ exists and it is not typical of a specific site.

Similar behaviours of the \( C_{N}^{2} \) observed above different sites are promising for describing a ‘universal physical model’ able to explain what is the origin of the \( \alpha \) effect. Masciadri & Egner (2006) proposed an explanation: starting from the assumption that the development of the OT depends on the gradient of the wind speed and the potential temperature, a parallel analysis of these two elements all along the troposphere in the two seasons can provide insights on the seasonal variation trends. Above San Pedro Mártir, no great differences have been identified in the potential temperature and its gradient between the summer and the winter. On the other hand, a substantial decrease of the gradient of the wind speed and its strength has been identified at a jet-stream level in summer. This fact could explain the decrease of the turbulence strength in summer at a jet-stream level. Besides, the rapid inversion of the wind speed gradient at around 15–16 km could explain the production of the OT at these heights which appears as a shift of the jet-stream \( C_{N}^{2} \) peak towards greater heights.

Fig. 5 shows the median potential temperature and wind speed profiles above Mt Graham, calculated in the two periods (winter and summer) in which \( C_{N}^{2} \) measurements have been collected. The potential temperature is retrieved from the ECMWF analyses at the same grid point as we discussed in Section 4. The wind speed profiles are obtained with the composite procedure described in Section 4, i.e. GS measurements have been considered for \( h < 2 \text{ km} \) and ECMWF analyses for \( h > 2 \text{ km} \). We observe a non-negligible wind speed increase at the jet-stream level in the winter as already observed above San Pedro Mártir. Also a similar inversion in the wind speed gradient in the higher part of the atmosphere above the jet-stream (at \( \sim 17 \text{ km} \) above sea level) is visible above Mt Graham as well as above San Pedro Mártir in the summer. Above Mt Graham, the median profile of the potential temperature shows that the typical ‘slope change’ identifying the position of the tropopause visible at 10–11 km in the winter is a little smoother and located at greater heights (\( \sim 13 \text{ km} \) above sea level) in summer. The level of the thermal stability obviously plays an important role in determining the strength of the OT triggered by the dynamic shear typical of the jet-stream. This fact might therefore play a role in the mechanism producing the shift towards greater heights of the jet-stream \( C_{N}^{2} \) peak, but is, in any case, coherent with what was found above San Pedro Mártir. The physical model proposed by Masciadri & Egner (2006) to explain the \( \alpha \) effect seems therefore to be consistent with what is observed above Mt Graham in this paper. We note that the fact that the wind speed is visibly one of the main causes triggering the seasonal variation of the \( C_{N}^{2} \) at the jet-stream level does not mean that for equivalent wind speeds, above whatever astronomical site, one has to expect the same \( C_{N}^{2} \) value. The absolute
strength of the $C_n^2$ in a precise region of the atmosphere, indeed, depends on the thermodynamic stability of the atmosphere in the same region.

6.2 HVR-GS: vertical distribution for $h \leq 1$ km

The OT vertical distribution with high resolution (20–30 m) in the first kilometre is obtained with the method called HVR-GS presented in Egner & Masciadri (2007). The HVR-GR data set is obtained by taking the integral of the $C_n^2$ profiles retrieved from the AC frames and redistributing the energy in the first kilometre according to the detected triplets in the CC frames. Three different strategies can be used to study the turbulence spatial distribution in the boundary layer. The usefulness of each method depends on the application one intends to give to the analysis. We study the following.

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**Figure 4.** Median $C_n^2$ profile obtained with the complete sample of 43 nights, the summer (April–June) and winter (October–March) time samples. Results are obtained with the standard GS technique. Dotted lines: first and third quartiles.

**Figure 5.** Left-hand panel: median potential temperature calculated using the ECMWF analyses. Right-hand panel: median wind speed calculated using the composite profile (GS below 2 km, ECMWF analyses above 2 km – see text) in summer (thin style line) and winter (bold style line).
Considering that the strategy (A) is not really useful (or $C = 20–30$ m) calculated with the sample ‘HVR-GS’ and the dome seeing contribution included (black line). The exponential decay is, however, an exponential factor, and it is therefore representative of 43 nights. The two profiles (with and without dome contribution) are shown in the proximity of the ground (Fig. 6, right-hand panel). To retrieve the typical scaleheight $B$ of the exponential decay of the mean $C_N^2$ profile, the measurements done below 125 m have been fitted with an exponential law (equation 12) as we already did in Stoesz et al. (2008):

$$y = A[e^{-(h/B)},]$$

where $A$ and $B$ are free parameters. The calculation is obviously shown only in the case in which the dome contribution is subtracted. The fit gives $A = 3.34 \times 10^{-15}$ and $B = 37.4$ m (Fig. 6, right-hand panel). If we limit the analytical fit to the first 30 m, the scaleheight $B = 28$ m. The exponential decay is, however, an absolutely arbitrary analytical law. The important issue is that these results definitely indicate that the HVR-GS technique is able to demonstrate that the turbulence decays above typical astronomical sites in stable night time conditions in a much sharper way than what has been predicted and quantified in the past. Indeed, the Hufnagel model in proximity to the surface (Roddi 1981) in night conditions states that the turbulence scales as $h^{-2/3}$ (Fig. 6). For the Hufnagel model (Fig. 6, left-hand panel), the $C_N^2$ decreases by one order of magnitude within 1 km while our results indicate that the $C_N^2$ decreases by one order of magnitude within $\sim 60–70$ m (Fig. 6, right-hand panel). It remains interesting that in the 800 m to 1 km range a visibly weak turbulence develops. One should expect a smoother connection between the boundary layer and the free atmosphere. We think that this is just an artefact effect due to the use of a quite different resolution below and above 1 km. From the point of view of the AO simulations, this small gap should not cause any problems. It should be enough to implement a weak convolution to slightly smooth out the $C_N^2$ vertical profiles at the interface located at 1 km so as to obtain a less abrupt connection of the $C_N^2$ profile above and below 1 km.

We note that the presence of no signal (therefore $C_N^2 = 0$) might potentially indicate that the turbulence strength is not equal to zero, but simply weaker than the threshold $C_N^2 = 10^{-16}$ (associated with an equivalent $J = 2.5 \times 10^{-15}$). In Masciadri et al. (2009), it has been calculated, in a post-processing phase, the most conservative case in which we assigned $C_N^2 = 10^{-16}$ where there is no signal. After a more careful investigation, we observed that the latest distribution is associated with too large a total $J$ in the boundary layer and, for this reason, it can be discarded.

Fig. 7 shows the results obtained following the strategy (C), i.e. the mean $C_N^2$ profiles associated with the $J$ (or $r_0$) related to 20–30, 45–55 and 70–80 per cent of the cumulative distribution. In Appendix C, the numerical values for the corresponding $J$ values are reported. Curiously, the first grid point near the ground of the 75 per cent case distribution shows a weaker value with respect to the 25 and 50 per cent cases. This is due to the fact that the third quartile dome seeing ($r_{34.75}$) that has been subtracted from the original value is particularly large (0.70 arcsec). The morphology of the $C_N^2$ in the first kilometre is very interesting, showing several thin layers and a very weak turbulence between 800 m and 1 km. We note that the sample on which we calculate the average in each slot, 20–30, 45–55 and 70–80 per cent, is of a few hundreds of $C_N^2$ profiles, therefore there are no doubts that this structure reproduces some real distribution. In terms of morphology of the turbulence profile, we find therefore that the higher the vertical resolution, the thinner the size of the detected layers. This conclusion is perfectly coherent with the turbulence structure resolved by balloons equipped for $C_N^2$ measurements (Azouit & Vernin 2005).
Figure 7. Mean $C_n^2$ profiles calculated from the corresponding $J$ (or $r_0$) values related to the 20–30, 45–55 and 70–80 per cent ranges of the $J$ cumulative distribution. The dome contribution is excluded. In Appendix C the numerical values for the corresponding $J$ values are reported.

Figure 8. Percentage of turbulence developed between the ground and the height $h$ with respect to the turbulence developed in the whole atmosphere ($\sim 20$ km) as retrieved from the HVR-GS measurements and extended to the first kilometre. On the left is shown a zoom of the picture centred on the first hundreds of metres.

Fig. 8 shows the percentage of turbulence $P(h)$ developed in the $(0, h)$ range with $h$ in the $(0, 1 \text{ km})$ vertical slab. The function $P(h)$ is defined as

$$P(h) = \left( \frac{\int_0^h C_n^2(h^*)dh^*}{\int_0^\infty C_n^2(h^*)dh^*} \right) \times 100,$$

where the $C_n^2$ profile is that associated with the 45–55 per cent case (Table C1 and Fig. 7, centre). It is worth noting that the error bars for the HVR-GS technique are of the same order as half of the vertical resolution, i.e. $\pm 12–15$ m. This is derived mainly by the definition of the zero point, i.e. the ground that is characterized by an uncertainty equivalent to half of the vertical resolution.

From Fig. 8, we retrieve that around 50 per cent of the turbulence developed in the whole 20 km is concentrated below $80 \pm 15$ m. This result is substantially different from the preliminary indications obtained in Egner & Masciadri (2007) and the turbulence seems to be much more concentrated near the ground. We also note that the $C_n^2$ morphology below 1 km decreases in a different way if we look at the samples ‘WB’ and ‘HVR-GS’. This is not a contradiction and it can be explained by the fact that the turbulence spatial distribution for the ‘WB’ and the ‘HVR-GS’ samples is not necessarily the same because the first is based on the AC frames while the second is based on the CC frames. It is interesting to note that the higher the vertical resolution, the sharper is the exponential decay of the morphologic turbulence structure.

We note that, simultaneously with our study, some other authors (Chun et al. 2009) recently investigated the turbulence structure near the ground at high vertical resolution. Even if the instruments employed were different, these studies present many similarities in the results. From a qualitative point of view, we note that, also in that case, the turbulence appears well confined near the surface. From a quantitative point of view, things are more delicate. Looking at table 3 (in that paper), it appears that their data reduction is more similar to our method (C) than to the other methods. Fig. 9 shows the $J$ profile retrieved from Fig. 7 (centre) overlapped with the $J$ profile retrieved from table 3 (Chun et al. 2009). While above Mt Graham the turbulence vertical sampling is 25 m, above Mauna
Kea the sampling increases from 15 m up to 80 m and it extends only up to 650 m. The turbulence vertical distribution appears very similar. We note that above Mauna Kea a local minimum is present at ~45 m above the ground more or less in correspondence with the abrupt detection break due to the sensitivity threshold from LOLAS (table 3, Chun et al. 2009). We highlight that the evident huge ‘turbulent vacuum zone’ between 560 m and 1 km (SLope Detection and Ranging, SLODAR) simply means that the turbulence is not measured in this vertical slab, not that turbulence is not present.

7 CONCLUSIONS

In this paper, we present the results of a study aiming to characterize the OT at Mt Graham. We present a general overview of the statistics (43 nights) of the $C_N^2$ profiles and all the main integrated astrometric parameters and their seasonal trends. The main conclusions we achieved are as follows.

(i) With a median seeing $\varepsilon = 0.95$ arcsec ($\varepsilon = 0.72$ arcsec without dome contribution), an isoplanatic angle $\theta_0 = 2.5$ arcsec and a wavefront coherence time $\tau_0 = 4.8$ ms, Mt Graham confirms its good quality in terms of turbulence characteristics typical of the best astronomical sites in the world. All the integrated astrometric parameters (the seeing, the isoplanatic angle, the wavefront coherence time and the equivalent wind speed) show a clear seasonal trend that indicates better turbulence conditions and weaker equivalent wind speed $V_0$ in summer with respect to the winter.

(ii) The ground layer is characterized for the first time with a high resolution (200–250 m and 20–30 m). The turbulence exponentially decays above Mt Graham with a much sharper profile than what has been supposed so far and expressed with the Hufnagel model. Three different strategies of analysis aiming to investigate the morphology of the turbulence spatial distribution have been presented. We find that around 50 per cent of the turbulence developed in the whole atmosphere is concentrated below 80 ± 15 m from the ground and 60 per cent of the turbulence in the first kilometre. This evidence together with the favourable large $\theta_0$ observed above Mt Graham (particularly in the spring/summer) represents extremely favourable conditions for astronomical observations assisted by a LGS/GLAO system such as ARGOS.

(iii) We observe that the higher is the vertical resolution of the tool used to measure the turbulence vertical distribution, the more sharply is the turbulence decreasing.

(iv) The percentage of turbulence developed below the primary mirror of the LBT (i.e. ~35 m from the ground) is around 33 per cent. However, this estimate has to be considered with caution because the uncertainty (2$\sigma$ ~ 25–30 m) is of the same order of magnitude as the vertical resolution ($\Delta H$ ~ 25–30 m), and in the first hundred metres the turbulence decreases very sharply.

(v) It appears evident that at Mt Graham, the turbulence decreases above the ground in a similar way to what was observed above Mauna Kea in a more or less simultaneous study (Chun et al. 2009) performed with different instrumentation.

(vi) A composite distribution of the turbulence on the whole 20 km is calculated to be used as input of AO simulations of the LBT Laser Guide Star system named ARGOS, and the calculation of the grey zones for the near-infrared J, H and K bands is done. The grey zone extends from a minimum of 200–378 m in J band with the ‘bad’–‘bad’ case up to a maximum of 200–3777 m in K band in the ‘good’–‘good’ case.

(vii) A clear $C_N^2$ seasonal variation trend has been observed in proximity of the ground and in the jet-stream regions. These mea-

suresments confirm the first evidence of the $C_N^2$ seasonal trend observed by Masciadri & Egner (2006) above other astronomical sites. The physical model proposed by Masciadri & Egner (2006), which is able to explain the seasonal effect of the secondary peak of the $C_N^2$ called the ‘$a$ effect’, is confirmed and refined.

(viii) For the first time, we observed a seasonal trend of the dome measured. This is certainly a topic that deserves a more careful investigation in the future.

(ix) We proved that the error in the normalization of the scintillation that has been recently demonstrated in the principle of the GS technique affects these measurements by an absolutely negligible quantity (0.04 arcsec). In other words, the median seeing retrieved from the GS (without correction) overestimates, by ~0.04 arcsec, the correct median seeing. From a general point of view, all the GS measurements obtained with a pupil size $D \geq 1.5$ m and a binary separation $\theta \leq 8$ arcsec are affected by this error of less than a few hundredths of arcseconds.

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APPENDIX A: NORMALIZATION OF SCINTILLATION FOR THE STANDARD GENERALIZED SCIDAR

An imprecision has been highlighted (Johnston et al. 2002) in the normalization of the autocovariance of the scintillation maps obtained with a GS. A generalization of this problem, extended to altitudes \( h > 0 \), has been presented more recently by Avila & Cuevas (2009). Results of these studies say that, to obtain exact results for the \( C_{\text{2N}}^2 \) at an height \( h \) from the ground, one has to multiply the \( C_{\text{2N}}^2(h) \) retrieved from the GS by a factor of \( 1/(1 + \epsilon(h)) \) where \( \epsilon \) is the relative error between the exact and erroneous autocovariances of the scintillation maps obtained with the GS. \( \epsilon(h) \) depends on a set of geometrical parameters related to the optical set up and the observed binaries, more precisely the pupil of the telescope \( D \), the height \( d \) at which the detection plane is conjugated below the ground, the ratio between the stellar magnitude of the binary, the angular separation \( \theta \) and the central obscuration of the pupil \( e \) expressed as a fraction of the primary mirror. The authors introduced an approximated solution for the correction valid for a simple circular telescope pupil and the exact solution valid for a telescope pupil shape formed by a primary and a secondary mirror. However, we calculated that, for our sample, the correction of all the \( C_{\text{2N}}^2 \) profiles has an absolutely negligible impact on the statistical analysis presented in this paper (in both cases i.e. approximated and exact solution) and the median \( \epsilon \) calculated on the whole 43 night sample changes, respectively, by just 0.03 arcsec and 0.04 arcsec. This means that the approximated and exact solutions are very similar in this case.

To prove that, we first note that in the LBT-GS, the scintillation maps and the corresponding autocovariance calculated in real time

\begin{figure}
\centering
\includegraphics[width=\textwidth]{Figure_A1.png}
\caption{Left: the correction factor \( \epsilon(h) \) calculated for \( D = 1.83 \) m, \( d = 3.5 \) km, \( e = 0.2 \) and the separation of all the binaries of Table 3. \( \epsilon(h) \) is the relative error between the exact and erroneous autocovariances of the scintillation maps obtained with the GS. The full thin line is \( \epsilon(h) \) calculated in the approximation of a full circular pupil \( D = 1.83 \) m without secondary; the dotted line is \( \epsilon(h) \) in the case of a circular pupil \( D = 1.83 \) m and a secondary \( D_s = 0.38 \) m. We note that the relative error has to be multiplied by 100, i.e. 0.1 is equal to 10 per cent.}
\end{figure}
Figure A2. Median $C_n^2$ profiles related to 43 nights (black line) and corrected by the normalization factor (red line).

Appendix B: Normalization of Scintillation for the HVR-GS

The error in the normalization demonstrated by Johnston et al. (2002) and Avila & Cuevas (2009), in spite of the wider binary employed, affects the HVR-GS measurements in the same negligible way in which the standard GS technique is affected. The reason is that this technique, thanks to the procedure called ‘normalization’ (see Section 5), uses the AC and the CC frames just to retrieve the vertical turbulence distribution in the atmosphere (i.e. the shape). The strength of the turbulence is corrected by the factor $f_g$ that, physically speaking, is equivalent to taking the turbulence measured with the standard GS and redistributing it following the

Table C1. Composite profiles for $h < 1$ km after the ‘normalization’ for the $f_g$ factor and the dome contribution included. These composite profiles are statistically representative for 43 nights. Column 1: the height; columns 2–4: the $J$ values for the ‘good’, ‘typical’ and ‘bad’ cases. In the last line are reported the $J$ values without the dome contribution (median values: $e_{d,25} = 0.35$ arcsec, $e_{d,50} = 0.52$ arcsec, $e_{d,75} = 0.70$ arcsec). The first grid point ($h = 0$) includes $C_n^2$ values between −12.5 m and +12.5 m.

| $H$ (m) | ‘Good’ $J$ (m$^{-1/3}$) | ‘Typical’ $J$ (m$^{-1/3}$) | ‘Bad’ $J$ (m$^{-1/3}$) |
|---------|---------------------|-----------------|-----------------|
| 1000    | 0.000000E+00       | 0.000000E+00   | 0.000000E+00   |
| 950     | 0.000000E+00       | 0.000000E+00   | 0.000000E+00   |
| 925     | 0.000000E+00       | 0.000000E+00   | 0.000000E+00   |
| 900     | 0.000000E+00       | 0.000000E+00   | 0.000000E+00   |
| 875     | 0.947308E-16       | 0.000000E+00   | 0.000000E+00   |
| 850     | 0.000000E+00       | 0.000000E+00   | 0.000000E+00   |
| 825     | 0.279192E-15       | 0.000000E+00   | 0.000000E+00   |
| 800     | 0.000000E+00       | 0.000000E+00   | 0.000000E+00   |
| 775     | 0.631038E-15       | 0.224192E-15   | 0.498846E-15   |
| 750     | 0.974615E-16       | 0.822231E-15   | 0.000000E+00   |
| 725     | 0.000000E+00       | 0.139250E-14   | 0.219769E-14   |
| 700     | 0.447308E-16       | 0.000000E+00   | 0.443846E-15   |
| 675     | 0.000000E+00       | 0.114500E-15   | 0.157692E-14   |
| 650     | 0.289577E-15       | 0.261962E-15   | 0.183635E-14   |
| 625     | 0.000000E+00       | 0.000000E+00   | 0.558077E-14   |
| 600     | 0.435769E-16       | 0.000000E+00   | 0.124112E-14   |
| 575     | 0.000000E+00       | 0.000000E+00   | 0.137462E-14   |
| 550     | 0.000000E+00       | 0.120673E-14   | 0.352438E-14   |
| 525     | 0.000000E+00       | 0.284692E-14   | 0.532192E-14   |
| 500     | 0.208654E-15       | 0.000000E+00   | 0.377000E-14   |
| 475     | 0.144000E-15       | 0.105146E-14   | 0.328038E-14   |
| 450     | 0.153692E-15       | 0.204692E-14   | 0.172654E-15   |
| 425     | 0.128692E-15       | 0.458077E-15   | 0.290846E-15   |
| 400     | 0.122231E-15       | 0.162846E-15   | 0.118231E-14   |
| 375     | 0.000000E+00       | 0.413077E-16   | 0.109462E-14   |
| 350     | 0.000000E+00       | 0.467115E-15   | 0.728231E-15   |
| 325     | 0.465385E-15       | 0.191885E-14   | 0.375588E-14   |
| 300     | 0.413077E-16       | 0.312077E-16   | 0.359250E-14   |
| 275     | 0.668462E-16       | 0.485431E-14   | 0.448385E-14   |
| 250     | 0.362192E-15       | 0.132192E-16   | 0.512432E-14   |
| 225     | 0.263146E-15       | 0.243788E-14   | 0.384731E-14   |
| 200     | 0.355769E-15       | 0.341577E-14   | 0.463577E-14   |
| 175     | 0.219654E-14       | 0.210588E-14   | 0.832846E-14   |
| 150     | 0.391923E-15       | 0.369450E-14   | 0.943177E-14   |
| 125     | 0.748615E-15       | 0.346750E-14   | 0.672115E-14   |
| 100     | 0.437669E-15       | 0.544700E-14   | 0.165801E-13   |
| 75      | 0.393888E-14       | 0.118840E-13   | 0.180021E-13   |
| 50      | 0.988535E-14       | 0.197208E-13   | 0.256638E-13   |
| 25      | 0.179186E-13       | 0.287454E-13   | 0.488174E-13   |
| 0       | 0.280439E-12       | 0.368246E-12   | 0.432148E-12   |
| 0       | 0.135920E-12       | 0.126611E-12   | 0.355804E-13   |

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shape of the profile reconstructed by the HVR-GS technique. The HVR-GS technique retrieves the $C_n^2$ profiles in the first kilometre. Let us assume an error $A = 1/(1 + \varepsilon)$ for the $C_n^2$ as indicated by Johnston et al. (2002) and Avila & Cuevas (2009). We should therefore expect that the corrected turbulence strength is $J'_0 = AJ'_0$ for each vertical grid point of $\sim 25$ m. However, when we multiply for the $f_{gl}$ factor (equation 11), the factor $A$ disappears. Indeed, $f_{gl}$ can also be written as $J_0/(A \cdot J'_0)$. We conclude that, whatever is the value of $A$, the error potentially introduced by the wide binary is not taken into account in the final value of the $C_n^2$ retrieved with the HVR-GS technique.

APPENDIX C: VERTICAL DISTRIBUTION FOR THE HVR-GS: $J$ VALUES

In Table C1 are reported the values of $J = C_n^2 dh$ obtained with the average of $J$ included in the 20–30, 45–55 and 70–80 per cent ranges.

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