Seeing is Believing: New Facts about the Evolution of Seeing on Paranal

Marc Sarazin[1]
Jorge Melnick[1]
Julio Navarrete[1]
Gianluca Lombardi[1,2,3]

[1] ESO
[2] National Institute for Astrophysics, Bologna Astronomical Observatory, Italy
[3] Department of Astronomy, University of Bologna, Italy

Since the commissioning of the VLT it has been known that the image quality delivered by the telescopes is better, and often much better, than predicted by the seeing monitor. The advent of new sensitive instruments to measure the optical turbulence profile of the atmosphere over Paranal has finally allowed us to understand the origin of this discrepancy: the presence of a highly turbulent layer so close to the ground that it is seen by the seeing monitor, but not by the VLT unit telescopes. In this article we tell the story of this elusive surface layer.

The *inconvenient discrepancy*

It has been known since the commissioning of the VLT that the image quality delivered by the UT's is at times significantly better than the seeing measured by the Differential Image Motion Monitor (DIMM). The difference is not subtle. Already in 1999 the careful observations made with the test camera during the commissioning of UT2 revealed an alarming discrepancy between the UT2 image quality and the DIMM seeing, with an average DIMM –UT2 difference of ~ 0.2″. During these tests that lasted several nights, UT2 was pointing at the same region of the sky and through the same filter as the DIMM, so there was no straightforward explanation for the lack of agreement. A dramatic manifestation of the discrepancy between the DIMM and the UT's is given by the time evolution of seeing on Paranal. Figure 1, shows in the left panel, a plot of the evolution of DIMM seeing since 1989 taken from the ESO astro-climatology web pages *(http://www.eso.org/astclim/paranal/seeing/)*. The DIMM seeing has degraded considerably over the past 17 years from a median value of 0.65″ in 1990 to more than 1.1″ in 2007. On the other hand, the right panel of Figure 1 shows that the image quality delivered by FORS2 and ISAAC seem to have improved with time, at least since the instrument values have been systematically logged through the quality control process! This result could however be a selection effect since some of the PI's requested special seeing conditions. We note in passing that the La Silla seeing has also slightly degraded in a similar period *(http://www.eso.org/astclim/paranal/seeing/)*.

We have been puzzling for a long time about the origin of this rather *inconvenient discrepancy*, but it has not been until recently, with the deployment of new sensitive instruments in the context of the ELT site testing campaign, that we have finally been able to draw a coherent picture. This article tells the story of the seeing on Paranal.

New data

FORS2 imaging data

A wealth of data has accumulated since the commissioning of UT2. For example, the Quality Control process (QC) systematically logs delivered image quality from several instruments together with environmental parameters such as wind speed and direction, air temperature, telescope position, and DIMM seeing. The most complete dataset for image quality is the one for FORS2, which will be used here. Figure 2 shows the relation between DIMM seeing and UT2 image quality measured during regular FORS2 operations. The FORS2 data has been corrected for wavelength and airmass using the standard formulae based on an infinite outer scale assumption. Only images taken at airmasses less than 1.5 and exposure times between 30 s and 300 s were used. The FORS2 measurements are automatically obtained using many objects on each frame, but only

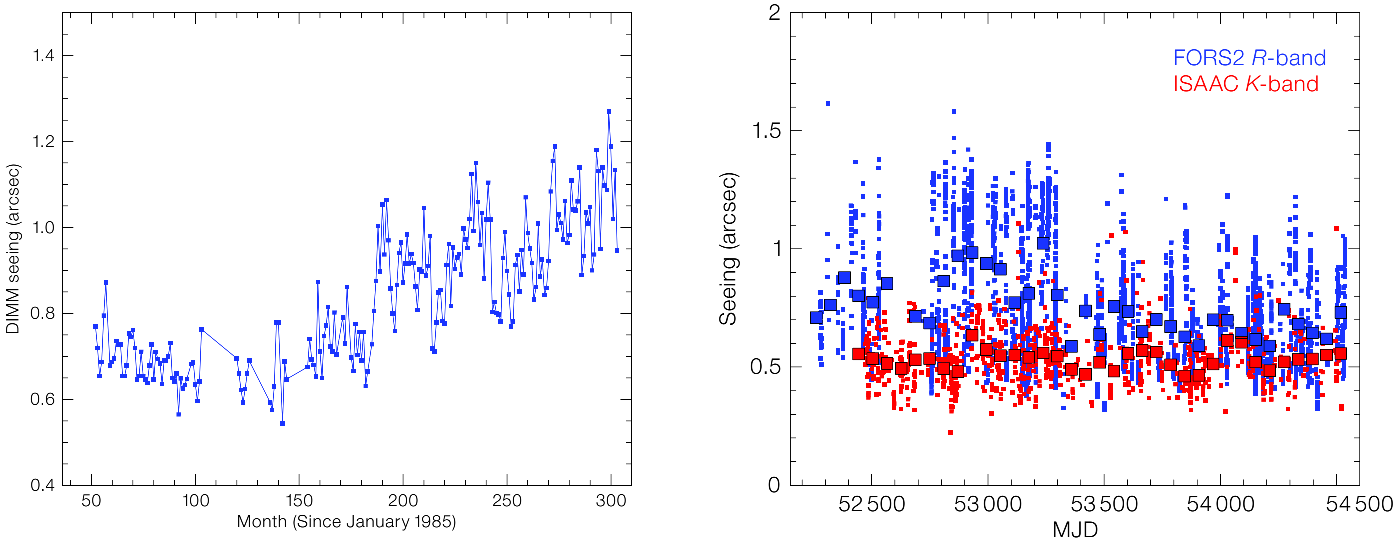


Figure 1. **Left:** Evolution of DIMM seeing on Paranal since 1989. **Right:** Evolution of the FORS2 image quality in the *R*-band and of ISAAC image quality in the *K*-band since January 2002 (MJD = 52 275). The big squares show the averages over 2-month bins.

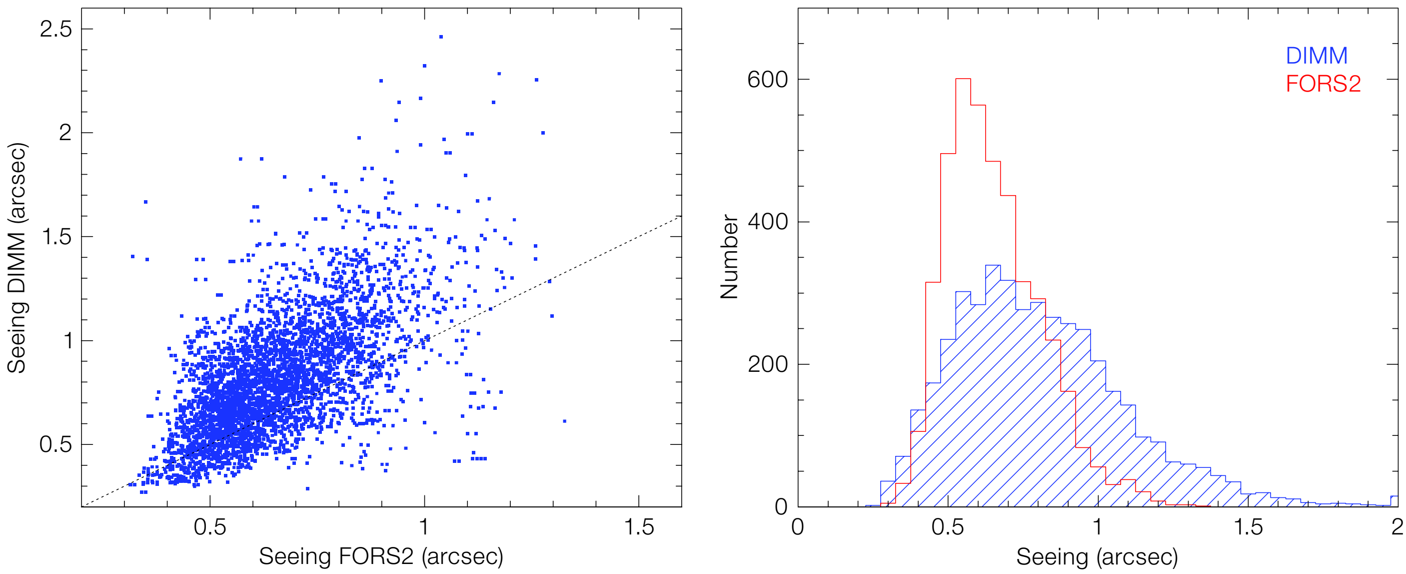


Figure 2. Relation between DIMM seeing and image quality measured by FORS2 between 2004 and 2006. In the left plot is shown a point plot, and the dashed line indicates DIMM = FORS2 seeing. In the right plot, the measurements are shown as histograms of the seeing values for both instruments.

values for which the image quality dispersion is less than 0.1″ rms have been retained.

The correlation between DIMM and FORS2 reproduces the trend observed with the test camera during the commissioning of UT2. The mean DIMM seeing is 0.81″ while the mean FORS2 image quality is 0.65″, so on average the DIMM overpredicts image quality by about 0.16″, similar to the value of ~ 0.2″ measured with the test camera. It may be tempting to apply a rule-of-thumb correction of ~ 0.15″ to go from DIMM seeing to UT image quality (at similar airmass and wavelength), but one should notice that for very good seeing conditions the DIMM seeing may be better than the FORS2 image quality, while under very bad conditions, the DIMM may indicate a seeing more than 1″ worse than FORS2. So it is important to understand the origin of the discrepancy between DIMM seeing and UT image quality.

Active optics Shack-Hartmann data

Real-time quality control of service-mode data at the observatory requires a reliable way of assessing whether the data complies with the seeing requirements set by the PI's. While this is straightforward for imaging data, it is not so for spectroscopy. Thus, the observatory operations staff typically rely on the FWHM of the stars in the guide probes to estimate the seeing. While this has its shortcomings, it seems to be sufficiently accurate for OB validation purposes. The possibility of systematically using the sizes of the (Cassegrain) Shack-Hartmann (SH) spots of the active optics system of the UT's has been investigated in this context by two of the authors (Julio Navarrete and Marc Sarazin). This has the advantage that the sizes are routinely logged by the telescope control software and therefore could provide a readily available real-time estimate of the image quality. Figure 3 shows, in the left panel, a comparison between the image quality measured by FORS2 and the SH for about 750 simultaneous observations between 2002 and 2007 (blue dots). The Shack-Hartmann data were corrected by the aberrations of the SH lenslet array (0.35″) measured on an internal reference source (green dots). The right panel shows the corresponding histograms. The median image quality measured by FORS2 is 0.64″, and 0.63″ by the (corrected) SH spots; both histograms are seen to coincide very nicely. The figure shows that indeed the (aberration-corrected) size of the SH spots provides an excellent proxy for image quality. Using the SH information we now have access to a much larger dataset to compare DIMM seeing with UT image quality.

Atmospheric turbulence profiles – $C_n^2(h)$

Modern site characterisation campaigns aim at determining the vertical turbulence profiles of the atmosphere at each site. The most direct way of doing this is to fly balloons equipped with very sensitive sensors that can measure the temperature and wind speed fluctuations as a function of altitude. Of course these experiments are costly and cannot provide real-time diagnostics of the conditions on a given night. Thus, a number of techniques have been developed to do the job from the ground. The Multi-Aperture Scintillation Sensor (MASS) is a compact single-star instrument that measures scintillation on four concentric zones of the telescope pupil using photomultipliers (Kornilov et al., 2003). A statistical analysis of these signals measures the vertical profile of turbulence $C_n^2(h)$ in six layers at 0.5, 1, 2, 4, 8, and 16 km above the telescope. A MASS unit developed at the Sternberg Institute (Moscow) under joint ESO-CTIO funding observed continuously on Paranal between 2004 and June 2007. In addition to its low-altitude resolution (about half the layer altitude, i.e. ± 250 m at 500 m and ± 8 km at 16 km), a distinct disadvantage of MASS is that it is blind to turbulence close to the ground (the ground layer), which produces little scintillation. We will show below, however, that for the purpose of understanding the discrepancy between

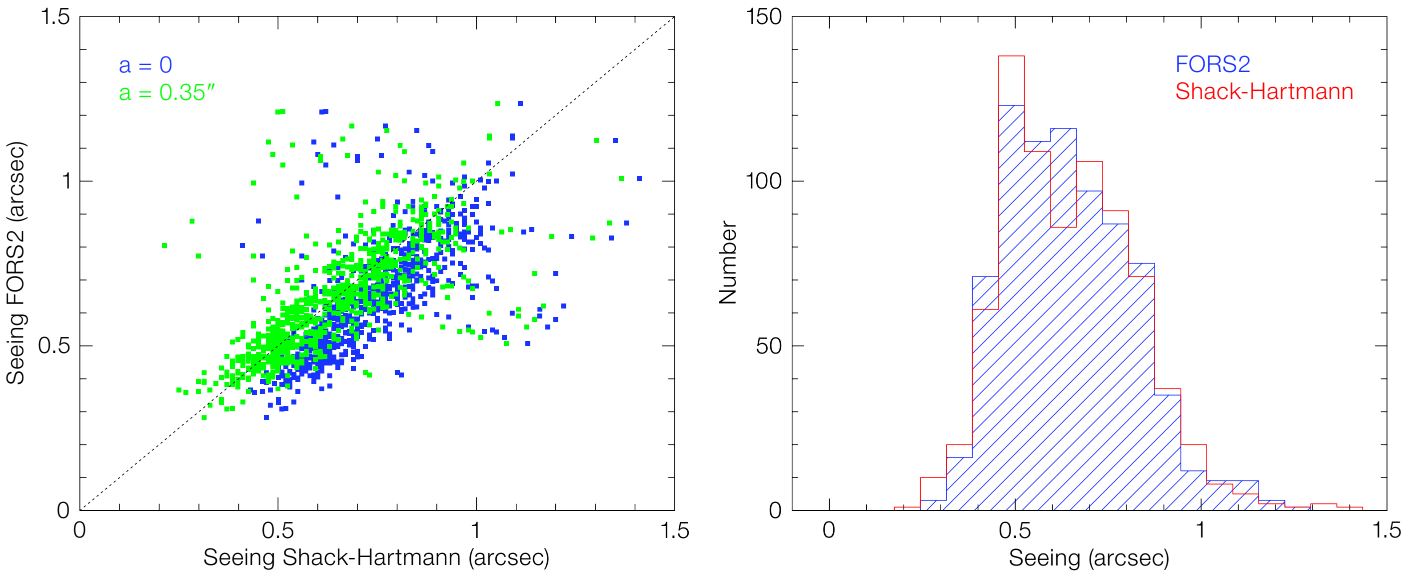


Figure 3. **Left:** Relation between the image quality delivered by UT1 estimated using the Shack-Hartmann (SH) spots of the active optics sensor, and the value determined on long (30 s–300 s) exposures with FORS2 in the *R*-band. The data have been normalised to airmass 1.0 and 500 nm wavelength. The blue points are the original SH data, and the green points show the values corrected for a lenslet aberration of 0.35″. The dotted line corresponds to FORS2 = SH. **Right:** Measurements presented as histograms for FORS2 and the SH.

DIMM and UT's, this turns out to be an important advantage.

The ground layer

A straightforward application of the MASS data is to integrate the profiles to measure the seeing. This is shown in the left panel of Figure 4 where the seeing measured by the MASS is compared to the seeing observed simultaneously by the DIMM. As expected, the MASS systematically underestimates the 'real' seeing because it does not see the turbulence that is close to the ground. Therefore, Figure 4 tells us that a significant fraction of the seeing over Paranal is produced by a turbulent layer located well below 500 m from the ground. This is something that was already known from previous experiments involving microthermal sensors on a mast (Martin et al., 2000). What is new is that we have a substantial body of simultaneous observations which we can use to quantify the contribution of the ground layer with excellent time resolution.

The seeing ε is linearly proportional to wavelength and inversely proportional to the Fried parameter r_0. If we assume that the atmosphere has only two turbulent layers, a ground layer (GL) and a high-alti-

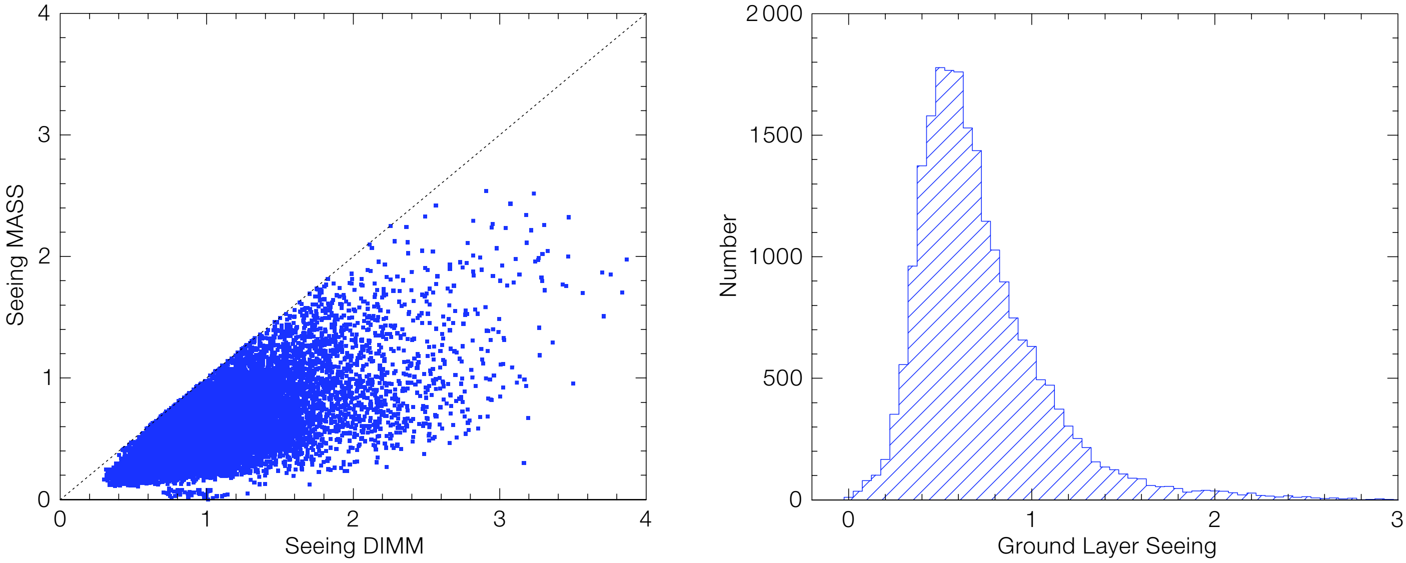


Figure 4. **Left:** Comparison between DIMM and MASS seeing (arcsec). The MASS seeing is always smaller indicating a significant contribution from a the ground layer (h < 500 m). **Right:** Histogram of the ground layer seeing contribution.

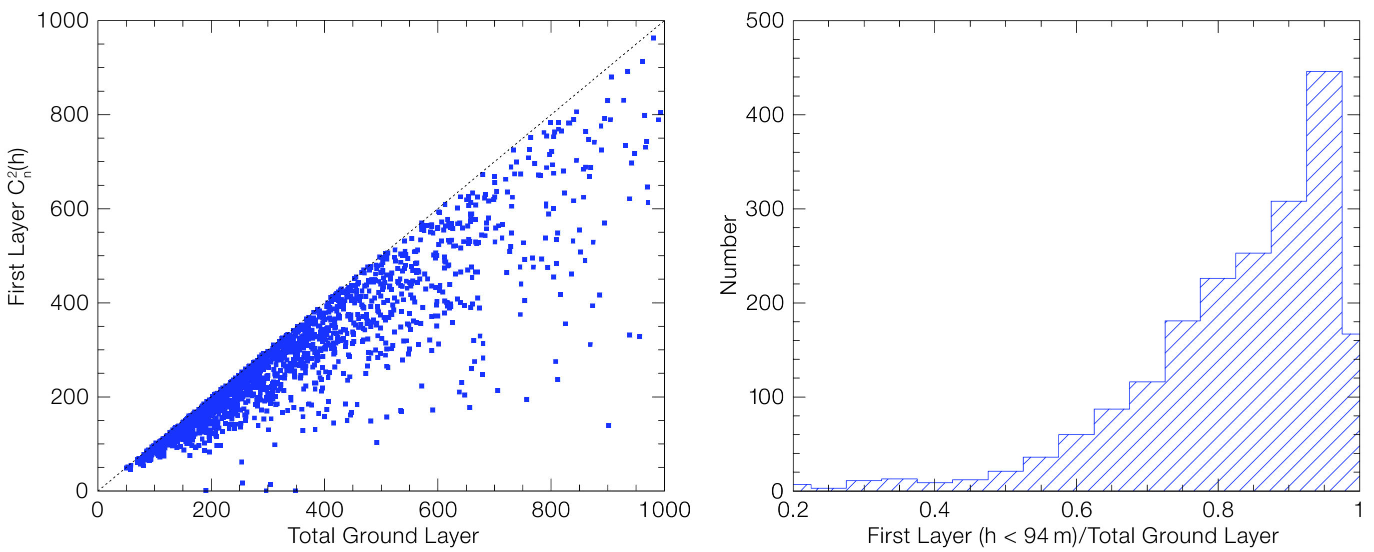


Figure 5. Left: C_n^2 (h) (h < 94 m) *versus* total ground layer turbulence measured by SLODAR. **Right:** Fraction of the total ground layer turbulence that comes from the first SLODAR layer. Most of the time the ground layer contribution is dominated by the h < 94 m component.

tude layer (HA), then the total seeing is: $\varepsilon_{Tot}^{5/3} = \varepsilon_{GL}^{5/3} + \varepsilon_{HA}^{5/3}$

Using this equation we can estimate the ground layer component since DIMM measures ε_{Tot} and MASS measures ε_{HA}. The result is presented in the right panel of Figure 4 that shows the histogram of ground layer seeing. The mean ground layer seeing on Paranal is 0.72″ with a rather large dispersion of 0.36″ (σ) indicating that the ground layer varies significantly with time. So the comparison between MASS and DIMM tells us that a substantial fraction of the seeing on Paranal originates in turbulent layers below 500 m altitude. The resolution of MASS does now allow us to say more, but there are other instruments that can get us closer to the ground.

SLODAR

The Slope Detection and Ranging instrument (SLODAR) uses an optical triangulation method on double stars to measure the atmospheric turbulence profile (Butterley et al., 2006). SLODAR, that has had observing runs on Paranal since 2005, gives C_n^2 (h) for eight layers with a resolution between 50 m and 100 m, depending on the separation of the double star and the zenith angle. While MASS measures the atmosphere between 0.5 and 16 km, SLODAR measures below 1 km, so both instruments are nicely complementary (although as stressed above MASS has a much lower vertical resolution). Figure 5 shows the distribution of the ratio of the contribution of the first (SLODAR) layer (h < 94 m) to the total ground layer turbulence determined by combining together DIMM, MASS, and SLODAR data taken simultaneously (Lombardi et al., 2008). The plot shows that most of the time the ground layer turbulence is concentrated below 94 m. The median value of the distribution is 0.86″ and the mean 0.82″, but the distribution is heavily skewed toward large values indicating that conditions where the ground turbulence is not below 94 m are quite rare. The strong turbulence at a mean altitude of ~ 50 m revealed by these observations suggests that the inconvenient discrepancy could be explained if much of this turbulence is in fact below ~ 20 m, so it is seen by the DIMM but not by the UT's. Some evidence in support of this hypothesis comes from the Lunar Scintillometer (LuSci) developed by Tokovinin (2007). LuSci allows the ground turbulence to be measured with a resolution of ~ 10 m from observations of the lunar disc. A very preliminary LuSci test run at Paranal in December 2007 indicates that a substantial fraction of the ground layer turbulence is indeed lower than ~ 15 m above the platform on Paranal. Hereafter we will refer to this (low) layer as the 'surface layer'.

Understanding the *inconvenient discrepancy*

We can test our hypothesis about the nature of the *inconvenient discrepancy* by correcting the DIMM seeing for the ground component using the MASS data and comparing the results with the UT image quality as measured by the SH spots. For this comparison we need to know the fraction of the total ground layer seeing contributed by the surface layer (h < 20 m). The SLODAR data tells us the average value is ~ 0.8. The best fit shown in Figure 6 is obtained for lenslet aberration a = 0.35″ and a mean surface layer fraction of 0.8. For these values the least squares fit (solid line) agrees within 1 % with the X = Y solution, but the histograms for the two datasets do not overlap exactly. The best match is obtained for a surface layer fraction of 0.7. This is not surprising since, as we have seen above, the value changes with time, so assuming a constant is just an approximation. The generally good agreement between surface-layer corrected DIMM seeing and UT image quality, however, provides convincing evidence that the surface layer is indeed the most likely explanation for the *inconvenient discrepancy*.

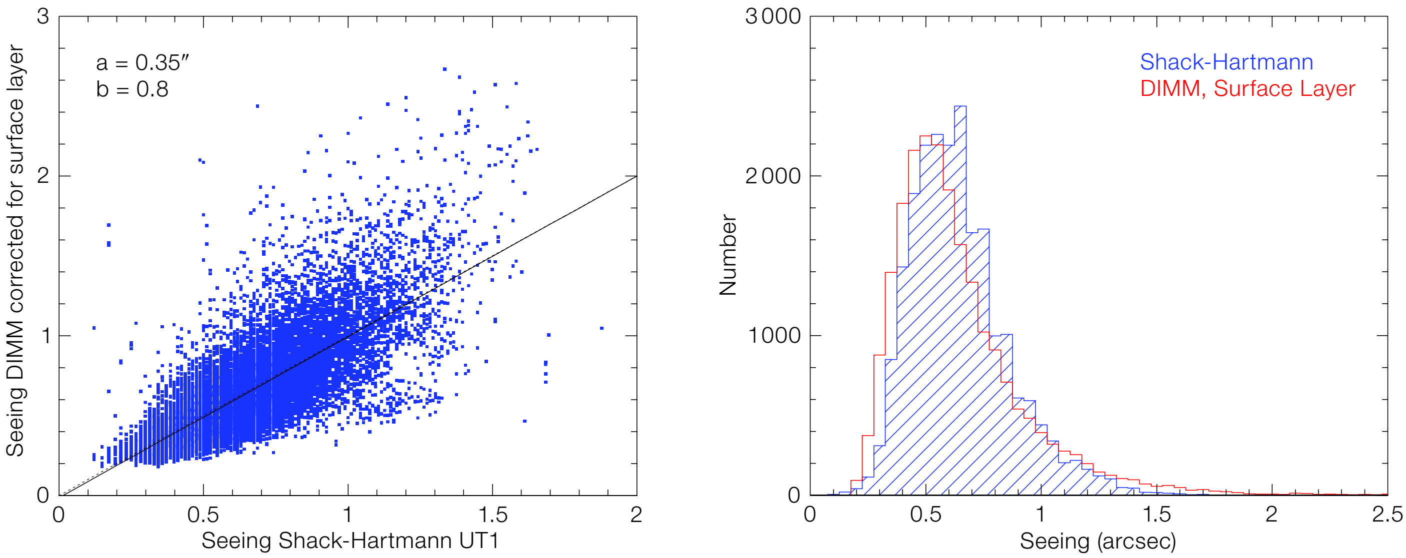
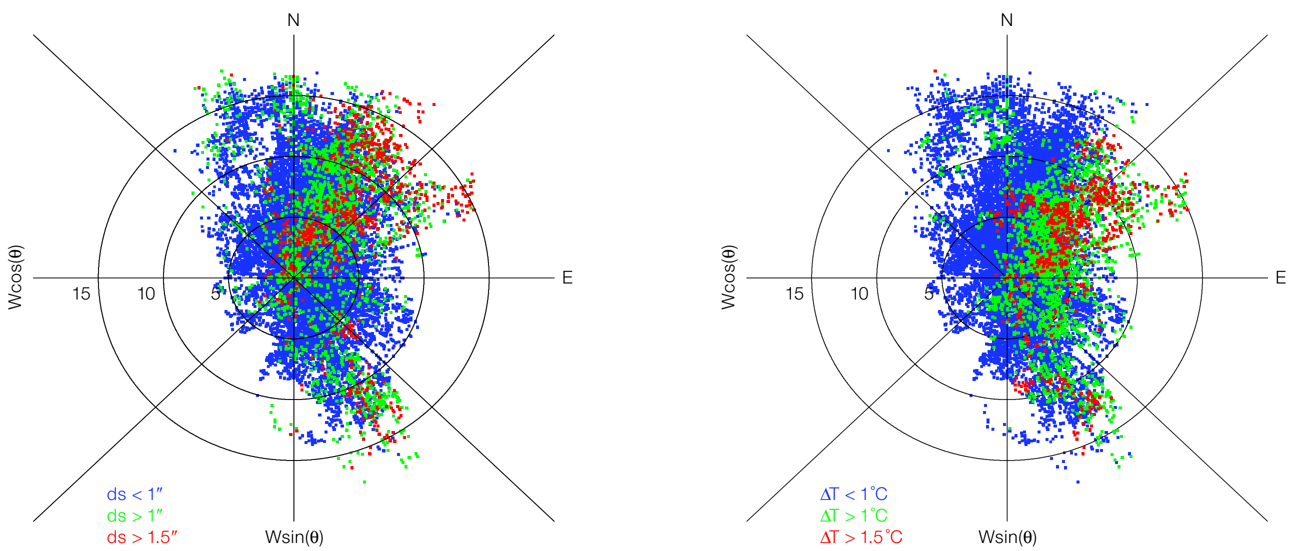


Figure 6. **Left:** Relation between DIMM seeing above the surface layer determined as described in the text, and the UT1 image quality estimated using the size of Shack-Hartmann (SH) spots of the active optics. The solid line shows a least squares fit to the data of slope 1.0. The best match of the two lines is obtained for an intrinsic SH spot size of a = 0.35″, and a surface layer which contributes about 80% of the total ground layer seeing measured comparing DIMM and MASS. **Right:** Histograms of DIMM seeing corrected for surface layer and the SH image quality. While the mean values of the two histograms coincide, the overlap is best for 70% surface layer contribution.

When the seeing is bad

The automated Vaisala weather tower on Paranal provides continuous data that we can use to investigate the conditions that influence the presence and strength of the surface layer. Assuming that the DIMM/UT discrepancy, ds (see caption of Figure 7), measures the strength of the *surface layer*, we can use the Vaisala data to check whether the surface layer strength correlates with Paranal environmental parameters. Figure 7 shows the wind-rose of Paranal colour coded according to ds on the left panel, and by the difference in temperature between 30 m and 2 m on the right panel. The discrepancy is seen to be strongest when the wind comes from the NNE and from the SSE (with a broad distribution about these directions), while the temperature gradient is largest when the wind comes from the NE and SSE. This suggests that the bad seeing occurs when the wind blows warm turbulent air from nearby summits along the Atacama fault (which traces most of the road between the Panamerican highway and Paranal) over the top of the mountain. A temperature inversion of 0.5˚ C is present most of the time on Paranal and there is a weak trend of the DIMM/UT discrepancy increasing with the 2–30 m temperature difference, indicating that local conditions may play a role in determining the properties of the

Figure 7. **Left:** The wind-rose of Paranal colour coded by the discrepancy between DIMM seeing and UT1 image quality; ds = $(\mathrm{DIMM}^{5/3} - \mathrm{SH}^{5/3})^{3/5}$. **Right:** Wind-rose coded by temperature gradient between 2 m and 30 m above ground.



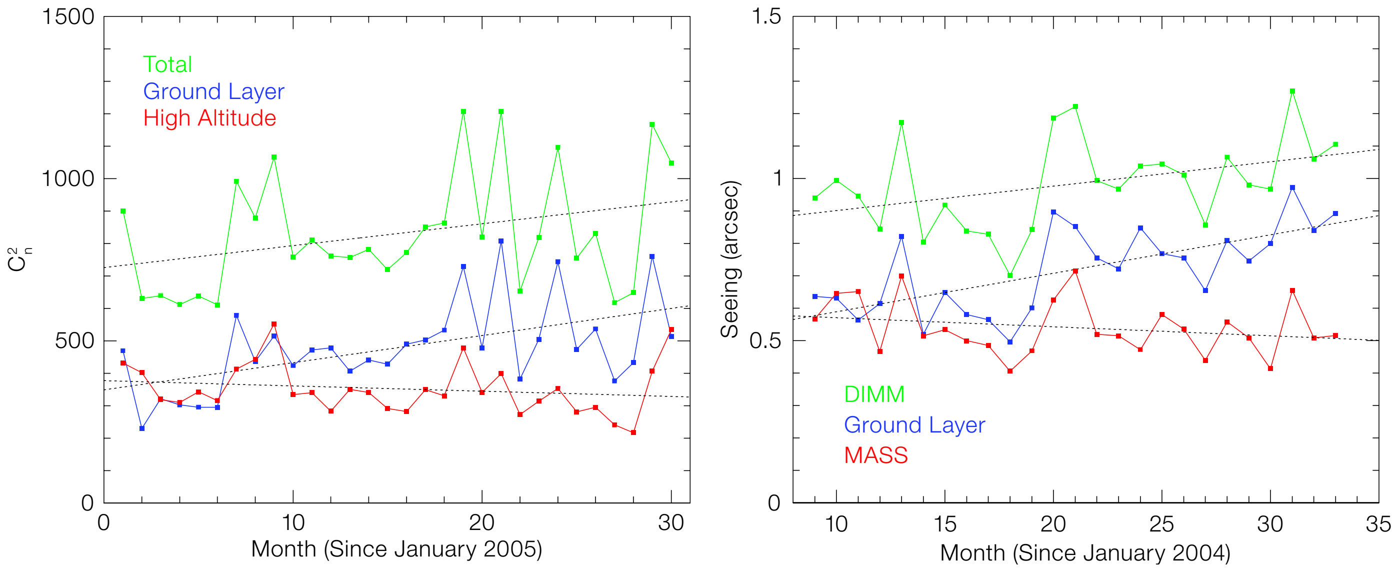


Figure 8. Left: Evolution of the components of atmospheric turbulence over Paranal (C_n^2) between 2005 and 2007 determined by combining DIMM, MASS, and SLODAR data (from Lombardi et al., 2008). **Right:** Evolution of the seeing components determined combining the DIMM and MASS data as described in the text.

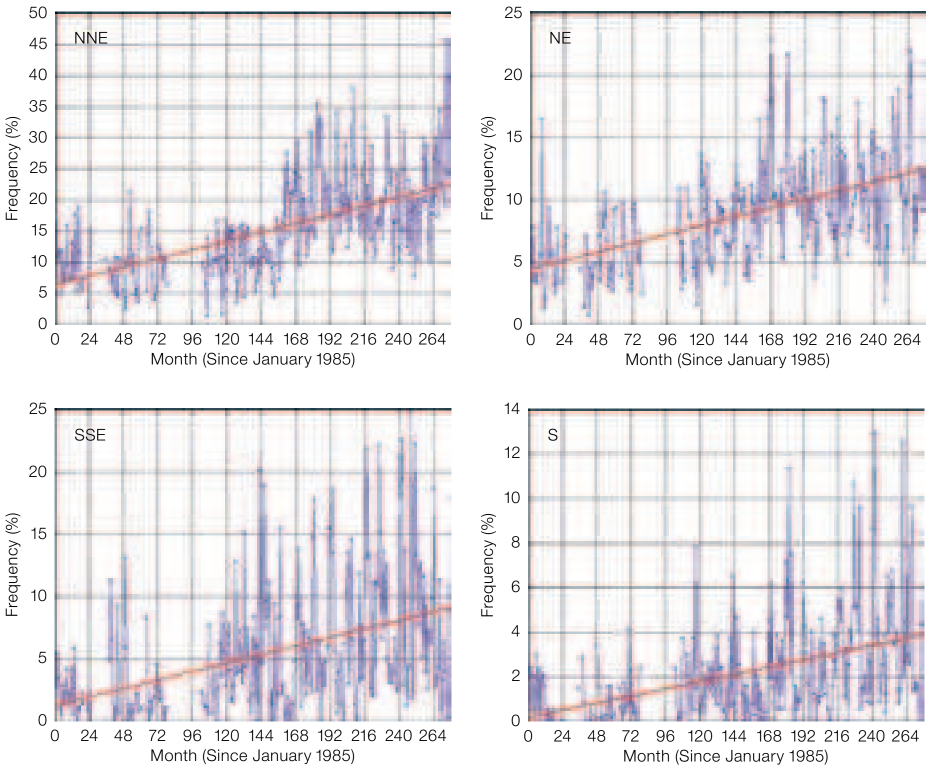
surface layer (e.g. by confining it to very low altitudes). An investigation of this aspect of the problem is underway, but is beyond the scope of this article.

Blown with the wind

If our interpretation of the *inconvenient discrepancy* is correct, we expect the surface layer to have become increasingly important with time, but the other components of the seeing to have remained constant. Lombardi et al. (2008) have examined this question using the combined DIMM+MASS+SLODAR data taken simultaneously between 2005 and 2007. Their results, reproduced in the right panel of Figure 8, show that this is indeed the situation. The degradation of DIMM seeing on Paranal is seen to be completely due to changes in the ground layer, while, if anything, the high-altitude layer seems to be getting better. A similar result spanning a longer time interval, albeit with lower altitude resolution, is obtained comparing the DIMM and MASS data only (right panel in Figure 8). The surface layer (which as we saw is the main component of the total ground layer) has become significantly stronger over the past four years, and from the evolution of the DIMM seeing shown in Figure 1 we infer that this has been going on for the past 12–15 years. Notice that, just as indicated by the FORS2 and ISAAC data displayed in Figure 1, the high-altitude layer seems to be getting better with time.

If the surface layer is *blown with the wind* over Paranal, we expect the wind distribution to have changed over the years. The evolution of the wind pattern on Paranal since 1985 is shown in Figure 9.

Figure 9. Evolution of the wind patterns over Paranal since 1985. The frequency of NE and NNE winds has increased dramatically since just about the time VLT commissioning started. The S and SSE wind fluctuations have increased such that during some months the frequency of these winds is also dramatically increased.



The analysis of the astroclimatology data *(www.eso.org/astclim/paranal)* shows that indeed the frequency of 'bad winds' (NE, NNE, SSE, and S) has increased over the past 15 years. The seeing is local, but the wind is global. The change in seeing over Paranal is due to changes in the wind pattern, which in turn must be caused by climate change on a global scale. Fortunately, at Paranal the turbulence blown by the wind is very close to the ground, so telescopes high above the ground don't see it. Unfortunately, telescopes close to the ground do!

Conclusions

We can safely draw two quite strong conclusions about the evolution of seeing on Paranal:

– The discrepancy between the seeing measured by the DIMM and the image quality delivered by the VLT Unit Telescopes, and the notable degradation of DIMM seeing observed over the past 15 years have a common origin: the presence of a thin, time variable turbulent layer – the *surface layer* – over the mountain that is seen by the DIMM, but not by the UT's.
– The *surface layer* is strongest when the wind blows from the NNE and from the SSE. These winds have become increasingly frequent over the past 15 years explaining why the surface layer appears more and more often. This change in the prevailing winds over Paranal is due to climate change. In fact, it is climate change.

Site testing campaigns must pay close attention to the surface layer through the use of micro-thermal towers, or sensitive astronomical instruments such as SLODAR and LuSci. Extensive campaigns on existing observatories now underway should be intensified and the results cross-correlated, especially if different techniques are used. Close attention must be paid to the local orography, and the effects of changes in the prevailing winds modelled. Seen through the light of modern site testing techniques and global climate change, it is sobering to realise that our ancestor's conventional wisdom – put thy telescope as high above the ground as possible – is still right!

References

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Photo: S. Brunier

View of the Galactic Centre above La Silla with the domes of the 3.6-m telescope and the CAT illuminated by the setting Moon.