The Half Arcsecond Programme (I)

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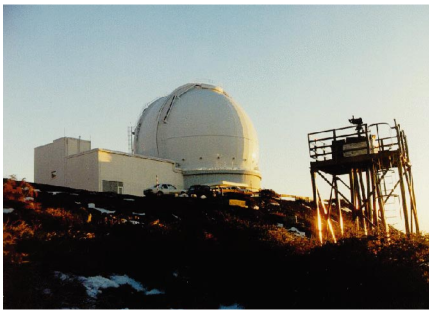


Figure 1. The ING DIMM tower near the WHT.

Over the last three years, the Half Arcsecond Program (HAP) has found some important and surprising results. These results, recently published in the MNRAS (Wilson et al., 1999, **309**, 379), are summarised on the HAP WWW site (*http://www.ing.iac.es/hap/haphomepage.htm)* and a short summary of the key conclusions follows.

The HAP was started by the ING in 1993 in order to optimise the image quality of the WHT, especially in preparation for NAOMI, the natural guide star adaptive optics system due to be commissioned in mid-2000 (see ING Newsletter No. 1). The goal of the HAP is to eliminate non-atmospheric degradations of the WHT's image quality, so that the measured image width for the WHT will be as close as possible to the intrinsic (site) seeing value.

Two main sources of image degradation can be distinguished in addition to the atmospheric seeing: (1) imperfections of the telescope itself, including tracking and focus errors and other optical aberrations, and (2) turbulence effects such as convection at the primary mirror and mixing of air at different temperatures in the light path, collectively referred to as dome seeing or artificial seeing.

An Early Result

One of the first problems identified by the HAP was the presence of two plumes of turbulent warm air flowing into the optical light path above the primary mirror. These were clearly visible in defocused (pupil) images from the WHT. The plumes emanated from the supporting fork structure of the primary mirror, heated by oil warmed during its lubricating passage around the WHT structure. It was clear that the WHT image quality suffered from this turbulence and that an engineering solution was required to reduce the temperature differential between the fork structure and dome air. Hence in September 1996 an oil cooling plant was installed to reduce and track the temperature of the telescope bearing oil to within a fraction of a degree of the dome air temperature. Subsequent pupil images showed the turbulent air plumes were eliminated, and also that heating of the air in the dome was significantly reduced during both night and day.

A Targeted but Sensitive Approach

Having removed the obvious contribution to dome seeing, more sophisticated and quantitative seeing measurement techniques were required to search for more subtle effects. In order to reduce the seeing of the WHT to that of the site, it was first necessary to accurately determine the site seeing. In October 1994 a Differential Image Motion Monitor (DIMM) was installed on a tower near the WHT (see Figure 1). A DIMM measures the seeing via the differential motion of stellar images and hence is unaffected by wind shake, poor tracking, focus, etc. and therefore gives an unbiased estimate of the atmospheric seeing. In fact the DIMM measures the Fried parameter (r_0) or spatial coherence length of starlight. For the standard (Kolmogorov) theory of atmospheric turbulence this is related to the seeing FWHM for a large telescope (in the absence of other aberrations) by:

$$FWHM = 0.98\, l \,/\, r_0 \qquad (1)$$

where l is the wavelength of observation. Hence the accuracy of the DIMM seeing estimates depends on the validity of the standard seeing model at the site.

The DIMM has been used by ING to provide an extensive set of seeing data for the WHT site. The results of the monitoring campaign between October 1994 to August 1998 are displayed in Figure 2, which shows median site seeing at the WHT to be 0.69 arcseconds, in good agreement with other surveys carried out at other sites on the Roque by collaborators at the IAC.

Initial attempts to measure the seeing obtained inside the WHT made use of the Cassegrain autoguider, but several subtle effects blunted the effectiveness of this approach. However, a set of observations based around the JOSE (Joint Observatories Seeing Evaluation) wavefront sensor, installed in preparation for NAOMI, was in progress at the WHT between 1995–1998. JOSE is a Shack-Hartmann sensor equipped with a fast readout CCD. The pupil of the WHT is re-imaged onto a lenslet array, so that sections of the aperture ~50cm in diameter are imaged separately onto the detector. The CCD camera records images of the spot pattern continuously at frame rates of typically 100Hz for a

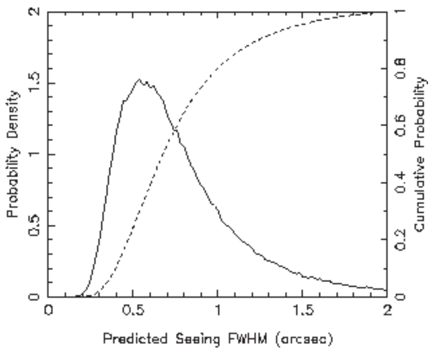
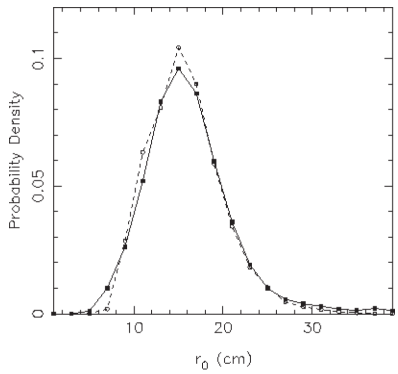


Figure 2. DIMM seeing measurements.

few tens of seconds, so that the temporal development of the wavefront distortion can be analysed. Centroids are measured relative to the mean spot location for each data sequence, so that static perturbations are ignored. The measurements are therefore unaffected by fixed (or very slowly varying) optical aberrations such as telescope defocus, but are sensitive to changing distortions due to atmospheric and dome turbulence. As for the DIMM, JOSE gives a measure of r_0, which can be translated to the seeing FWHM via equation 1. Correlating the JOSE (internal) and DIMM (external) seeing measurements provides a powerful diagnostic of WHT dome seeing.



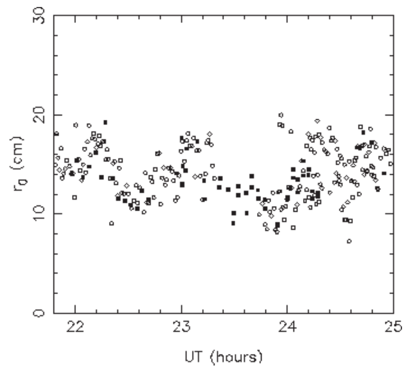


Figure 3 (left). Normalised probability distributions for contemporaneous JOSE (solid line) and DIMM (broken line) r_0 measurements determined from measurements on 18 nights between 1995 May and 1998 August.
Figure 4 (right). Example of contemporaneous JOSE (filled squares) and DIMM (open circles) r_0 measurements.

JOSE/DIMM Correlation

By collating JOSE and DIMM observations to form an integrated data set, it is possible to compare statistics of the seeing inside the WHT to the site seeing. In Figure 3 measured values of r_0 from DIMM observations (4500 measurements[a] on 18 nights) and contemporaneous JOSE observations (2998 measurements) are plotted. Clearly there is no significant offset in the distribution of r_0 between JOSE and DIMM.

The JOSE wavefront sensor data allows the validity of the standard turbulence model for the WHT site to be examined. Figure 5 shows the mean (relative) distribution of rms Zernike mode strengths for the seeing-induced wavefront aberrations at the WHT focus. The data are plotted against their theoretical values for the Kolmogorov turbulence model (Noll, R. J., 1976, *J Opt Soc Am*, **66**, 207). Clearly the measured distribution is close to theoretical expectation, so that the DIMM and JOSE seeing FWHM predictions are valid. In fact the data show evidence for an outer scale of turbulence (i.e. upper limit to the scale of the seeing aberrations) with a mean value of approximately 15 m. As a result the DIMM and JOSE predictions may somewhat over-estimate the WHT seeing at long wavelengths (R-band and longer), since equation 1 assumes an infinite outer scale.

Seeing arising from excess mirror or dome temperature is likely to be described poorly by the Kolmogorov model (Bridgeland, M. T., Jenkins, C. R., 1997, *MNRAS*, **287**, 87), with excess power in aberrations on small spatial scales (high order Zernike modes). Hence this analysis also suggests that there is no strong dome seeing contribution at the WHT. A similar analysis of JOSE data before oil cooling was implemented showed excess power on small scales, consistent with artificial seeing from the turbulent air plumes.

Conclusions

It is important to consider why the WHT does not appear to suffer from artificial seeing. It is generally accepted that excess temperature of the mirror, dome or support gives rise to artificial seeing. Figures 6 and 7 show the summation of several years data obtained during observing nights for the dome minus external air temperature and mirror minus dome temperature respectively. Figure 6 shows that large dome temperature excesses are very rare. Calibration of the temperature sensors has shown a drift in the external thermometer by ~1.5 K over the several years of operation and hence in reality the 1 K offset suggested by Figure 6 is even smaller. Large primary mirror temperature offsets are more frequent, but the differential is >2 K for only ~25% of observing time. We speculate that such a large offset occurs only during rapid weather changes where the large thermal inertia of the (thick) primary mirror retains excess thermal energy for one or two nights, but that the atmospheric seeing will in that case be sub-optimal due to rapidly changing weather conditions. It also seems that under normal circumstances, the considerable thermal inertia and good insulation of both the primary mirror and dome air mass prevent the mirror from absorbing significant heat from the air during the daytime, leaving it close to the air temperature of the previous night.

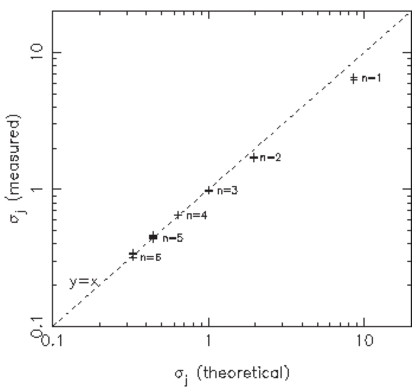


Figure 5: Zernike Modelling of JOSE Data.

The fact that no significant artificial seeing in the WHT has been detected after cooling the WHT's oil is certainly against common perception of the WHT seeing. In part this is due to reliance on the WHT's autoguider for seeing information. The autoguider

(a) We wish to thank the IAC seeing group for providing some DIMM measurements useful for our analysis.

has an independent focus, optical aberrations and several other 'features', and so gives only an approximate (and certainly pessimistic) estimate of the true WHT seeing.

In the absence of dome seeing, the remaining tasks for the HAP at the WHT are to optimise the tracking and focus of the telescope. The power spectrum of image motion measured by the JOSE sensor reveals a spike due to the known oscillation of the WHT support structure at 2.7Hz. Whilst this resonance contributes little power on average, the oscillation can have a significant effect on image width if it is strongly excited, for example by wind buffeting of the telescope structure. In future it may be possible to monitor the telescope drive encoders automatically, and to alert the observer to excess tracking errors at high frequencies. A significant contribution to the image FWHM at the WHT (as for all telescopes) may result from imperfect focus. Current methods for estimation of the optimum focus are limited by the inherent variability of the site seeing. Improved methods to focus and to track the focus of the WHT are under investigation.

In the next issue of the ING newsletter we will discuss the HAP at the INT and the future of the HAP.

HAP Publications:

1. Wilson, R. W., O'Mahony, N., Packham, C., Azzaro, M., 1999, "The seeing at the William Herschel Telescope", *MNRAS*, **309**, 379.

2. Packham, C., O'Mahony, N., Wilson, R. W., 1998, "Recent developments in the Half Arcsecond Programme", *New AR*, **42**, 431.

3. Azzaro, M., Breare, M., 1998, "Some meteorological parameters affecting the image quality of the WHT on La Palma", *New AR*, **42**, 471.

4. O'Mahony, N., Packham, C., Wilson, R. W., Rutten, R., 1997, "Characterisation and Optimisation of Seeing at ING Telescopes", 23rd IAU General Assembly, Kyoto. ¤

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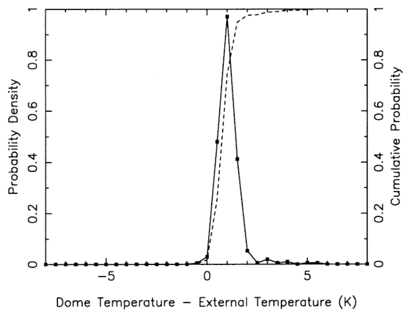

Figure 6. Dome-External Air Temperature Difference.

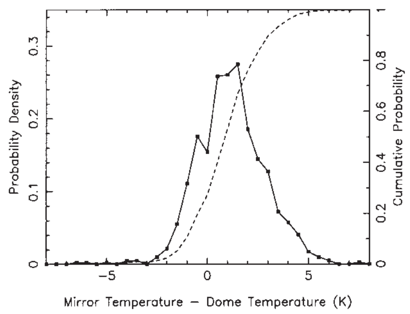

Figure 7. Mirror-External Air Temperature.

WHT Millenium Upgrade

Gordon Talbot (Head of Engineering, ING)

The Isaac Newton Group have embarked on a comprehensive upgrade of the William Herschel Telescope (WHT), involving replacing and enhancing many systems. The programme embraces a number of projects, and all ING engineering groups are contributing. The upgrade directly supports the NAOMI adaptive optics system and INGRID IR imager but also brings performance and reliability improvements to the WHT in support of other instruments. Previous, recent improvements include an Alpha computer based Telescope Control System (TCS), the introduction of 4k×2k EEV–42 detectors and improved dome seeing through oil cooling.

The programme includes:

– New Observatory Control System to replace the existing Instrument Control System for improved performance, ease of maintenance and development, further increased commonality between subsystems and reduced maintenance costs. Initially the system will support ING's new data acquisition system, ULTRADAS, for faster CCD readout, and the implementation of the 4k×4k two chip EEV–42 mosaic for use at prime focus and on UES. Instrument control will then be implemented sub-system by sub-system using DRAMA and EPICS (channel access) with appropriate mimic displays until all focal stations and instruments are converted. This project will build on basic control to provide more complex modes of observing —such as automatic guide star acquisition. Finally it will provide an efficient queue-observing tool to automate service observing.

– New autoguider. This will be a DRAMA based system similar to the INT system, replacing the existing FORTH based system that runs on unreliable, obsolete and irreplaceable hardware.

– New acquisition TV system will replace the existing, obsolete system with a modern supportable system that offers improved performance. Initially implemented as a stand-alone system the ultimate aim is to integrate with other telescope systems.

– Faster CCD readout through the ULTRADAS system. This embraces the production of a new data acquisition system (DAS), and its implementation for all science detectors at ING using the San Diego State University SDSU-2 CCD controller. Principle gains from the project are faster readout speed, and improved reliability —from both the DAS system and CCD controller— together with reduced maintenance requirements. The system will ultimately use a