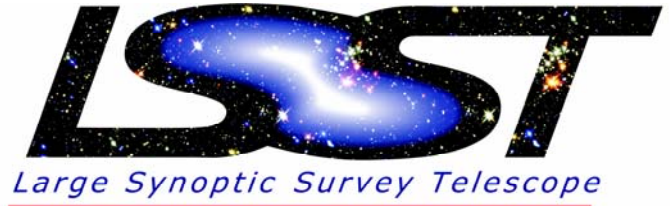


Studies of Atmospheric Distortion of Optical Wavefronts with the SOAR Shack-Hartmann WFS

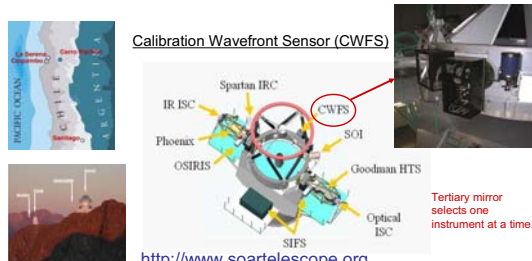


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The Shack-Hartmann Calibration Wave Front Sensor (CWFS) of the SOAR telescope at Cerro Pachon, Chile has been used to study spatial correlations of wavefront distortions created by atmospheric turbulence. The SOAR CWFS samples the 4.2 meter diameter telescope aperture with a lenslet spacing of 17 cm imaged in the pupil plane; exposures of 0.03 seconds duration were taken every 7 seconds during observing periods of approximately two hours on each of three successive nights in May of 2005 (please refer to 26.12 and 26.23 for related studies). Time-stamped data from the Cerro Pachon MASS-DIMM instrument and the SOAR weather monitors were acquired during the same periods. Spatial correlations of distortions in the observed optical wavefronts were computed for spatial wavelengths ranging from 17 cm to 4 meters. Our preliminary observations find a non-Kolmogorov distribution of turbulence.

When: 5/10/2005 5/11/2005 5/12/2005
2:30-5:00 UTC 3:30-6:00 UTC 3:30-6:00 UTC

Where: Southern Astrophysical Research (SOAR) Telescope



Longitude	70° 44' 01.4" W	Primary Mirror Diameter	4.2 meters
Latitude	30° 14' 16.8" S	CWFS 1024x1024 CCD	0.2989 "/pixel
Altitude	2738 meters	Shack-Hartmann Pitch	600 microns

Why: CWFS data was taken and analyzed in order to evaluate the impact of the Cerro Pachon atmosphere on LSST science requirements. Weak-lensing ellipticity measurements in an LSST image will be made down to 10^{-4} . They must be corrected for optical distortion due to the atmosphere so that residual effects are below this level in a stack of hundreds of images. Our measurements provide important input to LSST models of optical propagation through the earth's atmosphere and useful information on the Cerro Pachon site.

How: We obtained simultaneous data from multiple devices

Device	Data	Description
SOAR CWFS	1024x1024 30 msec exposures	Use to measure wavefront slope in x and y Directions ($\frac{\partial\phi}{\partial x}$, $\frac{\partial\phi}{\partial y}$)
MASS	Cn ² (z)	Strength of atmospheric turbulence at altitude z (meters)
DIMM	S FWHM	Strehl Ratio Seeing (Arcseconds)
SOAR Imager	4096x4096 15 sec exposures	Field of View contains CWFS star exposures
SOAR Weather Station	Wind Speed Wind Direction	Correlate with asymmetry in x and y directional slope measurements

CWFS DATA SAMPLE: IMAGES AND CENTROIDS

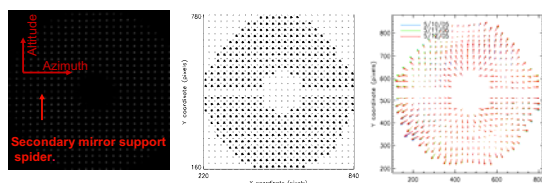


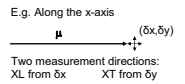
Figure 1: (Left) A CWFS image showing the projection of the SOAR aperture through the Shack-Hartmann lenslet array. (Middle) The centroids found for every image obtained on the first night of observation falling in a fiducial region. (Right) The average offset of the centroids from a rectangular grid having 600 micron (25 pixel) pitch.

What We Wanted to Measure: Atmospheric induced spatial and temporal correlations in wavefront slopes

For each frame we measure offsets of star image centroids formed by CWFS array relative to nominal position and assume we get the wavefront tilts averaged over lenslet pupils. From this we compute covariances.

$$\alpha_x = \delta_x / f_{lenslet} \quad \alpha_y = \delta_y / f_{lenslet} \quad \longrightarrow \quad B_s(\mu, \eta) = \langle \alpha(x, y)\alpha(x + \mu, y + \eta) \rangle$$

- Four combinations of measurement axes and directions XT, XL, YT, and YL
- L= Longitudinal •T=Transverse •Eventually this gets mapped back to the SOAR pupil
- Measure temporal covariances from frame to frame $\langle \delta(x,t) \delta(x+d, t+\tau) \rangle$



What We Did Not Want to Measure: Spatial and temporal correlations caused by telescope tracking errors

Tracking errors occurred during observation. To account for this, we piecewise fit the uniform motion of the Shack-Hartmann spots over intervals of several minutes (time between telescope readjustments).

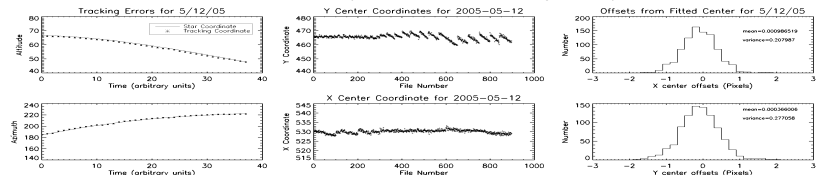


Figure 2: (Left) A plot showing the Altitude and Azimuth of the reference star hr5132 computed from its RA and DEC (line) and the coordinates reported by the tracking encoder. (Middle) The center of the Shack Hartmann array projected onto the CCD. (Right) The residual offsets of the centers relative to the fitted center.

What We Found: Non-Kolmogorov atmosphere and no atmospheric temporal coherence after 7 seconds

We average the covariances in and between images over each night. We fit them with a generalized function that allows for a non-Kolmogorov power spectrum (a Kolmogorov power spectrum demands an exponent of 11/3).

$$B_{L,T}(d) = W * K_{L,T} \left[\frac{d + (K_0/K_{L,T})^{1/\beta-4} D}{\rho_0} \right]^{2\beta-2} \left[\frac{\lambda}{d + (K_0/K_{L,T})^{1/\beta-4} D} \right]^2$$

$W(\text{wind})$ = Finite Exposure Decoherence Factor
 $K_{L,T}$ = L,T Relative Normalizations
 K_0 = Aperture size (n - 0) Normalization
 β = Power spectrum
 ρ_0 = Generalized Scale (Fried) Parameter

D = 0.163 m (lenslet aperture diameter); d = n x D (lenslet spacing); $\lambda = 500$ nm

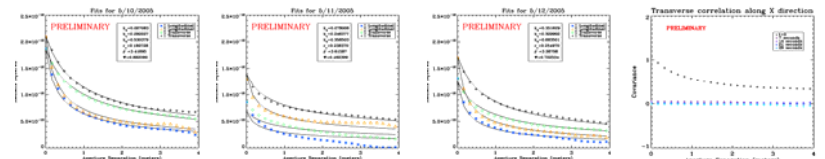


Figure 3: (Left 3 plots) Data from the first, second, and third nights, respectively. The six-parameter fits to the data are shown as straight lines. The first and third night's fits (preliminary) indicate non-Kolmogorov spatial turbulence in the atmosphere at Cerro Pachon. The second night's fits are still not understood. (Right) An example of the vanishing temporal correlation at seven seconds; data for other nights are very similar.

A Nice Check: Our covariance measurements provide an estimate of the seeing for comparison with DIMM data

- Use n=0 and n=5 covariance measurements as a multi-port DIMM.
 - Ratio separation/aperture (=5) similar to CP MASS-DIMM
 - Aperture size (16.3 cm) is eight times larger than CP MASS-DIMM

$$\sigma_{L,T}^2 = 2 [B_{L,T}(0) - B_{L,T}(s)]$$

(s = 5 x d)

- L → $\psi = 0^\circ$
- T → $\psi = 90^\circ$
- ... and s aligned along X and Y.



- Use Covariance Reduction Factors as prescribed in "Image motion as a measure of seeing quality", H. M. Martin, Astron. Soc. Pac., 99, 1360, 1987.
- Fully turbulent isotropic atmosphere with Kolmogorov power spectrum
- Taylor's "frozen screen" moving with the wind at velocity W.

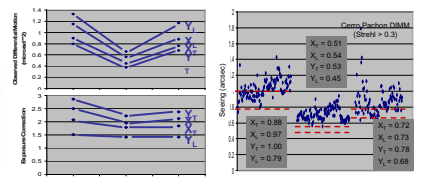


Figure 4: (Left) Upper plot shows observed Differential Motion. Lower plot shows correction for wind and exposure time. (Right) Range of Seeing calculated from covariance Measurements (Red lines) and seeing values measured by DIMM (blue dots).

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