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Measurement of Atmospheric Turbulence with a Shack–Hartmann Wavefront Sensor at the new MMT's Prime Focus

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ABSTRACT

In order to prepare for the adaptive secondary program at the new 6.5 meter MMT, we have begun a campaign to measure atmospheric turbulence with a Shack–Hartmann wavefront sensor (WFS) camera. Our first efforts, prior to second aluminization of the primary, consisted of taking turbulence data with our WFS camera with special coma–correcting optics at the MMT prime focus, without a Cassegrain secondary mirror. Our first measurements consisted of 1000 frames of ~10 millisecond duration, taken ~3 seconds apart. We measure a 5/3 power law structure function, suggesting Kolmogorov turbulence, with an r_0=15 cm, but with possible hints of an outer scale and tracking jitter in the structure function. At the end of our data acquisition, we deliberately put 2 μm of astigmatism into the primary mirror with its actuators, and in our analysis, we recover 1.7 ± 0.3 μm of astigmatism. A brief analysis of the low–order modal amplitudes with the 3 second frame delay shows that there are significant self–correlations of the low–order modes even on this long time–scale.

1. Introduction

The Multiple Mirror Telescope's (MMT's) six primary mirrors have been replaced by a single 6.5 meter diameter F/1.25 mirror[1]. First aluminization took place in situ in the Fall of 1999, and despite the need for a realuminization, images were obtained at Prime Focus with a specialized coma–correcting optical system[2]. A campaign was also begun in November 1999, to measure mirror figure and atmospheric turbulence with a Shack–Hartmann wavefront sensor (WFS) camera[3], which utilized these coma–correcting optics. This WFS camera will be invaluable for telescope figure measurements either at Prime focus or at a Cassegrain focus once the telescope comes back online after the second aluminization is completed in the Spring of 2000. But more significantly, having obtained 'static' wavefront measurements with the WFS camera in November 1999, and having completed the analysis of this data (detailed below), we are prepared to acquire fully–dynamic wavefront measurements of atmospheric turbulence at the MMT (at Prime focus or Cassegrain focus) with this WFS camera and our special–purpose wavefront reconstructor computer. These measurements will hence further verify two major components of the adaptive optics system for the new MMT, the WFS camera and the wavefront computer. The turbulence data will also allow us to test our reconstructor and predictor[4] algorithms, prior to going to the telescope.

2. Coma–correcting Optics for Prime Focus

The corrector (ssee Figure 1) baseline is an association of a spherical mirror and a meniscus lens that subtracts the coma introduced by the paraboloidal F/1.25 MMT 6.5m primary mirror and equilibrates the amount of self–introduced spherical aberration. The instrument is optimized for visible wavelengths across a 40 arcsecond field of view. The corrector was designed to be used with the wavefront sensor simultaneously with an F/7 high resolution (1/4") imager. The imager was used as a guider while the WFS recorded phase maps in order to characterize the atmospheric turbulence at the MMT. The field going in the WFS is only 3 arcseconds, but the full 40 arcsecond field of the guider was useful in aligning the instrument with the MMT optical axis. The F/# on the WFS detector is 2.05 assuming a lenslet focal length of 3.389mm. That gives a plate scale of 15.48"/mm or 0.372"/pixel.

For each pixel of tilt across a subaperture, assuming F/2.05 optics and a typical wavelength of λ=0.6 microns, we have the following conversions:

1pix/subap = 0.372 arcseconds = 12.09 microns of Peak–to–Valley tilt phase difference over pupil
= 20.14 waves/pupil (at λ = 0.6 μm) = 126.4 PV Rads/pupil = 31.6 RMS Rads/pupil.

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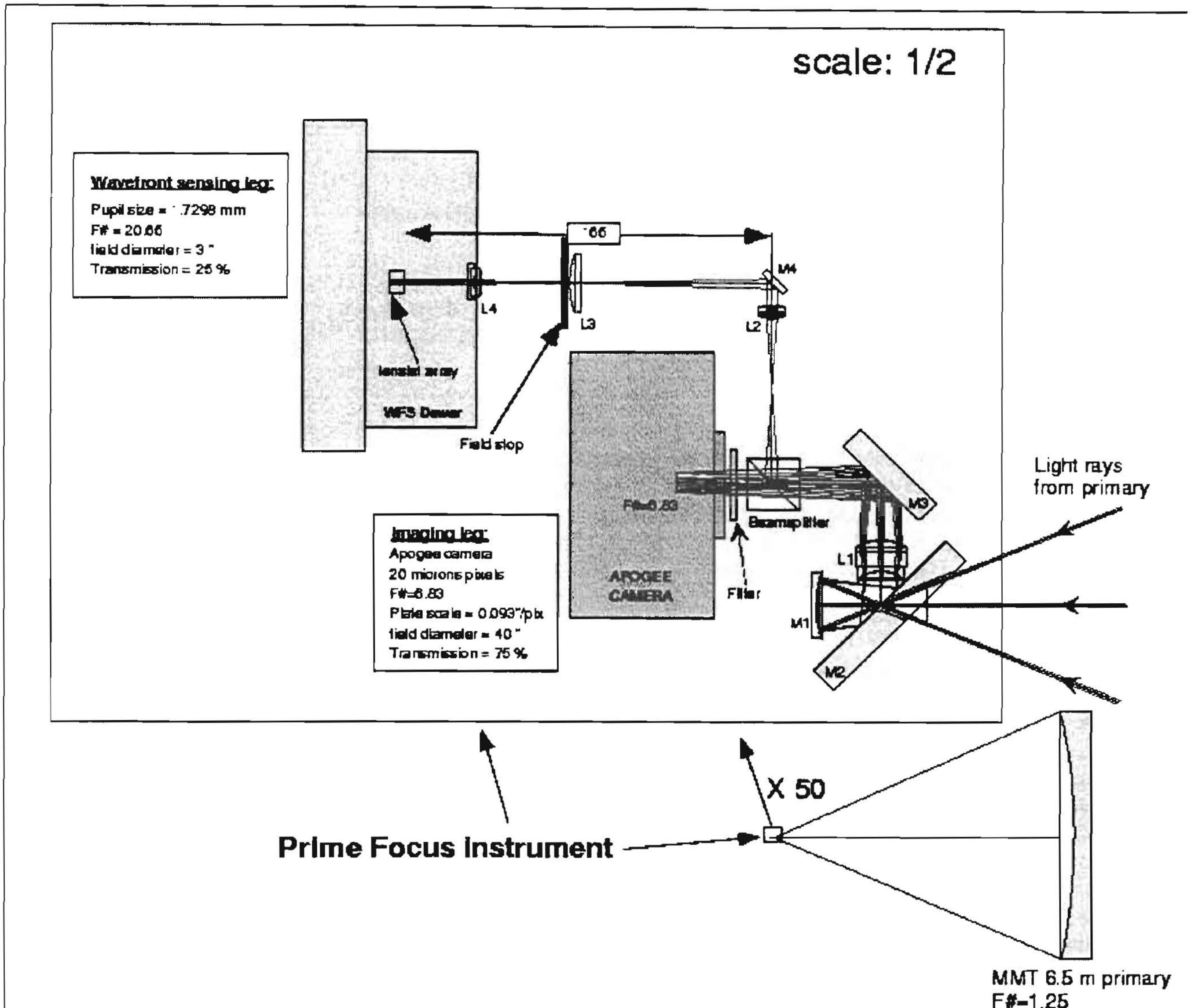

Figure 1: In the lower right of this diagram, we show the location of the new MMT prime focus optics and cameras relative to the primary mirror, and in the main part of the figure, we trace the light rays from the primary mirror through the coma-correcting optics to the WFS and Apogee cameras.

3. Results

Due to camera and telescope misalignment errors in this early state of the MMT telescope and due to the brevity of the Prime Focus campaign in October–November 1999, the Shack–Hartmann spots were not well–aligned near the center of their sub–apertures. Therefore, instead of using quad–cell techniques, the *daofind* task in IRAF was used to automatically locate the centroids of all the spots in all of the 1000 WFS frames. Of these 1000 frames, there were two sets of frames, lasting for 70–150 frames each, in which adjustments were not being made to the optical alignment, so that the data during these periods of time could be usefully analyzed. A specialized spot–ordering algorithm was used to put all of the spots found by *daofind* in each frame into their respective rows and columns. In the spot–ordering algorithm, we first locate the top–most spot in the column or the left–most spot in the row, and then require that the rest of the spots do not fall too many pixels away from a projected line from the last spot. There are several adjustable parameters in this algorithm, which were fine–tuned, so that >95% of the spots were found in each frame, though 1–2 spots were typically missed in any given frame. We needed to ignore the spots in the lower and lower right sides of the pupil due to partial illumination of these subapertures.

We then subtracted the average centroids of the significant static aberration (due to camera and telescope misalignment) from the centroids of each of the frames to determine the dynamic aberration. We determine that these dynamic aberrations obey the statistical properties of Kolmogorov turbulence (at least on small spatial scales), so we attribute these dynamic aberrations to atmospheric turbulence (as opposed to the unlikely case of mirror vibrations). Two such wavefronts are shown in Figure 2. In Figure 3, we plot the time–averaged structure function of the atmospheric turbulence and find that it obeys the 5/3 Kolmogorov power–law from r=0.5 meters to r=6.5 meters with little direct evidence for an inner or outer scale, and with a Fried coherence length of:

$$r_0(\text{fast, WFS}) \approx 15 \text{ cm}.$$

This fast WFS estimate of r_0 is a little higher than the 'slow' PSF based approximate estimates of $\sigma \sim 1 \pm 0.2$arcsecond seeing, giving:

$$r_0(\text{slow, imaging}) = (\lambda/\sigma) * (2\times10^5 \text{ arcsecs/radian}) = 12 \pm 2.4\text{cm (assuming } \lambda = 0.6 \text{ microns)},$$

taken during the same night. The 'fast' r_0 may be higher for several reasons. The 'slow' r_0 includes the static low–order telescope and camera alignment aberrations, and it was measured an hour or so earlier than the WFS data was taken, so the slow r_0 may be slightly different than the fast r_0. There does appear to be extra structure at large and small scales beyond what Kolmogorov theory predicts; this may be due to the dark current noise of the uncooled WFS CCD on small scales, and tip/tilt tracking jitter + low–order dynamic telescope aberrations (e.g. wind shake). Alternatively and more specifically, the dip in the structure function at ~2 m can be explained by an outer–scale of 10–15 m producing a rollover to a flat structure function at 2 m, a slightly smaller r_0, tip/tilt tracking errors at large scales, and no effect of the detector noise on the structure function at small–scales.

We acquired 12 frames of data with −2 microns of astigmatism deliberately put into the MMT primary mirror. By subtracting the average wavefront from before and after the astigmatism was added, we determine that 1.70+/−0.3 microns of astigmatism were put into the mirror (see Figure 4). There is less than 0.3 microns of aberration put into each of the higher order modes, so this gives an the estimate of the error for astigmatism. The angle of the astigmatism is roughly 20 degrees, whereas, we put in astigmatism at 45 degrees. The difference is partially due to the ~8 degrees of internal rotation of the CCD and lenslet array within the dewar which was otherwise aligned orthogonally to the telescope. The measured modal spectrum shows that there was −1.5±0.3 microns of defocus put into the system at the same time as the astigmatism. Perhaps this is due to some sort of backlash of the mirror in response to the commanded astigmatism, or maybe the inner actuators did not pull as much as the outer actuators were pushing and pulling.

We have also found self–correlations of the modal amplitudes over 3 second time–scales, as is evidenced in Figure 5 where we plot the modal amplitudes, $a_J(t)$, for three different modes, J, as a function of frame number (ignoring those frames where the tilt suddenly jumped by 20 waves or more), and where we also plot the time–delayed self–correlation $a_J(t+\Delta t)$ versus $a_J(t)$, where $\Delta t \sim 3$ seconds is the time between frames. This self–correlation of low–order modes ($J<6$) is likely due to low–altitude turbulence that stays constant or is slowly–changing until some gust of wind blows that turbulence away to be refreshed by a new hovering wavefront. The self–correlation of tilt and focus may also be due to correlated telescope tracking or defocus jitter, and the self–correlation of astigmatism may instead be due to wind–buffetting of the primary mirror.

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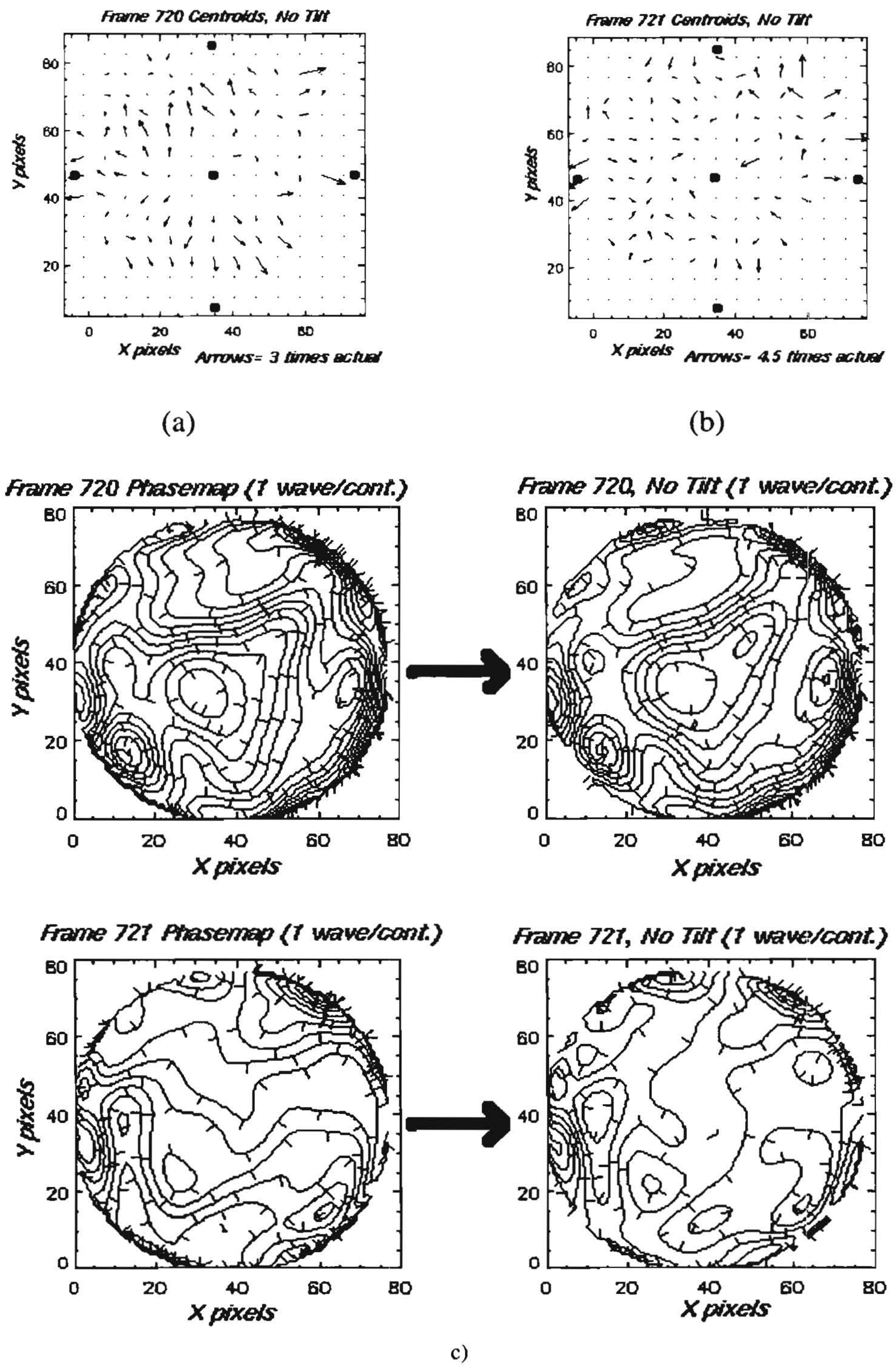


Figure 2: For two different wavefront instances, (a,b) with the list of ordered centroid positions, we subtract the centroid positions for the average wavefront, and then display the slopes as a vectormap across the pupil. and then (c) apply a least–squares reconstructor to determine the tilt–subtracted phasemap estimate . The aberrations shown here are time–varying and are due to atmospheric turbulence.

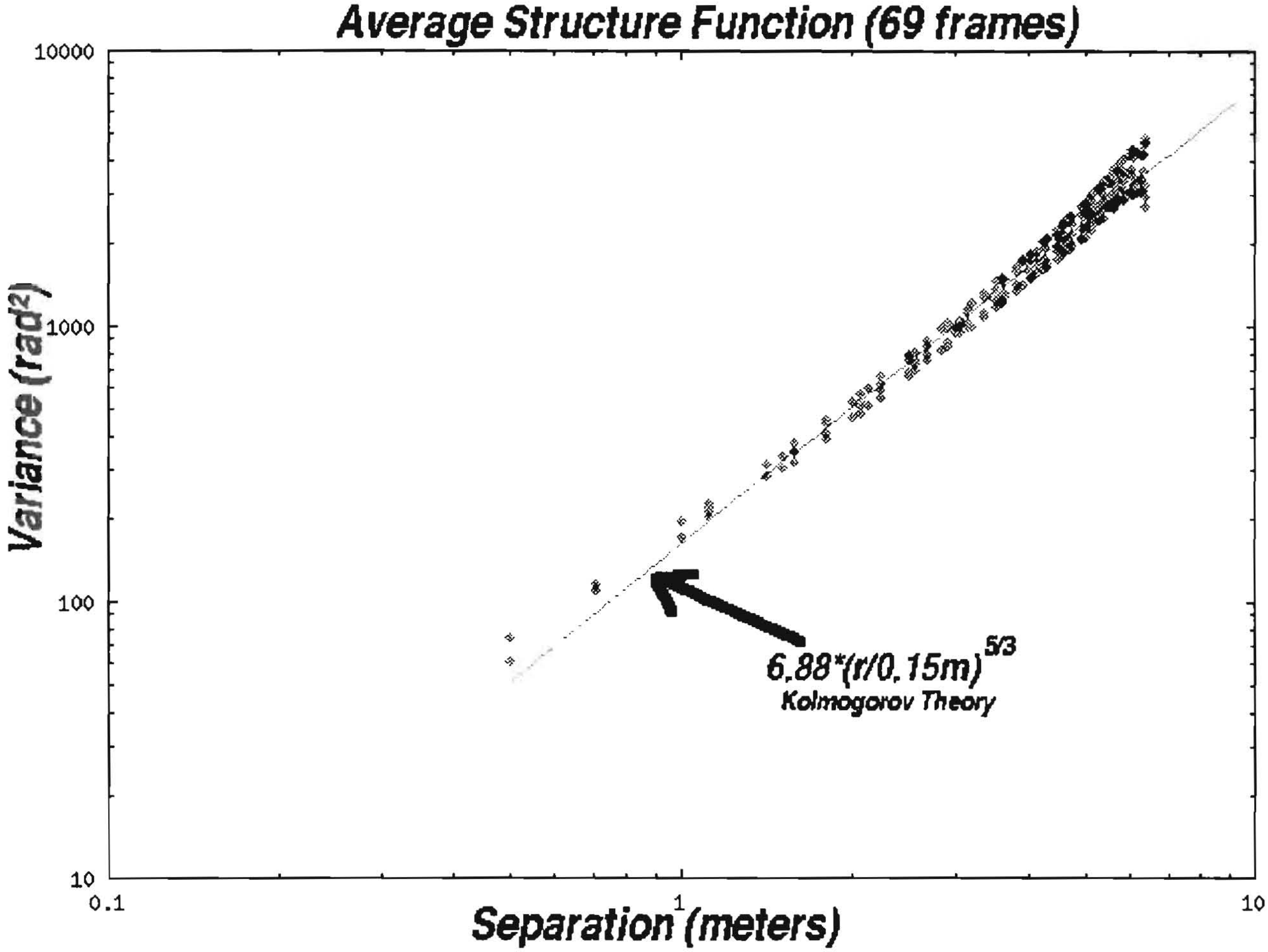
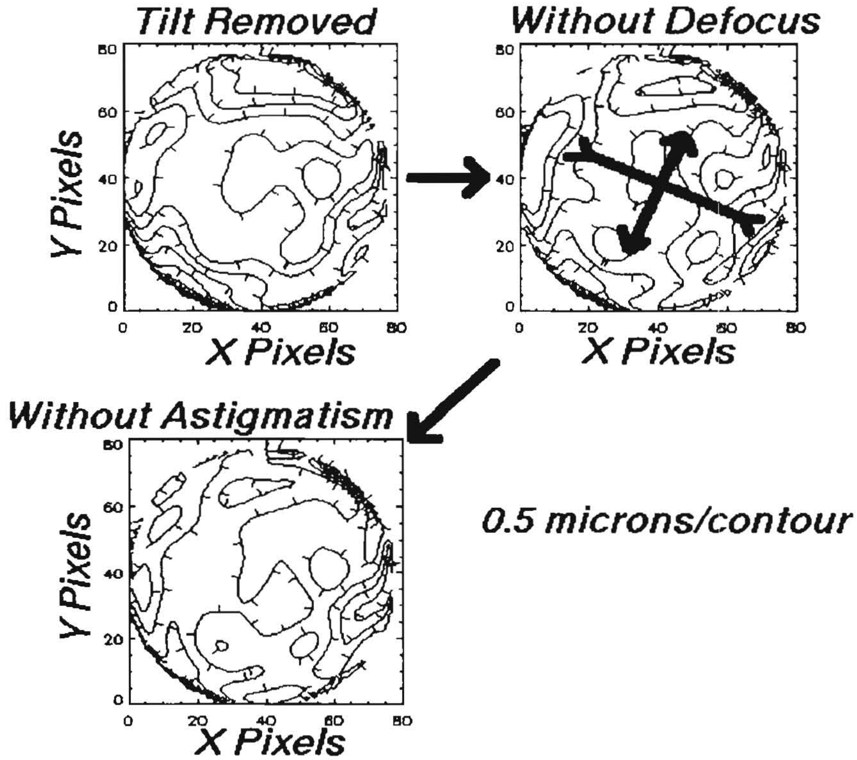


Figure 3: The average structure function, computed for frames 653–721, overlaid with Kolmogorov's theoretical power–law for a Fried coherence length of $r_0 = 0.15$ meters. Note the slight amount of extra structure at small and large scales. Also note that there is no strong evidence for an inner or outer scale in which there is a paucity of structure at small and large scales. However, there does appear to be a dip in the structure function at 1.5–2.0 meters. This can be explained by a von Karman turbulence spectrum that includes an outer scale of 10–15 meters (giving a rollover to a flat structure function at ~1.5–2.0 meters) and a slightly smaller r_0. This outer–scale explanation of the dip would be consistent with the apparent r^2 dependence of the structure function for $r > 2.0$ meters, with plausible tip/tilt tracking jitter as the tentative explanation of this extra structure at large scales.



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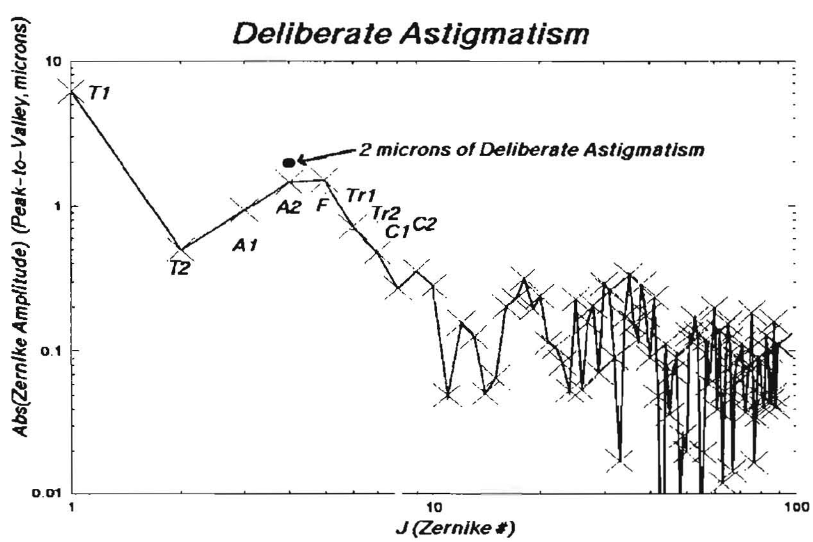

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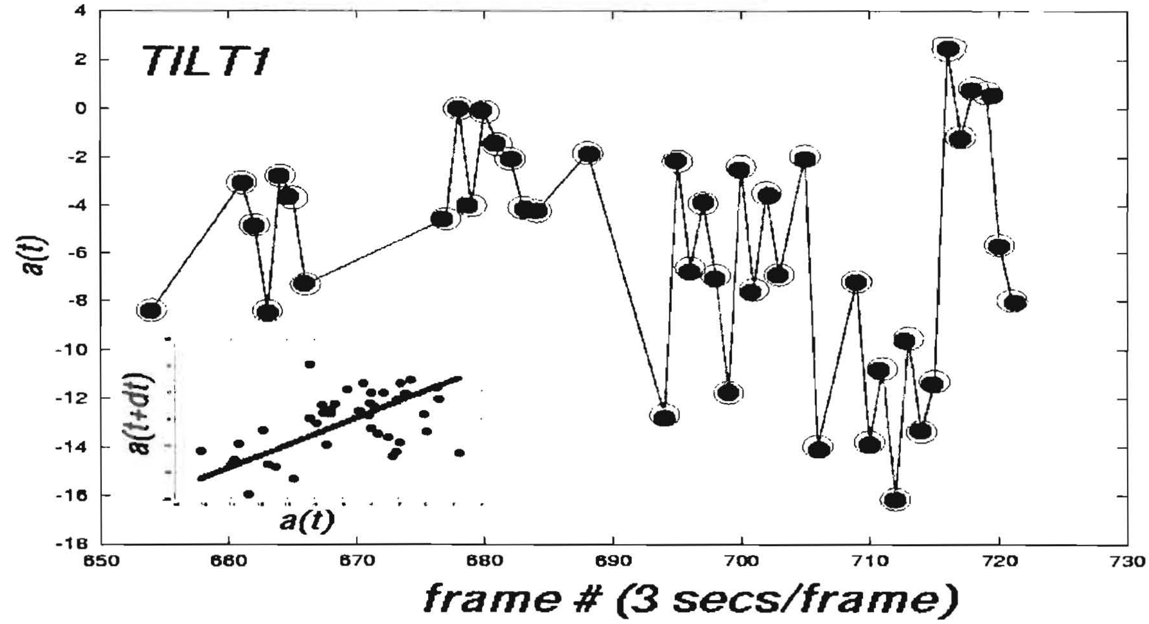
Figure 4: Two microns of 45 degree astigmatism was deliberately put into the MMT primary mirror. In (a), we show the resulting average phase map for frames #722–#733, after subtracting the average static phasemap without astigmatism over frames #653–#721. In (b), the Zernike spectrum is shown, with coupling of astigmatism to defocus evident.



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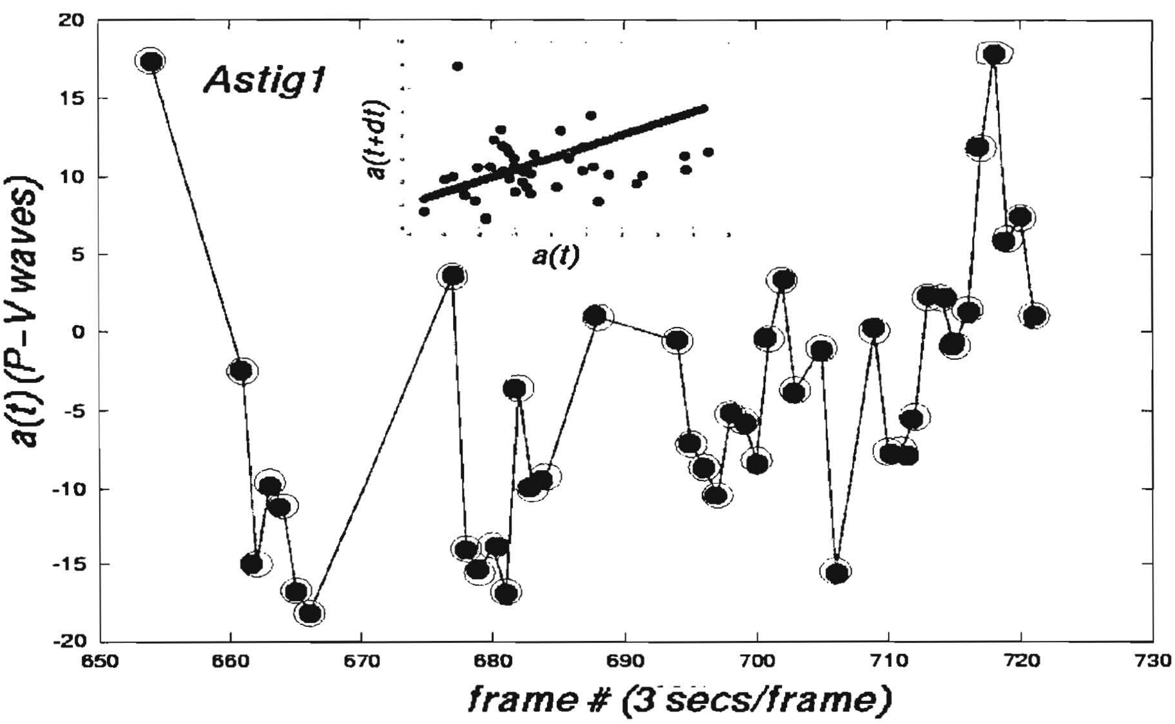

b)

Figure 5: Tilt in the Y direction and 45 degree astigmatism are plotted versus time. There is evidence for a self-correlation over several frames, as is confirmed in their one-frame delay correlation plot insets. The diagonal lines in the insets have a slope of 1. There is evidence for correlation for all modes with J<6, but little evidence for J≥6.