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An Interferometric Hartmann Wavefront Analyzer for the 6.5m MMT, and the First Results for Collimation and Figure Correction

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http://nemo.as.arizona.edu/~swest/pdfs/ih_sh.pdf (color version)

Abstract

The theory, optical, mechanical, and software design for an interferometric Hartmann wavefront analyzer for the 6.5 m MMT is presented. The instrument is modular so it can be used at the prime focus or any of the three unique Cassegrain foci. We discuss the first results at the f/9 Cass focus where the detected wavefront error was used to correct both collimation and the primary mirror figure distortion. Despite the fact that neither M1 nor M2 were thermally controlled at the time, it is found that two correction iterations produce an image psf near 0.1 arcsec p-p.

I. Overview

The 6.5m MMT will have 3 Cassegrain foci -- f/9, f/5, and f/15. The MMTO will provide facility wavefront sensors for the f/9 and f/5 focal modes. The f/15 instrumentation will have dedicated wavefront sensing provided by Steward Observatory's CAAO group tailored for the use of adaptive secondary mirrors.

The facility wavefront analyzers consist of two types. The first is a relatively high resolution modular wavefront analyzer whose configuration can be changed for use at either the prime, f/9, f/5 or f/15 foci. This provides over 30 phase apertures across the pupil diameter. It is primarily intended for stand-alone opto-mechanical studies of the optics, mirror support systems, telescope support structure, and the construction of elevation and temperature-dependent look-up tables. The instrument is based on the interferometric Hartmann (or Korhonen-Hartmann) technique invented at the Nordic Optical Telescope (NOT) and also used at the Vatican Advanced Technology Telescope (VATT) [1-6]. The second type of wavefront sensor resides permanently at the f/9 and f/5 Cassegrain foci. They have not yet been constructed, but will most likely be Shack Hartmann or curvature sensing units. They will provide nightly routine refinements to the look-up table collimation and figure correction.

Section II presents a brief overview of the theory of the interferometric Hartmann technique and contrasts it to a Shack Hartmann device. Section III outlines the design and opto-mechanics of the interferometric Hartmann analyzer. Section IV explains how the wavefront error is determined from the phase-differences detected by the analyzer. Section V summarizes the first results of active figure correction and collimation at the f/9 focus of the 6.5m MMT. Section VI explains our development of interactive software for collecting and analyzing wavefront data.

II. The Interferometric Hartmann Technique

The interferometric Hartmann analyzer directly measures wavefront phase differences in contrast to the Shack-Hartmann which measures wavefront gradients. Instead of a lenslet array, the interferometric device uses a simple Hartmann aperture mask array placed at the collimated re-imaged pupil. A single converging lens focuses the Airy patterns produced by the apertures. The relatively large Airy patterns overlap each other in the extra and intra focal areas adjacent to the focus. Groups of 4 adjacent apertures (a quartet) produce sharp interference in these overlapping regions. The position of the interference spots depends upon the phase differences in the corresponding 4 apertures.

The size of the diffraction spot from the Shack Hartmann lenslet is inversely proportional to the diameter of the lenslet (2.44/D), while the size of the interference spot from the Korhonen device is inversely proportional to the separation between apertures (1/d). Therefore, the interference spot can be made up to 7 times smaller than the corresponding spot from a Shack Hartmann device. Insofar as the accuracy of the centroiding algorithm increases with decreasing spot size, the accuracy in detected wavefront errors increases.

The position of the m=0 diffraction spot depends upon the phase differences between the 4 apertures. It is sensitive to all sources of phase difference (*including piston,* to which the

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Shack Hartmann is insensitive). The unwanted m=+/-1 diffraction is controlled by adjusting the aperture diameter (to modulate the m = +/- 1 intensities) and the aperture separation (to adjust the angular separation of the m=0 and m = +/-1 diffraction peaks) as illustrated in Figure 1.

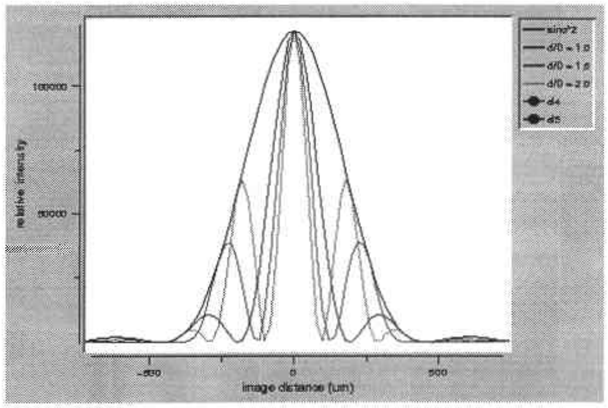

Figure 1: One dimensional diffraction formed by two Hartmann apertures (with identical phases) for several ratios of aperture-spacing to diameter (1, 1.5, and 2). This illustrates how the geometry is used to control suppression of unwanted interference orders. The intensity of the interference fringes is modulated by the diffraction envelope of a single aperture. The ratio of d/D=1 has the advantage of offering the best high-order suppression but has the disadvantages of having the widest m=0 fringe and more spatial averaging of the pupil phase function for a given spacing.

A significant limitation to the interferometric Hartmann technique is dynamic range. As the phase difference increases, the m=0 fringe shifts away from the center of the aperture diffraction. At the same time, one of the m= +/-1 fringes shifts towards the center of the aperture diffraction. Soon the spot centroiding routine becomes confused. Therefore this technique is best employed when the optics are already well on their way to being optimized. In practice, we have found this technique capable of measuring wavefronts with as much as a micron or two of wavefront aberration in several modes. Korhonen at the NOT reports being able to measure up to 10 microns of wavefront coma (private communication). Employing a finer Hartmann mask gives the device higher dynamic range because the phase difference is smaller between apertures.

Enlarging the optical bandpass has several advantages: 1) the instrument collects more light, 2) the m=0 interference fringes for different wavelengths overlap, and 3) the higher order fringes smear out into spectra helping to reduce their unwanted effects as shown in Figure 2.

For ease of illustration, the figures have been shown with the detector at the focus of the lens. However at this position, adding more Hartmann apertures simply causes the interference

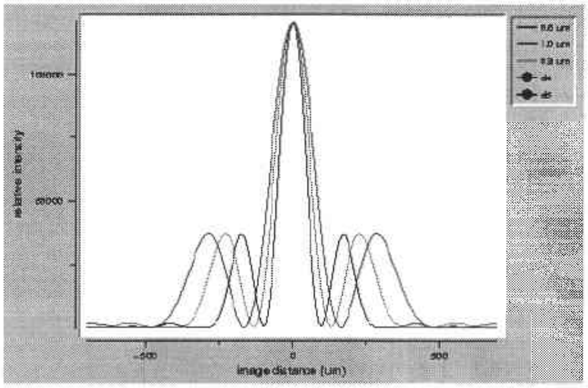

Figure 2: Interference shown for 3 wavelengths in a bandpass (0.6 blue, 0.8 green, and 1.0 micron). The m=0 fringes overlap while the higher orders "smear" into spectra reducing their unwanted effects.

fringes to become sharper, just like adding more rulings to a diffraction grating.

In order to detect the phase difference distribution throughout the entire pupil, the detector is placed either inside or outside of the lens focus so that adjacent m=0 diffraction peaks are spatially separated on the detector. The shift of the detector away from the lens focus is constrained by two criteria. The first is that the defocused airy patterns produced by the Hartmann apertures must significantly overlap to produce interference. The second constraint is to achieve the desired spacing between successive m=0 interference fringes. Typically, one places a given m=0 interference fringe onto the m=+/-1 fringe of the adjacent pattern or onto the minimum of the adjacent de-focussed sinc^2 aperture function.

Figure 3 shows diffraction created by a line of 8 Hartmann

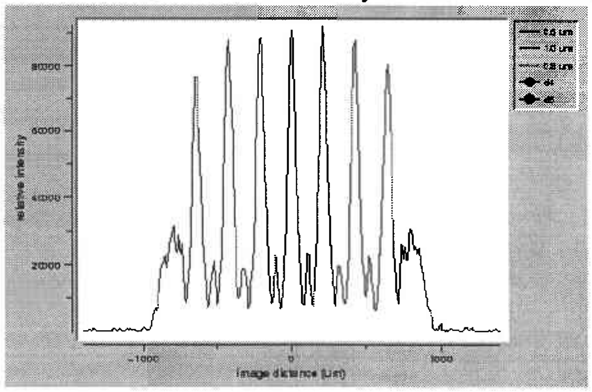

Figure 3: One dimensional diffraction formed with a line of 8 Hartmann apertures (with equal phases). The detector is shifted away from the lens focus to separate the m=0 fringes.

apertures when the detector is shifted away from the focus of the lens. Each pair of apertures produces a distinct m=0 interference. The edges of the pattern show residual higher order diffraction.

The diffraction effect of a 1/8-wave phase shift in one aperture is shown in Figure 4. Here, 5 apertures are modelled with a

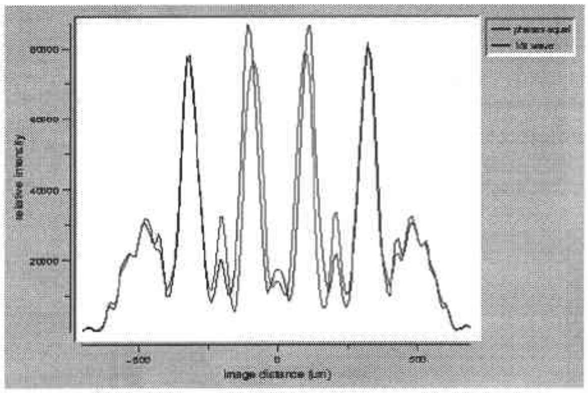

Figure 4: One-dimensional model of diffraction created by 5 Hartmann apertures in a line: with all phases equal (black) and with the center aperture having a phase shift of +1/8-wave. The two central fringes are shifted inward by the phase error. This is how phase differences are detected using an interferometric Hartmann wavefront analyzer. In practice though, the interference pattern is in two dimensions and each interference maximum is created by 4 apertures.

phase shift of +1/8 wave of piston in the center aperture. The two center m=0 fringes have shifted towards one another. This is how the interferometric Hartmann technique works except that in practice, the m=0 interference is formed in 2 dimensions by 4 apertures as described in section IV. The direction and magnitude of the spot shifts is proportional to the phase differences in the apertures.

III. Instrument Design

This section describes the opto-mechanical design of the interferometric Hartmann for the 6.5m MMT.

A. f/9 module

Two Apogee KX-260 CCD cameras were selected for use with the instrument (512 x 512 with 20 micron pixels). The optical design (using OSLO PRO) was driven to match the interferogram to this detector format. The Cassegrain f/9 module of the instrument is shown in Figure 5. The optics are very simple. A doublet collimator (MG 06 LAI 015) forms a pupil image. A Hartmann mask and blue-cutoff filter (RG 715) are placed at the pupil. Immediately following the pupil is a doublet focussing lens (MG 06 LAI 015). The interferogram is formed between this lens and its focus. A focal plane turret allows the user to select between a tilted pierced acquisition mirror or a laser diode reference source. The acquisition channel incorporates a 1:1 re-imager so the focal scale of the telescope is preserved. The geometry of the Hartmann mask is also shown in Figure 5. The ratio of aperture spacing to diameter was chosen to be 1.5.

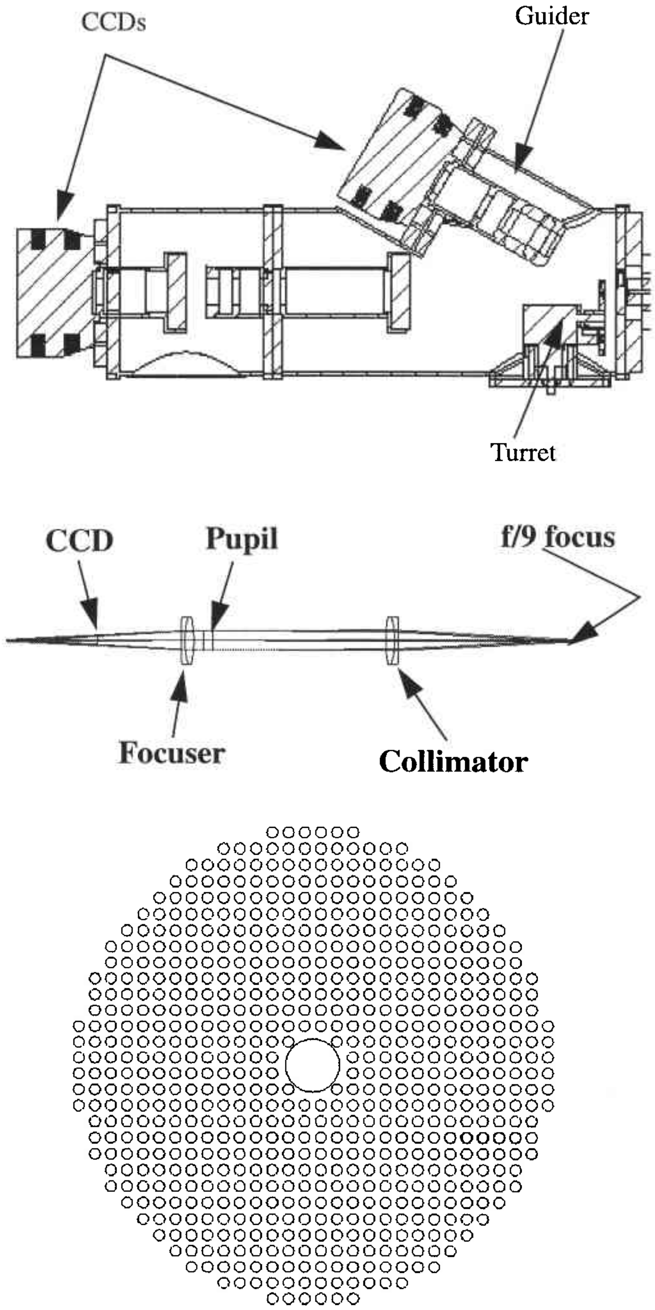

Figure 5: The Cassegrain f/9 module of the interferometric Hartmann wavefront sensor. A collimator forms a pupil where the Hartmann mask and filter are placed. A focussing lens is placed behind the Hartmann mask. The interferogram is formed between this focus and the lens. The turret provides a tilted pierced mirror for guiding and acquisition or a laser diode reference. The lower figure shows the geometry of the Hartmann mask in the 30mm diameter pupil.

The section of the instrument containing the Hartmann mask and focussing lens is replaceable to allow reconfiguration for the other Cassegrain foci of the telescope.