Technical Report 26

SEEING TESTS AT THE MMT

SPIE papers included in this report:

"Seeing measurements at the Multiple Mirror Telescope obtained with a very high quality 1.8 m primary mirror," F.H. Chaffee, R.H. Cromwell (1990).

"Site testing telescope on Mt. Hopkins," R.H. Cromwell, V.R. Haemmerle, N.J. Woolf (1990).

Seeing measurements at the Multiple Mirror Telescope obtained with a very high quality 1.8 m primary mirror[a]

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I. INTRODUCTION

Almost immediately after the first observations were made with the Multiple Mirror Telescope (MMT) in the late 1970's, two facts became evident: 1) The seeing at the MMT site was frequently of extremely high quality, and 2) the optics of the telescope, having been figured for approximately 0.6 arcsecond image quality, were inadequate to exploit the superior seeing. Thus in 1983 a program was initiated to refigure the MMT optics in order to remedy this situation.

The first step in this process was to refigure all secondary mirrors. The second was to produce a seventh 1.8 meter primary mirror (MMT7) of sufficiently high surface quality to achieve 0.125 arcsecond images. Finally, the original six MMT primary mirrors were to be sequentially refigured to the same high quality.

By early 1988 the first two steps above had been completed,[2] and MMT7 had been installed in the telescope. Initial tests revealed that the efforts achieved the desired result—images quantitatively better than any hitherto recorded at the MMT were routinely produced by the telescope containing MMT7. (Because of the impending conversion of the MMT to a 6.5 m telescope, the final step was abandoned.)

In the spring of 1988 we initiated a program at the MMT to quantitatively measure the seeing using MMT7. This paper reports the first year and a half of observations from that program.

II. MMT7: A HIGH QUALITY F/2.7 1.8 M MIRROR

In 1983 the MMT Observatory contracted with the Optical Sciences Center of the University of Arizona to produce a seventh 1.8 meter f/2.7 primary mirror for the MMT capable of producing 0.125 arcsecond images (FWHM). Such a high image quality was chosen because the seeing reported from the first several years of operation of the MMT suggested that on a significant percentage of clear nights, the observed image quality was limited by the 0.6 arcsecond (FWHM) performance of the best MMT telescope.

In consultation with the late David Brown of Grubb-Parsons, who was responsible for figuring the 4.2 m Herschel primary mirror to achieve similarly high image quality, a non-traditional set of specifications was devised to describe the surface of MMT7. These specifications address the departures of the polished surface from that of a perfect paraboloid as a function of spacial scale as follows:

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[a] Observations reported herein were obtained with the Multiple Mirror Telescope, a facility operated jointly by the Smithsonian Institution and the University of Arizona.

The rms surface irregularities between randomly selected pairs of points x cm apart on the mirror's surface shall be less than or equal to:

0.013 λ for x = 4 cm
0.024 λ for x = 8 cm
0.043 λ for x = 16 cm
0.077 λ for x = 32 cm
0.105 λ for x = 64 cm

where λ = 633 nm and where wavefront irregularities on reflection are twice the above values. These specifications apply to the entire surface excluding the outer 13 mm circumferential ring and the inner 25 mm circle. The former was specified not to depart from the true surface by more than 1/2 λ."

These tolerances demanded that non-standard polishing and testing procedures be used for MMT7, and these have been described by Anderson and Crawford.[1,2] The final measured figure of the mirror suggests it is capable of producing 0.1 arcsecond images.[2]

In January 1988, MMT7 was installed in telescope F in the MMT (at 4 o'clock in the hexagonal telescope array as seen by incoming photons), and tests were begun. It soon became evident that MMT7 was capable of producing images of very high quality.

III. SEEING MEASUREMENTS AT THE MMT

In May 1988, MMT7 was moved into telescope E (6 o'clock) for ease of access, and a program of seeing monitoring was initiated. In order to obtain an estimate of the seeing produced by the free atmosphere above Mt. Hopkins plus any contribution of the local mountaintop, a 31.75 cm site testing telescope[3] was erected outside the MMT building[4] to monitor the motion of an image of Polaris, and seeing measurements were taken with both MMT7 and this telescope over a series of 60 nights. Then the site testing telescope was moved inside the MMT building and mounted adjacent to MMT7 on the optics support structure, and simultaneous measurements were taken for another 90 nights. The intercomparison of these results has provided important insights into the physical nature of the seeing process and to the causes of seeing degradation in an observatory environment.[4] They also provide a credible context in which to interpret the seeing measurements obtained with MMT7. Typically, the quadrature difference between the size of image measured with MMT7 and that predicted from the site testing telescope is 0.47 arcsecond. This excess 0.47 arcsecond is caused in part by focus error in MMT7 (typically 0.2 arcsecond), the optical figure of MMT7 (0.1 arcsecond) plus residual mirror support errors, small collimation errors, surface errors in the secondary and three optical flats, mirror seeing and any possible small errors in the image motion theory.

For the nightly seeing tests only the image from MMT7 is used. Under most conditions, if an image from any of the other 5 mirrors is placed next to that of MMT7, the superiority of the MMT7 image is immediately apparent on the TV monitor. Four reflections are normally required to bring the light to the MMT combined focus. For seeing measurements a fifth mirror ahead of focus directs the beam to a Pulnix CCD TV camera with which the image is recorded at a scale of ≈ 22 (vertical) pixels per arcsecond. Best focus of the image is achieved by visual inspection of the real-time image displayed on a video monitor. Data are obtained on a star at a zenith distance of less than 30° of such brightness that the peak intensity of its image does not exceed the dynamic range over which the Pulnix camera and the video recording medium have been shown to be linear. (Modifications were made to the camera electronics to avoid its inherently non-linear response of 10-20%, a property we have found in several Pulnix cameras). Stars of spectral type K0-K5 were used exclusively to assure that the effective system spectral response was always the same. The combination of the average spectral energy distribution of K stars, atmospheric extinction, telescope spectral throughput, and the color dependence of image size gives 7165 Å as the effective system wavelength. (The FWHM of a seeing image is proportional to $\lambda^{-1/5}$). Eighty-six and a half (86.5) percent of the data were taken within 1 hour before sunrise, 10.2% within 1 hour after sunset, and the remaining 2.8% at random times throughout the night. The image is recorded for approximately 5 minutes via a Sony superbeta video cassette recorder onto video tape which serves as our archival storage medium. The taped images are analyzed later.

To determine the FWHM of a long-exposure, high signal-to-noise image, a PC-based video frame grabber is used to sum every fourth video frame of the star image for an "integration time" of 8 seconds. Thus, the true summed exposure time is 3 seconds, but the time over which this integration has been distributed is 8 seconds. (Each summed video frame is considered as having 3/60 second effective exposure time: 1/60 second is unique to one video field, 1/60 second is unique to the other (interlaced) field, and 1/60 second is shared in common between the two fields). No guiding of the telescope beyond the standard diurnal tracking is performed during an integration. The image is integrated over a 65 x 65 pixel area of the frame grabber (covering a sky area of 3.0 arcseconds in the elevation direction by 3.8 arcseconds in the azimuth direction). A sky background is determined and subtracted from the image by sampling 8 pixels that surround, but are well separated from, the star image. A FWHM value is determined in both the elevation and the azimuth directions using two respective 3-pixel wide slit scans of the image that pass through the image peak. (The slit length corresponds to 0.14 arcsecond in elevation and 0.17 arcsecond in azimuth). The computer requires 2 seconds to determine a pair of FWHM values. Thus, a new pair of values is determined every 10 seconds while the tape is played back continuously. If the FWHM exceeds 2 arcseconds, then the analysis window area is doubled and every other pixel in both dimensions is examined, keeping the total number of analyzed pixels the same. In the exceptionally rare case where the FWHM exceeds 4 arcseconds (0.9% of the measurements), a similar process is used to sample every fourth pixel in each direction.

Repeated measurements of many taped images show that a FWHM value is invariant with integration time over a range of 4 to 16 seconds. For shorter integration times, a FWHM value is sometimes smaller, suggesting that the low-frequency terms of atmospheric seeing are not fully sampled. For integration times longer than 16 seconds, a FWHM value is occasionally larger, due to residual tracking errors of the MMT. On this evidence we elected to standardize on 8 second integration times as an appropriate "long exposure." A final single "measurement" of the FWHM is the average value of nine 8-second integrations taken from 90 seconds of continuous image data. Both an elevation and an azimuth component are determined. Normally, three separate measurements are obtained from a standard 5 minute video record.

The elevation component is on the average slightly larger than the azimuth component due to atmospheric dispersion, an effect we can model accurately. Image motion analysis has shown that at a wind speed of greater than 6 m/s the MMT oscillates more severely in the elevation axis than in the azimuth axis, and the complicated dependence on wind orientation with respect to the telescope and building make properly accounting for this effect difficult. Also, the MMT elevation tracking errors tend to exceed slightly those in azimuth. Therefore, we give here only the results for the azimuth component, which is found to be negligibly affected by wind shake, tracking error and, of course, differential refraction.

The histogram of 784 image measurements from MMT7 from the first year and a half of observations is shown in Figure 1. The values measured at a zenith distance z have been corrected to the value expected at the zenith by the factor $(\sec z)^{0.6}$. Measurements were made on all clear nights except when infrared or special-purpose instrumentation required the removal of the seeing