

Technical Report 18

PRELIMINARY OPTICAL DESIGNS FOR AN MMT UPGRADE:
A 256-INCH FILLED-APERTURE
OPTICAL/INFRARED TELESCOPE

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An Invited Report to:

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1. Introduction

The purpose of this study is to develop a preliminary yet fully quantitative optical design for a proposed upgrade of the Multiple Mirror Telescope (MMT) on Mount Hopkins, to the maximum diameter, filled-aperture optical/infrared telescope that can be accommodated by the existing telescope mount and building. Specifically, the optical design for the new Maximum Mirror Telescope (MMT) is required to meet the following constraints and performance characteristics:

- A. The new MMT must accommodate a primary mirror of maximum diameter consistent with the constraint that the present MMT mounting, up to the altitude-axis journal bearings, should not require substantial alteration.
- B. The new MMT must "fit" within the present MMT building structure and operate therein without substantial modification to the existing building.
- C. The optical design must provide a flat optical focal surface approximately 50 inches behind the primary mirror vertex, which must include spectral coverage from $\lambda 3300 \text{ \AA}$ to $\lambda 11,000 \text{ \AA}$ and shall extend to $\lambda 16,000 \text{ \AA}$ if possible, all without refocus. The angular field diameter (field of view) must be at least 30 arcmin and shall be extended to 60 arcmin if possible. This focus must provide a spatial scale sufficient to resolve $2/3$ arcsec astrophysical image detail clearly, as viewed by a CCD detector having 27μ pixels. The design must provide atmospheric dispersion compensation (ADC) and must contain an 0.50-inch-thick flat plate near focus, representing the optical path characteristics typical of filters, vacuum windows and the like.
- D. The optical design must provide an all-reflecting $f/45.0$ infrared focus approximately 40 inches behind the primary mirror vertex. The infrared field of view must be at least 2.0 arcmin in diameter and geometric image aberrations upon a curved field of view must not appreciably degrade the Airy disk at $\lambda 5.0 \mu$ in collimated mode. The infrared secondary mirror must be physically small enough to "chop" the image with a ± 20 arcsec amplitude at 30 Hz, without appreciable mechanical deformation. The residual coma induced by a ± 20 arcsec chop amplitude should not substantially degrade the Airy disk at $\lambda 5.0 \mu$.
- E. The optical design must provide an ancillary focal expander-corrector to be used with the wide-field optical secondary mirror to produce an $f/9.00$ focus approximately 50 inches behind the primary mirror vertex. To the extent possible, the exit pupil of this corrector system shall be placed so as to minimally alter the optical performance characteristics of existing MMT auxiliary instrumentation. This focus must include spectral coverage from $\lambda 3300 \text{ \AA}$ to $\lambda 11,000 \text{ \AA}$ over a 3.0-arcmin diameter (or larger) flat field of view without refocus. The design must include atmospheric dispersion compensation (ADC) but no exit window.

- F. If practical, the primary mirror and wide-field optical secondary mirror should provide a "naked" all-reflecting Cassegrain focus corrected for 3rd-order spherical aberration.

The purpose of this report is to summarize and document a variety of calculations related to the above design specifications and to formulate recommendations based on those results. The studies reported here were intended as "first looks" rather than as definitive final products. In keeping with that perspective, they are reported in narrative style, rather than in a form appropriate for a professional journal.

2. Choice of Primary Mirror and Wide-field f/ratio(s)

The existing MMT mounting will just adequately accommodate a 256-inch diameter primary mirror, hence this dimension (approximately 6.5-m) was adopted (see Req. A). The existing interior dimensions of the MMT building will just accommodate an f/1.0 primary-mirror geometry at this mirror diameter, so that primary f/ratio was adopted provisionally (see Req. B), with the clear recognition that such an optically fast primary f/ratio represents an ambitious step beyond presently demonstrated mirror fabrication technology as well as a substantial step beyond conventionally known optical designs. However, to have initiated the study at a slower primary mirror f/ratio would have been incompatible with our dominant goal, that being to produce a self-consistent optical design proposal based on a maximum possible diameter primary mirror. This report will document that the f/1.0 primary mirror is viable.

The advent of CCD chips has lent new and graphic meaning to the old idea of "pixel size" in a detector. Sampling theory suggests that there must be at least 2 pixels in each linear dimension of a spatial information element in order to avoid undersampling effects such as aliasing. In practice, 3 to 4 pixels per element is usually found to be a more nearly optimum sampling factor. Let us choose (arbitrarily) a sampling factor of 3.5 (27 μ) pixels per (2/3 arcsec) spatial information element (see Req. C). This implies a wide-field (corrected) optical Cassegrain at f/4.50. One notes that if "seeing" conditions should permit, the ancillary focal expander-corrector at f/9.00 (see Req. E) could provide the capability for very high resolution (1/3 arcsec) imaging at the same sampling factor, over a limited field of view, in addition to its main intended use as an interface between the new MMT telescope optics and existing MMT instrumentation.

3. Optical Image Quality Criteria and Telescope Error Budget

Image quality is most properly and completely described in terms of modulation transfer functions which are, unfortunately somewhat expensive to calculate. They in turn are determined by so called point spread functions which themselves can be derived by ray tracing in the geometric limit where diffraction is unimportant as a source of aberration. Often it is convenient to average over the energy distribution within an image and simply quote an rms image diameter with respect to the image centroid. It is useful to note that if an image energy distribution were radially symmetric and Gaussian in profile, there would be 50% of the energy within the full width at half maximum

(0.83 rms diameter); 63.2% energy within 1.00 rms diameter; 80% energy within 1.27 rms diameter; and 90% energy within 1.52 rms diameter. The energy distribution within a real image may differ from these guidelines to the extent that the image is asymmetric and/or non-Gaussian but the concept of rms image diameter remains useful nonetheless for the purpose of quantitative discussion and intercomparison of related design-alternative systems.

Many contributions to the overall image degradation in a real telescope are of a random character which allows one to estimate the convolved effect by adding their individual rms amplitudes quadratically. Several of the most important of these factors will be mentioned below. However there exist other factors whose systematic behavior requires that they be added vectorially into the error budget. The most important of these is atmospheric dispersion which is a factor that scales inversely with observatory altitude (reciprocal air pressure) but directly with $\tan(\text{zenith angle})$. For an observatory at about 8,500 feet, a stellar image at $z = 60$ degrees will be elongated about 4 arcsec over the chromatic range $\lambda 3300 \text{ \AA}$ to $11,000 \text{ \AA}$. Said effect will occur in the instantaneous altitude direction and will rotate locally on the detector during an integration, even after field rotation has been properly accomplished. Clearly, an atmospheric dispersion compensator (ADC) must be incorporated as an integral part of any sub-arcsec imaging device which is used in moderate to broad passbands away from the zenith. A second systematic effect which does not add quadratically to the error budget is lateral chromatic aberration (lateral color) which results from the (possible) dependence of system magnification on wavelength in refracting devices such as corrector lenses. Lateral color causes a star image to be spread into a spectrum. It usually increases directly with field angle but can exhibit more complicated dependence in sophisticated field correctors.

We identify in Table 1 below several of the dominant random contributors to the overall error budget, together with estimates of their appropriate "shares" of the budget.

Table 1. Proposed Telescope Error Budget

Potential error item	Allowed rms amplitude (arcsec)	
	f/4.50	f/9.00
1. Optical design residual aberration	0.20	0.14
2. Optical fabrication	0.05	0.05
3. Mirror support system	0.10	0.10
4. Passive and active decollimation	0.12	0.10
5. Tracking and guiding errors	0.15	0.10
6. "Seeing" (atmosphere, shutter, mirror, etc.)	0.40	0.33
(quadratic) Total(s)	0.50	0.40

Facing the need for an f/1.0 primary mirror with our full error budget spent, lateral color lurking in item (1) in an unspecified way, and residual atmospheric dispersion after compensation not yet accounted for, we begin to appreciate the optical design task at hand! We shall adopt as a "rule of