The Multiple-Mirror Telescope

A large optical and infrared instrument of novel design nearing completion on Mt Hopkins is the first example of a class that could include telescopes much larger than any now existing.

Nathaniel P. Carleton and William F. Hoffmann

In the fall of the year 1609 Galileo Galilei made the first systematic celestial observations that employed a telescope, thus helping to bring the skies from the realm of mythology into that of physics.[1] Since his time, telescopes have increased nearly a hundredfold in size, with each major step providing a widening of our horizons. Galileo himself,[2] however, went to some length to demonstrate how an increase in scale, without a change in design or in materials, must inevitably bring a structure to a size where it will no longer function properly, and eventually, to the point where it will even collapse under its own weight.

The Hale Observatories' 5-meter and Soviet 6-meter telescopes may be the last major advances in the size of conventional telescopes because of this limit, and because of practical limits on the size of single optical components that can be fabricated and transported. Yet we can still anticipate that another large increase in telescope size will bring substantial gains in new knowledge. The University of Arizona and the Smithsonian Astrophysical Observatory have therefore designed and built an optical-infrared telescope of a new type that allows us to break out of the scaling limitation. This telescope, located at the Smithsonian's Mt Hopkins station (elevation 2606 meters), about 64 km south of Tucson, Arizona, is the first such instrument with high image quality relying on automatic sensing and control rather than on the structural integrity of a single massive primary mirror.

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The basic design is a cluster of six 1.8-meter Cassegrain reflecting telescopes, arranged about a common axis, with the six beams relayed to a single focal plane by two auxiliary reflections. The six images may either be superposed to form a single image or aligned along the axis of a spectrograph slit to take full advantage of slit geometry.

The combined light-collecting area is equal to that of a 4.5-m conventional telescope. The pointing directions of the six individual telescopes are locked together by the use of twelve pencils of laser light, which are generated essentially parallel to each other by a system of beam expansion and retroreflection. The resulting instrument, supported by an altitude–azimuth mount (figure 1) and enclosed in a unique rotating building, we call the Multiple-Mirror Telescope, or MMT.

There are two major reasons behind the desire for larger telescopes. First is the simple need to collect more photons, particularly for spectroscopy of faint, distant objects that are of great cosmological interest. With modern detectors, many observations are limited by photon-counting statistics, and require impractically long integration times with present telescopes. Second is the desire for the increased resolution corresponding to the diffraction limit of a large collecting aperture. This advantage can be directly realized in a space telescope, and also on the ground, for infrared wavelengths greater than 10 microns or so. At shorter wavelengths the distortion of wavefronts by inhomogeneities in the atmosphere limits the sharpness of actual images formed by all telescopes to about 1 arcsecond. The diffraction limit of existing telescopes for visible light is already far below this value ($1.22\ \lambda/d = 0.122$ microrad = 0.025 arcsec, for a wavelength $\lambda = 0.5$ microns and a telescope diameter $d = 5$ m). At the shorter wavelengths the image still contains information at spatial frequencies up to the diffraction limit, however, and this information may be retrieved with some success by the techniques of speckle interferometry and speckle imaging.[3]

In its first stage of operation, the MMT is intended to superpose images only to a reasonable fraction of the atmospheric-blur circle (about 0.2 arsec), and thus to address only the first of these major objectives. We shall immediately begin to learn, however, about the control problems in the real environment of an observatory, and thus we can begin to evaluate the practicality of coherent combination of images on the scale of visible or infrared wavelengths.

Evolution of the design

The idea of a multiple-mirror telescope is an old one. To our knowledge, its first serious application was by G. Horn d'Arturo at the University of Bologna, who constructed in the 1930's a prototype with a fixed, zenith-pointing segmented primary.[4] In the intervening years many designs have been proposed,[5] but none was actually brought to fruition except for another prototype constructed by Pierre Connes at Meudon,[6] which is a fully steerable, segmented-spherical-primary configuration of low image quality.

Beginning around 1970, the University of Arizona and the Smithsonian Astrophysical Observatory were separately considering various possibilities, trying to determine the relative utility and cost-effectiveness of such configurations as a segmented primary with a single secondary, an array of independently-mounted telescopes, the present design and others, and to find the optimum approach and mirror-element size. A single segmented

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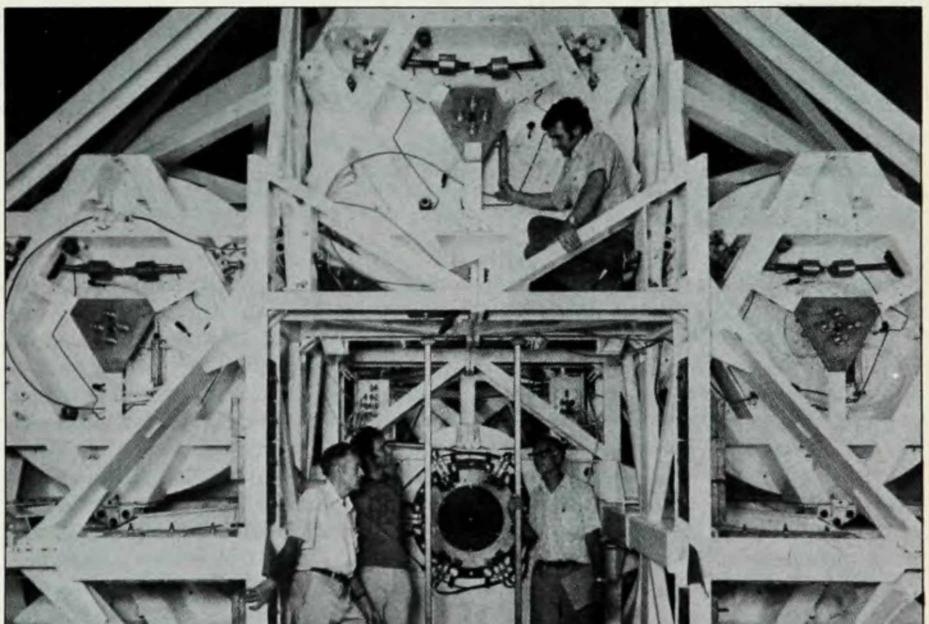
primary mirror requires either the construction of off-axis segments of a paraboloid, which is difficult, or—if it is spherical—elaborate compensation for spherical aberration if it is to have any appreciable field of view. An array of small telescopes requires duplication of expensive detector hardware, and a greater chance of limitation by detector noise, if the signals are combined after detection. Optical combination is difficult, although the recent development of high-quality fibers for optical transmission offers an intriguing possibility for a scheme to relay light to a central instrument.[7]

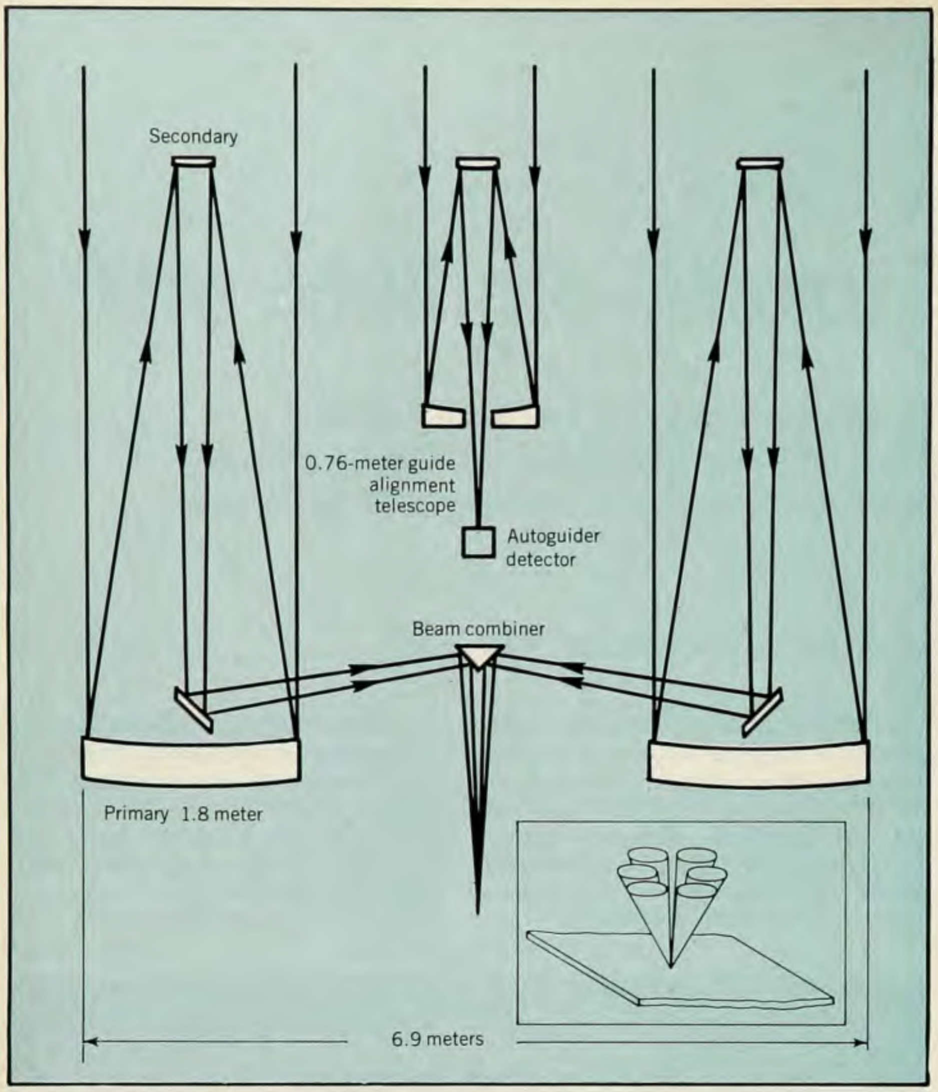
The design adopted for the MMT has the advantage of compactness, since a cluster of six telescopes with f/2.7 primary mirrors naturally has a structural envelope whose three dimensions are roughly equal. The optical systems of the six individual telescopes are of the standard Cassegrain design (paraboloidal primary, hyperboloidal secondary) and can be fabricated by conventional techniques. The use of a small number of major optical systems, each designed for low emissivity, lends itself to very-low-background performance in the infrared. The three most important considerations for the infrared are: the relatively small component telescopes, which can be designed with very low obscuration (small secondary mirrors) while maintaining a reasonable focal plane scale; the small optical elements, which can be frequently recoated to maintain low infrared emissivity, and the fact that the system can be baffled essentially by the cold sky, avoiding radiation from warm nonreflecting surfaces such as gaps between the sections of a single segmented primary.

The basic idea of the operation of the MMT is to monitor the three-dimensional positions of each of the six images of the sky, by sensing the pencils of laser light. The error signals from the laser-beam detectors are fed back to the individual secondary mirrors, which have focus and two-axis tilt controls. This is a minimum amount of control to use, since ideally one would sense and control tilt and translation of both primary and secondary mirrors. The result of this scheme is to keep the images superposed, but to allow some miscollimation of the individual telescopes to occur. It turns out to be possible to hold this miscollimation within acceptable limits by careful design of the optical support structure.

The paths of light shown in figure 2



Standing around the final image plane of the Multiple Mirror Telescope, and surrounded by its six primary mirrors, are Nathaniel P. Carleton, left, and William F. Hoffmann, right. Between them is N. J. Woolf, acting director of the MMT Observatory; J. T. Williams, the site manager, is above. In this novel 4.5-meter optical telescope, which may be the forerunner of future superlarge instruments, six images are superposed at the final Cassegrain image plane. The structure at this point can support instrumentation up to 2700 kg in weight and 4 meters long. Figure 1



Two of the six telescopes in cross section, showing the path of incoming starlight to the final composite image plane. The expanded insert shows the six f/32 cones from the beam combiner converging to a single image with a focal plane scale of 3.6 arc seconds per millimeter. The envelope of the six cones is f/9. Figure 2

represent a simple method of image superposition, which is one of several that can be used in the MMT. It provides a focus that approximates that of a conventional Cassegrain telescope with a six-hole mask over the aperture, with certain limitations. One is that the focal planes of the six telescopes cross at an angle to the central axis, so that images become out of focus in the "average" focal plane as one goes out from the axis, thus limiting the useful field of view. Another limit comes from vignetting by the beam-combiner facets. As the image point moves off axis, the beam from each telescope is pulled off center on its facet and eventually begins to miss the facet on one edge or another, thus losing light. Bringing the beams nearly tangent makes this limit very strict, although it minimizes the focal-plane-angle effect, and maximizes the filling of the apparent aperture. With the dimensions of our MMT structure one can obtain practical compromises that achieve up to a 5 arc-minute field of view in reasonable focus.

The present scheme also precludes any simple coherent beam combination because the crossing of focal planes at an angle causes the beams from two telescopes on opposite sides of the axis to produce about six interference fringes across the combined Airy discs at any wavelength, even on axis. These effects are not inherent in the basic MMT design, however. An alternative approach would be to use secondary mirrors that render the beams parallel, instead of converging, and then relay these beams such that they come out parallel to the central axis and nearly tangent to each other. Then if these beams are introduced into a small telescope (about 75-cm aperture for this case) they would be coherently combined, at an expense of two more reflections (for a Cassegrain combining telescope).

Optical components, support structure

In any large astronomical telescope the most important single item is the primary mirror. The MMT is no exception to this except that the word becomes plural. The availability in 1972 of a number of 1.8-meter lightweight mirror blanks developed for space application provided an added impetus for this project and determined many design features, including the size of the telescope. Each of these primary mirrors, figured to an f/2.7 paraboloid, has an associated 26-cm hyperbolic secondary, providing a final focal ratio of f/32 and a focal-plane scale of 3.6 arc seconds per millimeter. Figure 2 is a cross section of two of the six telescopes, showing how light from a star passes through each, and is relayed to the final focal plane by a tertiary flat and by a facet of a six-sided pyramid-shaped beam combiner. The particular beam combiner shown here provides an overall envelope of the six cones of f/9 and an unvignetted field of 46 arcseconds.

The lightweight mirror blanks provide a distinct advantage for the design of the telescope support structure as well as introducing unique challenges for fabrication and mirror support. The mirrors are 30 cm thick, and are formed from fused silica front and back plates each 2.5 cm thick, separated by an egg-crate structure of 1.0-cm-thick fused silica plates on a 7-cm spacing. (Fused silica has one-sixth the thermal expansion of Pyrex glass.) An 0.6-cm-thick circular cylinder at the edge of the blank provides additional connection between the front and back plates. The blank is assembled and heated in an oven to provide fusion between the internal egg-crate and drum structure and the front and back plates. In addition, to avoid grinding deeply into or through the front plate in forming the optical figure, the entire blank is "slumped" over a template in an oven to provide an approximation to the final desired mirror shape. The mass of each blank is 545 kg (compared with 1820 kg for a conventional 1.8 meter solid blank). The total weight of the six mirrors is thus 3270 kg, compared with about 35 000 kg for a single solid blank of equivalent collecting area. The mirrors are supported in the telescope by an air bladder as a back support and by two counterweighted roller chains bearing on the edges of the front and back plates for radial support.

For effective use of the MMT in either the optical or infrared region of the spectrum we require that the image size be limited usually by atmospheric seeing, not by optical imperfections. This has led us to restrict the image blur due to optical aberrations, figure imperfections, telescope miscollimation, and image superposition to be less than 1.0 arcsecond for 90% of the radiation. The individual primary mirrors are figured to give an image blur circle less than 0.7 arcsecond.

To limit the image degradation caused by telescope miscollimation to an acceptable amount, we require that relative motions of primary and secondary mirrors be less than 0.7 mm, and that the primary tilts be less than 2.5 arcmin. Conventional single telescope structures minimize relative motions by using truss work configured such that the primary and secondary droop by equal amounts and remain parallel, when the telescope is tilted. The MMT optical support-structure design utilizes this approach but must face the additional problem that when the MMT is pointed to the zenith, the primary and secondary planes "dish in." In fact, to meet the tolerances mentioned above was a challenge in design, in spite of the compactness of the structure, and this challenge was compounded by two additional requirements: that the thermal response time of all the members be roughly equal, and that the structural resonant frequencies be high enough to avoid producing instabilities in the secondary-tilt servo controls.

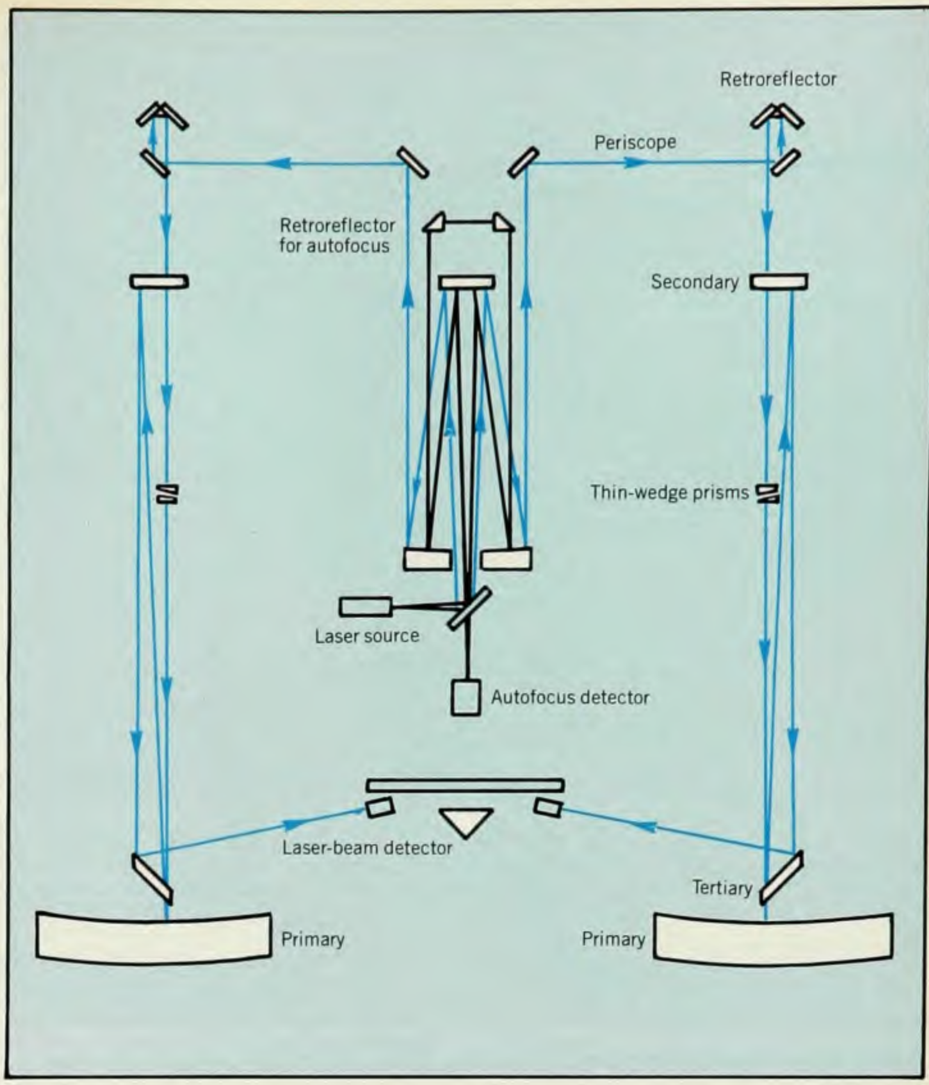
It proved possible to design (with extensive use of computer analysis) a structure whose mechanical and thermal flexures meet these requirements. It is interesting to note, though, that under expected conditions of temperature gradient, temperature change and elevation-angle change, the images would not remain superposed to our tolerances for more than a minute or so, if left uncontrolled. Therefore there is no question that we must continuously monitor and control the position of the images.

Image alignment system

Modern detectors would allow us to measure image misalignment in the MMT directly, using field stars as faint as 18th magnitude. The probability of an 18th-magnitude star appearing in a 1-arcmin field, however, is only about 5% at high galactic latitudes; also, reliance on field stars for alignment would rule out day-time infrared observing. Therefore, we have chosen to provide an internal reference for image alignment.

The basic elements of this system are shown in figures 3 and 4. In the center of the hexagonal MMT telescope array is a 0.8-meter, f/17 guide-alignment telescope of Ritchey–Chretien design with a 1-degree diameter field of view to provide for field acquisition and off-axis guiding.

For alignment purposes, this telescope serves as a collimator for a laser-generated point source. In order to maintain the desired 0.1 arcsecond collimation accuracy, a second laser system provides continuous automatic collimation. The outgoing beam is transferred to the periphery of the six large telescopes by three 1.8-meter-long periscopes and thence into the telescope apertures by six roof-prism–90-degree-prism combinations, which function as elongated cube corner reflectors. Both the periscopes and the cube corners have the property that the outgoing rays remain accurately parallel (or antiparallel) to the incoming rays if the device is tilted, so long as it behaves as a rigid body. A prototype of the periscope has been tested and found to have a



Laser beams in two of the telescopes. The outgoing beam from the guide alignment telescope is transferred to the edge of the 1.8-meter telescope aperture by a periscope and retroreflector. The remotely controlled thin-wedge prisms provide for adjustment of the direction of each laser beam. The beams are received on silicon quadrant detectors. Figure 3

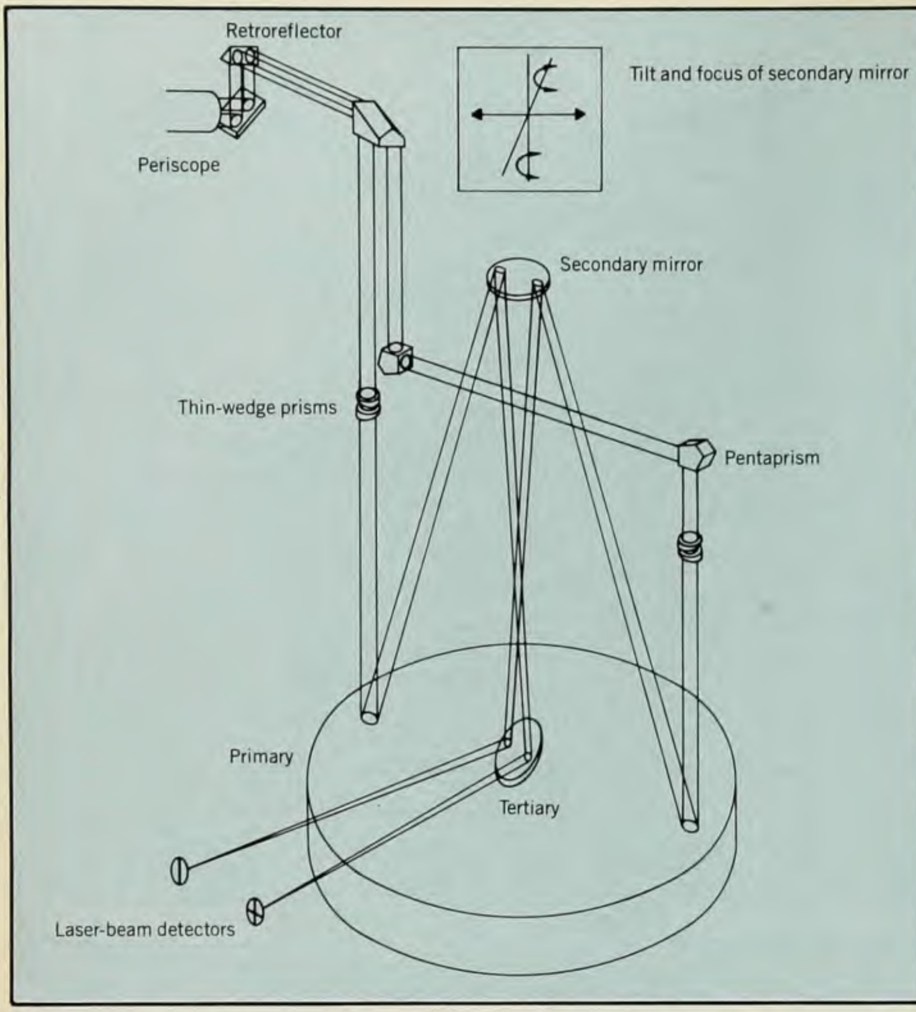
stability of better than 0.05 arcseconds.

Because a single marginal ray cannot distinguish between a change of focus and a tilt, a second beam is introduced into each aperture with a pair of penta-prisms, as shown in figures 3 and 4. Both beams are then sensed by silicon detectors at the focal plane, the focus beam by a split detector that senses the radial direction only (the pentaprisms giving invariance only in this dimension), and the main beam by a quadrant detector that senses both radial and azimuthal motion. The processed signals from these detectors are fed back to the tilt and fine-focus adjustments in the secondary hub. The tilt actuators are motor-driven precision differential micrometer screws, which provide tilt control with a resolution of 0.2 arc-seconds at the secondary (equivalent to 0.05 arcseconds in the focal plane).

The power in each of the laser beams is 10^{-9} watts, a level at which the focal-plane illumination due to scattering from the mirror surfaces is less than dark-night-sky background. The electromechanical bandwidth of the system is 10 Hz, more than sufficient to correct for misalignments due to gravitational and thermal distortion and adequate to compensate for low-frequency vibrations due to wind loading of the structure.

Pairs of thin wedge prisms shown in figure 4 provide for remote-controlled two-axis tilt adjustment of each of the beams for initial setting of the telescope focus and image position.

For guiding, an image-dissecting photomultiplier tube is located at the focal plane of the central telescope, sharing it with the laser system by means of a beam splitter. It has precision remote control of its position in radius and azimuth angle to provide for offset positioning and field derotation, and is capable of tracking stars down to 14th magnitude. The probability of such stars appearing in any 1-degree field of view in any part of the sky is at least 0.99. With the MMT it is particularly appropriate to use the guide alignment telescope as an autoguider because the six main telescopes are slaved to it by the image alignment system, and therefore there cannot be any boresight



Details of laser beam paths in one of the six telescopes. The straight-through beam at the left determines the azimuthal tilt. The combination of that beam and the second beam transported across the aperture by a pair of pentaprisms determines the radial tilt and focus. Figure 4

error or drift between the main and acquisition telescopes.

The image alignment system has 21 electromechanical servos continuously operating and 51 interacting parameters that must be properly set for each night's observing run. In order to keep the system tractable for both operation and maintenance, device control and monitoring is carried out by a multiplexing system under the control of a Tek-31 programmable calculator, which is in turn addressable by the Nova 800 minicomputer that controls the telescope pointing.

The telescope mount

The optical support structure, weighing 45 metric tons with all of its cargo, is in turn supported by a massive steel yoke. The alt–azimuth geometry permits it to rotate in elevation on two simple preloaded roller-bearing assemblies. The yoke is supported on an angular-contact thrust ball-bearing race, which is 2.5 m in diameter and contains 130 50-mm balls. This bearing was much less costly than a hydrostatic bearing system, and preliminary tests of the yoke showed it to rotate very smoothly. Under a full load of 120 tons it operates with an average coefficient of friction of 3×10^{-4}, and variations only a small fraction of the average. The yoke and bearing have a compliance of 0.1 arcsecond per 3000 Nm moment about axes perpendicular to the rotation axis, to resist temporary imbalance and wind forces. The torsional stiffness about the azimuth axis is sufficient for the lowest fundamental frequency of oscillation to be 2.5 Hz.

Both axes of the telescope are driven by essentially identical systems employing dc torque motors and straight spur gears of moderate quality. Each axis has two motor-and-gear box combinations that oppose one another during tracking to eliminate backlash, and the motor speeds are governed by tachometer feedback in a stable servo rate loop. The precision of the system for tracking is derived from on-shaft 24-bit encoders of the Inductosyn type. These encoders have an absolute accuracy of 1 arcsec and locally have the full 24-bit precision (0.08 arcsec) when their output is averaged over the response time of the telescope drives (bandwidth 0.25 Hz). The encoders give out a pulse for each incremental rotation of 0.08 arcsec. The tracking is governed by generating, via the minicomputer and a rate-multiplier device, a pulse train that represents what the telescope should be doing, and comparing this to the actual encoder output in an up-down counter system. The net running content of this counter constitutes a position-error signal that causes a compensation network to command the appropriate rate from the rate loop. thus, what we might usually think of as a tracking rate is actually given as a sequence of position commands, and the rate loop *per se* has the function of maintaining smoothness on a shorter time scale (bandwidth 25 Hz), to overcome friction variation in the gears, bearings, and so on.

The operation of the telescope is ordinarily completely controlled by the minicomputer, which is dedicated to this purpose. It converts object coordinates to the current epoch, calculates corrections for refraction and aberration of light (and for telescope flexure and misalignment), and commands appropriate position sequences for slewing and tracking in alt–azimuth coordinates. Except for one automatically controlled gain change, there is no distinction between tracking and slewing motions, so that near the zenith the azimuth rate may go right up to the maximum slew rate of 1.5 degrees per second. This allows tracking of an object that passes as close as 0.14 degrees to the zenith.

Commands for maneuvers such as raster scans may be stored in the computer or received from a separate computer dedicated to instrument and program control and to data handling. The operator may also command small guiding or searching motions by switches on a remote control paddle, and may initiate programs and the like, by means of other switches on this paddle.

The "dome"

We expect that the operation of the MMT and its associated instrumentation will be remotely controlled, for the most part, with the observer viewing the focal plane *via* a low-light-level television system. At the same time, we have recognized that the MMT is itself a complex and novel piece of equipment, and that it will generate a large variety of novel accessory instruments. Therefore, in planning the housing for the MMT we strove to provide both easy access to the telescope itself, and a large amount of laboratory space immediately adjacent to it, for the electronics used during observations and for the calibration and check-out of optical instrumentation.

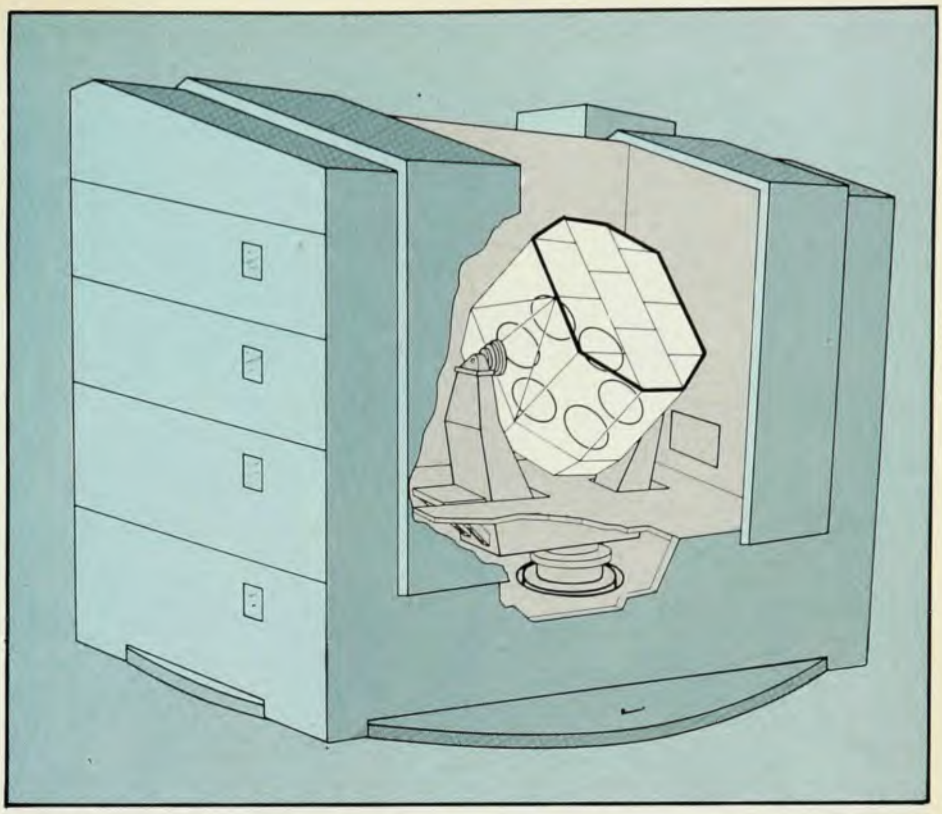
The alt–azimuth geometry offers unique advantages over an equatorial mount for the design of the telescope housing, since the rotation of the housing follows the telescope in one coordinate. Therefore, instead of a shell dome on top of a building whose working space is necessarily below the level of the telescope, we designed an enclosure in which the telescope is completely embedded, and which is slaved to it in azimuth rotation. The important considerations in the design were spatial, structural, mechanical and thermal.

Spatially, we wished first of all to provide an observing floor at the level of the top of the yoke, and then to work up and down from that level in providing additional space. We needed to be very efficient in the use of space, both for convenience in access and for making the best use of a very restricted site area. Structurally, we needed to provide support for the working space and for a shutter mechanism to expose the telescope. Mechanically, we wished to ensure smooth rotation of the building, and accurate following of the telescope. The building should permit observing in winds up to 72 km/hr, and should survive winds up to 225 km/hr. Thermally, we must prevent heat from the enclosed spaces or from the sun-warmed exterior from creating temperature gradients in the optical paths.

The resulting building, shown on the cover of this issue of PHYSICS TODAY and in figure 5, is unusual by astronomical standards. It is rectangular because it is less expensive to enclose space in such a shape, and the penalty in terms of wind torques and buffeting is calculated to be small. The lower part functions as a deep structural platform extending from the observing floor to well under the first floor, with principal truss planes that box in the telescope yoke. On this platform rest two three-story towers containing rooms and serving as the stowing location for bi-parting shutter leaves. The entire building, weighing 450 tons, rests on four massive conical steel wheels, 13 cm wide and 91 cm diameter, which roll on a flat steel track located about 1 m below ground level on a foundation independent of the telescope pier. The wheels are supported by an articulated linkage that allows the full width of the wheel always to be in contact with the track, thus distributing the load evenly, and they are guided by four wheels pushing radially outward against another track. Two of the support wheels are driven by 15-hp dc torque motors in a servo configuration very like that of the telescope itself, with the position information conveyed to the drive by a transducer connected between the yoke and the building.

The telescope is thermally isolated from the outside and from the heated rooms on either side and below by foam sandwich panels. The working spaces are also heavily insulated from the outside. Since all the surroundings conspire to produce temperatures at least somewhat in excess of the nighttime average, however, the telescope and its environs are actively cooled by means of refrigerated coils in the floor (which is a double slab, with foam insulation between upper and lower parts) and by conventional air-conditioning units that chill and stir the air, maintaining the telescope uniformly at about the expected nighttime temperature. All warm exhaust air from the building is dumped into the basement, which is carefully sealed by a skirt from the rotating building that dips into a liquid-filled moat at the top of the foundation. The air is then drawn through a tunnel and exhausted about 50 m from the building in the prevailing downwind direction.

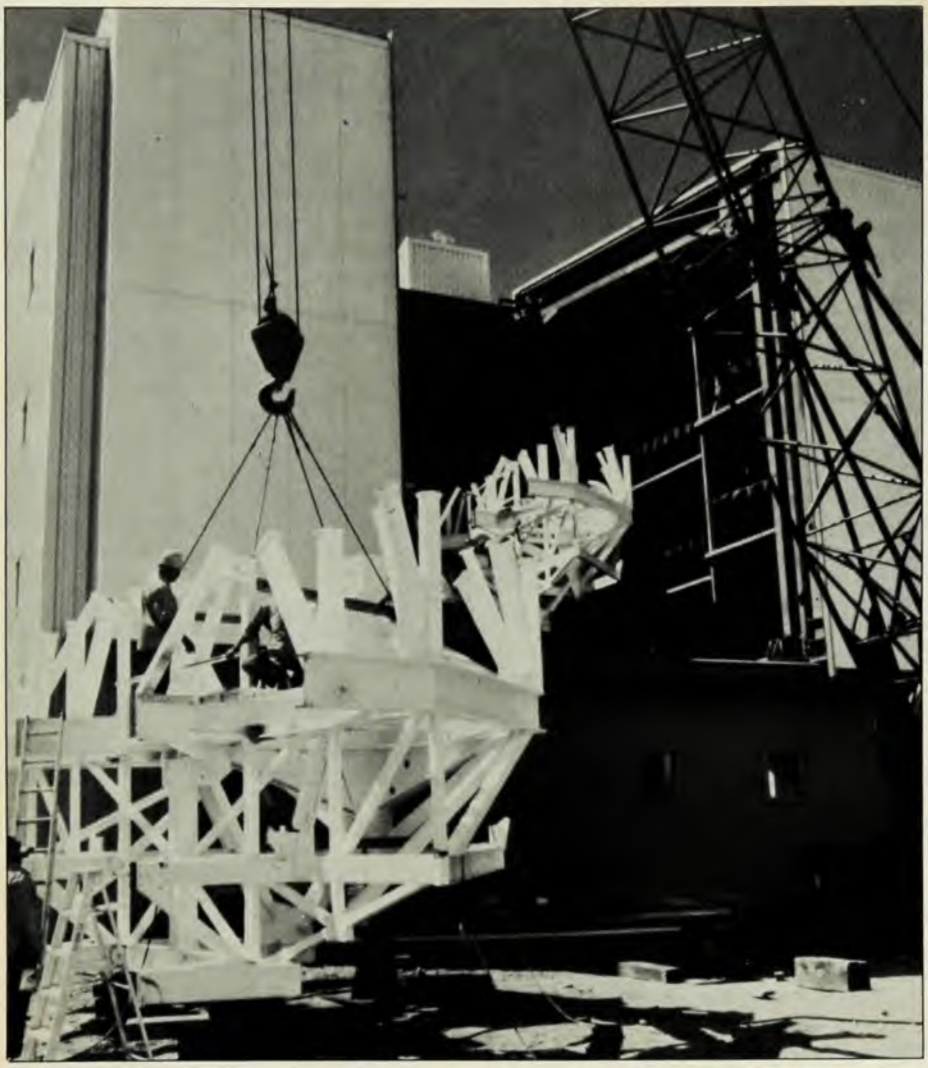
Electric power to the installation is furnished by two transformers, one to supply machinery and heavy loads, and one for instrument power. Grounding (always a problem on a dry mountain top)



The MMT and its building, in a schematic cutaway view. The telescope is in a well insulated chamber with a refrigerated floor as part of a thermal control system. The building surrounds the telescope with working space, but is mechanically isolated from it. Figure 5

MMT schedule highlights

1971	December	University of Arizona and Smithsonian Astrophysical Observatory agreed to collaborate in building the MMT.
1972	June	Telescope mount and optical-support-structure design begun
1973	January	Generation of surfaces on six primary mirrors begun
	March	Mt Hopkins summit chosen for MMT site
	July	Image-alignment-system prototype construction started
1974	May	Road completed to site
1976	March	Figuring of primary mirrors completed
	May	Foundation for MMT building poured
1977	October	Mount and optical support structure installation completed
1978	May	Primary mirrors installed in telescope
	May	Telescope and building tracking under computer control
	May	First light with two of the six telescopes
	October	Anticipated initial astronomical operation



The optical support structure being assembled; it was made in four parts for transportation. The heaviest single piece of the MMT is the central part of the yoke, measuring 2.7 × 2.7 × 4 m and weighing 28 metric tons. Figure 6

has been carefully considered both for lightning and for instrument grounds. Copper is buried all around, and particularly in all the test-boring holes that were made in the rock. There is a consistent scheme of branching grounds to avoid ground loops.

Instrumentation and observing program

The MMT represents a new stage in telescope design but is itself only the third largest now existing, being surpassed by the 5-m Mt Palomar and 6-m Soviet telescopes, and closely followed by several new instruments in the 3.5–4-m range. Nevertheless, there are certain features inherent in its design, which, combined with proper instrumentation, should give the MMT an advantage in some areas of observation. We illustrate here two areas that hold such promise: infrared photometry and low-resolution infrared spectroscopy, and high-resolution optical and ultraviolet spectroscopy of point sources. In each of these areas optimum instrumentation must be designed especially for the MMT, differing in significant ways from instruments operating on conventional telescopes.

Infrared photometry. Over the last several years observations with large telescopes in the 1–34 micron spectral region have yielded new knowledge concerning the earliest stages of stellar evolution, the conditions at the center of our galaxy and in the nuclei of other galaxies, the energy balance and surface conditions of planets, and the characteristics of circumstellar and interstellar dust particles and molecules. Observations in this region of the spectrum above 2.5 microns present unique difficulties because thermal radiation from the sky and the telescope completely dominates that from the astronomical source, such that the quantum statistics of this radiation at the detector provide the fundamental limit to the noise level of the detection system. Two techniques have evolved to cope with these problems. Subtraction of the slowly varying flux from the sky is achieved by rapidly switching the telescope beam between adjacent positions. This is most satisfactorily done by square-wave oscillation of the secondary-mirror tilt, since the comparison requires frequencies (10–20 Hz) that are too high for the entire telescope to respond. Radiation from the telescope is minimized by maintaining a very small obscuration by the secondary and its spider, and by utilizing an undersized secondary as the stop of the telescope, rather than the primary mirror. The cryogenically cooled radiometer is extremely carefully baffled in order to match the aperture of the telescope accurately; diffraction, however, prevents the baffle from having its full geometric effect. Hence we use the secondary as a stop so that the detector sees cold sky around the edge of the secondary rather than warm structure around the primary.

Construction of an MMT infrared system that will utilize both these approaches is now under way with NSF support. In addition to the basic alignment-tilt control of the secondary, a rapidly oscillating mount for special undersized, low-mass infrared secondary mirrors is being prepared. Six of these, providing fast (millisecond) beam switching, must operate in precise unison.

Provision for accurate alignment of six baffle apertures has been provided in a novel radiometer in which the beams from the six telescopes enter the vacuum region of the radiometer Dewar through six windows. The beam combiner, baffles and dichroic beam splitter for visual field viewing are all cryogenically cooled for minimum radiation background.

The first version of the radiometer will employ a liquid-helium-cooled indium-antimonide detector and broad or narrow band filters for observations in the 1–5-micron spectral region. This instrumentation should make possible a number of astronomical observations that are presently extremely difficult if not practically impossible. Some of these include identification of surface materials on the planet Pluto and on the satellites of Uranus and Neptune, measurement of highly red-shifted optical spectral lines from distant QSO's, and identification of molecular species such as molecular hydrogen in distant galaxies.

Optical spectroscopy of point sources. The diffraction-grating spectrograph, always a mainstay of astrophysical observation, is today particularly powerful because of the advent of electronic detectors that can image a two-dimensional field with high quantum efficiency and little detector noise. There has always been a frustrating mismatch, however, in doing spectroscopy of point sources, such as stars, nuclei of distant galaxies, and quasi-stellar objects, because there is no simple way to use the full length of the spectrograph slit. This problem is particularly annoying because large telescopes easily exceed the optical throughput of those spectrographs available for normal use; for high resolution the slit has to be made narrower than the atmospherically blurred image, and astronomers are accustomed to watching precious photons striking the slit jaws instead of going into their spectrographs.

Attempts have been made to solve this problem by the use of so-called "image slicers," which use combinations of tiny mirrors to relay the light from either side of the image into the slit, above and below the central part of the image proper. However, the practical difficulties of these devices are such that they have seen little actual use. With the MMT, on the other hand, the six images can easily be aligned next to each other along a spectrograph slit. Then by providing at the slit a separate tiny prism (approximately 1 mm square) of appropriate angle and orientation for each image, the six beams can be superposed on the collimator of the spectrograph. In this manner a given spectrograph will achieve the same optical performance (for point sources) on the MMT as it would on a conventional 1.8-meter telescope, but will take good advantage of the larger light-collecting area. A second array of six prisms, put end-to-end along the slit with the first, will allow light from a piece of sky near the object to pass through the spectrograph, providing a signal that may be subtracted from the object-plus-sky spectrum.

This kind of spectrograph is ideally suited for observations such as the determination of the redshifts of the spectra of very distant galaxies or QSO's, upon which our knowledge of cosmology depends strongly. There is a good prospect that many very distant clusters of galaxies will be identified in the near future by x-ray observations so that there should be a particularly attractive opportunity to extend the boundaries of our present knowledge.

Looking ahead . . .

As the MMT now goes into operation, we hope that it will soon be serving both as a productive large telescope and as a prototype demonstrating what is involved in the practical use of a multiple-mirror telescope. At this point, we have shown that it is possible to design and build an instrument of this type for a reasonable cost. Our total expenditure on the MMT has been about $7.5 million (reckoned in 1975 dollars). This includes all internal salaries and expenses, but excludes the cost of the primary mirror blanks. We estimate very roughly that the overall cost of the MMT is around one-third that of a conventional 4.5-meter telescope.

Our detailed experience in operating the MMT will show what it is like to use such a complex piece of equipment as a research tool, in the environment of a remote, cold, blustery mountaintop. If the problems of this operation prove tractable, as we expect, then our experience should strongly illuminate the way toward construction of much larger telescopes using similar principles. In fact, planning for two such efforts has already begun: the Universities of California at Berkeley, Los Angeles, San Diego, and Santa Cruz are making a design study for a 10-meter telescope, and a group at Kitt Peak National Observatory is making a long range study of the feasibility of a 25-meter instrument. These two steps, if they can really be taken, will amply fulfill the hopes that we on the MMT project have entertained since the beginning of our work, of breaking a path that would lead to a genuinely broadened horizon for optical astronomy.

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