Technical Report #21

ENGINEERING REPORTS ON THE MMT OSS, TRACKING, CO-ALIGNMENT AND CO-PHASING

June 1987

The following preprints are included in this report:

1. "The Optics Support Structure of the MMT," Blanco, D.R., Antebi, J., Davison, W. (1987).
2. "Tracking a 150 Ton Altitude-Azimuth Telescope to Sub-Arcsecond Accuracy," Barlow, D.J., Blanco, D.R., Poyner, A.D. (1987).
3. "Co-Phasing and Co-Aligning the Multiple Mirror Telescope," Janes, C.C., Montgomery, J.W. (1987).

The Optics Support Structure of the MMT

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Abstract

The six Cassegrain telescopes which comprise the MMT are held in place by a steel space frame called the optics support structure (OSS). The design and development of this structure, from concept to final implementation, is presented in the context of the history of the MMT project.

Background of the MMT concept

The concept of the MMT was born in an effort to build a large aperture optical telescope at low cost. The cost of constructing optical telescopes had traditionally followed a curve proportional to the cube of the primary mirror diameter. By subdividing the light gathering objective into small, easy to fabricate units, large apertures could be built at a cost proportional to the square of the diameter, rather than the cube. The idea can follow two basic forms; segmented mirror telescopes (SMT) where a single optical surface is made up of separate tiles, and multiple independent telescopes (MMT) with beam combining optics. Early efforts in the 1930's and 40's involved segmented, zenith-pointing fixed arrays, thus avoiding the gravitational flexures in an all-sky pointing telescope[1,2].

In 1970 the availability of several lightweight quartz mirror blanks of 1.8 m diameter from military surplus spurred a serious re-examination of the multiple mirror concept. A group of scientists at the University of Arizona's Lunar and Planetary Laboratories (LPL) and Steward Observatory had discussed the possibility of constructing a large aperture, low cost telescope to be used primarily for infrared observations. At the time no large telescope had been built specifically for IR use. A. Meinel at the University of Arizona (UA) proposed using six of the mirrors in an hexagonal array dubbed 'Project COLT' for its six shooter geometry[3] (figure 1). The proposed instrument combined the light from six folded Cassegrain telescopes to give the light gathering power of an equivalent conventional telescope of 4.5 m aperture. The MMT configuration was chosen rather than an SMT. Though an MMT introduces two additional reflections per telescope, it has two advantages: first, it does not require exotic and expensive off-axis optics; and second, it shortens the tube length, yielding a compact, stiff structure without fast optics.

The director of Smithsonian Astrophysical Observatory (SAO), F. Whipple, along with N. Carleton and other SAO scientists had also been interested in low cost approaches to large aperture telescopes. Discussions between G. Kuiper and F. Low of LPL, R. Weymann, director of Steward Observatory, and F. Whipple led to an agreement on a cooperative effort between UA and SAO. In December of 1971 the UA and SAO formally agreed on a joint project to be called the Multiple Mirror Telescope. Under this agreement SAO was to provide the mount, optics support structure (OSS), and building, while UA was to provide the passive and active optics and supporting cells. Additional engineering design tasks such as the control system and integration of the project as a whole were divvied between the two organizations with a major portion of the research and design work farmed out to consulting engineering firms.

Several features of the telescope were determined at the start of the project; an alt-azimuth mount was chosen because it not only yields a compact design, but also simplifies the OSS by limiting the gravity vector to act in one plane only. The telescope would use an active optics system to keep the independent telescopes aligned. This could be based on feedback either from a stellar source, or from a pinpoint artificial star. By illuminating the artificial star with coherent light the telescopes might possibly be kept in phase as well, though it was decided quite early to postpone phasing to a later development stage of the project. The infrared requirements of minimum blockage led to a slightly more conventional design using secondary spiders (figure 2).

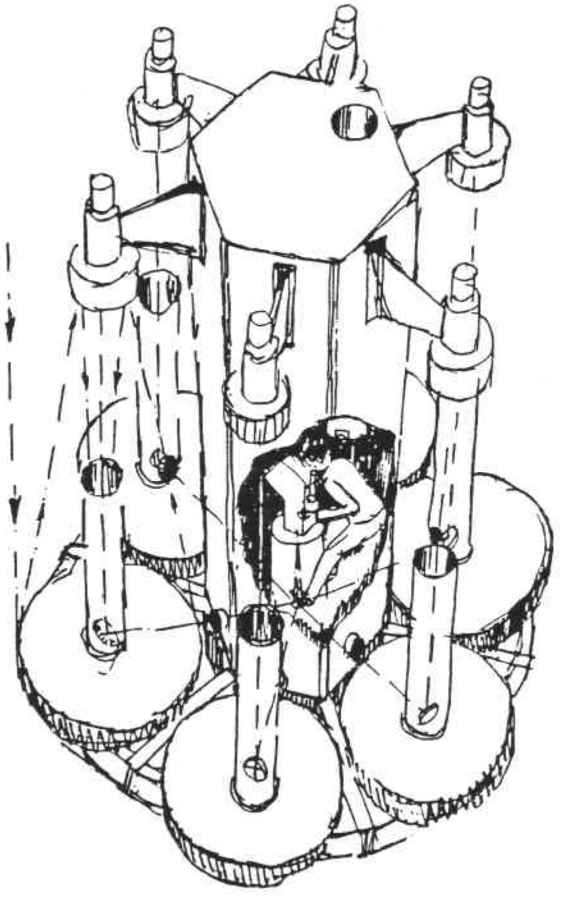

Figure 1. 'Project COLT', an early concept of the MMT c. 1970

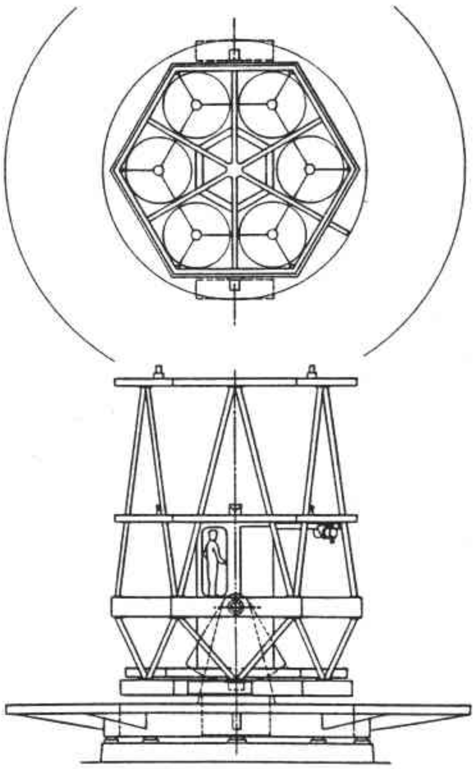

Figure 2. Second generation conceptual design of the MMT c. 1971.

The proposed modes of observation included six separate foci, a combined focus, pairs of Michelson interferometers, a fully phased array to produce images comparable to those of a diffraction limited single telescope of the seven meter class, and a six element image stacker for use with a high resolution spectrograph. The image stacker involves placing individual telescope images in a line along the spectrograph slit. Small prisms are used to realign the beams parallel to the collimator axis. The spectrograph thus sees six superimposed slow beams instead of an unfilled fast beam, with consequently improved resolution[4,5].

The mount and optical design

The design proceeded from the ground up. One of the first questions to be addressed was whether existing alt-azimuth telescope technology used in radio astronomy could achieve the fine tracking and pointing requirements of an optical telescope. In 1972, T. Hoffman, then director of engineering at SAO, and N. Carleton, SAO project scientist on the MMT, contracted Philco Ford corporation, a company with considerable experience in antenna construction, to examine the feasibility of rolling element bearings for the MMT azimuth turntable. Roller bearings, as opposed to the more traditional hydrostatic oil pad bearings, offered the attractive advantages of low initial cost and ease of maintenance. The results of the study indicated that though no roller bearing had ever been fabricated with the required capacity, smoothness, and accuracy, ball bearings did have the potential to meet the requirements with current fabrication techniques[6]. In view of the potential advantages and relatively small risk, ball bearings were selected.

The design specifications of the mount were completed with an acceptable level of confidence by 1972, and Philco Ford was contracted to detail and fabricate the mount, all before any detailed study of the OSS began. Meanwhile G. Sanger and M. Reed of UA Optical Sciences Center developed a design for the active optics system[7]. In this scheme the secondary mirrors are articulated with two tilts and a focus motion, all driven with an optical error-sensing feedback system. Feedback from a stellar source, it was felt, would be too limited. Given the small field of view of 5 arcminutes, the chance of a sufficiently bright guide star was slight, so the laser alignment system was chosen. A seventh, central telescope was added to collimate the laser beams and to serve as a guide telescope. A series of pentaprisms and elongated corner cube reflectors, chosen for their insensitivity to small structural deflections, would distribute the laser beams through the telescopes and return to a central sensing location. The automated algorithm involved first coaligning the telescopes by stacking the images of a bright star, then positioning the 12 laser beams on the centers of the four-channel photocell detectors by rotating steering wedge prisms in the laser light paths. After this, error signals generated by a shift of the laser beams on the photosensors would drive tilt and focus motions of the articulated secondaries at a 10 Hz rate. This greatly complicated the telescope, adding more than 100 optical elements, both passive and active, all of which had to be initially aligned and kept in collimation. Despite the added complication of this scheme, the project probably would not have proceeded without this or some similar plan. The laser alignment scheme became a major publicity feature for the telescope[8].

Development of the OSS

SAO selected Simpson Gumpertz & Heger Inc. (SGH), a structural engineering firm with experience in the accurate analysis of the deflections of radio-telescopes, to perform conceptual studies and to develop a preliminary design of the OSS. SAO defined the constraints and specifications. Close contact was maintained between SAO and SGH so that constraints found to be unduly restrictive could be modified to make them less burdensome while still satisfying the design objectives.

The requirements that controlled the design were: the alignment of the optical elements had to remain within specified limits as the telescope moved from zenith to horizon, and, for servo-control purposes, the lowest natural frequency had to be greater than 25 Hz. Clearances for the light paths had to be provided, through each of the six Cassegrain telescopes, to the centrally located beam combiner and instrument support flange, and also along the elevation axis to the Nasmyth foci. In addition, the alignment tolerances had to be satisfied under nominal wind and thermal conditions. The structure also had to fit in the already designed mount, and the layout of the six apertures and of the guide telescope and instrument support precluded simple efficient structural layouts such as a simple truss spanning between the elevation bearings.

SGH first developed and analyzed several structural concepts. As a result of these studies several deflection compensation schemes were developed, and it was determined that the design objectives with respect to relative deflections were achievable, but all of the configurations had natural frequencies well below 25 Hz. Consequently, a new set of configurations was investigated without paying particular attention to deflections and light path constraints until a configuration was developed with sufficiently high lowest natural frequency. This configuration was then developed into a preliminary design that incorporated deflection compensation concepts and satisfied the other requirements.

The governing deflection budgets were expressed in terms of combinations of primary mirror tilt and relative displacement of primary to secondary for each telescope. These requirements implied that the relative displacements across the diameter of a primary mirror and of primary to secondary had each to be less than about 2 mils, (0.002 in.). However, the constraint on displacements of the six telescopes with respect to each other and to the beam combiner did not control the design.

To obtain displacements that can be predicted to sufficient accuracy that they can be reliably matched to within 2 mils, the absolute displacements should be no more than 10 times larger, that is about 20 mils. If due to gravity loads a structure sags 20 mils, it can be shown that the frequency of the mode corresponding to this sagging deflection is about 22 Hz. Thus if the lowest natural frequency of the OSS was to be 25 Hz or larger, the constraint on absolute deflections would be satisfied automatically.

The following are basic features of the OSS design:

1. All global load paths are by truss action; bending stiffness is relied upon only for local behavior.

2. There are structural members within the primary mirror cells which act as major load carrying elements in the overall truss.

3. The structure has a number of independent load paths so that relative displacements at points of interest can be minimized by adjusting the relative stiffness of two or more parallel load paths. In addition different load paths carry the gravity loads for zenith and for horizon pointing so that the adjustments to minimize the relative displacements for these two cases can be performed independently.

4. Tunable members, that is members whose stiffness is adjustable, were incorporated at critical locations. This novel concept allows the stiffnesses of the various load paths to be adjusted within a certain range after the structure is erected and the actual relative displacements are measured.

5. To eliminate unnecessary flexure, all connections had nominally no eccentricities. Analysis showed that the tolerances on eccentricities could be set at a practical 1/8 in. for fabrication purposes without introducing a significant increase in flexure.

6. Standard structural sections were used throughout to control costs. Cross-sectional areas are available in sufficiently small size increments, and it was shown that the variations in cross-sectional areas due to manufacturing tolerances would have acceptably small effects on the predicted deflections.

7. Steel was selected over aluminum. Steel and aluminum have the same stiffness to density ratio, but steel has a lower coefficient of thermal expansion. Since the design objectives could be met with ordinary structural steel, no exotic materials were seriously considered.

8. Criteria for member selection included having the required axial stiffness, having a natural frequency in lateral bending of 30 Hz or more so as not to lower the overall natural frequency of the OSS, and having thin walls to minimize thermal lag.

9. Bolted connections were preloaded with high strength bolts to avoid slip and hysteresis. In flange connections the joints were preloaded axially so that operational loads were carried as changes in joint compression with no contribution to flexure by flange bending.

In the development of the preliminary design, the analyses were performed for an idealized pin-jointed truss. It had been anticipated that an analysis including the effects of bending would be performed as part of the final design; however, such an analysis was not performed since it was believed that the tunable members would allow for compensation between actual and predicted behavior and therefore could, in theory, be used to compensate for the approximations made in the analyses.

Design review and construction

The SGH design for the OSS was subjected to a careful review and independent verification by the Philco Ford corporation, Western Development Laboratories. The only significant change was the addition of short diagonal braces to further stiffen the trunnion plane. The design was detailed by Baresel Corporation of California. T. Hoffman at SAO revised the plans to combat the natural tendency of detailers to "improve" designs by making them thicker, heavier, and more rigid. In a design such as the OSS which is balanced for stiffness, more is not always better. The fabrication contract was awarded to Votaw Precision Tool Company of California.

The final design of the OSS is shown in figures 3 and 4. There are two global load paths, from the trunnion plane forward to the secondary plane, and from the trunnion plane aft to the primary plane, where tunable members are included to allow matching the global deflections of the primaries and secondaries. The primary plane is an open frame which is filled by the structure of the primary mirror cells. The mirror cells attach to this plane at three points per cell, two of which are shared by adjacent mirror cells (these are shown as dark circles in figure 4). Each mirror support point is suspended from the trunnion plane by a tunable strut. This allows tuning of the primary mirrors independent of the global load paths.

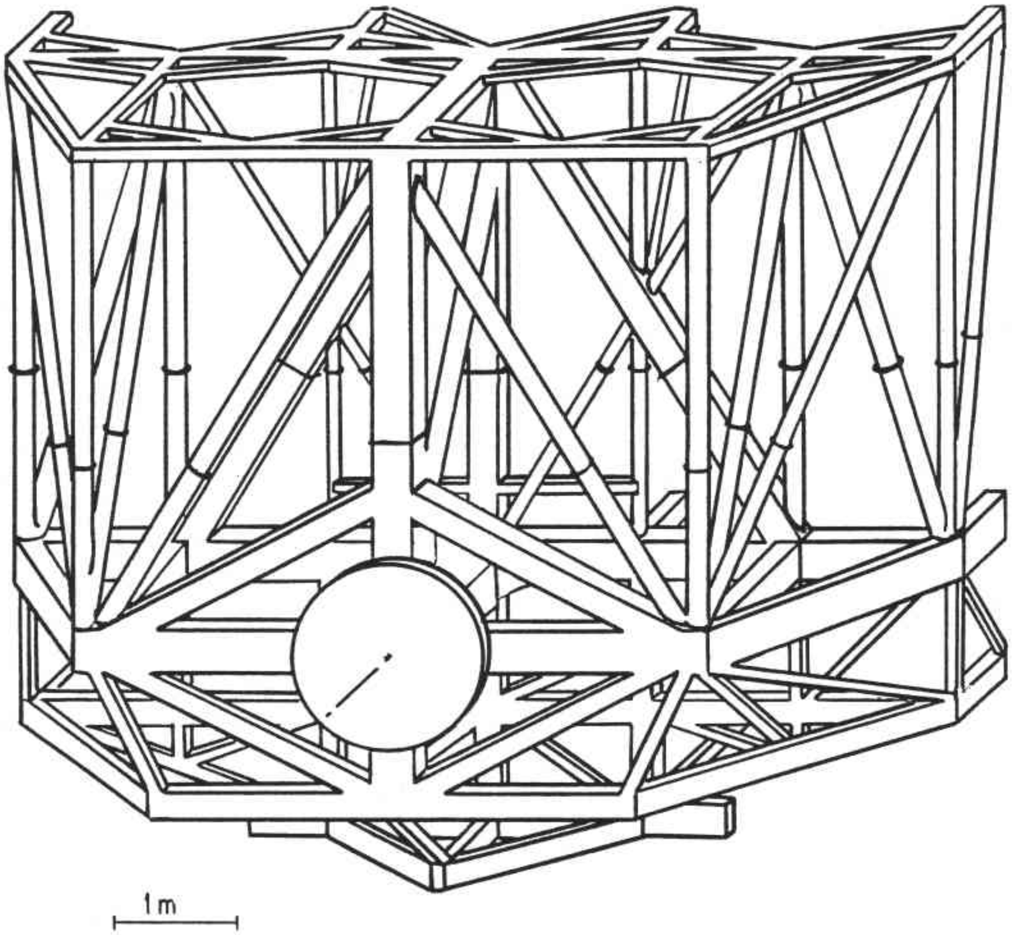

Figure 3. Side view of the OSS at zenith pointing. The elevation drive gear is in the foreground. Only half of the symmetrical structure is shown.

Another unusual feature of the MMT is that it is housed in a rotating building[9]. The alt-azimuth design suggested a minimum volume enclosure rotating with the telescope. The compact structure offered enough cost savings over the traditional full volume dome to more than pay the cost of a building drive and control. In addition, a corotating building would keep laboratories and control rooms close to the telescope. It was designed by Wallace, Floyd, Ellenzweig, and Moore, architects, with structural design by SGH, building services by Segner & Dalton, and rotation drive and control by Ford Aerospace, which was also the general contractor.

Fabrication of the telescope proceeded from 1974 to 1977. The three main weldments of the mount assembly, weighing about 125 tons total, were fabricated and assembled by de Bartolomeis corporation in Lecco, Italy. The critical fit to the azimuth bearing was produced by an iterative process of precise measurement and hand scraping. After testing, the mount was disassembled and shipped to the U.S.A. by sea. Site development began in 1974 with the construction of an access road and the removal of 35 feet from the top of Mt. Hopkins to make a small level area at the very summit[10]. The foundations for the telescope pier and building track were laid in 1976. By 1977 the building shell had been erected and the OSS installed. Optics were installed and first light occurred in May 1978. August saw the first demonstration of the laser alignment system. By 1979 the telescope was being used 10% of the time for astronomical observing, with the remaining 90% used for shakedown engineering.

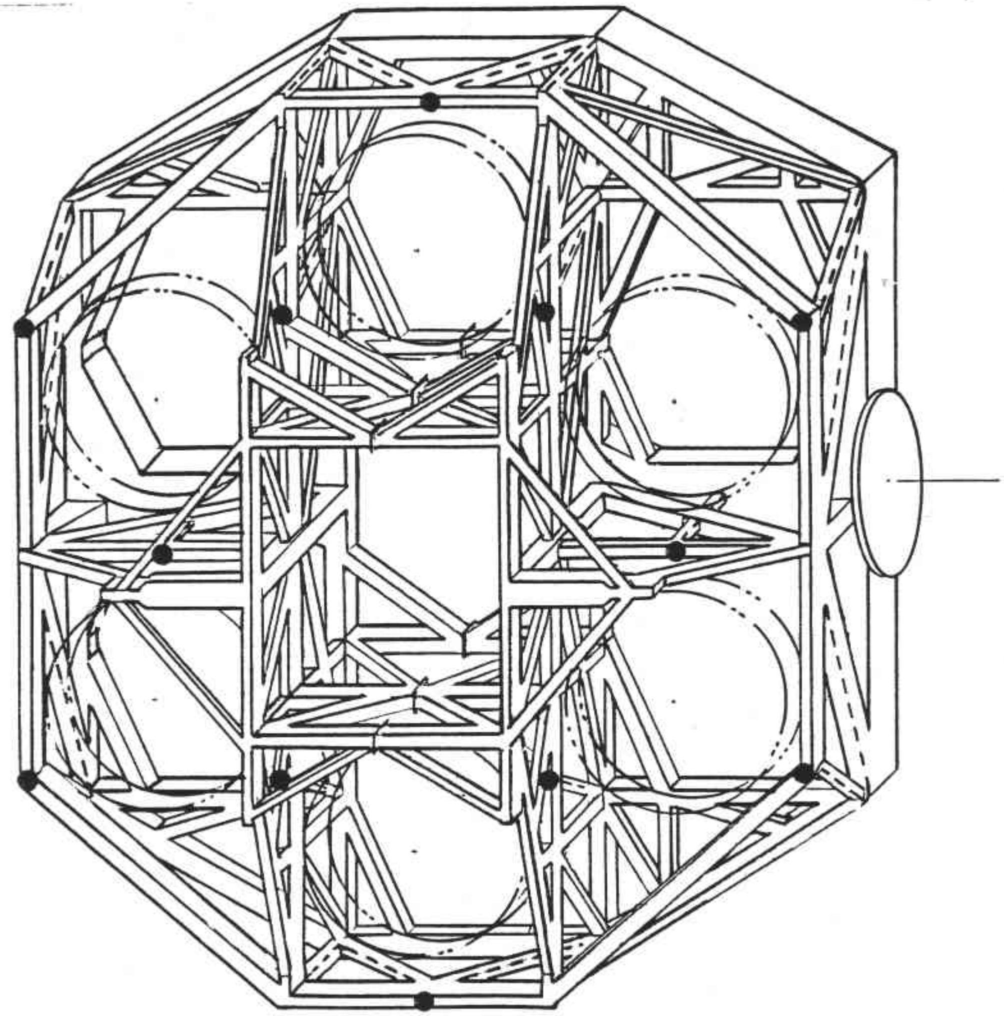

Figure 4. View of the rear three planes of the OSS from aft with the telescope horizon pointing. Mirror cell connection points are indicated by solid dots. Tunable members are shown as dashed lines.

The laser alignment system

Two goals had been set for implementing the laser alignment system, the first involved maintaining coalignment of the six image centroids to within 0.5 arcseconds diameter; the second goal was set at 0.1 arcseconds. By late 1979 the first goal had been realized, but only after a concerted effort by the engineering staff. Even so, the laser system had some very serious drawbacks. To start the system, the laser beams had to be positioned on the quad detector targets. These targets were about 2 centimeters in diameter, while the secondary mirrors and the wedge prisms could deviate the beam over a 600 centimeter diameter field. This and other unfortunate features made initializing the system a very lengthy, frustrating procedure. Moreover, the system could not be left in operation during the day unless the mirror covers were left open, exposing the mirrors to dust and other hazards.

The original actuator packages for both the secondaries and the wedge prisms used DC motor/tachometers and velocity feedback servo loops. These tended to consume considerable power - up to 40 watts in each secondary package - even when immobile, since the current applied to the motor would creep to the point of break away torque before a velocity error could be detected. This power was dissipated as heat distributed over the telescope structure which produced seeing effects inside the dome. Evidently the average 'seeing cell' was considerably smaller than the telescope beam and had little effect on the image. The effect on the one inch diameter laser beams was appreciable, and the alignment system would drive the telescope beams around to follow the seeing in the laser beams. Lower ambient temperatures effectively increased the motor breakaway torque making the whole problem worse by about 0.3 arcseconds per degree Celsius.

From the first time it was turned on it was obvious that the focal plane images had better short term stability with the laser alignment system off. In fact, the images showed sufficient stability that manual guiding made observations possible, though laborious, since it was punctuated by frequent breaks to restack the images on a bright star. In this way the telescope was gradually given over to astronomical research. Though the laser alignment system achieved its first stage design goals, a simpler, more elegant approach was needed. In 1980 J. Beckers, then director of the MMTO, made the decision to remove the laser system[11].

Removing the laser alignment system changed the engineering effort of the project away from perfecting a complex servo system to characterizing the basic performance of the telescope. The effort followed a two-sided approach to the problem of coaligning the telescopes. First, the original idea of guiding on a stellar source was demonstrated, but only in an experimental way. Autoguiding was not routinely used until more reliable hardware was implemented in 1985[12]. Through 1981 and 1982, Ulich and Davison studied the performance of the telescope. The intention was to derive a set of corrections which could be stored in software and applied 'open loop'.

The performance analysis results were at first confusing. The structure held the telescopes coaligned to within about one half arcminute, but the image motion within that range did not appear to repeat. There was also considerable hysteresis of the entire stack between tracking up and down in elevation.

Hysteresis

A search for sources of hysteresis in the system using stellar images, a precision inclinometer, and a lot of intuition, eventually found two major culprits; one source was in the linkage between the direct-driven elevation encoder and the OSS. The encoder was coupled to the stub axle of the elevation axis where it emerged from the elevation bearing. This bearing was fitted with an oil seal which was improperly installed. The friction in the bearing and seal proved enough to introduce two arcminutes of lost motion between the encoder and the OSS.

The second source was attributed to thermal effects primarily due to radiative coupling between the OSS and the sky. Radiation to the cold night sky cooled the structure up to 4°C below the ambient air. This not only produced local seeing perturbations, but actually warped individual struts in the OSS, thus producing image motion. This effect had been predicted in the SGH and Philco Ford studies. Though the effect was relatively small (about five arcseconds peak), it varied from night to night depending on the sky and ambient temperatures, foiling any attempts at software corrections.

The hysteresis in the elevation encoder linkage was corrected by reinstalling the offending seal and by installing a torque tube inside the hollow elevation axle. This is attached to the OSS at one end, and to the encoder at the other, passing through the inside of the bearing without contacting the bearing shaft. This simple mechanical fix reduced lost motion at the encoder from about two arcminutes to less than 1/4 arc second.

The temperature-induced hysteresis required a more subtle solution. The standard titanium dioxide "observatory white" paint used to coat the OSS turned out to be effectively black in the thermal infrared portion of the spectrum, and thus an excellent radiator. The spectral characteristics of a number of coatings were studied in an effort to find one which could decouple the radiative heat transfer. Eventually the entire OSS and the top of the building shutters were covered with a sticky-backed aluminum foil. This dramatically improved the stability of the OSS as well as reducing dome-induced seeing degradation.

Simultaneously, other changes were made as a consequence of the removal of the laser system. The original secondary actuators were replaced with a more stable digital electronic system using stepping motors. These could be turned off between movements, greatly reducing power consumption and consequent heat-induced seeing degradation.

With these improvements the measurements of image motion as a function of elevation angle showed remarkable repeatability on the order of 0.5 arcseconds across 60° of elevation. Temperature differences from night to night were seen to offset the flexure curve without changing its character. Once the structure performed repeatably, the effort turned to tuning the structure to minimize the spread of images at the focal plane.