PROGRESS REPORT ON THE PERFORMANCE OF THE MULTIPLE MIRROR TELESCOPE

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ABSTRACT: The MMT utilizes a number of most unusual features many of which will probably be included in future advanced technology telescopes. We report here on the performance of these unconventional functions as we have determined them until now.

1. INTRODUCTION

Astronomers today are studying techniques to reduce the cost of the construction of very large, 10-25 meter diameter telescopes. By using new advanced technological approaches they expect to bring the cost of these very large telescopes within the range of economical possibilities. The Multiple Mirror Telescope (MMT) incorporates many new technological features because its designers wanted to construct as large as possible a telescope at as low as possible an expense. They did succeed at this and as a result the MMT may be viewed as the first of the new generation of Advanced Technology Telescopes. A substantial effort is given by the MMT Observatory staff and by the staff of the two sponsoring institutions (Smithsonian Astrophysical Observatory and University of Arizona Observatories) to optimize the performance of the MMT especially in those areas where it serves as a test bed or prototype of the telescopes of the future. This paper will give an interim report on the performance of the MMT in those areas. It is not intended as a complete detailed report but will focus predominantly on those areas where significant new interesting information has become available. It will not discuss the instrumentation of the MMT. Some of that will be reported in other papers in this colloquium by Drs. Angel and Latham. A full recent description of the MMT can be found in Beckers et al (1981). Most of the results reported here supersede or complement the information given there.

2. THE MMT ALT-AZIMUTH MOUNT

The USSR 6 meter telescope and the MMT are the only large optical

C. M. Humphries (ed.), Instrumentation for Astronomy with Large Optical Telescopes, 11–19.

telescopes which use alt-azimuth mounts. All large telescopes being planned (e.g. 4.2 Meter Herschel telescope, 7.5 meter Texas telescope, 10 meter UC Berkeley telescope, Crimean 25 meter telescope, US 15 meter telescope) intend to use alt-azimuth mounts because of the substantial cost saving associated with their construction as compared to equatorial mounts both because of the less complex gravitational flexure effects and because of the smaller structure and building which they require. Modern computer technology makes the conversion of equatorial to alt-azimuth coordinates straightforward and the additional complexity of the rotation of the field of view is offset by the simplification of keeping the slit vertical as is desired by most spectroscopic investigations.

The MMT mount is supported on ball bearings (azimuth axis) and roller bearings (elevation axis) and driven in both axes by a torque motor-gear box-pinion/bull gear combination. Two torque motors with a fixed differential torque remove backlash in the drive. These drives were found to be entirely satisfactory, the only problem which was encountered was related to the smaller azimuth locked-rotor frequency than initially planned. This frequency turned out to be 2.2 Hz as compared to 4.2 Hz for the elevation drive. This lower frequency was caused by a rocking translational mode of oscillation of the mount on the azimuth bearing. Recent modifications increased the frequency to 2.8 Hz and we expect to increase it to 4 Hz by further improvements. Even already now the MMT is very immune to windbuffeting which becomes only significant for wind velocities above ~ 15 m/sec. With the improved stiffness of the MMT, windbuffeting will become even less of a problem especially since the average wind velocity at the MMT amounts to ~ 3 m/sec.

The position of the MMT is read out by means of Inductosyn encoders which have a 24 bit digital output (1 bit = 77 milliseconds of arc). The absolute accuracy of these encoders amounts to ± 2 arc seconds, but we find most of the variations to be systematic so that they can be corrected in the mount control computer. We do not know yet how well this ultimately can be done. At this moment, however, the MMT guide telescope (which serves as the reference) points to an accuracy of one arc second absolute after corrections are made for axes misalignments, systematic encoder errors, gravitational flexure and atmospheric refraction. That is better than any other existing telescope; it is largely due to the simplicity of the gravitational flexure effects and to the benign thermal environment of the telescope mount. We continue to improve the MMT pointing and we are giving special attention to the improvement of the absolute encoder readouts. This is of interest not only for future alt-azimuth drives but also for the blind tracking of the telescope which is sometimes necessary if there is no field star in the small MMT field of view (4 x 4 arc minutes). The maximum tracking speed of the MMT equals 90^{o}/minute per axis which enables us to track objects up to 10 arc minutes of the zenith.

3. MMT OPTICS SUPPORT STRUCTURE

The special optical configuration makes it possible to make the Optics Support Structure (OSS) exceedingly rigid because the space between the mirrors can be used and because the overall length of the MMT is very short compared to its diameter. The stiffnesses of critical OSS members have been tuned to minimize the flexure and to make the residual flexure as identical as possible between the six 1.8 meter telescopes. The flexure now amounts to ~ 25 arc seconds.

More important than the amount of flexure is however the repeatability of the flexure from hour to hour and from day to day. If repeatable it can be removed by slight tilts of the telescope secondary mirrors. Under thermally stable conditions the flexure is repeatable to ± 2 arc second or better. By careful examination and tightening of joints of the OSS we have reduced the mechanical hysteresis and slippage to less than 0.3 arc seconds. When the temperature changes the flexure variations are larger than ± 2 arc sec. The OSS has however a very short thermal time constant (2-10 min) so that it adjusts rapidly to thermal changes.

We have found one very interesting and unexpected source of thermal changes of the OSS whose elimination will result, we hope, in an even better repeatability of the pointing changes of the individual telescopes with elevation changes. This source of thermal changes is the result of radiation cooling. Since the Titanium Dioxide paint with which the OSS is covered has a high infrared emittance the OSS couples very efficiently radiatively to the cold sky. The OSS has therefore in its exposed parts temperatures below the air temperature, the amount of the temperature difference ($\simeq 2^{\circ}C$) depending on the sky IR transparency, on the wind velocity (the latter determines the amount of convective coupling with the air), and on the degree of exposure to the sky. These radiative thermal changes cause misalignments of 1-2 arc second. We plan to reduce the radiative cooling effects by covering the OSS with aluminum foil which reduces the cooling by an order of magnitude.

4. THE COALIGNMENT OF THE SIX TELESCOPES OF THE MMT

In the original design the six MMT telescopes were coaligned by means of the so-called "Laser Coalignment System" which generated six artificial laser stars in a central, seventh 75 cm diameter telescope and which were optically folded into each of the six MMT 180 cm telescopes which were then kept coaligned by guiding on the six laser-star images. For a number of reasons we have decided to implement a different coalignment system, the so-called Telescope Coalignment System (or TCS), which coaligns the telescopes on field stars and which relies on the extraordinary mechanical stability of the MMT (section 3) to keep the telescopes coaligned for long periods when no field stars are available.

The Laser Coalignment System was found less than satisfactory for a number of reasons. First we found that internal seeing in the MMT affected the laser images differently from star images because the laser-star only used 2.5 cm of the 180 cm aperture (or 0.02% of the area). A similar problem was encountered with a model for the USSR 25 meter telescope (Steshenko 1981). Specifically the seeing caused the laser image to move at a few Hertz rate which in turn caused a servo-introduced motion of the stellar image amounting to ~ 0.3 arc sec RMS motion for every one degree differential between the air and building

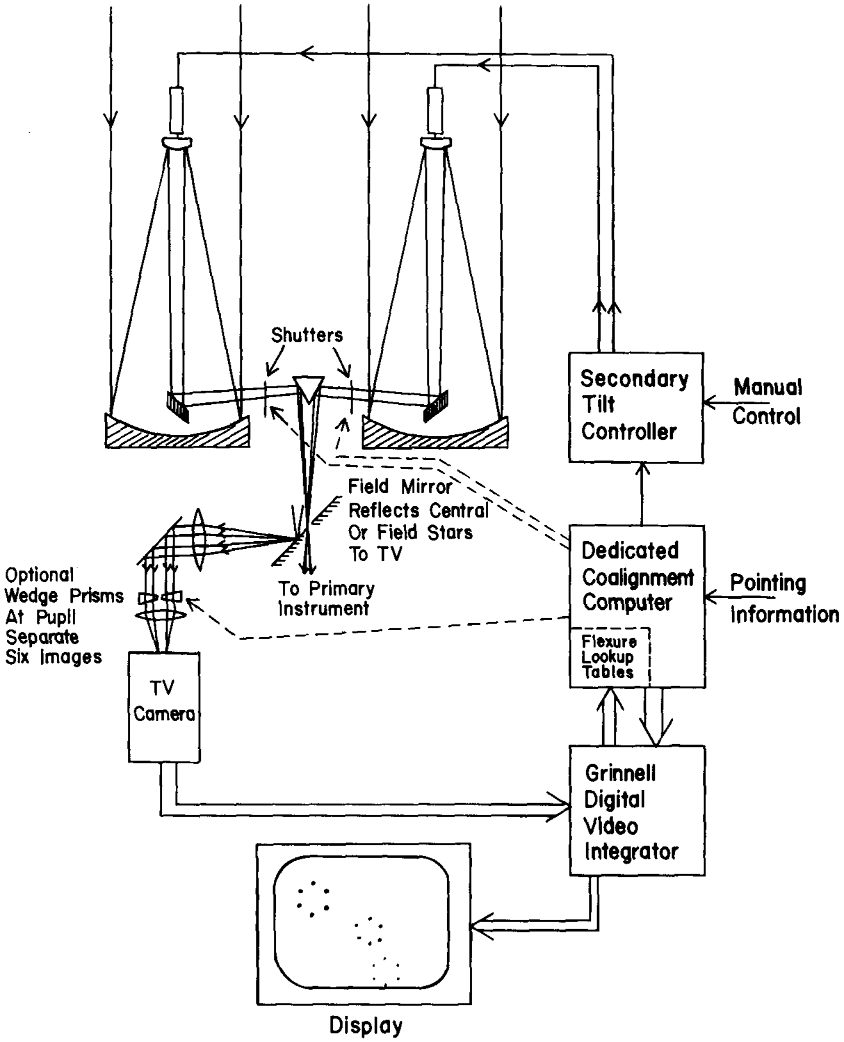

Figure 1 Sketch of the MMT Telescope Coalignment System. The position of a field star is determined by a digital television system separately for all six telescopes. If incorrect the tilts of the desired secondaries are adjusted.

floor/yoke temperature. In the last year we have reduced these thermal differentials substantially (section 5 and 6) but for critical coalignments we expect that internal seeing will continue to be a problem. A second problem with the laser signal was its contribution to scattered background light especially for very deep sky imaging (V = 24-25). Because of the changing optical interfence patterns in this scattered light it is very hard to correct. Thirdly insects often interrupted the laser beams causing undesirable interruptions in the coalignment. The fourth reason to replace the laser system was the result of its complexity which made it very hard to operate and to maintain.

Figure 1 gives a sketch of the TCS as it is now being implemented. The TCS uses a three stage intensified digital television system which examines all or a portion of the field of view of the MMT. In this field of view a star image is identified by the MMT operator on which the telescopes will be coaligned. The insertion of a wedge prism assembly in the image of the pupils formed by the transfer optics causes this image to be separated in six separate images on the television even if the images in the MMT focal plane are combined. The computer can then determine the locations of these six separate images. If these do not correspond to the desired locations then a command is given to the steppermotor controlled secondary mirror tilts (1 step = 59 millisecond of arc) to move the images.

Figure 2 shows a demonstration of the TCS functioning using two of the MMT telescopes. When unlocked from the computer control

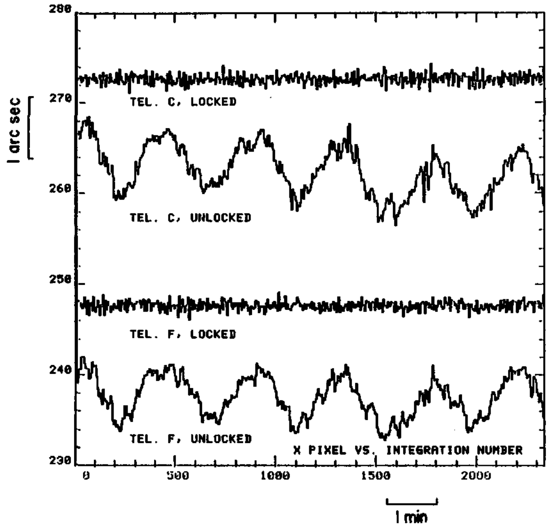

Figure 2 Result of a test of the TCS. The azimuth location of images of telescopes C and F as measured by the digital television is shown both in the unlocked and locked configuration.

the images from the two telescopes show substantial motions consisting of both a 1 arc second peak-to-peak oscillation due to uncorrected systematic errors in the elevation encoder (see section 2) and a systematic image drift. When locked to the computer control both images stabilize to a 0.15 arc second RMS accuracy. Much of the residual variations in the locked configuration in Figure 2 is probably the result of uncorrected seeing motions. The rate of control was 4-5 Hz so that the typically few Hertz seeing motions are not fully corrected, or may even add to the image motion due to aliasing. We plan to increase the computer control rate to 10 Hz so that the seeing motions of the MMT images, often different in the different telescopes, will be largely eliminated thus enhancing the total image sharpness by means of the so-called "image shrinking" techniques (Angel and Woolf 1980). This rapid guiding feature can of course only be used in case a bright enough star image (15th magnitude or brighter) is present near enough to the object being studied to share the same image motion. Often that will not be the case. Sometimes there will even be no star image present in the small 4 x 4 arc minute MMT field of view to do slow guiding and autoguiding on. In that case the MMT will be coaligned on a nearby star outside the normal field of view and then tracked "open loop" using the gravitational flexure and thermal corrections described in section 3 to keep the telescopes coaligned for as long as possible before having to go back to the coalignment star.

5. THE MMT BUILDING

One of the most unusual departures from conventional telescope technology is the MMT building. It closely surrounds the telescope, being almost an integral part of it. It follows the azimuth rotation of the MMT by means of an electronic sensor. The relatively large shutters of the building leave the MMT very exposed to the outside air. The absence of a narrow dome slit and of a windscreen we believe to be a major factor in giving the often excellent seeing experienced at the MMT. This exposure demands of course a very high immunity to windbuffeting of the telescope itself as discussed already in section 2.

The walls and doors of the telescope chamber are heavily insulated to prevent heating from the surrounding offices and from outside during the daytime. Although the floor of the chamber had been equipped with cooling pipes for refrigeration, we decided not to implement that expensive system. Instead both the heavy concrete floor and the heavy metal yoke have been covered by a layer of insulation consisting of 19 mm of styrofoam and 19 mm of plywood. This insulation causes the surfaces of these thermally massive units to stay close to air temperature with a relatively short time constant. In addition we draw air at night through the telescope yoke to further enhance thermal equilibrium.

As a result of the good insulation of the telescope chamber the air temperature in the chamber stays close to the temperature of the previous night all day long. At the end of the day it may have risen by a few degrees and the outside and inside air temperatures become again equal near sunset. At that point we generally open the building for night observing.

The radiation cooling discussed in section 3 for the OSS is even worse for the top of the MMT building which is also painted with TiO_2 paint. There the temperature drops ~ 6°C below the air temperature on a clear and calm night. We have noticed seeing deterioration effects due to this cooling above the telescope and we are planning to apply an aluminum foil surface to the roof of the building which according to tests will decrease the thermal differences by an order of magnitude while only increasing the surface heating by sunlight a little.

6. THE IMAGE QUALITY AT THE MMT

The image quality of a telescope is determined by three factors: (a) the optics, (ii) the site seeing, and (iii) the man-made seeing in the telescope, in the building and surrounding the building. The site seeing is determined once the site is chosen. Because of the importance of a good image quality (the image size is generally as important as the telescope size) it is essential that telescopes be located at the best sites. The MMT site has often excellent seeing, occasionally so good that no atmospheric schlieren are visible at all in out-of-focus images, the optics themselves being the main contributor to the image quality deterioration.

The MMT primary mirrors have optical irregularities amounting to 0.1 waves (632.8 nm) RMS which consist mostly of a set of concentric circular zones. They were initially specified to give a concentration of 90% in an 0.7 arc second diameter image, and they meet that specification. However, because of the unexpectedly excellent site seeing we are presently considering to refigure the surfaces of the mirrors to allow better image quality.

Man-made seeing comes from three sources: (i) Thermal inertia of thermally massive components. We reduced thermal inertia effects as much as possible by applying a layer of heavy insulation to the offending surfaces. For one component, the primary mirrors, this is of course not possible. Although they are lightweight, eggcrate mirrors they do have some thermal inertia whose seeing effects have not yet been eliminated; (ii) Active heating by electronics and other heat sources sometimes associated with observer's instrumentation. We continuously attempt to reduce this to the maximum extent possible. Also the observer himself generates 25-50 watts of body heat which is noticable at good seeing conditions; (iii) Radiation cooling already discussed in sections 3 and 5 for the OSS and the MMT building which we are eliminating by changing the surface covering from high emissivity IR surfaces (TiO_2) to low emissivity surfaces (Al foil) thus reducing radiative cooling effects.

The average image quality at the MMT equals 1-1.5 arc second with 2 arc seconds being poor seeing and 0.5 arc seconds being very good seeing. We will continue our efforts to reduce image size. The occasional absence of atmospheric seeing effects make us hope that it will be possible to occasionally reach better than 0.5 arc second image quality. To fully utilize such good seeing requires implementation of an observing strategy which indeed places experiments demanding and capable of using the excellent image quality on the telescope on those good nights. No such strategy has as yet been defined for the MMT.

7. INTERFEROMETRY

The MMT turns out to be very capable of doing interferometric measurements even though this was not one part of the original design goals. With its 690 cm edge-to-edge distance it is the largest telescope in the world from the interferometry point of view. In order to achieve interference the pathlengths between the telescopes used have to be equal to much better than $\lambda^2/\Delta\lambda$ where $\Delta\lambda$ equals the bandwidth. For optical measurements (e.g. $\lambda = 0.5\mu m$ $\Delta\lambda = 0.01\mu m$) and for the infrared (e.g. $\lambda = 10\mu$ $\Delta\lambda = 4\mu$) this means equality to much better than 25μm. Low and McCarthy (1981) have measured the variation of the pathlength differences with elevation and find a systematic variation of about 60μm and a random variation of ± 15μm. The latter may be associated with thermal variation. By reducing the OSS radiation cooling and by measuring its temperature we want to characterize the latter. To do interferometry effectively other conditions have to be met. Some of these relate to optical configurations and have been discussed by Shannon (1981). For optimum interferometry it is also essential that all participating telescopes have equal polarization and retardation effects. The two off-axis reflections in the MMT cause a problem in this respect since they combine to give a significant linear retardation in the optical region of the spectrum. In the far infrared, retardation is not a problem (McCarthy 1980). In addition interferometry requires good tracking since a one arc second tracking error at the MMT causes on-axis a 34μm pathlength difference.

To date the MMT has been used both for IR Michelson interferometry and for optical speckle interferometry. Both experiments used only opposite pairs of telescopes. In the future we plan to further identify the origins of pathlength variation and then correct for them as much as possible open-loop with separate pathlength compensating optics. The improved telescope tracking, already discussed, is of course also important in this context.

8. CONCLUSION

The MMT is now used for 80% of the nights for astronomical observing. Because of its significance as a prototype of the Advanced Technology Telescope it is important, however, that a substantial effort be given to further engineering studies. Already the MMT program is resulting in substantial benefits both for astronomical research and for telescope engineering. This is very much the result of a strong synergistic effort by both the Smithsonian Astrophysical Observatory, University of Arizona Observatory and Multiple Mirror Telescope Observatory staffs. We acknowledge the help of all at those institutions who have contributed to the results described in this paper. The work reported in this paper was supported in part by a grant #AST 79-25421 from the National Science Foundation

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