MIRRORS: FABRICATION, PROCESSING, TESTING AND TOLERANCES

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The construction of very large telescopes is impeded by very large costs. Much effort is going into finding ways to get below the traditional cost-scaling trend line [1]. We will address several factors that lead to reduction in cost without reduction in performance. Clearly, a very fast primary f-ratio is necessary. The practical lower limit is set by three factors:

1) width of the Nasmyth platform
2) new optical processing techniques
and 3) maintenance of collimation.

Optical Processing

Polishing large mirrors by traditional methods becomes prohibitively expensive for fast primaries because of the time required to polish from the nearest sphere to the desired asphere. The first point of departure for the future is to directly diamond mill the required asphere. This requires a precision machine to avoid generating in zonal errors or astigmatism. The Optical Sciences Center (OSC) is currently installing such a machine, the Large Optical Generator (LOG), which can handle an 8-meter diameter circular mirror or segments of a 15-meter asphere. It is scheduled for first operation in August 84. The initial precision will be a surface error of 3 μm RMS; close enough for final trueing by small polishing tools. It is anticipated that addition of interferometer control will enable milling

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to an optical surface to 0.1 μm RMS; thus the final step is simply to polish out the residual tool marks.

The first task for LOG is to make the aspheric segment masters for the 10-meter submillimeter telescope (SMT). Several mirrors of optical quality are pending in which the time saved even at 3 μm RMS should significantly lower the cost of finishing the mirrors.

The question of rapid polishing of a diamond-generated surface is being explored. A belt polisher has removed the residual tool marks in less than an hour. Thus in principle we can generate a precision aspheric surface and polish it in a very small fraction of the time required by traditional methods. More important, it enables astronomers to consider faster f-ratio primary mirrors than ever before. These advances also have been combined to make possible a new type of mirror.

The Mosaic Monolith Mirror

A mirror up to 8 meters diameter has some advantages as a monolith rather than a segmented one, mainly in that should the control system develop problems the monolith would still yield reasonable performance whereas a segmented one would be useless. Above 8 meters diameter a segmented mirror appears to be necessary. It has the convenience of modest sized panels to be handled during polishing and re-aluminizing. In the studies of the Texas 7.6-meter telescope we addressed a new mirror concept. The objective was to be able to use the existing 2.9-meter aluminzing tank yet have the passive backup stability of a monolith. The solution was to make a monolith wherein the reflective faceplate could be removed in panels for re-aluminizing: the mosaic monolith mirror (M^3).

The theory of the M^3 is simple. The polished faceplate is a thin shell with little strength over large dimensions but large strength between points of contact with the monolithic substrate as illustrated in Fig. 1. The thin shell can be polished so that it is smooth over the scale of a few points of contact with lesser regard for the accuracy of the entire surface. Thus when the faceplate is drawn into contact with the substrate a smooth and accurate figure results, the accuracy being determined solely by the LOG-milled surface of the substrate and its great stiffness. If active tuning of the figure is required it is done by control of the monolith. Flotation of the M^3 is entirely within the substrate. The substrate is never removed from the telescope.

One simple way of attaching the faceplate is to use vacuum pads as shown in Fig. 2. An external 0-ring provides the seal. The contact surface is given a final cleaning with an air blast while the mirror panel is held about 1 mm above the contact surface. The mirror is then lowered into contact and the vacuum turned on. A reasonable vacuum system resevoir could maintain vacuum for many days without active pumping. We have done an experiment of over a hundred replacements of a panel on a substrate and found accuracies below the limit of detection of interference fringes—far better than would be required.

Translated into practice: we would mill the substrate on LOG and then attach pre-machined faceplates while the substrate is on the LOG, milling the final mirror figure on the faceplates. We would prefer to polish all faceplates at one time without removal from the substrate (possible on the LOG table). One could, however, polish the panels individually on a small machine using the belt polisher. We would further assemble the lightweight monolith of many segments permanently joined together and thus be able to manufacture all components of the mirror in the Angel 3-meter furnace. The question of cementing together is being explored, but it appears the high stiffness of the assembled monolith would limit thermal effects to low-order Zernike polynomial terms controllable by the mirror figure-control subsystem.

The potential impact on the 7.6-meter telescope of the M^3 design and LOG processing procedures is shown in Fig. 3. The primary is f/1.25 and the Nasmyth focus f/13.5. In Fig. 4 we show an f/4 pseudo-prime focus that yields a 1-degree field and a good match of best seeing to pixel dimensions. A very small secondary for IR observations is also possible as shown in Fig. 5. The secondary is surrounded by sky, and a central hole in the secondary eliminates reflection of the Nasmyth flat assembly.

Testing

A key element in optical processing is the ability to test the mirrors in the optical shop. A skillful optician can make rapid progress as long as he is provided with accurate maps of the surface error. The art of interferometry has been advanced by the introduction of instruments that instantly process the data and present them in any of several modes useful to both the astronomer and the optician. The OSC has developed a 10.6-μm interferometer that yields results from unpolished surfaces whereby during grinding the mirror can be figured very close to the final performance, accelerating completion of the mirror. A similar instrument operating at 0.63 μm can meet the requirements of testing high-resolution space mirrors.

The validity of any interferometer test depends on a reliable null test lens or mirror. Null optics become very sensitive to manufacturing and positioning errors, so a fundamental test like the Hartmann test is necessary to establish correctness of the conic constant of the primary. Even so, we recommend postponing work on the secondary until the conic constant of the primary is measured at its final value. This procedure allows the primary conic constant useful latitude during final figuring of the primary,[2] the secondaries then compensate the final focus for residual spherical aberration.

System imaging tolerances

Encircled energy remains a fundamental measure of mirror quality and can be directly calculated from a variety of tests. It is popular recently to specify RMS surface error, but this alone is insufficient to define the encircled energy. Adding the specification of RMS at several spatial frequencies improves definition of encircled energy, but it still is not exact. The specification of encircled energy adequately combines RMS and correlation length when the optics are not diffraction-limited, which is invariably the case when large telescope mirrors are considered. Encircled energy is usually calculated from measures at a discrete grid of points in the aperture whether using a Hartmann or an interferometer test. The value thus does not include diffraction effects and the actual image will have equal or better concentration than is indicated by the encircled energy value.

Collimation tolerances

There is a subtlety with regard to decollimation tolerance that is especially important for a fast primary mirror. Separate tolerances are usually given for tilt and decenter. The result is an engineering limitation that is tighter than necessary. In reality the important tolerances are allowable coma and field tilt. Coma can be zero over a very large range of tilts and decenters when these values lie within a band as indicated in Fig. 6. Thus for any decenter of the secondary due to gravity sag of the telescope tube there is a tilt of the secondary that results in near-perfect imagery but a slightly tilted focal surface and a trace of astigmatism. Both field tilt and astigmatism can be compensated by a slight lateral shift in position of the field corrector of a Cass system. A paper in press[3] gives a full discussion of these questions.

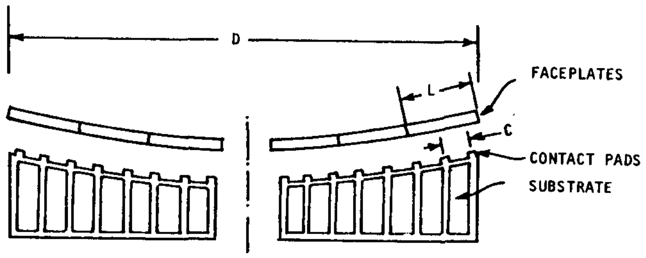
Conclusions

We conclude that telescopes with primary f-ratios in the f/1.0 to 1.5 range can be had with excellent imagery and at significantly reduced cost. For very large mirrors the M^3 concept is a logical compromise between the segmented and monolithic options. Direct diamond milling to the final figure will reduce processing time. For any very large mirror some degree of active figure tuning seems prudent as well as open-loop adjustment of collimation to meet the zero-coma condition. The astronomical/optical community thus enters a new round of very large telescopes accompanied by the necessary advances in fabrication, processing, testing and image control.

References:

1. A.B. and M.P. Meinel, Opt. Eng. 18, 645 (1979).
2. R.H. Noble, F. Cobos, F. Francisco and J. Sasian, Appl. Opt. 21, 3181 (1982).
3. A.B. and M.P. Meinel, Opt. Eng., in press.

Figure 1. MOSAIC MONOLITH MIRROR



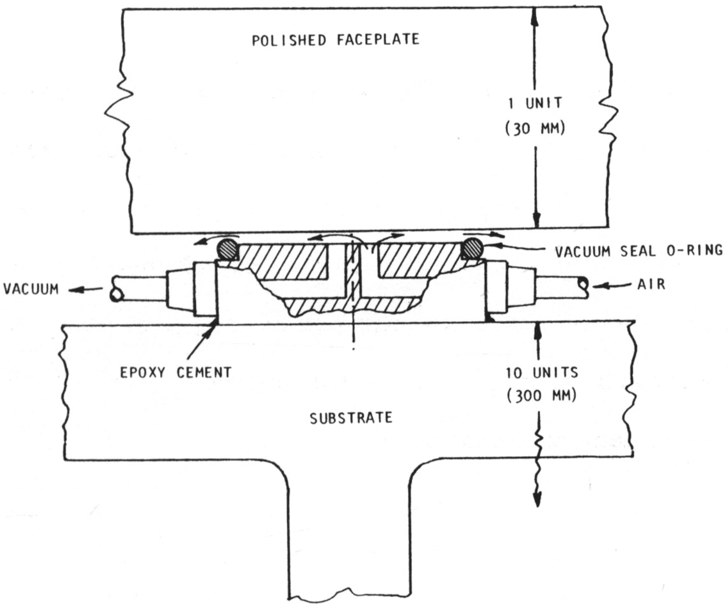
FACEPLATE

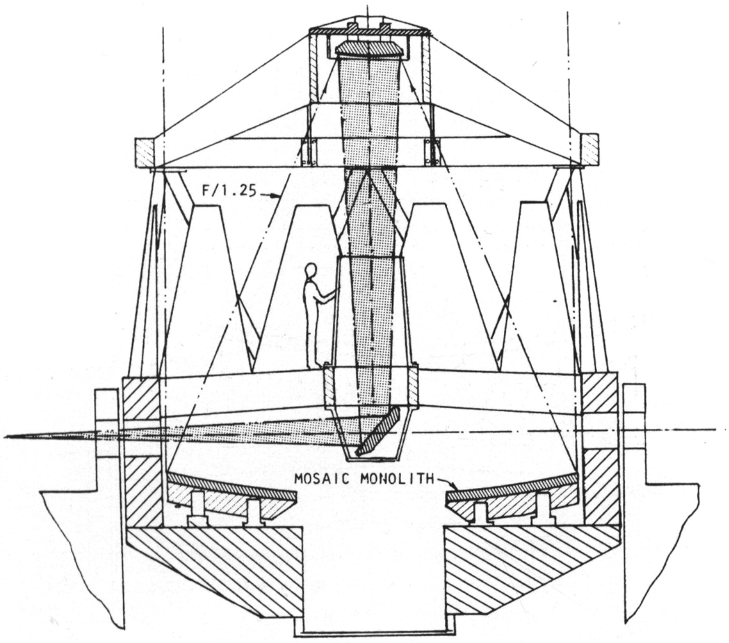
LOW STIFFNESS OVER DIMENSION L
HIGH STIFFNESS OVER DIMENSION C
POLISH SMOOTH OVER DIMENSION ≈2C
VACUUM CONTACT TO DEFINING PADS

SUBSTRATE

HIGH STIFFNESS OVER DIMENSION D
CONTAINS FLOTATION FUNCTIONS
CONTAINS FIGURE TUNING FUNCTIONS
IS NEVER REMOVED FROM TELESCOPE

Figure 2. CROSS-SECTION OF AN ATTACHMENT PAD

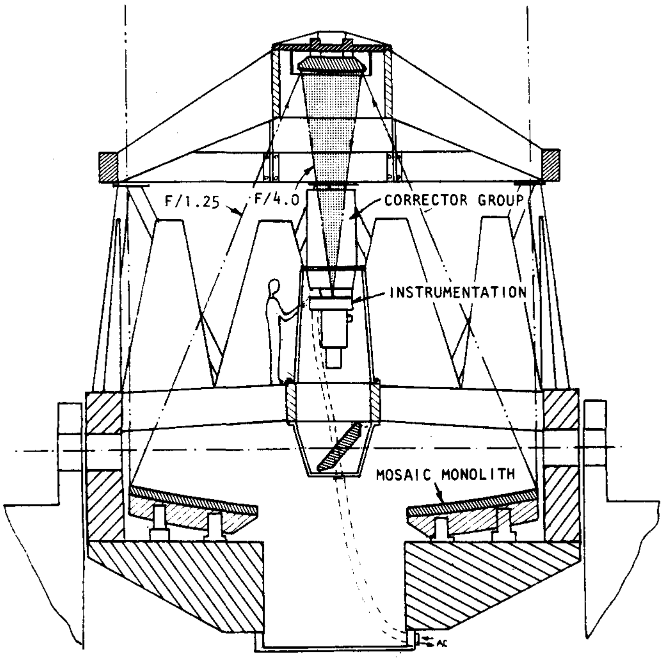




F/13.5 NASMYTH FOCUS

Figure 3.

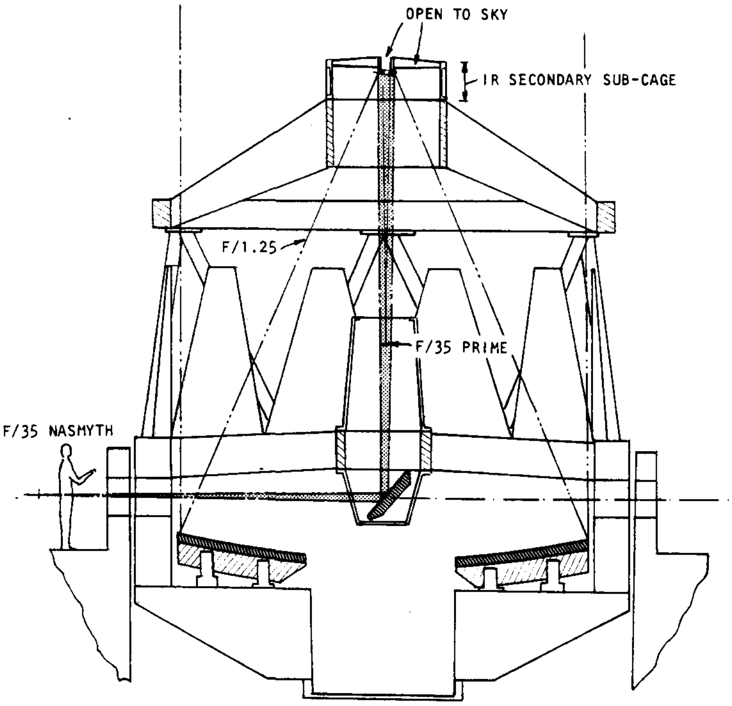
Basic configuration for an F/1.25:13.5 Nasmyth focus telescope. The shaded upper cage assembly removes for changeover to other focal configurations. A mosaic monolithic mirror is shown. The downward cant of the upper ring assembly is to reduce wind shake.



F/4 EPPS PRIME FOCUS

Figure 4.

An F/4 "prime" focus arrangement (Epps) where the secondary has the same diameter as the F/13.5 Nasmyth. The corrector group provides excellent imagery over a field of 30 to 60 arcmin diameter.



F/35 INFRARED FOCI (NASMYTH & PRIME)

Figure 5.

An F/35 IR focal arrangement where the sub-cage is a separate vane and mirror unit configured so that sky is seen surrounding it. A hole in the secondary removes the reflected image of the Nasmyth flat assembly. Note that focus could be either at the Nasmyth or Epps focus.

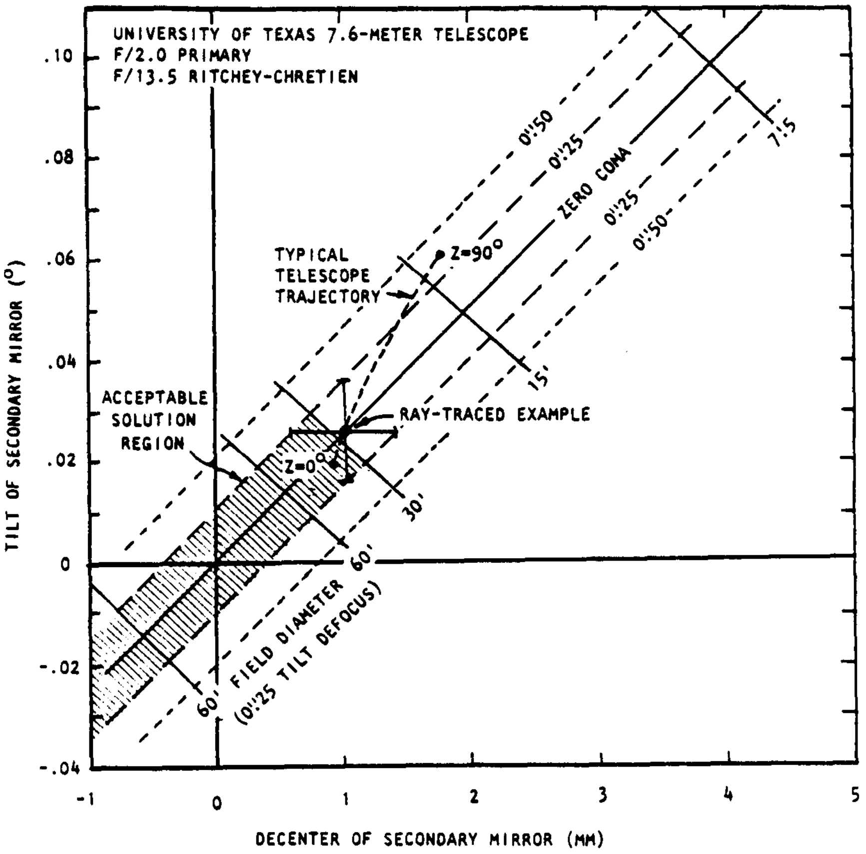


Fig. 6. The shaded area is where the residual coma and focal surface tilt is acceptable without correcting for tilt defocus. A rather poor structure is represented by the "typical" telescope trajectory. Under conventional tolerancing the ellipse defined by the crossed lines for the "traced example" would have to be centered on the origin.

DISCUSSION

J. Wampler: Is the principal advantage of the M^3 primary the reduction of the cost and difficulty of later handling and aluminizing?

Meinel & Meinel: Yes, both for observatories with limited funds and facilities or for very large telescopes where conventional monoliths are impossible to make.

R. Bingham: How does the Mosaic Monolith Mirror concept compare with other concepts as regards its weight?

Meinel & Meinel: The relative weight is not much different because the reflective panels will be only 2-3cm thick.