LARGE MULTI-LENSED TELESCOPE: A RECEIVER FOR POINT SOURCES IN THE SKY

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Abstract. A large 80" (2-meter) multi-lensed, computer-controlled and encoder-pointed telescope will be described. It is being used as the receiver in the new high-performance lunar laser ranging station on Mt. Haleakala on the island of Maui, Hawaii; however it could also be used for other astronomical applications when the moon is not up. This telescope, which was designed for applications requiring aperture but not field, could impact the design of future very large astronomical instruments intended mainly for point-source spectroscopy and similar applications. The telescope and its performance to date will be discussed.

In the London Science Museum, a 48-inch (1.2-meter) diameter mirror from Sir William Herschel's 40-foot (12-meter) telescope of 1789 is on display. The explanatory note describing this 4-foot mirror points out that it is the first of two speculum metal mirrors of this size which Herschel cast and polished. This first mirror -- which weighed nearly half a ton -- was found to be too thin, though it was used by Herschel in the first observations made with his 40-foot telescope. It was, however, replaced four years later with a mirror twice as thick. The instrument I am going to describe evolved in an attempt to address this general problem: as telescopes get bigger and bigger, their mirrors need to be made correspondingly thicker and thicker.

My interest in large telescopes stems from my involvement in the late 60's with the Lunar Laser Ranging Experiment which was a part of NASA's Apollo program. During a visit to Perkin-Elmer to discuss the cube corners which they were making for Apollo 11, I was shown a portion of their program in active optics. In particular, they showed me a large mirror made up of pie-shaped segments which were actively servoed (using white light fringes at adjacent edges to control the relative phases of the segments and laser beams to control their angular orientations) to behave as a single large mirror. The purpose was to test the feasibility of taking a mirror apart and then putting it back together in space without any loss of its optical integrity. Seeing this, combined with my reading of the Whitford Report,1 started me thinking about possibilities for large receivers.

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The major problems -- the technical difficulties and costs of constructing large telescopes -- would be greatly compounded if attempts were made to build very much larger telescopes along traditional lines. The restrictions on very large mirrors that result from their great weight led Paul Harvey, then an undergraduate at Wesleyan University, and myself to investigate (beginning in 1968) the possibility of using thin film optics for mirrors and thus eliminating the problem of body forces.²

We tried stretching a piece of thin aluminized mylar ("super insulation") over a circular chamber which could be evacuated so as to pull the plastic into a concave shape. Although we did not expect this type of "thin film mirror" to equal the resolving power of its glass counterpart, we felt a host of exciting uses could probably be found for very large but optically only fair-to-good mirrors for telescopes.

To test the idea, a 36-inch (0.9-meter) diameter mirror was constructed from a solid aluminum back plate and a concentric aluminum ring that formed the circular aperture over which the mylar was stretched. An O-ring of 40-inch (1-meter) diameter served to form the vacuum seal between the mylar and this ring, while another one between the ring and the back plate formed the other seal. The 0.0005-inch (0.001-cm) aluminized mylar was held by 36 cables attached to grommeted tabs around its circumference. In order to provide for tension adjustment, these cables were passed through holes around the outside of the back plate and fastened to 36 radially arranged turnbuckles at the rear of the back plate of the mirror. When completed, the entire mirror weighed 150 pounds; however, the actual "mirror" itself weighed less than an ounce per square foot.

Two problems were found with this type of mirror. First, the experimentally observed shape of the mirror was an oblate spheroid, i.e., too flat in the center. To correct this, we utilized electrostatic forces to adjust the mirror's radial shape. A set of concentric conducting rings behind the mirror were charged to various voltages relative to the aluminized surface of the mirror which was held at ground potential. With a mirror to conducting ring spacing of several millimeters and a voltage of about 1 kV it proved possible to "tune" the mirror to a parabolic shape. The second and more serious problem resulted from the 20% thickness variation in the mylar itself. On drawing the partial vacuum needed to shape the mirror, these variations were substantially exaggerated and gave the mirror a mottled appearance under either the Focault or Ronchi tests. Since this problem involved no symmetry of the mirror, its solution could easily be realized only by finding and using plastic of better thickness uniformity.

The f/5 36-inch diameter mirror we finally used had the optical property of focusing 50 to 60% of the specularly reflected light into a circle with an angular
radius of 30 sec of arc. Without the electrostatic correction, this angular radius was about 60 sec of arc. And though this quality of mirror would not permit the degree of spatial filtering required for many applications, the concept of electrostatic shaping might still be useful in forming and shaping very large thin film optics in space.

The next thin film telescope effort, which began in the spring of 1969 with Wesleyan undergraduate Mike Sultzer, led directly to the building of the large telescope which is the subject of this paper. Our idea was to construct a mosaic telescope having aperture but not field which would be applicable to point-source astronomy. The decision was made to design and construct a multi-lensed receiving array in which the light from the individual lenses, on passing through co-registered pinholes in their focal plane, would be brought together by optical links onto a common photomultiplier.

The difficulty with using mirrors in this kind of approach (and therefore the attendant high costs) is that the individual mirrors need to be registered and maintained (probably servoed) to an angular tolerance equal to twice the angular resolution that one wishes to achieve. A considerable experimental advantage is gained by using transmission optics, since it is required that lateral displacements of the image that results (either because of a sideways motion of the lens or because the lens is rotated) be less than the desired resolution times the focal length of the lens. For example, in the case of an array composed of 7 1/2-inch (19-cm) diameter f/10 lenses of approximately 1-inch thickness, an instrumental resolution of two seconds of arc would require (1) that the sideways positional stability of the various lenses be less than $0.8 \times 10^{-3}$ inches $(2 \times 10^{-3}$ cm), and (2) that their angular registration be held to something like $3 \times 10^{-3}$ radians (as contrasted with the $5 \times 10^{-6}$ radians which would be required in the case of reflecting optics in order to achieve and maintain the same resolution!).

For his senior thesis, Mike constructed the framework for a 40-inch (1-meter) diameter multi-lensed receiver which seemed to bear out our initial thought that this approach could be exploited to build a low-cost, large-aperture receiver that would be rigid enough to permit absolute or "blind" pointing. The mechanical advantages of a mosaic type of telescope is that the instrument's length is set by the focal length of an individual lens -- thus permitting a compact instrument of reasonable f-number. Further, the aspect ratio of the large optical mosaic is set by the individual lens diameters rather than by the size (diameter) of the entire mosaic structure itself. Thus one has, in effect, a "thin film" optical element which, except for the limitations arising from the transmission of the glasses used in the lenses, can be used to construct a telescope for most applications involving point-source, or (as we
shall see) nearly-point-source, objects in the sky.

Following the conclusion of this effort, and steadfastly resisting the temptation to build the world's largest telescope, I began construction in 1970 of the essentially $8' \times 8' \times 8'$ (2.4 m $\times$ 2.4 m $\times$ 2.4 m) instrument shown in Fig. 1. The idea for this type of telescope also occurred independently in France. However, their "grand collecteur," which at last report lacked the necessary funds and manpower for completion, differs from mine in many details of design and construction philosophy.

My instrument, which can best be understood by referring to the overall optical schematic diagram, Fig. 2, contains an array of 80 achromatic lenses, each 7 1/2 inches (19 cm) in diameter. The individual lenses perform essentially at the diffraction limit for the range of about 4000 å to 1 μm. By using achromatic lenses, while minimizing the mechanical and the optical problems associated with covering the visible portion of the spectrum, we obtain a desirable several seconds of arc resolution: For a singlet of this size and f-number (f/10), spherical aberration would limit the resolution and hence the minimum operating stop size to about 14 seconds of arc rather than the 3 or 4 seconds of arc stop which this instrument is capable of employing.

The 80 f/10 achromatics constitute a clear aperture equivalent to that of a single 67-inch (1.7-meter) diameter optical element. The effective "equivalent-aperture" of this telescope in the visible region of the spectrum, considering its high 75-80% transmission efficiency and taking into account the obscuration necessary in a conventional telescope, is about 80" (2 meters).

Referring to the overall optical schematic, we see that after being collected by the initial 7 1/2" f/10 lens, the incoming light passes through an initial diaphragm (pinhole) which is 0.004 inches (100 μm) in diameter. This corresponds to a field diameter of approximately 11 seconds of arc. Each of these individual pinholes was mechanically coregistered and "referenced" to look at the same 11 seconds of arc in the sky. This was done to essentially a second of arc accuracy by setting the instrument in a vertical position and auto-collimating each of the lens-pinhole combinations to a mercury reference table. This involved mechanically moving the individual pinhole assemblies in the horizontal plane of the back plate until they were correctly positioned. They were then secured in place.

Behind this initial pinhole the emerging f/10 cone of light passes through a smaller diameter lens of focal length 3 7/8 inches (9.8 cm). This smaller lens is a part of a movable assembly that includes the pinhole and the lens at two ends of a tube arrangement which translates axially using a ball slide bushing to permit focusing of different colors. The total movement possible with these assemblies is approximately 3/4 inch (1.9 cm). To permit this, it is necessary
Figure 1
Figure 2
to have a high degree of perpendicularity of the focusing mechanism with respect to the back plate. Also, the assembly must have essentially no mechanical play, otherwise the pinholes would sag depending on the orientation of the telescope at any given instant. To achieve this in-and-out focusing, all of the assemblies within a given 60° section are linked together and motor driven with cams in the shape of Archimedes spirals. This conveniently serves to convert angular motion into uniform linear motion. The focal requirements of the smaller lens, which is used to make the light parallel following this 11 sec of arc pinhole, are necessarily less than those of the large initial lens, and hence do not require any adjustment with color. Emerging from this small lens is a parallel beam of light approximately 0.4 inches (1 cm) in diameter. This in turn reflects off two of the 160 small front-surface mirrors (two for each of the lenses in the front-face array) which are in this back plane area. Each small mirror is high-efficiency coated for the visible range of the spectrum. The center configuration of 80 mirrors gives the appearance of a cake covered with candles. The diameter of this cluster of 80 mirrors is only 6 inches. The emergent group of parallel pencils of light out of this central array of mirrors is focused by a 6-inch (15-cm) diameter f/5 lens onto a common pinhole.

The individual central mirrors can be finely adjusted about their axes of rotation, but only roughly adjusted in tilt. The mirrors further from the center are finely adjustable in all coordinates. It is important to note that in this back plane area, where one has introduced reflecting elements, the beam diameter is smaller by a factor of 20 and therefore all angular sensitivities are less critical by exactly the same amount. In other words, the stability requirements of this back plate assembly are more nearly at the minute of arc level than at the second of arc level.

The pinhole at the final focus is, in fact, not one but a series of pinholes fixed onto an accurately registering wheel which can be rotated on electrical command to permit the field to be selected. The available field ranges from the full 11 seconds of arc down to about 3 seconds of arc in five steps.

The process of registering the initial pinholes onto the final common pinhole, while avoiding vignetting of the rays inbetween, is straightforward and systematic but somewhat time consuming (2 days -- once one learns how). The essential requirement, however, is that once tuned it must stay tuned. Just as a multi-stringed instrument must stay tuned throughout a performance, so must all these multi-mirrored adjustments. Experience to date seems to indicate that this instrument, once tuned, stays tuned for performances of one-half year or longer.

The initial pinhole size was set by the requirement that it should not substantially cut down the packing factor (related to the final brightness) achievable
in the final image restoration or where the various beams run parallel to each other. One could, however, reasonably go up to half a minute without too much loss in this respect. This problem comes about because of the long distances (~50" or 125 cm) involved in bringing the beams together. The angular spread resulting from a finite sized pinhole gives rise to a mushrooming in size of the individual beams.

One point worth noting is the 660-lb weight of front-face optics in this 80" diameter surrogate mirror is less than the total weight of Herschel's "too thin" original mirror. A further point is that the individual beams (light paths) are brought together by articulated optical links to the final variable and therefore field-determining pinhole, rather than by light pipes. The reasons for not using light pipes are two: (1) they are lossy and (2) they throw away spatial information. The first of these, the transmission loss, would result in a factor of two reduction in the overall efficiency and thereby give away much of the increase in aperture made possible by a synthetic combination of smaller elements. The second disadvantage of light pipes is a loss of brightness: the direction of a photon may be known upon entering a light pipe, but it is no longer well defined at emergence.

For successful operation of this type of telescope, the different apertures must stay aligned when the telescope points to different parts of the sky. To assure this, the front and back plates in this essentially all-aluminum structure were pinned together and rigidly constructed. In this regard, the choice of f/10 for the large lenses represented a compromise of image quality and depth of focus with the resultant instrument length.

The mechanical integrity of both the front and back plates in lateral deformation was measured to be \( \leq 0.0002" \) (0.0005 cm) (<1/2 sec of arc in pointing error). In front-to-back sag the front sags less than 10/1000" (0.025 cm) and the back only a few thousands (\( 10^{-3} \) cm). The front plate sag is well within the theoretical depth of focus \( \left[ 4\Lambda (f\text{-number}) \right]^{2} \approx 0.020" \) (0.05 cm)\] and therefore contributes no problem. The back plate sag, were it much greater, would begin to introduce some angular spreading between the individual light beams and require a focus change for optimum spatial filtering.

The diameter was set when work first started on this large multi-lens telescope. The initial thought was to utilize it as the receiver in a mobile lunar laser ranging station,\(^5\) and as a consequence, the wide-load truck limit for U.S. roads (8' or 2.4 meters) set the upper limit on the diameter of the instrument.

One final important point on the overall optical scheme is that though it was conceived as an instrument with aperture but not field, the insertion of dove prisms (image rotators) in the parallel rear image plane rays would permit proper overlaying of the images up to the order of 120 sec or 2 minutes in diameter.
while still maintaining a 1 sec of arc image resolution quality. The field limit
is set by the inequality in focal lengths of the various sets of lenses. Because
the insertion of this type of prism involves only transmission optics, the me-
chanical problems associated with this type of image restoration would be essen-
tially trivial and had I thought of this possibility at the outset, it certainly
would have been done.

The telescope has an elevation-azimuth type of mounting and utilizes a
hydrostatic (oil) bearing for the azimuth axis and conventional ball-type
bearings for the smaller elevation axis. The elevation-azimuth type of mount
was selected initially not only because of the mobility requirement and therefore
the attendant necessity to operate at sites of varying latitudes, but also (and
structurally most important) to minimize the gravitational distortions and
thereby to permit absolute pointing. Guidance is accomplished by on-line com-
puter control.

The azimuth bearing utilizes a hollow 8' (8.4 meters) diameter welded steel
ring of rectangular cross section [12" (30 cm) high x 6" (15 cm) wide] whose under-
side has been Blanchard ground to a flatness of a few thousandths of an inch.
This ring floats on three hydraulic bearings located at the three corners of the
triangular base that provides the three-point support on the concrete piers under
the instrument. The azimuth drive consists of a friction roller drive spring
loaded against the diameter of this bearing. An optical 20-bit absolute encoder
is mounted on the azimuth axis to provide angular information. Two tachometers
mounted at 180° from each other provide the required velocity feedback signal
for the drive on this axis. The use of two at 180° summed in series provides a
signal sensitive to angular motions but insensitive to an undesirable back and
forth "slipsh" mode which otherwise might be excited.

The elevation axis is also friction driven against a 24-inch (61-cm) dia-
ter wheel attached to the elevation axis. Because of the greater radial stiff-
ness of this axis only one tachometer is employed. A second absolute 20-bit
optical encoder is mounted on this axis to yield elevation information. The
least significant bit corresponds to 1.24 seconds of arc. The torque available
on both axes is in excess of 100 ft-lbs, and the overall system stiffness is
such that little if any wind-loading could be seen on tracking a star in a wind
gusting to between 30 and 40 mph (45-60 kmph).

The total instrument weight, including the base and bearings, is just about
4 tons. More important, however, is the fact that the concept provides the po-
tential of going to a substantially larger instrument with considerable cost and
weight advantages, without entering into the regime in which body forces play a
constraining role in the design.
A station for observer guiding has been arranged by providing optical access to the image formed by one of the 80 lenses. This image, which falls on a cross-hair field fixed in the back plate, is brought out for viewing through a hole bored in one of the elevation axes by utilizing an optical link. Thus, to observe, a person need only to stand on the side trunnion of the instrument as it is being used.

Though insensitive to ambient temperature, this type of instrument is sensitive to temperature gradients, either front to back or side to side. Qualitatively this is easiest to understand in the front-to-back case where the temperature difference would affect the relative sizes of the front and back plates. For example, a front-to-back temperature difference of 1°C would result in the outermost row of pinholes being centered on a radius that is different from the radius corresponding to the outermost row of lenses by almost $10^{-3}$ inches ($2 \times 10^{-3}$ cm) -- over 2 sec of arc. Because of this problem the instrument is equipped with thermisters and heating elements throughout the inside of its structure. This was done in order to permit selective heating in response to existing gradients and thereby minimize their effects. To date it has only been operated at night when thermal gradients across the almost completely aluminum structure have not been a problem. Daytime observations using this instrument, however, may well need to take advantage of this capability.

Since its conception, the instrument has been moved twice. The first move to 5,000 feet (1,500 meters) came early in 1973 when it came to Boulder, Colorado where I had accepted a position with the Joint Institute for Laboratory Astrophysics. The second move, a year ago last fall, was to 10,000 feet (3,000 meters) atop Mt. Haleakala on Maui, Hawaii. There it became the receiver for the high performance laser ranging station, established for NASA by the University of Hawaii for purposes of lunar laser ranging. Experience to date in Hawaii has shown that this telescope-type represents a viable concept. The tracking is smooth and the light gathering power agrees closely with expectations. In April, 1977, scientists there successfully achieved lunar ranges with this instrument acting as the receiver. What is not yet clear at this time is whether or not the full capability of this telescope for point-source astronomy will be realized. Certainly there still remains perhaps a year of debugging to be done. However, given its present use in a program with a specific mission orientation, it remains to be seen to what extent it can be used for other purposes involving point-source astronomy.

In conclusion, though the time to complete the instrument, even allowing for the two moves, exceeded my most pessimistic estimates, this merely reflects the complexity of even an apparently simple new idea and the large number of small problems which arose requiring careful design for their solution. The concept is
however viable. In addition to its use for ranging and possibly as a receiving antenna for long range optical space communication, it is also applicable to stellar spectroscopy and photometry. Indeed, for applications requiring light gathering power without too large a field of view, this type of instrument appears to be very attractive on economic grounds and its success for stellar observations could have a major impact on the design of future very large astronomical instruments intended for point-source spectroscopy and similar nearly-point-source applications.

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To list all the people who have contributed to this work would involve an enormously long list of names. I would, however, like to single out three people: Dick Young, of Wesleyan University's Science Machine Shop; John Andru, of JILA's Machine Shop; and Vernon Hill, of the University of Colorado, Department of Physics and Astrophysics, Machine Shop. The care and incredible skills of these men are evident to anyone who has seen the instrument.

References
4. The suggestion in France for this type of telescope was I believe due to Professor J. Rösch of the Pic-du-Midi Observatory.