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New generation optical telescopes and plans for a large optical telescope in India

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Abstract. The large optical telescopes which are being made now or are under planning differ from the older telescopes in many basic features : the primary mirrors are faster (*f*/2 or so) and much lighter, the altitude-azimuth mounting is most common, and the enclosures for the telescopes are much smaller and simpler. These changes have been possible due to the advances in computer technology and controls, which make it possible to make intelligent systems based on closed loop control at low costs. The reduction in the overall size of any telescope has naturally led to large savings in the costs, and the new designs of enclosures have minimized the dome seeing effects. The most impressive outcome of the intelligent-system approach has been the implementation of active optics which allows one to get optical aberrations below half seconds of arc. A 4m size telescope which uses many of these modern features is being proposed for our country.

Key words : large optical telescopes—mounting

1. Introduction

The modern telescopes being planned or built currently differ so strikingly from the telescopes built a decade ago that these could justifiably be classified as being of a new generation. The major differences have come about due to the uninhibited use of modern advances in the area of servo-systems and computers to the various very demanding and precision technologies of optical telescopes. The beginnings of the revolution that has led to the new generation telescopes can be traced to the multi-mirror telescope, which was the first large telescope involving radical departures from the classical methods (Barr 1990). It successfully used : (1) several small telescopes mounted on a single frame to get an equivalent large telescope of 4.5 diameter, (2) alt-azimuth mount for pointing, and (3) a very simple box type enclosure, to obtain images with spread as small as about one second of arc, and a pointing accuracy of one second of arc. Over the last two decades several large telescopes have been proposed (of sizes ranging from ~ 2m to 12m) which use the new ideas on mirror technology, tracking and drive, thermal control, enclosures etc. In the following we discuss these new ideas which have made it possible to build telescopes > 8m in diameter, and at the same time improve on the optical and tracking performance as compared to the relatively smaller (large) telescopes of earlier generations. In the last section we discuss the plans for a future large telescope for our country.

2. Main thrusts

The main characteristics of the large telescopes being built now can be gauged by studying table 1. The goal of minimising costs and overall sizes is achieved by : (a) selecting a low mass primary mirror with a small f-ratio, (b) using alt-azimuth mount for tracking, and (c) using friction drive, instead of precision gears.

Table 1. List of telescopes planned or under-construction
(Reference : Advanced Technology Optical Telescope IV, 1990, and Progress in Telescope and Instrumentation Technologies 1992)

Telescope	Primary Mirror	Drive	Remarks
WIN (NOAO)	3.5 m, *f*/1.75 Borosilicate honeycomb	Friction	Nasmyth focii
Apache Point (ARC)	3.5 m, *f*/1.75 Borosilicate honeycomb	Friction	
Galileo	3.6 m, ULE Meniscus		*f*/6 Cassegrain; *f*/11 Nasmyth
MMT Conversion	6.5 m, *f*/1.25 Borosilicate honeycomb		*f*/5.3, *f*/9, and *f*/15 Cassegrain focii
Magellan	8 m, *f*/1.2	Friction	*f*/6.3, and *f*/15 Cassegrain focii
JNLT	8.2 m, *f*/2 ULE meniscus	Friction or Direct	Ritchey Chretien; *f*/12.5 focii at Cassegrain and Nasmyth; *f*/35 with chopping secondary for IR
Columbus	2 × 8 m, *f*/1.8 (binocular) Borosilicate honeycomb	Gear or Direct	*f*/5.4, and *f*/15 Cassegrain focii; *f*/33 combined focus
Gemini	2 × 8 m, *f*/1.8 Borosilicate honeycomb or ULE meniscus	Friction	*f*/6, and *f*/16 Cassegrain focii; *f*/20 Nasmyth focus
VLT (ESO)	4 × 8 m, *f*/1.8 ULE meniscus	Direct	Ritchey Chretien; *f*/15 focii at Cassegrain and Nasmyth
Keck	10 m, *f*/1.75 Segmented	Friction	Ritchey Chretien; *f*/15 focii at Cassegrain and Nasmyth; *f*/25 focus for IR

These characteristics are possible to achieve without sacrificing the exacting requirements on the performance, through use of closed loop servo systems and fast computers. The difficulties faced in making large telescopes with reasonable masses can be appreciated by making the simple observation that the deflection of a disk under self-weight is proportional to fourth power of diameter and inversely proportional to second power of thickness (d^4/t^2), and the deflection of a truss under self-weight increases as square of the length. Thus, any attempt to maintain a high enough rigidity, to keep distortions under gravity as negligible, would lead to an increase in mass which is much faster than the gain in area. The modern techniques of servo systems beat this limitation by applying real time corrections for the possible distortions.

In addition to the telescopes, the enclosures too are much smaller and lighter—this not only reduces the costs but it also improves the thermal characteristics and seeing of the observatory. In addition to the telescope and enclosure, a lot of attention is paid to the overall thermal control. The overall impact of the new design features is to promise image sizes of less than 0.3 seconds of arc and a pointing accuracy of 1 second of arc at affordable costs.

3. Various developments

In this section we present important developments in the technologies of mirrors, active optics, mechanical structure, drives, and thermal control.

3.1. *Mirrors*

The mass of the mirrors can be reduced either by using thin blanks or by using materials of low effective density. For any choice of the blank, the support system needs to satisfy the requirements on : number of supports, accuracy of supporting forces, and the resistance to wind loading. To get an order of magnitude estimate consider an infinite plate of glass, with a thickness t, supported on a two dimensional grid of points separated by a along the two axes. For $t = 20$ cm, and $a = 50$ cm, the maximum deflection under the force of gravity is 0.03 μm. In practice, the mirror is supported by application of the requisite forces at these points, and any errors in these forces would lead to distortions in proportion to $(d/a)^2(\Delta F/F)$, where d is diameter of the mirror, and ΔF the typical error in requisite force F. Thus, larger the number of supports, greater is the accuracy required on the supporting forces.

The focal ratio of the primary mirror is kept low to reduce the overall size. A fast primary requires higher accuracies in the optical alignment as well as polishing of steep aspherics. As an example, for the $f/12.5$ Cassegrain focus of JNLT an accuracy of 0.13 mm is needed in the centering of secondary mirror in order to keep the image size below 0.1 seconds of arc; the corresponding accuracy on secondary mirror tilt is 12 second or arc.

The high accuracies of supporting forces and of alignment can be achieved through real time closed loop control of these, by the technique named Active Optics which we will discuss in the next section. The polishing of fast mirrors can be done through use of active computer controlled laps in which the shape and the distribution of polishing forces is regulated in real time (Martin *et al.* 1992; Walker *et al.* 1992).

The thermal characteristics of the mirror can affect its shape as well as the seeing—in order to keep the figure undistorted due to the change in the temperature between the workshop and the site the coefficient of thermal expansion should be uniform to $< 10^{-8}/^{\circ}$C, and in order to keep the seeing effects below 0.5 second of arc the mirror temperature should not be higher than the ambient air by more than 1°C.

There are three alternatives being tried for very large glass mirrors, namely segmented, meniscus and honeycomb, and in addition metal mirrors are being developed. We discuss below the relative merits of each of these.

Segmental mirrors are based on an ancient idea, and many millimeter wave telescopes have used this idea very fruitfully. The large area of the mirror is made up with many small segments; each of these segments can be thin and light because of its small size. The mountings of individual segments are adjusted, using feedback from the aberrations in the images obtained, so that all of these in effect form the surface of a good large mirror. The most impressive example of such mirrors is the primary of W. M. Keck 10 m telescope (Nelson *et al.* 1989). The mirror is made of 36 segments, each of size ~ 1.8 m and 7.5 cm thickness; each of the segments has a shape appropriate to its radial location in the 10 m hyperboloid of 17.5 focal length. The thermal behaviour of these ULE glass segments is excellent because of the thinness—the time constant for thermal equilibrium with the air is only one hour. Each of the segments has its own cell and a passive support system, and the cells are adjusted in position and tilt to ensure that the segments combine to give a coherent large mirror. The main difficulties in such mirrors are in fabrication of the off-axis segments, and in the very elaborate and complex control of the mirror cells.

Meniscus mirrors can be thought of as segmented mirrors with welded joints between the segments. These joints provide the advantages of continuity across the boundary, as well as the disadvantage of transfer of forces and moments across the boundary. Examples of such mirrors are the 8m diameter and 20 cm thickness ULE glass mirrors of the VLT of ESO. These mirrors are extremely flexible, and in order to keep the figure these mirrors need a control of the supporting forces (distributed at about 200 points) with a fractional accuracy $\approx 10^{-4}$; the changing wind forces can be $> 10^{-4}$ of gravity forces and these lead to distortions which are hard to correct. The thermal time constant of these mirrors is large (several hours) and the effects of mirror seeing could be large if the air temperature changes faster than 0.2°C/hr. The distortions due to the inhomogeneity of the thermal expansion, coupled with the large temperature changes, could be partly corrected by active optics. In general, due to the extreme flexibility, any large scale distortions and aberrations can be easily corrected with active optics.

Honeycomb mirrors of borosilicate glass are being developed at Steward Observatory (Angel *et al.* 1990) for sizes up to 8m. These mirrors are made of two face plates of about 3 cm thickness, which are separated by a lightweight honeycomb about 60 cm high. As a consequence of the large overall thickness these mirrors are much stiffer than the meniscus mirrors. The high stiffness implies that a much larger fractional error ($\sim 10^{-2}$) in the supporting forces is acceptable, and consequently the mirror can resist wind forces much better—a gradient of 10 m/s in the wind speed over the full face of a 8 m mirror would lead to an image spread of less than 0.1 seconds of arc, if the average wind forces are fully balanced in each one third of the face (this can be achieved by having hydraulic supports and then interconnecting these within each one third). The thermal time constant is less than about one hour, if air circulation is maintained in the honeycomb core too. However, due to the large coefficient of thermal expansion the temperature needs to be maintained uniform to about 0.1°C.

Metal mirrors are being considered for large telescopes because of ease of handling and because of the good thermal conductivity (Rozelot *et al.* 1992). One of the important reasons for reluctance to use metal mirrors had been the possible dimensional instability i.e. creep, but with the successful use of active optics to correct for the small distortions the possibility of creep is not a deterrent in itself. In France a serious effort is being made to develop aluminium mirrors and there is a hope that soon such mirrors would be used in large telescopes.

3.2. *Active optics*

As we mentioned in the preceding two sections, the ability of a modern telescope to deliver good images despite the relatively less rigid (and low mass) subsystems depends on real time corrections through use of active optics. The use of active optics has been brought to a high level of perfection by ESO in their NTT (Tarenghi & Wilson 1989). The principle of active optics is illustrated in figures 1-3 (taken from the report National Large Optical Telescope, 1992). From figure 1 it can be seen that there are at least three main parts to the system : a wavefront analyser is used to analyse the aberrations in the image formed by the telescope (this is done by integrating the image over a period > 10s to average out the fluctuations due to the atmosphere), the control system transforms the information on aberrations to the requisite forces and movements to be applied to the mirrors, and finally the mirror

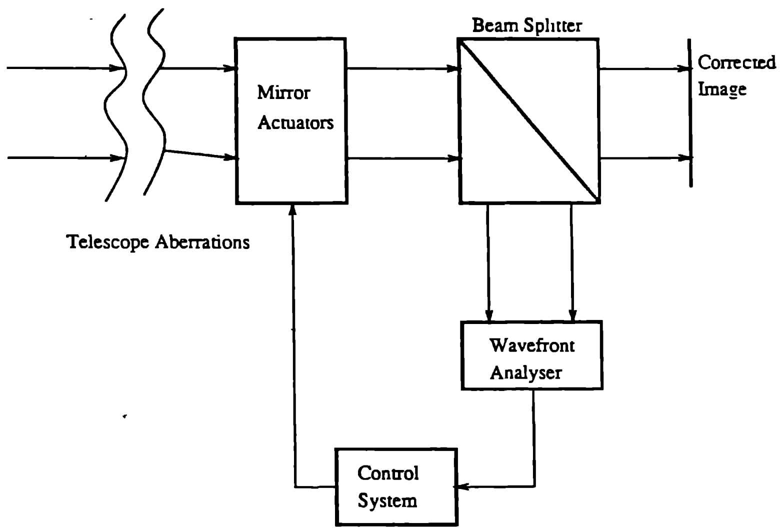

Figure 1. Illustration of active optics. The wavefront analyser works on average images integrated over long periods (> 10s) to eliminate the atmospheric effects.

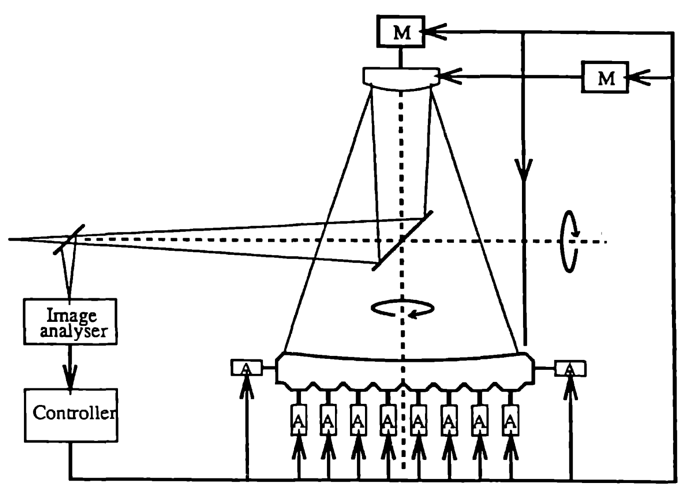

Figure 2. Principle of active optics control. The actuators (A) on the primary mirror are used to correct the figure, whereas the motors (M) are used to move and tilt the secondary mirror.

actuators apply these forces and movements. In figure 2 this is further illustrated; the actuators on the primary mirror would be force actuators for a monolith mirror, and would be position actuators for a segmented mirror. The functioning of wavefront sensor is illustrated in figure 3 : a two dimensional array of microlenses is used to image the different regions of the wavefront onto an imaging detector, the deviations of the image of any region from its expected position (as given by the image of the reference beam from the pin hole) are a measure of the errors in its slope. In the case of a segmental mirror, the slope errors only provide partial information and a measure of piston error is obtained by analysing the interference effects in the images of wavefront regions covering the boundaries between two segments (Chanan *et al.* 1988). Probably the most difficult part in implimenting active optics is the development of precision actuators—force actuators having an accuracy of 1 in 10^4 for meniscus mirrors, and position actuators having an accuracy of about 100 Å for segmented mirrors—and the successful use of these on NTT and Keck telescopes has opened the way for routine use of active optics in the future.

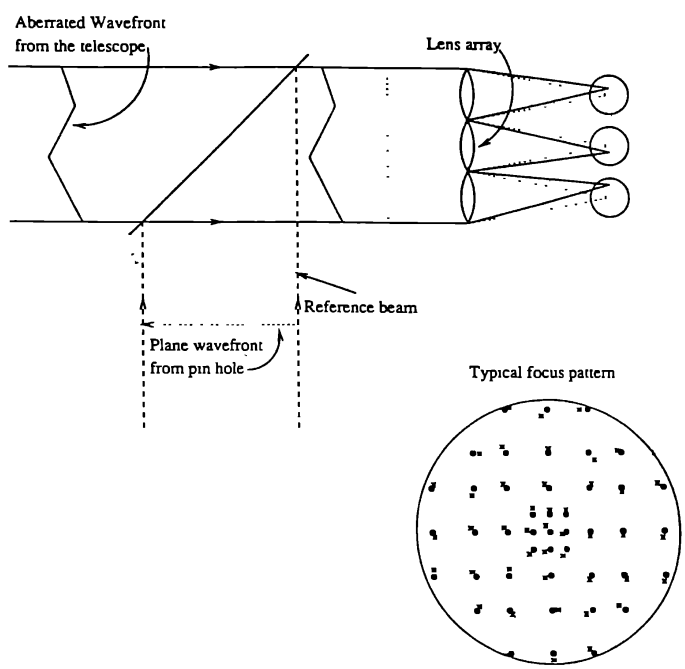

Figure 3. Principle of Shack-Hartmann wavefront sensor. The lens array is used to make individual images, on the detector, of several (≥ 20) subapertures of the wavefront. The positions of these images (shown as crosses) and those of the corresponding images from the reference beam (shown as filled circles) are compared to derive the tilt errors of the wavefront.

3.3. *Mechanical structure and axes*

The use of altitude azimuth axes has been facilitated because of the high precision angle encoders and advances in closed loop control. The structures for alt-azimuth configuration are much smaller as compared to those for equatorial configuration, and this has led to a large reduction in the costs. Further, the use of closed loop controls obviates the need for precision machining, and the usual machining accuracies ≈ 20 μm/m are acceptable provided the structure has repeatable performance.

Although alt-azimuth is the most favoured configuration today, several other configurations have been proposed for affecting economy—a common feature of many of these is the use of a spherical structure which is rotated on pads for achieving tracking (or other) motion along any axis (see, for example, Babcock 1988).

3.4. *Drives*

The drive has to serve two functions : firstly to point with an adequate accuracy (typically 1 seconds of arc in a modern telescope), and secondly to track the object with a high accuracy (typically 0.1 seconds of arc for the new generation telescopes) with the help of star-trackers. In order to achieve the pointing accuracy, the drive should be repeatable to that accuracy over periods of weeks, so that an adequate base of observational data is always available for characterising the system and hence eliminating any possible inherent inaccuracies. Given such a repeatability it is possible to get the pointing accuracy with high precision angle encoders mounted on the axes; perhaps the most promising of such encoders is the tape encoder rolled on the perimeter of the drive-disk (see, for example, Jäger 1992). Tracking is typically done under the guidance of a star tracker working in the focal field of the telescope; however there is a hope that in the future inertial sensors (gyroscopes) of adequate precision would be available to provide a more versatile alternative solution.

The signals from a star-tracker need to be integrated for several seconds, in order to average out the atmospheric perturbations and to collect enough photons from faint stars. Thus the drive system should be able to provide an accuracy of 0.1 seconds of arc over several seconds, while working unaided by the star-tracker; with the availability of the guidance of the star-tracker there is no requirement of a long term accuracy. This short term accuracy of drive can be obtained with a smooth friction drive and incremental angle encoders, and this provides a low cost alternative to the use of precision gears. The Keck telescope uses friction drive and many other telescopes have either used it or are proposing to use it. A very high performance and stiff drive can be obtained by using the disk of the drive as rotor of the motor, such drive is being considered for JNLT and VLT (see table 1).

3.5. *Thermal control*

In recent years a lot of attention has been paid to the thermal control of telescopes, enclosures, and the neighbourhood of telescopes. The overall aim of the control is to minimise the temperature difference between the atmosphere and any part of the telescope or its immediate neighbourhood which is exposed to the atmosphere. The primary mirror and parts of the telescope are made light to minimise the thermal inertia and time constant, any heat dissipation from the telescope into the atmosphere is kept low by enclosing the various motors etc. in insulated and temperature controlled boxes, and the oil of hydrostatic bearings is adequately precooled before reaching the bearings. The enclosures of the telescope is made as small as possible and it is kept at the expected night time temperature by cooling during the day. Further, the enclosure, including the space between its double skins of the walls, is adequately ventilated by the ambient air during the observations. The ventilation of the enclosure during observations is arranged such that the primary mirror also gets enough air flow on its surface. The support facilities, e.g. air-conditioning, computers, control room etc., are kept far away from the telescope enclosure. With all such precautions it has been possible to eliminate to a great extent the bad seeing effects of the telescope and dome.

4. Plans for a large national telescope

Some years back the Vainu Bappu Telescope, the largest of Indian telescopes, became operational. While, with its 2.3 m diameter, it provides new possibilities to Indian astronomers, a consideration has to be given to the future needs of observational facilities. The present period has a special significance in the planning of large telescopes because of the emergence of several new technologies, improvements in performance, and reduction in the costs. With this background, the Department of Science and Technology had appointed a Working Group (with S. N. Tandon as its Chairman) to study the feasibility of a large national telescope and to define the main parameters and design features of the telescope. The group submitted a report last year, and in the following we present a summary of the report.

In our country there are several telescopes of about 1 m diameter aperture and the VBT at Kavalur of 2.3 m diameter aperture. Thus the astronomers of our country have to try their luck to get observation time on foreign telescopes for those problems which require a larger telescope. In future, our astronomers would be at a greater disadvantage in attacking many problems on the forefront of astronomy unless they are provided with access to a modern telescope of a much larger aperture.

In contrast to the prevailing situation of optical telescopes in the country, the Giant Metrewave Radio Telescope (GMRT), being developed by TIFR, is going to be the largest telescope of its kind in the world. As a consequence of its unprecedented sensitivity, the astronomy community in the country is looking forward to new breakthroughs, e.g. in the study of origin of galaxies, to be made by observations of the far reaches of universe. The new exciting results obtained through observations with GMRT would open up new areas for observations in other spectral bands. Thus the results obtained with GMRT would provide new opportunities for attacking the problems in forefront with large optical telescopes. Therefore, in order to derive full scientific benefits from the GMRT, the development of this outstanding radio telescope should be complemented by a sufficiently large modern optical telescope.

It can be concluded that in view of the international trends, the need to support GMRT observations with optical observations, and the interests of Indian astronomers it is highly desirable that the development of a large national telescope is taken up without any delay.

4.1. *The proposed telescope*

A 4.2 m diameter aperture telescope is proposed to be built—while it is small as compared to the largest telescopes being built in the world, it has about four times the collecting area of VBT (the largest Indian Telescope at present), and with its modern design and new instrumentation it would provide the Indian astronomers with an order of magnitude more powerful tool of optical observations. The most important features of the telescope are described below.

The telescope would incorporate the three most important features of present day large telescopes : (a) a fast light weight primary mirror of focal length 8.4 m (*f*/2), (b) an alt-azimuth mount for compact mechanical structure, and (c) active correction of the optics during the observations to obtain sharp images. These important features would be complemented by a very compact and low-thermal-inertia enclosure for minimisation of the thermal disturbance in the nearby air, to get the best possible images. Some of the details are listed below.

Optical configuration : The optical configuration would be Cassegrain with a *f*/2 primary, and two focci (a *f*/8 for wide field observations and *f*/13 for high resolution observations).

Active optics : The primary mirror would be a 20 cm thick slab of ultra low expansion glass. As this mirror is very thin, the principle of active optics would be used to control the support forces such that the mirror gives sharp images. The active optics would also include corrections to keep good alignment of the primary and secondary mirrors.

Mechanical structure : The mechanical structure to support the optics and the bearings would be made of tubes of mild steel and would be divided into several parts which can be transported conveniently and joined together with fasteners. The typical accuracy required for the structure is 10″ as against the final accuracy and short term stability of 0.1″; this requirement could be met by the normal machining accuracy of 20 μm/m coupled with avoidance of any internal stresses to give stability.

The choice of the altitude-azimuth drive coupled with a fast primary mirror would lead to a very compact overall structure of about 7 m diameter by 14 m high; the overall mass of the moving parts would be about 40×10^3 kg. A sketch of the mechanical structure is shown in figure 4.

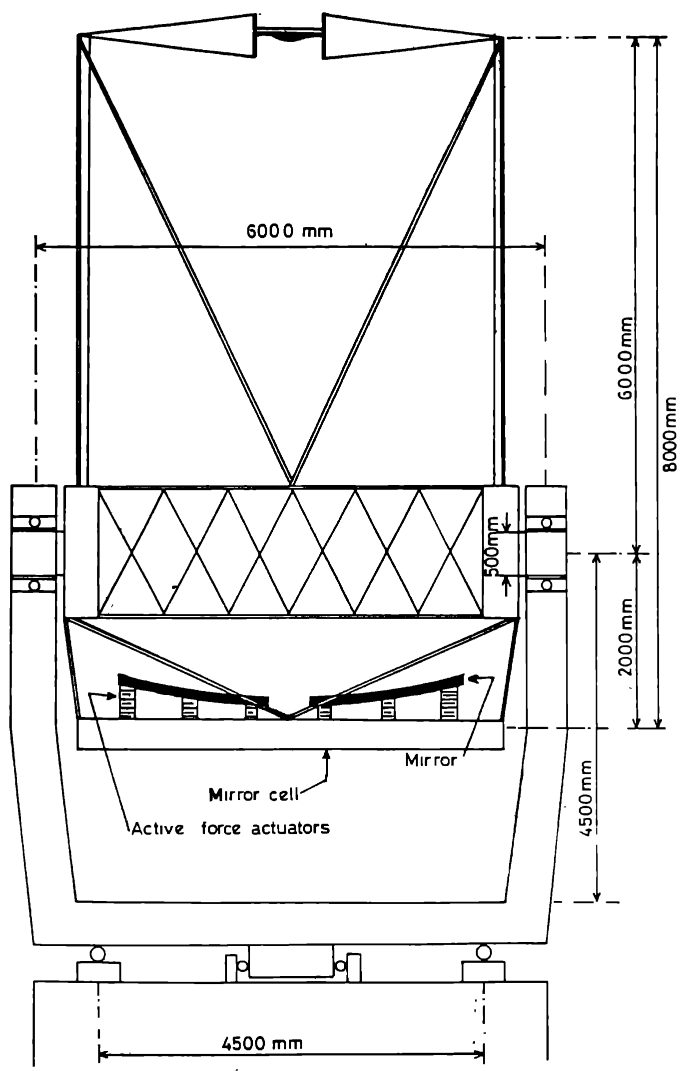

Figure 4. A sketch of the mechanical configuration of the proposed 4.2 m telescope is shown. Note that no Nasmyth focii are proposed.

Drives and control system : The drives for the two axes would be provided by friction gears coupled to torque motors. The pointing is achieved with reference to absolute and incremental angle encoders mounted on the two axes, and finally with reference to guide stars; the control bandwidth would be about 1 Hz.

Buildings : The enclosure for the telescope would be a low weight and low thermal inertia octagonal or circular based prism—the size would be about 20 m diagonal and a height of about 15 m. All the service facilities, and the control room etc. would be housed in another building placed far away to minimise the thermal perturbations near the telescope.

4.2. *Location of the telescope*

The usefulness of the telescope depends very directly on the weather conditions prevailing at the site. Thus the site should not only provide a large number of cloud free nights, but the atmospheric turbulence should also be low to provide sharp images. The locations of our existing telescopes are not very good from this point of view and it is desirable that a better high altitude site is selected for this telescope.

On the basis of the work done by Uttar Pradesh State Observatory, we already know of two very good sites—Devasthal and Mornaula in Sivalik ranges—at a height of about 2300 m. These sites provide about 200 good nights per year, and at Devasthal the seeing (sharpness of the images) is often better than 1″.

Whereas the final decision on the site can only be taken after further investigations, the existing information provides us with two very good prospective sites in Mornaula and Devasthal.

4.3. *Project management, time schedule and budget*

Although the project is envisaged as a collaborative effort between many institutions, a major share of the work and the project coordination would need to be done at a lead institution. Within the framework of the lead institution, an independent project team (of astronomers and engineers) would be established which reports to a national monitoring committee including representatives of the various participating institutions.

The project team would consist of a project director who should be an experimental astronomer, and about six other astronomers and engineers. The main job of this team would be to ensure that the specifications of the telescope as a whole and of each sub-system individually are met in good time, through the necessary checks and coordination with the various collaborating institutions and other agencies.

Of the many subsystems involved in this project, some need a longer time scale than the others. The primary mirror and its support are subsystems which need attention first. The order for the blank should be placed in the first year, and work on the optical workshop, which would figure the mirror, should be started simultaneously. In about three years one should have developed the techniques to fabricate the large mirror; the work on primary mirror could start then and it could be expected to be ready in five years.

The design of the framework and drives would be completed in two years and it would take another two years to fabricate the parts, assemble them and test in the workshop with dummy loads. The basic design of buildings and other facilities, e.g. coating plant for the mirrors, would be finalised in two years, and fabrication work would start after that. The site would be selected in about two years so that the construction work can start early.

The details of the instruments for observation and the computer would be finalised in the first two years, and the responsibility for their development would be given to the various institutions so that these would be ready before the fifth year. Starting from the end of the fifth year, integration of the various subsystems and debugging could start, and the first observation would be made after another six months. At the present price level, the cost of various subsystems for the telescope is estimated as follows (figures in brackets give the foreign exchange component in percentage).

(a) Mirror	
Meniscus blank	Rs. 7 crores (100)
Figuring and Supports	Rs. 10 crores (60)
(b) Framework and Drives	Rs. 6 crores (40)
(c) Sensors and Guidance	Rs. 5 crores (60)
(d) Service facilities	
(Coating plant, computers etc.)	Rs. 5 crores (40)
(e) Telescope Building	Rs. 5 crores
(f) Buildings for services	Rs. 5 crores
(g) Instruments for Observation	Rs. 6 crores (60)

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