# THE TWO-MIRROR TELESCOPE (2MT)

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## SUMMARY

Two eight-metre mirrors on an alt-azimuth mount are considered as a Future Large Telescope. The combined collecting area is ten times that of a four-metre class telescope, and the main modes of use are for optical spectroscopy and infrared imaging. In one square arc second, at 10μm wavelength, the telescope with adaptive auxiliary optics will yield 30 to 100 fully resolved image elements (not speckles). The mechanical arrangement proposed to give path length stability is to link the two tube centre sections along a horizontal axis and to use a total of four altitude bearings. A combined focus is necessary for the highest angular resolution, but other work such as spectroscopy can be carried out either at a combined focus or using separate instrumentation for the two eight-metre apertures. Twin prime and Cassegrain foci and horizontal Nasmyth platforms are intended for such pairs of spectrographs and other instruments, depending on their weight and field requirements. A pair of prime focus spectrographs with f/0.8 cameras is one appropriate system. (The horizontal Nasmyth platforms to accommodate larger spectrographs are a feature of this telescope which is not feasible in other MMT-type configurations). Another significant capability is that for a coudé-type light path from either aperture to the vertical axis. This can be achieved with four reflections (including the primary) for some applications. In addition to the conventional uses of the coudé light path, there is the possibility of using it to produce interferometric links to other telescopes. These links may be important as a future extension of the instrument.

1. <u>Introduction</u>. The Two-Mirror Telescope will be referred to here as the 2MT. Perhaps more rigorously defined as a two-aperture telescope, it has two eight metre primary mirrors. It could be described as a two-mirror version of the Multiple Mirror Telescope (MMT), although it is intended that most optical work would be carried out with separate instrumentation on the two apertures, for efficiency. Two-mirror telescopes of this type have not been discussed at any length although a two-mirror system is part of the interferometer proposed as the

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University of Arizona Versatile Array (Woolf et al., 1983; Angel et al., this colloquium). Two-mirror systems are mentioned by Humphries at this colloquium.

Many concepts for Future Large Telescopes have been put forward, for optical and infrared observations. One of the strong themes to emerge is that of obtaining high angular resolution. Woolf and Angel (1980) pointed out that a 15-metre class telescope should be capable of yielding diffraction limited images at, say, 10μm wavelength. This is achieved with adaptive optics using aperture elements as large as three metres, controlled by guiding at optical wavelengths on a field object. This produces fully resolved images, not speckle patterns. The basis of Future Large Telescope studies has been renewed by this proposal, since it establishes a qualitatively new rationale for 15-metre telescopes, in addition to the anticipated large reduction in observing time. The number of picture elements resolved in a given field will be proportional to the area spanned by the telescope's aperture. There are other worthwhile methods on smaller telescopes of improving angular resolution at optical as well as infrared wavelengths, but probably any of those methods can also be applied on future large instruments. The predictability of the diffraction-limited image should also be useful in establishing the quality of images obtained. It will enhance all work which relies on images taken sequentially. On present telescopes such work is degraded by variable and unpredictable seeing.

The 2MT as described here will yield at least 30 resolved picture elements measured to half peak intensity in one square arc second at 10μm wavelength. The ultimate resolution would not be increased by putting the telescope in space. The 30 elements may be increased to 100 by using the aperture at different position angles, as discussed below. The capability for infrared observations will be in addition to that for optical work, in particular for optical spectroscopy.

The scientific justification for future large telescopes has been reviewed notably by the committee chaired by P. Strittmatter (1980). The types of observation most relevant to the present proposal are those involving optical spectroscopy (at any resolving power) and many using the 1 to 5 and 7 to 13 μm wavelength regions. Many of the points discussed here, especially the optical systems, are relevant also to other telescope designs.

The background to the 2MT concept and the numerical aims of its design are shown in Tables I and II. Table I outlines the technical and scientific advances which have enabled this to be done, and Table II gives a self-consistent set of numerical aims for the performance of a Future Large Telescope. These aims are adopted for the 2MT.

### Table I

### Summary of developments emerging with and since the Disney (1972) array concept

| | |
|---|---|
| General | Subdivision of aperture into an array, segmented mirror or MMT |
| | Construction and use of the MMT |
| | Engineering for 7 to 15 metre mirrors |
| | Segmented mirror telescope design |
| Imaging | Application of seeing theory to telescope design |
| | Practicality of 0.2 arc second resolution at 10μm |
| | Adaptive optics and software control |
| Instrumentation | Requirement for infrared and optical use |
| | Applications of single, separate and combined foci |
| | Spectrograph developments |
| | Implementation of multiple-object spectroscopy |

### Table II

### Numerical aims of the 2MT as a Future Large Telescope

The wavelength range will be 0.3μm to 20μm.

With active optics the angular resolution will be less than 0.2 arc seconds most of the time (giving at least 30 resolved elements per square arc second) at 10μm.

The collecting area will be about ten times that of a four metre class telescope.

Optical spectroscopy (with diffraction gratings) will be possible with slits of width 0.4 arc seconds at a resolving power of 50,000.

The field of view for multiple object spectroscopy will be 20 arc minutes in diameter or larger (giving 50 to 100 objects down to magnitude 20.5 in a random field).

Although the aims in Table II are self-consistent, the slit width of 0.4 arc seconds at 50,000 resolving power may be increased as discussed later.

2. General Concept. The general concept of the 2MT is shown in Fig. 1. On an alt-azimuth mount, the two mirrors are spaced along the horizontal (altitude) axis. The altitude axis is defined by four bearings which determine the

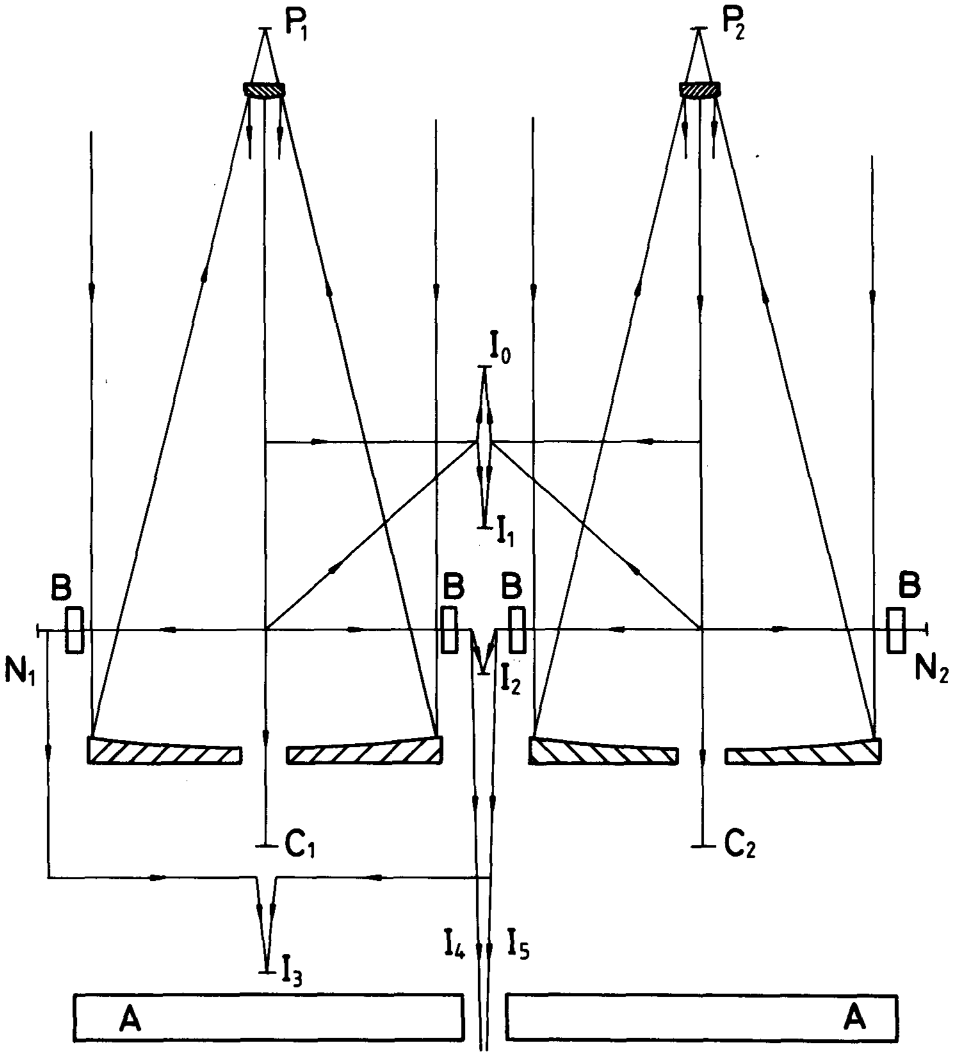

Figure 1. Positions of the various focal stations which can be incorporated in the 2MT concept (see text). For simplicity, folding flat mirrors are omitted. The four altitude bearings are denoted by B. The base represents the azimuth turntable.

alignment and distribute the loads on a horizontal baseline. (This principle is used on various radio telescopes, in particular those of elliptical or cylindrical form.) Conventional prime, Cassegrain and Nasmyth foci are shown at $P_1$, $P_2$, $C_1$, $C_2$, $N_1$ and $N_2$. It can be seen that Nasmyth foci on a platform which remains horizontal are practical in this structure whereas they would not be for additional primary mirrors as in the MMT.

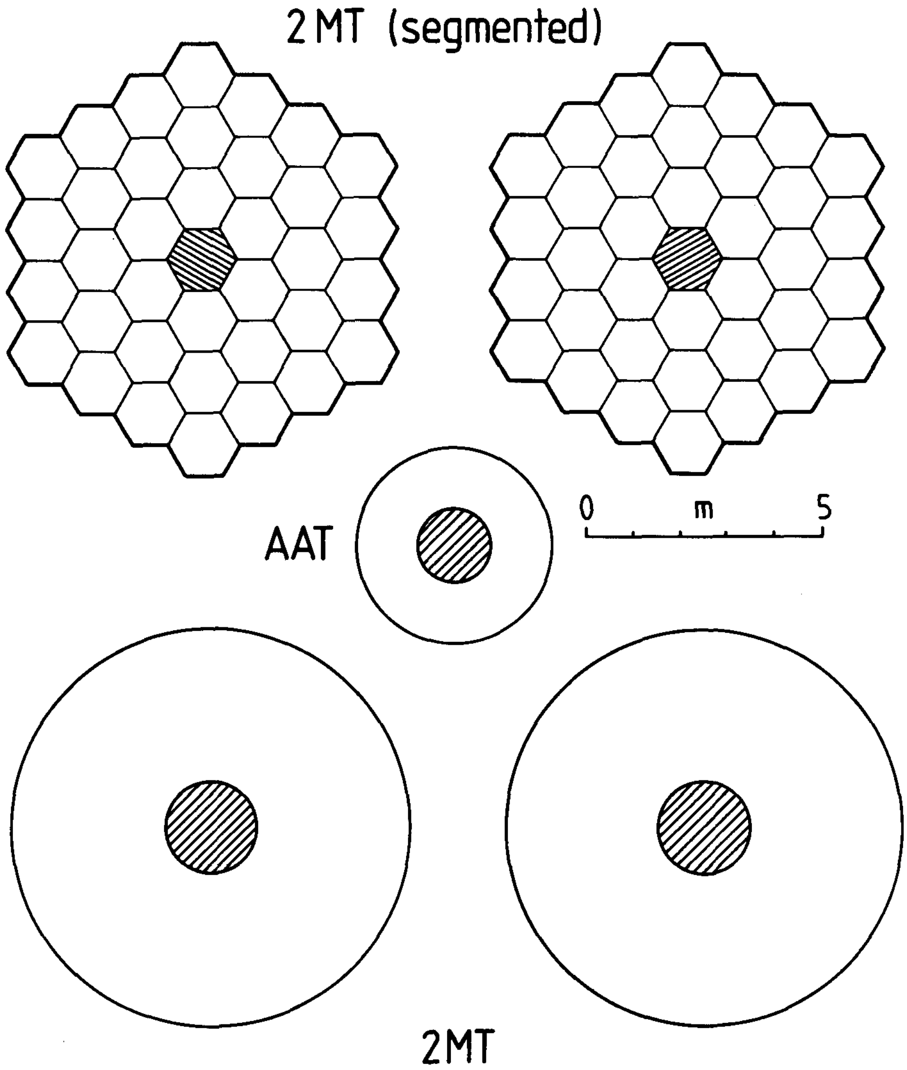

Figure 2. Primary mirrors of the 2MT. The upper diagram shows two hexagonal 36-segment mirrors, and the lower one shows two circular apertures. The gap is the maximum value (two metres). For size comparison, a typical four-metre class telescope is also shown.

More unusual foci of a Nasmyth or coudé character exist near $I_3$, $I_4$ and $I_5$. $I_3$ is a coherent combined focus, and $I_4$ and $I_5$ are paths to a coudé focus or interferometric links to other telescopes. Interferometric links are considered to be a possible extension to this concept.

The light paths indicated by $I_4$ and $I_5$ exhibit differential field rotation, but could be suitable for (high-resolution) spectroscopy of bright stars in the simple form shown; that would be typical coudé work.

Combined foci which move in altitude with the optical structure include $I_0$, $I_1$ and $I_2$. $I_1$ and $I_2$ are coherent combined foci of the type described by Beckers and Hege (1982), and $I_0$ is an incoherent combined focus.

The prime foci of the two telescopes would be used with separate instruments, including field correctors or spectrographs running in parallel, or various secondary mirrors may be required as described by Bingham (1983a).

The primary mirror arrangements are shown in Fig. 2.

The primaries may be 36-segment mirrors as described by Nelson (1982) and at this colloquium, the control system being discussed by Mast and Nelson (1982). (These aperture segments are not necessarily those used for the adaptive imaging system. The adaptive elements may be in an auxiliary instrument, and would be situated near a pupil image unless the field of view is very small). The alternative structure for the primary mirrors, appearing equally likely at the time of writing, is the monolithic casting described by Angel at this meeting. Fig. 2 also shows that there is a gap between the two primaries to accommodate the two central bearings and beam paths shown in Fig. 1.

The general arrangement is consistent with the potential availability of the large mirror technology mentioned above. Another factor influencing the design is that the aperture is filled in one dimension; the effect is that the diffraction patterns given below have at least 61 per cent of the flux in the central maximum (more if the two metre space between the apertures can be reduced). The elongated shape of the dual aperture for a given area increases the ultimate angular resolution as described later.

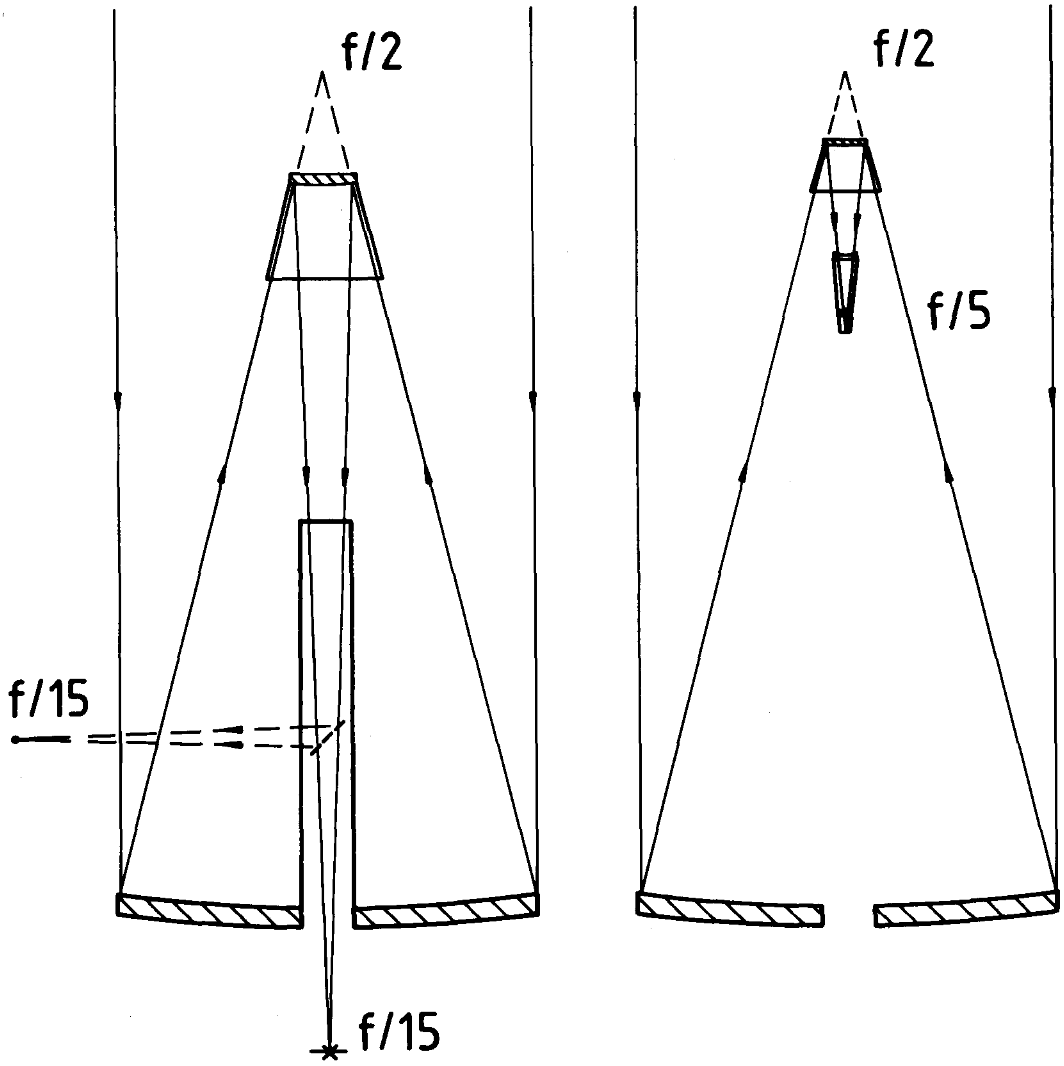

Figure 3. Alternatives of normal Cassegrain and internal Cassegrain (Bingham 1983b) foci with 20 arc minutes field. (At any one time, both telescopes would normally be fitted with similar optics; these different systems are shown in juxtaposition so that they can be compared.)

Fig. 3 (left) illustrates the optical system with sky baffles for an f/15 Cassegrain focus (20 arc minutes field) and Nasmyth foci. Fig. 3 (right) shows an internal f/5 Cassegrain focus (Bingham 1983b) which has aberrations corrected over the same field of 20 arc minutes diameter. These systems are alternatives for multiple object spectroscopy over such a field, also requiring correction of atmospheric dispersion. In the case of the f/5 system, it is possible that prisms for this purpose may be incorporated in one of the lenses without additional air-to-glass surfaces.

3. Spectrographs. For the usual reasons, optical spectrographs for the 2MT must be designed in outline at an early stage: especially as several different foci may be involved, we need to see the mechanical structure and optical characteristics required from the telescope.

Cross-dispersed instruments pose the largest problems with eight metre apertures. In Table III, the limitations for given échelle and detector characteristics are contrasted for different telescope sizes.

Table III

Spectrograph example using a given échelle and detector

Given parameters:
Resolving power $\lambda/\delta\lambda = 50{,}000$
Blaze angle of échelle 63.5 degrees
Width of échelle 400 mm
Deviation from Littrow condition 14 degrees
Slit image width = 2 detector pixels
Detector height perpendicular to dispersion = 1000 pixels
Order separation = 4 arc seconds

| Telescope aperture diameter (metres) | Slit width (arc seconds) | Number of orders within detector (if equispaced) |
|---|---|---|
| 4 | .73 | 55 |
| 5.6 | .52 | 39 |
| 8 | .37 | 28 |
| 11.3 | .26 | 20 |
| 16 | .18 | 14 |

From Table III, it can be seen that the telescopes of different sizes from four to 16 metres diameter collect photons at the same rate! This is given by the product of the telescope area, slit width and number of orders. The cross-dispersion problem is discussed by Walker and Diego in these proceedings.

Table III illustrates one of the advantages of using two eight-metre apertures rather than one of 11.3 metres which would have half the light-grasp. Even at eight metres aperture, the slit width of 0.37 arc seconds is narrower than necessary to define the source properly under most seeing conditions. The slit width (or "étendue") of such instruments could be increased by one of the methods described by Bingham (1983c). Recalling that the main value of an échelle is to obtain many resolved spectral elements on a small detector, the problem may alternatively be reduced by using a large detector. That could be a row of detectors in a coudé spectrograph, or the system described by Enard in these proceedings, although it may be difficult to record a total length of spectrum equal to an échelle system. Gaps between detectors placed in a row may be filled using mirrors and a second row of detectors (Bingham 1978).

The list of probable spectrographs (including both échelles and coudé systems) is given in Table IV.

Table IV

Spectrographs for the 2MT

| FOCUS | |
|---|---|
| Nasmyth or Cassegrain | Two separate échelles for the two foci with R ~5 x $10^4$<br>Separate spectrographs each with two or three optical channels and R ~$10^4$ |
| prime | Separate fast spectrographs with R ~$10^3$ |
| coudé or combined focal stations | Segmented aperture system (with parallel spectra from sub apertures) and R ~$10^5$ at coudé<br>Separate spectrographs for the two beams<br>One spectrograph with a dual camera |

The "dual camera" refers to a system described by Bingham (1983c) which acts both as a spectrograph camera and a beam combiner.

For the most efficient use of the two primaries, separate spectrographs will be requred for two foci in some applications and this deserves some comment. Any MMT-type system may be used efficiently with independent instrumentation for the separate primaries, when coherence of the full aperture is not required. The construction of two spectrographs of a given type, which the 2MT may need, should be feasible for such a large facility. Prototype or unique instruments can be used at a combined focus, or, if that is not suitable, with half the total telescope. That is, of course, a larger proportion than would be available for a prototype instrument if there were more primary mirrors. These two options for prototype instruments should make it reasonable to use them from time to time.

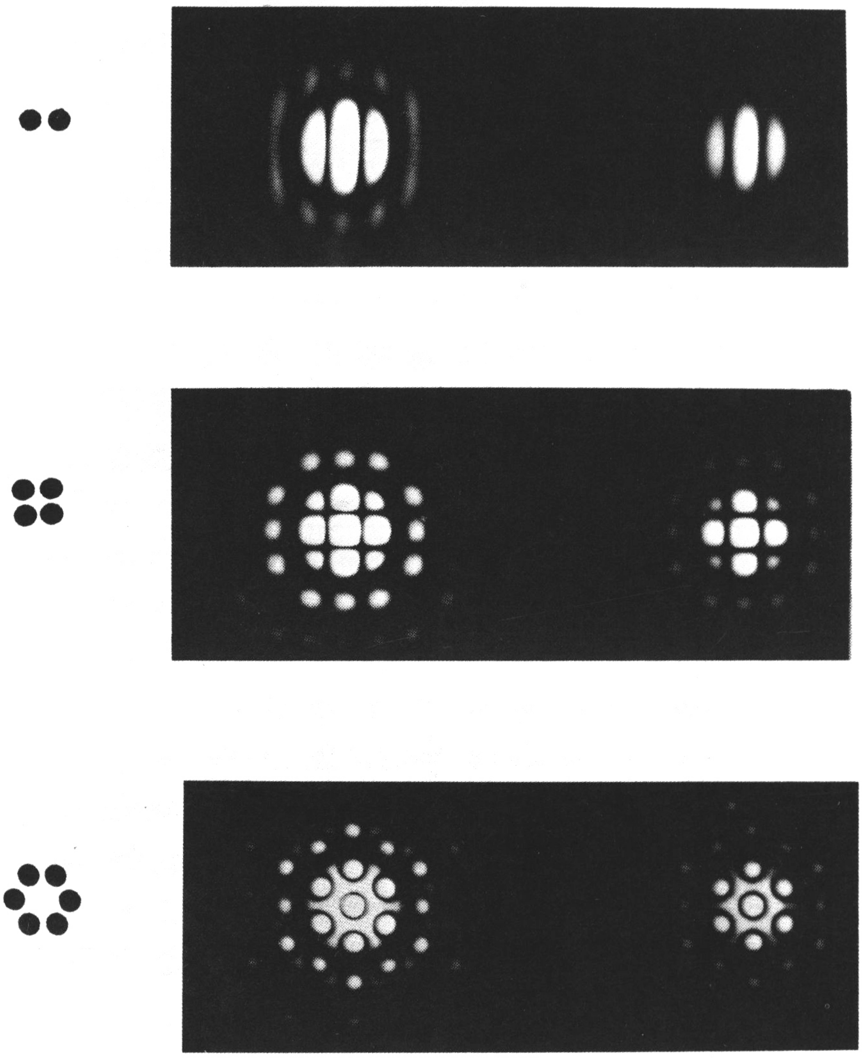

Figure 4. Photographic diffraction patterns reproduced from different pages of Meinel et al. (1983) for comparison.

The use of separate spectrographs for the two prime foci alleviates the problem of producing very fast camera systems. For an entrance slit width of one arc second and a slit image width of 30μm, a relative aperture of f/0.77 is required for an eight metre telescope. Cameras for such an application have been described by Bingham (1982). A relative aperture of f/0.55, which is more difficult to achieve, would be required for a single telescope with the equivalent collecting area (11.3 metres diameter).

4. Diffraction-limited imaging. Diffraction-limited (infrared or speckle) observations could be obtained from the individual apertures or from the optically combined beams. The combined beams are obtained at the coherent foci indicated in Fig. 1. For comparison, the diffraction patterns of systems of two, four and six apertures are indicated in Fig. 4. This is reproduced from parts of

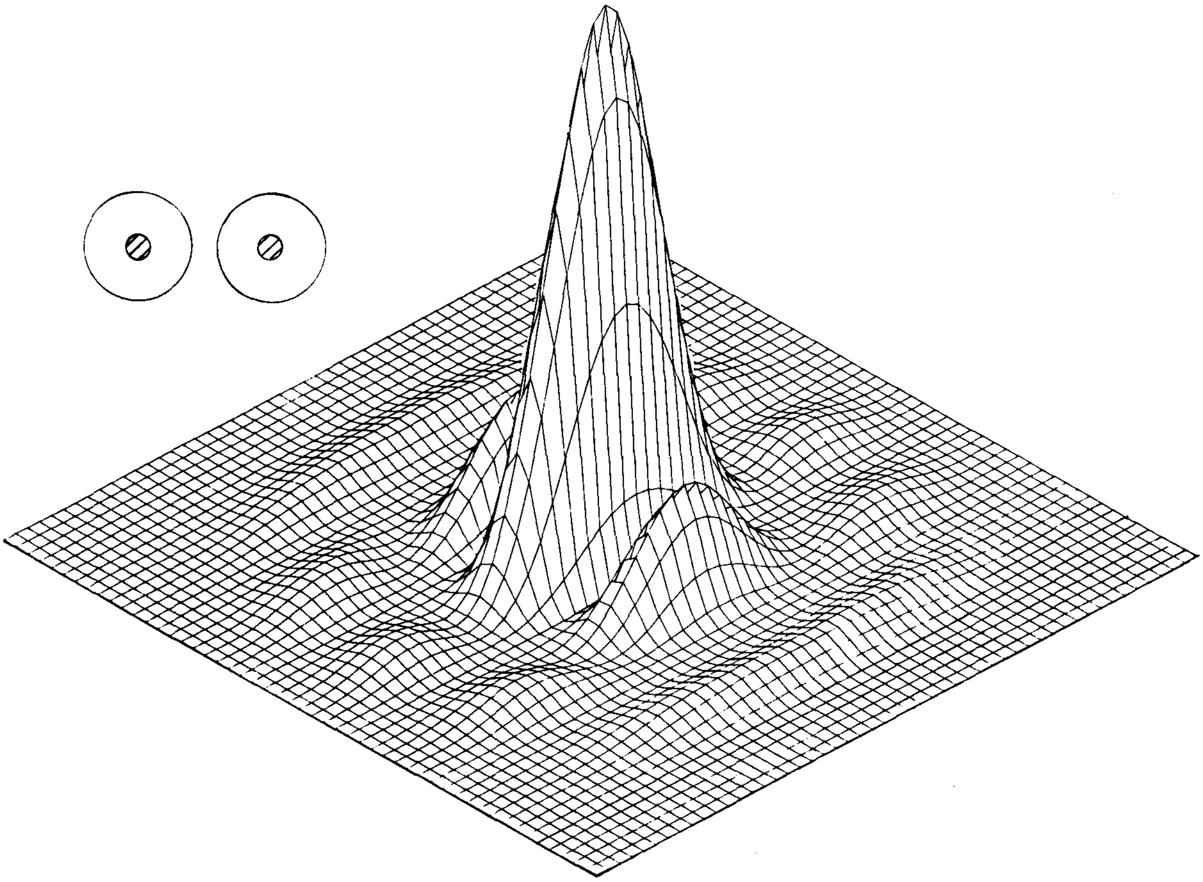

Figure 5. The point spread function of two eight metre mirrors with central obstructions and a two metre gap. One square is equivalent to 0.02 arc seconds for $\lambda = 8\mu m$.

three separate figures in Meinel et al. (1983). It can be seen that the system of two apertures gives a relatively simple pattern which should be easy to interpret in the presence of noise and complex object structure.

The computed diffraction pattern from two apertures separated by half a radius (2 metres) is shown in Fig. 5. (Figs. 5 and 6 are due to C. Dunlop and J. V. Major.)

The sidelobes to the main beam have about twice the intensity obtained from two apertures in contact, but this is the worst case; no problem is expected in keeping the necessary optical and mechanical structure within this 2 metre gap. As the Fourier plane (Fig. 6) is fully sampled, the sidelobes can be removed in data processing (without attempting to enhance the resolution).

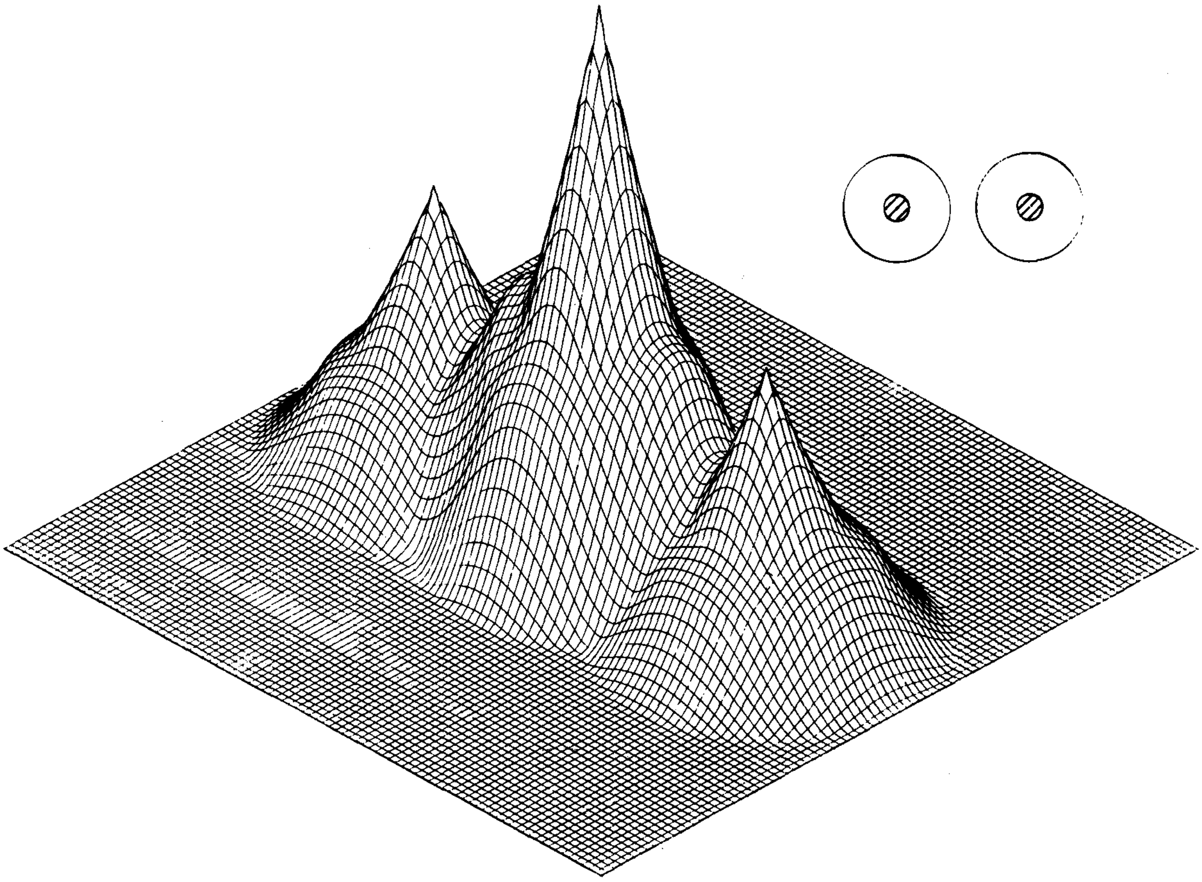

Figure 6. The modulation transfer function corresponding to Fig. 5. One square is equivalent to 0.242 arc sec $^{-1}$ for λ = 8μm.

Typically at 10μm wavelength, the size of the central maximum of the diffraction pattern is 0.1 x 0.3 arc second at half maximum intensity. The resolved picture element is elongated in different position angles in celestial coordinates depending on the hour angle of the object field. By making a series of observations, an image with a symmetrical resolved patch of diameter 0.1 arc second can be obtained. This form of image reconstruction has recently been discussed by Traub and Davis (1982). They develop a Fourier transform method of deriving the optimum estimate of the original scene when an elongated, diffraction-limited aperture is used at various position angles. Traub (1983) has confirmed the method by experiment. The use of an elongated resolution element, when the full series of observations is not available, is common in Radio Astronomy. (As the 2MT is pointed as a unit, the instantaneous profile is not dependent on declination, unlike large radio instruments.)

The problem of adaptive compensation for seeing has been discussed by Hardy (1982) in general terms and in relation to infrared imaging by Woolf and Angel (1980), and Woolf (1982). These papers show that sub-apertures of 3 metres are appropriate for diffraction-limited adaptive optics at 10μm in good seeing conditions. In the 2MT, these can be produced by seven segments covering each eight-metre aperture. The adaptive components can be situated at pupil images on a scale greatly reduced from the primary mirrors, and need have no relationship with the hexagonal segments which might be used to form a segmented primary mirror. (However, it might be useful to align the joints between segments to avoid introducing more diffraction spikes). The adaptive movements should maintain an approximation to a continuous surface. This can clearly be achieved by deforming a flexible mirror, or by controlling the movements of discrete mirror elements so that they act as if hinged at a point on each boundary with another element. Discrete hinged elements are appropriate when controlling the movements with optical guide star images as described by Woolf and Angel (1980). The hinge principle can be extended to the gap between the two eight-metre apertures. The two aperture elements adjacent to the gap should make adaptive movements with the constraint that they act as though linked to a universal hinge or pivot at the centre point of the gap.

The use of only the two apertures of the 2MT provides useful degrees of freedom since the exact pointing of one aperture and the length of one path to the focus are arbitrary. It is hoped to discuss the effect of adaptive optics on two apertures using the hinge principle in more detail elsewhere, in particular to study the phase errors due to the gap.

4. Structure. The mechanical structure of the 2MT has the important functions of:

(a) providing distributed support and alignment along the horizontal altitude axis;

(b) providing a partially compliant centre tube section which defines the aperture separation but derives its alignment from the four altitude bearings (two for each eight-metre section);

(c) providing a rigid top frame which mechanically links the two secondary mirrors and maintains the alignment of the two axes.

A rigidly linked, twin top section is obtained by twinning the top frame of the California Ten-Metre telescope (Nelson 1982 and references therein). The derived double frame is illustrated in Fig. 7. It can be seen potentially to provide the required coupling very effectively. The California tube design has a centre section which is also hexagonal, but rotated $30^{\circ}$ compared with the top frame. This conveniently provides the capability for a laterally compliant link between two apertures as required at this point, to be consistent with the alignment provided by the altitude bearings. This is shown in Fig. 8, when the two short horizontal members represent a link which allows alignment while determining the separation of the two apertures.

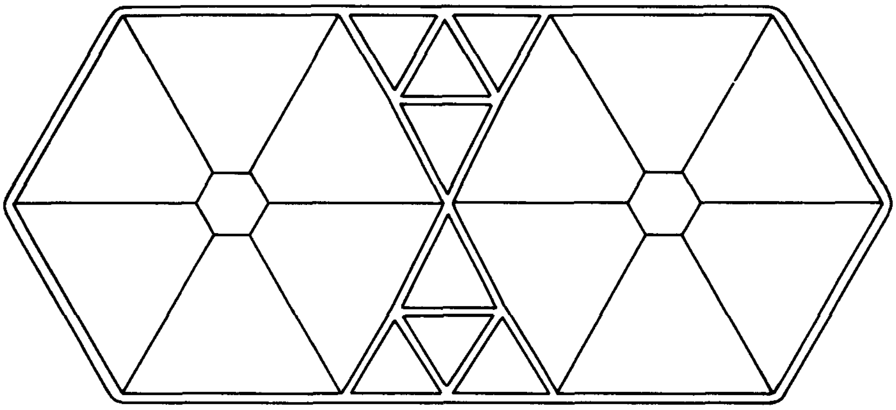

Figure 7. The top frame structure, adapted for the 2MT from the University of California 10-metre segmented single aperture design. This illustrates how the tube ends and secondary mirrors can be rigidly joined to ensure alignment.

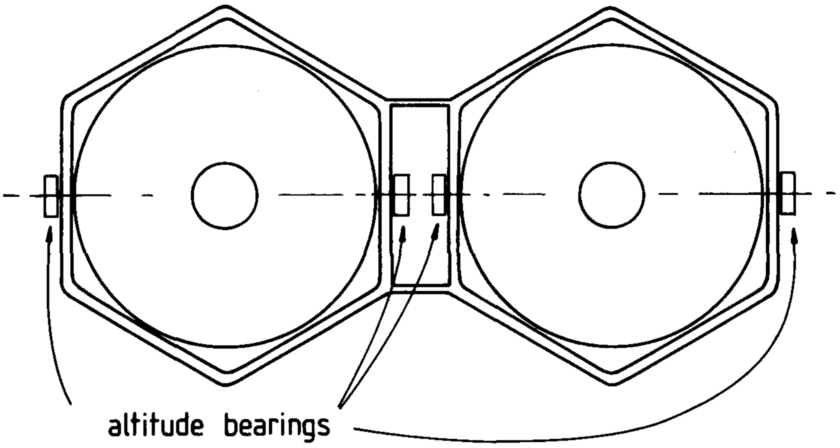

Figure 8. The centre section of the telescope showing the schematic positions of the altitude bearings and the horizontal links which supply the minimum connection between the two hexagons see text).

Although simple circular mirrors are indicated in Fig. 8, this frame was derived from the University of California's segmented mirror system and so is equally suitable for that.

A building concept for the 2MT has been outlined by A D White and is shown in Fig. 9. The up-and-over shutter is appropriate for the aperture shape and will optimise the image quality by providing the choice in operation of the size of the opening. The largest opening must be used to reduce temperature differentials (ideally to ~0.2°C), but this type of shutter can also provide a reduced opening to act as a windshield when that becomes essential. The building may be compared with those for other telescope designs. It is not so high as one for a telescope with a single circular aperture with the same area and the same focal ratio as in the 2MT. A four (square array) or six (hexagonal array) mirror MMT of similar area, although more compact, would probably not be accommodated in a building with the adjustable shutter as proposed for the 2MT because large extensions to the shutter opening would be required over the zenith and at the horizon. A supplementary windshield would of course need equal openings.

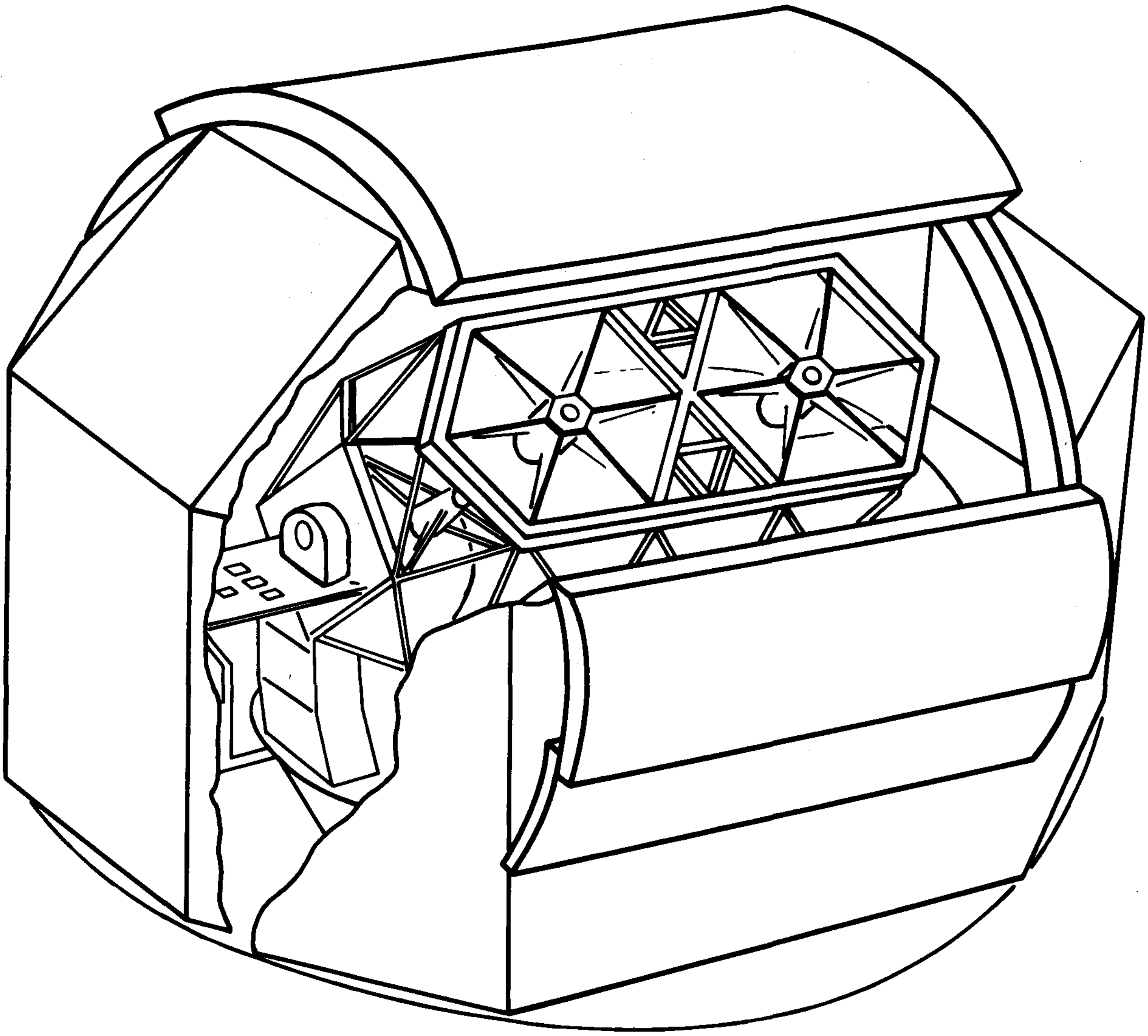

Figure 9. A schematic building for the 2MT

A substantially new material has been suggested for such buildings by M C Morris. The material is used in a stressed-skin construction and consists of a light sandwich of stainless steel sheet and insulating layers. This material was originally developed for offshore oil rigs.

6. Conclusions. The characteristics of the 2MT and its instrumentation include the following.

There are two eight-metre mirrors which give

(a) ten times the collecting area of a four metre class telescope

(b) ten to 30 times the number of resolved picture elements compared with a four metre class telescope, at the diffraction limit.

The maximum baseline for interferometry (corresponding to the maximum spatial frequency) is 18 metres (to be compared with the 11.3 metre diameter of the single aperture of the same collecting area).

The aperture is filled in one dimension, increasing the central energy concentration in the diffraction pattern compared with less filled apertures.

The determination of phase errors can take advantage of the degrees of freedom inherent in a single aperture.

The use of separate spectrographs (and other instruments) for the two apertures (a) gives an increase in light grasp compared with a single aperture (b) is feasible because only two instruments are required and there are useful modes for unique or prototype instruments.

The 2MT is effective with a "dual off-axis" spectrograph camera (Bingham 1983c)

The main interferometer axis is horizontal and therefore relieved from some gravitational and thermal distortion.

The tube structure is supported by four altitude bearings against sag and vibration. The two central bearings are feasible in this horizontal configuration of two mirrors.

There are horizontal Nasmyth platforms for each aperture.

There are coudé paths which may allow (a) an insulated spectrograph room to be used (b) extension of the system for interferometric links with other telescopes using a reasonable number of reflections.

The building differs in design from those which would be required for different aperture shapes. It has the capability for incorporating an up-and-over shutter giving an adjustable opening, allowing the optimisation of ventilation and windshielding according to conditions.

Acknowledgements. The author is very grateful to the following: Mr C Dunlop and Dr J V Major for sending me the results of their diffraction calculations in advance of publication; Mr A D White for the building concept in Fig. 9; Dr R Ellis for discussions on astronomical applications; Dr W A Traub for preprints on image analysis from apertures extended in one dimension; Mr M C Morris for his suggestion of a skin material for the building; and Dr I G van Breda for comments on the manuscript.

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## DISCUSSION

R. Wilson: Do you consider daylight IR use to be compatible with telescope seeing?

R. Bingham: If it is to be compatible at all, the use of a dome will surely be preferred to the schemes which would expose the telescope to the Sun.