Vistas in Astronomy, Vol.28, pp.531-553, 1985
Printed in Great Britain. All rights reserved.

0083-6656/85 $0.00 + .50

THE WILLIAM HERSCHEL TELESCOPE

A. Boksenberg
Royal Greenwich Observatory, Herstmonceux Castle, Hailsham, East
Sussex BN27 1RP, U.K.

SUMMARY

The construction of the new 4.2m altazimuth-mounted telescope is now nearing completion. It, and some of its instrumentation, are described in some detail.

1. INTRODUCTION

As part of the Isaac Newton Group of telescopes based on La Palma in the Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias, The Royal Greenwich Observatory, on behalf of the UK Science and Engineering Research Council and the Netherlands Organisation for the Advancement of Pure Research, is installing a new 4.2m altazimuth-mounted telescope. This telescope, known as the William Herschel Telescope, was designed by the RGO in conjunction with Freeman Fox and Partners and manufactured by Grubb Parsons Ltd (Northern Engineering Industries plc) in Newcastle; it is due to become operational in 1987. A substantial complement of instruments is being prepared by the RGO and university groups in Britain and the Netherlands for general use.

The WHT will be the world's third largest telescope with a single main mirror and it is expected that the already proven excellent observing conditions on La Palma, together with the most up-to-date instruments and detectors, will give it the edge over its larger rivals, the 5m telescope in the USA and the 6m telescope in the USSR. The telescope has been assembled and thoroughly tested at the Grubb Parsons works (Plate 1) and has met its stringent performance specifications. It is now dismantled and ready for shipping to La Palma. The WHT is the largest telescope Grubb Parsons has built but after a century in the business with many famous telescopes constructed, including the Isaac Newton Telescope, it is their last. The WHT building with its distinctive dome now is nearing completion on the mountain site (Plate 5) and will be ready for the installation of the telescope by the RGO, starting late in 1985.

2. GENERAL OPTICAL DESCRIPTION

The telescope is of classical Cassegrain optical configuration. The paraboloidal primary mirror is made of a glass-ceramic material (Cervit) having near-zero coefficient of expansion over the operating temperature range. It has a clear aperture of 4.2m and a focal length of 10.5m (f/2.5). Its diameter-to-thickness ratio of 8 makes it thinner than for most large telescopes built in recent years, but it is not classifiable as a thin mirror and raises no special problems for its support system. The precise diameter of 4.2m was determined by the availability of the mirror blank, made by Owens-Illinois. The mirror is now undergoing its final stages of figuring at Grubb Parsons (Plate 3). It is believed that this will be the most accurate large mirror yet made, concentrating 85 per cent of the light of a distant star into an area only 0.3 arc sec in diameter. The mirror figure was specified by means of the irregularities in the wavefront reflected from it. It is necessary for the mirror to be very smooth and accurate on scales of 20cm or less, since this is about the size of the atmospheric cells above the La Palma site. Portions of the mirror separated by larger distances than this may be tilted relative to one another so long as they direct the light within the 0.3 arc sec tolerance. Thus, the mirror is accurate to within 1/50 of the wavelength of light at a scale of 2cm, about 1/15 wavelength at 8cm and about 1/2 wavelength at 1m or more.

The focus of the uncorrected primary mirror would show strong coma off-axis but the incorporation of a three-element correcting lens (Fig. 1) before the prime focus will give an unvignetted field of 40 arc min diameter extending to 60 arc min diameter at nominally 0.6 transmission. The effective focal ratio of the primary mirror with corrector is f/2.8.

When not operating at prime focus, a convex hyperboloidal secondary mirror, made of Zerodur, 1.0m in diameter, directs the light through a central hole in the primary mirror to the main instrumentation mounted at the Cassegrain focus beneath the primary mirror cell. The telescope also incorporates a third main mirror, a flat, angled at 45°, which can be motor-driven into position at the intersection of the axes, just above the primary mirror, so that the light from the secondary is diverted sideways either through one of the altitude bearings to the Nasmyth platforms where particularly large or massive instruments can be placed, or to an intermediate, folded Cassegrain position for use of small, subsidiary, instruments. As desired during the night, instruments mounted at any of these four stations can be selected within minutes by the motion of the single Nasmyth flat mirror. The effective focal length of the telescope for the Cassegrain and Nasmyth foci is 46.2m (f/11). The available unvignetted field diameters are 15 arc min at the direct Cassegrain focus and 5 arc min at the Nasmyth and folded Cassegrain foci.

To compensate for the rotation of the star field which occurs in an altazimuth-mounted telescope, motor driven turntables are provided for the instruments at the prime focus and Cassegrain observing stations. Instruments will not be rotated at the Nasmyth stations but an optical image rotator will be introduced when required. To reduce both light loss and polarization in the image rotator, prisms of fused silica with total internal reflection are used rather than mirrors (Fig. 2). Fused silica lenses cemented to these prisms, with a final element of UBK7 glass, extend the optical path (as is necessary to provide an accessible focus) to give an effective focal ratio of f/11.2. With the telescope refocussed by moving the secondary mirror downwards by 3.82mm, the position of the final focus is identical to that of the normal Nasmyth focus. The final image rotates at twice the angular speed of the rotator optics, which also change the image parity. The image rotator partially vignettes the Nasmyth field; the unvignetted field is 2.5 arc min in diameter.

Holes in the structure of the telescope will allow for the eventual addition of coudé mirrors to provide a light path emerging from the telescope building for an interferometric link to another telescope.

3. TELESCOPE TUBE

The telescope tube is of conventional open truss form (Plates 1 and 2). A rectangular box section centrepiece carries both the altitude bearing trunnions and the Serrurier trusses which support the primary mirror cell at one end and the secondary mirror or prime focus assembly at the other. The trunnions are thick cylindrical steel forgings which bolt to the outer faces of the centrepiece and whose bores clear the light paths to the Nasmyth foci. A motorized counterweight is fitted in each corner of the centrepiece to provide altitude balance trimming.

Attached within the centrepiece is a set of spider vanes which supports the 45° Nasmyth mirror assembly and a sky baffle structure. The Nasmyth mirror is mounted on a motor-driven turntable indexed at four 90° positions which allows it to direct the secondary light beam to any of the two Nasmyth focal positions or the folded Cassegrain position. Alternatively, in the fourth rotation position, through an additional motor-driven mechanism which tilts the mirror cell about pivots at

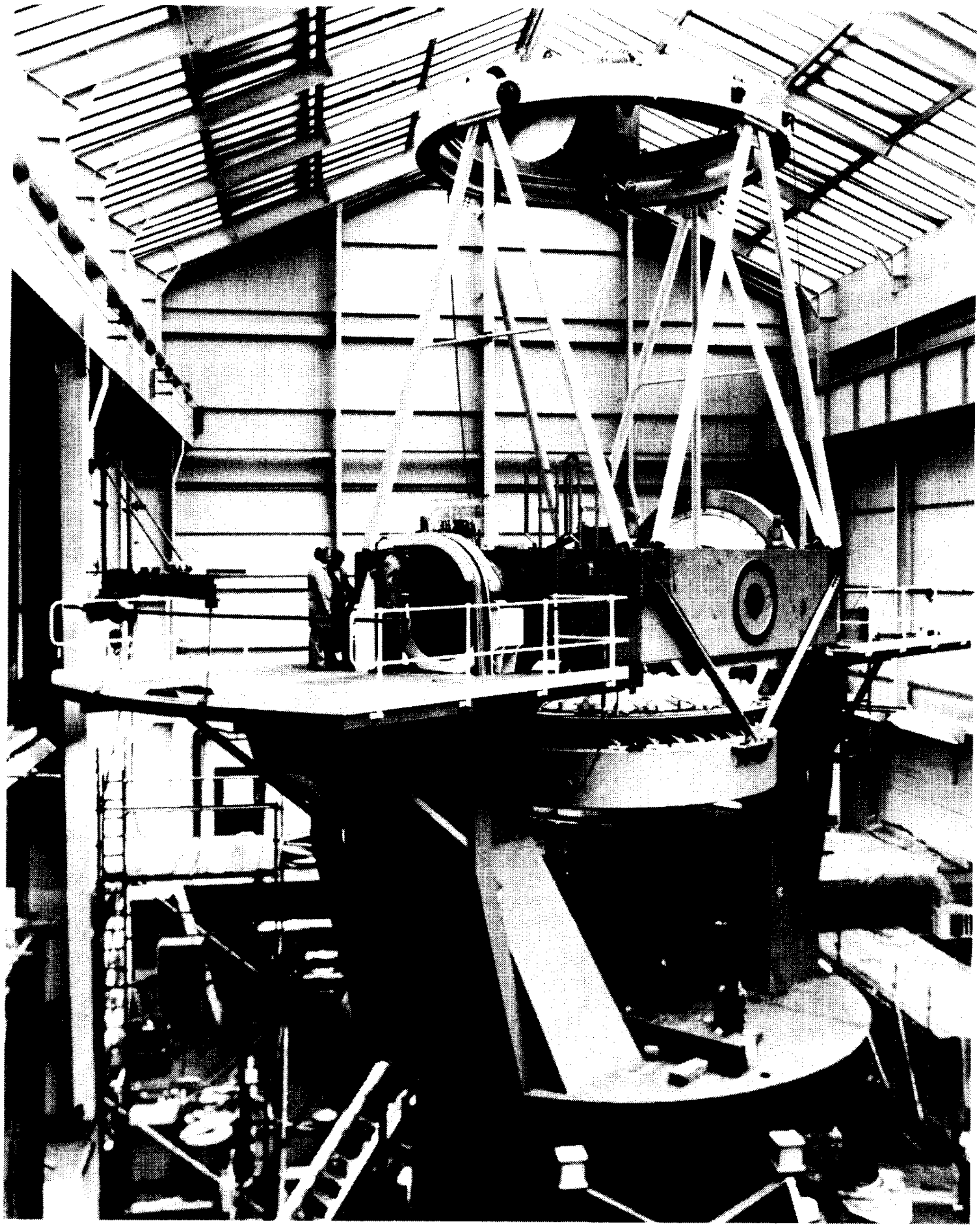

Plate 1. The William Herschel Telescope undergoing testing at the Grubb Parsons Ltd works in Newcastle, as it was before being dismantled for shipping to La Palma.

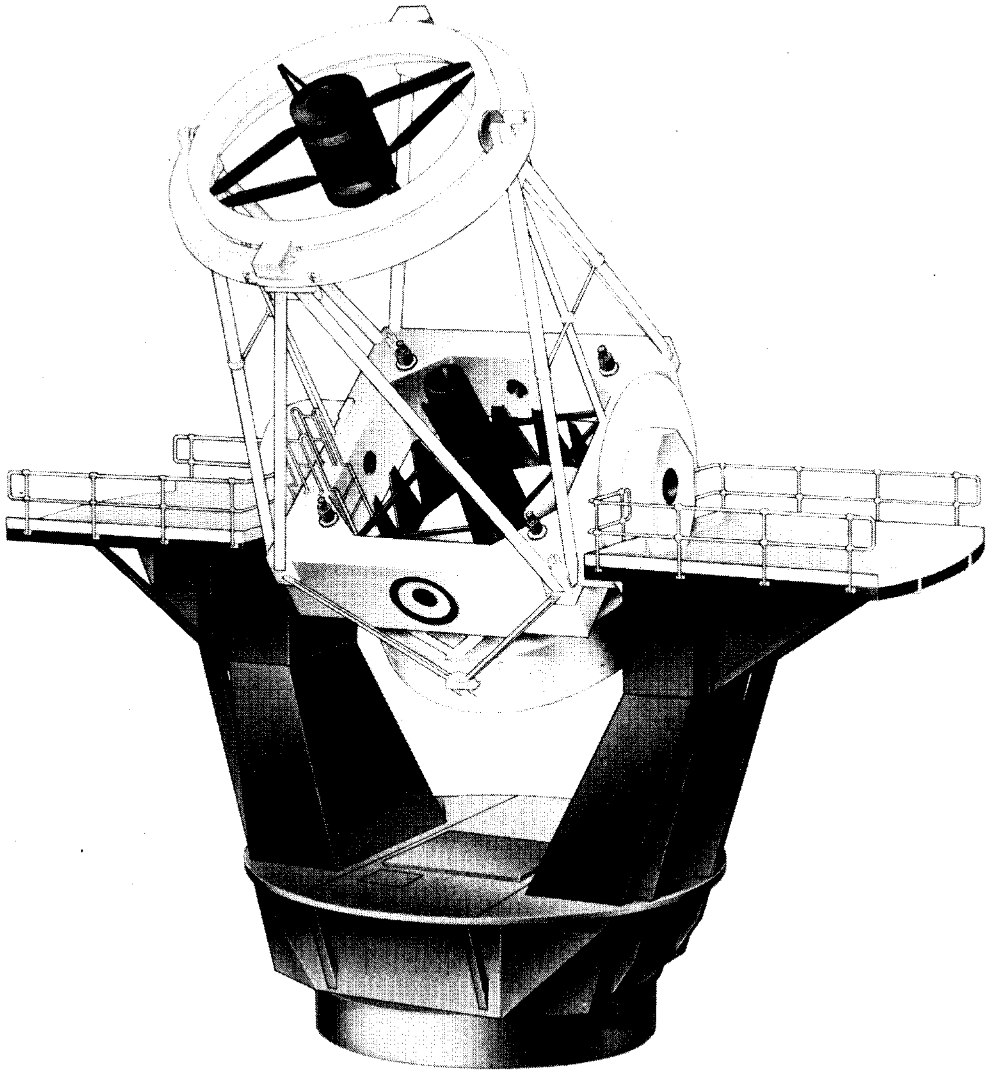

Plate 2. Artist's construction of the William Herschel Telescope, showing the open mirror cover, the Nasmyth assembly with sky baffle structure, and the top end movable ring with secondary mirror assembly.

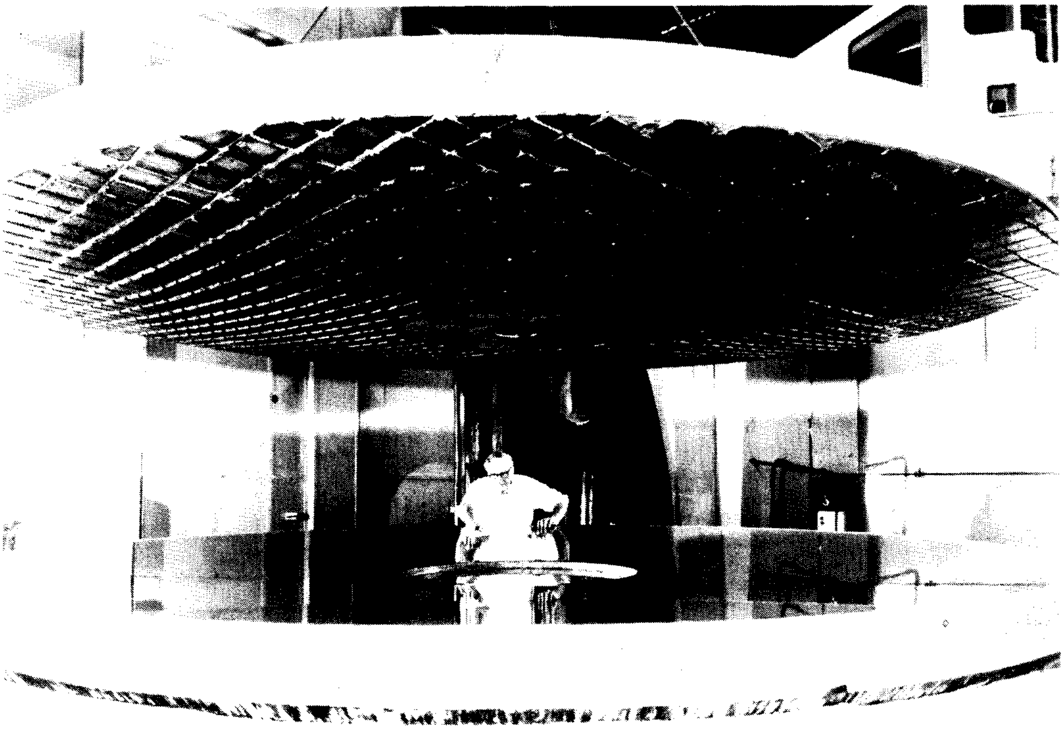

Plate 3. The 4.2m mirror of the William Herschel Telescope undergoing its final stages of figuring at the Grubb Parsons Ltd works in Newcastle.

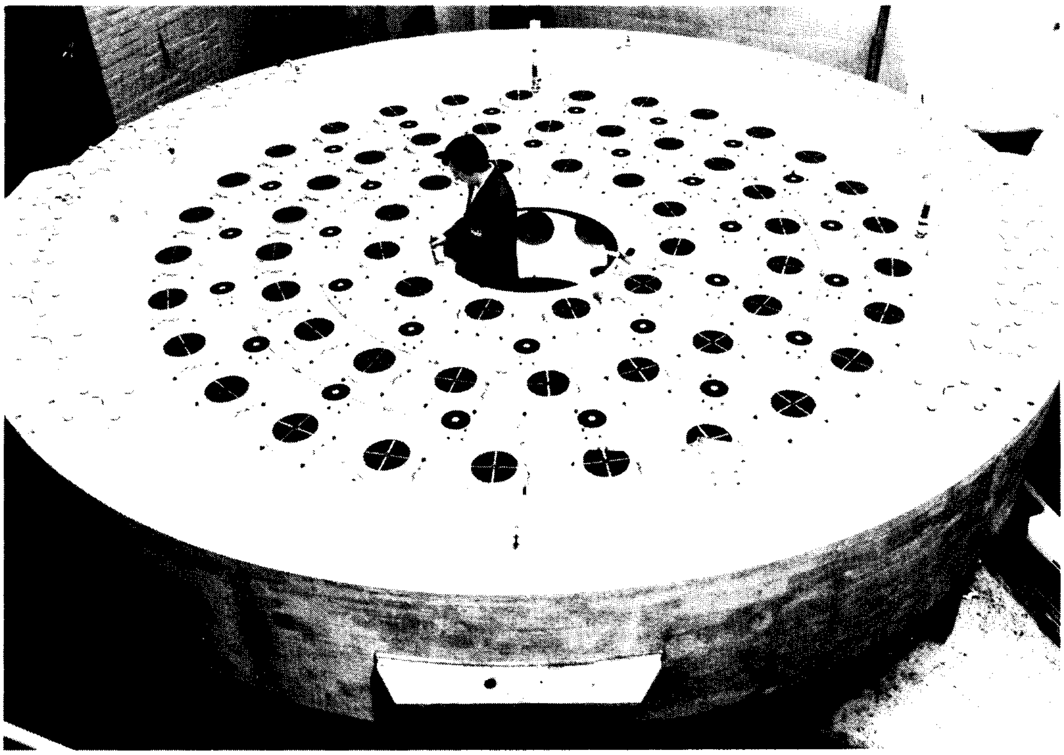

Plate 4. The 4.2m mirror cell and support systems showing the array of pneumatic cylinders with (smaller) spring loaded rest pads.

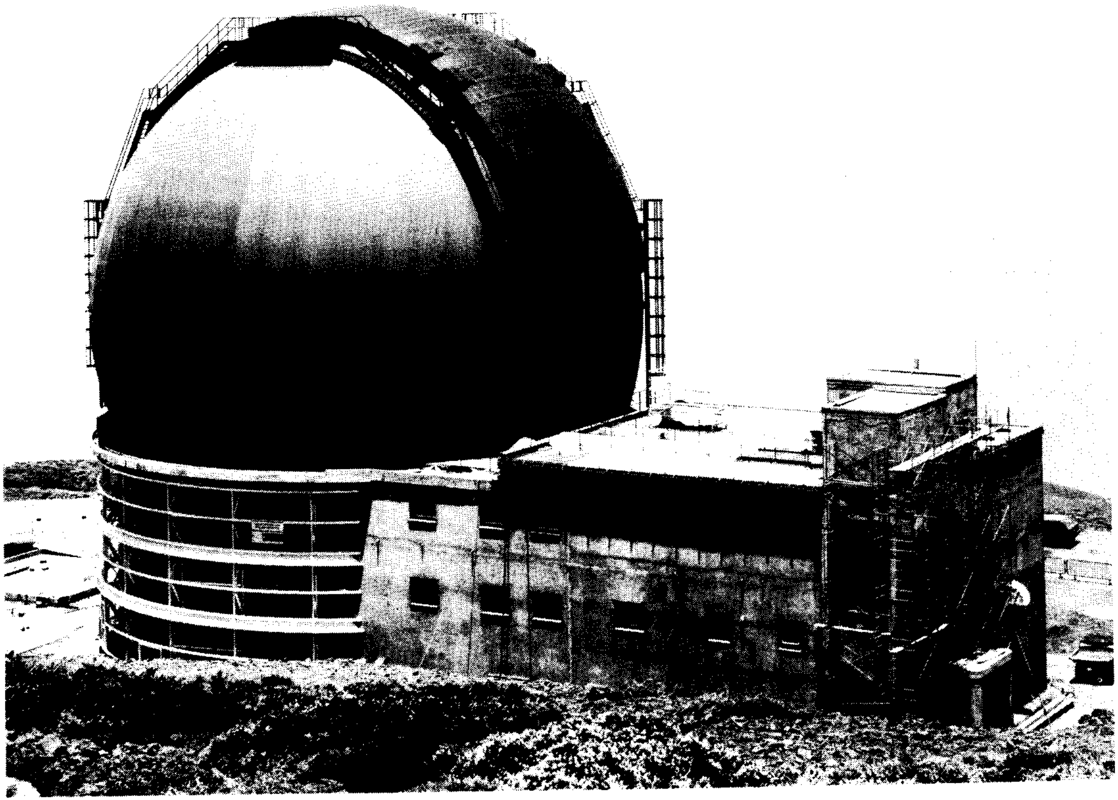

Plate 5. The William Herschel Telescope building with its onion-shaped dome, now nearing completion on the Observatorio del Roque de los Muchachos in La Palma.

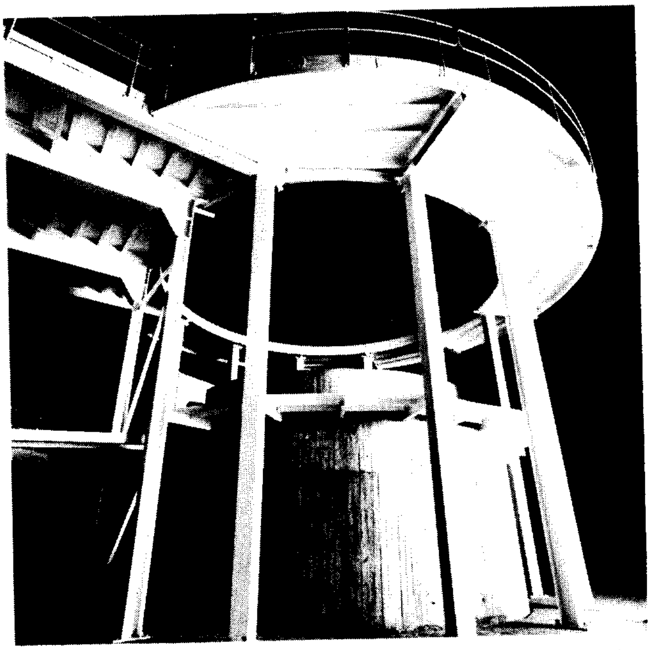

Plate 6. A perspective view of the cylindrical pier which will support the William Herschel Telescope within its building, showing the steel Cassegrain platform and its vertical supporting girders.

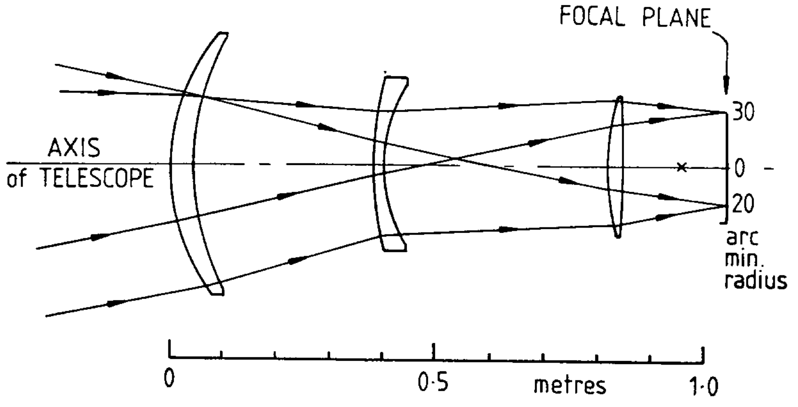

Figure 1. The three element prime focus corrector of the 4.2m telescope. The first two elements are of UBK7 glass (Schott) and the rear element is of fused silica. The configuration is based on a design by Wynne (1974).

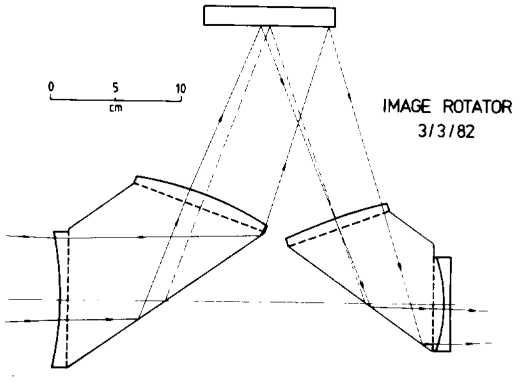

Figure 2. The Nasmyth image rotator. The prisms with their extended lenses are of fused silica (Heraeus Homosil) and the final lens element is of UBK7 glass (Schott) and is cemented to the adjacent silica surface. There is a clearance of 30cm from the final element to the focus.

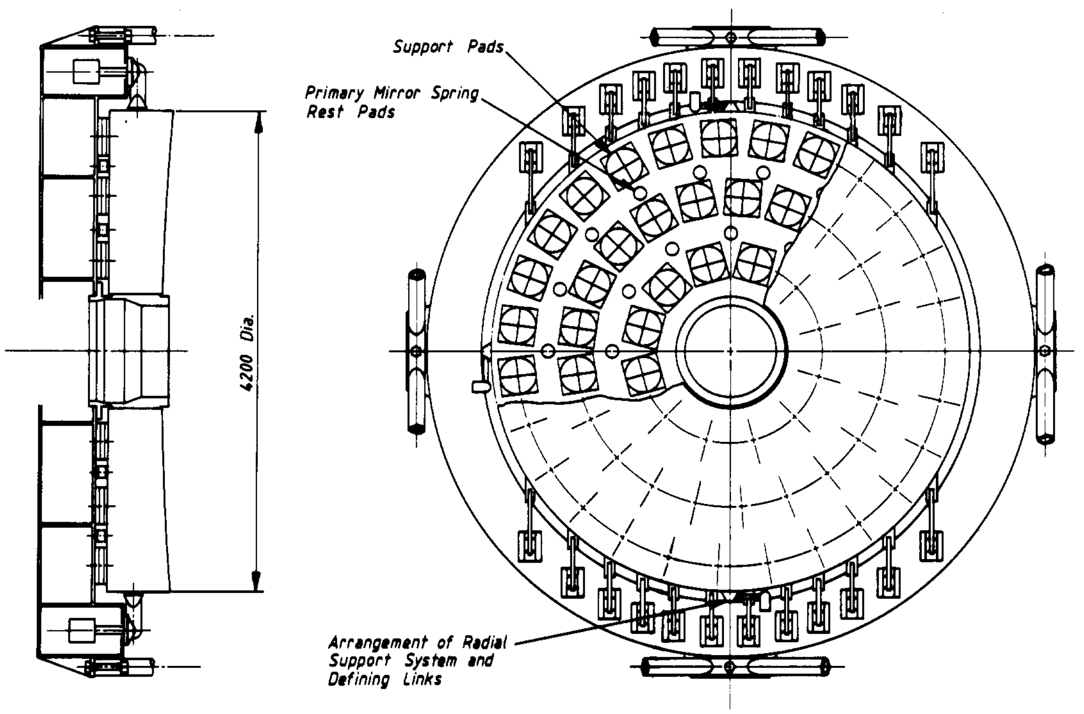

Figure 3. Primary mirror cell showing the axial and transverse support systems.

the lower end of its backplate, the mirror can be stowed facing outwards (against a dust cover) just clear of the light beam, for use of the direct Cassegrain focus.

The secondary mirror assembly is attached to a motor-driven focussing mechanism housed in a cylindrical drum which is supported by a system of pre-tensioned spider vanes within a movable ring able to pivot about its horizontal diameter inside a fixed top end ring carried by the upper Serrurier trusses. The movable ring can be rotated by means of a motor drive through 180° and motor-driven latches lock it securely to the fixed ring in either of its two positions. Signal and power leads are accommodated within a cablewrap device. For the change to prime focus operation the telescope tube is lowered to near-horizontal and the mounting ring rotated to bring the secondary mirror assembly facing outwards so that it can be easily removed from the focussing mechanism. The prime focus unit then is attached in its place and is in its operating position with the ring remaining in the rotated position. The whole semi-manual operation takes about 30 minutes. The rotating end ring feature obviates the conventional need to change complete top end rings and the associated requirements for large handling equipment and large dome clearance; also, only one, permanently installed, focussing mechanism is needed. The prime focus unit incorporates a precision motor-driven turntable to which cameras or other instruments can be attached, and a cablewrap device takes electric cables to instruments mounted there. The unit also has an internal flange for carrying the prime focus corrector lens assembly. No observer cage is provided so the prime focus instruments must be controlled remotely like those at all the other foci.

The primary mirror cover is suspended below the centrepiece on A-frames which support a circular baseplate carrying the cover petals and drive assembly. The lower Serrurier trusses carry the primary mirror cell in which the axial and transverse support systems for the mirror are mounted. The cell is a welded steel fabrication basically consisting of a stiffened flat disc with a box section cylindrical surrounding wall. Between the top face of the cell wall and the mirror cover baseplate is a system of manifold ductwork for ventilating the primary mirror. Below the primary mirror cell is an extension piece which carries the Cassegrain instrument turntable and its cablewrap system.

4. MIRROR SUPPORT SYSTEMS

4.1 Primary Mirror

The mirror has sophisticated axial and transverse support systems (Fig. 3 and Plate 4).

The axial support system consists of two sub-systems: an axial flotation system made up of an array of pneumatic cylinders employing roll-diaphragms as seals together with a pumping system providing the gas pressure needed to support the full mirror weight, and an axial defining system which locates the mirror in its correct axial position at three points around the mirror edge. Load sensors in the axial definers provide signals which control the pressure in the pneumatic cylinders; the system also allows fine height and tilt adjustments to be made. A system of spring loaded rest pads supports the mirror when the pneumatic system is not pressurized.

The cylinders of the axial flotation system, a total of 60, are arranged in three concentric rings on the floor of the mirror cell. The optimum arrangement was determined by use of a finite-element computer analysis of mirror deflections (Mack, 1980). The cylinders are divided into three sectors each of 120°, symmetrically disposed about a diameter perpendicular to the telescope's altitude axis. All the cylinders in each group are connected by a system of manifolds and pipes to an individual controller housed inside the mirror cell. Each of the three controllers have two sets of electrically-operated valves: one connects the cylinders to a pressurized nitrogen reservoir, the other opens the cylinders to a vacuum tank. The valves are controlled by the output of the associated load cell in such a way that the force exerted by the mirror on the defining point is maintained at 0 ± 5kg during tracking at all angles of the telescope tube from the zenith down to the horizon. The total weight of the primary mirror is 16.5 tonnes.

The mirror is supported in a transverse direction by weighted levers coupled by link arms to brackets connected to the edge of the mirror in much the same way as a conventional push-pull radial support system. However, as the mirror will not rotate with respect to the gravity direction, the weighted levers and linkages are arranged to act only in the vertical direction and are spaced unequally in such a way that each pair of weighted levers, one pushing and the other pulling, effectively supports a 'slice' of the mirror equal to one-twelfth of its total weight. This efficient arrangement is only possible in an altazimuth mounting. In plan view the force applied by each pair of weighted levers acts through the centre of gravity of its slice, but in elevation all the forces are applied in the one plane containing the centre of gravity of the whole mirror. Transverse definers take the form of tangential links tying the mirror to its cell at three 90° positions.

4.2 Secondary Mirror

The mirror is supported axially by a mechanical six-point load distribution lever system cemented to the rear face of the mirror, and transverse flotation is provided by a conventional system of push-pull levers and counterweights. These support systems are accommodated in a cell which is attached to a backplate at three points; one attachment point incorporates a spherical bearing, while the other two are adjustable by means of motor-driven push rods which allow change of tilt or collimation of the mirror. Surrounding the mirror cell but not directly attached to it is a lightweight sky baffle.

5. TELESCOPE MOUNTING

The mounting is of the altazimuth type, with vertical and horizontal axes of rotation (Plate 2). The altitude axis trunnions on the telescope tube centrepiece are supported on cylindrical hydrostatic bearings carried on stiff columns which are attached to a base box. The latter is a fabricated structure that forms the central unit of the mounting. The base box is mounted on a flat, horizontal, annular ring girder which is supported axially by six hydrostatic bearing pads, to provide the altitude axis; six associated radial bearing pads provide centralizing forces. The bearing assemblies are supported on stools set on the building pier.

Horizontal attachment faces on brackets at each side of the telescope rigidly fixed outboard of the columns enable large instruments to be carried for the two Nasmyth foci. Each Nasmyth focal station also has an observer access platform, independently supported from the base box to minimise the transmission of vibrations from the observer to the instrument. These focal stations can be reached at all positions of the telescope from an annular steel balcony in the building.

Cabling for the telescope services and instruments passes from the building pier, through an azimuth cable twister to the base box, then up one column and over an altitude cablewrap to the telescope tube centrepiece. 144 cables, 2 water lines, a nitrogen line and 6 high pressure oil hoses feed through the azimuth cable twister and 89 cables, a water line and a nitrogen line pass over the altitude cablewrap.

In the centre of the upper surface of the base box is a rectangular rising platform with the aid of which the Cassegrain instruments can be mounted and serviced. At its lowest position its surface lies flush with a load-bearing floor attached to the base box and the columns. The floor has removable plates which cover cantilevered rails. By rotating the telescope in azimuth these rails can be aligned with rails fixed in a close-fitting, annular, raised steel platform (Plate 6), and accurately supported in height with the aid of pneumatically operated lever assemblies.

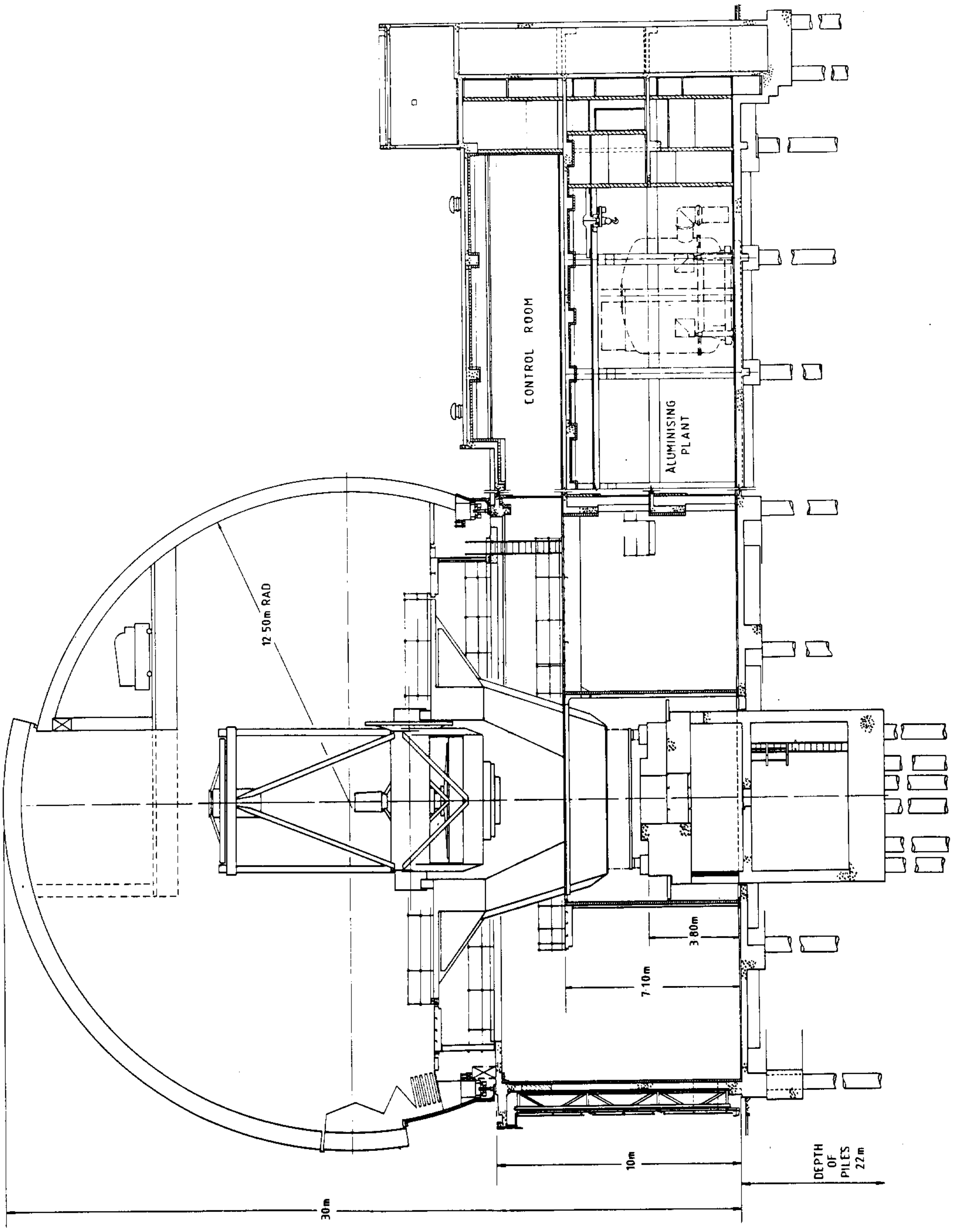

Figure 4. Cross-section through the dome and building.

The rails carry a handling trolley to support the mirror and its cell off the telescope, for use during the aluminizing procedure. The trolley enables the mirror and cell to be brought away from the telescope, on a radial extension to the platform, so that the mirror can be lifted clear with the aid of a crane suspended from the dome, then lowered to the building ground level. There it is washed, then lifted onto the aluminizing tank lid mounted on another trolley moving on rails set in the concrete floor, and finally taken to the aluminizing plant.

6. TELESCOPE DRIVES AND CONTROL

Identical precision straight spur gears are fitted to the two axes of the telescope, and the driving torque to each of these is provided through pinions by two direct-current torque motors supplied from individual power amplifiers sharing a common control signal. The azimuth drive gear is mounted on the building pier and the motor units are fitted onto the ring girder of the telescope mounting. The altitude drive gear is fitted to the telescope tube centrepiece and its motors are attached to a plate carried on one column of the telescope mounting. A tachogenerator and an electromagnetic brake are fitted to each motor shaft. Maximum roations are 0-95° from the horizontal and ± 270° about East.

For each axis, the servo control system has three feedback loops: (a) current or torque, which is generated within the control electronics, (b) velocity, from the tachogenerator and (c) precision rate, which is developed either from a 17-bit incremental shaft encoder driven through a pinion off the main gear or a 20-bit roller driven encoder, each giving the same accuracy of 0.03 arc sec. Absolute position is obtained from a pair of gear driven shaft encoders on each axis of the telescope. It is intended that the telescope pointing accuracy be 1 arc sec or better after compensation by the computer control system for all repeatable errors. On each axis the drive amplifiers are electrically biassed so that the two motors assist for slewing but oppose for tracking. The maximum slewing speed for both axes is 1° $\sec^{-1}$ with acceleration during slewing reaching a maximum of 0.3° $\sec^{-2}$. For tracking, a local torque loop around the two motors in each axis maintains continuous gear tooth contact during all tracking accelerations up to a maximum of 0.02° $\sec^{-2}$. On the rare occasions when tracking an object which passes closer to the zenith than about 0.2°, observing will have to cease temporarily while the telescope traverses a 'blind' region through which it will not be able to track continuously. During this time, which will be less than 3 minutes for the WHT, the telescope will slew through a large azimuth angle (180° if the object happens to pass through the zenith), to reacquire the object as it leaves the blind region.

The instrument turntables are also driven by servo-controlled direct-current torque motors, but the requirements for precision are not as high as for tracking. The position angles are controlled with an accuracy of about 5 arc sec.

In normal use, all the telescope drives are controlled from an operations desk by means of a computer system which communicates with each of the motors and encoders through a parallel CAMAC system. When slewing, the telescope position is monitored using the absolute encoders and a drive rate calculated to move the telescope to the desired position in the shortest possible time. This calculation is performed 20 times a second. While tracking, information from the incremental encoders is used to define the drive signals. The computation of the drive signals includes coordinate transformations, calculation of the telescope mechanical deformations and misalignments, and simulation of the servo components. All the instrument turntables and cablewrap devices are controlled in sympathy with the telescope motion, as well as the positions of the dome observing slit and windscreen.

7. DOME AND BUILDING

A schematic cross-section through the dome and building is shown in Fig. 4. The telescope is

Figure 4. Cross-section through the dome and building.

supported by a reinforced concrete pier in the form of a hollow cylinder 7m in diameter and 4m high (Plate 6). This puts the centre of rotation of the telescope at a height of 13.4m above the ground. The dome is onion-shaped, of 21m internal diameter, with shutters covering an observing slit 6m in width. A pair of up-and-over shutters with a windscreen coupled to the lower shutter will allow observations down to 12^o above the horizon. The dome is supported on a rail set onto a cylindrical concrete building structure which internally is open to ground level. A circular hole in the centre of the concrete floor allows clearance for the pier which is supported on independently piled foundations to isolate the telescope from building vibrations and wind disturbance. Set on one side of the cylindrical drum is a 3 storey rectangular annex of conventional construction. This contains the mirror aluminizing plant, the operations control room, computer room, dark rooms, workshops, offices and various services. Because no unnecessary activity takes place in the dome there is very little thermal disturbance of the air near the telescope, which greatly improves the chance of achieving perfect ′dome seeing′. This is further facilitated by large extractor fans set into the cylindrical structure.

8. EVOLUTION TO THE PRESENT DESIGN

The telescope and building were designed in consultation with Freeman Fox and Partners by a team at the RGO led by William Goodsell with John Pope as telescope project engineer and Rowland Milner as civil engineer. The astronomical specification was laid down by representatives of the UK astronomical community in the 1970s. In the event, the early configuration proved to be too expensive to be accommodated within the available funding. The present design of the telescope and building originated in a detailed reappraisal completed in January 1980 by members of the RGO, Freeman Fox and Partners, Grubb Parsons Ltd and the wide UK astronomical community. The combined group popularly was called the Tiger Team.

The Tiger Team early recognised that the altazimuth mounting had already enabled a very economical design to be evolved for a high performance telescope and, although a saving of about 20 per cent could be made, there was more scope for the cutting of building costs. The building had been designed in the style of those current at the time, as, for example, those for the Kitt Peak National Observatory and the Anglo-Australian Observatory 4m telescopes. Studies of atmospheric microturbulence on the La Palma observatory site showed that temperature fluctuations at night are confined to a thin layer near the ground as the prevailing wind sweeps up the slope of the site. The measurements of microthermal fluctuations are correlated with seeing measured by the Polaris trail method. Because local seeing is confined to such a thin ground layer it was decided that a figure near 10m for the height of the telescope altitude axis above the ground level was ample. This allowed a very large reduction in the size of the telescope building and pier without compromise of performance. With this much reduced telescope building, an attached annex housing the aluminizing plant, operations control room, workshops, offices, etc., was necessary, but it could be of conventional construction since it bears no load from the dome and so was economically tailored to the minimum practical needs.

The dome itself was reduced in diameter, and therefore cost, by making the telescope more compact. The dome radius was set principally by three factors. The obvious and most important was the telescope primary focal length. Originally specified at f/3.2, the focal ratio of the mirror was reduced to f/2.5, and the dome radius then could be reduced by over 2m. With a redesigned triplet lens field corrector there was little extra deterioration of image quality at the prime focus over the large field angle required. Design work by Charles Wynne at the RGO showed that a corrector for an f/2.5 telescope covering a 1^o field could in fact be made to give a total image spread not exceeding 0.5 arc sec in the spectral range 340-852nm, with some refocussing needed for the shorter wavelengths. The Team considered shortening the focal length of the primary mirror even more, but the cost of figuring the mirror would increase as its speed was increased, and new test equipment associated with making the secondary mirror would have had to be manufactured.

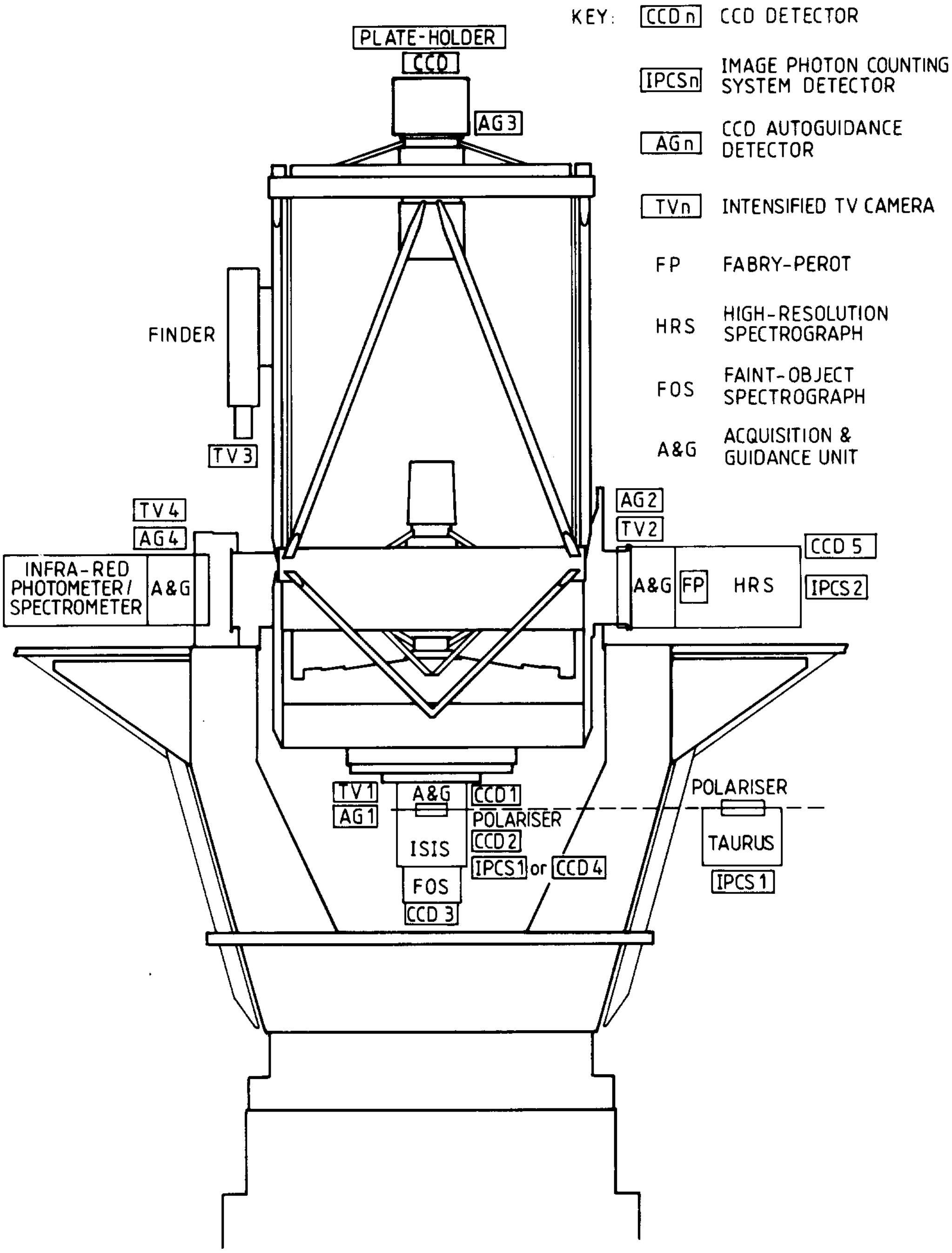

Figure 5. Schematic outline showing the arrangement of the instruments and related equipment at the four principal foci of the telescope.

Moreover, at focal ratios faster than f/2.5 the triplet corrector cannot cope with a large field, although more than 15 arc min is still possible at f/2.0. Thus there were significant cost and scientific penalties, while there was little compensating benefit since the minimum dome radius was set by a second factor, namely the constraints imposed by handling the primary mirror for aluminising.

These two factors (focal length and mirror handling) set the maximum length for the Nasmyth platforms to fit the available space. It shortened them from the generous 6m length originally specified, but in the process of rebalancing the telescope some length has been retrieved, reducing the working distance from tube axis to Nasmyth focus by 0.5m, so that there is still space for an instrument more than 4m long. At the same time, the clearance behind the Cassegrain mounting face for an Acquisition and Guidance Unit and instrumentation was reduced from 4.2 to 2.8m (leaving space, however, for an instrument 2.0m long). This shortened the columns of the telescope and made it possible to simplify their design, increase the stiffness and still save weight. From these two changes the mass of the telescope was reduced from 250 tonnes to 200 tonnes, with consequent economy.

A major operational benefit introduced by the new building configuration with reduction in dome volume, which the Team was quick to note, was the increased potential for improved dome seeing, not only because of the minimal heat input to the air in the vicinity of the telescope and its sight-lines but also because of the relative ease with which the dome could be ventilated. To speed this, the dome aperture was made wide and unconstrained and large extractor fans were incorporated in the cylindrical building structure.

Originally all three astrophysical telescopes on La Palma had been specified to have the same f/15 Cassegrain focal ratio, with the intention of simplifying the transfer of instruments between them. This benefit, of dubious utility, was abandoned as the optimum focal ratio for the Cassegrain focus of the WHT was considered against cost and scientific benefit. Because the instrument clearance at the Cassegrain station had been reduced it was no longer possible, for example, to build a straight-through spectrogaph with a 15cm collimator beam (to fit available gratings) if the f/15 focal ratio was retained, and it would be necessary to fold the telescope beam and lose light at an unnecessary reflection. At f/11 this extra mirror is not necessary. A secondary mirror to produce a faster Cassegrain focal ratio than this must be larger than about 1m diameter; then it begins to obscure a significant amount of light by its shadow and also would have entailed purchase of new test equipment for its manufacture. The secondary focal ratio was thus set at f/11. Finally, a plan for an f/35 secondary mirror for infra-red work was postponed, simplifying the top end.

The budget for the design, erection and manufacture of the WHT, its control system, dome, building, aluminizing tank and other plant, and a full set of instrumentation is £15M (October 1984 prices). The equivalent cost of the original design is £25M. The design evolved by the Tiger Team currently is being brought to realization by a team of engineers and scientists at the RGO now led by Michael Morris, with Brian Mack as telescope project engineer, Rowland Milner as civil engineer and Neil Parker responsible for the instrumentation and its supporting infrastructure.

9. INSTRUMENTATION AND RELATED EQUIPMENT

9.1 System Outline

The utility of any telescope depends hugely on the capability of the instruments it feeds. The continual, rapid increase in the functional sophistication of instrumentation for optical astronomy, and the frequent introduction of major enhancements or of fundamentally new instruments, means that a description of the suite of instruments now in preparation for the WHT should be taken in some respects as illustrative. Nevertheless, there is a basic requirement for versatile and efficient spectrographic instruments, these representing the major analytical technique of the astronomer, and for highly sensitive imaging detectors both to serve in such spectrographs and for direct imaging purposes. Such equipment for the WHT, in concept at least, will persist for the foreseeable future. There will be, of course, a continual trend towards higher optical efficiency and increased detector sensitivity; the clear potential for this can be seen from the fact that the overall efficiency of the telescope and a typical complex instrument with its detector rarely exceeds a few per cent, and that this is some orders of magnitude greater than was available just a few decades ago.

After a call for competitive tender to propose and produce instrumentation for the WHT, several groups in the UK and Netherlands astronomical communities are now involved in the production of the core instruments to be brought into use over the first few years of telescope operation. Production of some instruments, and the instrumentation support infrastructure including control system and acquisition and guidance facilities, together with the general coordination and management of all the instrument work, is the responsibility of the RGO.

The core instruments and related facilities now in production, design or planning stages are: a versatile intermediate dispersion double spectrograph (known as ISIS), a fixed-format highly efficient low dispersion spectrograph (known as the Faint Object Spectrograph, FOS) functionally integrated with ISIS, a polarization unit incorporated within ISIS and also available for the FOS, an imaging Fabry Perot interferometer with additional imaging options (known as TAURUS II), a high-dispersion echelle spectrograph, a Fabry Perot unit for the latter, infrared instrumentation yet to be fully specified, a prime focus camera for photographic plates or electronic detectors, an Image Photon Counting System (IPCS II) and a charge-coupled device (CCD) camera system both with several head units to operate with the above instruments as appropriate or to be used for direct imaging, and units to provide acquisition and guidance facilities for these instruments. Fig. 5 shows the disposition of these instruments and detectors around the four principal focal stations of the telescope. The rapid changes between Cassegrain and Nasmyth foci made possible by use of the movable Nasmyth flat mirror will allow, for individual objects, near-simultaneous observations with different instruments, as well as matching of the needs of different observing programmes with the prevailing conditions so facilitating ʹflexible schedulingʹ of observing allocations.

The number of instruments and detectors that will be either in use or mounted and available for use at any one time, together with the problems of handling very large quantities of high-bandwidth data, require the adoption of an integrated system approach to the management of the observing functions. Particular features of this are the use of distributed processing and networking. Each instrument, detector system, and acquisition and guidance unit has its own microprocessor controller linked to a system control computer through a ʹutility networkʹ. The telescope control computer also is linked to the system computer so that instrument and telescope functions can be readily coordinated. The microprocessors each contain appropriate command repertoires to handle the complex local control functions and safety interlock procedures, and only high level, time non-critical, instructions and data are moved around the network. Central mimic displays giving the status of each instrument can also be handled by the distributed microprocessors in this way. A large semiconductor memory external to the system control computer will be used to gather and display data from the IPCS II and the CCD detectors via a high-speed parallel data bus, and also for arrray processing functions such as on-line flat-fielding for presentational purposes while observing.

Much effort has been invested in producing spectroscopic and image processing software for the Digital Equipment Corporation VAX computer based Starlink system distributed in the UK over the centres of activity in astronomy. For this reason a VAX computer has been chosen as the WHT's system control computer. Apart from its executive, coordinating and recording functions it will be used for carrying out data reduction using Starlink software both for on-line assessment of the progress of observations, and for full data processing which the observer may then continue on returning to home base. The use of a VAX system also has the inverse advantage that specific processing procedures written at the telescope to cover observers' special requirements then can be used on the home computers.

Like the telescope, all the instrumentation and related facilities are being built to be operated fully remotely. Initially the observers will be positioned inside the nearby control room as is now conventional, but it is planned that a substantial proportion of observing will be conducted from a control room in the RGO's home base in the UK, possibly also linked to the observers' home institutions. The need for travelling to the distant observatory site thus obviated, flexible scheduling of different programmes, according to observing conditions, becomes a practical proposition.

Specific instruments, facilities and devices mentioned above are now described in some detail.

9.2 Cassegrain Acquisition and Guidance Unit

This unit, now in production at the RGO, provides a rigid support for the acquisition television camera and autoguider systems it contains, and a mounting for the Cassegrain instruments, all of which must be held in registration with the telescope focal plane. Basically it is a cylindrical structure with axial length equal to its radius (65cm) and annular flanges at each end to enable attachment to the Cassegrain turntable of the telescope and for the mounting of instruments. A specific sectional view of the unit with the ISIS and FOS instruments attached is outlined in Fig. 6; not all the structural detail nor all of the components protruding from or within the structure are shown.

Within the structure, two independent radially movable probes each carrying a mirror allow the same television camera to view the central 1.5 arc min either of the direct telescope field (when also light from an integrating sphere illuminated by chosen comparison lamps may be sent to the instrument) or of the inclined slit jaws of the spectrograph with the mirrored telescope field. An alternative image scale is provided by a focal reducing lens which can be brought before the television camera to give a 4 arc min field. The camera uses a Secondary Electron Conduction television tube with preceding intensifier stage, now conventional in this application, and has an associated system of interchangeable filters; it is mounted on a motorized slide to allow remote focussing. There is electronic provision in the camera system both for on-target integration before readout and accumulation of a succession of images in an integrating digital memory. An autoguider probe system within the same structure works in a sector outside the central 9 arc min of the Cassegrain field. The autoguider is based on the use of a CCD as detector, which is fed by means of a scanning prism assembly which can rotate about the instrument axis and be moved radially to acquire an appropriate guide star. It too has remote focussing capability and an associated system of interchangeable filters. A separate filter assembly set below the acquisition and autoguider probes is provided for use with the attached instruments. This has two filter slides, one for neutral density filters and the other for colour and interference filters. Yet another filter assembly is included with the comparison lamps integrating sphere to avoid the need for filter changing between alternate exposures on an astronomical object and related comparison arcs.

In addition to the main instrument mounting face, the unit has an auxiliary focal station with the full unvignetted 15 arc min Cassegrain field available for multi-object spectroscopy using optical fibre probes. The focal plane is external to the cylindrical case structure and is fed by a large movable flat mirror supported on slideways at its upper and lower edges. The fibre optic system requires its own autoguider sensor because the main autoguider probe is occulted. The same focal station is also available for small instruments not requiring the large field, and then is fed by means of a radially movable probe carrying a small mirror which does allow the use of the unit's autoguider probe. Such an instrument, for example a CCD camera, will be used to complement the main instrument mounted on the unit, with the operational convenience of rapid interchange between them. The future incorporation of an image stabilization system, basically a high-bandwidth autoguider probe and actuated mirror, is planned as an optional feed for the main instruments to take advantage of the marked reduction in instantaneous image size this gives.

An atmospheric dispersion corrector will be mounted just above the unit, within the telescope tube.

9.3 ISIS

This versatile Cassegrain instrument consists of two intermediate dispersion spectrographs which can be operated one at a time or simultaneously, and are separately optimised for the blue and red spectral regions. This is to be the workhorse instrument of the telescope and is expected to be used for the majority of the observing programmes. It is being produced by the RGO and Oxford University in a collaborative effort with the design and construction carried out dominantly at the RGO. A sectional view of ISIS complementing Fig. 6 is shown in Fig. 7.

The main design goals are to provide: a range of dispersions between 130 and 16 A mm^{-1} in first order, corresponding to a range in resolving power respectively between 800 and 7000 when using a narrow (0.5 arc sec) slitwidth; maximum possible throughput; high operating efficiency in both the setting-up and observing modes, with the capability of operating the blue and red spectrographs as a single unit; rapid interchange between ISIS and the FOS, which share the same slit assembly; long slit (4 arc min), multi-slit and fibre optic feed capabilities; a cross-dispersed mode capable of recording the wavelength range from 300 to 1100nm with a resolving power of about 2000; facilities for spectro-polarimetry; and full capability of being remotely operated.

The optical layout of ISIS (with the FOS) and its main components are shown in Fig. 8. The f/11 collimators are 5° off-axis paraboloids and give 15cm diameter beams. Both the folded blue and red cameras, each of 50 cm focal length, are based on a design by Wynne (1977). The collimator-camera included angle is 40° for both channels. The blue channel generally will use the IPCS II as detector and the red channel, a dual-CCD camera. The projected slit scale at the focal plane (14.7 arc sec mm^{-1}) gives good matching of the intrinsic resolution of the detectors (better than 30 microns FWHM) and the good seeing typical of La Palma. The slit assembly consists of two remotely interchangeable units mounted on a common slide catering for conventional long-slit spectroscopy and for multi-object work both with multiple slits and with optical fibres fed from the auxiliary focal station of the Acquisition and Guidance Unit. An exploded illustration of the slit assembly and other operational components is given in Fig. 9. This is a highly versatile arrangement, allowing the observer to change quickly between these different modes of observation in response to changing atmospheric conditions or scientific requirements. The slit area also accommodates a dekker slide, an anamorph lens system (to give improved matching of the collimated beam when working at steep grating angles), and half-wave and quarter-wave polarization slides, all located above the slit, and a Wollaston prism slide and a field lens (associated with the anamorph system) mounted below the slit. The elements of the polarization unit are to be provided by Durham University.

There are two optical folding units (Figs. 8 and 9). The first, immediately below the slit, can accommodate either a fused silica prism and a dichroic filter or two dichroic filters, and a clear position. The second folding unit gives the option of either a folding mirror for the red

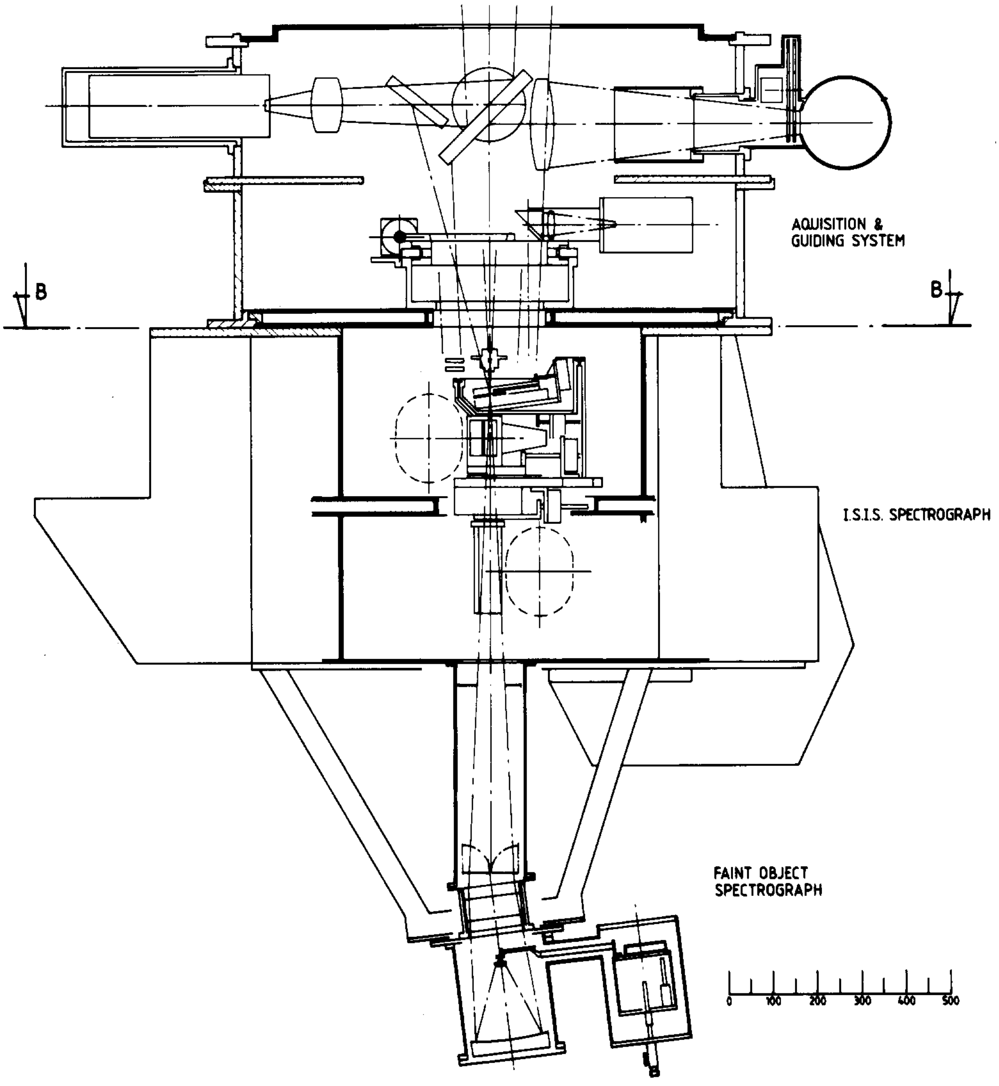

Figure 6. Sectional view of the Cassegrain Acquisition and Guidance Unit with the ISIS and FOS instruments attached (section A-A in Fig. 7). The protruding ISIS detectors are not outlined and only selected elements of the internal structures are shown. The scale is in mm.

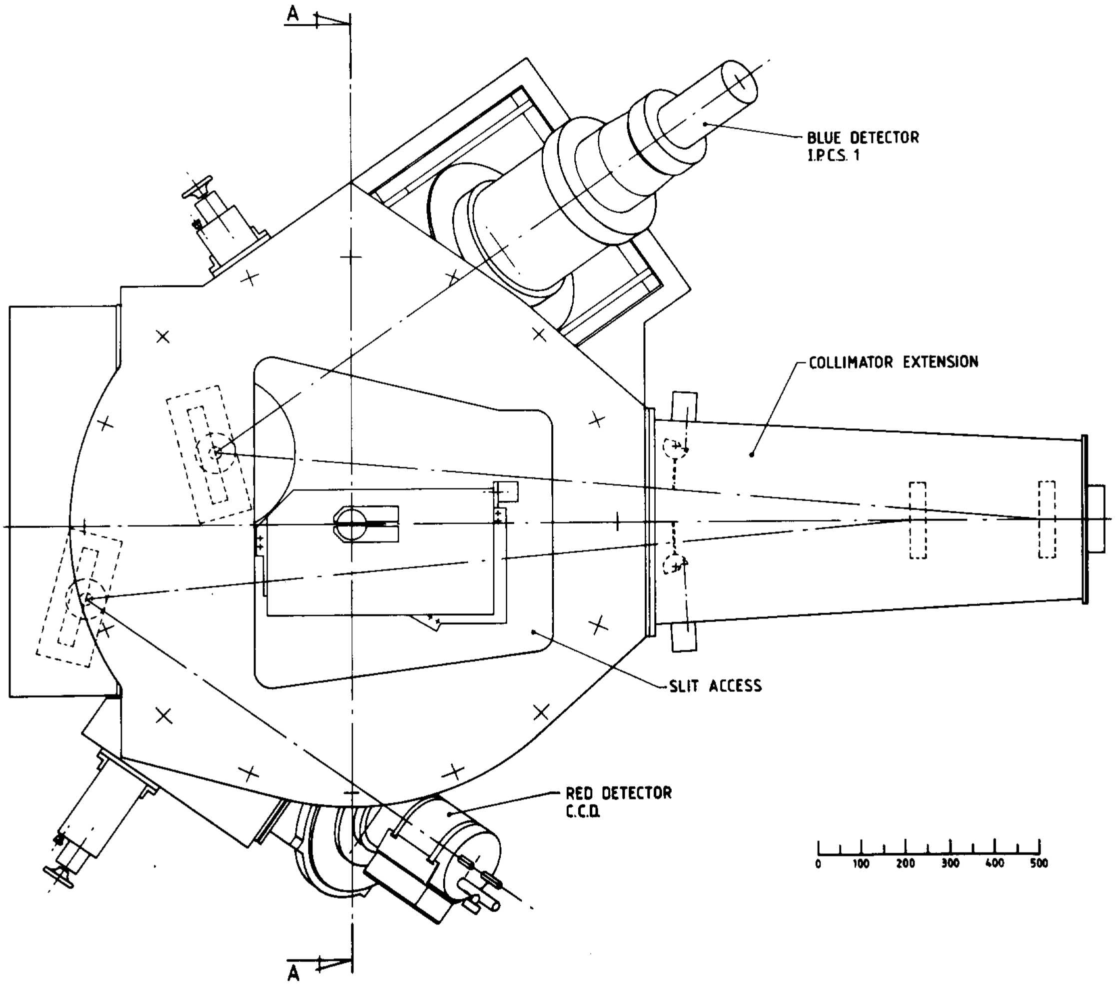

Figure 7. Outline of the ISIS and FOS instruments as viewed at section B-B in Fig. 6 (Fig. 6 is the view on section A-A). The scale is in mm.

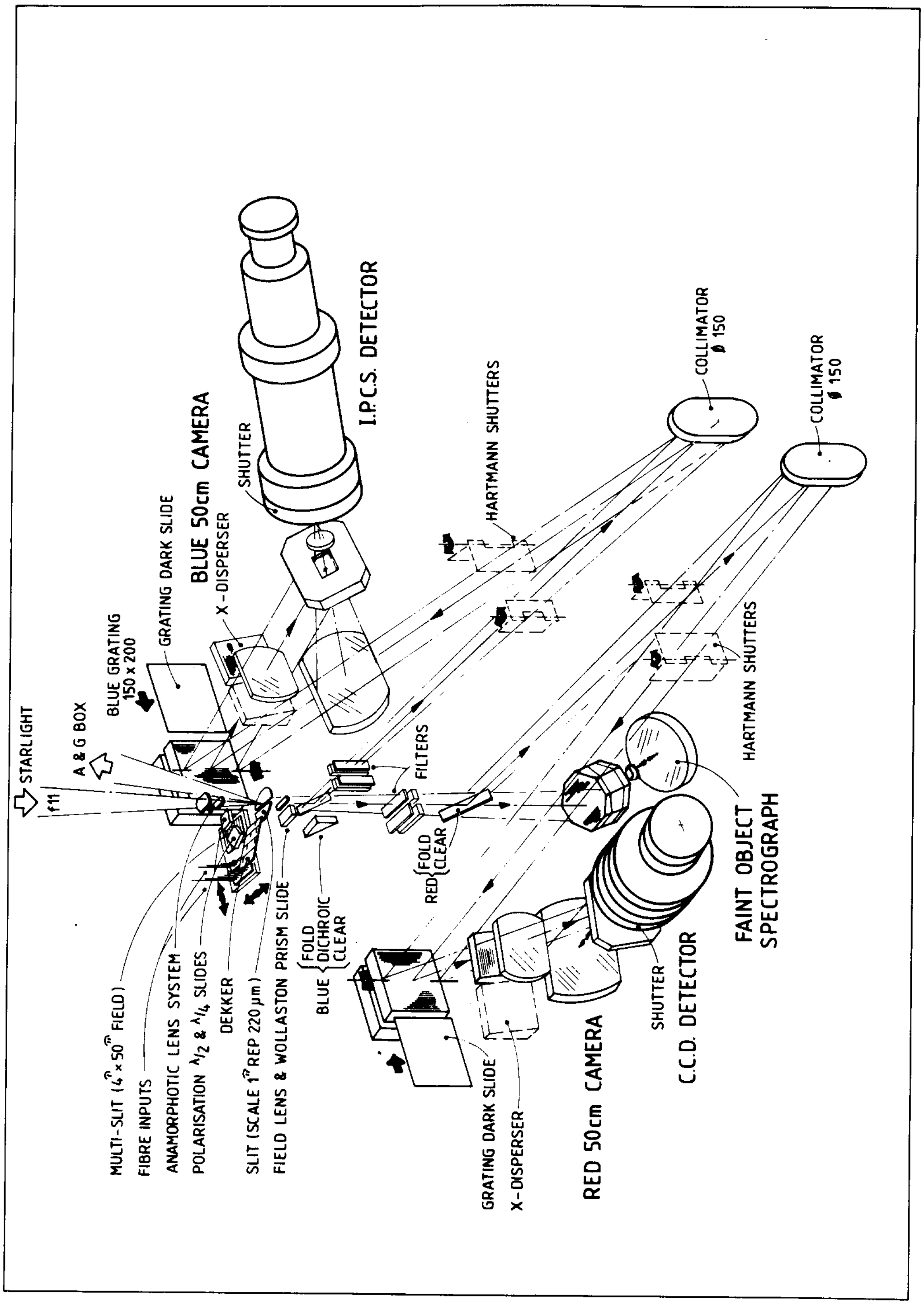

Figure 8. Schematic optical diagram of ISIS with FOS. The dimensions given are in mm.

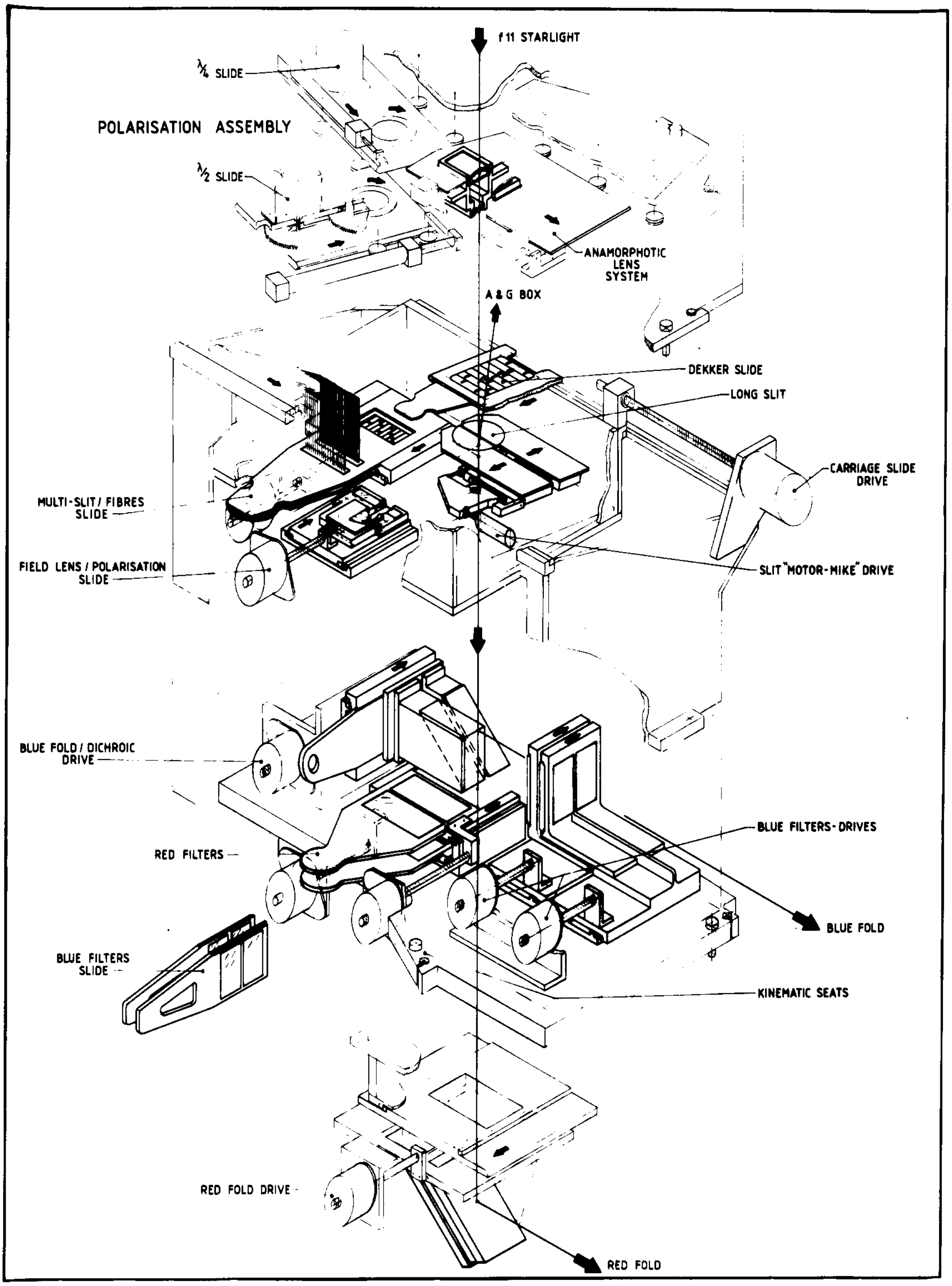

Figure 9. Exploded illustration of the items in the ISIS slit area.

channel, or a straight-through path to the FOS. The dichroic filters sharply split the light into two wavebands which are appropriately passed to the blue and red channels; several dichroic filters with different cross-over wavelengths in the range 480 to 600nm will be available for mounting as required. In addition to the filters provided in the Acquisition and Guidance unit separate below-slit neutral density and colour filter slides are available for the two channels. A pair of remotely controlled Hartmann shutters is placed in front of each collimator for focussing purposes. The initial grating assemblies will accept only a single grating at a time but a future development will allow mounting two gratings back-to-back, with remote selection. The grating cells accept standard gratings with a ruled area of 15.4 x 20.6cm, and can be rotated remotely. The blue channel camera is designed to operate over the wavelength range 300 to 600nm and has an accessible back focus to accept either the IPCS II or a CCD camera. The red channel camera is optimized to cover the wavelength range 400 to 1100nm. Two GEC CCDs mounted side by side on a common block are used as the detectors for this channel. In both cameras a rapidly operating light-tight shutter is provided behind the folding mirror to isolate the detector from the spectrograph when required.

The main structure of ISIS is a steel fabrication which has been designed using finite element analysis methods. Although ISIS is large and massive (1.5 tonnes) it will be sufficiently rigid to limit shifts in the image plane at the detectors to less than 5 microns over an hour of tracking on the sky.

9.4 Faint Object Spectrograph

The FOS is a collimator-less dedicated (not versatile) spectrograph designed to have the utmost efficiency for use at low dispersion and covering the widest possible wavelength range (Wynne 1982a,b). It is shown in outline in Fig. 6. The FOS employs a transmission grating whose substrate is cemented onto a cross-dispersing prism which in turn is cemented onto the aspheric plate of a Schmidt-type camera, so eliminating four glass-air surfaces. The grating lies in the divergent beam from the ISIS slit assembly when the straight-through mode is selected. The resultant complicated aberrations are satisfactorily corrected by appropriate adjustments in the separation, tilt and centering of the rest of the components of the system. A CCD detector is mounted on a cooled finger which supports it at the internal focus of the Schmidt-type camera so avoiding the need for a further reflecting surface to provide an external focus as for the ISIS cameras. A similar spectrograph, built jointly by the RGO and Durham University, is operating on the Isaac Newton Telescope.

9.5 Taurus II

Taurus is a wide-field (9 arc min) imaging Fabry Perot interferometer originally developed jointly by the RGO and Imperial College, London (Atherton et al. 1982) to map velocity fields of extended or multiple astronomical emission-line sources, using a servo-controlled scanning Fabry Perot etalon as a narrow-band tunable filter. Effectively, it allows two-dimensional images to be recorded in many adjacent narrow wavelength bands. Typical observing programmes relate to the study of gas in external galaxies, HII regions, supernovae remnants, and other kinds of nebulae.

A new, fully automated version, Taurus II, is being built by the Kapteyn Sterrenwacht Werkgroep in Roden, the Netherlands, with some technical input from the RGO. This is to be one of the Cassegrain instruments. The etalons have 65mm clear aperture and are piezo-electrically scanned through a stabilizing servo-loop using capacitance micrometers and sensors. A set of four etalons is planned, with gaps ranging from 10 to 600 microns, giving respective free spectral ranges from 9900 to 164km sec^{-1} and resolutions from 280 to 4.7km sec^{-1}. Four high-precision mechanisms, each a servo-controlled wheel, are used for interchanging etalons, input focal plane and pupil plane filters, and input focal plane apertures or masks, and there is also a variety of minor mechanisms for camera focussing, control of a shutter, etc. The detector to be used with this instrument is the IPCS II.

Taurus II has three primary modes of use:

i) Imaging spectroscopy, in which the etalon is stepped in synchronism with the readout of the detector, resulting in a three-dimensional data set (two spatial and one spectral) which is calibrated using monochromatic and continuum lamp sources. Such data sets are used to derive velocity fields, spatially discrete line shapes and intensities, and continuum maps.

ii) Narrow-band imaging, without an etalon but using any of the 16 possible filters through which to image the sky. A typical application for this mode is the construction of emission-line-ratio maps.

iii) Multi-object spectroscopy, using grisms in place of the etalons and masks with patterns of slits inserted in the input focal plane aperture wheel.

9.6 Detectors

The CCD camera system for the WHT is being developed jointly by the Radiosterrenwacht at Dwingeloo in the Netherlands, and the RGO. It is a development of the CCD camera designed by the RGO for the Isaac Newton Telescope. The new design retains the flexibility of programmable waveforms, but emphasis has been placed on the ability to drive and read out several different CCD chips either together or separately. Large format CCDs, now in development by more than one manufacturer, also can be accommodated.

The IPCS II is an evolution from the original IPCS developed at University College London (Boksenberg 1982). A new CCD-based readout system to replace the Plumbicon tube system, and new centroiding electronics employing an interpolative method, (Boksenberg et al. 1985) are under construction at UCL. This will be preceded either by the four-stage intensifier also used in the original system but with a new coupling lens (Worswick and Wynne 1985) or by a microchannel plate intensifier with tapered fibre optic or lens coupling.

REFERENCES

Atherton, P.D., Taylor, K., Pike, C.D., Harmer, C.F.W., Parker, N.M., and Hook, R. 1982. Mon. Not. R. astr. Soc., 201, 661.
Boksenberg, A. 1982. Phil. Trans. R. Soc. Lond. A., 307, 531.
Boksenberg, A., Coleman, C.I., Fordham, J. and Shortridge, K. 1985. Advances in Electronics and Electron Physics, 64A, 33.
Mack, B. 1980. Applied Optics, 19, 1000.
Worswick, S.P., and Wynne, C.G. 1985. The Observatory, 105, 95.
Wynne, C.G. 1974. Mon. Not. R. astr. Soc., 167, 189.
Wynne, C.G. 1977. Mon. Not. R. astr. Soc., 180, 485.
Wynne, C.G. 1982a. Optica Acta, 29, 137.
Wynne, C.G. 1982b. Optica Acta, 29, 1557.