

*The William Herschel Telescope, appropriately named after the great amateur astronomer who discovered Uranus, and was the world's first observational cosmologist, will be the third largest single-mirror telescope in the world, and is now being brought into action on La Palma in the Canary Islands.*

This summer sees the start of operation of the 4.2-metre (165-inch) William Herschel Telescope (WHT) on the Canary Islands. The telescope will complete the original plan for three astrophysical telescopes built at the Roque de los Muchachos Observatory by the Royal Greenwich Observatory (RGO) for astronomers in Britain, the Netherlands and Spain. The idea of the telescope was to produce the largest possible telescope with the finest possible technical specification with the money available. The excellence of the astronomical conditions on La Palma dictated stringent limits for the sharpness of its images and the accuracy with which it tracked stars. The most important of these from the point of view of designing the telescope was the fine seeing, with star images of 1.0 arcsec or better 40% of the time; at their best star images are 0.3 to 0.6 arcsec. This summer is the final test of whether the tight specification is going to be met, after the years of calculations and design work at RGO, and of testing and construction in the Grubb Parsons factory.

Under the blunt and outspoken, skilled and energetic project engineer Brian Mack, the William Herschel Telescope has been reconstructed in the dome at 2400m

(7,870 feet) on the Roque de los Muchachos. It 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 5.1-metre (200-inch) telescope in the USA and the 6-metre (236-inch) telescope in the USSR. For a time during its erection it was possible to push the 160 ton telescope around by hand; by now the gears have been meshed and it is no longer free, but can be accurately controlled. It towers above the visitor who enters the dome at ground level. The dome is small and hugs the telescope — no voluminous spaces to be filled with hot air that causes convection and therefore bad seeing. The dome is cold — not just because it is unheated but because of the screens and cavity walls that protect the telescope from the warmth of sunlight striking the dome and its supporting wall.

**ALTAZIMUTH DESIGN**

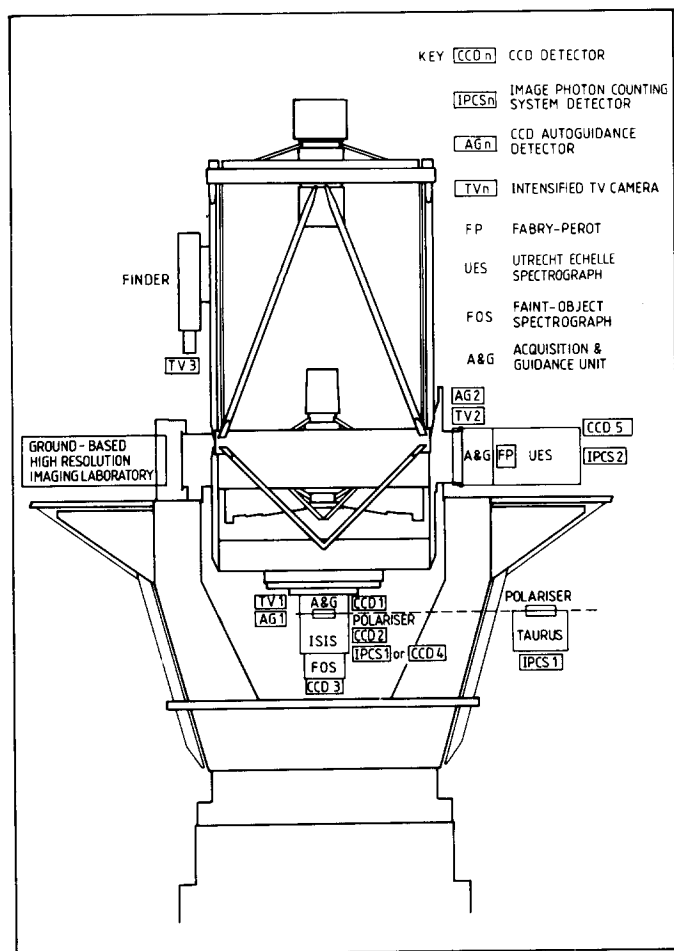
The telescope design is based on construction principles by James Nasmyth, a Victorian engineer, inventor of the steam-hammer and holder of numerous patents in canal making. A keen amateur astronomer, Nasmyth built the first "trunnion-vision" telescope on an altazimuth mounting.

Altazimuth mountings are like guns, with the altitude motion of the telescope corresponding to elevation, and the azimuth corresponding to the bearing around the horizon; they were of course the commonest way of holding a telescope before the invention of the equatorial mounting. Nasmyth's idea was to add a third mirror to a Cassegrain telescope mounted on an altazimuth mount, such that the light beam was deflected out of the telescope tube along the altitude axis, through the trunnion which supported the altitude bearing. Nasmyth could sit on a stool mounted on the azimuth bearing with his eye at the trunnion, in relative comfort. He was too old to climb a ladder to the stars, he said, so he brought the stars down to him. The deflected foci are called the Nasmyth foci. Nasmyth's telescope was of such quality that he was the first to see the solar granulation, described by him as a "willow leaf pattern".

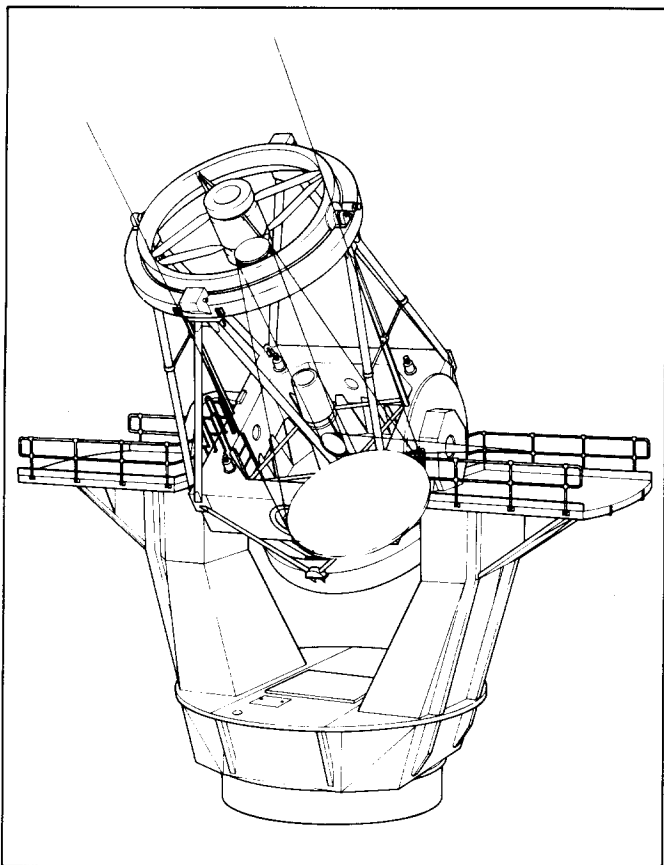
The altazimuth-mounted William Herschel Telescope has two Nasmyth foci deflected by the third flat mirror (called the Nasmyth mirror), as well as the conventional Cassegrain focus. At the Nasmyth foci are two large horizontal platforms, which can take large instruments, holding them horizontal, fixed relative to gravity.

**NASMYTH INSTRUMENTS**

By contrast to the rigidly-boxed instruments mounted at the Cassegrain focus, which moves to all attitudes, instruments at the Nasmyth foci can be simple optical benches as if in a laboratory. This gives astronomers the opportunity to try out novel ideas in an instrument in an experimental way, without having to constrain their imagination as well as the components by enclosing the instrument in a rigid box.



▲ The instruments on standby at the foci of the William Herschel Telescope will be switch-selectable to be deployed as needed.



▲ *Optical diagram of the Nasmyth focus of the Herschel Telescope, with light reflected from the large primary mirror, the secondary at the top of the tube and the 45° elliptical Nasmyth flat embedded at the centre of the telescope.*

The Nasmyth mirror gives astronomers who use the Herschel Telescope another advantage — it is easily switchable to direct the light beam to either of the Nasmyth foci, or to fold out of the way so that the light beam can reach the Cassegrain focus. Thus an astronomer can have at least three instruments on standby through the night to deploy on his programme as it is necessary; alternatively he can switch from one instrument to another as conditions change through the night. To give an example of both these scenarios:

Astronomer A has the position of an EXOSAT X-ray source observed by the satellite. He uses the low resolution spectrograph at the Cassegrain focus to survey the optical objects which might be responsible for the X-rays. On the real-time display of data from one of these he sees that it has an emission line spectrum, indicating the presence of gas which might be being accreted on to a compact object such as a neutron star or black-hole. He switches to the high resolution spectrograph for a closer, longer look at the emission lines. He can see the  $\lambda 4686$  ionised helium emission line which is enhanced by a flux of X-rays, so he is pretty sure this is the X-ray candidate, and he notices that H-beta is double, indicating that the gas is flowing round an accretion disk, one side receding, the other approaching. He takes a second exposure. On the second spectrum he sees that the ratio of the two components has altered, so the orbital period might be small. He alternates for the rest of the night between exposing spectra and CCD images, the latter giving him the light curve of the binary star, the former its velocity curve.

Astronomers B, C and D, on the other hand have quite distinct requirements. B has a new infrared camera set up on the Nasmyth focus. He uses it in the afternoon to study star formation regions: the sky is as black in the daytime as at night to an infrared astronomer. At twilight he hands the telescope over to astronomer C who needs high dispersion spectra of bright stars. It does not matter to him that there is a moderate background of sun- or moonlight. C switches the Nasmyth mirror to the other Nasmyth focus where there is a high dispersion spectrograph. C follows his programme in twilight and while the Moon is above the horizon, but when the Moon sets he hands over to D. D folds the Nasmyth mirror away and uses the telescope at the Cassegrain focus while the sky is dark to obtain low dispersion spectra of faint galaxies, to obtain redshifts of distant clusters: their light would be swamped by moonlight.

Each of these three astronomers gets the conditions which he can use, and none of them is inconvenienced by adverse conditions which would affect his programme. Scheduling of the telescope can be flexible, without being constrained by the usual night-by-night division of telescope time.

#### TELESCOPE DRIVES AND CONTROL

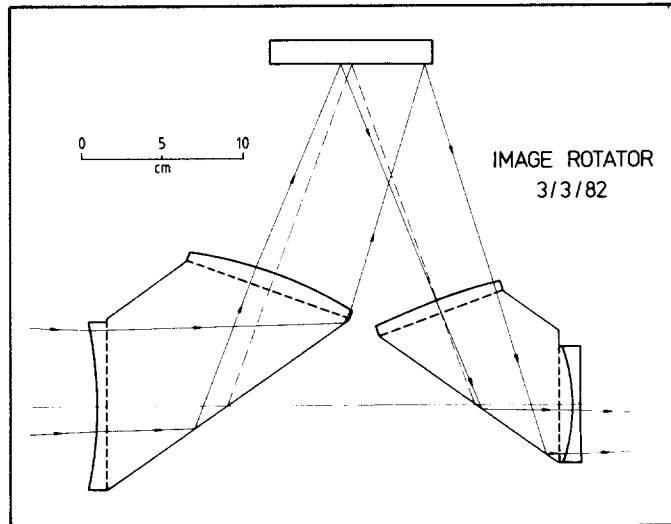
Because the WHT is symmetric relative to gravity, and compact, it is very responsive to its controls. Essentially because the lengths of its structures are small, their frequencies of oscillation are high, and they respond positively to low frequency pushes. The telescope is actually pointed and tracked through identical precision straight spur gears which are fitted to the two axes of the telescope. It is intended that the telescope pointing accuracy be 1 arcsec or better after compensation by the computer control system for all repeatable errors, but this will not be tested until the telescope begins operating. The WHT can rotate by a maximum of 0–90° from the horizontal and  $\pm 270^\circ$  about East.

The altazimuth mounting has some special features that optical astronomers are not used to, although radio astronomers will find them familiar when they come to observe. Astronomers will have to be careful in slewing to their next object always to 'unwind' the azimuth rotation, otherwise they may be stopped during the next integration when they reach a 270° limit. The maximum slewing speed for both axes is 1° per sec with acceleration during slewing reaching a maximum of 0°·3 per sec per sec. These limits set the size of the 'blind spot' at the zenith: the telescope cannot rotate in azimuth by 180° instantaneously if the object happens to pass through the zenith. On the rare occasions when this happens, observing will have to cease temporarily. For the WHT the blind spot is 0.2 degrees radius and the interruption lasts at most 3 minutes.

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. All the instrument turntables and cable wrap devices are controlled in sympathy with the telescope motion, as well as the positions of the dome observing slit and windscreen.

Turntables play a bigger rôle in altazimuth telescopes like the WHT than in equatorial telescopes. Imagine the telescope tracking a nebula up to the zenith. The preceding side of the image is upwards. After passing the

zenith, it is the following side of the image which is upwards. If an instrument is fixed to the telescope and remains stationary relative to it, then before the zenith its 'upward' side receives the western portion of the image, afterwards the eastern. The image rotates relative to the instrument and, to follow it, the instrument should itself rotate. This is the philosophy adopted at the Cassegrain focus — the instrument is mounted on a turntable to follow the image. (If an astronomer doesn't need the instrument to be rotated he can switch the turntable off!)



▲ The three-reflection Nasmyth image rotator uses the total internal reflections of two right angle prisms, with lens faces to compensate for the extra path length in the reflection off the plane mirror.

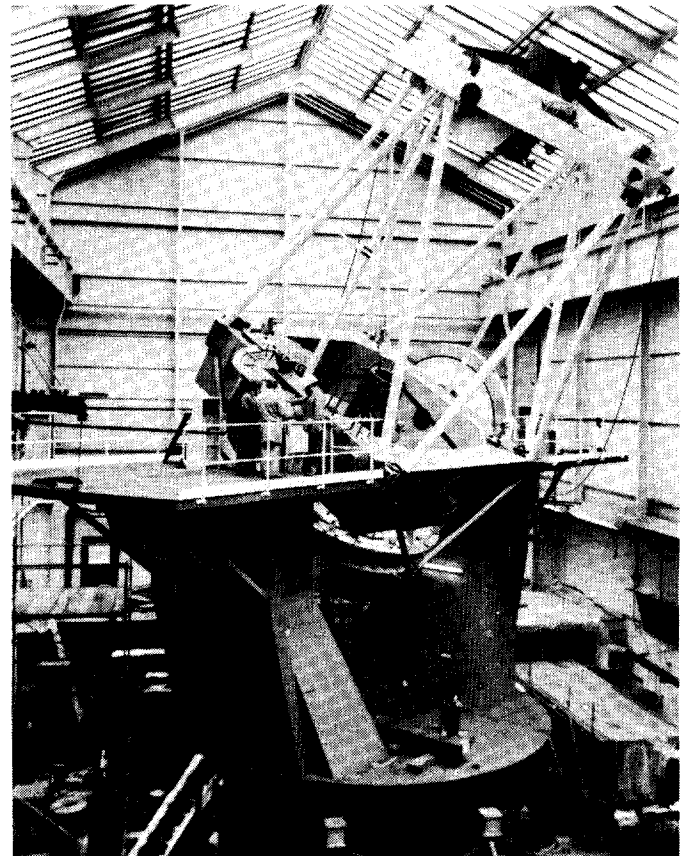
At the Nasmyth foci, however, a train of three reflections is used to de-rotate the image and to keep it stationary on a fixed instrument. Sometimes, however, a Nasmyth instrument won't need to look through the image (de-) rotator: why worry about the East and West side of a star image, for instance? So the three-reflection (de-) rotator will be removed from the light beam. Since the light beam does not pass through the (de-) rotator any more the focus would be moved outward if the (de-) rotator was simply three mirrors, so the WHT uses one mirror and two prisms which have lenses attached to their faces. The lenses slightly alter the focus of the telescope to the same position it would have if the (de-) rotator was absent. The instrument rotator and the image (de-) rotator are part of the telescope control system, and the astronomer need not worry about their operation, only whether they are there.

**TELESCOPE OPTICS**

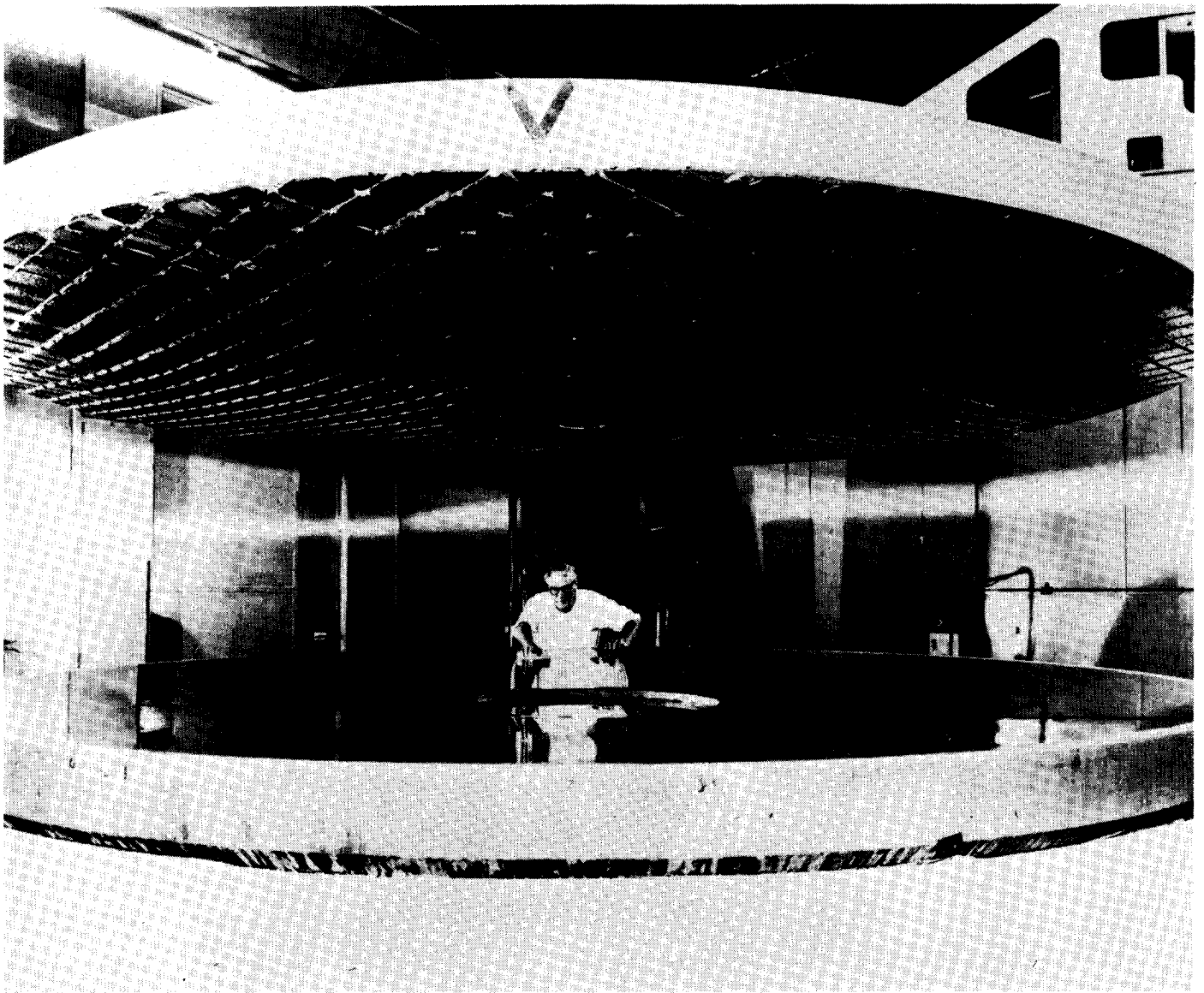
So as not to degrade the excellent La Palma seeing, the WHT has the finest large optics money can buy. The telescope is of classical Cassegrain optical configuration. The paraboloidal primary mirror is made of a glass-ceramic material (Cervit) having near-zero coefficient of expansion over the operating temperature range. As the temperature of the mirror falls during the night, the mirror contracts completely imperceptibly and retains its expensively bought figure. The mirror has a clear aperture of 4.2m (165 inches) and a focal length of 10.5m (34.4 feet) (f/2.5). The precise diameter of 4.2m was determined by the availability of the mirror blank, made by Owens-Illinois as part of the 4m series of blanks for telescopes of the 1970's. The mirror, figured by David

Brown of Grubb Parsons, concentrates 85% of the light of a distant star into an area only 0.3 arcsec in diameter. The mirror figure was actually 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 (about 8 inches) or less, since this is about the size of the atmospheric cells above the La Palma site. Portions on 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 arcsec 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.

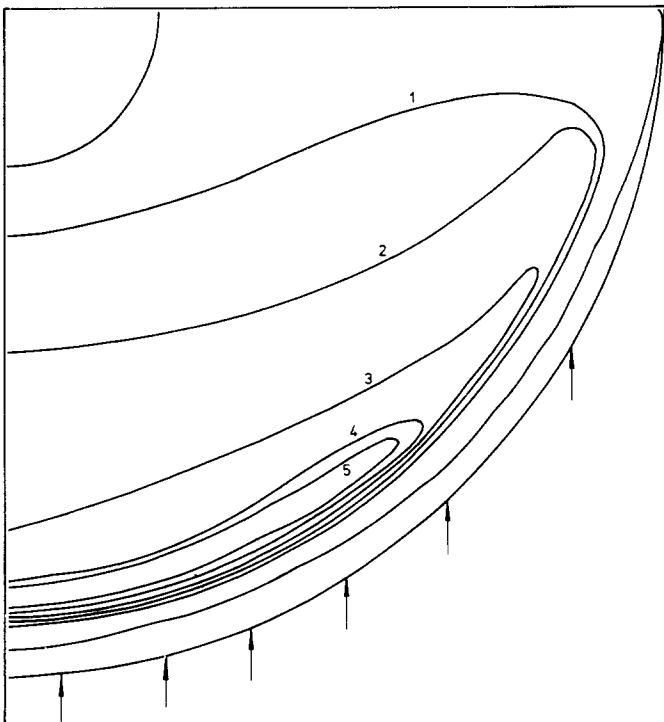
The mirror's diameter-to-thickness ratio of 8 makes it thinner than for most large telescopes built in recent years, but it is not really classifiable as a thin mirror and raises no unusual problems for its support system. Nevertheless the optical performance of a telescope depends on controlling the deformation of the mirror surface when the mirror is contained in a mirror cell. In fact, a large mirror would bend by hundreds or thousands of times the optical tolerance if not mounted properly. The images would be useless. The problems for large telescopes become severe very rapidly, since the deflections of a structure increase with its weight multiplied by the lever arm at which the weight is applied, and divided by the cross-sectional area of its material, which provides the stiffness. The deflections of a telescope thus increase as the square of the telescope mirror size, so that in this sense a 4.2-metre (165-inch) telescope is about three times more difficult to make than a 2.5-metre (98-inch) telescope.



▲ Above and facing page: The William Herschel Telescope undergoing tests at the Grubb Parsons works in Newcastle-upon-Tyne, before it was shipped out to the island of La Palma in the Canary Islands.



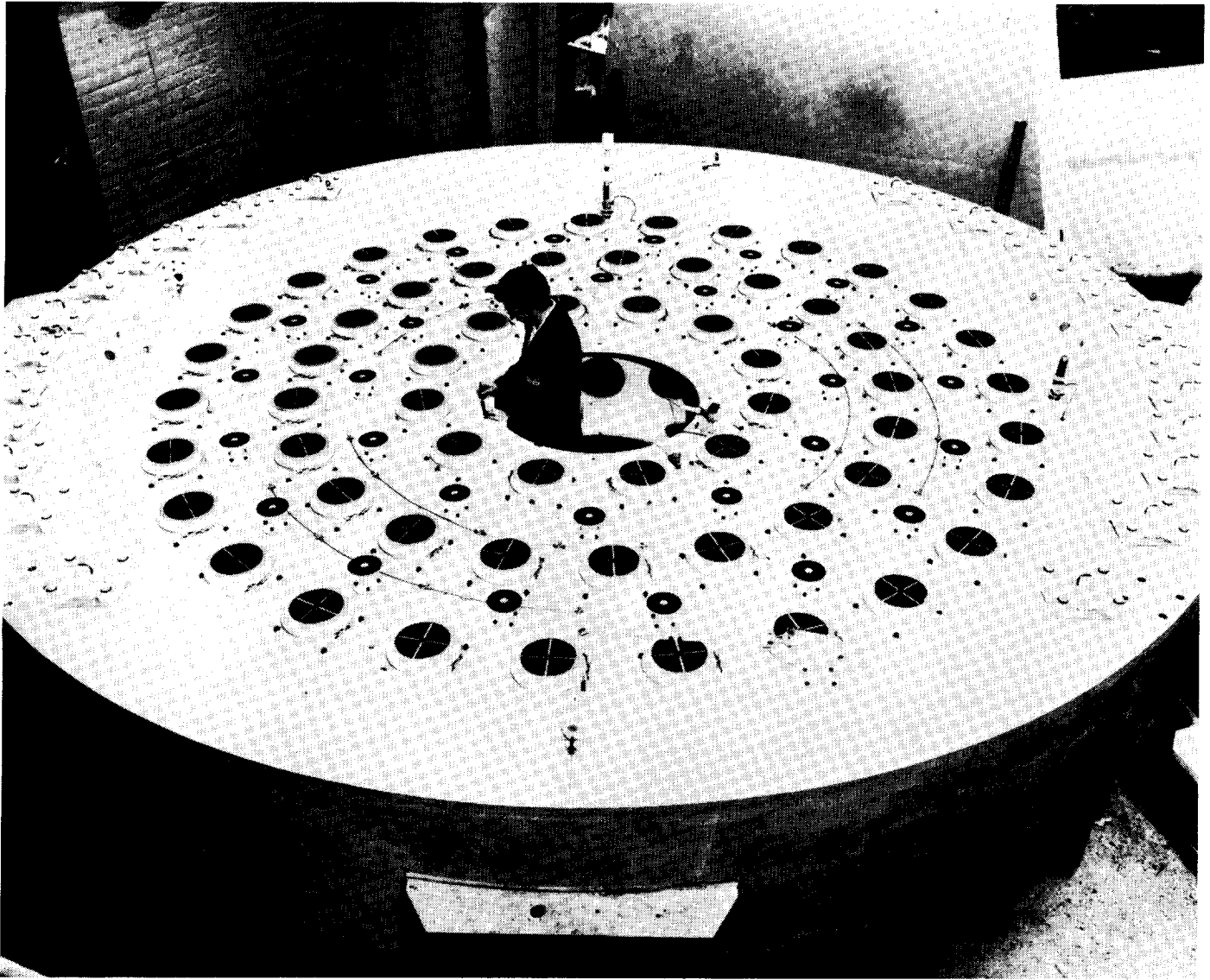
▲ The 4.2m mirror of the William Herschel Telescope in its last stages of figuring at Grubb Parsons. Above is the check pattern of the pitch lap used in the figuring process.



Calculations for the WHT mirror show that when it stands on edge in its cell pointing to an object on the horizon a ridge or wrinkle appears at the lower edge, as the mirror compresses under its own weight; however, the height of the wrinkle is only 1/10 the wavelength of light and does not significantly disturb the figure of the mirror.

The focus of the uncorrected primary mirror, which, at  $f/2.5$ , is quite deeply worked, would show strong off-axis coma. To correct this Charles Wynne has designed a three-element correcting lens to put in front of the prime focus. This will give an unvignetted field of 50 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 altered to  $f/2.8$ . The corrector and the Cassegrain secondary mirror are mounted back to back, and the switch from Cassegrain focus to prime focus is by flipping the two optical

▲ In the most severe case, when the primary mirror of the William Herschel Telescope stands on edge in its cell, a ridge appears at the lower edge, of peak height 50nm (about 1/10 of the wavelength of light). In this contour diagram of a quarter of the mirror the ridge is labelled in units of 10nm. (10nm equals one hundred-millionth of a metre)



▲ The 4.2m mirror cell and support system showing the pneumatic pads (hot-cross buns) and smaller doughnut-like spring-loaded rest pads.

components over in the top end ring. For financial reasons the prime focus of the telescope will not be brought into operation until much later.

The Cassegrain and Nasmyth foci are the first to be commissioned. They use a convex hyperboloidal secondary mirror, made of Zerodur, 1.0m (39.4 inches) in diameter which 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 third main mirror, the Nasmyth flat, angled at 45°, 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 to the Nasmyth platforms, or folded back so the beam goes to the Cassegrain. The effective focal length of the telescope for the Cassegrain and Nasmyth foci is 46.2m (151.5 feet) ( $f/11$ ). The available unvignetted field diameters are 15 arc min at the Cassegrain focus and 5 arc min at the Nasmyth foci.

#### DOME AND BUILDING

The telescope is supported by a reinforced concrete pier mounted on piles driven through the volcanic ash to a thick layer of basalt rock 20m (66 feet) below the surface. The pier puts the centre of rotation of the telescope at a height of 13.4m (44 feet) above the ground. The dome

is 21m (69 feet) internal diameter, and a pair of up-and-over shutters with a windscreen coupled to the lower shutter will allow observations down to 12° above the horizon. The dome is onion-shaped to allow the up-and-over shutter to track back past the zenith. Sideways moving biparting shutters are not used, because they stick out from the dome like sails and not only spoil the flow of air over the dome but sustain enormous forces in high winds. The dome is capable of supporting its own weight in ice buildup. The dome is supported on a rail set on to a cylindrical concrete building structure. Set on one side of the cylindrical drum is a 3-storey rectangular annex. This contains the mirror aluminizing plant, the operations control room, computer room, dark rooms, workshops, offices and various services.

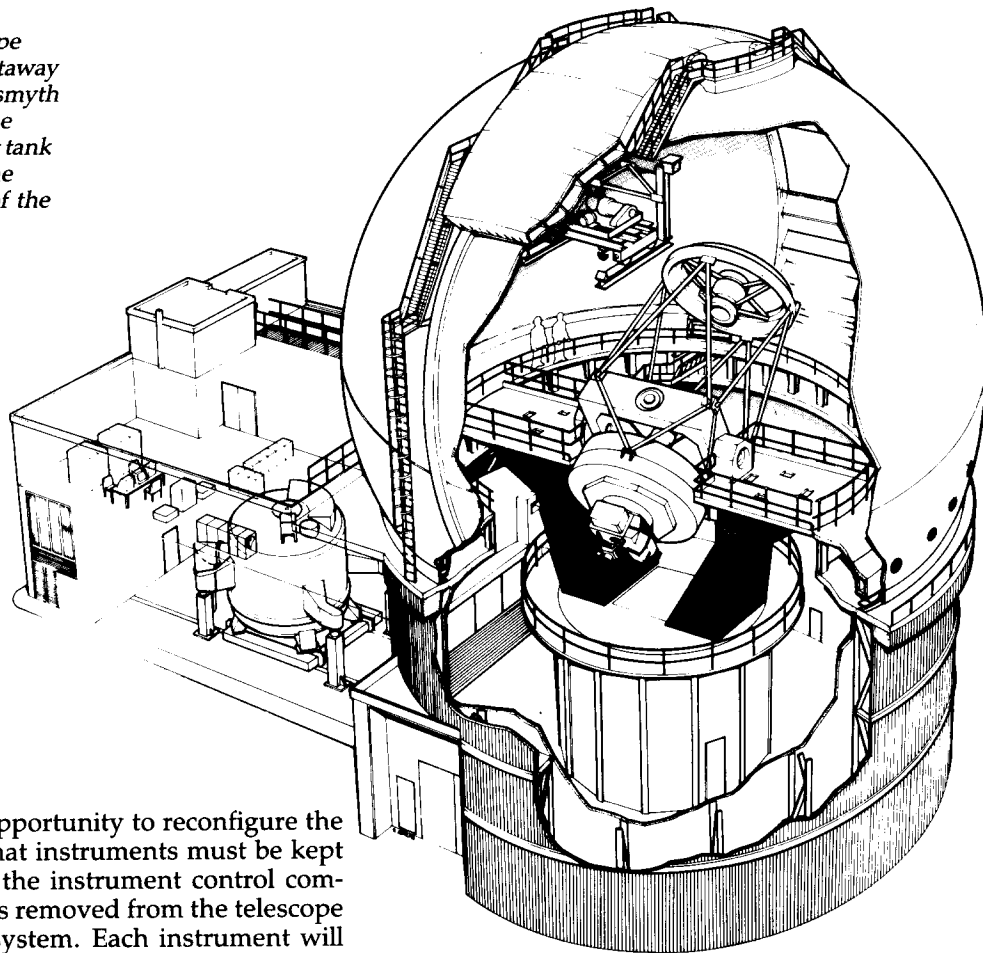
Because no unnecessary activity takes place in the dome there is very little thermal disturbance of the air near the telescope, which greatly improves the chance of achieving perfect 'dome seeing'.

#### REMOTE OBSERVING AND FUTURE INSTRUMENTS

The WHT will be used at first with stand-alone instruments, but in the near future RGO and its university partners expect to create for it a versatile suite of interconnected instruments. The switchability of the

## THE WILLIAM HERSCHEL TELESCOPE

*The William Herschel Telescope points to the south in this cutaway drawing showing the large Nasmyth platforms (left and right of the telescope) and the aluminising tank under the control room (in the block-like annexe to the left of the dome).*



Nasmyth mirror and the opportunity to reconfigure the telescope quickly means that instruments must be kept on standby, connected to the instrument control computer. Their standby heat is removed from the telescope by a refrigerated cooling system. Each instrument will be controlled locally by its own microprocessor connected by a utility network called Ethernet. The instruments can be commanded and data collected via this network. The VAX computer which is in overall charge of the instruments can host STARLINK-type software for data reduction and can be connected via intercontinental packet-switch networks to computers anywhere in the world. In this way astronomers will be able to observe on the WHT without leaving their home desks.

This will be convenient and even efficient: but the real effectiveness of any telescope depends hugely on the capability of the instruments it feeds. There is a continual, rapid increase in the sophistication of instruments for optical astronomy, and astronomers frequently introduce major enhancements or fundamentally new instruments. There is also a basic requirement for versatile and efficient spectrographs these representing the major analytical technique of the astronomer, and for highly sensitive 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 and probably together make up 90% of the use of the telescope. 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 WHT and one of its typical complex instruments and detectors rarely exceeds a few per cent. Low though it seems, this is enormously greater than was available just a few decades ago.

Efficient instruments mean that as much as possible of the available light can be used. Good seeing, good optics and good tracking mean that unwanted light from the sky can be excluded from the instruments and make the measurements clearer. The lack of artificial light in the La Palma sky (if lighting development can continue to be controlled) means that the unwanted light is, in any case, small. All this adds up to good prospects for making measurements of fainter stars, galaxies and quasars. And fainter means, usually, more distant — the William Herschel Telescope is designed for cosmological problems, and named fittingly after Britain's greatest and first observational cosmologist.

These then are the prospects for the future. The present reality of astronomy, now, is that British, Dutch and Spanish astronomers this year will be travelling to the Canary Islands, and the La Palma mountain tops, to use what we expect is at this time proving to be one of the finest telescopes in one of the finest sites in the world.

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*Paul Murdin, until recently the head of the Royal Greenwich Observatory's La Palma operation, is the head of its Astronomy Division at Herstmonceux.*

*Alec Boksenberg is the Director of the Royal Greenwich Observatory and the inventor of the Image Photon Counting System, used at La Palma and on the Anglo-Australian Telescope.*

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**Facing page:** A close-up view of the 4.2-metre William Herschel Telescope inside its dome at the Roque de los Muchachos Observatory on La Palma. The two large Nasmyth platforms (left and right of the telescope) are clearly shown.