DESIGN OF THE 4.2 M HERSCHEL TELESCOPE AND INSTRUMENTS

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The UK Science and Engineering Research Council (SERC), through the Royal Greenwich Observatory (RGO), is installing on the island of La Palma, a 4.2 m altazimuth telescope, as part of the Observatorio del Roque de los Muchachos, at an altitude of 2300 m in the Canary Islands. The telescope, known as the William Herschel Telescope, is fully designed and manufacture has begun. It is due for completion in the mid-1980's. The telescope, dome and instrument design have all interacted with one another, particularly in the search for economy. Among the proposed instruments is a novel collimator-less spectrograph.

1. TELESCOPE AND DOME

1.1 Mirrors and Supports

The primary mirror is of glass-ceramic material (Cer-Vit) having a near-zero thermal coefficient of expansion. It will have a clear aperture of 4.2 m and a focal length of 10.5 m (f/2.5). The parabolic mirror, which is being made from an existing blank bought at an advantageous price, has a thickness-to-diameter ratio of 8, thinner than most large telescopes made in recent years, but not classifiable as a thin mirror (like UKIRT which has a ratio of 16). The prime focus camera can be replaced by a secondary mirror which will direct the light to a Cassegrain focus or, when a 45° flat mirror is interposed, to either of the two Nasmyth foci outside the altitude bearings. All three of these foci will be of focal length 46.2 m, (f/11). The available fields are ½° diameter at prime, 15' at the Cassegrain and 5' at the Nasmyth foci.

The primary mirror will be supported axially on three rings of pneumatic cylinders employing roll-diaphragms as seals. The optimum radii for the mirror support rings have been determined using a finite element computer analysis of mirror deflections. It is intended that the three rings of supports shall operate at the same pressure and that this shall be derived from a small air pump and exhaust valve

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system controlled by the electrical output from load cells incorporated in the axial defining points. The mirror will be supported in a transverse direction by a system of lever weights acting only in the gravity plane, an efficient arrangement only possible in an altazimuth mounting. The convex secondary mirror will be supported axially by a mechanical six-point load distribution system cemented to the rear face of the mirror, and transversely by a conventional lever-weight system.

1.2 The telescope and its mounting

The telescope tube is conventional (Fig 1): a rectangular box section centrepiece will be carried on the altitude bearings with serrurier trusses fastened to it which support the primary mirror cell at one end and the secondary mirror or prime focus assembly at the other. A set of spider vanes attached to the centre section will support the 45° Nasmyth flat mirror and also the sky baffle. The 45° mirror will be motor-driven into any of four positions. It will be clear of the light beam when observing at the Cassegrain focus, in the path of the light beam directing it through one altitude bearing or the other to the Nasmyth foci, or in the path of the light beam directing it to a broken Cassegrain focus on the centre section. Thus it will be possible to mount different instruments at these four observing stations and to direct the light beam within minutes from one instrument to another as desired during the night.

The secondary mirror will be mounted on spider vanes in a ring at the end of the tube which can be rotated through 180°. For the change to prime focus operation the telescope tube will be lowered to horizontal and the mounting ring rotated to bring the secondary mirror facing outwards so that it can be easily removed. The prime focus unit will then be attached in its place in a semimanual operation expected to take about 30 minutes. No observer cage will be provided and instruments at the prime focus must be controlled remotely, it is expected that Cassegrain instruments will also be remotely controlled.

The telescope will have an altazimuth mounting. The vertical axis is formed by a horizontal flat annular bearing track rotating on six hydrostatic (externally-pressurised) oil pads. This bearing track is formed on the underside of a box-section ring which is bolted to the mounting base. From the base rise two columns on which are mounted the cylindrical hydrostatic bearings which form the elevation axis and carry the telescope tube. Horizontal attachment faces on brackets rigidly attached to the columns at both ends of the altitude axis will enable large instruments to be carried at the two Nasmyth foci. Each Nasmyth focal station will also have an observing platform which will be independently supported from the mounting base to minimize the transmission of vibrations from the observer to the instrument. Observers will gain access to these Nasmyth platforms from the dome. Motor-driven turntables will be provided at the prime focus and Cassegrain observing stations to rotate the instruments to compensate for the rotation of the star field which occurs in an altazimuth-mounted telescope.

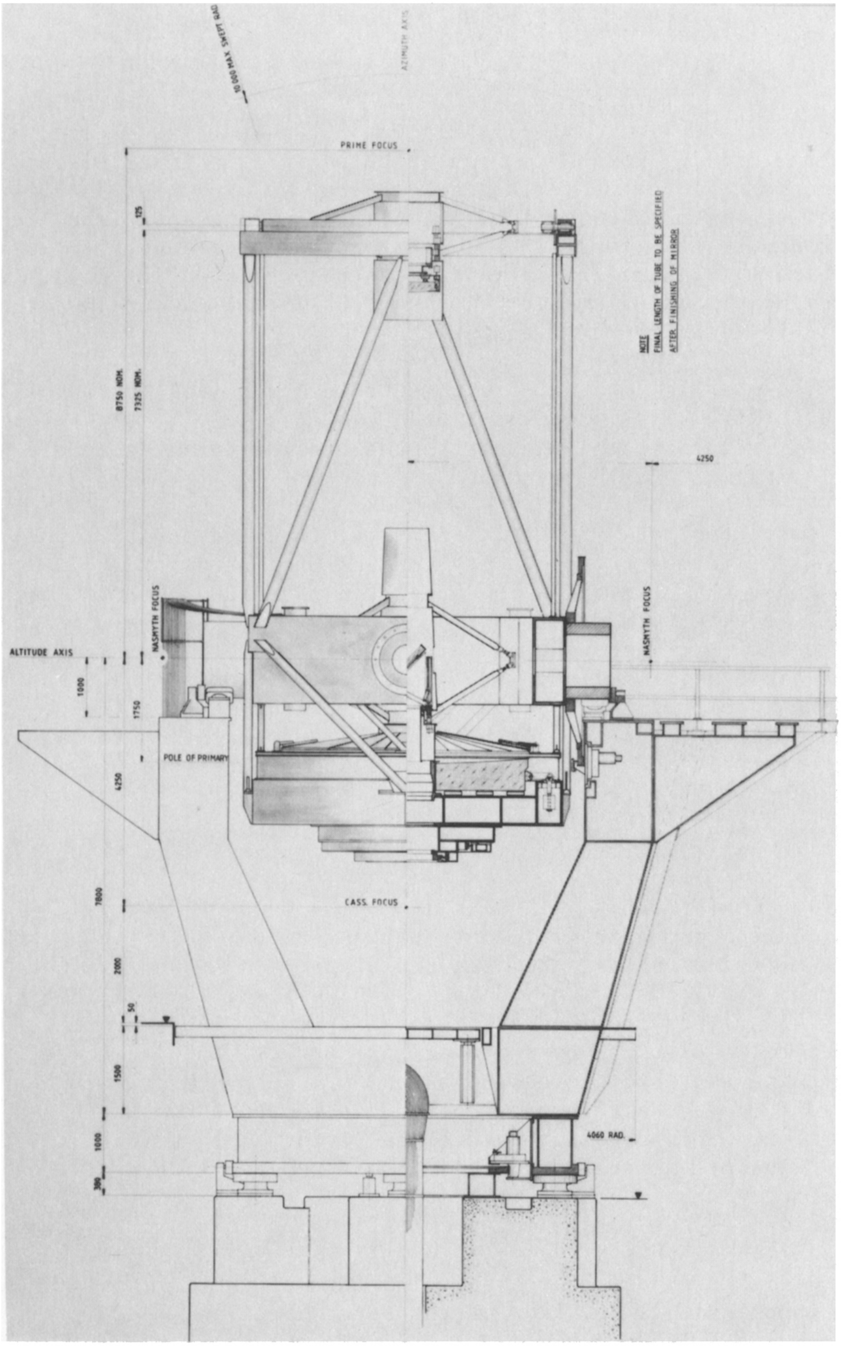

Fig 1. 4.2 m William Herschel Telescope - general arrangement.

Instruments will not be rotated at the Nasmyth observing stations but an optical image rotator will be introduced when required.

1.3 Telescope drives and control

Identical spur gears will be fitted to the two axes of the telescope and the driving torque to each of these will be imparted through two direct-current torque motors each having its own power amplifier supplied with a common control signal. The amplifiers will be electrically biassed so that there is a local torque loop around the two motors which will maintain continuous tooth contact during conditions of the maximum tracking acceleration of 0.02°/sec^2. The deadspot at the zenith is less than 1° diameter.

A tachogenerator and an electromagnetic brake will be fitted to each motor shaft. The motors will be capable of driving the telescope at a maximum velocity of 1°/sec with acceleration during slewing reaching a maximum acceleration of 0.3°/sec^2.

The servo control system will comprise three feed back loops: (a) current or torque (b) velocity and (c) precision rate. The incremental encoder which provides the precision rate feed back for each axis will take the form of a shaft encoder driven from the main gear through an anti-backlash pinion. A resolution of 0.05 arc secs or better is aimed at. Similarly the absolute position of the telescope will be obtained from shaft encoders. It is intended that the pointing accuracy shall be 2 arc secs or better after compensation for all repeatable errors by the computer control system. The rotating instrument mountings will also be driven by servo-controlled DC torque motors, but the requirements for precision are not as high as for tracking and the position angle will be controlled with an accuracy of about 5 arc seconds.

The control computer will control the motions of the telescope, its instrument turntables, the dome and windscreen as well as the operation of the autoguiding and focussing devices. It will communicate with all motors and encoders through a serial CAMAC system. When the telescope is slewing the computer will monitor the telescope position using the absolute encoders and will output a drive rate calculated to move the telescope to the desired position in the shortest possible time. This calculation will be performed 10 times per second. When the telescope is tracking, the pulses from the incremental encoder will be counted; the computer will sample this count and output a digital drive voltage to the motor amplifiers 100 times per second. The computation of this drive voltage will include coordinate transformations, calculation of the mechanical deformations and misalignment of the telescope and simulation of the servo components.

1.4 The Dome and Building

The telescope will be supported by a reinforced concrete pier in the form of a hollow cylinder 7 metres in diameter and 4 metres high. This will put the centre of rotation of the telescope at a height of 12 metres above the ground. The dome design is not finalised; one design is for an onion dome 23 metres internal diameter with shutters covering an observing slit of 6 metres width. An up-and-over shutter will constitute the upper windscreen and allow observations to z = 55°; observations to z = 78° will be possible when a lower pair of biparting shutters are opened (like the Lick Observatory 3 m telescope dome). The aluminizing tank will be in an annex to the dome, on top of which is the Control Room having access to the telescope at Cassegrain focus level. The annex will contain some small dark-rooms, offices, and small workshops but has been kept to a minimum size, with most major support services (comprehensive workshops, library, dark-rooms etc) elsewhere on the site.

2. ECONOMIC CONSTRAINTS ON THE PRESENT DESIGN

The telescope was designed in consultation with Freeman, Fox Ltd by the La Palma Observatory procurement team at RGO, led by William Goodsell and John Pope, to an astronomical specification laid down by representatives of the UK astronomical community in the 1970's. The early specification proved in the event to be too expensive for the amount of money available, mainly because it called for the telescope to be mounted 20 m high above the ground (like the Anglo-Australian Telescope) and because it provided for generous spaces to accommodate large instruments. In its present form the telescope and building date to a specification re-written in January 1980 in an effort coordinated between the design engineers at RGO and the wide UK astronomical community. The combined group was popularly called The Tiger Team.

The team early recognised that the altazimuth mounting had already enabled a very economical design to be evolved for a high performance telescope and that there was more scope for the cutting of building costs, particularly the height and size of the dome. Studies of atmospheric microturbulence on La Palma 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 have been correlated with seeing measured with Polaris trail techniques. These measurements (McInnes 1981, summarised by Bingham 1981) show that seeing is 1" or better for some 40% of the time when the sky is clear. Because local seeing is confined to such a thin ground layer it was decided that an elevation of 10 m for the height of the telescope 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. Since the telescope building is so small, an annex to one side of the drum which supports the dome is necessary, but it is of conventional construction since it bears no load from the dome and has been economically tailored to minimum practical needs. Since no unnecessary activity takes place in the dome, there is minimal heat input into the air near the telescope.

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Thus there is a greatly improved chance to ensure the best possible 'dome seeing'; because the dome volume is small it may relatively easily be ventilated, and large fans and a large dome slit are intended to speed this.

The dome itself was reduced in diameter, and therefore cost, making the telescope more compact. The dome radius was set principally by three factors, happily concordant. 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, so the dome radius could be reduced by over 2 m. There is consequently deterioration of image quality obtainable at the prime focus over a large field angle with a triplet lens field corrector. For the 4.2 m telescope, the scientific specification called for an 0.5 degree field for which the corrector is of manageable dimensions. The specification for the figure of the mirror, which has been given in terms of r.m.s. errors in shearing interferograms at shears of 2 to 128 cm, is intended to match the best seeing at the site, i.e. 0.5" FWHM. Design work by Charles Wynne at RGO has shown that a corrector for an f/2.5 telescope covering an 0.5° field can in fact be made to give a total image spread not exceeding 0.5 arc sec in the spectral range 365-852 nm. Refocussing for the shorter wavelengths gives ½" images for 340-405 nm. The effective focal ratio at the prime focus is f/2.8 because the corrector has a negative power. Thus shortening the focal length to f/2.5 was in fact possible without affecting the original specification for prime focus field. The team considered shortening the focal length of the primary even more, but the cost of figuring the mirror would increase as its speed increased, and new test equipment associated with making the secondary mirror would have to be manufactured. Moreover, at focal ratios faster than f/2.5 the triplet corrector cannot cope with a ½° field, although 15' 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 the second factor of the three mentioned above, namely the constraints imposed by handling the primary mirror for aluminising. The mirror is to be wheeled on a carriage from the telescope to a platform whence it will be lowered by a roof crane to the ground for washing and 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 6 m length originally specified, but in the process of rebalancing the telescope some length has been clawed back reducing the working distance from tube axis to Nasmyth focus by 0.5 m, so that there is still space for an instrument more than 4 m long. At the same time, the clearance behind the Cassegrain mounting face for an Acquisition and Guidance Box and instrumentation was reduced from 4.2 to 2.8 m (leaving space however for an instrument 2.0 m long). This shortened the legs 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 190 tonnes with consequent economy.

Originally all three astrophysical telescopes on La Palma had been specified at the same f/15 Cassegrain focal ratio, with the intention of simplifying instrument portability. This benefit, of dubious utility, was abandoned as the optimum focal ratio for the Cassegrain focus was considered against cost and scientific benefit. Because the instrument clearance at the Cassegrain had been reduced it was no longer possible, for instance, to build a straight-through spectrograph with a 15 cm collimator beam (to fit available gratings) if the f/15 focal ratio was retained, and it would be necessary to turn the telescope beam through a right angle and lose light at an unnecessary reflection as the light entered a spectrograph like the one at the Anglo-Australian Telescope. 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 1 m diameter. It begins to obscure a significant amount of light by its shadow and would entail purchase of new test equipment for its manufacture. The secondary focal ratio was thus set at f/11. 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 4.2 m telescope, its dome, building, control system, aluminizing tank and other plant, and mirror, and a full set of instrumentation (to be described below) is £10.5 M (January 1980 prices).

3. INSTRUMENTATION; A COLLIMATOR-LESS SPECTROGRAPH

The Royal Greenwich Observatory (RGO) issued to the UK and Netherlands astronomical communities an announcement of opportunity to build the instruments for the telescope, and several instruments were chosen from the three dozen proposals. Most proposed instruments were for the Cassegrain focus. Apparently astronomers regarded the Nasmyth focus with its alternatives of image rotation on a 3-mirror image de-rotator with attendant lightlosses as a poor second choice to the Cassegrain focus, even given the ease and economy with which an instrument could be built there. The instruments chosen consist of the prime focus camera described above, including a CCD detector; a high resolution spectrograph at the Nasmyth focus, with Image Photon Counting System as a detector; a near infra-red photometer with focal plane chopper; a Fabry-Perot system (TAURUS) for velocity mapping and a spectropolarimeter. Proposals are still being considered for an intermediate dispersion spectrograph a common polarisation analyser, an auxiliary photometer and some other instruments.

One of the most novel instruments with exciting astronomical possibilities is the proposal from an RGO group (Bob Fosbury, Ian van Breda, Jasper Wall and Charles Wynne) to make a collimator-less Faint Object Spectrograph (Fig 2) where the design has been optimised around efficiency and the widest possible wavelength coverage for low dispersion spectroscopy. The spectrograph is not intended to compete with the intermediate dispersion spectrograph and would not offer versatility in resolution, wavelength centre, output format or

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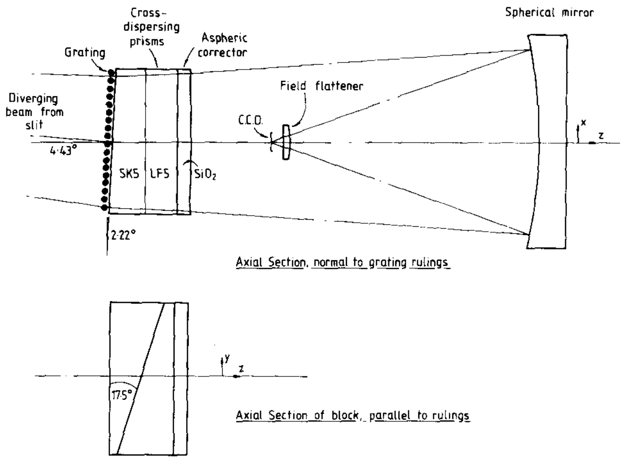

Fig 2. This is Wynne's detailed design for a collimator-less spectrograph in the AAT's f/8 beam, which, diverging, enters from the left. It passes through the cross-dispersing prism, aspheric corrector plate (and transmission grating) and is brought to a focus at a CCD detector after reflection at a spherical mirror and passing through a field flattening lens.

be designed for long slit capability. The scientific case rests on the desire to make an instrument which will provide spectrophotometric data on faint objects such as galaxies where the small aperture capability of the Space Telescope offers a smaller advantage than with point sources (Fig 3).

The first design aim was to reduce the number of optical components in the spectrograph. Over the wide spectral range required by astronomers every optical surface in an instrument causes considerable loss of light. This is particularly true of reflecting surfaces, which typically give 80% reflectivity. Uncoated transmitting surfaces transmit 96% at each air-glass surface. The original spectrograph for the Anglo-Australian Telescope has 4 reflecting surfaces and 6 air-glass surfaces, and the throughput for these alone is 0.32 f where f is the size of the central obstruction in the camera, (f ~ 0.7). There is thus considerable scope for improvement. The first surface to eliminate is the reflection necessary to bring the spectrum to an accessible focus. Hitherto image-tubes have been the most sensitive detectors available, but their large physical bulk, in relation to the photosensitive area, means that their use entails at least one additional reflecting surface in a spectrograph camera, as compared with what would be needed for a small detector that could lie within the camera in the shadow of the Cassegrain secondary mirror. The use of solid-state detectors therefore offers the possibility of eliminating one

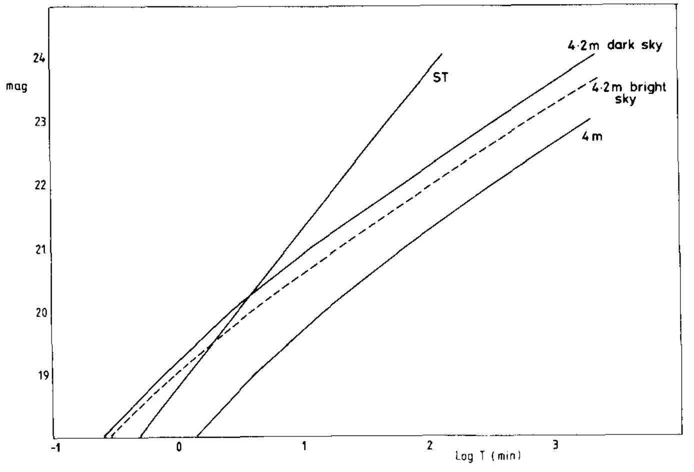

Fig 3. An estimate of the integration time required to reach a S/N of 10 in a 10 A band (at ~ 4500A) with three different telescope - spectrograph combinations. The curve labelled 4 m is based on the actual performance of the 25 cm camera + IPCS on the AAT. The curve labelled ST is an optimistic estimate for a Space Telescope instrument for looking at point sources: for the larger apertures required for resolved galaxies the performance would be poorer in the optical band. The curves labelled 4.2 m are based on an estimate of the overall efficiency of a collimator-less spectrograph with a CCD detector on the William Herschel Telescope. The entrance apertures were assumed to be 2" square for the ground based telescopes and 0.2" square for the ST. Dark and bright sky for the 4.2 m cases refer to m = 21.5 and 20.8 per square arc sec respectively.

mirror surface. For low dispersion spectroscopy with a high aperture camera, a further gain can be achieved by using a transmission grating in place of the more usual reflecting one. For the coarser gratings, their efficiency is higher, their use makes possible a more compact and hence more efficient camera, and where a Schmidt-type camera is used, the aspheric plate can be cemented to the grating substrate, eliminating two air-glass surfaces. When such a system is placed on a collimated beam, a cross-dispersing prism can also be cemented between the grating and the aspheric plate, to separate overlapping first and second orders which are both recorded, to be summed later. Recent work by Charles Wynne has shown the possibility, in a low dispersion spectrograph, of eliminating the collimator mirror, the grating lying directly in the divergent beam from the slit. The grating then introduces large aberrations of complicated form. There are 10 to 15 1st order aberrations, but all except a few can be corrected to quite a high level by modifications in the separation, tilt and centering of components of the rest of the system, without introducing additional

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air-glass surfaces. Systems like this are being designed not only for the 4.2 m William Herschel Telescope but also for the 2.5 m Isaac Newton Telescope also to be re-erected on La Palma, and the 3.9 m Anglo-Australian Telescope. They use a "shorter than a Schmidt" camera (Wynne 1977).

The range of apertures and grating rulings over which such a collimator-less spectrograph can be corrected has not yet been fully explored. Systems have been computed with an f/15 beam on gratings of 150 l/mm, and 300 l/mm, and at f/8 on a 150 line grating, giving image spreads within some 20μ over a spectral range at least 350 to 1000 nm. The elimination of the collimator makes cross-dispersion more difficult, involving a doublet prism. This can be cemented into the grating-corrector block, but is likely to involve some light absorption below 350 or 340 nm. The gain in speed is worth this sacrifice, and in any case it should be noted that presently available CCDs are insensitive below 350 nm.

The spectrograph contains four glass-air surfaces and a mirror and has a throughput therefore of 0.68, compared with 0.32 f in the spectrograph mentioned above, with the further gain of the transmission grating over the reflection grating, and CCD detector over photocathode detectors.

The detector proposed for the spectrograph is a CCD mounted on a cooled finger. The cooling will be provided by a liquid N_2 dewar, and, to maintain temperature stability, it will be necessary to reduce convective cooling by evacuating the camera. Presently the designers intend to use an RCA thinned back-illuminated CCD which has a high quantum efficiency over a broad wavelength range. The relatively high inherent noise of this device makes little impact on signal-to-noise ratio in the sky-limited low resolution observations envisaged. However, because the CCD is not very sensitive in the ultraviolet and sky background is large in the red, the spectrograph can be used for at least half the month with about a 1 mag loss of limiting magnitude due to moonlight at Full Moon.

A CCD detector 1.5 cm x 1 cm, with pixels 20μ square, will yield well-sampled spatial resolution (0.4 arcsec/pixel) and a well-sampled or true spectral resolution of 3.0 nm in 1st order and 1.5 nm in 2nd order. This is a conservative estimate for 2 arcsec images; the resolution would be doubled for a 1 arcsec image.

The spectrograph is for the Cassegrain focus. It would probably not be possible to design a collimator-less spectrograph for the focal ratio at the prime focus, so a prime focus spectrograph trades one reflection-loss for another. Indeed a prime focus instrument would probably need to view the sky through a corrector in order to obtain enough field for satisfactory Acquisition and Guidance facilities in high galactic latitude fields.

A restricted long-slit mode is possible if one order is sacrificed by filters. Wynne has shown that the astigmatism and coma resulting from the grating in an f/8 diverging beam can be corrected so that good images are obtained over 18 mm of the slit.

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