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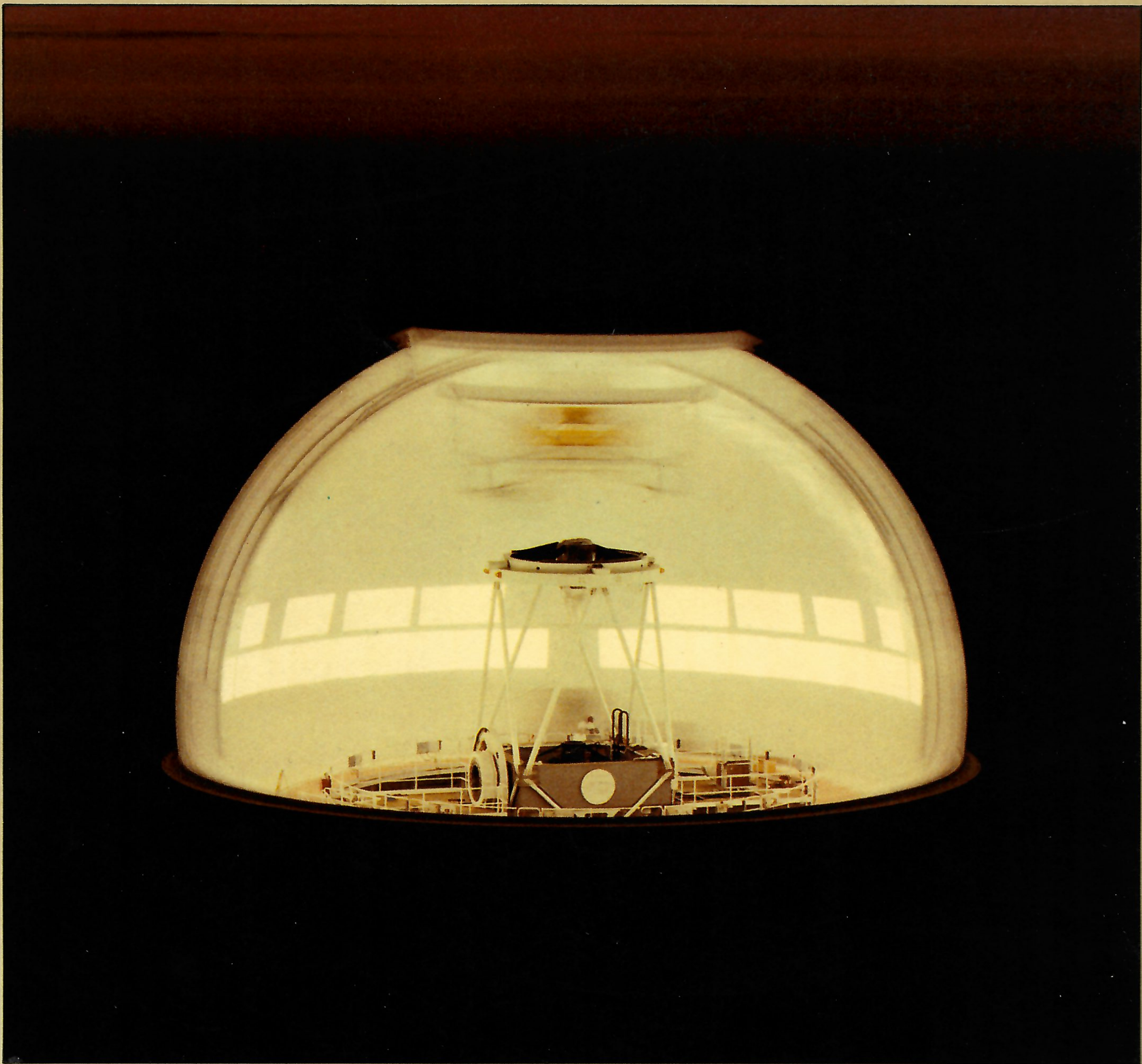
ROYAL GREENWICH OBSERVATORY



TELESCOPES INSTRUMENTS RESEARCH AND SERVICES

October 1 1985 – September 30 1987

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Contents

Abbreviations

The following abbreviations are used in the text:

AAO	Anglo Australian Observatory
AAT	Anglo Australian Telescope
A&G	Acquisition and Guiding
CCD	Charge coupled device
ESO	European Southern Observatory
FOS	Faint Object Spectograph
IAC	Instituto de Astrofisica de Canarias
IDS	Intermediate Dispersion Spectograph on the Isaac Newton Telescope
INT	Isaac Newton Telescope
IPCS	Image Photon Counting System
ISIS	Intermediate dispersion Spectrograph and Imaging System
JKT	Jacobus Kapteyn Telescope
KPNO	Kitt Peak National Observatory
MSSO	Mount Stromlo and Siding Spring Observatories
NFRA	Netherlands Foundation for Radio Astronomy
PATT	Panel for the Allocation of Telescope Time
RAL	Rutherford Appleton Laboratory
RGO	Royal Greenwich Observatory
ROE	Royal Observatory Edinburgh
SLR	Satellite Laser Ranger
TAURUS	A type of Fabry-Perot interferometer
UCL	University College London
UES	Utrecht Echelle Spectrograph
WHT	William Herschel Telescope

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Introduction

The William Herschel Telescope, joining the now well-established Isaac Newton Telescope, Jacobus Kapteyn Telescope and Carlsberg Automatic Meridian Circle, dominates this report covering the past two years at the Royal Greenwich Observatory. This giant new telescope was assembled and commissioned on La Palma by engineers and scientists of the RGO in an astonishingly short time. It worked beautifully and its first assigned observations were carried out in August 1987 by university astronomers from our international community. Since then it has been intensively used by many groups. I am delighted to say that without exception the astronomical programmes have been completed successfully with many important new results obtained. Some of these results are shown on the back cover.

But more broadly this report is intended to show a representative range of the activities of the Royal Greenwich Observatory. I can say with pride that it highlights the remarkable successes of the staff of the Observatory and our partners in the university communities at home and abroad.

Alec Boksenberg

The William Herschel Telescope

The WHT, which is the third largest single-mirror telescope in the world, was completed in July 1987.

Telescope erection on La Palma

Installation of the telescope started in the autumn of 1985 when a part shipment containing the azimuth bearings and the hydraulic pumping system arrived on site from the UK. RGO staff who formed the installation team then started the critical job of installing the azimuth bearings and the plant. The bearings were then grouted in place by a contractor using a special epoxy grouting system designed to maintain maximum stiffness between the bearings and the concrete pier.

The major shipment of all the remaining telescope components including the drive system, mirrors and aluminizing plant was arranged for the spring. The M.V. Ston was chartered earlier because of the special facilities on the ship for lifting heavy loads. It sailed on 2 April 1986, arriving in La Palma eight days later. Pickfords then transported the major parts of the telescope, which totalled 350 tonnes, to site over the next four weeks. Some of the loads were very large, 6 × 8 metres and weighing 30 tonnes. These presented the haulage contractor with a number of difficult problems negotiating the very tight bends and steep gradients on the mountain road.

Installation started as soon as loads began to arrive on site and very good progress was made by the RGO team and its subcontractors during the rest of 1986. The installation of the cables and control room progressed in parallel, and commissioning using the telescope control computer started in March 1987. The mirror was aluminized in May and installed in the telescope shortly afterwards.

The azimuth and altitude bearings were the first major items to be commissioned and initial tests indicated that the design natural frequency of 4 Hz for the structure and bearings had been achieved in practice. This justified the careful mechanical design and analysis the RGO put into the telescope and eased the task of the servo control system and software design. Astronomers will like the accurate tracking, rapid offsetting and resistance to wind shake which this produces.

Primary and secondary mirrors

The Cervit primary mirror and its secondary met the full specification and they were completed by Grubb Parsons in time to be shipped with the telescope. The quality of the mirror is extremely good. The optical wavefront reflected from the mirror differs from perfection by only about one wavelength of visible light, peak to peak. The profile errors in the surface itself are, of course, half that, and the slope of the mirror surface has errors of only 0.04 arcsec root-mean-square on baselines of eight centimetres. The quality of this mirror will never limit the resolving power of the telescope, even in the excellent seeing conditions at the La Palma site.

Aluminizing plant

The plant was produced by Balzers of Liechtenstein who subcontracted the large vacuum vessel to Grazebrook Limited, a UK firm. The plant has been installed in the WHT plant room and the commissioning tests successfully carried out. During the aluminizing process, a total of 28 g of aluminium is evaporated, 4.4 g being deposited on the 13 m^2 surface of the primary mirror, to create a reflective surface 125 nm thick. The power consumption of the plant rises to 85 KVA for the 15 seconds duration of the evaporation stage. It is planned to re-aluminize the mirrors once a year.

Building and dome

The dome, which weighs 320 tonnes, was completed by the Canadian firm Brittain Steel in 1984. Large fabrications were assembled in Vancouver and shipped to La Palma where they were erected to form the ring girder carrying the transport system and the arch girder which supports the shutters and wind shield. The skin of the dome was fabricated on site from 6.3 mm steel plate and the wind shield and shutters were constructed from aluminium alloy. A 35 tonne crane, supported from the arch girder, is built into the upper part of the dome. This was used during the telescope construction; it will remain in place to remove the mirror for aluminizing and for telescope maintenance.

Astronomical commissioning

The real test of an astronomical telescope is how it performs when turned towards celestial objects.

The first stellar images were obtained at the Cassegrain focus during June 1987. Initially, there were problems with the support mechanism of the primary mirror; there were gas leaks and the electronic control system had faults. Another difficulty occurred with the mounting of the Cassegrain secondary mirror. However, by the end of July, after solutions to these problems had been found, good images had been otbained with integrating TV systems at both the Cassegrain and prime foci. At this stage, the pointing of the telescope was reliable to an accuracy of 5 arcsec (rms) over the whole sky and the tracking was good. Dome following was in operation with no noticeable vibration of the telescope.

It had been agreed that some astronomical observations would be undertaken as soon as the performance of the WHT fulfilled certain criteria. In this way, the later stages of commissioning would benefit through the feedback from astronomers using the telescope. Consequently, the new TAURUS II interferometer and IPCS II detector were mounted on the WHT on 12 August. On the morning of 15 August, the first complete TAURUS observation was made. The first observing run relating to a PATT application took place from 22 August to 7 September. This was for a programme called 'TAURUS observations of rotation curves, intergalactic gas and star forming regions'. Although the original allocation of three weeks was curtailed to two because of troubles with the dome shutter drive, much good astronomical data was obtained. The Principal Investigator, Dr E. A. Valentijn from the Kapteyn Astronomical Institute in Groningen, wrote a report entitled "The William Herschel Telescope is excellent" which described the pioneering TAURUS run.

For any large modern telescope, assembling all the hardware combined with writing computer software and testing the whole system is a complex operation. The first astronomical observations with the WHT were made after an encouragingly short time. Although many commissioning tasks remain, none of these appears to present a fundamental problem.

Michael Morris
October 1987

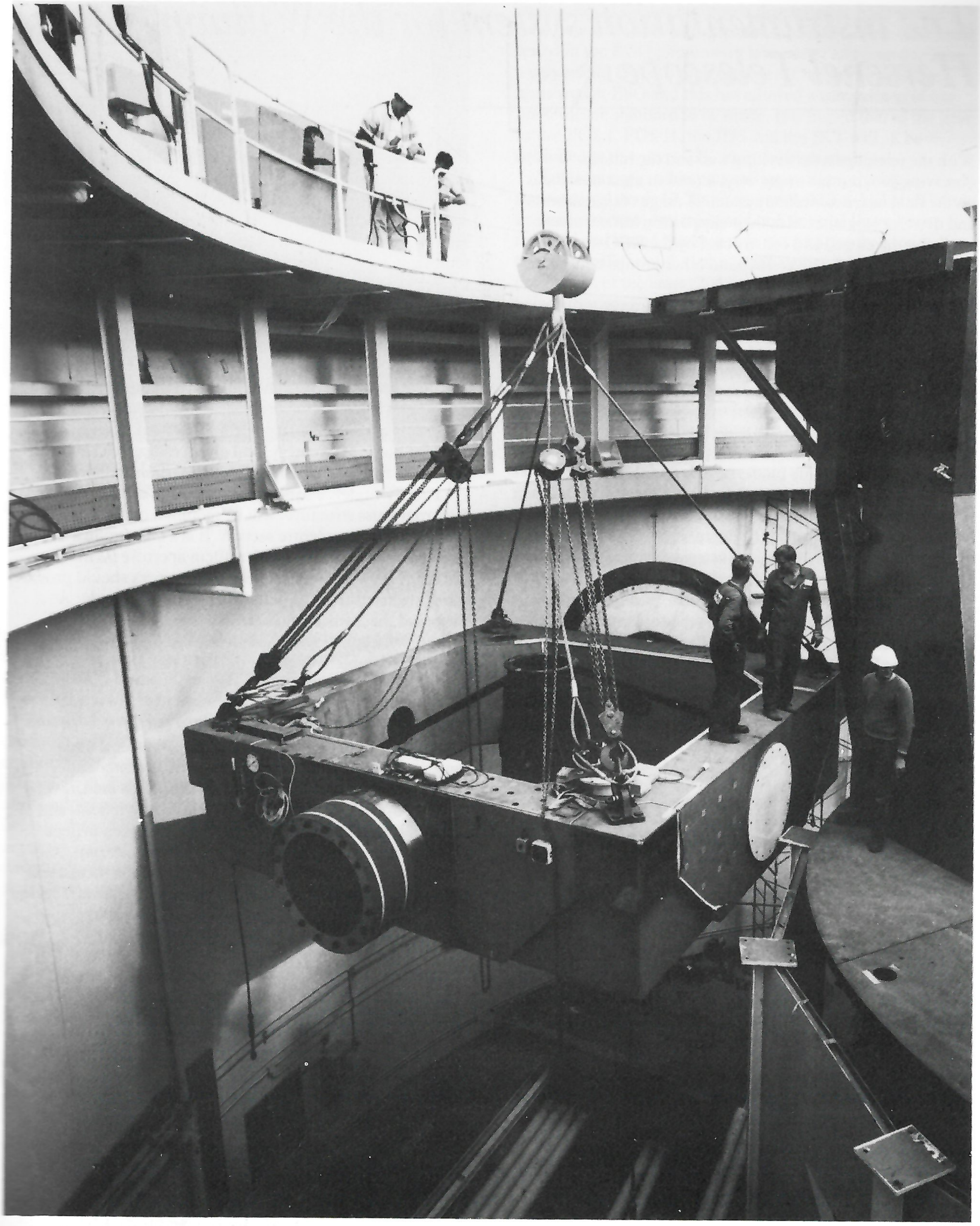


Fig. 1 The centre section of the William Herschel Telescope about to be lifted into position on the telescope forks. Note the altitude drive gear on the far side of the section.

The instrumentation system for the William Herschel Telescope

With the telescope now working well and the interim observing programme under way, attention must now focus on the final instrumentation system. A range of instruments and detectors together with their supporting infrastructure are being developed and constructed by the RGO in collaborations with universities and other groups both in the UK and Netherlands.

The instrumentation system will become progressively more versatile as individual components are completed. The interim package of instrumentation consists of TAURUS II and the Faint Object Spectrograph (FOS II). These use two stand-alone detectors: a laboratory CCD system, and the prototype CCD IPCS developed by UCL. The interim Acquisition and Guidance (A & G) Unit, which has been designed at the RGO, was manufactured under contract.

Acquisition and guidance facilities

The interim Cassegrain A & G Unit contains two probes: a manually retractable slit viewing system for use with the FOS, and a fixed probe for offset guiding for use with the FOS and TAURUS. Both systems feed a Westinghouse ISEC TV camera mounted on a slide to accommodate the differing focal plane positions. Simple, but effective, autoguiding has been implemented using error signals from the TV microprocessor.

The final Cassegrain Acquisition and Guidance Unit is more complex, containing:

A slit assembly.
An acquisition probe.
A calibration/comparison system which uses the reverse side of the acquisition mirror to allow simultaneous calibration of the first object whilst acquiring the second object.
A large feed flat for use with aperture plates and optical fibres.
A small feed probe to feed small instruments, for example a CCD camera at the position of the aperture plate.
An autoguider system.
Colour and neutral density filters.

The final A & G Unit wll have fully automatic control of its systems commanded by local microprocessors interfaced to the system computer.

The design of the mechanical components for the full A & G Unit is complete and manufacture is well advanced. The optical design has also been finished and various parts procured. Lenses and mirrors provide a choice of four different images on the TV used in this unit: the direct sky image, the slit field of the spectrograph, and each of these at a reduced scale for field viewing. The focal reducers are parfocal so that the focus adjustment at the TV camera when changing images (which does not disturb the telescope in any event) is very small and hence fast. This is achieved by the use of a relatively weak lens which converges the f/11 beam to an intermediate focus, followed by a small 1:1 relay lens which places the f/4 focus at the same position as the f/11 focus. This configuration leads to an aberration-corrected design. Other optics provide for a comparison lamp source, correctly imaged to simulate the telescope over a wide field, and for the image used by the autoguider.

The autoguider detector is to be a Peltier-cooled CCD. Experiments have been carried out to determine the degree of cooling necessary and the noise performance achievable from a Peltier-cooled CCD as these limit the performance of the overall control system. It has been determined that a two-stage cooler is necessary, and that a readout noise of around 15 electrons rms is possible with GEC CCDs. However, some chips have been found to have a large temperature-dependent l/f noise that makes them unsuitable for Peltier-cooled applications. Careful selection of devices is therefore necessary in this application. A prototype head has been designed, manufactured externally and tested. Tracking an artificial star has been demonstrated.

To minimize thermal effects arising from the Peltier cooler and the other heat-generating components within the autoguider region of the unit (~ 50 W), the lower section of the A & G case is partially sealed and fan ventilated to within 1.5°C of dome ambient. A local glycol radiator is being considered to reduce further this temperature difference.

The TV finder, a squat tube supported on a small Serrurièr truss structure, will be mounted on the top face of the main telescope centre section. It is a Cassegrain system of effective focal ratio f/6.5 with a 40 cm aperture f/2 main mirror. The Westinghouse ISEC TV camera should provide integrated sensitivity to better than 17th magnitude. A proposed mechanical and optical design is finished, and contracts for construction are to be placed. The assembly should be complete by the middle of 1988.

ISIS and FOS II

The ISIS (Intermediate dispersion Spectroscopic and Imaging System) triple spectrograph is currently under construction at the RGO in collaboration with the University of Oxford. ISIS is an extremely versatile instrument, and in particular the slit area is extremely complex, requiring a high degree of engineering precision. It includes an anamorphotic lens system, the slit components themselves (providing long slit, multislit or fibre-optic facilities), dekker and filter assemblies and polarization slides. A large percentage of the components in the slit has been manufactured in the RGO workshops and is ready for integration with the control electronics. ISIS has two camera systems of similar format each with a focal length of 50 cm. The 'red' camera is optimized for use with a CCD, and the 'blue' camera for use with the IPCS. The camera components are currently being manufactured at RGO, and an optical test bench has been assembled.

Further finite-element analysis has been carried out on the main ISIS structure, the camera components and the collimator. Installation of the SAP80 finite-element analysis programme on the IBM PC/AT at RGO has allowed a finer mesh to be used, and for the mathematical models to be refined in relation to the previous finite-element analysis programs running at the Rutherford Appleton Laboratories. The main support structure, the collimator extension and the ISIS handling system have been manufactured under contract, and the Oxford University workshops have manufactured some smaller components including the collimator assembly, slit alignment, cross dispersion units and Hartmann shutters. By the end of 1987 it is planned that individual assemblies will be undergoing tests on the telescope simulator at the RGO.

FOS II, the Faint Object Spectrogaph, is a joint project between the RGO and Durham. The project was accelerated to provide spectroscopy on the WHT in 1987 and 1988, and FOS II and its interim support structure (which will later be

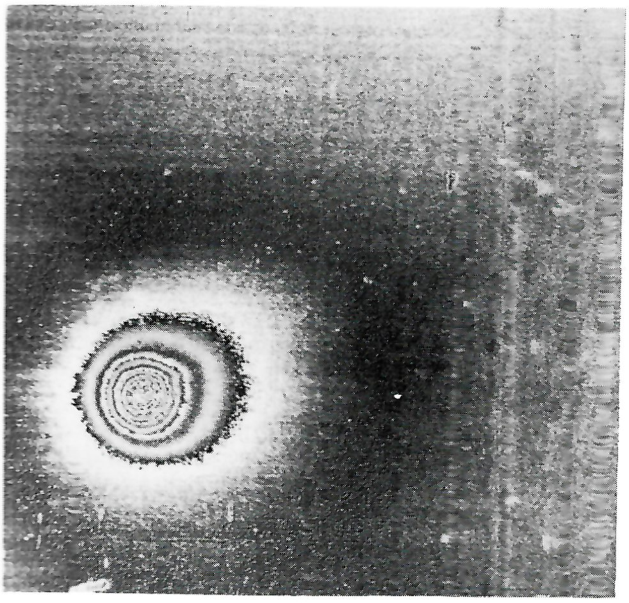


Fig. 2 An image of Comet Halley taken on the 36-inch telescope at Herstmonceux using a GEC MA703 (1500 × 1500 pixel) CCD.

replaced by ISIS) are being commissioned on the telescope in September and October 1987. (Some aspects of the optical design of FOS II and other WHT instrumentation are discussed elsewhere in this report in 'Optics at the RGO'.)

Extensive work has continued on both solid-state detectors with analogue readout (CCDs) and photon-counting area detectors. Although of lower quantum efficiency, the latter have an important part to play in observations where time variations and absence of readout noise or thresholding effects are important. Work on these detectors is described in the next two sections. Most of this research has important implications for other WHT instruments in addition to ISIS.

CCDs

The supply of small CCDs remains a problem although the situation has eased somewhat with the opening of the new production line for GEC CCDs at EEV in Chelmsford. The first devices received from this line were extremely good, having virtually none of the low light level traps which were a feature of devices produced at the Hirst Research Centre, and showing much better charge-transfer efficiency. Unfortunately, EEV later encountered production difficulties and were unable to make any working devices for several months. These problems now seem to have been solved and further chips have recently been received. With standard CCD chips, most of the blue and ultraviolet radiation is absorbed by the electrodes before reaching the photon-detecting region. To overcome this disadvantage, chips can be thinned and illuminated from the 'back'. A contract with EEV, funded jointly by the AAO and RGO, to produce a thinned blue-sensitive version of the P8603 has continued. Although working devices with enhanced blue sensitivity have been produced, the project has been delayed by a lack of CCDs with which to experiment and there still seem to be difficulties in getting the devised procedures to work reliably. The project is therefore still some way from completion.

An alternative way of getting blue sensitivity is to coat a thick CCD with a mixture of fluorescent laser dyes. The techniques to do this have been developed at ESO and they have now coated several chips for the RGO. These have been tested in the RGO photometry laboratory and found to have a very useful UV and blue response. One device was also measured at ESO and this has allowed a comparison of our photometric standard to be made. It is hoped that in the near future FOS I, FOS II, the IDS and the JKT will all be equipped with coated GEC chips of high quality.

Tektronix are still having difficulty in producing astronomical grade CCDs. Two small (512 × 512 pixel) set-up grade devices, one thick and one thinned, have been received and tested but these are not sufficiently good to be astronomically useful. A top-grade device is still awaited and production of the large (2048 × 2048 pixel) devices is not being attempted until the problems with the small devices have been solved.

Several CCDs from Thomson-CSF have been tested. These are similar in format to the GEC devices but use four-phase clocks which in principle can provide better charge-transfer efficiency. Their performance is very similar to that of the GEC devices except that they have a threshold of about $300e^-$. A recent design modification by Thomson is said to have overcome this threshold effect but none of these new devices has yet been bought or tested.

Thomson are engaged in two development programmes which may be of future interest. The first is to produce a buttable version of their standard small device. A pair of chips will be able to be butted together on one of their short sides to give a 2 chip 'building block' which can be extended to a 2 × n array by further butting on the long sides. The second project is a large (1000 × 1000 pixel) monolithic device. Both these programmes are being partially funded by potential customers but they will also become available, albeit somewhat later and at a higher price, to those who have not sponsored the development.

The involvement of the RGO in the AAO-funded large (1500 × 1500 pixel) GEC CCD development is now over. The fourth and final batch contained several working devices but only one of these had sufficiently good charge-transfer efficiency to be useful for astronomy, and it was fairly poor cosmetically. Most of the devices have now been sent to the AAO where they are considering using this 'good' device on the AAT if they can overcome the problem of the silicon breaking away from the CCD package, which has occurred in several of the devices they have run.

CCDs are no longer being made at GEC's Hirst Research Centre and the new production line at Chelmsford is not capable of making a device as large as 40 × 40 mm. However, funding approval has just been obtained for the development of a 30 × 10 mm 'spectroscopic' CCD by GEC, and this project has a much greater chance of success for the following reasons. The active area of this CCD ($3\,cm^2$) is much less than that of the (1500 × 1500 pixel) chip ($16\,cm^2$) and the production yield of CCDs is a strong function of their area. The production line at Chelmsford is modern and dedicated to CCD production unlike the old, general purpose facility at Hirst Research; finally, payment will only be made if the devices meet an agreed specification.

The new-generation CCD controller for the 4.2 m WHT is being developed in a collaboration with NFRA, Netherlands. The overall design is nearly complete and most of the circuits have been constructed as prototype PCBs. Tests to confirm that the data from an array of CCDs, all driven, read out and digitized to 16 bit accuracy from one controller, have proved successful. The final prototype system is due for delivery in December 1987. A fibre optic data link to transfer the data at high speed from the telescope has been installed and commissioned. An interface to accept the data from an array of CCDs (being read out at the same time) and to transfer them into a VME system has also been completed and commissioned.

Photon-counting detectors

Production of the electronics of the engineered version of the CCD IPCS is nearing completion at UCL. Successful tests of the UCL prototype have been carried out on the INT Intermediate Dispersion Spectograph (IDS). It was also the detector used on TAURUS for the first successful observing run on the WHT in August/September 1987. Plans have been made to use it on the Manchester Echelle, also on the WHT, later in the year. The new CCD IPCS shows improved detective quantum efficiency and resolution over the plumbicon readout IPCS I.

The collaboration between RGO, Imperial College and Instrument Technology Ltd continues on the development of a 40 mm microchannel plate intensifier. This collaboration now also involved UCL, whose CCD IPCS prototype has proved invaluable for two-dimensional imaging tests on completed intensifiers. Despite limited funds, the report period has been particularly successful for the project. Two astronomically usable tubes have been produced on the RGO-funded processing chamber at the ITL factory in Hastings. This chamber allows two cathodes to be made for each intensifier and the better one to be selected while still under vacuum. Removal of field emission points can be carried out during processing by high voltage cathode spot knocking. During manufacture, the microchannel plates must be scrubbed to remove residual gases from the glass substrate. This process is monitored both in terms of the gases released and the pulse-height distribution of events seen at the phosphor. From this, it is possible to establish the correct optimisation between gain and cleanliness. This leads to optimum lifetime characteristics.

The tubes have been tested both in the laboratory and on the 30-inch telescope at Herstmonceux. The following are the most important results:

(i) A resolution of 33 microns full-width half-maximum resolution has been achieved across the full 40 mm field. Further improvements are expected in the future.
(ii) A gain of 10^7 photons per event with no optical feedback from the phosphor is typical of both devices.
(iii) Differential event pulse-height distributions show a peak to valley ratio of 3:1, indicating space charge limited operation of the channel plates.
(iv) On the first tube, the red sensitivity at 8000 Å has dropped by only a few percent over a period of eight months of extensive testing. The second tube, which benefitted from results with the first tube, has shown no loss of sensitivity over a period of four months.

These results show that we now have the capacity to produce an astronomically usable tube with good resolution, efficiency and lifetime.

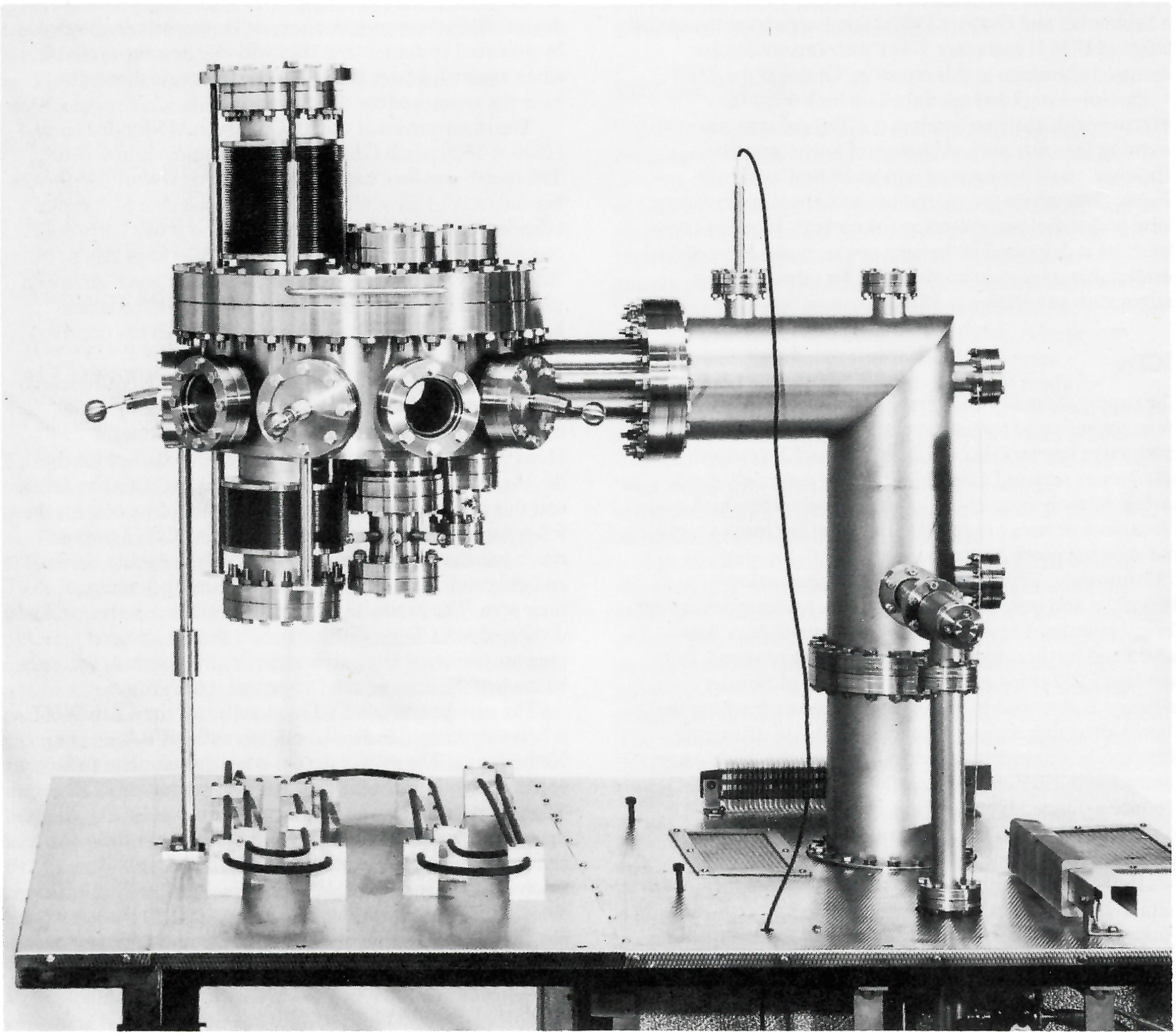


Fig. 3 The production chamber for 40 mm diameter cathode microchannel plate image tubes.

Other instrumentation

TAURUS II is a wide-field imaging Fabry-Perot interferometer which has been built in collaboration with the Kapteyn Sterrenwacht Werkgroep in Roden, The Netherlands. It is designed for multi-object work and can accommodate a number of dedicated aperture masks. Like other instruments on the WHT, the instrument is fully microprocessor controlled allowing, for instance, remote selection of an aperture mask or one of the four etalons. Each etalon can be remotely and independently tuned to a defined frequency passband. Two TAURUS II units have been produced, one for the AAT and one for the WHT. Both have been successfully commissioned, and the WHT version was used during August 1987 for the first PATT-allocated observing session on the new telescope. This session was extremely successful.

The Utrecht Echelle Spectrograph (UES) is being designed and manufactured at the University Observatory at Utrecht, under a contract placed by RGO with the Netherlands Foundation for Radio Astronomy. A formal specification was issued in May 1986 and at that time design work was already well under way.

The instrument is intended to be similar from the astronomer's viewpoint to one being produced for the Anglo-Australian Telescope by a team at University College London. It is hoped that this similarity will be beneficial in the use of the spectrographs and data reduction as well as in the production phase. The two groups are working closely with each other and with RGO.

The role of the RGO optics group in these two projects has included the design of the spectrograph cameras (700 mm focal length). Also, jointly with UCL, the group has selected and tested material for the large cross-dispersing prisms; nine wedges of optical grade fused silica are to be assembled into three 54° prisms with 30 cm base width and 15 cm apex length. All the optics, including the echelle and the optical table for the UES, are being procured by RGO.

Optical coating for the large optics in both the AAT and WHT instruments is being carried out at RGO. This has involved the design of special supports for these exceptionally valuable items in a planetary gear which ensures uniform coating thickness.

An acquisition and guider facility is to be produced for the UES. The integrated instrument will be mounted at the drive-side Nasmyth focus of the WHT and is due for commissioning during the first half of 1989.

In June of this year the Joint Steering Committee approved the Ground-based High Resolution Imaging Laboratory (GHRIL) for installation on the non-drive side Nasmyth focus. It is hoped that the facilities that it will include are a large optical table, an environmental enclosure, a detector and data acquisition system, a link to the on-site data-reduction VAX and an integral optical alignment facility.

Infrastructure

The Utility Network forms the backbone for communications between the system computer and the microprocessor controlled instrument. The hardware conforms to the IEEE802.3 Ethernet specification; the local area network (LAN) with a bandwidth of 10 Mbit/second can support up to 1024 nodes spread over a total distance of more than 2.5 km. All units on the WHT will initially interface to the Utility Network via 4-port asynchronous concentrators, manufactured by Sension Ltd, Cheshire. The network protocols conform to International Standards at the lowest two layers, and support an in-house 'transport' layer.

The procurement and testing of the network hardware has now been completed. The message protocol has been developed and tested in Forth, and is currently being implemented in Fortran on the VAX. During August 1987 the first part of the network was commissioned on the WHT, allowing communication between the FOS microprocessor and the interim CCD VME system. A Detector Memory System is being produced at RGO for use with both IPCS II and CCD detectors. The system is based around the high performance VME bus and uses the 32bit 68020 microprocessor running a Forth system. Its main functions are to collect data from either of the detector systems, to store that data in a large (probably 32 Mbyte) VME semiconductor memory, to display the raw data on a high-resolution colour monitor, and to transfer the images to the system computer for data reduction. The detector memory system will also provide a fast and efficient means of image assessment. In particular, it will enable an IPCS image to be displayed as integration proceeds, and CCD images to be manipulated with simple image-cleaning functions.

The hardware for the VME system consists mostly of individual VME boards purchased from a variety of manufacturers. The integration of these into the Detector Memory System is complete. In addition a high speed detector interface (DICI), common to both IPCS and CCDs, has been developed at RGO. It utilizes bit-slice microprocessors to enable it to carry out windowing the paging of IPCS Images 'on the fly' at up to 200 KHz or to accept and sort pixel data from multiple CCDs simultaneously.

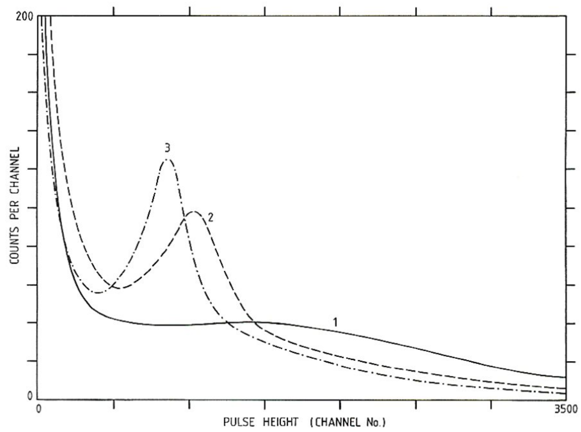


Fig. 4 The pulse-height distribution for a microchannel plate during scrubbing in the processing chamber. Note the decrease in gain and improvement in shape of the distribution as scrubbing proceeds. The sharper the maximum, the easier it is to discriminate between true signal pulses and signal-induced noise.

Michael Morris
October 1987

Acquisition and guiding with the Isaac Newton Telescope

During 1987, acquisition and guiding on the INT have been brought close to specification. The telescope now points with a rms accuracy of 4 arcsec, so, given good co-ordinates, the object of interest should be very close to the field centre. Acquisition is most critical at Cassegrain, and to help identification in ambiguous cases the cardinal points are shown on the acquisition TV display in the correct orientation for the current position of the instrument rotator. An accurate scale is also shown. Once the target has been identified, the night assistant marks its position on the TV screen with a cursor. The acquisition software will then offset the telescope to bring the target onto the designated field centre. In practice, acquisition with slit sizes as narrow as 0.5 arcsec is now extremely straightforward.

Objects too faint to be seen by the acquisition TV have to be found by the traditional method of a blind offset from a nearby star of accurately known position. This can be done by either a simple calculated offset of the telescope, or (more accurately) by acquiring a guide star while pointing at the offset star and then using a motion of the autoguider probes to define the offset.

At present there is an awkward gap in these techniques for objects at the limit of detectability by the TV. Because the TV has to be able to resolve narrow slits, it has small pixels (about 0.2 arcsec) and hence offers poor contrast in average seeing. The solution may lie in image processing in the instrumentation computer to enhance contrast; it is already possible to transfer images from the acquisition TV to the computer, and observers in fact do this routinely to keep a record of the precise location of the spectrograph slit in their fields.

Acquisition at prime focus is much easier than at Cassegrain, since the observing done at this focus is direct imaging with CCD chips subtending several arcmin. As a

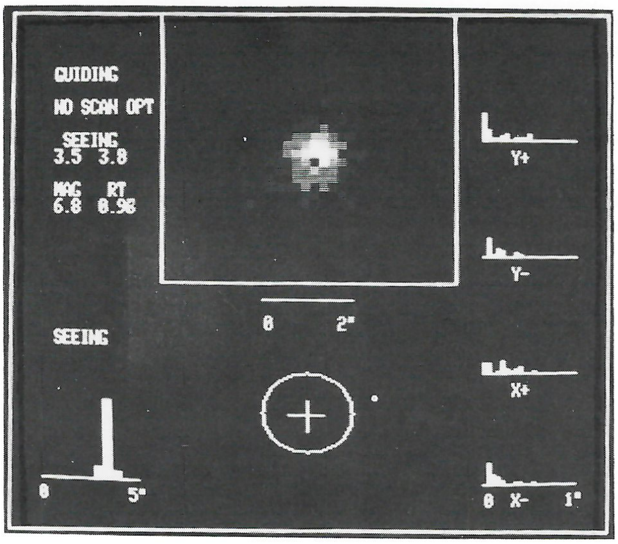


Fig. 5 This shows the display at the telescope console from the INT autoguider system. The image detected by the autoguider is shown at the top centre of the screen. Movements of the star relative to the optical axis appear as corresponding movements of the cross relative to the circle (bottom centre). The right-hand side of the screen displays histograms of the error signals.

check for observers the acquisition TV views the field through the finder telescope and displays it together with an overlay showing the position of the chip at the current position angle of the prime focus cone unit.

The finder is used for acquisition of guide stars both at Cassegrain and at prime. This is rather easier than measuring positions beforehand since the accessible field for guide stars, especially at Cassegrain, is rather small and peculiarly shaped. The procedure is extremely simple; the night assistant calls up an overlay onto the acquisition TV, which outlines the currently accessible field for guide stars. A suitable star is selected with a cursor, and the guide probes are then driven automatically to the correct position for the autoguider to lock on and complete fine positioning of the probes. While guiding is in progress, the autoguider software displays continuously updated histograms of guiding errors, seeing, and transparency.

Charles Jenkins
October 1987

Fibres on the Isaac Newton Telescope

Observational astronomy can be divided logistically into two broad camps – detailed studies of a few individual objects, or statistical surveys of a particular class of object. Surveys imply large samples and, as a result of the cut-throat competition for telescope time, such programmes were impracticable until recently. With the advent of the multi-object fibre-optics system on the Anglo Australian Telescope (AAT), however, it became possible to envisage obtaining spectra of 200–300 objects per night. Other systems are currently operating on the UK Schmidt and at Steward Observatory. This represents something like a tenfold increase in telescope efficiency and, with a mind to extending this to allow British astronomers access to a northern system, we have been developing a fibre-optics instrument on the INT. We have in addition to look towards the 4.2 m WHT whose field imaging system will be coming into operation in a few years.

The fibres in our development system on the INT are located within a brass aperture plate mounted in the modified photographic plate-holder. From there the 15-metre fibre-bundle is led down the telescope and through the spectrograph access-port to a slit unit mounted in place of the usual adjustable slit of the Intermediate Dispersion Spectrograph (IDS). With no automated fibre alignment mechanism (as yet), the aperture plates are mounted and dismounted with the telescope at the access-park position. This operation only requires 15–20 minutes, however.

Optically one of the main difficulties in using fibres is focal ratio degradation; basically, a proportion of the radiation emerges at a faster f/ratio than the input value due to scattering in transit through the fibre. This problem is least for an input f/ratio of about f/3 which is close to the INT prime value of f/3.3. However, we are then faced with feeding an f/11 spectrograph. Rather than redesign the collimator, Ralph Powell and Cyril Taylor have used microlenses to directly modify the output f/ratio. A 1 mm diameter rod lens, made from UBK7 glass, is directly abutted onto the slit end of the fibre.

We already noted that the fibres have an aperture of 2.5 arcsec at prime. This effectively means that we have a 2.5

arcsec slit at the IDS – i.e. unmodified, this system provides only low resolution spectra. To cope with higher resolution requirements we have incorporated a manually adjustable slit unit. Obviously this will result in further light losses, cutting down the overall efficiency of each fibre from about 70 percent to about 40 percent (for typical slit widths). However, with up to 40 objects per fibre field, such losses can be tolerated, if not exactly welcomed.

Finally, to calibrate the system, both in the photometric response and in wavelength, it is essential that light from the calibrating source travels the same path as starlight. To that end, a hollow-cathode lamp has been mounted at the prime focus. This directly illuminates the primary mirror and provides wavelength calibration. At present the fibre-to-fibre response and flat field calibrations are obtained using light scattered off the inside of the dome.

In many respects the INT system is very similar to Gray's AAT set-up. However, we have chosen to work at the prime focus, which has an unvignetted field of 40 arcmin diameter, rather than the 12 arcmin available at Cassegrain. The WHT system will be similar at the prime focus. There are, however, some complications at the prime focus. First, with a plate-scale of 24.675 arcsec/mm, we require fibres of a smaller diameter than those used at AAO if we are to avoid undue sky background. We use 105-micron (2.5 arcsec) diameter Spectran 820 fibres, which give good response in the ultraviolet. The transmission rises from about 40 percent at 3000Å to 80 percent at 5000Å. The second problem lies in dealing with the optical distortions at prime, which are strongly dependent on the distance from the optical axis.

To investigate the distortions and the alignment of the telescopes, plates have been obtained and measured. As a result we now know that there are very stringent requirements on telescope alignment and reproducibility of the axis of the telescope on the fibre field. The image distortion means that alignment must be two dimensional, and new procedures for the prime focus assembly must be invented.

Neill Reid and Hans Schild
October 1987

The La Palma Data Archive

Most of the observations made using La Palma telescopes result in electronic images which are archived on magnetic tape. The Isaac Newton Telescope alone has already yielded around 800 tapes (some 20000 observations in 4 years) and the flow of data is accelerating as the William Herschel Telescope becomes operational.

Management of the data, and access to it, are provided by the La Palma Archive software, which has been written by a joint UK/Netherlands team (notably Ger van Diepen and Ernst Raimond). The Archive will store observations in a highly structured form, and will allow automatic retrieval of the data onto FITS tapes. More than 10000 observations from the Isaac Newton Telescope have already been loaded into the database. An observations catalogue is being maintained on the VAX/750 computer at Herstmonceux, and this can be interrogated by users from anywhere in the world, via the data-communications networks. La Palma observations are thus accessible (after the 1-year proprietary period) to the entire astronomical community.

The archive can also be used to carry out statistical analyses of the way in which the La Palma telescopes have been used. For example, one might wish to know the fraction of the average night that is actually spent integrating astronomically interesting photons; or what is the distribution of zenith distances of observation. Fig. 6 shows the results of one of the analyses carried out using a pre-Archive observations catalogue, by Benn and Martin 1987: the distribution on the sky of observations made with the Isaac Newton Telescope between 1984 and 1986 (cf. Q. J. R. Astr. Soc., **28**, 481–496).

Chris Benn
Ralph Martin
Ed Zuiderwijk
January 1988

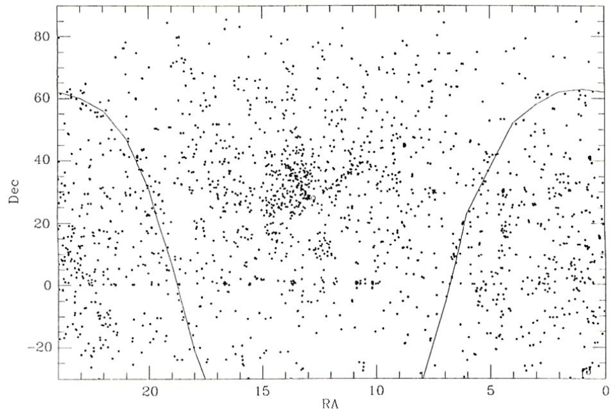


Fig. 6. Distribution on the sky of 9056 observations made with the Isaac Newton Telescope between 1984 and 1986. Many of the dots represent multiple observations of a single object. The open circles and solid curve mark the galactic poles and plane respectively. Note the concentration of observations to high galactic latitudes (where interstellar absorption is less).

ADAM – Astronomical Data Acquisition Monitor

ADAM was developed for the La Palma Isaac Newton and Jacobus Kapteyn telescopes (INT and JKT). It provides a data acquisition environment on the Perkin-Elmer instrumentation computers which is used for nearly all PATT-scheduled observing. One can think of ADAM as being a data reduction system, with a command language, application programs and a common disc data format, plus the extra capability of being able to control instruments and detectors in real time.

History

The decision to purchase Perkin-Elmer computers as instrumentation computers for the INT and JKT was made before Starlink existed and before VAXes were in common use in Astronomy. By the time that La Palma came into operation Starlink was in full swing, but the wealth of VAX/VMS-based data analysis software was not available at the telescope. It is not trivial to move applications from VAXes to Perkin-Elmers and in practice only vital data display and analysis programs were made available on-line.

Recognising that astronomers of the 1990s will demand access to data reduction software at the telescope, it was decided several years ago that the computers in overall charge of the William Herschel Telescope (WHT) and its instruments should be VAXes running VMS.

In 1983 ROE and MRAO decided to implement ADAM on a VAX in order to acquire data at the UK Infra-Red Telescope and the James Clerk Maxwell Telescope, and RGO supplied them with the Perkin-Elmer ADAM system. ROE built VAX ADAM, retaining the concepts and the nomenclature of the original system but re-writing much of the code, and in particular they arranged that VAX ADAM application programs should look exactly like Starlink applications.

About a year ago RGO decided to adopt this VAX ADAM for the WHT. Shortly afterwards not only did the Anglo-Australian Observatory (AAO) decide to use ADAM for VAX-based instrument control, but Starlink decided to adopt it as the Starlink environment. For Starlink the data acquisition capabilities are irrelevant, but for the observatories there is the prospect of a common software environment at the telescope and back at the home institute. This does not mean that all data acquisition systems will look identical at all telescopes, but it does mean that applications will be completely transportable – this is perhaps the most important consideration for the astronomer.

Experience

At the RGO this is the second time that we will use an ADAM system to control a telescope and its instruments. What have we learned from our experience and what will be different this time round?

Firstly, the good experience: ADAM has been a success in providing a unified environment for data acquisition and analysis. It is highly modular with a large proportion of the system being infrastructure so the amount of work to accommodate a new instrument or observing mode is relatively small. For example, because all detectors write their data in a standard format, there need only be a single image display program. Similarly, there are a total of four CCD cameras on the INT and JKT, two in spectrographs and two used for direct imaging – exactly the same CCD software is used in all cases.

Secondly the less good experience: we produced a system that is very easy for astronomers to modify by writing command procedures or by writing their own Fortran programs. However we have found that as a general rule astronomers demand turnkey systems and modifications by users have been disappointingly rare. Indeed the major users of command procedures have been the system developers – not those for whom they were intended – and the use of too many command procedures has made the system slower than it would have been if Fortran programs had been used instead. Again, ADAM was not originally envisaged as encompassing the telescope as well as the instruments and so there have had to be quite a few ad hoc add-ons to allow communication with the telescope, with TVs and with autoguiders. Finally, the very fact that any applications that were to run on the Perkin-Elmers had either to be written from scratch or else converted from VAX programs meant that not very much data analysis and data assessment could be done at the telescope.

WHT ADAM

Given the existence of the Starlink and VAX ADAM infrastructure, we can concentrate on those areas that are specific to the WHT, its instruments and its detectors. From the outset we have been thinking in terms of a system that can control the telescope and its instrumentation in a unified way – this is after all vital if remote operation is ever to be a possibility. There has been considerable debate about how astronomers will observe, and Robert Laing and Charles Jenkins have coined the term 'Structured Observing' to describe their thoughts on this, which have been accepted by RGO astronomers and by the La Palma Users' Committee. The prime requirements for structured observing are:

- control of all instruments (including the telescope) from a single point
- efficiency and parallelism
- automation of standard operations
- off-line simulation and checking of proposed observations
- data evaluation facilities
- remote operation and flexible scheduling

The model that emerges is of a 'control file' which describes a sequence of observations in tabular form, with the columns of the table containing information like object names, exposure times and filter names.

The astronomer will prepare control files using an editor specially created to know something about control files. Then, prior to performing his observations, he will pass his control file through a compiler that will check that all necessary details are known (for example; does the specified object exist in the catalogue? is there a filter called GG395 in the currently-loaded filter slide?) and that it makes sense to perform these observations at the planned times (for example: will the object be visible?).

Experience with the ADAM system on the INT and JKT demonstrates the soundness of the concepts behind the system. At the RGO we are in a unique position to build on that experience to create a second generation ADAM system to integrate all aspects of the WHT – telescope, instruments, detectors and data analysis – and to provide unrivalled facilities to the astronomer observing with the WHT.

William Lupton
September 1986
revised September 1987

ADAM structure

The ADAM system is highly modular – the telescope and each instrument and detector have their own ADAM tasks to be responsible for them – (called device or d-tasks). Much of the device-specific detail need be known only to the relevant d-task. In order to observe, these sub-systems must be coordinated and this can be done either by using a command language or by writing specialised ADAM tasks (called control or c-tasks). The final category of task is the standard application program (or a-task).

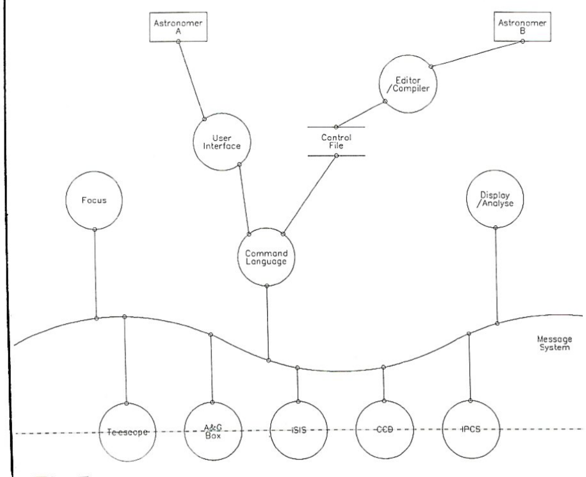


Fig. 7.

The diagram illustrates all this. The wavy line represents the "message system", which allows any ADAM task to communicate with any other ADAM task. The bubbles below the wavy line are the d-tasks, one per instrument, and they can be coordinated either by "Command Language" or else by a c-task such as "Focus". "Display/Analyse" represents all a-tasks.

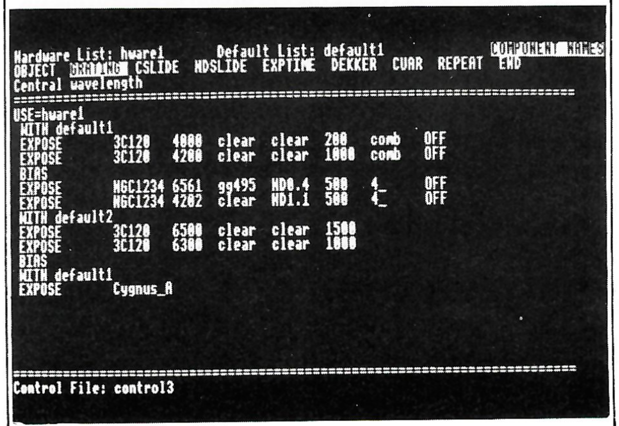
The above description applies equally to any VAX ADAM system and, apart from the term "c-task", to Perkin-Elmer ADAM. What follows is specific to the WHT ADAM system.

Note the two methods of connecting an astronomer to the command language. He can either go directly via a user interface or else he can choose to go via the intermediate stage of producing a compiled control file. The important point about using compiled control files is that they can be created and checked in advance.

The dashed and dotted line shows the level at which instruments can be simulated. All d-tasks will have a "simulate mode" which will make them behave as though their hardware were there even when it is not. This will allow astronomers and engineers to run the system on any VAX and, depending on the sophistication of the simulation, may even produce realistic simulated data. For example, if the CCD could produce simulated data where the width of stellar images is a function of the simulated telescope focus position, then it would be possible to develop and test an automatic telescope focus procedure on any VAX anywhere.

Control files

A control file is like a table. Each row corresponds to an observation and each column corresponds to a parameter of an observation. A fragment of a control file might look like this:



```
Hardware List: hware1        Default List: default1          COMPONENT NAMES
OBJECT  GRATING  CSLIDE  NDSLIDE  EXPTIME  DEKKER  CUAR  REPEAT  END
Central wavelength
===========================================================================
USE=hware1
 WITH default1
 EXPOSE        3C120   4000 clear clear 200   comb  OFF
 EXPOSE        3C120   4200 clear clear 1000  comb  OFF
 BIAS
 EXPOSE        NGC1234 6561 gg495 ND0.4 500   4_    OFF
 EXPOSE        NGC1234 4202 clear ND1.1 500   4_    OFF
 WITH default2
 EXPOSE        3C120   6500 clear clear 1500
 EXPOSE        3C120   6300 clear clear 1000
 BIAS
 WITH default1
 EXPOSE        Cygnus_A
===========================================================================
Control File: control3
```

Fig. 8.

Of course many parameters are missing. What is the spectograph slit width? What is the grating angle? One doesn't want to be concerned with these for every observation so they are assumed to have the values that were defined when the current instrument configuration was selected. We expect that the normal way of working will be for astronomers to use standard configurations but with their own selections for which parameters should be defaulted and which parameters should be specified for each observation.

One of the vital points about control files is that they can be created and checked away from the telescope, either at the astronomer's home institute before the observing run or else perhaps on the afternoon of the observation. We cannot always expect every detail of each observation to be determined in advance so it will also be possible to execute commands directly from within the control file editor or, for those that wish, completely to eschew control files and work at the command language level as is currently done at the INT and JKT. Those that really want to do their own thing can even write Fortran programs that provide direct access to the instrument and detector control programs.

The high-resolution imaging programme on La Palma

The time has come to realize the old dream of improving the spatial resolution in the visible beyond the 1 arcsec seeing limit. We now have the optical technology (photon-counting detectors, single-mode fibres) and the computer technology (fast processors, large storage) that are necessary to deal with the image degradation that is caused by atmospheric turbulence. Moreover, radio aperture synthesis has given us plenty of experience in diffraction-limited imaging.

This new situation has triggered a tremendous amount of work in all parts of the world. Following the initial successes of Labeyrie with speckle interferometry, many algorithms have been developed to achieve diffraction-limited images with large single-dish telescopes. Apart from classic speckle, there is triple correlation, Knox–Thompson, exponential filtering etc, which have all been used more or less successfully to achieve a resolution of 10–50 milliarcsec on a variety of objects. At the same time, at least five multi-telescope arrays are operational or being built, and several more have been proposed. With their longer baselines they will be capable of 1 milliarcsec resolution or better, which is nicely matched to radio VLBI.

However, the facts of life with ground-based interferometry are that the atmosphere imposes a limit of 15th magnitude at best. Fainter objects can only be observed if they have such a bright object as a reference within the so called 'isoplanatic patch', which is only a few arcsec in size. There are three methods to overcome this limit. One can try to find an atmosphere-independent quality that can be integrated longer than 10 msec. One can also try to create an artificial reference object by reflecting a laser beam from the 80 km sodium layer. Also one can try to find the money for a space project. There are currently more than 10 proposals for space interferometry projects, some of which have baselines of more than a kilometre. Before they are funded, the techniques will have to be demonstrated from the ground.

The Roque de los Muchachos Observatory on La Palma is in a better position than most to make a contribution to high-resolution imaging. It is an excellent site, with subarcsec seeing for a significant number of nights. Moreover, it serves a community with a strong radio aperture synthesis tradition. Finally, but most importantly, it offers the right kind of facilities to make rapid progress.

In 1985–7, a number of pilot projects were conducted on the 2.5 metre Isaac Newton telescope, using the IPCS and the IPD as detectors. Initially, the TAURUS box was used as a suitable vessel to mount extra magnifying optics, but in 1987 the much more accessible Imaging Box (built by RSRE Malvern to an optical design of the RGO optics group) became available. The experiments included speckle interferometry and optical aperture synthesis using a variety of masks. There was also a successful experiment with spectral image sharpening, using the INT spectrograph and the IPCS. Most of the observations have yielded useful data and several results have been published.

It has become painfully clear, however, that the usual way of time allocation on optical telescopes is not conducive to rapid progress in high-resolution imaging. The experiments are complex and require good seeing conditions. Very often it is not possible to make use of the full nights allocated, either because the conditions are not good enough, or because something is wrong with the instrument. Fortunately, the new GHRIL is expected to change this situation by offering more suitable observing. GHRIL stands for Ground-based High Resolution Imaging Laboratory. It is an optical table on a Nasmyth platform of the 4.2 metre William Herschel Telescope, protected by an enclosure. Observers can set up and prepare their instruments without interfering with the normal observations. Since the light can be redirected from Cassegrain to Nasmyth in less than a minute, it becomes possible to obtain short periods of observing time when the conditions are good and the instrument is ready.

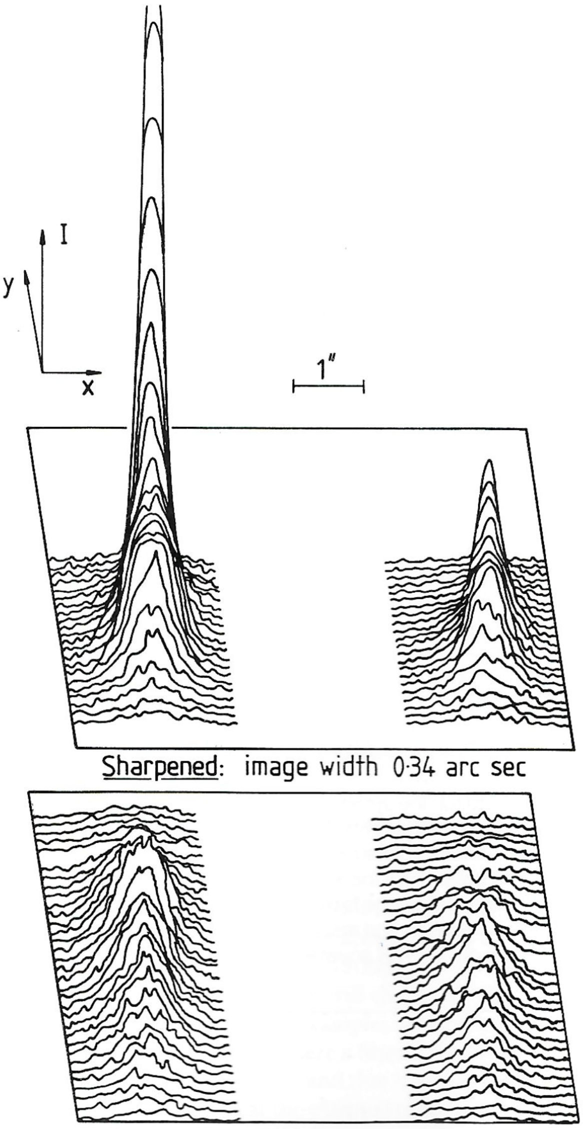


Fig. 9 This shows the results of a preliminary experiment in 2D image sharpening using the components of a double star with a separation of about 5 arcsec. The observations were made on the INT with the IPCS as detector. The photons from the brighter component (magnitude about 12) were used to select the moments of good seeing and to correct for image motion. By this process, the FWHM of the image of the fainter component of the double star is decreased from 0.82 arcsec to 0.34 arcsec.

If necessary, the instrument can remain on standby for weeks. Since it is often difficult to obtain a suitable detector, a range of photo-counting detectors and a simple data acquisition system are offered on the GHRIL as well. There are also facilities to calibrate and set up the instrument. This infrastructure is provided by the instrument building group of the IAC Tenerife, in collaboration with NFRA Dwingeloo.

It is expected that many types of high-resolution imaging techniques will make rapid progress under GHRIL-type conditions, producing valuable scientific results in the process. Some of the techniques may be developed into common-user facilities, like for instance an image sharpening device on the WHT acquisition and guiding box which has the capability of feeding CCDs or spectrographs with 'sharpened light'. In any case, the GHRIL users will function as a watchdog for dome seeing, which leads to better quality observations at all foci. Finally, other non-imaging projects can also have easy access to a large telescope via the GHRIL.

In the longer term, there should be a dedicated array of small telescopes on La Palma in about 1995, with a baseline of 100 metres or more. The GHRIL could play an important role here by allowing work on optical correlators to progress in parallel with the work on beam combination.

Jan Noordam
October 1987

Optics at the RGO

The search for greater efficiency in astronomical observations pushes the optical designer to look at new ways of improving the transmission, field size and image quality of the system he designs. The problem of matching image scales to detector pixel sizes, coupled with the threshold and sensitivity limitations of the detector used, has a major influence on the choice of final focal ratio for the system while the spectral coverage required may limit the range of materials which can be used. The evolution of an optical design involves reconciling the astronomer's requirements with the physical and optical possibilities.

Outlined below are some examples of the design work and optical investigations which have been undertaken in the past two years. A theme that runs through much of this work is the provision of facilities for the acquisition of spectra of faint objects and the ability to handle extended fields for survey work.

Faint Object Spectrograph (FOS)

Following the commissioning of the FOS for the INT, the collaboration between the RGO and Durham University has continued with a new design of a faint object spectograph for the WHT. The instrument, which eventually will form the third channel on the WHT ISIS, was brought forward so as to be available for use on the telescope in 1987. As its name implies, the system is designed for work on faint astronomical sources, and so a major consideration is to keep the instrument transmission high by reducing the number of reflecting and refracting surfaces. The primary disperser is a transmission grating mounted in the diverging beam coming from the spectograph entrance slit. Cemented to the back of the grating is a cross-dispersing prism assembly and the aspheric corrector plate for the Schmidt type camera which forms the rest of the spectrograph. A fixed format spectrum is obtained, and the aberrations introduced by operating the dispersing elements in an uncollimated beam are reduced to tolerable levels by modifications to the spectrograph camera. The CCD detector is mounted internally in the camera so that it lies in the shadow of the telescope secondary produced in the expanding beam. The throughput of the optical system is similar to that of the INT FOS, that is about 70% at the peak of the grating blaze.

The new spectograph has a spectrum format which is designed for the new, blue sensitive, thinned 512 × 512 Tektronix chip. The spectral range covered is 3500Å to 10 500Å, and the dispersion in the first order is 400Å/mm. A GEC chip, coated to improve its blue response, can be used as an alternative detector with a spectral range limited to 3500Å to 9500Å.

TAURUS II

TAURUS is an imaging Fabry–Perot interferometer in which the spacing of an etalon can be varied in a series of small steps. Earlier versions of the instrument have been used successfully on the INT, AAT and other telescopes. Two interferometers built according to the original general principle but to a new detailed design (TAURUS II) have been constructed by the Kapteyn Sterrenwacht Werkgroep at Roden in the Netherlands. One of these is for use at the f/11 Cassegrain focus of the WHT and the other for use at the f/8 Ritchey–Chrétien focus of the AAT. The optical design of the collimators and cameras for these two TAURUS II instruments was done at RGO.

TAURUS II has a capability greater than that of earlier versions. In particular, the wavelength coverage has been extended to the range from 3650Å to beyond 1 micron. In spite of the difference in focal ratio, the collimators for the WHT and AAT are compact three-element telephoto systems of similar design. The f/2 camera of focal length 120mm (see Fig. 10) consists of two cemented triplet components and two doublets. The design minimizes the number of air–glass surfaces. The wavelength range has been extended by making the inner components of the triplets of calcium fluoride crystal. There is no perceptible loss of efficiency in the presence of the external stop at the etalon.

The optimum choice of focal length for the camera depends on the angular size and surface brightness of the astronomical object. As an alternative option to the f/2 camera normally used, an f/4 camera has been designed and built so as to provide a larger image scale on smaller fields.

Preliminary designs have been made of an interferometer which uses etalons of smaller cross-sectional area than those

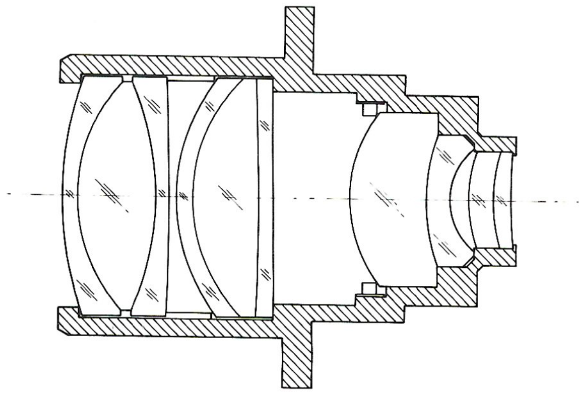


Fig. 10 A cross section of the f/2 camera lens in TAURUS II.

in the existing TAURUS systems. The advantages of these smaller etalons are economic; it is practicable to provide a greater choice of central wavelength for the same cost. Consideration has also been given to a pilot design for an instrument in which the etalons of a TAURUS-type interferometer can be replaced by a transmission grating (in the form of a grism) to produce a mode of operation similar to that of the LDSS described below.

The Low Dispersion Survey Spectrograph (LDSS)

The Low Dispersion Survey Spectograph (LDSS) is a system designed to obtain spectra of objects lying in the apparent magnitude range 20 to 23. In the case of these faint objects one requires a spectrograph of high efficiency avoiding light losses that occur in fibre feeds. The LDSS system is a focal reducer providing a collimated space where grisms of different dispersion may be placed. A focal plane mask is used to isolate the objects to be studied together with regions of night sky, and multiple spectra may be recorded on either a CCD or an IPCS detector.

The system is designed to work at the f/8 focus of the AAT and covers a field on the sky of about 12 arcmins (110 mm); the collimated beam diameter is 70 mm. With this large field size, as compared with the collimated beam, transmitting optics rather than reflecting optics have to be used. To keep the efficiency as high as possible the spectral range is limited to approximately one octave (3700Å to 7500Å) so that high efficiency, multi-layer anti-reflection coatings may be used. The system is designed for 4-metre class telescopes and the matching of the image scale to the detector requires a camera with a focal ratio of f/2.

The overall layout of the optics is shown in Fig. 11. Despite the relatively large number of air–glass surfaces, the use of three-layer anti-reflection coatings gives an overall throughput for the combined camera and collimator of about 80% and for the optics plus grism of 60% at the peak of the blaze of the grating. The image spread over the wavelength range 3700Å to 7500Å is better than 50 μm for the combination of collimator and camera. The field angle of the collimator is ±5.7° and that of the camera is ±6.8° to allow for the dispersion that occurs at the grating.

The optical design problems which arise in the Low Dispersion Survey Spectrograph (LDSS) are threefold. First, there is the problem of secondary spectrum inherent in transmitting optics. The magnitude of this secondary spectrum can be reduced by careful choice of materials and for LDSS the Schott glass FK54 has been coupled with the short flint glasses KzFSN2 and KzFSN4. Because FK54 has a large coefficient of thermal expansion, the doublet lenses were joined with an optical grease instead of a cement.

Secondly, the collimator must cover an extended field of view; therefore, it must be a flat-field anastigmat construction and must comprise separated components. In addition to collimating light from the field mask, it must image the exit pupil of the telescope into an accessible pupil position in the collimated space where the dispersing element can be placed. The simplest system meeting these requirements appeared to be a telephoto construction with a field lens near the mask. The complete collimator system consists of four doublets. This type of design also has the advantage of reducing the overall length of the instrument. Collimators have been designed for both the f/8 focus of the AAT and the f/11 Cassegrain focus of the William Herschel Telescope.

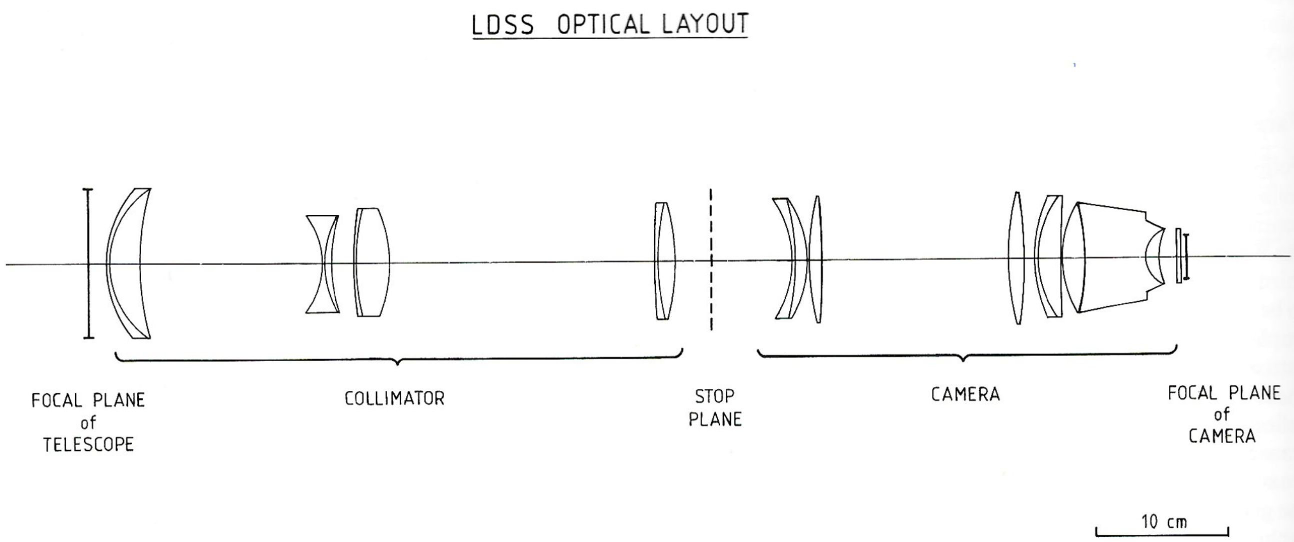
Thirdly, the f/2 camera design also poses problems because the aperture stop for the system lies on the dispersing element which is some distance in front of the camera. Most designs for f/2 photographic lenses use an internal aperture stop to reduce the aberrations and keep the physical size of the lens small and therefore are not readily applicable to this instrument. The camera design for LDSS has been based on a configuration used for an eyepiece which has an external stop. The back focal distance of the camera has been made large enough to accommodate a CCD mounted inside a cryostat.

The system was commissioned on the AAT in May/June 1986. At present it has two grisms giving dispersions of 840 Å/mm and 160 Å/mm. Using the larger detector size (available with the IPCS) and the low dispersion grism, 80 to 100 objects may be observed simultaneously.

Atmospheric dispersion correction at Cassegrain focus

Work is in progress at the RGO on the provision of optical fibre feeds to spectrographs for the simultaneous recording of spectra of many objects. Atmospheric dispersion can cause a heavy loss of efficiency for this method of observation and indeed for other forms of multi-object spectrographs planned for La Palma. We have therefore been investigating possible atmospheric dispersion correctors (ADCs).

Fig. 11 The optical layout of the LDSS.



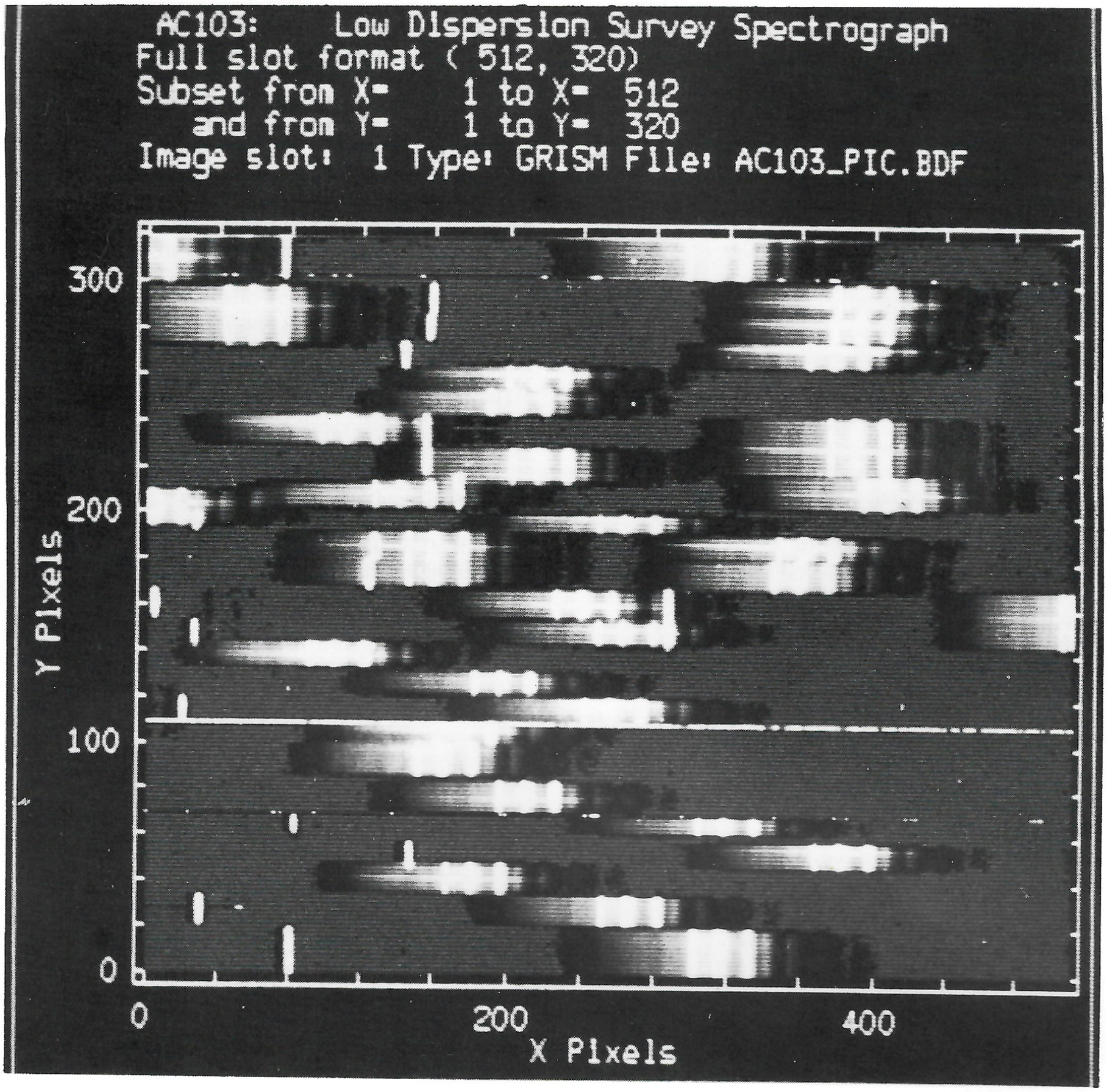


Fig. 12 An LDSS multi-slit observation made using the RGO CCD system on the AAT in May 1986. The exposure time was 4000 seconds. Zeroth and first order (850Å/mm) spectra of 20 slitlets are seen with objects visible above the sky background in almost all cases. The bright [OI] and NaD night sky lines are clearly visible in each spectrum. The apparent blue magnitudes of the objects are in the range 21 to 23½.

Correctors for a Cassegrain focus were studied first. Correctors are known, for use in collimated light, consisting of a pair of doublet zero-deviate prisms, independently rotatable to tune for zenith distance. However, in a convergent light beam, such as that at a Cassegrain telescope, these correctors introduce quite large aberrations. We have found that, by a critical choice of the types of glass used, and by the introduction of slightly curved surfaces at the interface between the doublet prisms, these aberrations can be made negligibly small for a Cassegrain focus corrector. A corrector of this form, involving only two air–glass surfaces, has been designed for the f/11 focus of the WHT to cover a field of 30 arcmin (20 cm) diameter. The aberrations induced by the ADC will give geometrical image sizes less than 0.1 arcsec in diameter over the spectral range 3650Å to 10 140Å.

ADC at prime focus

The work in ADCs at Cassegrain focus led us to investigage the possibility of correction at prime focus, where fibre feeds are also being considered. The problem here is different in two ways. First, at the large angular apertures of the primary mirrors (f/3 on the INT and f/2.5 on the WHT), a large enough field of good resolution suitable for multi-object spectroscopy can be obtained only after the addition of a field corrector. Therefore, if an ADC were to be provided at prime, it would work with the field corrector. Secondly, at prime focus relative apertures, the aberrations of our Cassegrain type correctors would become prohibitively large. A different approach is therefore needed and this we found in the form of a pair of doublet prisms as before; however, in this case the prisms have all their surfaces curved, instead of plane, so that the centres of curvature of all five surfaces lie close to the focal plane of the telescope. As before, by a suitable choice of the types of glass, the aberrations arising from the tipping of the surfaces can be made negligibly small. The remaining aberrations of the system can then be shown also to be small, apart from a first order astigmatic aberration, in the form of a tangential field curvature, which is inherent in such a system. If the ADC and the field corrector be considered together, this ADC aberration can be readily corrected by a redesign of the field corrector with no deterioration of its performance in other respects.

A system of this kind has been designed for the f/2.5 focus of the 4.2 metre WHT, covering an unvignetted field of 40 arcmin tuneable for correcting atmospheric dispersion over zenith distance 0° to 70°. This gives geometrical image spreads over the whole field within ½ arcsec over the spectral range 3900Å to 7000Å, and also over the wider range 3300Å to 10 000Å except at the extreme edge of the field, where the spread is still less than 1 arcsec. Fig. 13 shows the form of this system.

Field correctors

Our work on prime focus ADCs led to the surprising result that in a combined ADC and field corrector system for an f/2.5 telescope, the residual aberrations which limit performance arise predominantly from the field corrector. The 4.2 metre telescope was originally planned to work at f/3.2, with a field corrector consisting of three separated lenses covering a field of ½° diameter. Financial pressures in 1980 made it necessary to shorten the focal length to f/2.5, and more recent pressures from astronomers have urged the desirability of a wider field angle. These needs can be combined with atmospheric dispersion correction. Alternative forms of field corrector to the normal triplet system have been studied. The earliest field correctors covering fields upwards of ½° were designed about twenty years ago by Wynne and consisted of four separated lenses. These were later superceded by triple correctors, which gave substantially as good imagery even with the fastest apertures (about f/3) then being considered. It emerges that for even faster apertures, in particular f/2.5, a four-lens corrector is a competitor to the triplet corrector. We expect to decide the form of the corrector for the WHT in 1988.

ADC for slitless survey spectroscopy

A technique that is being increasingly used for statistical surveys and for searches for particular kinds of object, involves the automatic scanning and measurement of objective prism type plates with computer analysis and classification of spectra. This work uses, for example, plates taken on the UK Schmidt Telescope with an objective prism.

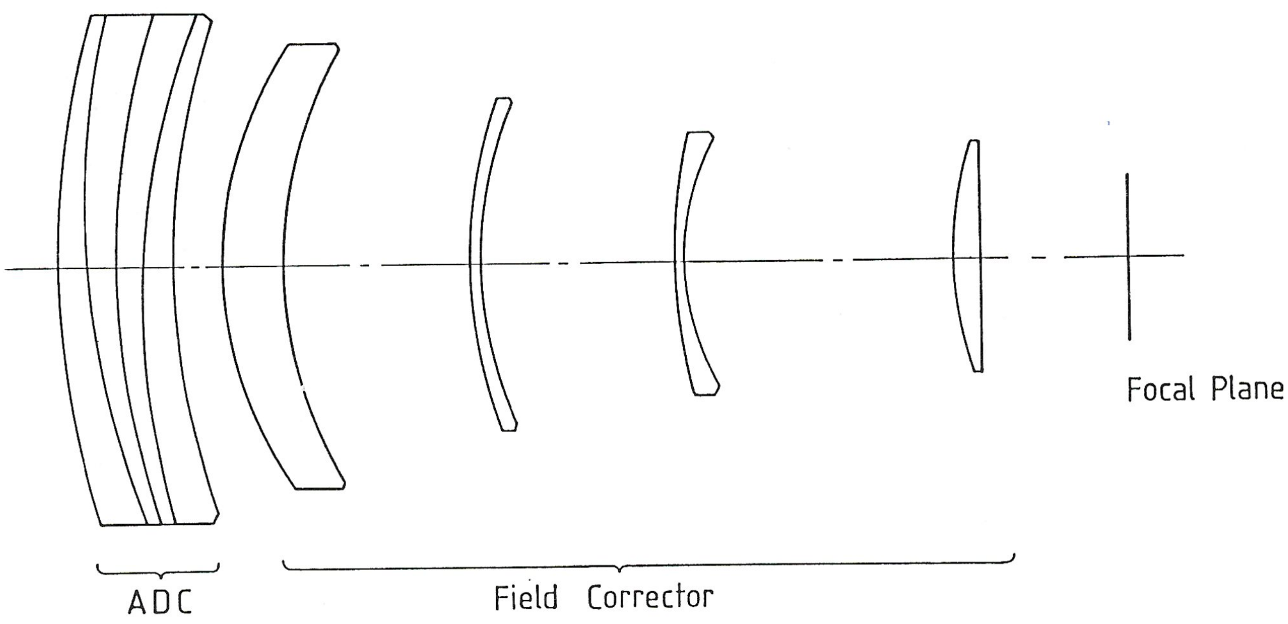
The very small aberrations arising in our prime focus ADC suggested a further possible development of its use. If an ADC were made with much larger prism angles than those discussed above, then tuning for atmospheric dispersion correction would require only small rotation angles from the null position, and at wider settings the device could be used for objective-prism type slitless spectroscopy. For example, an ADC on the WHT with angles nine times those needed for atmospheric correction at 70° from zenith would give a stellar spectrum 2.2 mm long, which is similar to that obtained with the medium-dispersion prism on the UK Schmidt Telescope. The WHT system, with a plate scale of 3½ times larger, would have a corresponding reduction in overlapping of spectra. This facility would involve no loss of image quality in the normal ADC mode, and little extra cost.

Optics for other WHT, INT and AAT instruments

During the report period, there has been the continuation of several projects concerned with instrumentation for the 4.2 metre telescope. The specification and procurement of optics for the ISIS intermediate dispersion spectrograph has been undertaken. There has been continuing liaison with University College, London, over the echelle spectrograph for the AAT and with Utrecht over the similar system which is being produced for the WHT. The optical design work on these echelle spectrographs and that on the Acquisition and Guiding Unit of the WHT is described briefly elsewhere in this report (in 'The instrumentation system for the William Herschel Telescope').

The overall layout and optical components were designed for a special instrument which was constructed by RSRE, Malvern, for use on the INT for experiments on seeing and image formation. The designs included a reducing lens, atmospheric dispersion corrector, a collimator (f/15) and a camera unit (f/11). By reversing camera and collimator, the optics will function on the GHRIL facility to be constructed on the WHT. (See the article 'The High-resolution imaging programme on La Palma' elsewhere in this report.)

Fig. 13 The design for a corrector system at the prime focus of the William Herschel Telescope described in the text.



Larger survey telescopes and associated instruments

In the course of discussions among astronomers of possible new telescopes, there has been considerable interest in a wide-field survey telescope, possibly of 2 to 4 metres aperture, to carry further the work of existing Schmidt cameras. In an essentially long-term study, we have been investigating possible forms for such a telescope, and of associated multi-object spectrographs.

Work for other establishments

We were asked for a new camera design to replace the present 25 cm f/1.6 cameras on the RGO spectrograph of the AAT. The existing lens is inefficient when used in the preferred grating-normal-to-camera configuration; furthermore, a wider field and spectral range together with better resolution are needed. The layout of the spectrograph would make it difficult to accommodate a folded form of camera. We have designed a new straight-through camera meeting these requirements.

The COSMOS automatic measuring machine at ROE gives very precise records of plates from the UK Schmidt Telescope, but has a limited dynamic range due to scattered light. We were asked to suggest means to improve this. We have designed an optical system to re-image the scanned image of the emulsion on to a physical slit in front of the photomultiplier, which should greatly reduce the stray light. The design was complicated by the unusual position of the aperture stop of the relay imposed by the scanning optics above it.

New vistas in astronomical optics

Various new telescopes are now projected, and new observing techniques are emerging, that will require for their efficient use new optical imaging systems beyond the range of current knowledge.

For example, many telescopes with apertures from 7.5 to 16 metres are under active development. If these are to be used for imagery with any of the types of detector at present available or projected, their efficient use will require instruments (for example high performance spectrograph cameras) working at much higher numerical apertures than are at present known.

Similar problems arise with existing 4 to 5 metre telescopes used with optical fibre feeds for multi-object spectroscopy. The transmission of an image through a fibre seems inevitably to involve some increase of image size (often considerable) and commonly also some increase in numerical aperture of the beam, so that appropriate matching to a detector requires a spectrograph of corresponding higher aperture. Moreover for the simultaneous recording of many spectra, the spectrograph camera must cover an extended field not only in the dispersion direction but also in the orthogonal direction ('along the slit'); with existing types of wide aperture camera this would involve a much larger central obstruction of the aperture. Again, different collimators are needed. In conventional spectrographs the field of view of the collimator is very small relative to that of the camera, so that a simple device such as an off-axis paraboloid is adequate. For many stacked spectra, an extended field anastigmat collimator becomes necessary.

The efficient use of very large telescopes, and of multi-object fibre-fed spectroscopy on existing telescopes, therefore require imaging systems of higher numerical aperture, wider field, and lower central obstruction than are at present known. New approaches to this problem are being investigated.

Another problem of general interest concerns wider-field telescopes. With existing large telescopes, the addition of known forms of field corrector can give high quality imaging over field diameters from 40 arcmin to 1°, depending on the telescope. For the very much wider fields of 4° or 5° needed for adequate sampling of very rare objects, it seems that a special purpose large telescope would be necessary. Such designs have been proposed, but are inevitably costly. For less rare types of object, an adequte number for study may occur over a smaller field of say 2° diameter, and it appears that good imagery over such a field is possible using new types of corrector system that could be installed on existing telescopes. Different solutions are needed for telescopes with paraboloid prime mirrors and for Ritchey–Chrétien telescopes. Both types are being studied.

Most large telescopes at present have a single primary mirror; on the other hand, the Multi Mirror Telescope has six. Preliminary studies have been made of a telescope with two primary mirrors; this arrangement may offer the best practical solution to the problems of optical and mechanical design of spectrographs and devices for obtaining high-resolution images on a very large telescope. The division of the aperture leads to better application of diffraction gratings, which otherwise need to be scaled up in proportion to the telescope aperture. The use of two primary mirrors on an altazimuth mounting places the main axis for interferometry and high-resolution imaging in a horizontal plane; this reduces problems of thermal and structural stability.

Charles Wynne, Richard Bingham and Sue Worswick
October 1987

The Carlsberg Automatic Meridian Circle

The CAMC began operation on La Palma on 1 May 1984. By October 1987 it had made over 300 000 observations from which the positions, magnitudes and proper motions of nearly 35 000 stars have been derived. Over 4000 positions of solar system objects have also been determined.

The observations made in 1984 and 1985 were published in Carlsberg Meridian Catalogues Nos. 1 and 2 of which 470 copies were printed and mailed to observatories and groups of astronomers who might have an interest in the data. The observations made in 1986 are being prepared for publication as Carlsberg Meridian Catalogue No. 3 which will be printed in December 1987. The meteorological data, including extinction and seeing, have been published in limited editions at 6-monthly intervals.

The CAMC results have already made an impact in several areas of astronomical research. A few of the important results are discussed here.

Fundamental star reference frame (FK5)

About 45 000 observations have been made of 1300 stars in the fundamental catalogue FK5. The positions and proper motions in the FK5 define the positional and kinematical frame to which all stars are ultimately referred. The systematic errors inherent in the FK4 are in the process of being removed by a group working at the Astronomisches Rechen-Institut, Heidelberg. The observations made by the CAMC are being used in the formation of the FK5.

Linking FK4 to the extragalactic frame

The systematic defects of the FK4 can also be removed by comparing it with the VLBI extragalactic frame. The extragalactic frame has ab initio no detectable rotation and has been established with milliarcsecond accuracy. The problem of relating the two frames lies in bridging the magnitude gap between the bright stars of the FK4 (limiting magnitude ~ 7) and the faint optical quasars of the extragalactic frame. This is being overcome by the CAMC which observes the positions on the FK4 system of 12th–13th magnitude stars around the quasars. The positions of about 4000 such stars have been measured so far.

Another way of establishing the link between the FK4 and extragalactic reference frame is to observe radio stars whose radio positions have been measured with the VLA relative to the extragalactic frame to an accuracy of ~ 0.03″. The radio positions of about 30 stars have been published so far. These have been given high priority on the CAMC programme.

Extension of the FK4 reference frame

The FK4 provides a coverage of 1 star per 5° × 5° with a limiting magnitude ~7. This has been extended through the International Reference Stars (IRS) to 1 star per 1° × 1° with a limiting magnitude ~9. The IRS constitutes the most reliable extension of the FK4. The latitude of the CAMC permits it to observe a wide declination range of the IRS (+90° to −45°). Over 20 000 of the 40 000 stars in the IRS have been observed with the CAMC and the positions sent to the US Naval Observatory which is the international centre for collating observations of the IRS.

Hipparcos

The Hipparcos satellite requires input positions to an accuracy ~1″. Many thousands of stars on the programme have standard errors of ~1′. A concerted effort within Europe is being made to improve these positions. The CAMC has completed the 3000 stars allocated to it. These stars together with the other stars in Catalgoues Nos. 1 and 2 have been sent to the Hipparcos Input Catalogue team at Meudon. Besides these star positions, 5200 observations of 59 minor planets have been sent to the Bureau des Longitudes, Paris, for updating the orbits of minor planets in preparation for their observation by Hipparcos.

Giotto flyby of Comet Halley

The encounter distance of the ESA spacecraft Giotto with comet Halley in March 1986 was very critical. The success of the mission depended on the predicted path of the comet. Its position before encounter was derived from photographic plates using reference stars with reliable positions. Under contract to ESA, CAMC observed the positions of 350 reference stars in the declination range 0° to −20° which were used successfully to update the comet's position.

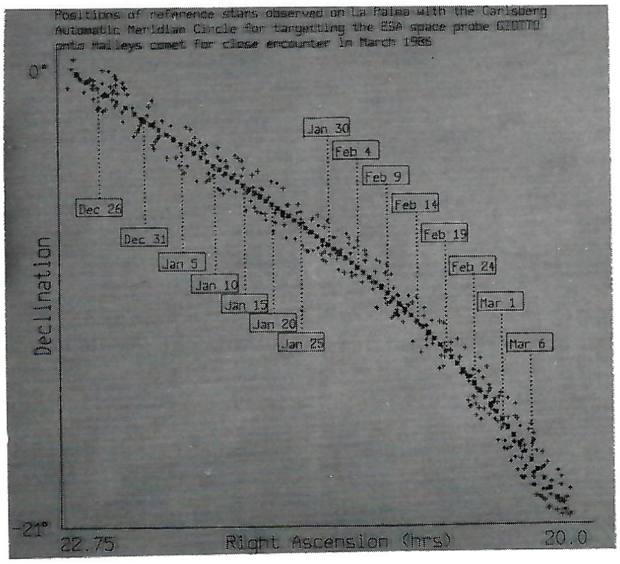


Fig. 14 Giotto encounter with Comet Halley. The path of Comet Halley (asterisks) and the reference stars (crosses) observed with the CAMC. The positions of the stars measured with the CAMC were used to derive the precise position of the comet on photographic plates as it approached the rendezvous with the Giotto spacecraft in March 1986. The positions of these reference stars had previously been taken from the SAO catalogue which is very inaccurate in southern declinations (σ ~ 0.9″). The CAMC observations reduced σ to 0.15″.

Voyager II encounter with Uranus (January 1986)

The observations of solar system objects have been sent to JPL and the International Minor Planet Center. The 54 observations of Uranus made in 1984 proved to be of considerable importance in resolving discrepancies in the ephemeris of Uranus which were introduced through systematic errors in the reference stars taken from the SAO catalogue. The CAMC positions, which are referred directly to the FK4 system, revealed the systematic errors in the positions determined relative to the SAO. JPL will continue to incorporate the CAMC observations for the Voyager encounter with Neptune and the Galileo encounter with Jupiter at the end of this decade. JPL describe the CAMC data as 'the latest and seemingly most trustworthy available'.

Physical studies of asteroids

The 500 photoelectric magnitudes of the asteroids Ceres, Pallas, Hebe, Iris, Flora, Hygiea, Eunomia, Psyche, Melpomene and Harmonia obtained by the CAMC in 1984 have been analysed at Uppsala and Queen Mary College. Multiple scattering factors and absolute magnitudes have been derived. Even though the magnitude errors of the CAMC observations are considerably larger than those of conventional UBV photometry (the CAMC was not designed to do photometry), this is well compensated for by the large interval covered in phase angle and time. These studies continue with the 1985 and 1986 data.

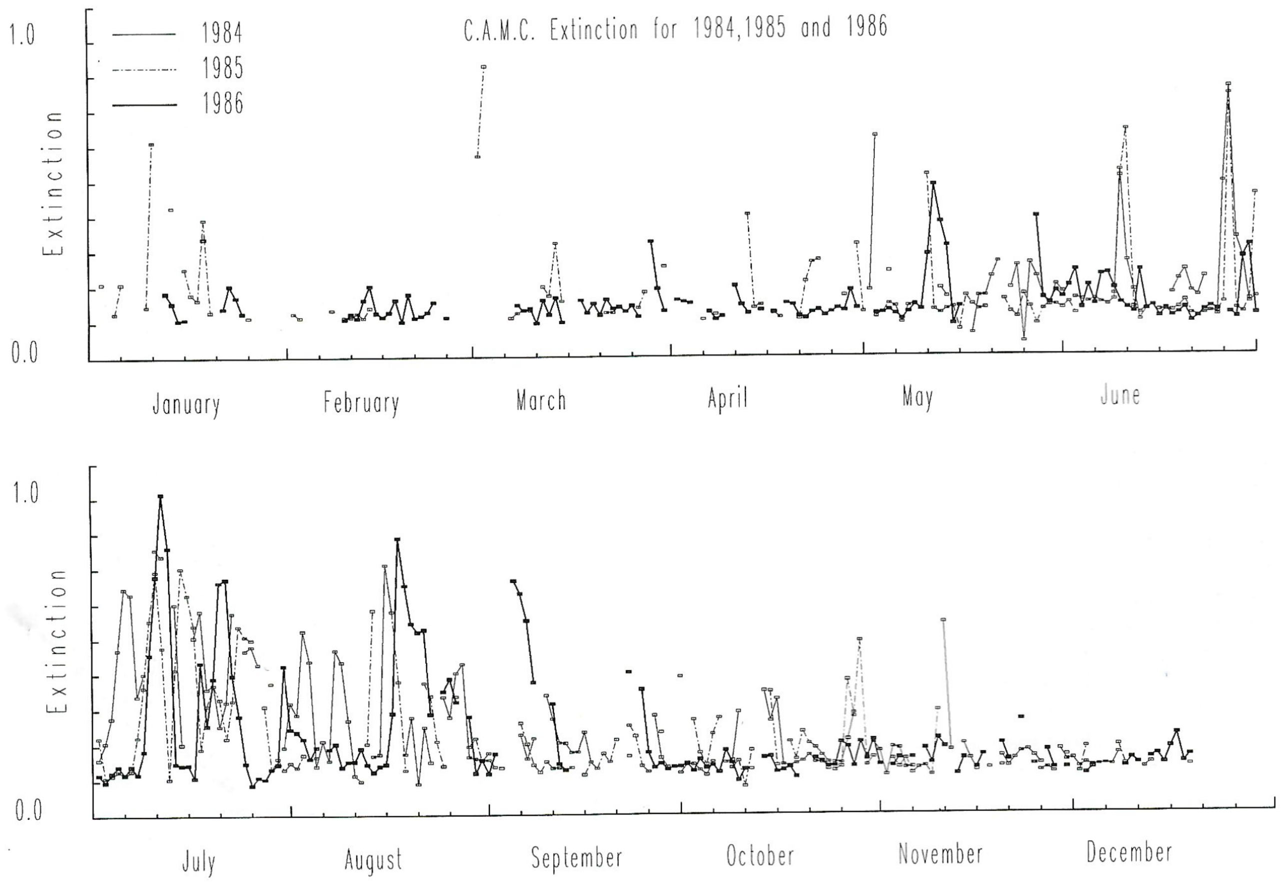
Other programmes

In addition to the programmes mentioned above, the CAMC is also observing the positions of reference stars for the following programmes:

4 galactic clusters in southern hemisphere (Reiz, Copenhagen).
South galactic cap (Murray, RGO).
North galactic cap (Strömgren, Copenhagen).
23 Kapteyn areas (Reid, RGO).
10 Schmidt Fields (Murray, Reid, Requieme (Bordeaux)).
10000 stars in O, B associations (Le Poole, Leiden).
378 geodetic stars (Geodetic Inst., Hanover).
2000 G dwarfs within 30 parsec (Olsen, Copenhagen).
7000 G and K giants within 300 parsec (Olsen, Copenhagen).
3200 A5–GO starts in NGP (Knude, Copenhagen).

L. V. Morrison
October 1987

Fig. 15 Extinction on La Palma. The photoelectric registration of the CAMC slit micrometer, which measures the positions of the stars, also permits the measurement of their magnitudes. Between 50 and 60 photoelectric standards are observed nightly and from these the extinction is calculated. The figure shows the results for the period 1 May 1984 (when observations began) until December 1986. The results clearly show the prevalence of Sahara dust during July and August. Gaps in the data are due to periods when the telescope was not in operation because of maintenance, mechanical or electronic failure, or bad weather.



Schools and the RGO

In 1986 more than 70000 people visited the RGO during the summer msonths. Not all of these came out of a burning desire to learn more about the universe, but when a survey was taken over a couple of days towards the end of the season 37% of visitors gave 'astronomy' as the main reason for their visit while a further 31% equated astronomy and the castle as equally attractive. If this sample is representative of the whole season, the 37% represents around 26000 people and I think this shows what an enormous number there must be who find astronomy a fascinating subject.

In our work with schools our aim is to develop the interest which so many people, old and young, have in the universe. We cannot encourage too many youngsters to expect to take up a career in astronomy as we know how few openings there really are, but we can use astronomy as a spring-board for interest in science and the scientific method in general. Of course there are a few who are really keen on astronomy and I hope we can particularly help them.

Most of the guided tours we give are to primary schools. In secondary schools it seems that there is as yet no place in the syllabus for astronomy, although we have had some preliminary discussions with science advisers from the Department of Education and Science who are beginning to think that astronomy should be in the secondary school curriculum. Even when older pupils do visit, they generally know little more astronomy than primary school children and rarely know about anything outside the solar system. However, we are successful if we can encourage them to go home and make very simple scientific observations for themselves, for example:

- how the Moon changes its appearance through the month, and how this relates to the times of moonrise and moonset
- that some constellations are visible throughout the year and others are not
- that Venus is never visible in the middle of the night
- that stars are of different colours
- noting the times and directions of motion of artificial satellites or meteor events
- that planets are only ever found in a band of constellations around the sky.

There are many such things an enquiring young school child can observe for him/herself with no more equipment than a warm jacket. Of course if he/she has binoculars so much the better!

Young children are particularly interested in space because so much of children's fiction these days is based outside the confines of the reality of the Earth. I don't believe they find much conflict in realising that stories such as Star Trek or ET are fiction, but it often sparks an interest in what *are* the facts about space and how we know. They are always curious to know if a professional astronomer believes there could be other life in the universe and then of course what that life form would be like.

But how much interaction do we have with schools at the RGO? I have already mentioned the guided tours we offer. These are available at any time throughout the year and are often done by retired members of staff. We have two programmes. In a Junior Guided Tour children up to about 15 years are shown round the Equatorial Group of Telescopes in a tour lasting about an hour. Reflecting and refracting telescopes are demonstrated; equatorial mounts, domes opening and rotating are shown and children are told what the telescopes can do with mention of such things as parallax, magnitude and radial velocity (most people are aware of the Doppler effect, if not by name). Bits about quasars or variable stars etc are included according to the interests of the guide, and the age or level of interest of the children. It is so much more rewarding to show around a group whose teacher has already taught them some astronomy! Simple worksheets are available for teachers to adapt to their own class needs, and worksheets are also available on the history of Herstmonceux Castle and the Nature Trail in the grounds. A visit to Herstmonceux can be a good educational day out!

We also have a Full Guided Tour for A-level students, which could be adapted to suit the particular interests of the group. They visit such places as the SLR, the Time Department and the computer area. As the number of requests is not great we also occasionally show senior pupils round the electronic workshops or the instrument science labs as requested.

In East Sussex, astronomy falls under the umbrella of Environmental Studies, and we have a close link with East Sussex Education Authority Environmental Education Adviser, Mr Peter Burton. With him we have organised events such as teachers' workshops relating to a BBC series on astronomy for schools. We have also organised special events such as those linked to the reappearance of Halley's comet or the centenary of the Greenwich Meridian. On the special Open Day to mark the 20th anniversary of SERC in September 1985 we were visited by about 1300 4th–6th year pupils from all over the South East. Peter Andrews lectured to them all, in groups of 150 or so, on Halley's comet!

Our Public Information Unit is constantly receiving letters from school children especially since we agreed to be included in the book 'Free Stuff for Kids'. One whole class wrote to the RGO asking for the free leaflets offered, in what their teacher explained was a handwriting exercise! The PIU receive about 100 letters a month, many of them from children. Apart from the requests for leaflets there are those asking for material for projects, often vaguely on 'Space' or 'The Universe'. But this is all an important part of our responsibility as the Royal Greenwich Observatory, funded as we are by taxpayers.

There are numerous other activities at the RGO linked with astronomy education, such as the O-level course which Graham Appleby and others are running with Eastbourne Astronomical Society using many of RGO's facilities, but otherwise independent of RGO. The Manpower Services Commission has for the past few years provided the funding for a project to catalogue the vast archives of the RGO, and within this project workpacks are being produced for use by schools. Occasionally, we have taken pupils for a week of work experience, but it has been difficult to find projects which are satisfying to both parties at this level. In the past we have been able to employ young people between school and university, but this is not possible at present when the staff complement is being reduced. Of course our links with astronomy education beyond this level are very close and well known.

According to a BBC Horizon team who were recently filming at the RGO, astronomy is the second most popular subject with their viewers – after the human body! I have no idea how this was measured, but it clearly means that we astronomers must be doing quite a good job in relating the excitement and fascination of our subject to the general public.

Margaret Penston.
April 1987

The analysis of satellite laser ranging data

The satellite laser ranging station at Herstmonceux has been in operation since October 1983, making regular range measurements, each of typical accuracy 4.5 cm, to the geodetic satellites Lageos and Starlette. These satellites are covered with corner-cube retroreflectors to return a laser beam to the emitting telescope, and they are very dense, so they are little affected by drag and by solar-radiation pressure. Lageos, at a height of 6000 km, is also little affected by the uncertain higher harmonics of the gravity field and by tidal perturbations, and so is very useful for determining Earth rotation and the coordinates and movements of the observing stations. Starlette, at a height of 950 km, is more affected by the higher harmonics and by tides, and so it is used for evaluating these effects.

The data acquired at Herstmonceux are contributed to the international data bank at Goddard Space Flight Center, and in return the total international set of laser data is available through RGO for analysis by UK researchers. Laser range data are about a factor 100 more precise than any tracking data previously analysed in the UK, and so new computer software was needed to analyse these data. A package of programs for this purpose, SATAN (for satellite analysis), has been gradually developed at RGO, and has been implemented at RGO, at the Universities of Aston and Newcastle, and at the Rutherford Appleton Laboratory and the Royal Aircraft Establishment.

The analysis programs compute the orbit of the satellite in the J2000 frame by numerical integration of the equations of motion, with a force model that includes the harmonics of the gravity field up to some specified degree and order, perturbations by the Sun, Moon, Venus, Mars, Jupiter and Saturn, the attraction of lunar and solar solid Earth tides and ocean tides, solar radiation pressure, drag and Earth albedo radiation pressure. For Lageos a gravity field model of degree and order 20 is used, but for the lower satellite Starlette a model of degree and order 48 must be used. For low satellites the drag is computed from the atmospheric density, which is itself evaluated from a model which takes into account the varying effect of solar flux and geomagnetic activity. Lageos is affected by a variable drag-like force, which is applied in the force model as an empirical deceleration. It causes the orbit to decay at about 1 mm/day, and is thought to be mostly due to charged-particle drag. In addition to computing the orbit, the program computes the partial derivatives of the coordinates of the satellite at any time with respect to the initial parameters (such as the initial coordinates and velocity of the satellite), so that the initial estimates of the parameters of the orbit can be improved by fitting the orbit to the laser range measurements. The positions of the observing stations in the J2000 frame are computed from an initial estimate of their geocentric coordinates by applying polar motion, the variable rotation of the Earth, nutation, precession and solid Earth tides. Partial derivatives with respect to the Earth-rotation parameters and the station coordinates are also computed, so that improved estimates of these parameters can be obtained from the range data.

For Lageos, after best estimates of the parameters have been obtained, the computed orbit gives root-mean-square residuals from the observed ranges of about 10 cm. For the lower satellite Starlette the residuals are about 50 cm, due to the greater difficulty of modelling and determining the forces, particularly the effects of the ocean tides and the higher harmonics of the gravity field. The ocean tides consist of numerous constitutents with a range of periods, and with amplitudes up to a few cm. Even for Lageos they cause perturbations of the orbit of about 70 cm. If these effects are not modelled correctly then the effect on the residuals is much smaller than this; there is an increase in the root-mean-square residuals for Lageos of only about 5 cm if they are omitted entirely. Their effect is absorbed by corrupting the values obtained for the solved-for parameters, and to avoid this it is necessary to have a good orbital model.

Station	*Single shot accuracy*	*No. of passes tracked 1984 Jan to 1987 Jun*	
	cm	LAGEOS	STARLETTE
Herstmonceux UK	4.6	1468	749
Monument Peak USA	1.9	1331	949
Matera Italy	14.0	1204	1159
Yaragadee Austrl.	1.3	1186	699
Quincy USA	0.9	1179	956
Arequipa Peru	15.0	957	1329
Greenbelt USA	0.7	847	584
Orroral Austrl.	5.0	821	0
Simosata Japan	5.8	796	346
Maui Hawaii	3.0	790	67
Fort Davis USA	5.2	713	0
Mazatlan Mexico	2.0	696	367
Wettzell FRG	6.0	634	104
Grasse France	3.9	424	121
Graz Austria	2.8	423	366

This table summarises the results achieved by the most productive SLR stations. The numbers of passes tracked are at best about one third of those that are possible.

Station coordinates and movements

The international MERIT campaign to monitor Earth rotation was held from September 1983 to October 1984 inclusive. It provided a stimulus for considerable international activity using several observational techniques, and in particular many laser ranging stations have continued to track Lageos intensively, so that there is now an excellent Lageos data set from about 1984 onwards. These data have been analysed at RGO and by other analysis groups to give the coordinates of the laser stations as well as the Earth-rotation parameters. For about fifteen of the most accurate and productive stations (Herstmonceux being one of them) the coordinates have now been determined to an accuracy of about 3 cm in a geocentric frame, and these stations now provide a network of points which can be linked to local geodetic systems by conventional surveying or by making observations of GPS navigation satellites, from which the relative positions of points up to 100 km apart can be obtained to a few cm accuracy. Variations of the distances between stations due to movements of tectonic plates on the Earth's surface are now becoming apparent from laser ranging data. Movements are of the order of 10 cm/yr, and it is still difficult to achieve this accuracy from laser data. The problem is that although many of the laser stations have a range-measurement accuracy of 1–5 cm, the best orbital model of Lageos is at present accurate to only about 10 cm, and this error can affect the station coordinate values. The usual method of overcoming this problem is to use a span of about a year of Lageos data, and then the effects of the orbital model errors average out. An alternative method that can be used for stations within a limited geographical region (for example Europe) is to use arcs of the orbit that have been tracked simultaneously by several stations. Then the errors of the computed orbit along each arc can be determined from the range measurements. If about 15 such corrected arcs are combined then accurate station coordinates can be determined, and this number of simultaneously-tracked arcs can be achieved in about 2 months if the stations are operating intensively.

This technique will be useful for the analysis of the data from the Wegener–Medlas campaign, which has been taking place in Europe from 1986 onwards. Three mobile laser rangers operate at about fourteen sites in the Eastern Mediterranean region, for about two months at each site, while the fixed stations in Europe provide a reference frame. The mobile lasers will visit the same sites again after about 2 years, and the changes in baselines will be used to determine crustal motions.

In order to test this short-arc technique the Lageos data from four of the fixed European stations (shown in Fig. 16) have been analysed in five groups, in each of which there were sufficient arcs to give a good solution. The distances between pairs of stations were determined for each group, and the variations of these distances are plotted in Fig. 17. The scatter of these values is only a few cm, and in some

Fig. 16 The locations of four of the fixed SLR stations in Europe.

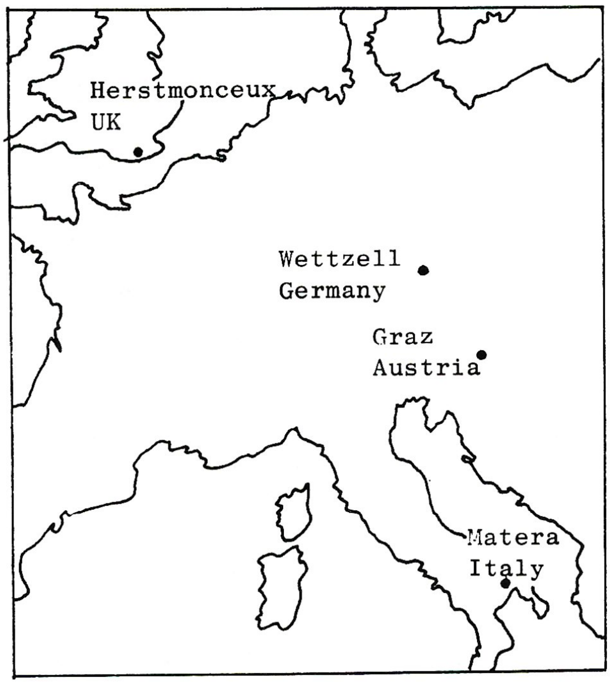
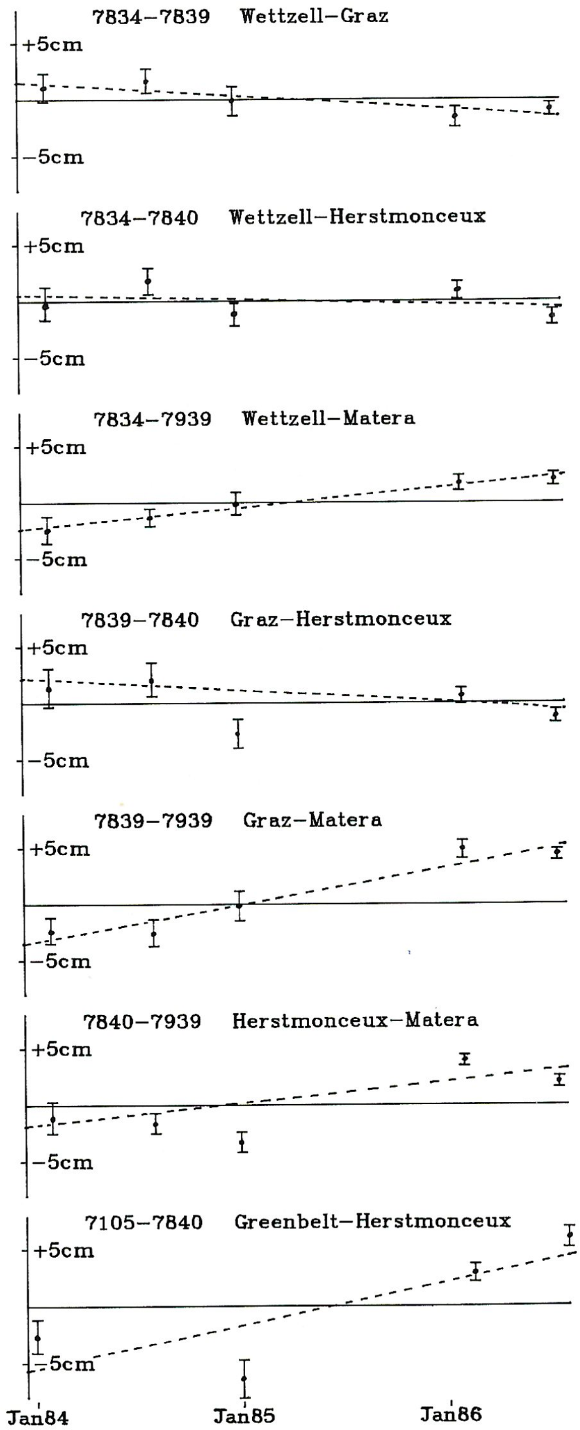


Fig. 17 Variations of determinations of the distances between SLR stations by the short-arc method.



cases they show distinct evidence that the distances between stations are varying. These results imply a motion of Austria towards Germany of 1 cm/yr, and a motion of the south of Italy away from Austria of 3 cm/yr. The same technique has been used on the transatlantic baseline from Herstmonceux to Greenbelt (near Washington DC), and gives evidence for an increase in distance of about 4 cm/yr (the value from the geological record is 2 cm/yr).

Earth-rotation parameters

The rotational orientation of the Earth relative to a celestial frame is affected by precession, nutation, polar motion (a wobble of the axis of rotation around an axis fixed in the Earth) and by its variable rotation rate, which is described by the non-uniform time scale UT1. Polar motion and UT1 can be determined to an accuracy of about 2 milliarcsec and 0.2 millisec respectively by both SLR and VLBI.

Solutions for polar motion and UT1 have been made at RGO from SLR data, and are in close agreement with those of other analysis groups. It has also been demonstrated that it is possible to determine the local components of these quantities using the Lageos data from Herstmonceux alone, with an accuracy that is only about 3 times worse than that of the best solutions. The advantage of the Herstmonceux solution is that it can be made within a few hours of the satellite passes.

A. T. Sinclar
G. M. Appleby
October 1987

M dwarfs, brown dwarfs and missing mass

The most important problem in observational cosmology is undoubtedly the nature, origin and extent of dark matter in the universe. Over the last ten years missing mass – or 'unseen' mass as it should more properly be called – has been postulated as supplying the shortfall between the total visible matter and the mass required from dynamical arguments. While evident on large scales, both from galactic rotation curves and the velocity dispersion of galaxy clusters, the original detection of missing mass was for the region within a few hundred parsecs of the Sun, the solar neighbourhood. Using the motions of K giants at large distances above the plane, Oort derived an estimate of the local mass density of gravitating matter. His value of ~ 0.15 $M_\odot pc^{-3}$ has essentially been confirmed by subsequent analyses. It exceeds by a factor of two the total mass density that we can attribute to main-sequence stars, white dwarfs, gas and dust.

The local missing mass, however, differs in one important respect from the large-scale dark matter; the dynamical arguments require that it be distributed in a disc. This obviously implies dissipation during formation and hence baryonic matter. This reduces the options to low-mass stars, cool white dwarfs, black holes or comets. Massive black holes ($\sim 10^6 M_\odot$), from pregalactic or population III massive stars, can be ruled out by the observed presence of wide, unperturbed binaries high above the plane; lower mass black holes wreak havoc with the X-ray background; surveys have failed to find any very low luminosity ($M_{bol} >$ $+16$) white dwarfs, which may mean we do not yet know how to identify them; and comets remain inscrutable. Recently, however, attention has centred on the lowest mass main-sequence stars (M dwarfs with masses of $\sim 0.1 M_\odot$ and the even lower mass brown dwarfs (objects too small to ignite hydrogen in the core during the contraction along the Hayashi tracks) as the solution to this problem.

Observationally, brown dwarfs and M dwarfs can be expected to look very similar. Both have luminosities less than one thousandth that of the Sun and hence mass-to-light ratios of more than 100, as well as temperatures of less than 3000 K. Thus surveys aiming to determine the luminosity function – the number per unit absolute magnitude per unit volume – generally start by looking for faint, red objects. There is, however, a crucial difference in interpreting results from these surveys. M dwarfs are hydrogen burning, and therefore have visible lifetimes of more than 10 Gyr, longer than the Hubble time (regardless of H_0), in fact. Therefore what you see is what there is. Brown dwarfs, on the other hand, are visible for only a few hundred million years. Thus each brown dwarf found represents a veritable host of older, fainter compatriots, and a correspondingly higher mass density.

Measuring machines and multicolour UK Schmidt plates have considerably simplified the logistics of M dwarf surveys through the use of deep I-band (effective wavelength 8000Å) plates. Until 1980, most studies of the stellar luminosity function used blue light, either through (B–V) colours or objective-prism spectra. This region of the spectrum effectively saturates for stars cooler than ~3500K at (B –V) ~1.6. This is not the case at longer wavelength, and both (V–I) and (R–I) remain good effective temperature indicators for even the coolest known stars. A variation in effective temperature is interpreted as a change in luminosity, and stellar luminosities are derived from the calibration of absolute magnitude – either in a specific passband or bolometric – against colour (the H–R diagram) given by nearby stars with measured trigonometric parallaxes.

Reid and Gilmore originally applied this technique using photographic V and I photometry from the COSMOS measuring machine at ROE. Their results showed a peak in the luminosity function at $M_v = +13$ ($M_{bol} \sim +10$), confirming previous studies, followed by a steep drop in number density. There were, however, very few stars in their sample fainter than $M_v = +15$. Since then Hawkins (ROE) has repeated these surveys, but using R and I plates and extending the data to fainter (apparent) magnitudes. Although (R–I) has a shorter baseline than (V–I), and is therefore less sensitive to temperature (i.e. luminosity) variations, the stars are brighter in R and the plates are deeper, allowing the survey to cover a larger volume. As a result, the Hawkins survey has substantially more faint stars, and these data suggest that the luminosity function has a local minimum at $M_v \sim +15$ followed by a subsequent rise in number density at fainter magnitudes. This hypothesis is, by and large, supported if we combine all available surveys to form a bolometric luminosity function (Fig. 18).

In themselves these extra stars are woefully insufficient to provide the local missing mass; they add a mere 0.002 of the required $0.07\ M_\odot\ pc^{-3}$. However, an increasing luminosity function implies even more stars at fainter magnitudes. Moreover, Hawkins has suggested that the dip at $M_{bol} \sim$ $+12$ marks the transition between M dwarfs and brown dwarfs. If so, this demands two modifications in the analysis. Firstly, brown dwarfs are cooler than M dwarfs at a given luminosity (or more luminous for a given temperature), requiring that we translate the faint end of the luminosity function to higher luminosities, partially obscuring the dip. Secondly, because of the shorter lifetimes, we should increase the number densities by somewhere between a factor of 10 and 100. Clearly this would have an impact on the local mass density – in fact, we end up with a positive embarade de richesse – so it becomes necessary to demand how to differentiate brown dwarfs from M dwarfs.

One method of tackling this question is by locating the individual stars on the H–R diagram; as we already noted, brown dwarfs lie at higher luminosities for a given temperature. However, this is easier to state than to achieve. Firstly we require a distance, which limits the method to

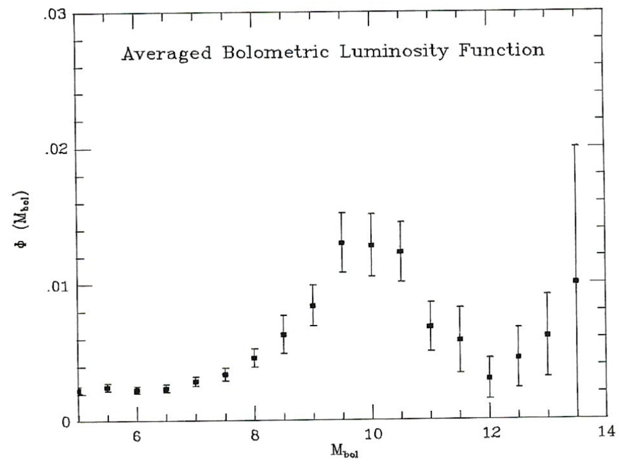


Fig. 18 The bolometric luminosity function.

stars with known trigonometric parallaxes; secondly, we require a temperature. Molecular bands dominate the atmospheres of these cool stars – notably TiO in the visual and H_2O in the infrared. Thus modelling the atmospheric structure of these stars is extremely difficult. Moreover, the steam bands are coincident with the water vapour absorption in our own atmosphere, which complicates the observations. However, the longer wavelength data are crucial, since most of the flux is emitted in these regions. In a 3000K star, about 30% of the total flux comes from wavelengths beyond 3 microns while only 1% originates in the overstudied blue region (wavelengths < 5000Å)

In order to obtain observations of any accuracy, it is essential to minimise the terrestrial water vapour – i.e. observe from a dry site – and Mauna Kea, at 14000 feet, is the driest there is. Working at this altitude, above a large proportion of the water in our atmosphere, we can map the spectral energy distribution through all but the most opaque water bands. However, as infrared detectors are as yet mainly limited to single-channel devices, only the brightest stars can be observed.

Fortunately, despite all the qualifications, there are parallax stars which have intrinsic luminosities below $M_{bol} = +12$ but are still bright enough to observe – notably the two stars van Biesbroeck 8 ($M_{bol} = +12.6$) and VB 10 ($M_{bol} = +12.9$). Reid and Gilmore originally obtained infrared spectra from 1.2 to 2.2 microns using UKIRT. Berriman and Reid have refined these observations, obtaining additional 3 to 10 micron data for a small sample of low luminosity stars. Fig. 19, which shows the results for VB 8, dramatically illustrates the problems of doing without the spectra. Since the infrared JHKL passbands have been chosen to avoid the terrestrial water vapour, they also lie neatly on the peaks of the stellar flux distribution. Thus any attempt to estimate the total flux by blackbody fitting or flux summation overestimate the total flux by ~ 1–3% and the temperature by ~2–7%.

In the absence of an accurate grid of model atmospheres one resorts to blackbody fitting, anchoring the flux at 2.2 microns where there is little backwarming or line blanketing, and equalizing the area under the curve with the observed total flux. The strength of the H_2O absorption is primarily dependent on temperature, although there is some variation with metallicity. For disc stars ([Fe/H]) > ~ −0.5),

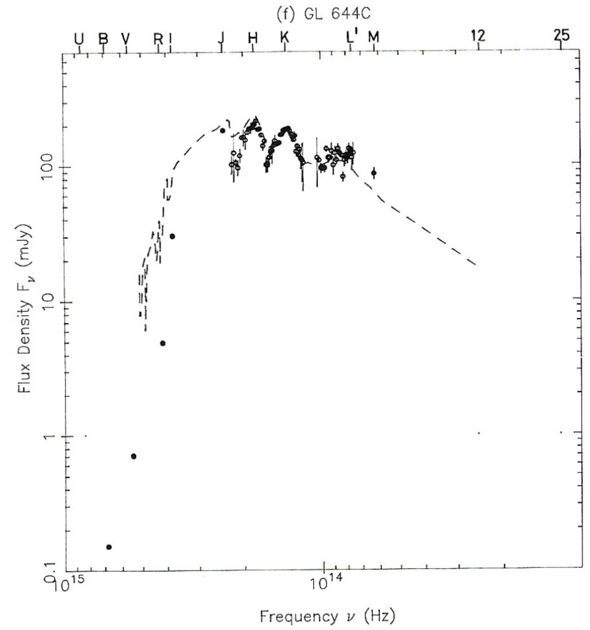


Fig. 19 The infrared spectrum of VB8 (Gliese 644C).

however, once the H_0 band-strength to temperature relation has been calibrated, broadband photometry, provided it extends to JHK, is sufficient to define a moderately accurate temperature.

Fig. 20 presents the resulting H–R diagram, including stars observed by Berriman and Reid, several other very low luminosity stars and hotter stars calibrated by Mould and Hyland and by Perrin et al. Also shown are the most recent theoretical main sequences and brown dwarf evolutionary models calculated by D'Antona and Mazzitelli, as well as old calculations by Grossman, Hayes and Graboske. Two things are immediately clear. Firstly, there is a striking discordancy between the newer tracks and the observed main sequence; secondly, there is no obvious discontinuity moving down the main sequence, as might be expected if the stars with luminosities below $M_{bol} \sim +12$ (log L/L⊙ ~ −3) were non-H-burning brown dwarfs. On the contrary, even the lowest luminosity stars, such as LHS 2924, lie on a smooth continuation of the higher mass main sequence. At the very least, this restricts brown dwarfs (amongst this group) to masses of > 0.07 M⊙.(The theoretical limit for H-burning is ~ 0.08 M.).

There are two other tests which can be applied to the hypothesis that low luminosity M-dwarfs are in truth brown dwarfs: the prevalence of H-alpha emission and stellar kinematics. The former is generally held to be produced by chromospheric activity, which decays with time. Thus brown dwarfs might be expected to have prominent Balmer line emission. However, Giampapa and Liebert (Steward) have studied a moderately large sample of these low luminosity stars and find that 50% of the stars fainter than $M_v = +17$ have no detectable emission. Similarly, only a relatively small fraction of the stars in their sample have the low space velocities associated with young stellar objects.

It is entirely possible that one or more of these low luminosity stars with H-alpha emission and a low space motion could be a brown dwarf. Yet these results show that old (several Gyr) and (presumably) H-burning stars persist to luminosities of $M_{bol} \sim +13$. Thus there is no simple switch from long-lived M-dwarfs to ephemeral degenerates at this point in the H–R diagram. In all likelihood then, the

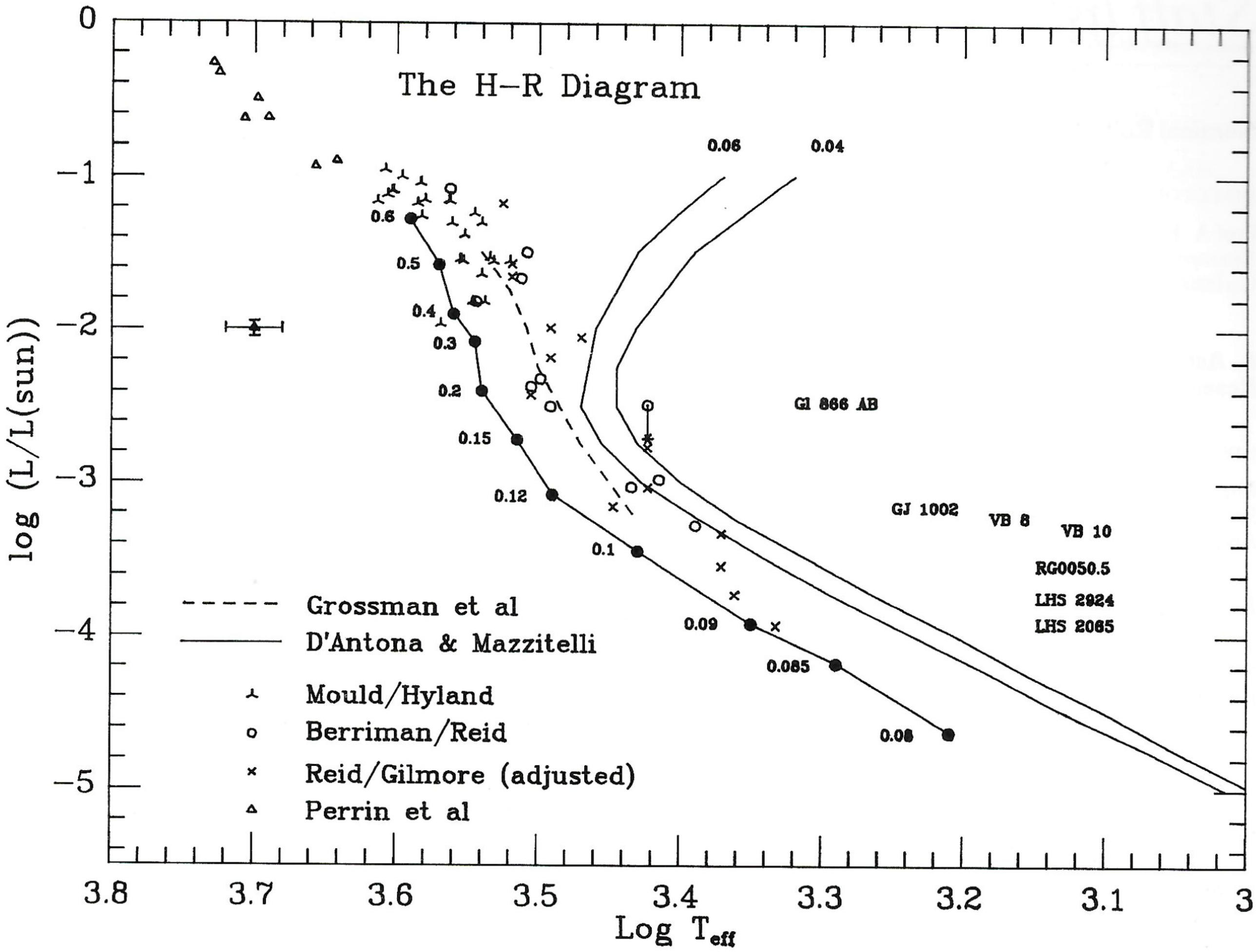


Fig. 20 In this H–R diagram, observations are compared with theoretical models of hydrogen burning stars and brown dwarf models as explained in the text.

dip at $M_{bol} \sim +12$ in the luminosity function is nothing more than that – a dip in the stellar luminosity function, comparable to the well known point of inflexion at $M_{bol} \sim +6$.

However there are still some interesting consequences of the changed luminosity function shown in Fig. 18. To convert this to a mass function it is necessary to use a mass–luminosity relation. While this is relatively well-determined for high mass stars, the faint end is exceedingly imprecise. Extrapolating a power-law fit implies that the limiting mass for hydrogen burning (HBLL) occurs at $M_{bol} \sim +11$. We have already rehearsed the arguments against this limit. Thus it comes as something of a relief that the latest theoretical models suggest that the mass–luminosity steepens sharply at $M \sim 0.1\ M_\odot$, with the HBLL at log $L/L_\odot \sim -4.5$. This means that a change of 1 magnitude in M_{bol} corresponds to a very small change in mass. Transforming the luminosity function in Fig. 18 to a mass function produces Fig. 21.

The net result from these studies is that we still have no unequivocal candidate for the local missing mass. However, if the luminosity function in Fig. 18 and, more important, the theoretical mass–luminosity relation are borne out by future studies, we do have evidence that the stellar mass function is increasing rapidly as we approach the HBLL. If this increase continues beyond the minimum mass for hydrogen burning – and there is no reason to suspect that fragmentation (or aggregation) mechanisms know anything about stellar structure – then these lower mass fragments

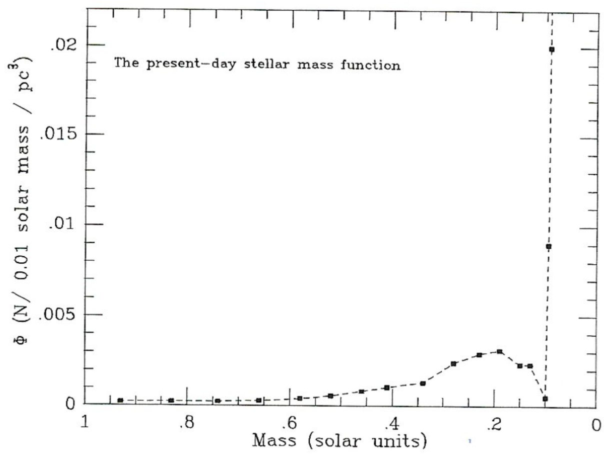


Fig. 21 The present-day stellar mass function for masses less than that of the Sun.

could still provide enough dark matter to supply the local mass defect.

We are still at the stage where the stellar luminosity function cannot be regarded as well-defined at extreme low luminosities. Few very low luminosity stars are known. It is important that such new stars as are found, whether from proper motion (Bessell (MSSO) and Probst (KPNO)) or photometric (Hawkins) surveys, are observed over sufficient wavelength range to obtain accurate temperatures and are also attached to astrometric parallax lists for distance determination. Eventually, one might even prove to be the long-sought brown dwarf.

Neill Reid
October 1986

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Abbreviations

H Split function
N Non-complement
P Part-time
S Secondment

Publications

Publications by H M Nautical Almanac Office

The preparation and publication of almanacs, ephemerides and tables for positional astronomy and navigation are carried out in close collaboration with the Nautical Almanac Office of the US Naval Observatory. The following volumes were published by Her Majesty's Stationery Office, jointly with the US Government Printing Office.

The Astronomical Almanac for 1987 and for 1988.
The Nautical Almanac for 1987 and for 1988.
The Air Almanac for 1986 July–December and for 1987.
The Star Almanac for Land Surveyors for 1987 and for 1988.
Astronomical Phenomena for 1987, for 1988 and for 1989.
Sight Reduction Tables for Air Navigation, Volume 1, Selected Stars Epoch 1990.0.

The following *NAO Technical Notes* were published.

57 Ground illumination. B.D. Yallop, 1986.
63 The computation of angular atmospheric refraction at large zenith angles. C.Y. Hohenkerk and A.T. Sinclair, 1985.
64 Algorithms for calculating the dates of Easter. B.D. Yallop, 1986.
65 Determination of polynomial coefficients from B-spline coefficients. C.Y. Hohenkerk, 1986.
66 TOPPS: a system for printing tables. C.Y. Hohenkerk, 1987.

The following *RGO Astronomical Information Sheets* were prepared and issued.

48 Closest approach of Polaris to the North Celestial Pole in AD 2100. B.D. Yallop and C.Y. Hohenkerk, 1985.
49 Astronomical and calendarial data sheet for 1991. G.A. Gibbs and A.F. Strong, 1986.
50 Earliest sighting of the New Moon in 1987. B.D. Yallop, 1987.
51 Astronomical and calendarial data sheet for 1992. A.F. Strong and C.Y. Hohenkerk, 1987.
52 First sighting of New Moon in 1988. B.D. Yallop, 1987.

Time and SLR Publications

Royal Greenwich Observatory Time Service Circulars Series A Nos. 1913 to 2016 and *Series B* Nos. 33 to 51 were published. *Series B* was terminated at No. 51.

Royal Greenwich Observatory Time Service Notices Nos. N8 to N11 and Nos. D18 to D26 were also published.

The following *SLR Technical Notes* were issued.

6 Short-period variations in UT1. J.Y. Xia, 1985.
7 The radial velocity of orbits determined from SLR data. A.T. Sinclair, 1985.
8 The determination of Earth rotation parameters from laser ranging to LAGEOS. J.Y. Xia and A.T. Sinclair, 1986.
9 SATAN-programs for the determination and analysis of satellite orbits from SLR data. A.T. Sinclair and G.M. Appleby, 1986.

CAMC Joint Publications

The following articles relating to the Carlsberg Automatic Meridian Circle on La Palma were issued as joint publications of Copenhagen University Observatory, the Royal Greenwich Observatory and the Instituto y Observatorio de Marina (San Fernando).

Carlsberg Meridian Catalogue No. 1. Observations of positions of stars and planets made in the year 1984.
Carlsberg Meridian Catalogue No. 2. Observations of positions of stars and planets made in the year 1985.
Carlsberg Automatic Meridian Circle La Palma Meteorological data for 1984.
Carlsberg Automatic Meridian Circle La Palma Meteorological data for 1985 January–June.
Carlsberg Automatic Meridian Circle La Palma Meteorological data for 1985 July–December.
Carlsberg Automatic Meridian Circle La Palma Meteorological data for 1986 January–June.
Carlsberg Automatic Meridian Circle La Palma Meteorological data for 1986 July-December.

La Palma Notes, Reports and Manuals

Other series of publications produced by RGO relate to the telescopes and instrumentation of the Isaac Newton Group of Telescopes on La Palma. *RGO/La Palma Technical Notes* and *La Palma Manuals* are produced for the benefit of all members of the astronomical community who use these telescopes. Individual copies may be obtained from Mrs Beryl Andrews of the La Palma Users Unit at Herstmonceux. The Electronics Department in the Facilities Division produce *Electronics Notes* and *Electronics Reports*; these describe the electronic hardware and software of the equipment it designs and builds. Although mainly for internal RGO use, these are circulated more widely.

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