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THE AUSTRALIAN NATIONAL UNIVERSITY'S 2.3m NEW GENERATION TELESCOPE AT SIDING SPRING OBSERVATORY

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Abstract: The story of the birth and construction of the 2.3m Telescope at Siding Spring Observatory is told. Details of the intricate control system of the telescope, building and instrumentation are described. The Telescope encompassed all the features of the New Generation Telescopes of the late 1970s: a thin primary mirror, an alt-azimuth mount and a rotating building. It has operated continuously for 28 years, used by Australian and international astronomers. It has a prodigious science output helped by state of the art instrumentation developed by engineers and astronomers at Mt Stromlo and Siding Spring Observatories.

Keywords: 2.3m Telescope, New Generation Telescopes, Australian National University, Siding Spring Observatory

1 INTRODUCTION

This is the story of a small team of engineers and technicians who rose to the challenge to build a New Generation Telescope at Siding Spring Observatory, (SSO), to fulfil the urgent need of the astronomers of Australia.

It is also the story of the visionary foresight of the members of the Chancellery[1] at The Australian National University who saw the enormous hurdles that Mt Stromlo and Siding Spring Observatories (MSSSO) faced but put their faith in the capabilities of the staff. They also realised the great technical, scientific and financial advantages of the proposed design and recognised the dire need of the Australian astronomers. The Chancellery could never formally fund the project because of the financial climate but it stood by the Observatories until the job was done.

Here is the story as told by Don Mathewson (Acting Director of MSSSO, 1977-1979, Director of MSSSO, 1979-1986), John Hart (Opto-Mechanical Engineer, Head of Opto-Mechanical Department), Hermann Wehner (Opto-Mechanical Engineer); Gary Hovey (Control Systems – Engineer) and Jan van Harmelen (Electronics Engineer, Head of Electronics). Figure 1 and Figure 2 show the four engineers who built the 2.3m Telescope.

2 THE CONCEPTION AND BIRTH OF THE 2.3m TELESCOPE

2.1 1977

By 1977 the need for a new Australian optical telescope had become urgent. The telescopes at Siding Spring Observatory were heavily oversubscribed, e.g. the Anglo-Australian Telescope was five times oversubscribed.

From 1970, funding for a conventional 60-in telescope from Boller and Chivens had been requested annually by Olin Eggen (who was Director of MSSSO from 1966 to 1977), but without success.

In June, Eggen asked Mathewson to take over the carriage of the project, which brought him into contact with Ian Ross, the newly-appointed Deputy Vice-Chancellor of The Australian National University. Mathewson made Ross aware of the urgent need of Australian astronomers for a new telescope.

In October Mathewson became Acting Director of MSSSO. It was the start of a new era of optical telescopes. Vince Reddish, Director of the UK Schmidt Telescope at Siding Spring Observatory was extolling to Mathewson the virtues of the UK Science Research Council's 3.8m thin mirror telescope on Mauna Kea. The light weight of the mirror meant that the whole telescope structure could be made much lighter, with considerable savings in construction of the telescope and mount.

The Multi-Mirror Telescope at Mt Hopkins in the USA had just been built and it had an alt-azimuth mount which was proving very successful (see Beckers et al., 1981). Alt-azimuth mounts provide a simple solution to problems associated with horse-shoe or fork flexures of a conventional equatorial mount and the changing loading on the declination bearings as the polar axis rotates. For alt-azimuth mounts the vertical loading is constant and symmetrical. Azimuth rotation causes no load changes, and tube flexure is in one plane. It allows massive instrumentation to be mounted at the two Nasmyth foci on a platform almost level with the elevation axis. Interchange of instruments at the two foci can be easily achieved by flipping a plane mirror. The instruments are easily accessible.

Figure 1 (above): (left to right), John Hart, Hermann Wehner, and Gary Hovey examining a model of the 2.3m Telescope (courtesy: Bob Cooper).
Figure 2 (right): Jan van Harmelen, Electronics Engineer.

A third development is a spin-off from using an alt-azimuth mount. If the building rotates in azimuth with the telescope its size over a conventional dome can be dramatically reduced. Also the building space can be used very effectively because of the rectangular cross-section. It is much easier to control the much smaller volume of air which now surrounds the telescope, and this leads to better seeing. The Multi-Mirror Telescope had a rotating building which clearly demonstrated these advantages.

2.2 1978

On 16 January 1978 Mathewson wrote to Reddish suggesting the UK Science Research Council and the Australian National University collaborate to build a 2.5m thin mirror telescope with an alt-azimuth mount and a rotating building at Siding Spring Observatory. However, Reddish did not think the Council could fund the project at that time.

On 20 January, a Working Party on New Generation Telescopes organised and chaired by Mathewson, was held at Mt Stromlo Observatory. Among the participants were Don Morton from the Anglo-Australian Observatory; John Bolton, Director of the CSIRO's Parkes Radio Telescope; and John Hart and Hermann Wehner from MSSSO. The meeting approved a 3m thin mirror, alt-azimuth mounted telescope with a rotating building to be built at Siding Spring Observatory and to be funded by all Australian universities. It was named the 'Universities Telescope'. Figure 3 shows Don Mathewson posing with a model of the Universities Telescope.

Figure 3: Don Mathewson with a model of the Universities Telescope (courtesy: Keith Smith).

On 10 February Donald Low, Vice-Chancellor of the Australian National University informed the Australian Science and Technology Council that it was withdrawing its 60-in telescope proposal in favour of the Universities Telescope. On 3 May Ian Ross, the Deputy Vice-Chancellor of the Australian National University, chaired a Universities Telescope meeting held at Mt Stromlo Observatory. All Australian universities were represented, and there was full support this proposed national facility. On 11 October, Mathewson wrote a formal proposal for the Universities Telescope, the cost of which was estimated at $3 million. The Universities Commission, the relevant funding body, was notified by the Australian Vice-Chancellor's Committee. This produced great interest around the astronomical world, and reports appeared in many international newspapers.

Figure 4: Norman Cole's Optical Shop. Norman is on the right. The blank being machined is that of the 2.3m primary mirror for the Wyoming Telescope (courtesy: R. Gehrz).

2.3 1979

During April-May in 1979 John Hart, Hermann Wehner and Ben Gascoigne visited Kitt Peak National Observatory in the USA and other centres to study recent developments in telescope design and construction, particularly the Multi-Mirror Telescope. In Tucson they also met Norman Cole, an optician who apart from earlier carrying out optical work at Kitt Peak National Observatory had recently made a 90-in thin and fast primary mirror for the University of Wyoming's telescope on Mt Jelm (Figure 4). This telescope had an equatorial mount and a conventional dome. The CerVit blank of their mirror had been purchased from Owens-Illinois of Toledo, Ohio.

Unfortunately on 11 May 1979 the Universities Telescope Project collapsed, as no funds were available from any source. As a last resort, Don Mathewson phoned Henry Cossitt of Owens-Illinois who located their last CerVit blank, 97 inches in diameter and 21 inches thick, under a tarpaulin in the backyard. CerVit was a revolutionary low expansion glass-ceramic that had been successfully used for telescope mirrors, including the Anglo-Australian Telescope. Unfortunately Owens-Illinois had stopped production because of environmental concerns. A few days later, John Hart, Larry Barr (from Kitt Peak National Observatory) and Norman Cole inspected the CerVit blank, which was too opaque for stress tests and was badly chipped. However on 17 May, Hart sent a report that the blank was satisfactory for slicing in two: from one blank, two mirrors 90 inches in diameter and 9 inches thick could be produced.

Mathewson put a formal proposal to the Australian National University that MSSSO should build a 90-in thin mirror alt-azimuth mounted tele-scope in a rotating building at Siding Spring Observatory for a cost of $1 million. On 21 May the University gave approval for the blank to be purchased on condition that it did not break in slicing and that they could sell it back to Owens-Illinois if the project collapsed. On 23 May, John Coleman, Bursar of the University, sent the order two hours before our option expired.

The blank was satisfactorily sliced into two by a surprisingly primitive process, witnessed by Hart, Barr and Cole. The mirror blank was mounted on a cart towed by a tractor in a yard at the back of the glassworks. A large and continuous loop of wire was driven around a series of wheels, with the mirror blank pulled against the wire to provide tension. A slurry of grinding grit was squirted onto the wire where it entered the advancing cut in the blank. Every now and then the tractor driver would start the tractor and nudge it forward to re-establish tension in the wire as the cut advanced. The overhanging upper slice of the blank was supported on the bed of grit accumulating behind the wire, protecting the blank from cantilever stress.

Norman Cole had made the 90-in thin mirror for the Wyoming telescope; L & F Industries had made the mirror housing and Boller and Chivens, the support system. Fortuitously our blank was just the right size to duplicate this mirror system. Hart successfully negotiated with the three parties to do this at a very attractive price.

In effect, this ‘off the shelf’ primary mirror cell purchase became the start of the project. We then designed and built our telescope around it, incorporating many new features to suit our needs and budget.

No funds were available for the project from the University Council, the funding body for such large projects to Universities. They also rejected Donald Low’s request that the ANU’s Large Equipment Grants would be assured for the next four years. The Chancellery told Mathewson that the project could never formally be funded but they would do their best to keep funds running but the project could be stopped at any time. At this point Mathewson sold the remaining blank to Robert Kirschner of McGraw-Hill Observatory, University of Michigan, at a profit—this helped considerably.

On 9 November Mathewson told the Chancellery that the cost had increased to $1.4 million. This increased to $3.2 million by the end of the project in 1984. Miraculously, the Chancellery, at all stages, managed to supply the funds.[2]

In June, the Design Study Group was set up. The group was Don Mathewson (chair), John Hart, Hermann Wehner, Gary Hovey, Jan van Harmelen, Ted Stapinski, Mark Downing, Alex Rodgers and Norman Stokes. Hilton Lewis joined the group later and Ted Stapinski left to become Engineer in charge of the Starlab Project. Detailed design of the telescope commenced.

3 SITE TESTING AND SELECTION

Van Harmelen started the site testing program using micro-thermal data obtained from sensors on three towers erected at SSO. Summer lightning activity and birds damaged the sensors and the data was unreliable.

David Griersmith who had recently completed his Ph.D. at MSSSO, made seeing observations at Siding Spring Observatory with two 8-inch Tinsley Telescopes used in site testing for the Anglo-Australian Telescope. He found no difference in seeing across the mountain. Vince Ford and Joanne Fisher compared images of stars taken with the Anglo-Australian Telescope, the UK Schmidt and the 40-in Boller and Chivens telescope and also found no difference in seeing between the three sites.

The area between the 40-in and 24-in Boller and Chivens telescopes and slightly below them was known amongst astronomers to be a low wind site. Vince Ford and Don Mathewson made wind flow measurements at this site. They tied smoke canisters to 4m-long poles and observed the smoke patterns whilst carefully avoiding the blobs of molten lead that cascaded around their heads! They put a dob of paint on the area with the smoothest flow. Later, core drilling found solid rock under this location. This site was selected for the 2.3m Telescope because it was also close to electricity and water supplies and was easily accessible from the road.

4 THE OPTICS

The chosen alti-azimuth mounting allows the use of Cassegrain and Nasmyth optical arrangements, both using the same primary mirror, but, of course, separate secondary mirrors. The latter are mounted in interchangeable telescope tube front ends. The use of the alt-azimuth arrangement results, however, in the rotation of the field in the focal plane—essentially, a third axis. To counteract this rotation, instrument rotators have to be fitted at each focal station.

The detailed optical design for the telescope was carried out at Mt Stromlo Observatory, with Ben Gascoigne as consultant. The choice was for conventional Cassegrain optics, i.e. a paraboloidal primary mirror combined with a hyperbolodial secondary mirror, with separate, matched secondaries for either focus. The Cassegrain optical arrangement has its focus just behind the primary mirror cell, with instruments attached to the instrument rotator on the mirror cell. In the Nasmyth optical arrangement the light, reflected by the secondary mirror, is further reflected by a flat mirror at the intersection of the azimuth and altitude axes, along the hollow altitude axis to a focus outside the telescope mounting. Hence rotation of this flat mirror creates two focal positions, where instruments can be mounted to the respective rotators.

As mentioned elsewhere, the material chosen for the blank of the primary mirror was CerVit, a vitreous ceramic manufactured by Owens-Illinois of Toledo, Ohio. The advantage of CerVit is its low coefficient of thermal expansion, of the order of $0 \pm 1 \times 10^{-7}$/ºC, which assures an almost unchanged optical figure within the range of normal telescope operation.

The size of the purchased blank permitted a finished mirror diameter of 2,337mm and an edge thickness of 220mm. The focal ratio of the primary is f/2.05. The achieved diameter to thickness ratio is 13:1 (equivalent flat plate), a substantial departure from the previously accepted ratio of about 6:1. The mass of the mirror is close to 2,000kg. The diameters of the secondary mirrors are 280mm (Cassegrain) and 355mm

(Nasmyth). Both optical systems have a focal ratio of f/18.

The contract for the optical work was let to Norman Cole of Tucson (Arizona) in mid-1979, who previously had converted his spacious garage into an optical laboratory. There he carried out all grinding and the initial polishing of the primary mirror. For final polishing and figuring to the required tolerances the primary mirror was transferred to the Optical Sciences Center of the University of Arizona in Tucson, where a vertical test facility (tower) was available. Here the mirror was supported at all times on a support system very similar to that designed for final use in the primary mirror cell of our telescope, i.e. an air-pressurised bladder supported the mirror such that only a very small, but constant contact pressure remained on the three mirror support points .

Tests of the optical adequacy of the mirror surface were carried out with the assistance of Optical Sciences Center staff, who produced computer-generated contour maps of the mirror surface after each polishing run to identify areas requiring further figuring work. Artificial double star tests were carried out to determine the mirror's resolving power. Wehner was present during some tests, but particularly the final ones. His presence assured that detailed findings from the test results could be implemented immediately and without time-consuming exchange of information over long distances. On 13 February 1983 Wehner recommended acceptance of the mirror to Mathewson. The primary mirror subsequently arrived at Siding Spring on 7 April 1983. During the final stages of polishing, Hermann Wehner, Norman Cole and the Optical Sciences Center formed a brilliant team of experts who complemented each other and produced an exceedingly high-quality mirror.

Both secondary mirrors were also produced by Norman Cole. After they arrived in Australia in early 1984 further acceptance tests were carried out by William James of Melbourne. The secondary mirrors are mounted in interchangeable telescope tube front ends. The Nasmyth flat which was made by Gabe Bloxham (of Mt Stromlo Observatory) can be removed from the tube centre for light to pass to the Cassegrain focus.

Since the Cassegrain optical arrangement was to be dedicated to infrared work, the secondary mirror was fitted to a 'chopping' mounting, with adjustable chopping frequency, amplitude and rotational position. This mounting was produced by the Physics Section of the RAAF Academy in Victoria. It was designed such that the telescope imaged only a minimum of 'locally'-produced infrared radiation, apart from the signal received by the telescope. Access to the Cassegrain focus for installation of instruments and access for observers, is via a hydraulically-operated platform, permanently located close to the telescope mounting.

At the time of the installation of the 2.3m Telescope the only facility for the aluminizing of mirrors available for the Australian National University telescopes was a 1.3m plant in the 24-in telescope building annex. After negotiations, we arranged to use the 4m aluminizing plant of the Anglo-Australian Telescope. Fortuitously, this plant had been fitted with a tank insert for a planned 2.4m Coudé mirror, but since it was no longer required the tank was modified for our primary mirror.

5 THE TELESCOPE STRUCTURE

5.1 The Scheme

For reasons of both economy and performance, it was decided at the outset of the project that the telescope would have an alt-azimuth configuration carrying a thin and fast primary mirror. This would facilitate a simple, compact and rigid structure as required for the highest possible pointing performance. Importantly, it would also allow the use of a compact rotating building that conformed closely to the telescope. Relative to this building, the only telescope motion would be nodding in altitude. In effect, the telescope can be contained within a slot in the building, with support facilities being thermally isolated in the surrounding space. Open areas on each side of the telescope would be used to accommodate two Nasmyth instruments, with rapid interchange achieved by flipping a flat tertiary mirror.

A Cassegrain focal station dedicated to infrared instruments would also be included by providing 1m of clearance between the base of the primary mirror cell and the throat of the telescope fork. The Cassegrain instrument would be deployed by removing the tertiary mirror and swapping the secondary mirror top end structure. The Cassegrain configuration would minimize thermal emission by having an unobstructed secondary mirror form the entrance pupil and having as little as possible structure within the beam. The support struts for the secondary mirror would be hidden behind glancing-incidence reflective masks to effectively replace structure with relatively darker sky background.

The upper level of the building would be used to accommodate the unused top end and the travelling crane used for the interchange. The crane would also be used to handle other instruments and equipment, as well as the primary mirror when re-aluminizing was needed.

The price paid for the alt-azimuth configurtion is that of field rotation. This would be dealt with by having identical instrument rotators at each of the three focal stations.

5.2 Mirror Support

The primary mirror has a mechanical diameter of 2,337mm and a vertex thickness of 160mm. This thickness is less than half the value that would be used for a traditional design. The difficulty in using a thin mirror is to prevent it from flexing significantly under its own weight. To isolate our mirror from bending stress, axial support is provided by an air bag and radial support by a mercury belt. The air bag supports almost all the axial component of mirror weight regardless of altitude angle. A small vane pump continually feeds air to the bag. The air then leaves the bag through a passive pressure regulator so that the pressure in the system is proportional to the sine of the altitude angle. Within the regulator, a weighted diaphragm simply blocks the open end of the exhaust tube to give very accurate pressure control. A hole in the centre of the bag is made larger than that in the mirror, so compensating for the radially-varying mirror thickness and load. The mirror position is accurately controlled by three defining points behind the mirror that carry a small proportion of the mirror weight.

The mercury belt used for radial support takes the form of a fabric-reinforced rubber tube, much like a bicycle tube, located in a 10mm radial gap between the mirror and the housing. So contained, it has a contact width of 37mm, and is almost filled with mercury. The ratio between the contact width of the belt and the average thickness of the mirror is arranged to be slightly greater than the ratio between the density of the mirror and that of mercury so that the mirror floats in the mercury. Neutral buoyancy is achieved by adjusting the amount of mercury in the belt so that there is no radial movement as altitude angle is changed.

5.3 Rolling Element Azimuth Bearing

An early consideration faced by the design team was the possibility of using a rolling element slew-ring bearing for the azimuth axis in place of the more conventional hydrostatic bearing. Such a passive system has the potential to be simpler, cheaper and maintenance-free, but friction torque must be very low in both its average value and its fluctuation to avoid compromise in pointing and tracking performance.

Our studies concluded that a conventional cylindrical roller slew-ring bearing would not be acceptable because of scuffing friction. An innovative means of substantially reducing friction, however, was to use an axial ball bearing. Such bearings use shallow raceway grooves in the opposing bearing faces to guide the balls. Usually, the radius of the groove profile is only slightly larger than that of the balls in order to increase contact area and load capacity, but this also increases scuffing friction to levels that would be unacceptable to us.

We were proposing to use a bearing with a pitch circle diameter of 1,400mm in order to have adequate stiffness and stability. The expected telescope load of 30 tonnes was very low for a bearing of this size, and this offered the possibility of substantially reducing friction torque by increasing the ratio between groove profile radius and ball radius (conformity factor). This approach was reinforced by the knowledge that bearings fail by fatigue, and our lifetime requirement was low when measured in terms of rotational travel.

Designing for a lifetime equivalent of 100 years, we concluded that very favourable performance could be achieved. An adverse consequence of increasing conformity factor was that lateral stiffness would be reduced considerably, but we planned to avoid this problem by adding a ring of cylindrical rollers arranged for radial support. This addition was normal in conventional slew-ring bearings anyway, and caused very little increase in friction.

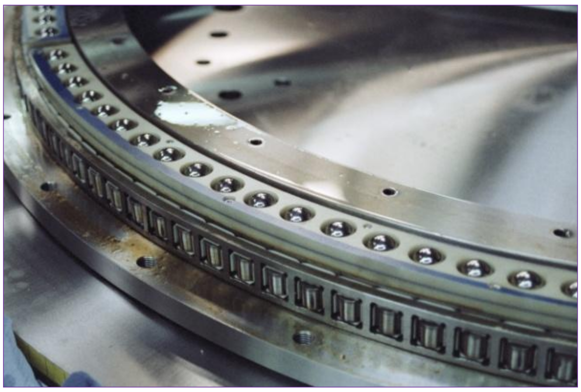


Figure 5: The modified azimuth bearing in the laboratory at Rothe Erde. The upper ring has been removed to show the ball race that provides axial support and the roller race that provides radial constraint.

We approached several slew-ring bearing manufacturers with this proposed design, but were unable to persuade any that this was the best solution. Our preferred supplier, German company Rothe Erde, was, however, prepared to design and manufacture a conventional cylindrical roller slew-ring that they were confident would meet our demanding torque requirement, and we proceeded with purchase.

Manufacture of this high-precision bearing was completed in June 1982, but testing showed that it fell well short of the required performance. After some discussion, Rothe Erde agreed to modify the new bearing by grinding raceway grooves into the flat thrust faces and fitting balls in place of rollers. The conformity factor was calculated to deliver the previously specified lifetime of 100 years.

Figure 6: A craftsman in the workshop of John Grout hand-scraping the azimuth-bearing flange of the telescope fork.

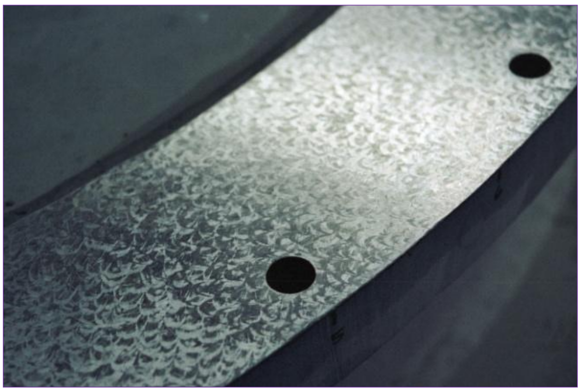


Figure 7: The finished azimuth-bearing flange of the fork, showing the characteristic pattern of hand-scraping. The surface is flat to 5 μm RMS.

The duly modified bearing was completed and re-tested in November 1982, and easily satisfied the torque requirements. Under the specified load of 30 tonnes, the required maximum torque at low speed was 250 Nm, with a maximum allowable fluctuation 60 Nm. The measured maximum starting torque was 95 Nm, and the measured mean running torque was 67 Nm, this being almost as low as the allowable fluctuation. Figure 5 shows a view of the modified azimuth bearing in the test laboratory at Rothe Erde. The news of this result was telephoned to Mathewson, who received it with great relief.[3]

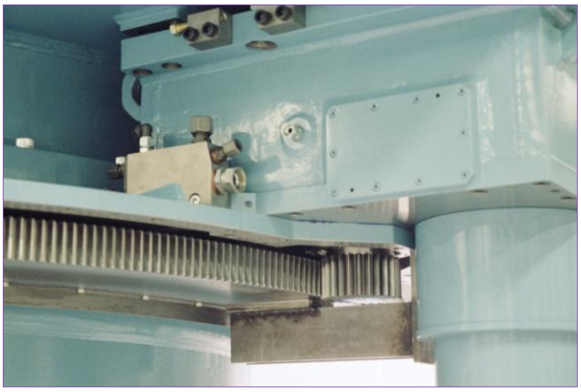


Figure 8: The main gearing of the azimuth drive showing one of the two gearboxes that apply torque in opposite directions. The gearbox is temporarily supported from a bracket attached to the underside of the ring gear to facilitate alignment.

5.4 Alt-azimuth Mount

The alt-azimuth mount was initially designed in-house to achieve a simple, rigid and compact structure with high natural frequencies, as required for good dynamic performance. This was checked and refined by consulting engineers MacDonald, Wagner and Priddle using finite slice computer analysis, who then produced the fabrication drawings. Machining drawings were produced at Mt Stromlo Observatory. Manufacture of the main structural components was contracted to the Newcastle State Dockyard, who did the machining after subcontracting fabrication in the Newcastle area. Smaller components were constructed within the Australian National University's precision workshops at Mt Stromlo and at the Research School of Physical Sciences in Canberra.

This type of work was unusual for the State Dockyard, but they were keen to diversify because their traditional heavy engineering work was waning. They had an old but comprehensive range of large machine tools that could easily accommodate the structural components of our telescope, and they were receptive to our involvement in using optical alignment methods to achieve high levels of layout precision.

An unusual requirement for the mount was that the azimuth bearings needed an exceptional level of flatness to ensure adequately even support the low-friction azimuth bearing that had been made by Rothe Erde. To achieve this, the newly-completed base and fork of the telescope were shipped to John Grout Machine Tool Reconditions in Sydney. Their staff include a European migrant who still had the largely-lost skill of hand-scraping flat surfaces. He applied this process to the bearing flanges, with precision flatness measurements being made by observatory staff along the way. The result was a flatness of 5 μm RMS over the 1,570mm diameter of the flanges. Views of the scraping process being applied to the flange on the telescope fork, and the finished surface, are shown in Figure 6 and Figure 7 respectively. The fork was inverted for this operation.

5.5 Precision Spur Gears

Drive for each axis is provided by two gearboxes applying torque in opposite directions to a common ring gear in order to eliminate backlash. Movement is produced by simultaneously increasing torque in one gearbox and decreasing it in the other. The preliminary design was done in-house, before seeking out a specialist gear drive supplier for detailed design and manufacture. One of the world's leading suppliers, Maag of Zurich (Switzerland) was contracted for this work. Hardened and precision-ground spurs gears of the type used in turbine powertrains were adopted because, for reasons of speed rather than pointing accuracy, they also require the ultimate in bearing and gearing precision. A lubrication system that injected low viscosity turbo oil into all gear meshes and bearing (including the azimuth bearing) was utilised.

A view of the primary gearing in the azimuth drive is shown in Figure 8. The large ring gear has a pitch circle diameter of 2,000mm and a thickness of 50mm. The pitch circle diameter of the pinion is 100mm, providing a speed reduction ratio of 20:1. A further reduction of 5:1 within the gearbox provided a total reduction ratio of 100:1 from the drive motor to the telescope. The ring gear remains stationary as the two gearboxes move around it. Identical gearing is used for the altitude drive, except that the main gear there rotates between the two fixed gearboxes.

5.6 Superstructure

A classical Serurrier truss superstructure was used to support the primary and secondary mirrors, but with a twist. A Serurrier truss has a form that does not create rotational deflection under lateral load. Significant translational deflection is unavoidable, but the differential effect is annulled by making it equal for both mirrors.

For our telescope, an additional feature is that differential axial deflection is also annulled. The condition required to achieve this is the strut angles should be the same for the primary and secondary trusses. The primary and secondary trusses no longer share common anchor points on the centre ring, but the deflection that occurs between the separated anchor points is easily determined, and then compensated by slight changes to the truss geometry. This truss geometry is shown in Figure 9. This arrangement results in very compact lower truss units that can be easily changed for the purpose of tuning performance. The trusses that provide support in the azimuth direction were made lighter than those that provide support in the altitude direction because only the latter carry lateral load. The super-structure thereby has less lateral deflection. Mounts for all mirrors, including the Nasmyth tertiary, are also designed to annul rotational deflection by means of counter-flexure mechanisms.

Figure 9: The modified Serurrier truss geometry, showing the equal apex angles of the upper and lower trusses.

5.7 The Extended Support Network

An important part of the project was the enthusiastic and valuable support that came from people beyond the team itself.

Figure 10: Coonabarabran Shire Council workmen excavating the rock for the telescope pier foundations (courtesy: E.W. Simmonds).

Senior staff at the Multiple Mirror Telescope in Arizona were very generous in providing detailed design information about their telescope. They had recently commissioned their telescope, and like us, they had decided to use a rolling element azimuth bearing. They too had concluded that friction torque could be greatly reduced by using balls rolling in a raceway groove of relatively large section radius. Unfortunately for them, they did not adequately deal with the corresponding reduction in radial stiffness, and subsequently had to resort to a number of other compensations. The data they provided us with was very useful in our process of avoiding such problems. Likewise, information they provided about the bogie carriages under their rotating enclosure was very useful.

All the specialist contractors involved provided great cooperation and willingness to adapt their expertise to our unusual and niche requirements. The Newcastle State Dockyard allowed us free access to their facilities so that we could work directly with their staff to align their massive machine tools with precision optical measuring equipment. Machine tool reconditioners John Grout likewise allowed us to work with their staff to achieve exceptional levels of precision with the flatness of the bearing mounts, providing rare hand-scraping skills.

Figure 11: After positioning the rail segments and bolting them down, the running surfaces are being ground (courtesy: E.W. Simmonds).

German bearing manufacturer Rothe Erde engaged in a program of experimental manufacture and testing to achieve extraordinarily low friction in the rolling element azimuth bearing, largely out of interest in the outcome.

Swiss gear manufacturer Maag re-employed a retired designer with great experience and expertise in specialised gearing systems design, and then manufactured the system with great precision.

The Research School of Physical Sciences and Engineering made their precision workshop facilities available to supplement our own very capable workshop in construction of telescope components.

6 THE BUILDING

This concept of floor design is completely influenced by the fact that the building co-rotates with the telescope. This permits the provision of access space close to the instrumentation so the building can be made much smaller, thereby saving construction costs. The 2.3m Telescope building incorporates these facilities.

The design of the building commenced early 1979, since the building had to be completed in time for the installation of the telescope. The conceptual design of the building was produced at Mt Stromlo by Hermann Wehner. The detailed structural analysis of the entire structure, including the building bogies, any architectural work, and the preparation of the necessary contract documents for the various trades were carried out by our consultants, MacDonald, Wagner and Priddle of Sydney. They also produced the structural analysis of the telescope mounting.

The influence of wind-induced forces on the building was analysed initially at Mt Stromlo Observatory by Hermann Wehner and Bela Bodor. To assess the structural design of the building, wind tunnel tests were carried out by the CSIRO Division of Environmental Mechanics in Canberra. A model of the building (scale 1:100), mounted on a sensitive balancing system, was tested at various building attitudes and wind speeds to determine overturning and rotating moments. The test rig was manufactured at Mt Stromlo Observatory. The results were used by MacDonald, Wagner and Priddle to optimize the design. The adopted maximum wind speeds were 18m/sec (65km/h) operational and 45m/sec (162 km/h) survival. Resistance to over-turning was further aided by the use of 55 tonnes of reinforced concrete as floor material on level L2. The building has a square footprint of 14m side length, and a height of about 12.5m. Its steel frame rotates on a fixed rail with four two-wheel bogies, designed for a total load capacity of 200 tonnes, and placed one at each corner of the base frame.

In July 1981, Ed Simmonds (formerly of Building and Grounds at the Australian National University) was appointed site engineer to ensure close supervision of all site work. He played a very important role and proved invaluable to the project.

Simmonds suggested soon after taking up his appointment that it would be worthwhile to consider the addition of a partial floor space under the lowest stationary level L1 thereby making use of the natural surface slope, without having to fill the remaining cavity. This proposal was readily accepted and incorporated in the consultant's scope of work.

Figure 12: Having assembled the base of the building steel frame, the main structural columns are erected (courtesy: H.P. Wehner).

Core drilling at the selected site was carried out showing solid rock close to the original surface. At the same time holes for the lightning protection earthing rods were drilled in several places within the building footprint. Earthing mats were laid in this space and connected to the earthing rods.

Excavation of the pier foundation followed (Figure 10). Simmonds reported in late 1981 that excavation work for the installation had been completed. Framing up for and placing of the reinforced concrete foundations followed, being completed in March 1982.

Placing of the building rail segments immediately followed, since the building centre was still accessible for alignment measurements prior to the construction of the telescope pier. The rail segments, 43 of them, were cast in Sydney and machined at Mt Stromlo Observatory and at the workshop of the Australian National University's Research School of Physical Sciences. Once in place and grouted to the concrete base, the running surfaces of both the main, load carrying wheels and the side restraint rollers were ground using a bench grinder mounted to a radial, rotating frame, guided on the rail and swivelling about a bearing in the building centre (Figure 11). A major set-back occurred when it was found that the grout that initially was used broke up under the wheel loads and it was necessary to regrout the rail. Rail segments were removed in succession, cleaned of the old grout and re-bedded on a layer of epoxy grout. Precise alignment was maintained by accurate measurements to adjacent segments.

Next, the central telescope pier was formed up and cast. It is entirely independent from the surrounding building structure in order to avoid the transmission of external vibrations to the telescope.

The contract for the manufacture, corrosion protection and erection of the steel frame for the building went to the local firm of Coonabarabran Engineering in September 1981. Their workshop in Coonabarabran was not very spacious, so some of the structural steelwork spilled over onto the footpath and the access lane, very much to the amusement of the local residents. The contract required the inspection of all welds by X-ray. Ed Simmonds supervised this work, but only found two welds which had to be redone. All structural steel was painted with a zinc-rich compound to provide adequate corrosion protection. Figure 12 shows the erection of the steel framework.

The building design provides for six floors, four of which are in the rotating part of the building. Level L0, the lowest level, covers only about 40% of the building floor area and is used

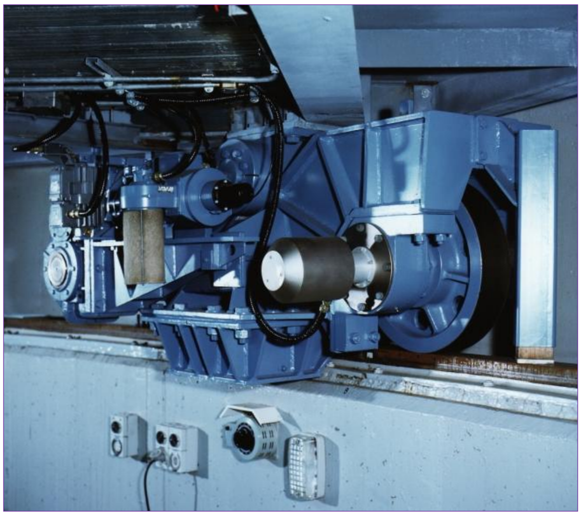


Figure 13: One of the four building bogies in position. The bogie shown is driving. It is fitted with gearbox and motor, on the left, and rotation-limiting switch unit, on the right (courtesy: R. Cooper).

for storage of spares, as well as containing the tea-room and toilet. Level L1 gives access to the building rotation bogies (Figure 13), the telescope cable wrap within the pier, the Cassegrain access platform mechanism, oil pumps, etc. Level L2 is the general entrance level. It gives access to the telescope mounting, and houses most of the control electronics cabinets. Level L3 is the Nasmyth observing level. An infrared instrument laboratory and instrument storage are also on this floor. Level L4 contains the telescope control console and the computers. Level L5 is for the telescope front end storage and houses the small crane used during front end inter-change, lifting instruments to the observing floor, level L3, and also primary mirror handling when the latter requires re-aluminising. Access to the wind-screens is possible from this floor.

Figure 14: The building steel frame is complete. The truck carrying the panels for the wall cladding has arrived (courtesy: H.P. Wehner).

The building is fitted with a side-opening, single-leaf shutter, which covers the slit through which the telescope observes during periods of use. The slit width is 3.5m. The design was shared between MacDonald, Wagner and Priddle (structural) and Mt Stromlo Observatory (operational). In order to prevent wind gusts from shaking the telescope two windscreens were provided, one vertical and the other horizontal. Both were controlled from the console, making it possible for the telescope to observe through a small aperture only.

In order to reduce costs, internal wall cladding was fitted only in the console and computer areas and the laboratories. The contractor for this work was Stramit Industries, who used their panels of compressed straw, treated with a fire retardant, and covered on both sides with a suitable architectural material (Figure 14). Someone thought that leaving an off-cut of Stramit outside in the rain and sun would awaken the forces of nature and produce sprouting of wheat, or whatever—and it did—fortunately not in the material fixed to the building walls. The cladding work was completed at the end of 1982.

Haden Engineering was awarded the contract for ventilation and air-conditioning, for completion by mid-1983. Ventilation required the installation of two fan units on the nearest building aprons, suitable ducting and air registers, blowing filtered, outside air into the telescope space. It was later found that exhausting air out of the building and replacing it with fresh, outside air, entering through the slit, gave better results in equalizing the air temperature around the telescope. Air-conditioning was only provided for the console and computer areas on level L4.

The building crane, supplied by Consolidated Lifting Services, was installed during early 1983.

Ed Simmonds left the site in February 1983, and Hermann Wehner took over supervision of the construction.

Barry Webb and Associates measured earth resistances around the building site and designed the lightning protection system, largely as proposed earlier by Gary Hovey and Hermann Wehner. Air terminals were installed, connected to the building steel frame. The building rail was connected to several earth terminations outside the building footprint. This system was also installed during 1983.

A major hitch occurred when it was found that cracks in the bogie wheels between the wheel webs and the rims had developed. The manufacturers, Schmidt and Muller of Sydney, were required to rectify these faults by replacing all wheels with cast ones, as was initially specified. This work involved removing one bogie at a time, shipping it to Sydney, having its wheels replaced, shipping it back to site and re-installing and re-aligning it. This work entailed a considerable time delay and extended involvement of site staff. The bogie wheels have been operating satisfactorily since.

The hydraulically-operated Cassegrain access platform was manufactured by a firm in Camden, NSW, which specialised in similar platforms for trucks, etc. It is mounted as part of the building structure on level L2 and provides access to this focal position during instrument changes, instrument maintenance and, of course, observers.

On the whole, the building was essentially complete at the time of the official opening on 16 May 1984.

7 THE CONTROL SYSTEM OF THE TELESCOPE AND BUILDING

Control of the 2.3m Telescope and its building is best divided into the following areas: computer and data-communication systems, control software, time system, axis and rotator servos, auxiliary systems, building drive and meteorological system.

7.1 Computer and Data Communication Systems

Two prior developments at MSSSO provided legacies for the 2.3m project: in 1979 the Computer Section had taken delivery of the first digital Equipment VAX 11/780 computer in Australia. The VAX and its VMS real-time operating system were held in such high regard that Ted Stapinski decided that the telescope control computer would also be a VAX 11/780. This seemed somewhat excessive at the time but proved to be an inspired decision. The advanced machine firmly placed the computer as an integral part of the telescope control and banished decisively the notion that a telescope should be (at least partly) functional even if its control computer was inoperable. Much later the VAX 11/780 was replaced with a MicroVAX II. This had little impact upon the control code, however an arrangement whereby the VAX system clock was electrically phase-locked to the observatory time system had to be abandoned in favour of a software alternative.

The second legacy was a microprocessor-based data acquisition and communication system which had been developed for other smaller observatory telescope projects. Called the Microprocessor Time, Encoder and Control system (MTEC), it was designed largely by Michael Ellis (Ellis et al., 1980) and provided a data communication system needed to get data to and from control cubicles, windscreen and focuser drives and the meteorological system. It used a message-based asynchronous data transmission over RS-422 lines and proved extremely reliable. The MTEC system requires the control computer to issue a command or interrogation message to each remote station and await replies. With a cycle time of 20Hz, the MTEC system presents the computer with data from the telescope which is delayed by 100ms. Since this delay was deemed undesirably long for the servo loops which control the telescope axes and the instrument rotator, it was decided to implement a supplementary byte-serial, bit-parallel synchronous transmission system designated the Telescope Control Link (TCL).

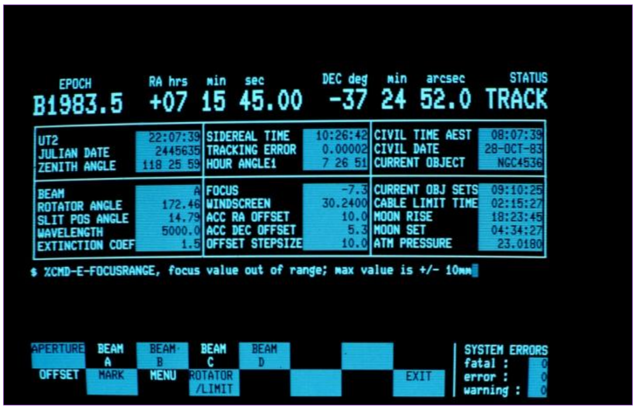
The TCL also uses the RS-422 line standard but over a 9-pair cable. The design of the digital logic for the TCL and for many of the associated interface cards was carried out by Mark Downing who later became one of the senior detector engineers at Mt Stromlo Observatory. Both of these data transmission systems are still in use after three decades of use though they are now destined for replacement by an industrial Ethernet system.

7.2 Control Software

Design and coding of the telescope control software was commenced by project software engineer Hilton Lewis in early 1983. In early 1986 the position of software engineer was taken by David Hoadley. With the electronics and control systems now largely complete, Hovey and Hoadley had time for a more careful assessment of control algorithms and program structure. A new control system was written over the following two years. It is difficult now with the powerful graphical display systems of today to understand the problems we faced then: how to make ergonomic and customisable displays, how to create messages which could be dynamically removed from the display when no longer relevant, how to communicate everything needed by the observer without excessive complexity. Even though the VAX architecture, compilers and libraries were excellent for their time, graphic displays and integrated development environments were a luxury that still lay in the future (see Figure 15 and Figure 16).

By 1988 the revised VAX telescope control system was complete and met with wide acceptance from observers. Offsetting, rotator control, pointing error correction, accurate coordinate conversion, fast configuration from user files, and informative fault diagnosis were all efficiently and intuitively implemented. This system hosted several additions such as the oscillating secondary and an infrared tip-tilt seeing correction system and also survived the change of computer from the VAX 11/780 to the MicroVAX II without problems. The 2.3m Telescope saw two decades of VAX control.

During the 1990s, a paradigm shift away from VAX architecture towards less expensive and more capable UNIX-oriented systems together with the eventual demise of Digital Systems Corporation threatened the maintainability of VAX systems and precipitated yet another system redesign. Commenced by Gary Hovey and Mark Jarnyk in 2005, this incarnation of the control system uses a compact PCI industrial machine and runs the QNX6 real-time operating system. Sadly, Mark died of cancer in early 2006 so the final control system was written by Jon Nielsen. Despite Hoadley's exceptionally well-commented code, Hovey chose to not to simply port the VAX software but to use it as a template to develop a new system incorporating TCSpk, a proprietary astrometric kernel (Wallace, 2002).



```
   EPOCH       RA hrs  min   sec      DEC deg  min  arcsec     STATUS
B1983.5        +07     15    45.00    -37      24   52.0       TRACK

UT2                    22:07:39  SIDEREAL TIME       10:26:42  CIVIL TIME AEST      08:07:39
JULIAN DATE             2445635  TRACKING ERROR       0.00002  CIVIL DATE          28-OCT-83
ZENITH ANGLE          118 25 59  HOUR ANGLE1          7 26 51  CURRENT OBJECT        NGC4536

BEAM                          A  FOCUS                   -7.3  CURRENT OBJ SETS     09:10:25
ROTATOR ANGLE            172.46  WINDSCREEN           30.2400  CABLE LIMIT TIME     02:15:27
SLIT POS ANGLE            14.79  ACC RA OFFSET           10.0  MOON RISE            18:23:45
WAVELENGTH               5000.0  ACC DEC OFFSET           5.3  MOON SET             04:34:27
EXTINCTION COEF             1.5  OFFSET STEPSIZE         10.0  ATM PRESSURE          23.0180
$ %CMD-E-FOCUSRANGE, focus value out of range; max value is +/- 10mm
```

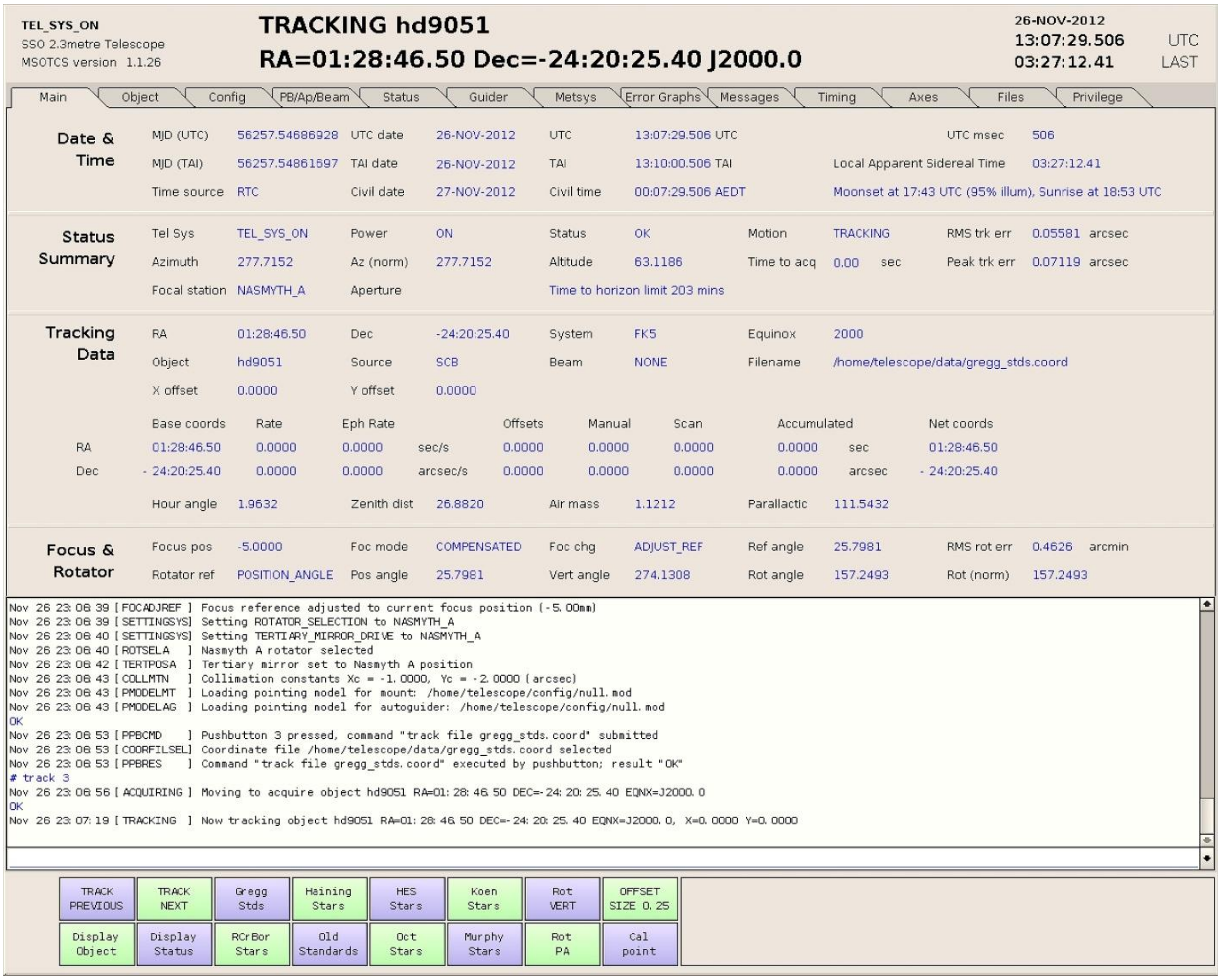
Figure 15: Original telescope display on an 80 character by 24 line VT52 terminal.

Named MSOTCS in the hope that it would be of use for other observatory projects, this new system was released to observers in late 2008. It preserves all of the functionality of the old VAX system but provides improved coordinate conversion accuracy, integrated pointing correction and engineering functions, and ease of maintainability (Nielsen and Hovey 2009). Nielsen's attractive and masterfully-written QNX control system should last for the remaining life of the telescope.

7.3 Time System

In the 1980s there was no computer network time, and observatories had to use autonomous sources of astronomical precise time. A Rohde & Schwarz time system based around a high-quality oven-controlled quartz oscillator was procured. This provided the control computer with precise UTC and stable pulses used to clock the data transmission systems.

The time was aligned to UTC (Australia) by a hierarchy of three methods: the Telecom speaking clock was dialled on the telephone to roughly align the time and to allow the second to be



TEL_SYS_ON
SSO 2.3metre Telescope
MSOTCS version 1.1.26

TRACKING hd9051
RA=01:28:46.50 Dec=-24:20:25.40 J2000.0

26-NOV-2012
13:07:29.506 UTC
03:27:12.41 LAST

Date & Time
MJD (UTC) 56257.54686928 UTC date 26-NOV-2012 UTC 13:07:29.506 UTC UTC msec 506
MJD (TAI) 56257.54861697 TAI date 26-NOV-2012 TAI 13:10:00.506 TAI Local Apparent Sidereal Time 03:27:12.41
Time source RTC Civil date 27-NOV-2012 Civil time 00:07:29.506 AEDT Moonset at 17:43 UTC (95% illum), Sunrise at 18:53 UTC

Status Summary
Tel Sys TEL_SYS_ON Power ON Status OK Motion TRACKING RMS trk err 0.05581 arcsec
Azimuth 277.7152 Az (norm) 277.7152 Altitude 63.1186 Time to acq 0.00 sec Peak trk err 0.07119 arcsec
Focal station NASMYTH_A Aperture Time to horizon limit 203 mins

Tracking Data
RA 01:28:46.50 Dec -24:20:25.40 System FK5 Equinox 2000
Object hd9051 Source SCB Beam NONE Filename /home/telescope/data/gregg_stds.coord
X offset 0.0000 Y offset 0.0000

	Base coords	Rate	Eph Rate		Offsets	Manual	Scan	Accumulated		Net coords
RA	01:28:46.50	0.0000	0.0000	sec/s	0.0000	0.0000	0.0000	0.0000	sec	01:28:46.50
Dec	- 24:20:25.40	0.0000	0.0000	arcsec/s	0.0000	0.0000	0.0000	0.0000	arcsec	- 24:20:25.40

Hour angle 1.9632 Zenith dist 26.8820 Air mass 1.1212 Parallactic 111.5432

Focus & Rotator
Focus pos -5.0000 Foc mode COMPENSATED Foc chg ADJUST_REF Ref angle 25.7981 RMS rot err 0.4626 arcmin
Rotator ref POSITION_ANGLE Pos angle 25.7981 Vert angle 274.1308 Rot angle 157.2493 Rot (norm) 157.2493

```
Nov 26 23:06:39 [FOCADJREF ] Focus reference adjusted to current focus position (-5.00mm)
Nov 26 23:06:39 [SETTINGSYS] Setting ROTATOR_SELECTION to NASMYTH_A
Nov 26 23:06:40 [SETTINGSYS] Setting TERTIARY_MIRROR_DRIVE to NASMYTH_A
Nov 26 23:06:40 [ROTSELA   ] Nasmyth A rotator selected
Nov 26 23:06:42 [TERTPOSA  ] Tertiary mirror set to Nasmyth A position
Nov 26 23:06:43 [COLLMTN   ] Collimation constants Xc = -1.0000, Yc = -2.0000 (arcsec)
Nov 26 23:06:43 [PMODELMT  ] Loading pointing model for mount: /home/telescope/config/null.mod
Nov 26 23:06:43 [PMODELAG  ] Loading pointing model for autoguider: /home/telescope/config/null.mod
OK
Nov 26 23:06:53 [PPBCMD    ] Pushbutton 3 pressed, command "track file gregg_stds.coord" submitted
Nov 26 23:06:53 [COORFILSEL] Coordinate file /home/telescope/data/gregg_stds.coord selected
Nov 26 23:06:53 [PPBRES    ] Command "track file gregg_stds.coord" executed by pushbutton; result "OK"
# track 3
Nov 26 23:06:56 [ACQUIRING ] Moving to acquire object hd9051 RA=01:28:46.50 DEC=-24:20:25.40 EQNX=J2000.0
OK
Nov 26 23:07:19 [TRACKING  ] Now tracking object hd9051 RA=01:28:46.50 DEC=-24:20:25.40 EQNX=J2000.0, X=0.0000 Y=0.0000
```

Figure 16: Current telescope display: MSOTCS running on QNX6 compact PC1 system.

identified; a HF time signal station was received using a Japan Radio NRD-515 communications receiver and the position of the time pips compared with the time system using a storage oscilloscope; finally the Sydney ABC TV signal was received via a satellite B-MAC receiver and a synchronizing pulse extracted to enable a digital counter to measure the offset to UTC to a precision of a few microseconds. The CSIRO National Measurement Laboratory facilitated this measurement by simultaneously measuring the same TV signal in Sydney and the system was calibrated using a Cesium-beam atomic clock belonging to the Department of National Mapping in Canberra (Figure 17).

Currently the control system relies on network time mediated via the NTP protocol which is thought to have an absolute accuracy of approximately 30ms. It is proposed to add a GPS timation receiver to regain a degree of autonomy. It is sobering to realise that after centuries during which astronomical observatories were the source of all precise time, we have become routine customers of the satellite and telecommunication industry!

7.4 The Axis and Rotator Servomechanisms

The two axes of an alt-azimuth telescope need to be driven at continuously variable rates to track a celestial object. Moreover, a ‘third axis’—the instrument rotator—must be similarly controlled to counter the field rotation inherent in such a mount.

Early in the project Gary Hovey commenced the specification of the drive components and design of the servo electronics: frame-less, permanent-magnet, DC torque motors of INLAND manufacture were employed with velocity feedback provided by similar DC tachogenerators. The motors were driven in an anti-backlash ‘virtual power loop’ using INLAND linear servo amplifiers. The locked-rotor resonances of the telescope structure were explored by Hovey using an analogue frequency response analyser and found to be in the region of 8 to 10Hz.

Of particular help with the servo system design was a design study for the Multi-Mirror Telescope at Mt Hopkins, Arizona. Engineers at Ford Aero-Space provided considerable information and advice on that project. Servo modelling was done using a number of crude, in-house computer programs (this is before the era of MATLAB and similar applications) and the final adjustments were performed empirically during commissioning. The servos and their associated axis encoders were interfaced to the control computer via the synchronous TCL data communications system. The servos for the three rotator drives were of similar design but, because of the relaxed angular accuracy, did not require the two-motor anti-backlash system. The rotator circuitry was the last of the telescope electronics to be made and was able to take advantage of sub-racks, circuit card hardware and card connectors to the European DIN standard which was a substantial improvement over the older ISEP components used elsewhere.

As well as purpose-built electronics, the Servo and Rotator cubicles containing these systems required a complex array of electromechanical relays for control, sequencing and protection; this was designed by Jan van Harmelen who was able to standardize much of the design so as to allow it to be re-used in other cubicles.

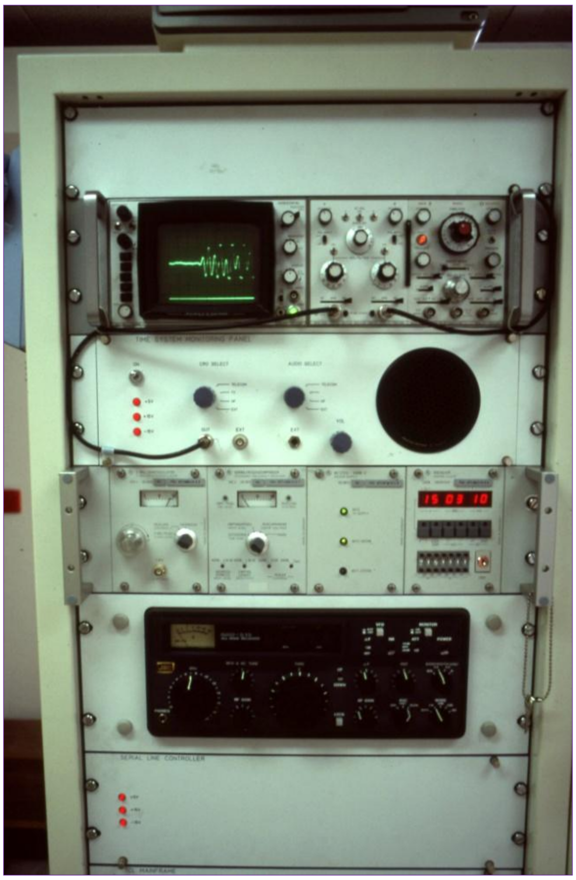


Figure 17: Time-system in operation in 1984 with the time-pip from radio VNG clearly visible on the long-persistence oscilloscope.

Van Harmelen and Hovey supervised a small coterie of technical officers who constructed and wired the cubicles, wired circuit cards and manufactured the numerous interconnecting cables. The servo control aspects of telescopes such as the 2.3m are explored in Hovey 1986a and 1986b (Figure 18).

7.5 Auxiliary Systems

Many of the smaller sub-systems of the telescope are controlled from a cubicle called the Auxiliary Systems Cubicle (ASC). This comprises a mixture of electromechanical relays, dis-

Figure 18: Servo cubicle during commissioning; Gary Hovey is measuring the driving point admittance of the azimuth axis.

crete component logic and microprocessor-based electronics. It was designed by Jan van Harmelen, and is interfaced to the control computer using the asynchronous message-based MTEC data transmission system.

The ASC is responsible for bearing/gear lubrication, primary mirror support air pressure, mirror cover and building shutter drives. Other minor systems such as the Cassegrain focus access platform, the gantry crane and the top-end clamping system are included with auxiliary systems but, apart from safety interlocks, are not involved with telescope control. The 2.3m Telescope has interchangeable top-ends which carry different secondary mirrors according to which of the Cassegrain or Nasmyth foci is in use. Control of the top-end clamping system involves electrical actuation of the clamps in sequence followed by crane operations to remove or install the top-end. The sequencing of these operations and the safety interlocking of the crane, clamping drives and the telescope is handled by a simple relay logic system. Commissioning such a plethora of sub-systems was quite a time-consuming process; the various status, signalling and safe-failure modes needed checking to confirm that the control computer was correctly seeing the telescope hardware and that generated error messages were valid and informative for the observer.

Figure 19: Senior Technical Officer John Findlay and Gary Hovey at the partially-completed control console.

The 2.3m Telescope was built in an era when the astronomer’s control console was still considered to be the hub of the installation. Also designed by Jan van Harmelen, we include it here amongst the auxiliary systems. As well as the operating controls for the telescope and building systems it contains some of the relay circuitry needed to start up and shut down the telescope, and to signal faults. Even though remote observing was anticipated in the early stages of design, we failed to envisage operation of the telescope with no person present in the level L4 control room. Thus the console electronics were those most needing revision in May 2006 when some projects required completely unattended operation (Figure 19).

7.6 Building Drive

The building rotation drive was a major item which was deemed to be outside our in-house engineering capabilities. Hermann Wehner, who was responsible for the building design and building systems, initiated the basic design. Unlike the Multi Mirror Telescope building which used single-wheel bogies, our four bogies had two wheels each and the drive was through one wheel on each of two diagonally opposite bogies. The building drive does not receive commands from the control computer but instead is autonomous and simply regulates the angular offset between the telescope azimuth and that of the building direction.

Clearly high powers and large inertias were involved, but there were more subtle issues. Three firms were approached for proposals and quotations for a suitable building drive system. Of particular concern was the possibility of anti-phase oscillations where one of the diagonally opposite bogie motors unloads and the other makes up all of the torque until it decelerates and the two swap effort. ASEA indicated that they had experienced the problem on paper manufacturing web drives. Accordingly they were given a contract to produce a stand-alone building drive cubicle and to supply the shunt-wound DC drive motors. The installed system comprises a single Tyrak 8A thyristor converter driving two Thrige-Titan LAK112 DC motors; the difference between the armature currents (motor loading) is used to control one of the motor fields providing the necessary torque stabilisation. The outermost servo loop comprises a PI controller which closes the loop around an LVDT which measures the building-to-telescope error. The system functions smoothly: there is an initial lag of up to 1.7° as the telescope accelerates but the building-to-telescope azimuth error when tracking is less than 0.1°.

To ensure that the building drive servo was stable, the torsional stiffness of the building needed to be as high as practicable. We also had the design challenge of how to prevent the rotating building from overturning in the event of a catastrophically high wind. Both problems were neatly solved by adding a 55 tonne concrete slab into the floor-plane of level L2.

7.7 Meteorological System

Meteorological measurements of wind speed and direction, temperature, humidity and barometric pressure are made using standard Weathertronics and Vaisala sensors mounted atop the building. The analogue voltages from the Weathertronics frame are digitized by purpose-built electronics and sent via the asynchronous MTEC system to the computer for display, logging and safety alarm purposes. The wind-speed, temperature and humidity are also displayed on analogue meters at the observer's control console. A rain detector is also installed and has an electrical interlock to the building shutter so that the latter is automatically closed upon the detection of rain. Meteorological data are logged, archived and made available via a web server. The meteorological system was designed by Gary Hovey who constantly had to explain to sceptics that, yes, the azimuth of the building *was* added to the wind direction measured with respect to the rotating building!

8 INTEGRATION OF THE TELESCOPE AND BUILDING AT SIDING SPRING OBSERVATORY

An obvious requirement for a telescope installation is the need to ensure that assembly problems are discovered and dealt with before the structure is transported to site. Prior trial assembly of the mount is essential. Fortuitously, the Research School of Physical Sciences had, in its early history, built a large machinery hall to allow the construction of the Homopolar generator during the 1950s. This cavernous building included an overhead crane that made it ideal for our trial assembly, and it was kindly made available for this purpose. Trial assembly commenced in mid-1983, and was completed a few months later. A party was held to mark the successful completion of the exercise, as shown in Figure 20.

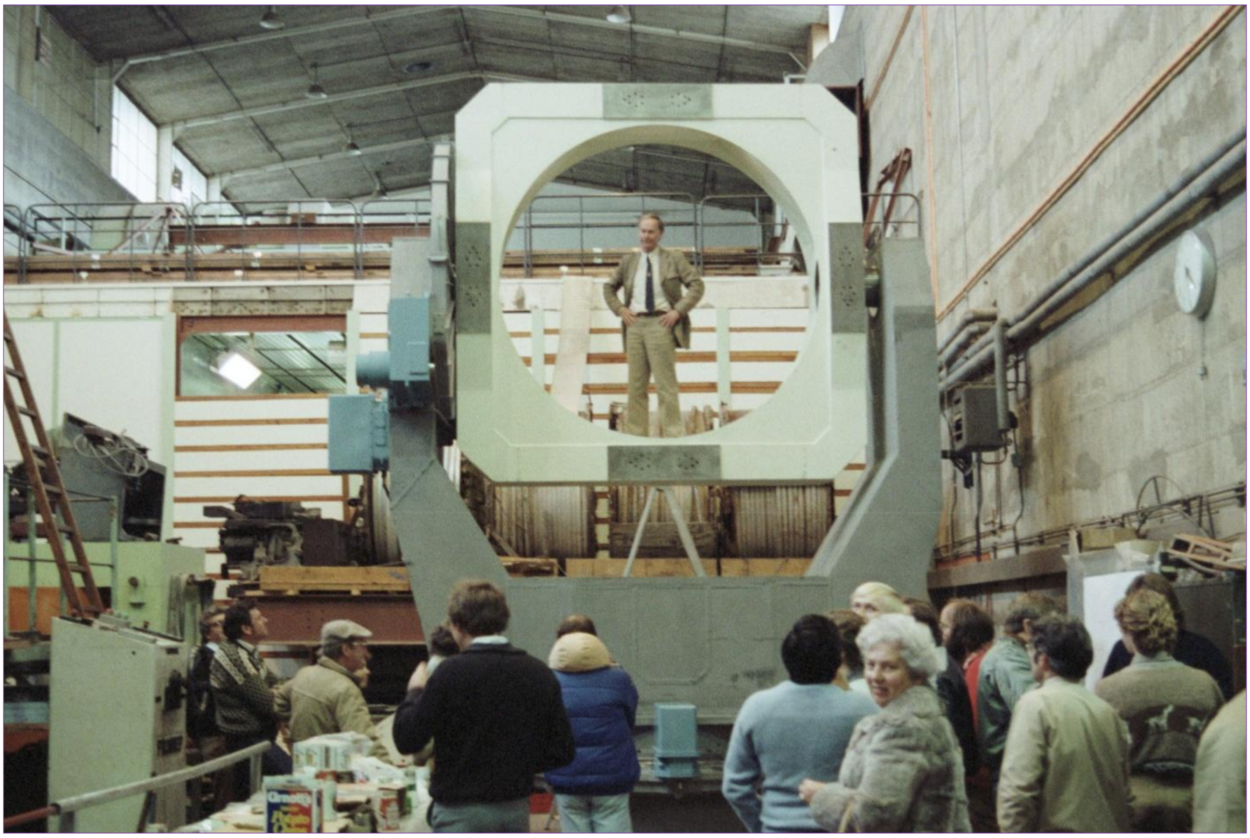


Figure 20: The telescope mount in the machinery hall at the ANU's Research School of Physical Sciences at completion of the trial assembly. Don Mathewson is standing in the centre ring of the mount.

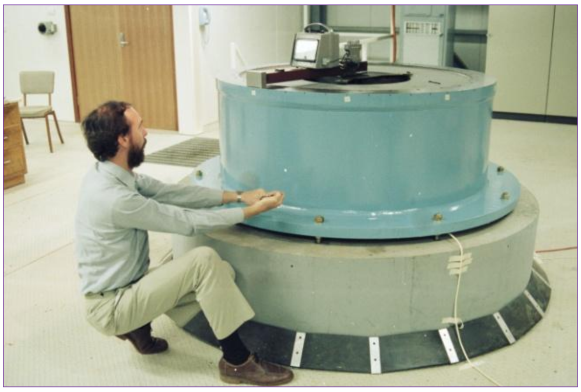


Figure 21: The telescope base being adjusted to accurately level the azimuth bearing mounting face. The measuring apparatus used was that previously devised to measure face flatness during the hand-scraping process.

After completion of the trial assembly, the mount was disassembled, loaded onto trucks and transported to Siding Spring Observatory over a period of a few weeks in November of 1983. The base and azimuth bearing system were installed first and adjusted so that the bearing flange was level to within one arc second. The adjustment process is shown in Figure 21. The mounting of the azimuth bearing and ring gear is shown in Figure 22.

Delivery of the telescope fork and altitude axis centre ring was synchronised with the arrival of a large mobile crane that had travelled from Brisbane. The crane was hired for several days in order to do a few hours of work because most of the time was consumed by travel. The major structure of the telescope mount was thus installed onto the newly prepared base. Figure 23 shows the telescope fork being lifted into the building, with a small crowd of spectators watching.

Detailed assembly work then continued for several months. Figure 24 shows its status in January 1984, when most components were in place. A dummy mirror is mounted in place of the real mirror, allowing the telescope to be balanced for drive testing. The primary mirror was kept in safe storage until assembly was otherwise complete. Figure 25 shows it finally being installed. Figure 26 shows the final structure.

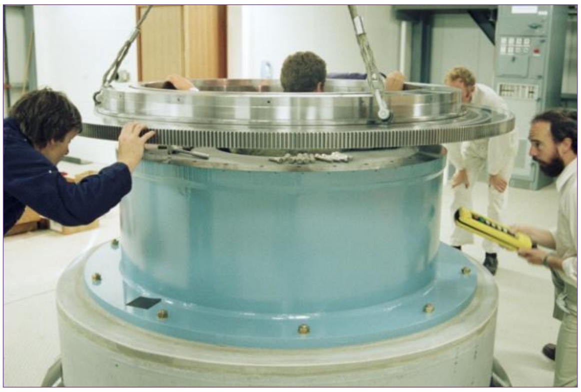


Figure 22: Mounting of the azimuth bearing and ring gear in preparation for installation of the telescope fork.

Necessary to the success of the 2.3m Telescope project was a major upgrade to the electric power distribution system at Siding Spring Observatory. The mountaintop which hosted the existing ANU 40-in, 24-in and 16-in Boller and Chivens telescopes was fed with three-phase power at a non-standard voltage of 1400V using autotransformers each end for step and step-down and would need augmenting. A scheme was devised by Gary Hovey and the chief engineer of Ulan County Council at Gulgong, NSW, to take the mountaintop feeder and re-insulate it for operation at 22kV. The Ulan engineer designed a system incorporating high voltage switchgear located in the utilities building which could feed the output of the existing 500kVA Petbow generator backwards through the existing step-down transformer and so feed energy at 22kV to the Australian National University's mountaintop area. A new step-down transformer was installed near the pump-house and an arrangement of 22kV regulators connected in open-delta fashion restored the voltage to LV (415V three-phase) to compensate for the feeder transformer being run in reverse. The new system potentially gave us 500kVA of power on the mountaintop and meant that we retained the back-up power capability of the site generator. It functioned well for 31 years until its recent replacement with a separate generator set and automatic LV changeover system.

The 2.3m Telescope was officially opened on 16 May 1984. The telescope was operational at that time, but commissioning work continued for many months as activity progressively transitioned to a full observing schedule. The Telescope has performed with great success over the 28 years since its opening. Changing technology has progressively revealed a problem, however, in that our diminishing supply of electronic spare parts is becoming difficult to replace. This led to the commencement of an upgrade program in 2011. For the most part, this involved modernization of drive system electronics and control systems. The original design team was re-assembled for the exercise, and they expect to complete the task in 2013.

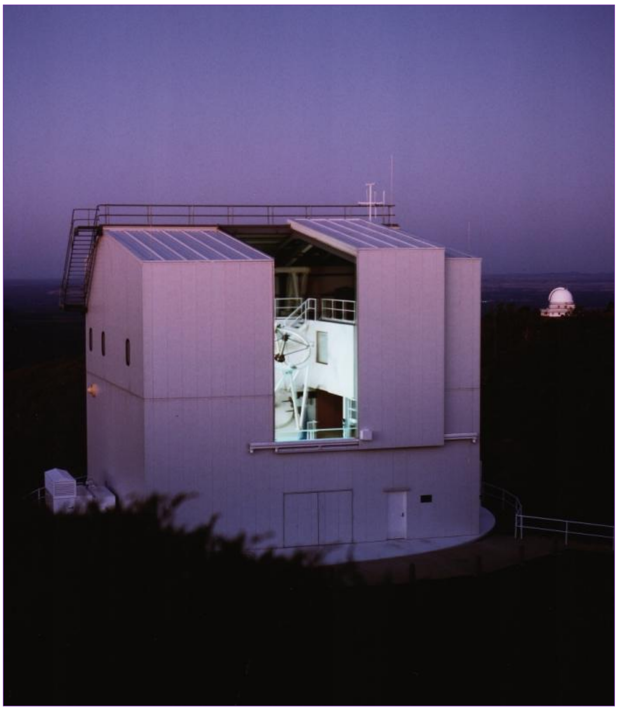
9 INSTRUMENTATION

Limited resources meant that no permanent instruments were available for the telescope at the time of its opening. However, while the telescope was under construction, design and construction started on the Double Beam Spectrograph for one of the two Nasmyth focal stations

The design team for the Double Beam Spectrograph was led by Alex Rodgers, who was inspired by similar work done by his colleague

Figure 23 (top left): The telescope fork being lifted into the newly-completed building.
Figure 24 (top right): The newly-assembled telescope in drivable condition, with a dummy mirror in place of the real mirror.

Figure 25 (bottom left): The primary mirror being installed in the completed telescope.
Figure 26 (bottom right): The 2.3m Telescope installed in the building.



from Hale Observatory, Bev Oke who visited Mt Stromlo Observatory to help with the design. It was designed as a state-of-the-art high-efficiency spectrograph providing intermediate resolutions ranging between 40 and 240km/s over a spectral range of 300-1000nm with a 1.5 arcsec slit. Interchangeable diffraction gratings are used in a collimated beam of 150mm diameter. To maximize efficiency, the beam is split into two bands at a wavelength of 580nm. Mirrors on the blue side are coated with aluminium, while those on the red side are coated with silver. The system is continually flushed with dry air to maintain high reflectivity, as is especially required by silver. Folded Schmidt cameras are used to achieve the required small focal ratio (f/1.1) with high throughput. The original PCA detectors were replaced by Loral Fairchild CCD detectors in September 1984 and later by Tektronix CCDs which remained in use until the Double Beam Spectrograph was decommissioned.

Design of the second Nasmyth instrument, the Nasmyth B Imager, was commenced in 1985. Again, design of this instrument was led by Alex Rodgers, with advanced optical design done by Damien Jones of Prime Optics. It is a combined imaging system and low resolution spectrograph operating over the wavelength range 300-1100nm, accepting the whole 6.6 arcmin Nasmyth field without vignetting. The system uses exotic glasses to be achromatic across the whole wavelength range. Collimated and telecentric beams are provided in different sections of the instrument. The former accommodates diffractive prisms for spectroscopy. The latter accommodates narrow band interference filters, allowing uniform response across the field.

Given that the alt-azimuth configuration of the telescope causes field rotation, instrument rotators were required at all three focal stations. Design and construction of these commenced after the telescope opening. Indeed, considerable development and commission work continued on the telescope itself after its opening. A temporary instrument rotator was installed in 1984, and used to mount the Boller and Chivens Echelle Spectrograph that had been built for the 40-in telescope at Siding Spring Observatory in 1980.

The Cassegrain infrared system was installed in 1985. For the new installation, the system included a chopping secondary mirror mount built by the Physics RAAF Academy at the University of Melbourne.

The Cassegrain Echelle spectrograph continued to be used as the main Nasmyth instrument until it was joined in 1986 by the Double Beam Spectrograph. These instruments were made much more useful with the installation of the three new instrument rotators in mid-1988. This allowed the instrument suite to be properly tracked for field rotation.

The first generation of instrumentation was completed with the commissioning of the Nasmyth B Imager in October of 1991. Thereafter, it was interchanged with the Echelle spectrograph. The tertiary mirror of the telescope allowed rapid and remotely controlled switching between the two Nasmyth focal stations.

A major upgrade was made to the Cassegrain infrared instrument system in the early 1990s, with the building of CASPIR and a tip-tilt secondary mirror mount to allow correction of low-altitude seeing. CASPIR was a cryogenic near infrared imager with spectroscopic and polarimetric capabilities. Given its many operating modes, compact design was required to fit it within the restricted space available at the Cassegrain focus. The cryostat chamber is only 500mm long.

A variety of temporary instruments was installed through this period. A notable example was a Fairchild camera that was mounted at prime focus for the purpose of imaging Comet Halley during its 1986 appearance. The Nasmyth secondary mirror was removed to allow this, and the camera was mounted inside the focus carriage so that focus could be adjusted. Facilities for remote operation were also in place, allowing a number of publicity events to be conducted. On one occasion, the entire membership of the Federal Parliament attended an evening in the lecture theatre at Mt Stromlo Observatory, where they saw live images of the comet transmitted from the 2.3m Telescope at Siding Spring Observatory, which was remotely controlled from the lecture theatre.

More recently, a major modernization of the instrument suite was completed in March 2009 with the deployment of the Wide Field Spectrograph (WiFeS). This is a very successful example of a modern integral field spectrograph. An E2V detector upgrade is currently underway.

10 THE OPENING OF THE TELESCOPE

The day of the grand opening of the 2.3m Telescope had finally arrived, 16 May 1984, and Siding Spring Observatory turned on its best weather. The marquee where the guests would have lunch was erected near the Lodge. The first of nearly 200 guests were arriving and the place was a hive of excitement. Astronomers from around Australia were coming. The Astronomical Society of Australia held a special meeting in Coonabarabran to coincide with the opening of the telescope, so many astronomers were present.

Then disaster struck as the Chancellery's charter plane was still at Canberra, grounded because of a heavy fog which was not expected to clear for several hours. Meanwhile, the Prime Minister's Royal Australian Air Force plane had already taken off, because military planes were not grounded.

Bob Hawke, the Prime Minister, was scheduled to open the telescope in about an hour, and he arrived with his 'minders'. They told him he should continue with the opening as planned without waiting for the Chancellery members as he had very important meetings that afternoon back in Canberra. Don Mathewson then drew the Prime Minister aside and told him that for seven years the MSSSO and the Chancellery had been working hard, crossing almost insurmountable barriers for this moment and it would be an unforgettable calamity to continue with the ceremony without members of the Chancellery. Bob Hawke thought for a moment and then told his minders to cancel the meetings.[4]

Don Mathewson then asked Peter Gillingham, the on-site engineer in charge of the Anglo-Australian Telescope, if he would show the Prime Minister over 'his' telescope. Peter leapt at the chance. Somebody then turned to Mathewson and commented that it may not be a wise move for the Prime Minister to see the bigger (3.9m) telescope, to which Mathewson replied,

> Bigger but not better! It's ideal because the PM has a chance to compare an older generation telescope with the new generation. He can see the vast AAT dome filled with unusable space and the huge, cumbersome equatorial mount.

The fog eventually cleared in Canberra and members of the Chancellery duly arrived. The ensuing tour of the telescope went smoothly, except that an over-zealous Boy Scout on guard on the lower floor tried to prevent the Prime Minister from using the toilet!

When the Prime Minister reached level L3 of the building he was shown the Double Beam Spectrograph, which was designed to be the main workhorse for use at one of the Nasmyth foci. This instrument had two prominent arms which housed the separate red and blue cameras, and Alex Rodgers, the left-leaning and mischievous team leader for this instrument, had labelled these "RED (LEFT) ARM" and "BLUE (CENTRE-LEFT) ARM". This sardonic allusion to the Australian Labor Party's factional groupings was not lost on an amused Bob Hawke.

In his opening address, the Prime Minister said:

> The ANU is to be congratulated for its initiative in developing this telescope which sets new international standards in astronomical engineering and is the most advanced optical telescope ever built.
>
> There are good reasons for Australians to be proud of this achievement.
>
> The design and development of the telescope is very much a co-operative Australian venture. Apart from several components which could not be manufactured in Australia, construction took place in the ANU's own workshops and involved a large number of Australian engineering firms, supply and service companies and consultants.
>
> The astronomers, engineers and technicians at Mount Stromlo and Siding Spring Observatories, with the support of the ANU and the co-operation of industry, have created a facility which clearly demonstrates Australia's capacity to contribute to the advancement of high technology.

Figure 27: In the foreground, from left to right, are Don Mathewson, Bob Hawke (the Australian Prime Minister) and Peter Karmel (Vice-Chancellor of the Australian National University), watching the opening of the 2.3m Telescope at Siding Spring Observatory on 16 May 1984.

As he finished, the 2.3m Telescope and its associated building rotated smoothly and noiselessly through 90º to present the Prime Minister with the commemorative plaque for him to unveil (Figures 27 and 28).

After this, the lunch went on for hours, and that night a Barn Dance was held down in Coonabarabran attended by more than 300 people.

It was a truly happy and memorable day!

11 SCIENCE OUTPUT

11.1 A Powerful Tool for Australian Astronomers

The combination of this easy to use, efficient large-aperture telescope with a suite of instrumentation unequalled in other observatories in Australia has produced a prolific science output and contributed greatly to the development of Australian astronomy. The 2.3m Telescope has been used by astronomers from all Australian universities (and many overseas ones) and has been a vital tool for the theses of a multitude of Ph.D. students.

Figure 28: The plaque which Bob Hawke unveiled to open the 2.3m Telescope.

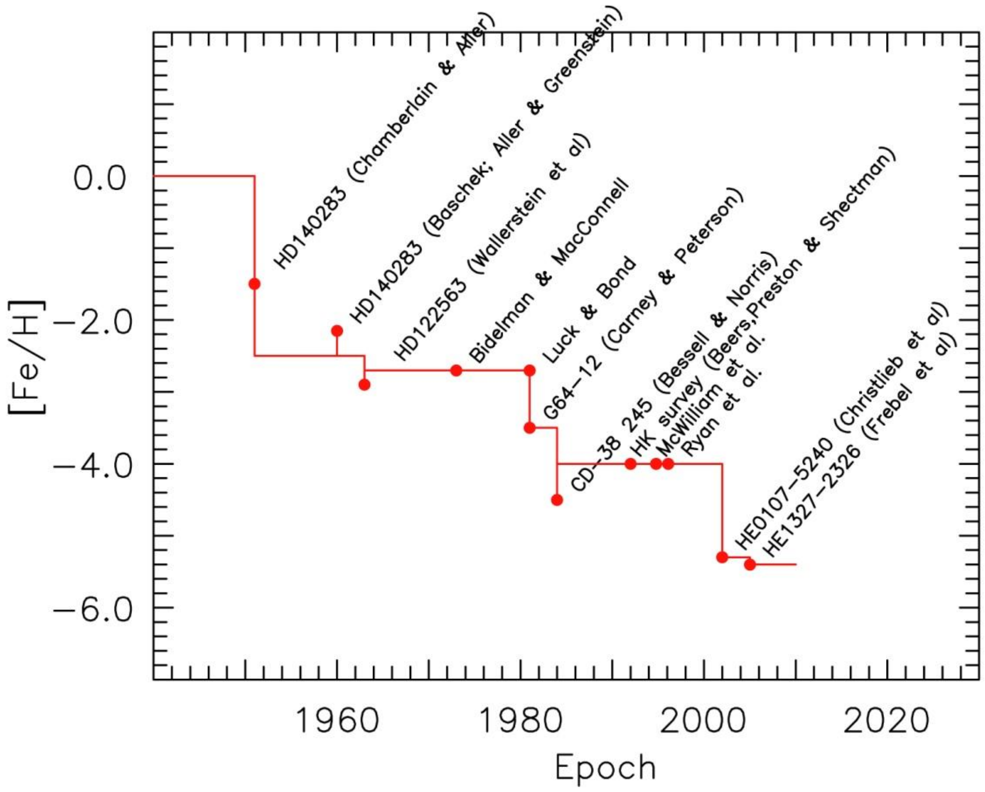


Figure 29: The diagram shows how the chemical abundance, [Fe/H], of the most metal-poor stars then known decreased as a function of the year of its discovery.

MSSSO allocates time on the 2.3m Telescope through a peer review process to the national and international community. Several astronomers from other Australian institutions are members of the Time Allocation Committee. On average about half of the time is given to external and collaborative projects involving MSSSO and external researchers.

11.2 The First Project

Shortly after the opening ceremony, even though the commissioning was not completely finished and the main instrumentation not yet built, the telescope was used to do I band photometry of 161 Cepheids in the Small Magellanic Cloud (Mathewson et al., 1986). These distance measurements yielded a major breakthrough, revealing that the Small Magellanic Cloud had been split into two by a recent collision with the Large Magellanic Cloud. These two galaxies were called the Mini-Magellanic Cloud and Small Magellanic Cloud Remnant.

It is impossible to detail all of the research projects that have been carried out using the 2.3m Telescope, but a few large programs have been selected to illustrate the types of research the telescope has contributed to.

11.3 Metal-Poor Stars in our Galaxy

During the first 25 years of 2.3m observations, the Double Beam Spectrograph was used extensively to discover the most metal-poor stars in our Galaxy. These stars are among the first to form in the Universe and tell us about the nature of the Big Bang and the conditions that existed at the earliest times. Mike Bessell, John Norris, and colleagues observed several thousand candidate metal-poor stars to discover objects containing less iron, by factors as large as 40, than were known when the 2.3m Telescope was commissioned. Indeed, the most iron-deficient of these are 400,000 more iron-poor than the Sun, and were most likely formed only 100,000,000 years after the Big Bang. The discovery of these objects has been followed up by high resolution, high signal-to-noise spectroscopy with the world's 6-10m telescopes, and has led to major advances in our knowledge of the nature of the first stars and the manner in which the first chemical elements heavier than lithium formed in the Universe. For reports on the two most iron-poor stars known, which were discovered during programs undertaken with the 2.3m Telescope, see Christlieb et al. (2002) and Frebel et al. (2005).

Figure 29 shows how the chemical abundance, [Fe/H], of the most metal-poor star then known decreased as a function of the year of its discovery (where [Fe/H] = 0, –2, –4, ... refers to Fe fraction of the star relative to the abundance of Fe in the Sun, of 1, 1/100, 1/10000, ..., respectively). The decrease of [Fe/H] since ~1980 results in very large part from discoveries made with the 2.3m Telescope.

11.4 Evolution of the Galactic Disk

Another very significant contribution to our understanding of how the galactic disk evolved since it began to form was made from observations with the 2.3m Telescope. We need to know how the chemical properties and velocities of the disk stars changed with cosmic time since the disk began to form.

We use the relatively rare subgiant stars for which it is possible to measure fairly accurate ages. Our stars come from the RAVE stellar survey of about 500,000 stars, which is large enough to generate a useful sample of nearby subgiants of all ages. We observed about a thousand subgiants with the echelle spectrograph modified to give a full multi-order echelle format with a CCD detector, and measured their velocities, temperatures, element abundances and surface gravities. Combined with proper motion data from other sources, this gives us all the data needed to derive observationally the age-velocity-metallicity relation in the solar neighbourhood.

We find that the average metallicity of the stars has gradually increased over the last 10 Gyr, from [Fe/H] = – 0.5 to solar. The random velocities of the stars appear to increase for the first 3 Gyr of their lives, as they interact with their environment, but then stay roughly constant. This makes sense. The higher velocities of the older stars mean that they spend only a small fraction of their orbits near the Galactic Plane, and this reduces their interaction with spiral arms and molecular clouds (Haywood, 2008).

11.5 The Final Stages of Stellar Evolution

A big, very successful project was the study of the turbulent final stages of stars in the Magellanic Clouds. The Large and Small Magellanic Clouds are the nearest galaxies to our own Galaxy and they are ideal places to study stars. Most importantly, individual stars can be readily resolved in the Clouds with ground-based telescopes, and the 2.3m Telescope is ideally suited for studying the final luminous stages of stellar evolution there. Highly evolved stars have turbulent lives: they pulsate with large amplitude; they undergo periodic nuclear burning episodes that lead to the contamination of the stellar surface with large amounts of carbon; and finally they eject their outer layers in a strong stellar wind leading to the formation of a planetary nebula. Particularly useful in studying these processes have been the near-infrared instruments on the 2.3m Telescope, especially the Cryogenic Array Spectrometer/Imager (or CASPIR). These instruments led to early calibrations of the pulsation period-luminosity relation for Mira variables (Hughes and Wood, 1990), the first detection of a second period-luminosity sequence obeyed by the semiregular variables (Wood and Sebo, 1996), and the first presentation of the now well-known multiple period-luminosity sequences for variable red giant stars in the near infrared (Wood, 2000) (see Figure 30). During the lifetime of the Spitzer Space Telescope, simultaneous observations made with both the Space Telescope and the 2.3m Telescope (and CASPIR) were crucial in determining the rates of mass loss in the final stages of red giant star lifetimes (Groenewegen et al., 2007).

11.6 Bulk Flows in our Local Universe

The advent of the 2.3m Telescope opened up a major area of research, observational cosmology, to investigate bulk flows of galaxies in our local Universe. For five years, the peculiar velocities of 1355 spiral galaxies were measured using the Tully-Fisher Relation. Five Ph.D. students (Figure 31) each worked on this project as part of their first year program. Rotation velocities were measured using long slit Hα spectroscopy with the Dual Beam Spectrograph on the 2.3m Telescope. The results showed that the ‘Great Attractor’ as postulated by UK and US observers to explain bulk flows, did not exist (Mathewson et al., 1992a). The bulk flow of some 600km/s extends well beyond the hypothetical Great Attractor at 4,400km/s to more than 8,000km/s (Mathewson et al., 1992b).

11.7 The Collision of Comet Shoemaker-Levy with Jupiter

There is no better way to finish this small sample of significant projects carried out with the 2.3m Telescope than to display one of the spectacular photographs taken by Peter McGregor and Mark Allen using the Cryogenic Array Spectrometer/Imager. The impact of Fragment K on Jupiter by Comet Shoemaker-Levy 9 is shown at 2.34 μm in Figure 32. Their photographs received international acclaim and were amongst the best taken of the collision (see McGregor et al., 1996).

12 CONCLUDING REMARKS

The factors that led to the construction of the telescope were an acute shortage of observing time, the need for a large telescope versatile enough to take full advantage of modern instrumentation, the lack of advanced facilities for the training of graduate students, and a desire to stimulate the development of astronomy in Australia.

The original specifications, as outlined by the astronomers and engineers at Mt Stromlo and Siding Springs Observatories (MSSSO), called for a versatile, precise and efficient telescope,

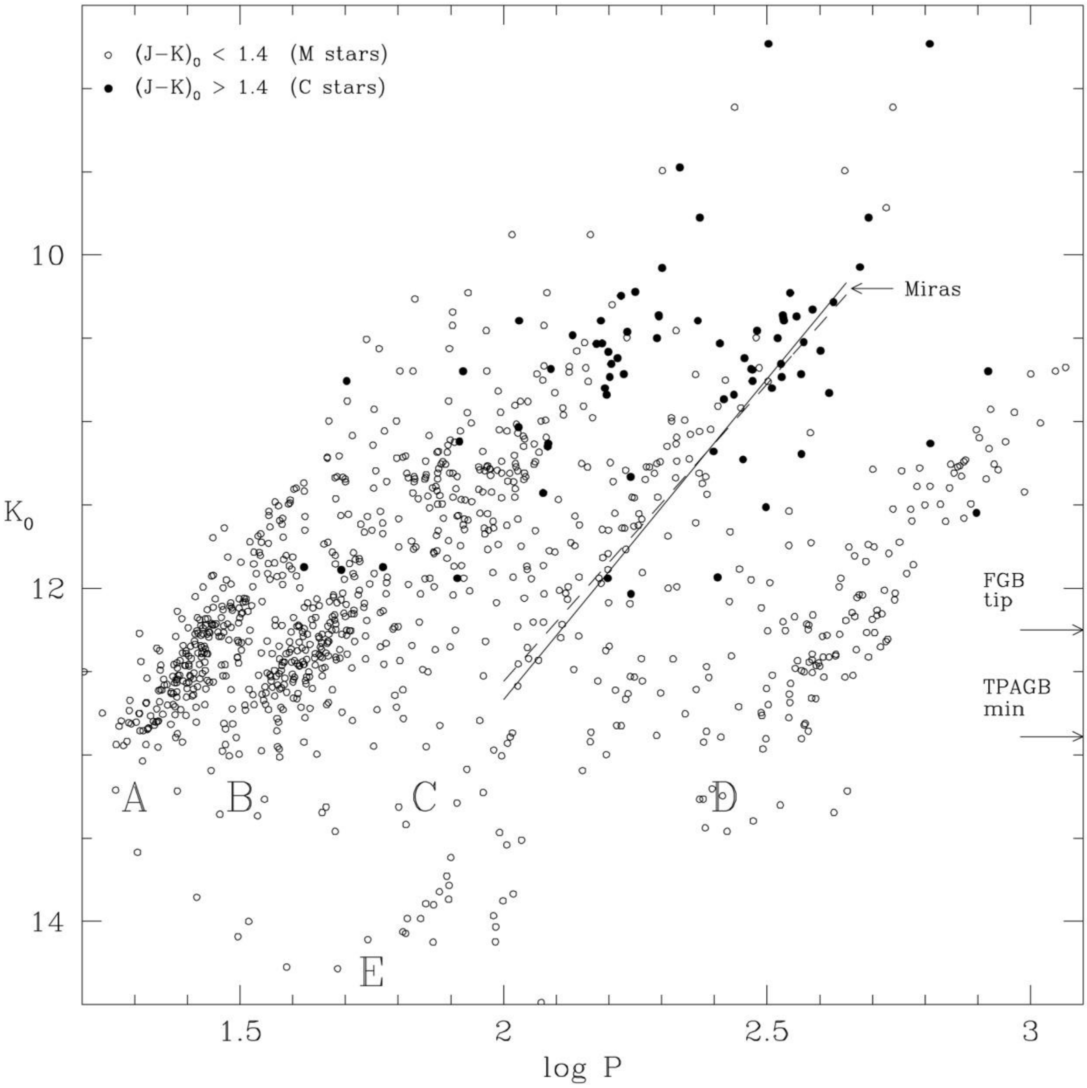


Figure 30: Variable LMC red giant stars plotted in the (K,log P) plane. The K magnitudes were obtained using CASPIR on the 2.3m Telescope, while the periods were obtained from the MACHO telescope at Mt Stromlo Observatory. Five period-luminosity sequences labelled A ... E can be seen. The positions of the tip of the first giant branch (FGB) and the minimum luminosity for thermally pulsing AGB stars with M ~ 1 Msun are indicated by arrows. The solid and dashed lines are the K-log P relations for Mira variables from Hughes and Wood (1990). Solid circles correspond to stars with J–K > 1.4 and they are assumed to be carbon stars. Other stars are assumed to be oxygen-rich stars. This figure is the first infrared version of the period-luminosity for variable red giants in the LMC.

Figure 31: Don Mathewson (centre) with Vince Ford (above Don) and Don's research group of Ph.D. students (clockwise from the left: Angela Samuel, Emmanuel Vassiliadis, Marcus Buchhorn, Carl Grillmair and Stuart Ryder) who studied the Large Scale Flow of Galaxies using the 2.3m Telescope in 1989.

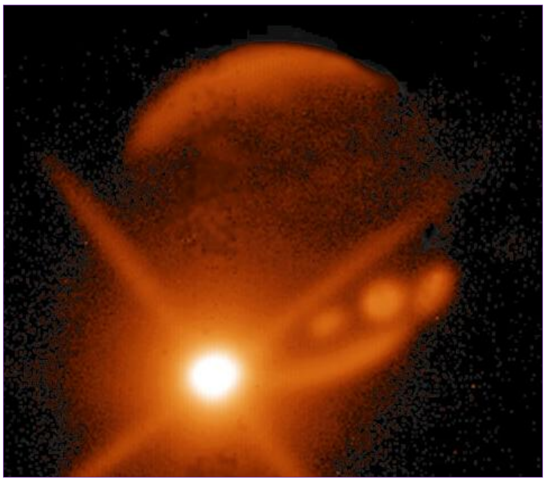


Figure 32: The impact of Fragment K of Comet Shoemaker-Levy on Jupiter, using CASPIR at 2.34 μm. The scars of three previous impacts can be seen on the planetary disk (image from Peter McGregor and Mark Allen).

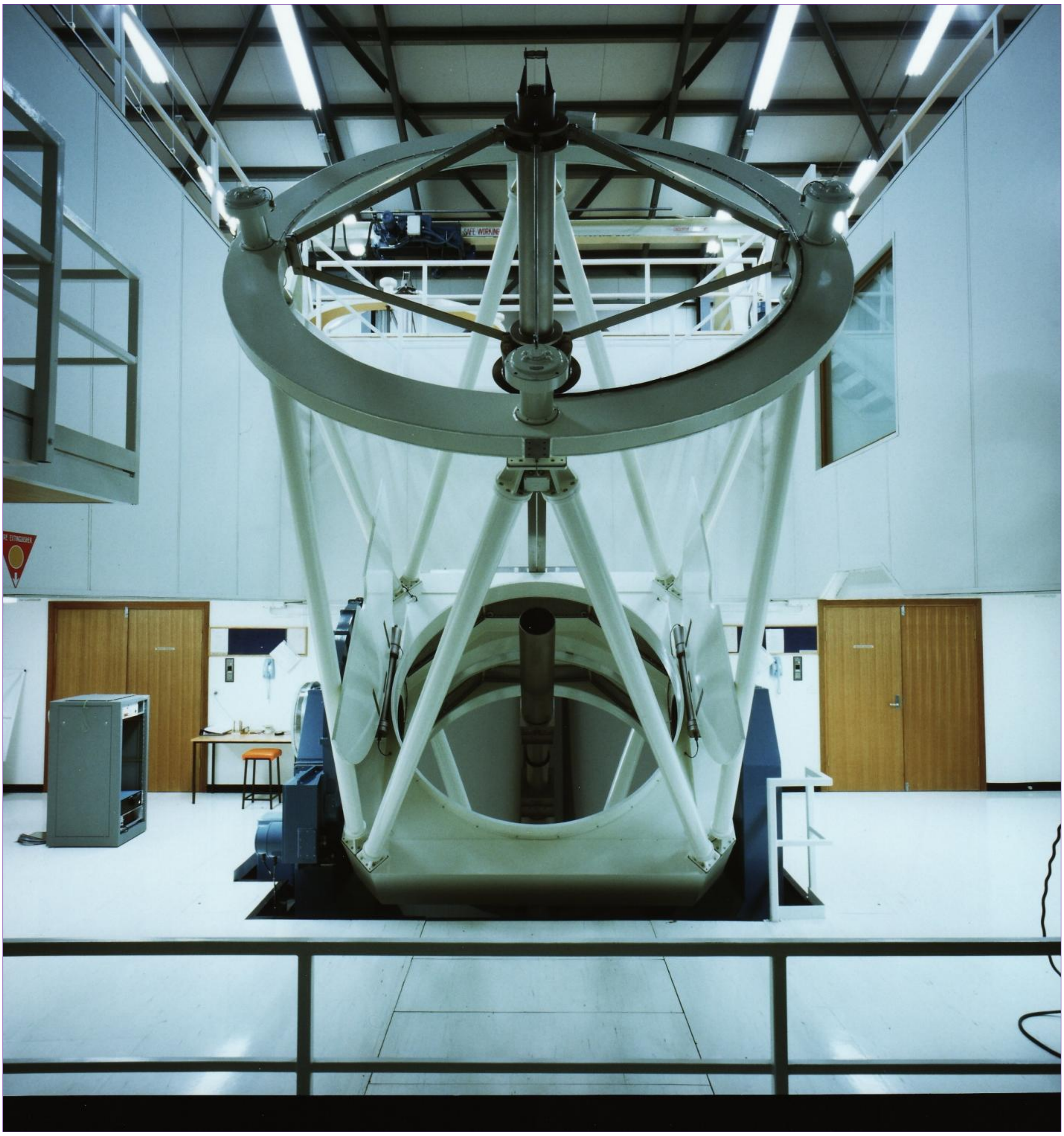


Figure 33: The rotating building places the 2.3m Telescope at the very centre of a laboratory where a variety of instruments can be mounted with ease.

equipped with advanced astronomical instrumentmentation, but costing a fraction of the price of a conventional telescope.

The final design is one of beautiful simplicity. An alt-azimuth mount and a thin primary-mirror keep the weight of the telescope to a minimum. A rotating building places the telescope at the very centre of a laboratory where a variety of experiments can be mounted with ease (see Figure 33).

A control-computer closely integrated into the operation of the building, the telescope and the astronomical instruments guarantees versatility, economy and efficiency because:

- the operational characteristics of the telescope can be altered easily, often simply by changing the telescope-control software;
- it is cheaper to implement and maintain complex control systems when the complexity resides in computer software rather than in specialised mechanical components; and
- the observer can exercise an unprecedented degree of control over the telescope, its environment, and its instruments.

Advanced astronomical instruments maximise the efficiency with which the collected light can be measured and analysed.

These instruments incorporate the photon-counting and infrared detectors already developed at MSSSO.

In all respects the new telescope met the original aims of its creators, and in many ways it surpassed those aims. The dream was translated into reality, a reality that was an inspiring example of the capabilities of Australian scientists, engineers and technicians—the concept was bold, the design was elegant, the implementation was professional.

In October 1985, the Institution of Engineers, Australia presented the 2.3m Telescope their Engineering Excellence Award and in September 1989 they also awarded it to the Dual Beam Spectrograph, the main instrument on the telescope.

The ingenuity and inventiveness of the engineers at MSSSO developed whilst building state-of-the-art instrumentation for the 2.3m Telescope was vital to the creation of the Advanced Instrumentation and Technology Centre which was opened in October 2006. This is now providing instruments for the world's largest telescopes.

13 NOTES

1. In the 1980s, 'the Chancellery' at the Australian National University comprised the Vice-Chancellor (Professor Donald Low and later Professor Peter Karmel), Deputy Vice-Chancellor (Professor Ian Ross) and the Bursar (John Coleman), and their support staff.
2. Professor Ian Ross, the Deputy Vice Chancellor, used to jokingly refer to Mt Stromlo as home to wild tribesmen who periodically raided the ANU to loot and pillage!
3. Indeed, the conversation was so protracted that Hart was presented with an $800 telephone bill when he checked out of his hotel the following morning!
4. At the time Don Mathewson thought: "Good old Bob, he's a real champion!"

14 ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the Chancellery of the Australian National University. They were superb. We don't know how they did it—but they did it! They provided $3.2 million (1980) out of University funds and we have a wonderful telescope. Also we thank the entire staff of MSSSO during this time. Everybody realized that it was an enormous challenge and everyone met and indeed, more than met, this challenge. In particular Norman Stokes and then Barry Newell, the Administration Officers, played a pivotal role. Thank you all very much.

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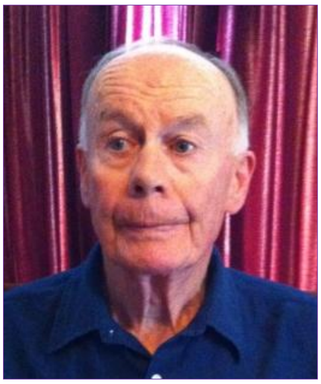
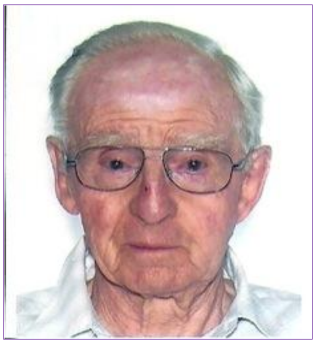


Don Mathewson joined the Division of Radiophysics, CSIRO, in 1955. He helped Chris Christiansen build his ‘Chris Cross’ radio telescope at Fleurs Field Station. In 1958 he went to Jodrell Bank, University of Manchester, to observe with the newly-commissioned 250ft steerable dish. Don has held visiting Professorships at Ohio State University, the Sternewacht in Holland and the University of Bologna. Don was Director of MSSSO from 1977 to 1986. During this time, the 2.3m Telescope was built. He recalls the strong camaraderie that existed between staff and students during these challenging times. From 1984, the opening of the telescope, to his retirement in 1994, Don, together with his group of students and Vince Ford, was one of the main users of this telescope. They investigated the splitting of the Small Magellanic Cloud and Large Scale Bulk Flows in the Local Universe. He was farewelled at the international Workshop on Large Scale Motions in the Local Universe on Heron Island. Don is an Emeritus Professor of the Australian National University.

John Hart studied mechanical engineering at the University of New South Wales, graduating in 1967. John started his career in Adelaide, working for the car manufacturer Chrysler, where he was involved with the design of brake and suspension systems for a popular car of the time, the Chrysler Valiant. In 1969, he took up an engineering position with The Australian National University, working at Mt Stromlo Observatory on the opto-mechanical design of telescopes and their instrumentation. He has worked there ever since. His first task was the renovation of the historic 30-inch Reynolds Telescope. He later led the opto-mechanical design of the 2.3m Telescope. More recently, he played a central role in the opto-mechanical design of the large new-generation instruments NIFS and GSAOI for Gemini Observatories, and of the new WiFeS integral field spectrograph for the 2.3m Telescope. He is currently involved in the opto-mechanical design of GMTIFS instrument for the Giant Magellan Telescope being built in Chile. These new instruments include many novel features. John is very proud of the creation at MSO of the Advanced Instrumentation and Technology Centre for which the work for the 2.3m Telescope played a pivotal role



Hermann Wehner studied engineering (Precision Instrumentation and Optics) at Munich, Germany, working during vacation times at Göttingen Observatory, developing astronomical instrumentation. In 1952 he accepted the offer of an engineering position at Mt Stromlo Observatory. The initial project was the refurbishment of the 50-inch Great Melbourne Telescope, as well as the design and implementation of telescope instrumentation, particularly electronic photometers. In 1960 Hermann was put in charge of telescope development at Siding Spring Observatory, involving visits to manufacturers in the USA. From 1964 onwards he became involved in the initial technical planning for a large telescope of the 4m class, resulting in his secondment to the Anglo-Australian Telescope Project from 1967 to 1975. There he was the Australian senior engineer and later Project Manager (1973-1975). Returning to Mt Stromlo Hermann was engaged in various engineering projects, most importantly the design and implementation of the 2.3m Telescope facility. In mid-2011 he was re-employed by The Australian National University as one of the 2.3m Telescope engineering team to assess the serviceability of this facility.

Gary Hovey was educated in Maryborough, Victoria, and graduated with an honours degree in science from Monash University in 1969. In September 1974 Gary received a Ph.D. from the Australian National University for a thesis en-

titled “Software Correction of Telescope Pointing Errors”. From 1975 to late 2002 he was employed as an electronics engineer with Mt Stromlo Observatory where his main professional interests were instrument and telescope control, precise time and the mathematics of celestial co-ordinate systems and telescope pointing. In 1979 Gary became one of the principal designers for the 2.3m Telescope and was responsible for overall system design, control system, algorithms for astrometry and control, electric systems and commissioning tests. Later in the 1990s Gary was involved in other telescope refurbishment programs and contributed to site-testing work in the Flinders Ranges in South Australia. In 1995 he played a major role in the design of a low-powered, cold-climate telescope mount (GMOUNT) which was deployed in Antarctica, and he went to the South Pole on a repair mission in late 2000. Like others on the 2.3m Telescope project, Gary looks back on it as the high point of a diverse career in providing the engineering fabric needed by astronomers. This was not just challenging work, but it also provided opportunities (some unexpected) to meet and learn from others.

Jan van Harmelen grew up in Rotterdam and studied electronic engineering at Delft University in the Netherlands. Jan lectured in electronics at the Western Australian Institute of Technology, now Curtin University, for five years. His wish to do more hands-on engineering made him join the Australian National University at their Siding Spring Observatory near Coonabarabran in the Warrumbungle Mountains in New South Wales. After four years he moved to Mt Stromlo Observatory near Canberra to become Chief Electronics Engineer in 1983. His involvement in building the 2.3m Advanced Technology Telescope and its instrumentation and many more projects to modernise older telescopes prepared him for his appointment in 1999 as Project Manager for designing and building two multi-million dollar, highly specialised instruments for use with the 8m Gemini telescopes in Hawaii and Chile. Jan retired in 2006 after 27 years with the Australian National University and moved to Geelong, but he maintains a continuing involvement with Mt Stromlo and Gemini Observatories.