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The Story of the Radcliffe Telescope

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The Radcliffe 74-inch in Pretoria, South Africa, used for the first time in 1948, was for several years the largest telescope in the southern hemisphere and one of the largest in the world – after the 200-inch Palomar (also 1948), the 100-inch Hooker (1918), the 82-inch McDonald (1939) and the 74-inch David Dunlap instrument in Toronto (1935), with which it shared fourth place. The history of its construction can be traced in interesting and sometimes amusing detail through the many files of correspondence (**1**) which are preserved at the South African Astronomical Observatory, its home since 1976.

1 ORIGIN OF THE RADCLIFFE OBSERVATORY

John Radcliffe, MD (1652–1714), was the most successful English physician of his day, numbering amongst his patients William III and Princess Anne, not to mention mere commoners such as Newton, Swift and Pope. It is not surprising therefore that when he died, never having married, he was able to bequeath a huge fortune, mainly for the benefit of his old Oxford college and for founding the Radcliffe library in that city. The residue of his estate was to be administered by trustees for charitable purposes. After spending some of it on the building of a hospital, also in Oxford, known as the Radcliffe Infirmary, the trustees finally set up the Radcliffe Observatory, Oxford, the foundation stone of which was laid on 1772 June 27. For 163 years the Radcliffe Observatory devoted itself mainly, like most others in those days, to positional astronomy using refractors (**2**).

By the early part of this century, largely due to developments in spectroscopy, astrophysics had become the area of greatest interest in astronomy. Although Britain had several theorists of first rank such as Sir Arthur Eddington and Sir James Jeans, its observatories, of which the old Radcliffe was typical, were outdated and unsuitable for the more up-to-date types of research.

It was when Harold Knox-Shaw (1885–1970) became Radcliffe Observer in 1924 that changes in the basic style of the Observatory came to be contemplated. Knox-Shaw (**3**) had worked previously at the Khedive's Observatory in Helwan for 16 years and had used the 30-inch Reynolds reflector there for pioneering photography of southern nebulae. Because of this experience, he saw very clearly the advantages of having a large reflector at a good southern site and set about preparing the ground for one. In about 1929 his opportunity arose – it turned out that the Oxford car manufacturer Sir William Morris was prepared to pay the then large sum of £100000 to

purchase the existing observatory and grounds for a much-needed extension to his pet charity, the Radcliffe Infirmary. The funds were thus available for the construction of the new establishment.

For the first time, the Radcliffe trustees were induced to invite an astronomer, the Astronomer Royal, Sir Frank Dyson (1868–1939), to serve with them and they soon saw the good sense of Knox-Shaw's proposal. The work of the Union Observatory, Johannesburg, as well as that of the southern stations of the Leiden, Yale and Michigan Observatories, was showing how excellent the climate of the South African interior is for astronomy. Accordingly, when in 1929 Knox-Shaw, Dyson and Eddington went to South Africa to attend a meeting of the British Association for the Advancement of Science, they took the opportunity to survey possible sites. They decided that a hill named Klapperkop on the edge of Pretoria, then a comparatively small town and the administrative capital of the Union of South Africa, was likely to be the most suitable place for their new observatory. The city fathers of Pretoria were so enthusiastic about the project that they offered to present the Trustees with the selected site. Before accepting, however, Dr W.H.Steavenson (1894–1975), a well-known amateur astronomer, was sent out for six months to check on the weather and seeing-conditions. His report was very favourable (**4**).

2 LEGAL PROBLEMS

By 1931 the sale of the old observatory was complete, but the first of the many problems that were to plague the project now appeared. The Attorney-General of the United Kingdom objected to the spending of a large sum of money by a charitable trust outside the country's boundaries. The situation was further complicated by a move on the part of Oxford University to force the Trust to spend their funds nearer to Oxford. Even Albert Einstein was persuaded to testify in the University's favour, perhaps on account of his friendship with Prof. F.A.Lindemann (Scientific Advisor to Winston Churchill), a supporter of the University's point of view. One of Einstein's biographers, Ronald W.Clark, remarks: 'it is difficult not to believe that Einstein's involvement was a tribute to his innocence rather than to deep convictions' (**5**). However, Knox-Shaw was not to be intimidated and he managed to line up a few big guns of his own – Dyson, Eddington, de Sitter, Plaskett, Schlesinger and Shapley – when the case was heard in the Court of Chancery in July 1934. The judge, Mr Justice Bennett, could not help remarking that the opposition was wooing the Radcliffe Trust more as an heiress than for love. Fortunately, the Trustees won the case and Oxford, by losing, as the last Radcliffe Observer A.D.Thackeray once wrote, enhanced its reputation as the home of lost causes. The formalities took another year to settle. A total amount of £65 000 was authorized by the court to cover the telescope, the buildings and the residences. If this amount seems small by modern standards, it was at that time a huge amount for a scientific project. The tradition of 'sealing wax and string' as the main materials for physical research died hard in Britain.

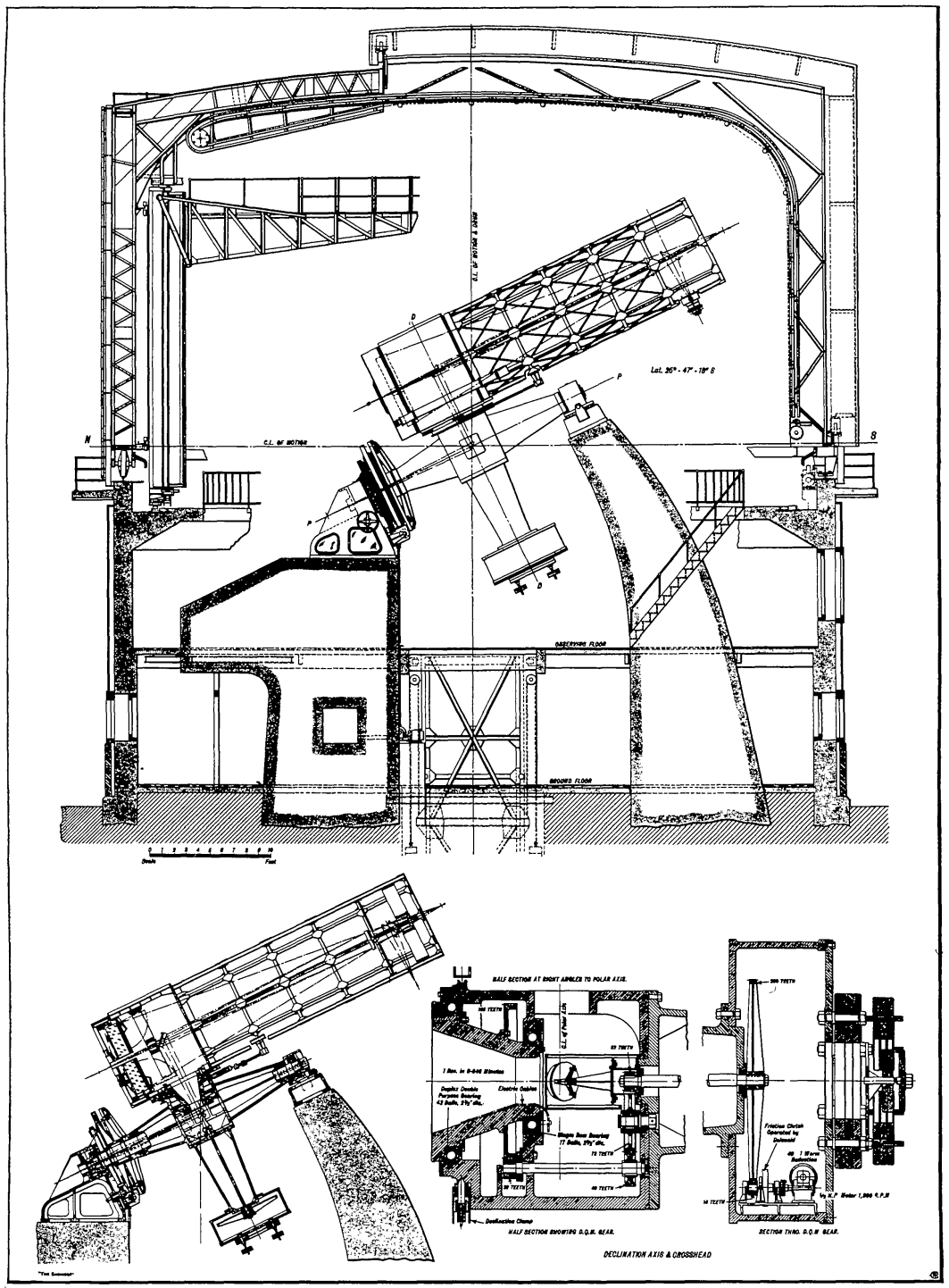

FIG. 1. Outline of telescope and turret which appeared in *The Engineer* during 1938.

3 THE DESIGN TAKES SHAPE

Knox-Shaw had begun discussions about a telescope with the long-established firm of Sir Howard Grubb, Parsons & Co. around 1930, but only with the favourable ruling in 1934 could concrete proposals be made. At that time its manager was Cyril Young (1875–1949), who had joined the original

concern in Dublin under Sir Howard Grubb in 1910 as Engineer and Designer (**6**). It was, in fact, Young who had been responsible for the design and construction of Grubb's later telescopes such as the 26½-inch Johannesburg refractor and the 40-inch reflector for Simeis. He was appointed as Manager following its purchase by Sir Charles Parsons and re-establishment at Newcastle upon Tyne in 1924. There he had continued with telescope work and had just, at the time we are concerned with, completed a 74-inch for Toronto.

At first, a 72-inch reflector was suggested for the new Radcliffe Observatory, but Young pointed out that a 74-inch on a two-pier English mount would not be any more expensive as the firm could then make use of jigs and patterns prepared for the Toronto instrument. In fact, the main change in the newer telescope was to be the inclusion of a coudé focus. This meant that the declination axis had to be very short so that light could be fed down through it and the R.A. axis to the spectrograph (see Fig. 1). The two-flat system has the advantage of full sky coverage over the one-flat coudé arrangement of the 100- and 200-inch telescopes. This design was repeated, except for small improvements, in the post-World War II telescopes built by Grubb's for the Mt Stromlo, Helwan, Tokyo and Haute-Provence Observatories. Thackeray, although in general disapproving of his telescope being used to study northerly objects, liked occasionally to mention that the Radcliffe coudé spectrograph at 26° south latitude could be used to measure more northerly stars than that of the 100-inch in California. Another interesting feature of the Pretoria design was the use of a tuning fork oscillating at 50·283 vibrations per second to control the sidereal drive motor. More complete descriptions of the telescope have been given by Knox-Shaw (**7**) and, anonymously, in *The Engineer* (**8**).

4 TURRET RATHER THAN DOME

Another unusual feature of the Pretoria installation was the decision to use a turret instead of a dome. This arose mainly from the need to have a convenient way of reaching the Newtonian focus. Two other telescopes built in the early 'thirties, the 61-inch Wyeth reflector at Oak Ridge, Massachusetts, and the 60-inch Rockefeller in Bloemfontein, both belonging to Harvard College Observatory, had been housed in turrets. A gantry of adjustable height and angle, swinging from a tower which could move on rails just inside the turret, provided convenient access for Newtonian observers. The diameter of the turret, 61 ft, seems large today but was dictated by the rather high *f*-ratio (4·8) of the primary and the asymmetrical two-pier mounting. Only in the case of the 200-inch telescope, then also under construction, had a much faster *f*-ratio (3·3) been risked. To reduce the effects of the large daily temperature fluctuations, the walls of the building were to have a thin outer skin behind which air could freely circulate.

5 OPTICS

The Newtonian, Cassegrain and coudé secondaries, as well as the subsidiary coudé flat mirrors, were to be made of fused quartz supplied by

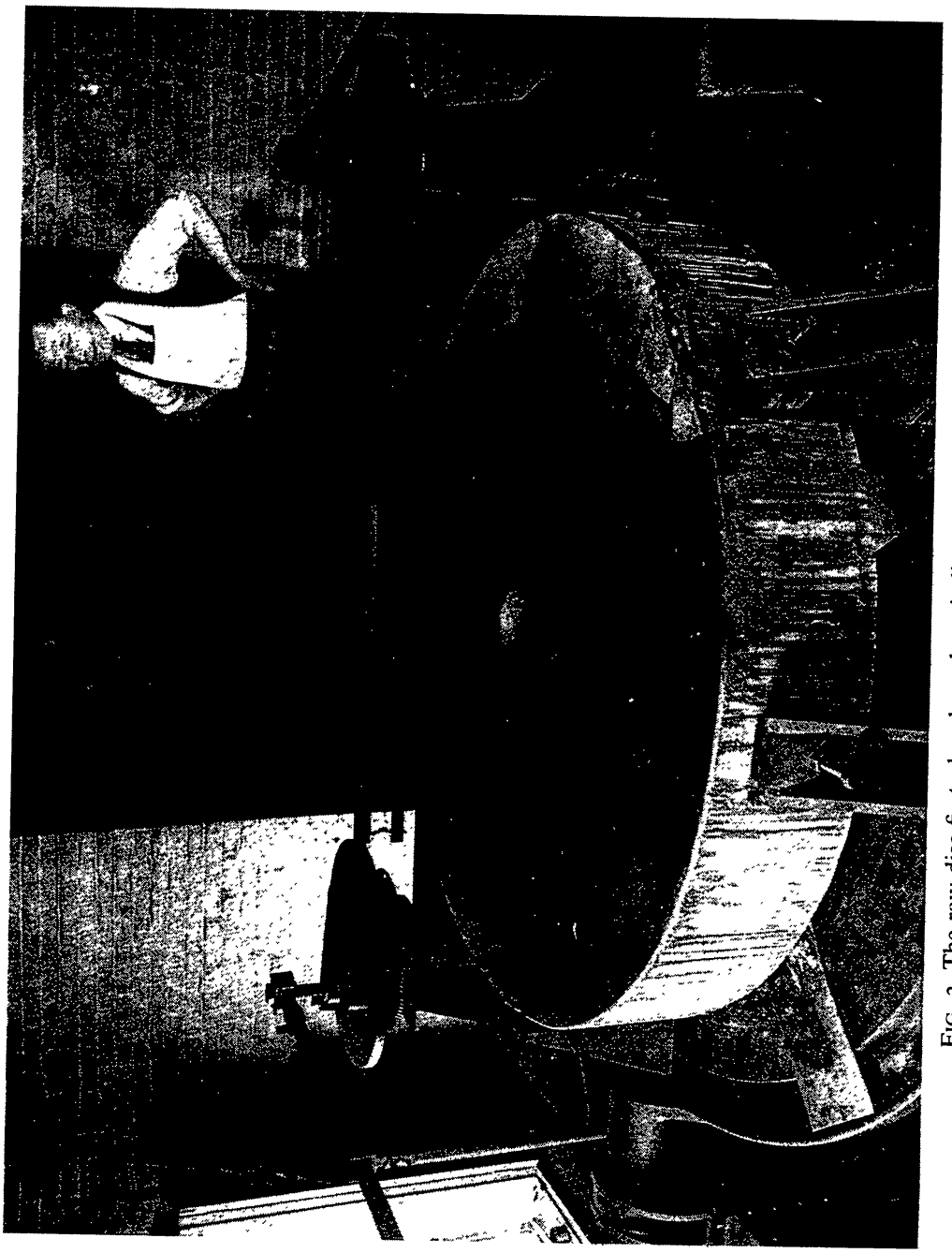

FIG. 2. The raw disc first placed on the grinding machine at Grubb–Parsons.

Thermal Syndicate in the U.K. This material had the lowest expansion coefficient of all glasses available at the time. Unfortunately, it was not then possible to make quartz discs large enough for the primary, and the seemingly safe choice of a special 'Pyrex' borosilicate glass was made for this mirror. Although its expansion coefficient was higher than that of fused silica, it was nevertheless a great improvement over plate glass, the only alternative. The use of Pyrex for large blanks had just become practicable thanks to the efforts of the Corning Glass Works to provide a disc for the Palomar 200-inch project. In fact, the 74-inch Toronto telescope contained the first large mirror of this material. Its blank had been cast successfully in 1933, apparently without difficulty, and its figuring had been completed early in 1935 (**9**).

6 THE SAGA OF THE MIRROR BLANK

Grubb's had already entered into negotiations with the Corning Glass Works, the only supplier of this material, for a Pyrex mirror blank of 76 inches diameter, before they had received the Radcliffe contract. Thus, they were ready to place an order as soon as the contract was signed. At first, things seemed very promising and delivery was expected to take place in 1936 July, though the actual date was 'uncertain'. Little did anyone at the time realize what that fateful word would finally come to mean.

Soon, Grubb's started receiving letters announcing delays from Dr O.A.Gage, head of the Corning division responsible for producing astronomical blanks: 'We have had an unexpected increase in business this fall which has necessitated the use of the furnace that we formerly employed for melting glass for these big discs' (1935 November 18); 'We regret that it has taken us so long to secure information as to when the Pretoria disc will be cast. We expect... we can cast your disc late in March or early in April... We are very much in hope that... the disc will be ready for shipment not later than sometime in August...' (1936 January 3); 'I am sorry to have to write unpleasant news to you but we will be unable to manufacture the disc, which you so kindly ordered from us, at this time but will be able to produce it sometime in May. One of the large melting units had to be repaired... repairs were much more extensive than we had anticipated... delayed by bad weather and flood conditions...' (1936 March 24). These were the same floods that had endangered the 200-inch blank which, in fact, left Corning with great publicity two days later. 'Again the unhappy task of writing to inform you of further postponements... probably be July 1st before it is (cast) and this will mean shipment about the first of next year...' (1936 June 2).

By this time Knox-Shaw was beginning to get really anxious. On 1936 July 4 he wrote to Young: '... No more news, I suppose, from the Corning people? I can hardly write the word without prefixing some opprobrious epithet!...'

At last, on July 16, Gage had good news: '... Your disc was successfully cast yesterday morning and is now in the annealer. Dr McCauley wishes to leave it there until probably late in October...'. (Dr G.V.McCauley had been the person most involved in the successful production of the 200-inch blank.)

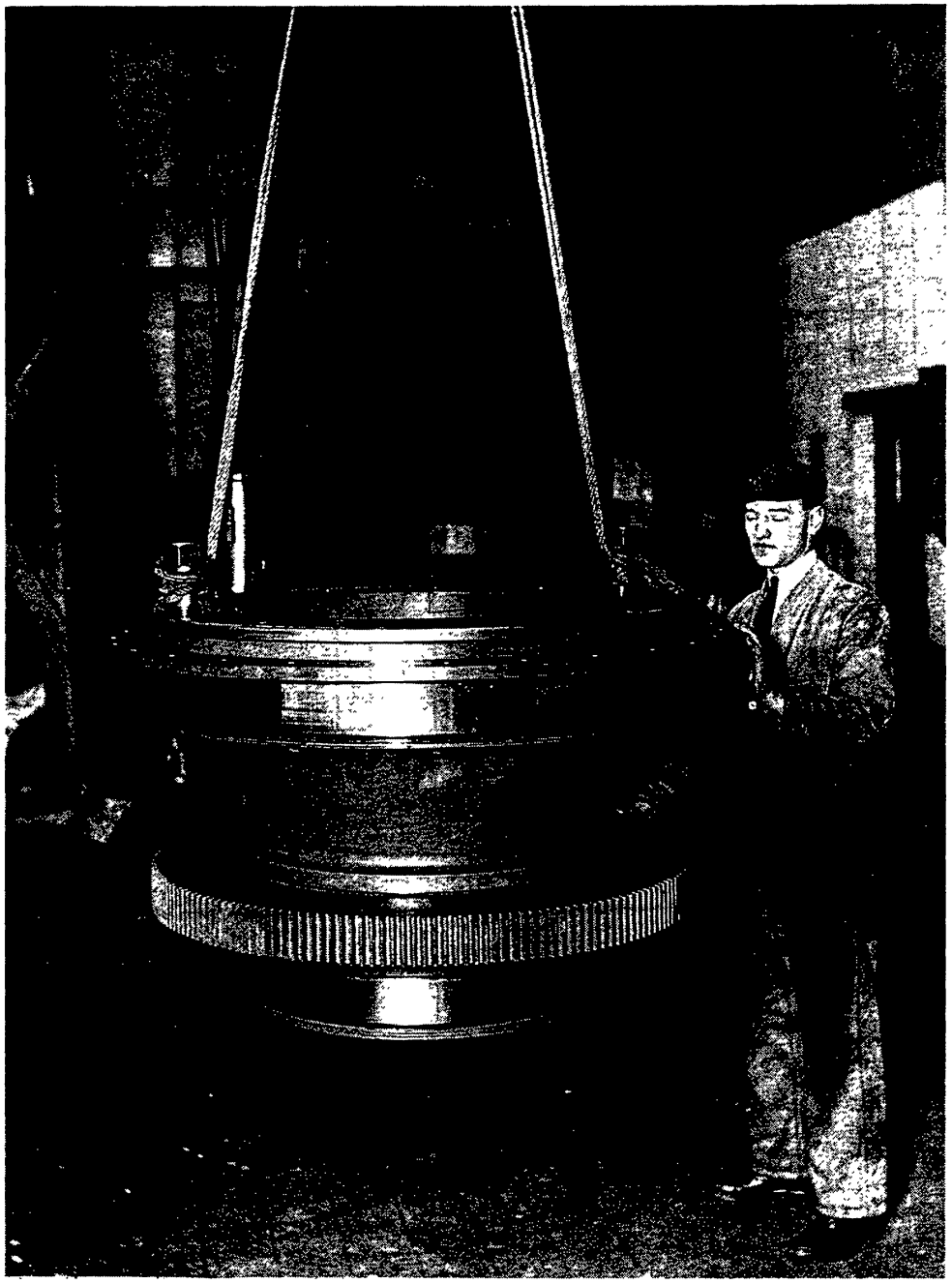

FIG. 3. Tommy Hall contemplating the declination axis. Its short overall length was necessary to avoid obstructing the coudé beam.

Hopes rose at this announcement. Optimistically, Young informed Knox-Shaw that the mirror should be received at the end of 1937 January. But this was not to be the case as Young had to cable Knox-Shaw, then visiting the construction site in Pretoria: CORNING REPORT MIRROR DISC USELESS PROMISE SHIP REPLACEMENT SEPTEMBER'. Knox-Shaw was devastated. '... instead of leaving here, as I should have done, full of satisfaction, I am cast in gloom of the deepest kind...'.

An explanation had been sent by mail from Corning on December 28:

'upon taking it out of the annealing furnace we find that the glass in some unknown way was contaminated during the pouring operation and is useless. A new disc will have to be cast. We regret exceedingly...'. In March a letter was received from T.Dunham of Mt Wilson who had obtained a piece of the defective disc for study. He reported that 'Large cords of "Poison Glass" run through it. Some are more than an inch wide, i.e. in diameter. Numerous cracks emanate from these cords deep under the surface. It is clear that the glass would be of no use for a telescope'. Cords are zones having a different refractive index from the bulk of the glass. They have the appearance of ropes or strands. More bad news was to follow (Gage to Young, 1937 April 30): 'This is a letter which I am very loath to write because it contains most unpleasant news... We have not been able to start to remake the 76-inch disc... For the last year we have been blessed with an especially large volume of business... it has become necessary to remove the equipment to another part of the plant... we cannot give you any definite promise now as to what our production schedule will be...'.

At this point it was realized by Young and Knox-Shaw that something serious would have to be done about Corning's lack of performance. Although another letter expressing disappointment was sent to Corning on May 19, instructions went off on May 20 to Mr F.Jno. Bell, the Parsons representative in Toronto, asking him to get in touch with Corning to expedite matters. Efforts were also made to try to find an alternative supplier for the blank. Bell was soon able to report: 'On May 24th I called at the Corning Glass Works and had a talk with Dr G.V.McCauley... The mold is now being made. Dr McCauley hopes to overcome the causes of defects in the first disc (which was poured from ladles) by selecting pieces of solid glass from the furnace; these would vary in size from about 300 to 600 lbs, and would all be from the same melt. Each piece would be carefully examined before being put into the mold. The mold would be in a beehive furnace and all glass melted sufficiently to make a solid disc...'. By June 8 some progress had been made: Dr McCauley has just started the preparation of your second disc and we hope to have it in the annealer early next week... If everything goes as we expect we should be able to ship sometime in the Fall...'.

Around this time Knox-Shaw received a copy of a report from Dr G.V.McCauley to Dr O.A.Gage, dated 1937 June 22:

'Owing to the necessity of having to complete a disc for the Calif. Institute of Technology, the annealing equipment was not available for immediate work and the recasting had to be deferred until June of 1937. Inasmuch as there was no tank available for making a melt of the special disc glass for this blank and inasmuch as there was ever present a chance that impurities might be introduced by ladling, it was decided to make the second disc from large pieces of glass which had been removed from the tank after the casting of July 1936. This glass could be inspected before casting... it was felt that a successful 76-inch disc could be made by this method... The actual casting of the disc was completed during the week ending June 19, 1937. In the process, two separate re-meltings were made... The disc will start cooling about June 28 at the rate of approximately 3° per day.'

Knox-Shaw felt that this report had confirmed his suspicions: '... Dr McCauley's report of June 22 is most interesting. He gives an entirely

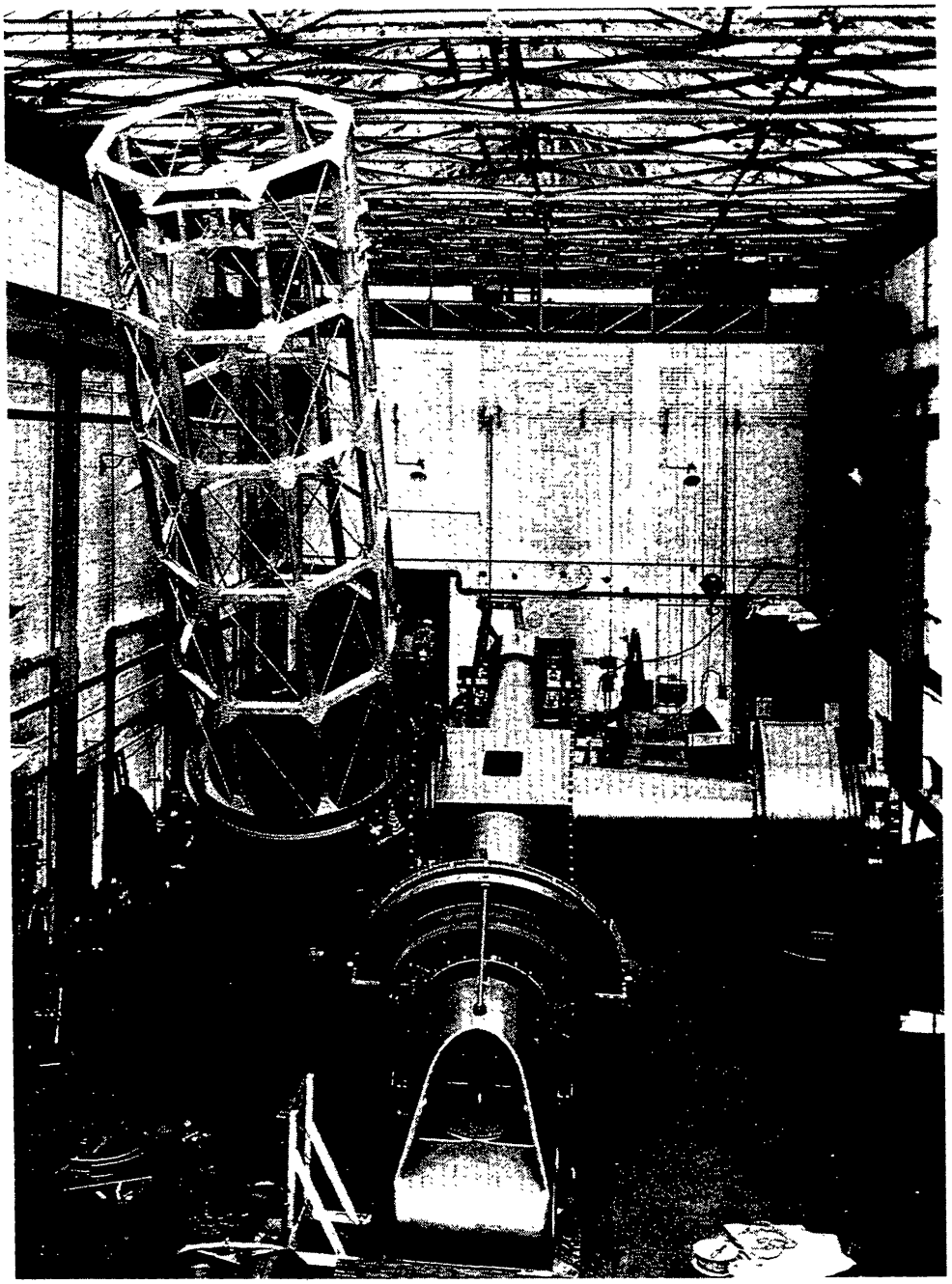

FIG. 4. The completed mounting in the works at Newcastle.

different reason for the delay in casting the second disc than he gave before, which apparently will be made of exactly the same glass as the earlier one....'

The second disc, perhaps not surprisingly, turned out a failure also and a further delay of six months was expected. By the time he heard this news, Knox-Shaw had taken up residence at the new Radcliffe Observatory in South Africa. He wrote to Young on September 29: '...The news...from Corning is so bad that I must refrain from sullying your ears with the only language that can be at all properly applied to it. All we can do is to urge very

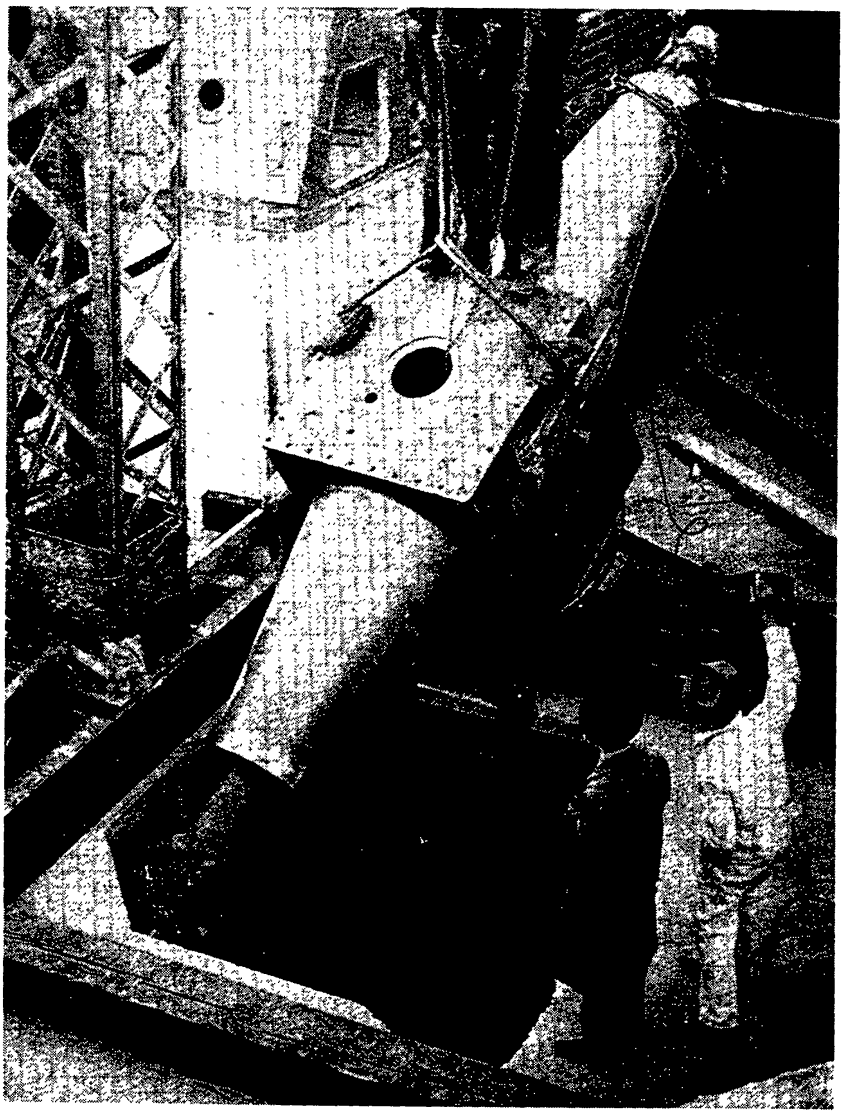

FIG. 5. The polar axis coming up through the lift shaft. No crane of sufficient capacity was available to lift it in directly.

strongly – we are not in a position, I suppose, to demand – that they proceed forthwith to cast another disc. I shall anxiously await news of what they themselves propose to do about it....'

Young showed more sympathy for the engineers at Corning in his reply to Knox-Shaw on October 11 '...you will see that they have already started work on making disc No. 3...I am sure they are as sick as we are over the failures, especially as it must mean a considerable loss to them....' Meanwhile Bell reported: 'Work is proceeding as fast as possible on the production of the third disc and this is expected to be ready for shipment next March. Dr McCauley feels very badly about the two failures and will take all known precautions to insure that the third disc will be satisfatory....'

R.O.Redman, who had been appointed Chief Assistant of the new observatory and was looking after the Observatory's interests in England before proceeding to Pretoria, commented sardonically to Young: '...It is

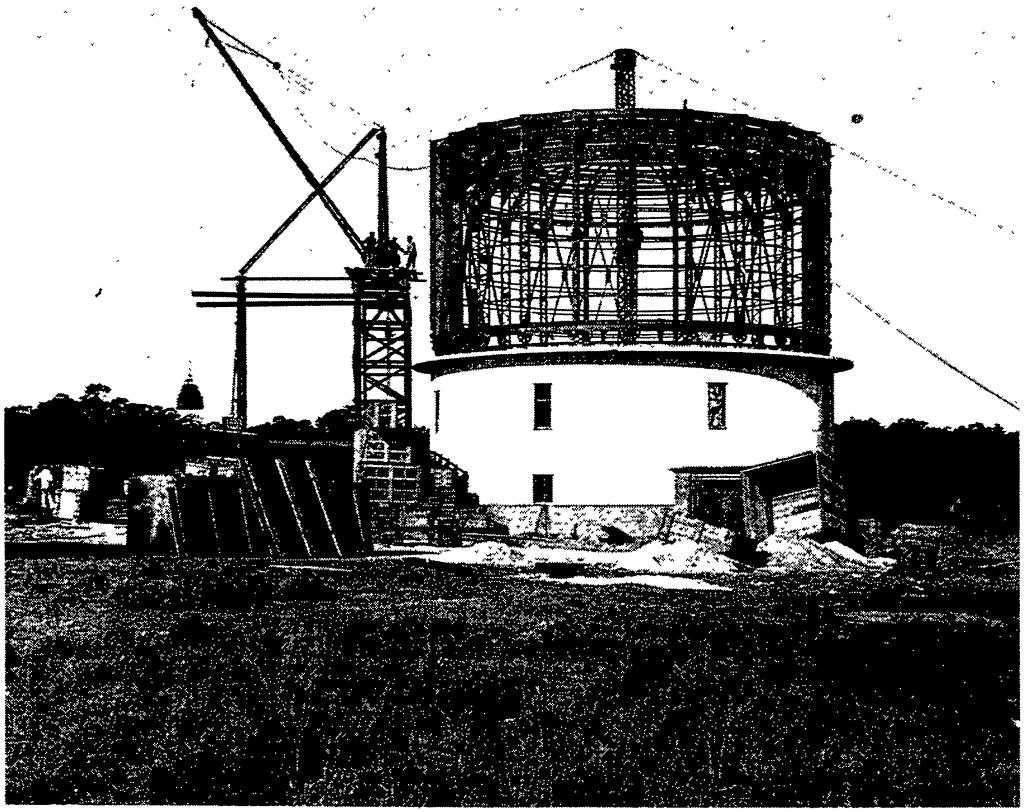

FIG. 6. When the turret skeleton was completed, the first piece of the telescope to be lifted in was the south bearing of the polar axis. In the centre of the turret the latticework pole used for mounting the heavy telescope parts can be seen.

good to hear that McCauley "feels very badly" about the mirror failures. The more conscience stricken the Corning people are and the more money they have lost on this job, the more care they are likely to exercise over disc no. 3....'

The work was, however, proceeding smoothly, as McCauley reported on November 26 '... we are now in the process of casting the individual blocks from which to make the final disc. We have decided upon this means as being the most likely to lead to success....'

By 1938 March 16 Bell was again having to investigate delays: '... I called at the Corning Glass Works and discussed the question of the delay with Dr O.A.Gage... Dr Gage regretted the abnormal delay which he recognized was a serious matter for us, and mentioned in passing that they were not without financial and other troubles in connection therewith... one unusual cause of delay was due to the 8000 lbs of glass having cracked into a few large pieces and many smaller pieces, instead of the reverse as expected.' Knox-Shaw's patience was severely tried as his next letter to Young showed: 'Re- Mirror Disc. --!! What else can one say?....'

By this time the telescope had been completed on schedule and the mechanical parts were on their way, minus optics, to Pretoria. Further reports followed from Corning: (1938 April 27) 'The special blocks which Dr McCauley has been grinding and polishing have been completed and are being placed in position in the mold. Dr McCauley will start melting down

the glass next Monday and we hope by the middle of the week to have the disc cast.' (1938 May 5) '... the disc is now being cast and will be placed in the annealing kiln today. Dr McCauley advises that approximately three months will be required for the annealing period. There is not a great deal of additional information that we shall be able to give you until the disc is removed from the kiln and carefully inspected.'

Finally, on 1938 August 15, Knox-Shaw heard the news for which he had waited so long: 'MIRROR DISC SATISFACTORY THEY HOPE DESPATCH AUGUST 20'. He replied to Young with relief: 'Your cable that arrived this morning was most welcome and cheered us up no end...'

The disc arrived in Newcastle on 1938 October 6. During November, Grubb's paid out $10000, the total cost of the contract, to Corning. The delay of just over two years was ultimately to prove much more serious than anyone had predicted.

7 ERECTION OF THE TELESCOPE IN PRETORIA

In spite of the frustration caused by the failure to obtain a mirror blank, the construction of the mechanical parts of the telescope had been going ahead at Grubb Parsons' works in Newcastle and the turret had been manufactured by the Cleveland Bridge and Engineering Company in Darlington. Both were pre-assembled in England for checking before shipment. The firm of Dorman Long in Johannesburg was given the contract for the erection of both items in Pretoria. The turret parts were sent out first and started arriving at site early in 1938 March. Several of them had been damaged in transit and had to be straightened out in Dorman Long's shop. To the horror of everyone concerned, it turned out that no crane of suitable capacity would be available for lifting the 15-ton polar axis through the slit and it would therefore have to be manoeuvred up through the hole in the observing floor that had been provided for the mirror hoist. Grubb's very wisely took out insurance cover for risks on erection!

The telescope parts arrived in Durban on May 13 and Hall, Grubb's man on the spot, went down to supervise their unloading. Knox-Shaw sent Young a progress report on May 27: '... the incompetence of the people doing the erection has irritated me almost beyond endurance. Their tackle is extraordinarily primitive – you should hear Hall on the subject! – and when there is an alternative way of doing things, as there usually is, they almost invariably choose the wrong one and have to do it all over again.' Young replied: 'I'm not surprised at you being wild with Dorman Long & Co., I shudder to think of the Polar Axis going up through the hole in the floor.' All 45 boxes of telescope parts had arrived by June 8, one truckload having been lost for a few days. 'They carted the polar axis up the hill on a 10-ton truck. Fortunately its springs held.' By June 24, Knox-Shaw could report: 'The getting of the polar axis up through the lift shaft was a terrible business (a little more of that sort of thing and my few remaining grey hairs would be turned white), and necessitated smashing the floor at one corner of the octagonal hole.' On July 15 the worst was over and Knox-Shaw wrote: 'All the heavy parts of the telescope are now erected, and it really looks like a telescope. Indeed its unusually large height above the observing floor makes

FIG. 7. Knox-Shaw surveys the 'extraordinarily primitive tackle' used to mount the telescope in Pretoria. Lifting was done using the latticework derrick in the middle of the picture. Its motive power was provided by means of six men operating a winch!

it look very impressive, even to an astronomer, while casual visitors on coming onto the floor just gasp.'

The remainder of the erection proceeded quite smoothly with only minor problems to be sorted out. Friction arose between Knox-Shaw and Hall at one point over the polar axis bearings, which he did not understand how to align, and also over the altitude of the polar axis itself, which was found to be too high due to a faulty clinometer which Hall could not believe was out of adjustment. Expressing his frustration in a private letter to Young, Knox-Shaw remarked: 'I consider Hall good at his job up to a certain limit. The trouble is he does not realise he has any limitations, and has been on one or two occasions extremely impatient of any criticism or advice on matters which we might be expected to know about as much as he... There were a few other matters on which I found Hall's stubbornness irreducible, such as his refusal to take what I considered adequate precautions to protect the telescope against rain, until we had 1/2 an inch over it....' Otherwise, 'He has been very keen throughout to give us a good job, and but for him Dorman Long would have got away with countless shoddy pieces of work. Except for a very few occasions I have found him a most pleasant man to deal with.' Young replied: '... sorry to hear he made himself unpleasant at times. Your expression "does not know his limitations" is apt, I rather suspected it. Sir C. Parsons had no use for people who would never admit that they were wrong.'* The finishing work dragged on. We hear in September: 'There has been even less progress than usual since I last wrote. The painting of the turret is not going at all well, as it is coming out patchy. It does not seem that the Dorman Long man who is doing the job really knows anything about painting, though they call him a painter.' Another minor source of aggravation was the electrician: in November, Knox-Shaw wrote: 'The electrician has not quite finished the wiring. He left the job unfinished ten days ago, and refuses to come back on it – it is a way they have in this country!' By 1939 January everything was in order and the correspondence had settled down to a series of minor enquiries about servicing and small improvements. The previous month Knox-Shaw had even found time to get married. All that was required to perfect his world was a 74-inch mirror.

8 OPTICAL WORKING

Once the mirror blank arrived in Newcastle, Grubb's wasted no time in getting to work. By November 4 the back had been ground and was being polished. But on December 4, Young wrote to Knox-Shaw to tell him that Armstrong, their chief optician, had died suddenly. However, no delay was anticipated as 'one of our optical men who used to be with us in Dublin knows quite a bit about parabolising & Manville about testing'. G.E.Manville (1910–88) had joined Grubb's while an apprentice in 1932, working initially on optical testing and later on the control of telescopes. He eventually became General Manager and a director of the Company, retiring in 1977.

* Mr G.M.Sisson writes (Sisson to Glass, 1988 April 17): 'Tommy Hall was a headstrong man, but a great one to get things done against all odds – say anything you like about him. I sent him on many a job with confidence.'

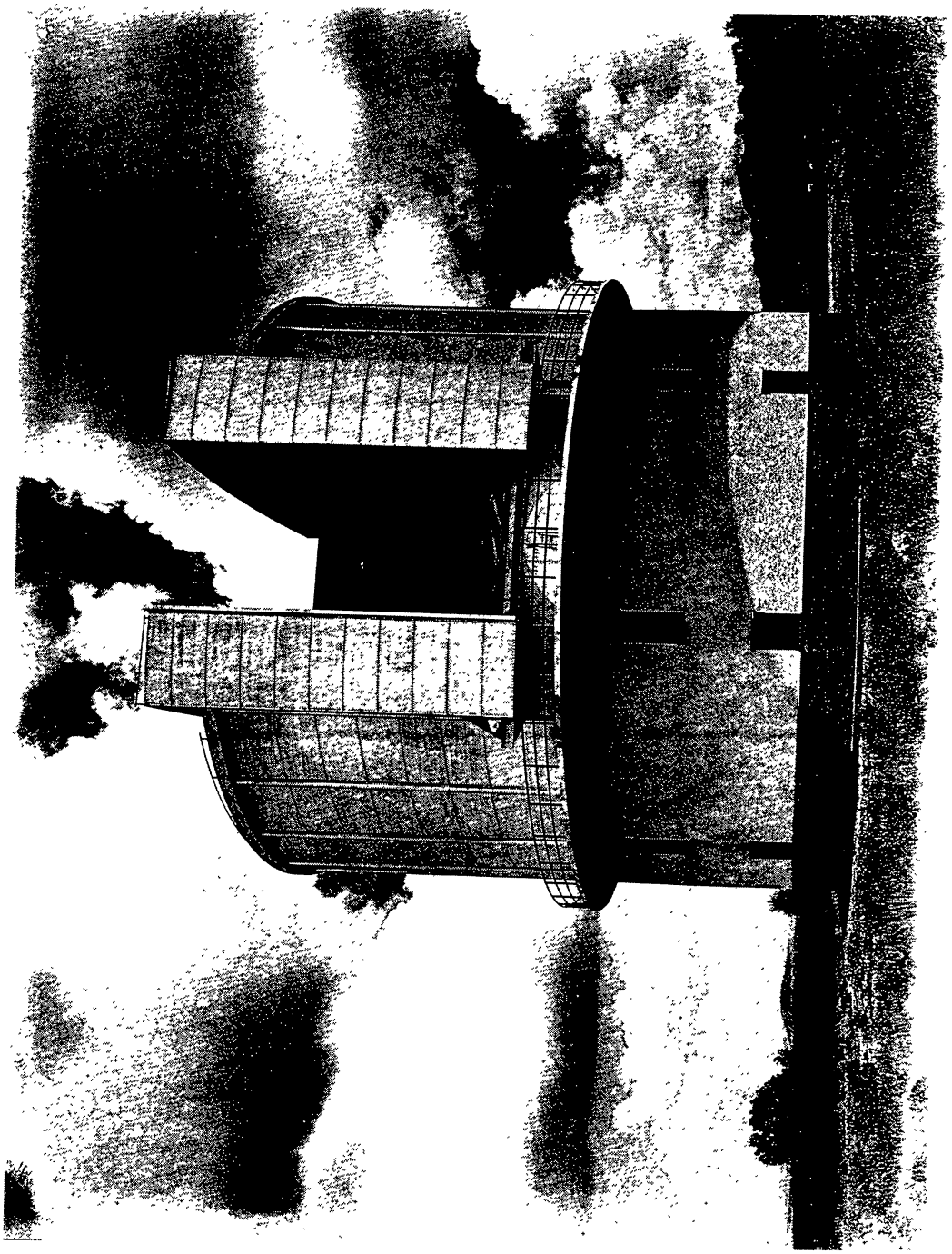

FIG. 8. The completed turret in Pretoria.

After the edge was ground, the disc was found to be about $\frac{5}{16}$ of an inch thicker on one side than the other, so it had to be turned over and ground to make the faces parallel. It was decided to remove a $\frac{1}{4}$ inch of glass from the front side to get well beneath the surface skin, which might contain inhomogeneities.

On 1939 February 24 Young told Knox-Shaw that Frederick Hargreaves (1891–1970, a highly successful amateur optician who later was one of the partners in the firm Cox, Hargreaves & Thomson) had agreed to 'make your mirror. I expect to complete it in record time.' In record time it certainly was – it took almost nine years! He continued: 'We hope to get Hargreaves to come here permanently. He would love to do so as his heart is entirely in this work. He was immensely impressed by what he saw here and in the Heaton works (the turbine manufacturing plant of the parent company, C.A.Parsons) and said he hadn't spent such an interesting day for a long time. I have taken a great liking to him and feel that we would get on together, & that it would be a real pleasure to work with him. As I think you know, Armstrong was a thorn in my flesh ever since we came here in 1925 & simply would not cooperate. The directors recognise that for the well-being of Grubb–Parsons we should get the best man we can, & H is obviously *the* man... We have finished edging the disc....'

On 1939 September 3 England entered the Second World War. On September 12, Grubb's had to notify the Radcliffe Trust that 'Owing to the war, we have been obliged by the Ministry of Supply to concentrate all our efforts on work required for the services. We have reluctantly therefore had to suspend work on the 74″ mirror, and it is extremely doubtful whether we shall be in a position to do any further work while the war lasts. Meanwhile we should be glad of your instructions as to what you would like us to do with the disc. We suggest we dig a hole in the space behind these works and bury the mirror, covering it with sandbags, etc., where it should be safe from anything except a direct hit.' Later they stated (September 15): 'We have had a great deal of trouble in endeavouring to obtain a "figure of revolution", but in spite of various alterations made to the polishing machine under Mr Hargreaves' direction we have been unable to get rid of the astigmatism. We have come to the conclusion that the trouble must be due to variations in the hardness of the glass and decided to grind a further $\frac{3}{16}$ inch off the surface. This was in process of being done when work on it was suspended'.

When Knox-Shaw heard of this he was aghast. 'I had expected that the work was even nearer completion than it actually was, as I had not heard before of the failure to remove the astigmatism... However, I am not accepting without a struggle the suggestion that nothing should be done to it for the duration of the war, and I am writing to Spencer Jones (the Astronomer Royal) asking him, if it is quite impossible to have this done in England, to explore the possibility of having the mirror finished in Pasadena.' Although this threat to patriotic pride soon had the desired effect, the next letter from Young informed him that the mirror had in the meantime been buried as suggested. 'The lawyers will have a plan showing the position and arrangement of burial, in case we all get blown up.' The five auxiliary

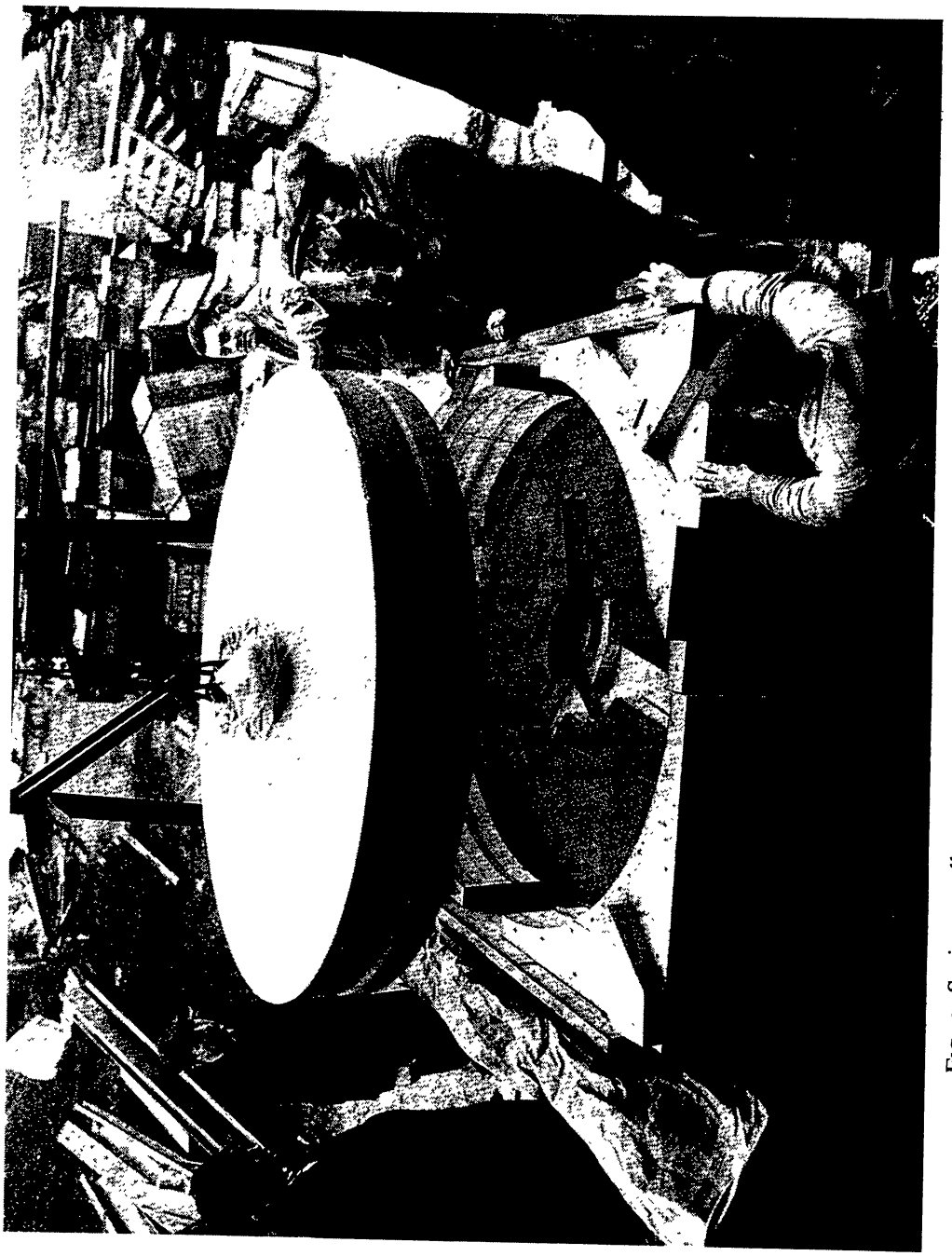

FIG. 9. Saying goodbye to 'an old friend' – the packing of the mirror before it left Newcastle for the journey to Pretoria. G.M.Sisson on extreme left.

mirrors, which had already supposedly been finished, were sent into the country for safety.

By October 31, Young wrote to say that if nothing could be done at Grubb's, they would take the matter up with Warner and Swasey. However, he went on, 'I don't want to raise false hopes but I have good reasons to think that we may be able to proceed in about a month's time owing to delays in the delivery of optical glass...'. On December 6 he reported: 'the first job to do before we can proceed with the mirror itself will be to alter the radius of the grinding tools... we cannot get any skilled men either for the optical shop or the mechanical shop for the love of money [*sic*]'.

On 1940 January 2 Knox-Shaw wrote: 'I am glad to hear there is a prospect of your getting going on the mirror again. In the meantime I have heard from the Astronomer Royal that Adams (Walter Adams, Director of Mt Wilson Observatory) has made a most generous offer to finish it for us, and we think that unless you are in a position to go ahead and continue work on the mirror until completed, which I hardly expect you are, then the best solution of the difficulty would be for the mirror to be sent to Pasadena as it is.'

Young was obviously not going to let the mirror out of his hands. Later that month he informed Knox-Shaw that one of the grinding tools had already been corrected and that the runner for the polishing tool had been ground true 'We are, therefore, going to dig the disc up as soon as climatic conditions allow (if I say any more the letter will probably be censored), and proceed with working... Manville has been training a number of fresh hands in the optical shop and has double the number he had a few months ago.'

By June 3, work was again in full swing. Manville had got rid of the astigmatism but the shape was not quite spherical due to a "bump" in the middle. A special 3-ft polisher was being made to reduce it. Young reported: 'Hargreaves has not been up yet but proposes to come on the 10th, I only hope he won't expect everyone here to be at his beck & call, or he may have to be squashed.'

After the fall of France later that month Knox-Shaw wrote: 'I should not be surprised to hear shortly that you have had to bury the mirror again. In any case I am afraid you have been having an unpleasantly lively time lately. They don't tell us exactly where the air raids are, but it is clear that Tyneside has had them at least once. You are all much in our thoughts these days.'

Work evidently continued, if intermittently, during the next few years. Most of Grubb's efforts were concentrated on war-related work such as coastal defence range-finders, gun sights, periscopes and even instrumentation for a wind tunnel at Farnborough where fighter planes were being developed.

In 1941 January, Knox-Shaw wrote: 'The mails are most erratic now-a-days, but we must be thankful that they do arrive eventually. I am glad to hear that the mirror is progressing. I think it is marvellous that you can carry on work of this kind.' There must have been some word of trouble with Hargreaves, because in May 1941 Knox-Shaw mentions: 'I can well imagine that you found H. difficult.' In fact Hargreaves' relationship with Grubb's had had to be terminated. The letter carried on: 'We live a peaceful life here, still to a large extent untouched by the war. I am afraid Tyneside has been

FIG. 10. D.S.Evans at work on the mirror cell.

having a bad time lately, but hope you have been among the fortunate ones. We think much of you people at home and marvel at the way you are carrying on.' In 1943 November, Young wrote that they had been able to put in a considerable amount of work on the mirror in the previous few weeks. The polish was very good, 'but still not good enough. A very small amount of glass removed from the right place would make it excellent, but it appears to be difficult to do this without removing too much elsewhere.'

As the war drew to a close in 1945, Knox-Shaw wrote to enquire: 'How is the mirror going? I am hoping that the pressure of your war contracts may now be lighter and that you will be able to work continuously on the mirror. The seas should very soon be relatively safe for its transport, and we are

naturally very anxious to get going. I am expecting to retire quite soon and I should like, if possible, to see the telescope completed before I do... Greetings to you all – it is delightful to think of you as being free at last from the threat of bombs and such like abominations'.

Young was also keen to retire – in fact he had been due to go at the beginning of 1940 – and to see the job completed. He replied in 1945 June that they were busy reducing a turned-up edge and that he had told Manville that he expected it to be finished by the end of the month, at which time he would be handing over to G.M.Sisson. In 1943 he had told Knox-Shaw: 'I've got a first rate assistant now, George Sisson, aged about 26, Charterhouse & Cambridge & a nice and clever lad. He will take over when I retire which I expect will be at the end of the war.' In 1945 Dr Steavenson again became involved with the new Radcliffe Observatory, this time because someone based in England was needed to monitor the progress of the mirror. In October, Knox-Shaw ventured to hope that it was finished. 'You will be as glad to get rid of it as we shall be to see it!' he wrote to Sisson. But there were still problems. A month later, Sisson replied: 'I am glad to say the mirror is going very well, but we have the greatest difficulty in determining its actual figure with sufficient accuracy to justify further working. If the weather favours us with still and reasonably warm days, we do very well if we can work it once a week, but normally once a fortnight is about the number of workings we can carry out. The turn down, which was our trouble on Dr Steavenson's last visit, has been quite eliminated. A good deal of work had to be done with the polisher to rectify matters, and naturally the rest of the figure was disturbed considerably. Our difficulties are very nearly overcome now, and we are feeling very optimistic.'

In 1946 March Sisson stated that Manville thought it would be possible to have the final inspection carried out that month 'but the difficulty with a big mirror is that you can never say for certain any completion date'.

By December 1946 Knox-Shaw was having to write: 'What news can you give us of the mirror?... we have heard indirectly that Dr Steavenson tested it in November and considered it satisfactory. It would indeed be cheering news, with which to start the New Year, if we could hear that it was really finished!' Sisson replied in January of the following year: 'subsequent to his inspection a good deal of argument has developed regarding a wrinkle near the edge. The departures from the ideal surface are about one millionth of an inch, and apart from this, the Mirror is smooth and very satisfactory. It is difficult to get anybody to commit themselves to an expression of opinion as to the effect of the small error when the mirror is in service. The Astronomer Royal has decided to take a second opinion, and we expect Dr Burch from Bristol University to visit us and carry out an inspection.' Burch's opinion was evidently favourable, but Sisson was still not willing to let matters rest. On May 30 he was writing: 'As you may have heard, Mr Bates of Bristol University has produced a new interferometric method of examining mirror surfaces, and this has been tried out most successfully on the Pretoria mirror. It has revealed... a zone at the extreme end (edge) of the mirror, about $1\frac{1}{2}''$ wide and perhaps over three millionths high. Manville has tackled it... We are going to have another go at it and knock off that little wrinkle. The new testing method has proved a wonderful help in assessment of narrow zonal

aberrations, and far from being glad to get rid of the mirror, we shall feel we have lost an old friend.' Bates's new instrument was the wavefront shearing interferometer, the first really quantitative means for testing telescope mirrors all over (**10**).

On July 23 we hear: 'The wrinkle on the edge of your mirror is now at last imperceptible, and we are expecting to hear any day whether the mirror is to be sent to Pasadena or to be sent direct to you for use silvered'.

No further reports exist of work being done on the mirror but it must have been officially accepted shortly afterwards as one can see to this day an inscription on the edge of its front surface which reads: 'Grubb-Parsons No 5108/10572/M1 Parabolic Mirror 74 inch aperture (76 inches diameter) $10\frac{7}{8}$ inches thick Central Hole 7 inches diameter Weight 1 ton $12\frac{1}{2}$ cwt Focal length 360 inches for the Radcliffe Observatory Pretoria (signed) G.Manville 29–10–47'.

In a later letter Sisson commented that they had made 12 Hartmann plates of the mirror. Each diameter had to be tested separately as the air became stratified in the test tunnel and made the mirror appear astigmatic. (Grubb's afterwards built a double-skinned testing tower, the outer wall of brick against wind and weather, the inner a steel skeleton on a separate foundation to support the measuring equipment. The vertical system of testing completely eliminated the problems formerly encountered.) 'The Hartmann Criterion derived from the visual Gaviola tests is 0·10 and the results of our measures on the photographic Hartmann plates show a Criterion of 0·14.' The Hartmann tests on the Toronto mirror had yielded a value of 0·20 for this quantity, a measure of the image diameter for a point object.

9 THE MIRROR ARRIVES IN PRETORIA

There had been much talk before the War of sending the mirror to Pasadena for aluminizing before shipping it to South Africa. However, when it eventually was finished, the decision was made to stick with silver in spite of its lack of reflectivity in the ultraviolet. The mirror was shipped after silvering in Newcastle, but unburnished: very gentle rubbing with plain cotton wool was the recommended method for the final polishing. The cell had to be altered because the mirror had a finished thickness of $10\frac{7}{8}$ inches at the edge instead of the $13\frac{1}{8}$ inches that had been expected when the mechanical parts were made. This arduous task, which involved much hand-drilling, and the installation of the mirror when it arrived, was carried out by David S.Evans, Second Assistant from 1946 to 1951, and three unskilled labourers, with advice from Henri Besaans, 'our local friendly engineer' (**11**). Redman had left for Cambridge the previous year to become Director of the Observatory there. He had personally done most of the maintenance required during the War.

The mirror was shipped in 1948 February on the S.S. *Dalesman*. It was 'stowed comfortably between decks, surrounded by bags of sugar with pressed fibre board on top, so it should have a comfortable and friendly journey'. It arrived at Durban harbour on April 14, nearly three weeks late, having been unable to enter the harbour for some time due to a gale. 'The railways transported it to Pretoria in the record time for a goods truck of five

FIG. 11. Harold Knox-Shaw with an antique refractor outside the front door of the telescope.

days, and we collected it at 8.30 a.m. on the 20th. At 3 p.m. we opened the lid of the case and had a peep inside.' By May 12 the mirror was safely mounted in the telescope and the asbestos-filled insulating pillows had been placed in position.

Only the Newtonian flat of the secondary mirrors had been sent at this stage and, of course, this had also to be mounted. During its aluminizing before the War a molten blob of aluminium had fallen near the edge and a small piece of fused silica surface had flaked away. Fortunately, however, only an elliptical portion of this circular mirror was actually going to be used and by an appropriate rotation the defect could be hidden from the pupil.

The early tests showed that astigmatism was present. At first it was thought that the flat was at fault, but rotating it in its cell showed no change

in the direction of astigmatism. The edge supports of the primary were also carefully checked, but to no avail. Finally, it was found that the pivots on which the nine primary supports rested were seized up. Once these had been freed, the astigmatism disappeared.

10 SECONDARY MIRRORS

The Cassegrain and coudé secondary mirrors, although they had been regarded as acceptable before the War, were found on critical examination during 1949 to be below standard. Hindle-type testing was employed to determine their figures, but the spherical auxiliary mirror was not of very good quality, which made the testing all the more difficult. Sisson and Manville did not regard the Cassegrain secondary as finished until 1950 February. Its absence had not mattered too much as the Cassegrain spectrograph which had been ordered before the War had not yet been delivered. ('Hope deferred maketh the heart sick' wrote Knox-Shaw to Messrs Casella, the dilatory makers of its mechanical parts.) The coudé secondary was finished in 1951 March but was not sent out for another year. It and the two flats were mounted in 1952 December and appeared satisfactory. The telescope could then be regarded as complete, having taken about 17 years from start to finish of the contract.

11 LATER HISTORY OF THE TELESCOPE

Even before the primary had arrived, the telescope had been put to use as a mount for some photometric cameras borrowed from the Royal Observatory, Cape Town, and its finders had been used by Redman and others for photographic photometry. However, its productive life as part of Radcliffe Observatory coincided with the appointment of David Thackeray (1910–78), at first in 1948 as Chief Assistant and later in 1950 as Radcliffe Observer when Knox-Shaw retired. Although circumstances were such that the latter had been able to make little use of the 74-inch himself, he had the satisfaction of seeing it in action to great effect during the twenty years that remained to him. When he died, a bronze plaque was erected to his memory on the north pier of the telescope. It reads:

IN MEMORIAM
HAROLD KNOX-SHAW
1885–1970
RADCLIFFE OBSERVER, 1924–1950. THROUGH WHOSE LABOURS
THE RADCLIFFE OBSERVATORY AND THIS TELESCOPE
WERE SET UP UNDER THE SOUTHERN SKIES
TO THE LASTING BENEFIT OF ASTRONOMY.

HE HAS LOVED THE STARS TOO TRULY
TO BE FEARFUL OF THE NIGHT.

In 1959 it at last became possible to aluminize the primary mirror thanks to the construction of a large coating plant designed by Michael W. Feast (then Second Assistant); before that the primary had to be re-silvered every

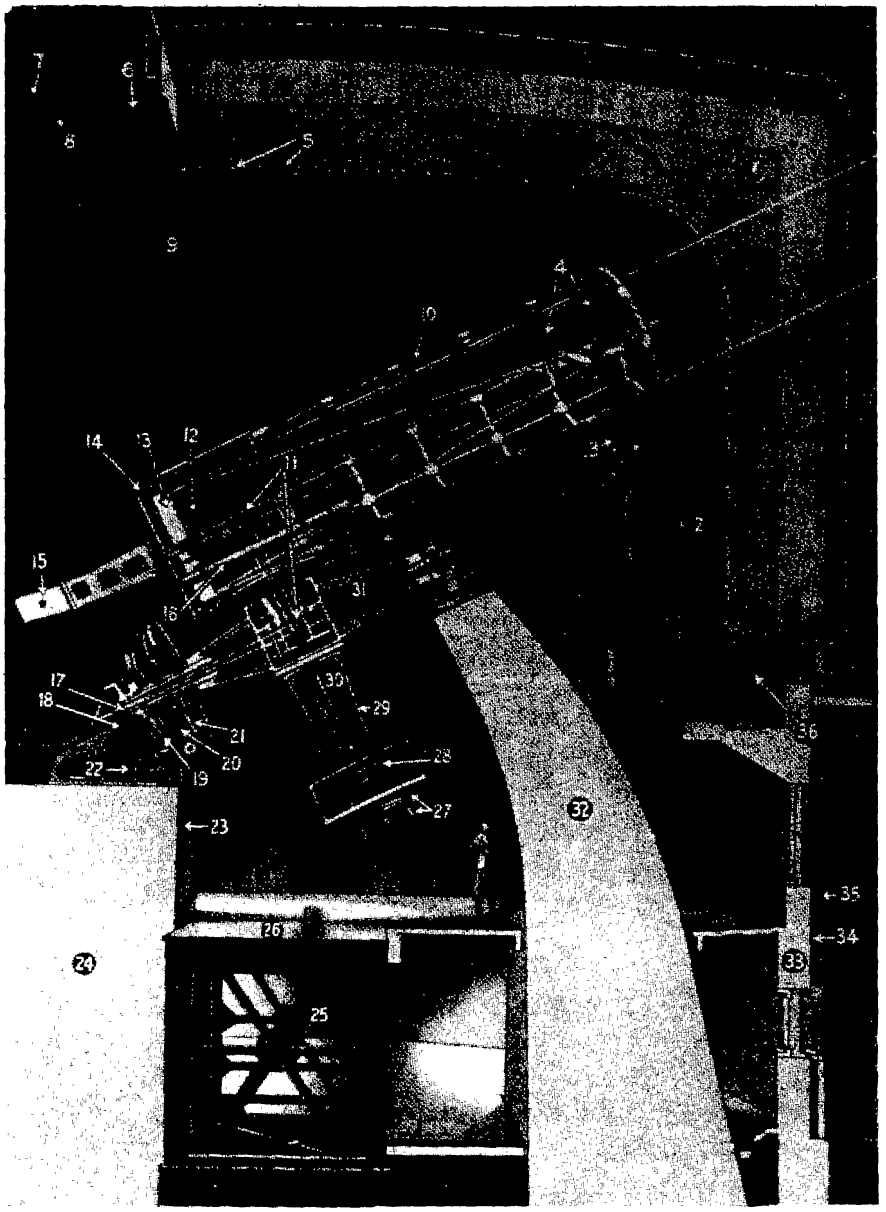

FIG. 12. Cut-away view of telescope and turret drawn in 1938 for the *Daily Telegraph* and *Morning Post* by W.S.Clatworthy. The optical system employed is shown by white lines within the instrument, indicating reflected light rays. 1, Observer's platform, raised or lowered on carriage and swung out as required. 2, Carriage of platform, travelling round turret on rollers. 3, Camera. 4, Edge-on mirror supports, obstructing light as little as possible. 5, Rollers of blind used to close aperture except directly in front of tube. 6, Two-feet air space between double shell. 7, Sheet steel, painted aluminium. 8, Insulating board. 9, 61ft. revolving turret. 10, The 35ft. duralumin lattice tube. 11, Flat mirrors. 12, Mirror shutters. 13, The 74in. mirror, a perfect glass slab silvered on its upper concave surface. 14, Mirror cell, showing how mirror is supported on sprung pads at base and round periphery. 15, Spectrograph which will be provided. 16, Small field telescope for locating desired objects. 17, Coudé focus. 18, Alternative hand drive. 19, Quick-turning gear wheel keyed to axis. 20, Driving circle, mounted free, but clamped to gear wheel for slow motion. 21, Sidereal circle, rotated by hand wheels. 22, Motor drive. 23, Compensating clock motion drive. 24, Concrete pier. 24, Lift and carriage which takes mirror to basement for resilvering. 26, Trap-door, over which tube is up-ended for removal of mirror cell. 27, Adjustable balancing weights. 28, Tube

few months. (The smaller mirrors had been aluminized since the start in a tank constructed by D.S. Evans.)

12 MOVE TO SUTHERLAND

The Radcliffe Observatory, Pretoria, although more adequately financed in its last few years than it had been earlier on, thanks to support from the Science Research Council of the United Kingdom, came to an end in 1974, when government funding was diverted to the newly constructed Anglo-Australian telescope. The Radcliffe foundation could not afford to run it unaided. The telescope and other instrumental assets of the observatory were sold by the Trustees to the South African Council for Scientific and Industrial Research for use at the Sutherland observing station of the South African Astronomical Observatory, whose director was then Sir Richard Woolley (1906–86). The telescope and turret were dismantled commencing in 1974 September. Reassembly at Sutherland was completed in 1976 February. The right ascension axis had to be changed from 26° to 32° inclination because of the change in latitude. Some quick thinking had to be done when it was found on lowering the polar axis into place that the mounting piers had been cast a few inches too far apart!

13 MODERNIZATION

When observing with the 74-inch restarted in its new location, its mechanical parts were showing their age. For example, the only indication of where it was pointing was by means of large setting circles which could be read, at best, to about 1 arcmin by means of verniers. In practice, the setting accuracy achieved was more like 3 arcmin, which is very poor by present-day standards. Some of the controls were too coarse to be of any use at all and had been abandoned – for example, slewing in R.A. was performed by hand using a large steering wheel and declination guiding had to be done by jabs on the set buttons. The clutches had become unreliable, requiring frequent attention to keep them operating. Money was made available for a programme of improvements initiated by the writer with help from Alistair Walker (**12**). The biggest change was the installation of absolute optical encoders having 19-bit (approximately 2 arcsec) resolution on each axis. The outputs of these are read by a minicomputer which applies appropriate corrections to give pointing positions accurate to better than 20 arcsec over most of the sky for any desired epoch. In the space of a few years all four of the R.A. and Dec fast and slow-motion drives were largely rebuilt and modernized. The turret azimuth was also encoded and automatic positioning was introduced with the programming help of Luis Balona.

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rotating gear. 29, Counterpoise arm, balancing tube. 30, Declination axis round which the tube is elevated. 31, Polar axis, round which instrument rolls. It is parallel to that of the earth. 32, Concrete pier. The piers are deeply bedded in the ground and partly hollow to avoid subsidence through their weight. The floors are cut away round them so that contact should not induce vibration, 33, Brick wall. 34, Six-inch air space. 35, Expanded metal skin. 36, Roller ring of turret.

Before 1978 all observing at the Cassegrain focus, which was by far the most frequently used position, had to be done at some personal risk from the tops of ladders, as the eyepiece could sometimes be 5 metres or more above the level of the floor. An integrating television camera now replaces the eye of the observer at the telescope and most of the controls of the auxiliary instruments have been made remotely operable. The observer now works, as at most large telescopes, from the comfort and safety of a warm room. In 1982 a chopping secondary giving an alternative Cassegrain focal ratio of f/50 was installed to a design of the writer's. This greatly improved the sensitivity of infrared photometry of wavelengths beyond 3 microns, where both telescope and atmosphere become luminescent. The mirror proper was made of Zerodur low-expansion glass ceramic and figured by Grubb-Parsons. Happily, its delivery was made on time!

14 CONCLUSION

At 50 years of age, this venerable instrument is still in great demand both by local and overseas observers. Its continued usefulness is a tribute to the efforts of its builders and those such as Harold Knox-Shaw and Roderick Redman, who gave large parts of their professional lives to ensure that it was built to the highest standards possible in their time.

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