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Airy's transit circle

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Abstract
The history of this remarkable instrument from conception to retirement is described. Its seminal design and construction are considered, in the context of both its astronomical purpose and the quantification of errors of adjustment necessary to ensure maximum precision of its output. Major modifications, operational procedures, and the programmes carried out with it are also detailed.

Keywords: *meridian instruments, Greenwich Observatory, positional astronomy.*

1 INTRODUCTION

Airy's transit circle (ATC), which came into use 150 years ago, is an instrument of unusual significance. Its innovative design gained it an immediate reputation for the accuracy of its observations, and was copied for other observatories. Some of its design features were later adopted in many new instruments world-wide. It provided the basis of the Greenwich Time Service for 76 years, and despite its design proving only partly suitable for the increasing demands of twentieth-century positional astronomy, it continued to fulfil a useful role until 1954. This working life of 103 years is unequalled by any other positional instrument. Its status was recognized by the decision of an international conference in 1884 to adopt its meridian as the prime meridian of longitude for the world.

When it was already in its 56th year Simon Newcomb, former Superintendent of the U.S. Nautical Almanac Office and arguably the most respected positional astronomer since Airy, wrote:

> With all its shortcomings, the Airy transit circle has proved to be the most serviceable meridian instrument ever constructed. The result is that the Greenwich observations during the past half-century afford the broadest basis we now possess for the determination of those stars of which accurate positions are most required. (Newcomb, 1906).

Twenty-five years later the Astronomer Royal, Sir Frank Dyson, announced that a new transit circle was to be built "as the present instrument is nearly worn out"[1]. Although the new instrument was erected in 1936, a number of problems were encountered during its commissioning, and then further delay was caused by the effects of the Second World War. Consequently useful programmes with it did not begin until 1957, following its relocation to the new home of the Royal Observatory at Herstmonceux Castle in Sussex, and Airy's instrument continued in use until the Meridian Department was closed down at Greenwich and transferred to Herstmonceux in 1954.

A very brief history of the ATC was published by one of its distinguished former observers as it finally neared the end of its active service (Witchell, 1952), and a concise description of the instrument is included in the Tercentenary history of the Royal Observatory (Howse, 1975:43-48)[2]. The significance of the new instrument was recognized from the start: the Council of the Royal Astronomical Society included a five-page account of it in its Annual Report to Fellows, believing that details of its construction "may have an importance greatly exceeding that of a new instrument of the National Observatory" and were an example of "the kind of changes which may be anticipated as necessary in the increase of dimensions likely to be given to the object-glasses of telescopes" (RAS Council, 1851).

2 AIRY'S DESIGN CONCEPTS

When Airy became Astronomer Royal in 1835, the principal meridian instruments in use at Greenwich were the Troughton Transit Instrument and Mural Circle, of which he remarked

"The state of the meridian instruments is most satisfactory".[3] As described elsewhere in this volume, however, from about 1843 onward Airy was engaged in a thorough review of the instruments that would be needed in future to maintain the Royal Observatory's long record of positional observations of the highest accuracy for the Sun, Moon, planets, and fundamental stars (Satterthwaite, 2001). As part of this review he had become aware that although the transit instrument continued to perform well, its aperture of five inches (12.7 cm) was insufficient to observe the much fainter minor planets then being discovered, or to determine the positions of very faint background stars in observations of comets obtained with equatorial instruments of much greater aperture. These positions were required for calculations of the comets' orbital elements.

Figure 1. George Biddell Airy in 1852 – the year after the ATC commenced operation.

Airy decided to install a new suite of positional instruments, which would include a transit circle and an electric chronograph. The first instrument to be constructed was the Altazimuth, completed in 1847, and both Airy and the manufacturers gained experience in its construction which was to prove useful in the manufacture of the transit circle.

In 1846 January Airy spent some time at his cottage in Playford, Suffolk, engaged in drawing up plans for the transit circle. He sought the advice of his friend Charles May (1800-1860), head of engineering at Ransome & May, a long-established firm of manufacturers of agricultural machinery based in Ipswich who were contracted to construct the massive parts of both the altazimuth and the transit circle. The precision parts and divided circles were entrusted to William Simms (1793-1860) of London, Troughton's successor and former partner.

This division of responsibilities demonstrates a major part of Airy's design philosophy. The instruments were to be made with a massive superstructure of cast iron, solidly mounted and with no provision for fine adjustments. The optical parts, divided circles, micrometers, etc. were to be manufactured to the highest standards of precision and attached to this superstructure. The cast-iron superstructure was to be made in as few pieces as possible, and these were to be bolted together, not screwed. The whole instrument was to be supported on massive stone piers.

Airy recognized that small errors of adjustment were inevitable in such instruments, however great the engineering skill applied in their manufacture, and that these would in any case be variable from one observation to another, due to the effects of changing ambient conditions. He therefore required the instrument to be as solid and structurally stable as possible in order to minimize such effects, and then made provision for determining the extent of residual errors of adjustment at regular intervals during the observing watch, so that appropriate corrections could be calculated and applied to the observed positions.

3 ERRORS OF THE TRANSIT CIRCLE

The errors to be measured and corrected for in the reduction of observations of right ascension (RA) and zenith distance (ZD) were an important consideration in finalizing the detailed design of the instrument. Errors which affect the observed RAs are level, azimuth, and collimation errors, and any departure from exact cylindrical form in the pivots; those which affect observed ZDs are errors in the determined zenith point, inaccuracies in the circle graduations, and flexure of the telescope tube.[4] In addition to the instrumental errors it is also necessary to know the error and rate of the clock used for the transit observations.

3.1 Errors Which Affect Right Ascension

Pivot errors should be very small in a well constructed and properly maintained instrument, and once measured require rechecking only occasionally to monitor the effect of any mechanical wear. Level, azimuth, and collimation errors vary continually with the prevailing conditions, and can also show long-term effects which can be very difficult to determine. They must therefore be monitored frequently.

3.1.1 Level Error

This is caused when the mechanical axis is inclined to the horizontal. Its effect is zero when the telescope is directed towards the horizon and increases to a maximum at the zenith. In the case of small transit instruments it was measured with the aid of an accurate spirit level placed across the pivots (a 'striding level'), but for larger instruments this would be both impractical and insufficiently accurate and a different procedure is used. The instrument is set vertical, with the objective downwards, and a trough of mercury placed beneath it to form a perfectly horizontal reflecting surface. Using a Bohnenberger eyepiece (Figure 2), which provides for the illumination of the 'wires' of the eye-end micrometer[5], the transit wire of the RA micrometer is set coincident with its own image reflected in the mercury surface. In this position the light-path 'wire–mercury–wire's image' must be exactly vertical. The micrometer reading for this position is read, the difference between this and the line-of-collimation (LOC)[6] determined at the time is the level error.

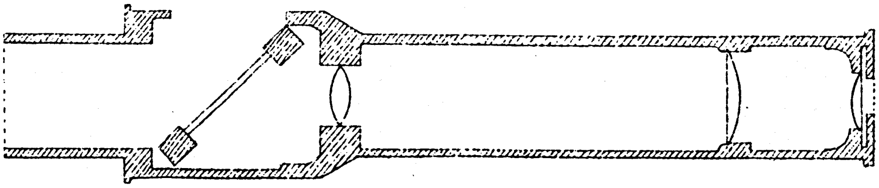

Figure 2. Diagram of the Bohnenberger eyepiece, described by Airy as the 'nadir eyepiece' (after Airy, 1853:Plate XVI, fig. 32).

3.1.2 Azimuth Error

This arises when the mechanical axis is inclined to the true east–west line. Its effect is zero when the telescope is directed toward the zenith, and increases to a maximum at the horizon. The azimuth error cannot be determined by direct measurement, but can be derived from observations of fundamental stars if the level error is small and the error and rate of the transit clock are known. When the corrected clock time (local sidereal time) is equal to the RA of the star, the star must be on the meridian.

There are three methods for determining the error: by combining 'above-pole' and 'below-pole' observations of the same star made twelve hours (or multiples of twelve hours) apart; by combining above-pole and below-pole observations of different stars made during the same watch; and by combining an observation of a very close circumpolar star (e.g. Polaris) with one of a 'clock star' (i.e. a star culminating south of the zenith).

3.1.3 Collimation Error

This is caused if the optical axis of the telescope is not exactly perpendicular to the mechanical axis. Its effect is to cause the telescope when rotated to trace out not the meridian, but an arc of a small circle separated from it by a small angle constant at any altitude. Collimation error can be determined from observations of a distant azimuth mark, or by the provision of a pair of collimating telescopes (see section 4.7 below).

3.2 Errors Which Affect Zenith Distance

Errors in the circle divisions are determined by a lengthy programme of readings of the circle microscopes at many settings of the telescope through a complete rotation, entailing thousands of readings. They are virtually constant, but over time it is possible for the measured position of a division to be altered by wear of the graduated surface, so division errors are re-determined at lengthy intervals.

3.2.1 Flexure

Flexure may be described as the sagging of the two telescope half-tubes under their own weight; when the telescope is set horizontal it may be measured by setting its ZD micrometer wire on the horizontal wire in each collimator in turn. It is usually constant, and therefore requires rechecking only occasionally. Unfortunately its effect at other settings of the telescope cannot be directly measured, and must be calculated on the basis of an assumption as to how it varies with altitude.

3.2.2 Zenith Point

The circle is set to read exactly 0° 0′ 0″.00 when the instrument is pointed toward the zenith. In practice, however, the reading will differ slightly from this by an amount which varies with ambient conditions, and a correction must therefore be applied to the observed ZDs. The zenith-point reading is taken at the same time as the level error is measured, with the instrument set vertically over the mercury surface. The wire of the ZD micrometer is set coincident with its own reflection and the circle micrometers read. This gives the setting for the nadir, and hence by subtracting 180°.0, for the zenith.

4 CONSTRUCTION

Airy published a detailed account of the design specification of the Transit Circle, including sixteen plates of detailed drawings (Airy, 1853). Figure 3 shows the general appearance of the instrument.

4.1 The Telescope and Axis

One of the most important considerations in the design of a transit instrument is the rigidity of the joint between the telescope tube and the east–west mechanical axis. Troughton had achieved this in the design of the existing transit instrument, but Airy's proposed instrument was very much larger and heavier, and required a correspondingly massive construction. He settled for a central 'cube' constructed as part of the axis, to which the telescope half-tubes could be rigidly bolted: "I propose that the whole be made of cast-iron: the axis being in two parts (which

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enables the founder to make the pivots of hard chilled iron while the rest is of soft iron) and each end of the telescope being in one part".[7] Airy required the pivots, of diameter 6 inches and bearing length about 5 inches, to be perfect cylinders to within 1/30,000 inch; it was found impossible to achieve this accuracy by mechanical means, and each pivot required six weeks of 'hand-finishing'.[8]

The cube is of 19 inches side, and the overall length of the mechanical axis was six feet. The telescope tube is almost twelve feet in length overall, and the whole assembly weighs almost 2000 pounds (907 kg). An elaborate system of counterpoises takes much of this weight, however, the residual weight borne by the Y-bearing supporting each pivot being about 150 pounds (68 kg).

Figure 3. The Airy Transit Circle. The north collimator housing has been tilted to the east, a position that permitted observation of objects low on the meridian.

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An arrangement for raising the instrument out of its Y-bearings and clear of the collimators was part of the original design. A pair of stirrups suspended from two massive screw-cut vertical rods can be wound up to raise the axis of the instrument (which must first be set horizontal), via bevel gears using a cranked handle accessible from the top of the steps. This enables the operator to raise both sides of the axis equally and simultaneously, so that it remains level throughout the operation.

4.2 The Objective

Airy had specified an objective of 8 inches (20 cm) aperture, giving a light-gathering power of more than two and a half times that of the existing transit instrument. Simms had intended to manufacture this using crown and flint glass blanks imported from France, but the flint glass was of poor quality so instead he "worked on" a lens bought in from Munich. He offered this to Airy for £300; after testing it and finding it satisfactory Airy authorized its purchase – at a reduced price!

> An object-glass of 8 inches clear aperture and 11 feet 6 inches focal length, having been placed in my hands by Mr Simms, I carefully examined it. I found that it shewed some objects not of the closest class (as ε Bootis and ζ Cancri) better, I think, than I had seen them before: that it separated η Coronae: that it did not separate γ Coronae (which, having witnessed the difficulty of that star in the great Pulkowa refractor, I was prepared to expect): and that it dispersed light no more than the best object-glasses usually do. At my recommendation, therefore, this object-glass was purchased by the Lords Commissioners of the Admiralty, at the price of £275.[9]

The separations of the double stars used by Airy were ε Bootis, 2″.7, ζ Cancri 0″.9, η Coronae 0″.66, γ Coronae 0″.48 (Lowne, 1981). The separation of η Coronae is just about at the theoretical limit of resolution for an 8-inch lens, so the objective was of good quality. The aperture of the Pulkowa refractor was 15 inches (38 cm).

The objective suffered from discoloration of the inner surfaces of its components. It was cleaned in 1871, 1873, and 1888, cleaned and repolished in 1891 and 1906. The Board of Visitors passed a resolution in 1930 drawing attention to the need for a new transit circle, the Astronomer Royal commenting that "the object glass, which is badly stained, is too thin to bear further polishing".[10] In 1946 it was reported that "The progressive deterioration of the objective through atmospheric corrosion is making observations with this instrument increasingly difficult".[11]

A quarter of a century after the ATC ceased operation, the National Maritime Museum, by then responsible for its preservation, invited the Royal Greenwich Observatory to undertake the separation and cleaning of the old objective. The task was undertaken by C M Lowne, who also took the opportunity to carefully examine and test the two components. He found that the severe staining of the inner surfaces was due to corrosion of the metal spacers, and was largely removed by careful washing. The optical tests were interesting; of course, the components had been repolished on several occasions so it was no longer the lens as Airy tested it. Lowne's most disturbing conclusion was that the lens now suffered from excessive coma, which appeared at the rate of 0″.22 per arc minute off-axis angle (Lowne, 1981:50). Coma as severe as this could well have contributed to a bisection error in observations made off-centre.

4.3 Field Illumination

Use of the transit circle at night requires some background light in the field, so that the transit wires can be seen in silhouette (at the expense of some diminution in apparent brightness of the image of the object being observed). In the ATC this was initially provided by a gas lamp (also used to illuminate the circle), via a field lens in the western end of the hollow axis and an inclined, annular, gilded reflector in the centre of the cube. The gas lamp was later replaced by a single electric lamp.

In 1908 a new field illumination system was fitted, in which light from a small, low-voltage electric lamp mounted on the centre of the objective illuminated a small, finely ground glass disk and was scattered uniformly down the axis of the telescope.[12] This provided a

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considerable advantage in that the intensity of the lamp could be controlled by the observer by means of a rheostat, and hence the field illumination could be minimized when observing very faint objects.

4.4 The Circles and Microscopes

The holes for the microscopes were bored on a conical surface through the western pier. An iron ring six feet in diameter attached to the telescope-axis assembly carries a silver band bearing the ZD graduations at 5′ intervals set into its outer face, bevelled so as to reflect the light from the central lamp into the microscopes. The objective assembly for each microscope is mounted directly onto the inner face of the pier. The microscope eye-end micrometers are mounted on a substantial brass plate on the outer face of the pier, and are arranged on a circle 21 inches in diameter (see Figure 4). This arrangement is very convenient for the observer, enabling him to set and read the micrometers from one position. If the microscopes had been mounted horizontally, as in earlier instruments with smaller circles, he would have been faced with gaining access to seven microscope eyepieces in a circle six feet in diameter!

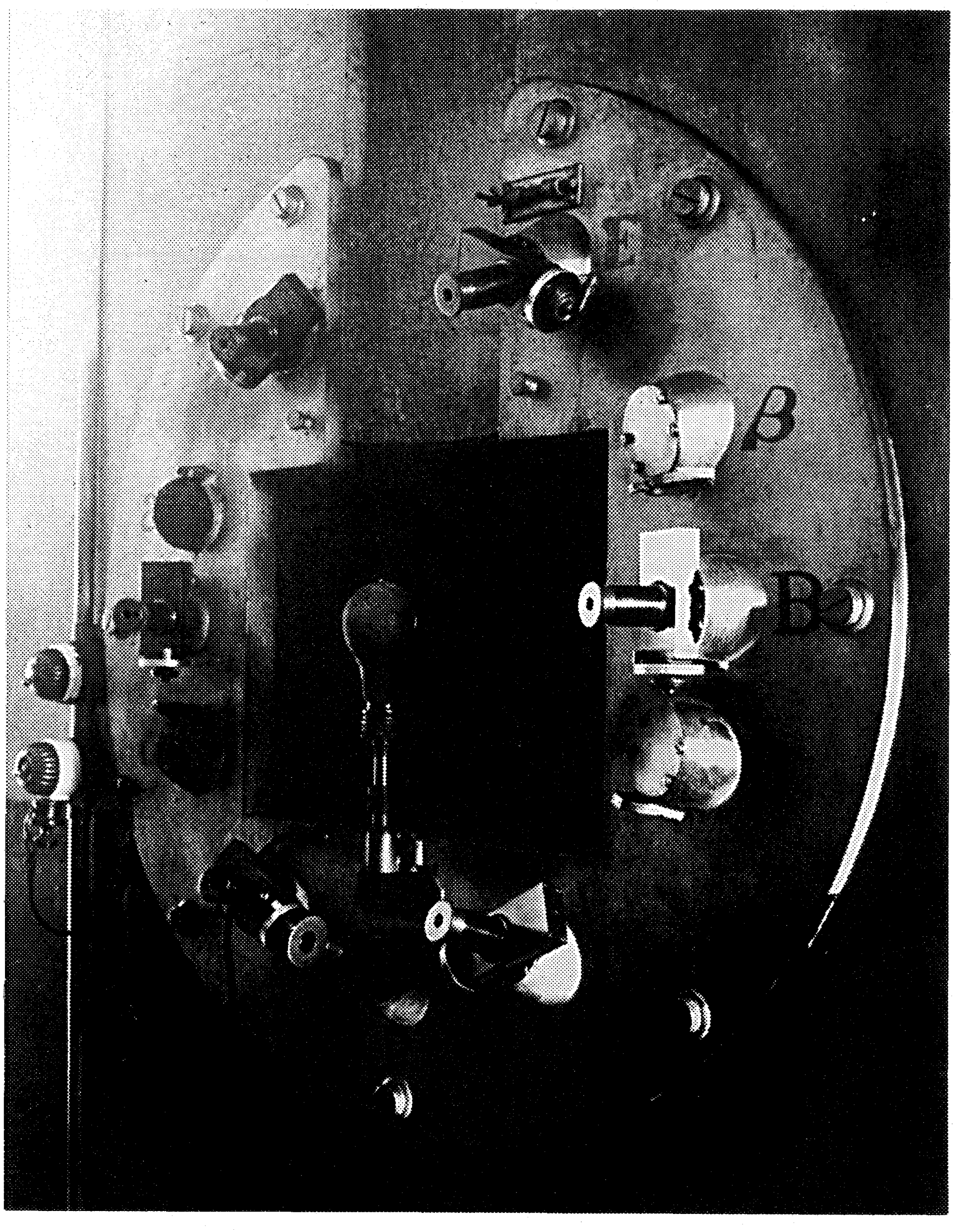

Figure 4. The six circle-reading microscopes and pointer microscope P. The single lamp illuminates the circle under each microscope.

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A lower-power 'pointer' microscope is mounted in the lowest position, for reading the whole degrees. The six high-power microscopes, each provided with an eyepiece micrometer, are mounted at 60° intervals. The four additional mounting points are provided for auxiliary microscopes used in measuring division errors of the circle at additional intervals of 20° and 25°. A simple graduated circle is provided to facilitate setting the telescope, carried on the reverse of the iron ring which carries the divided circle. The corresponding iron ring on the eastern part of the telescope axis provides balance, and is also used as a clamping ring, the clamps being controlled by long poles so that the observer can operate them from the eyepiece.

The precise dividing of circles for positional instruments had been an important factor in their development (see Chapman 1990); the graduations of the ATC were incised with a new dividing engine built by Simms, making it the first major instrument to have a machine-divided circle.

Airy can be criticised for choosing to use silver for the divided circle, for it tarnishes seriously and rapidly and in the polluted London atmosphere this caused frequent cleaning and consequent wear. Over the years many divisions became worn and indistinct, and some disappeared altogether. In 1921, in a unique operation, a number of divisions were recut *in situ*.[13] Worn divisions became a major problem during the last years of use of the ATC. The use of silver must have been a conscious decision by Airy, presumably on grounds of cost, for Troughton had avoided the problem forty years earlier by using an alloy of gold and palladium for his mural circle (Howse, 1975:27).

4.5 The Eye-end Micrometers and Wire systems

Two independent micrometer screw-heads were provided, each moving a frame carrying wires (see Figure 5a). The ZD micrometer moved a single horizontal wire vertically in the field. The RA micrometer wire-frame carried seven vertical wires, and moved horizontally across the field (see Figure 5b). These micrometers were replaced in 1915 when a new eye-end incorporating an impersonal micrometer was fitted (see section 5.2.2 below).

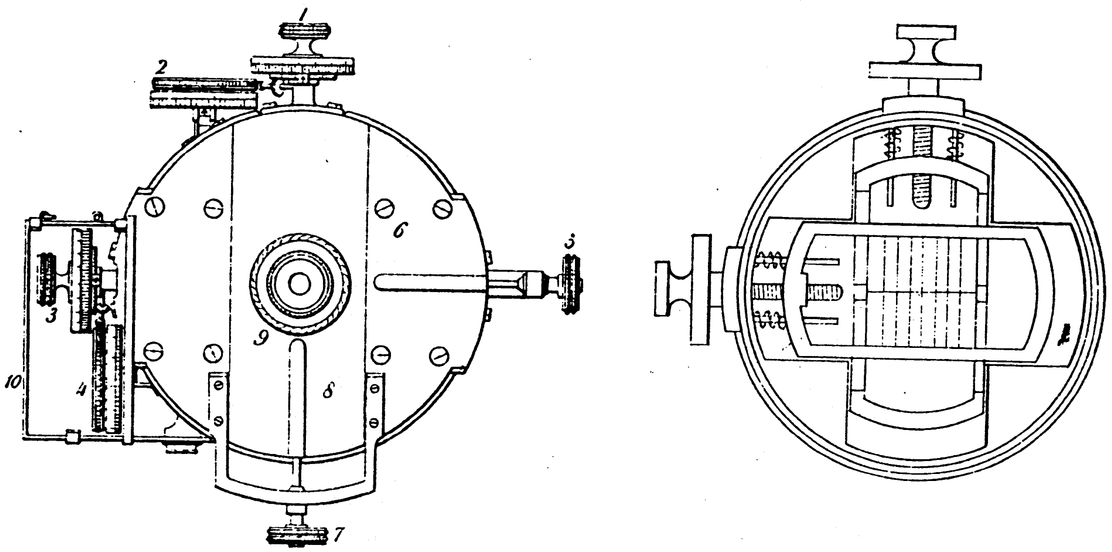

Figure 5. (a) The RA and ZD micrometer assembly. Note the provision to track the eyepiece across the field in both co-ordinates (after Airy, 1853:Plate XIV, Figure 7. See, also, Figure 8(a) below). Figure 5. (b) The wire-frame assemblies (after Airy, 1853: Plate XVI, Figure 27).

4.6 The Mercury Trough

Airy intended to observe stars with the TC both directly and by reflection, and therefore built into his design a mercury trough which could be used for this purpose, as well as for the determination of level and zenith point errors as described above. The trough was mounted on

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two iron bars in a parallel motion assembly which ensured that it was horizontal when used with the telescope at any altitude setting. The weight of the trough was counterpoised by large oval weights carried at the upper ends of the bars (see Figure 3), and a cistern was mounted at the north end of the pit to store and supply the mercury. An alternative position for a small mercury trough for use with the telescope in the nadir position was also provided, located beneath a removable panel in the floor of the pit.[14]

Problems were experienced with the mercury trough. In his detailed description of the instrument Airy refers to changes made to the trough and its mounting (Airy 1853) during the first year of operation. In 1889 an amalgamated copper bottom was fitted to the trough which "... much improved observations by reflection ..."[15], and the following year an entirely new trough made entirely of copper and amalgamated inside was mounted "... with very satisfactory results".[16] Use of a smaller and shallower mercury pool reduces problems due to disturbance of the mercury surface caused by transmitted vibrations, draughts, etc., as well as reducing the difficulties of managing large volumes of mercury.

Matters were further improved in 1948, by the substitution of a spare mercury trough from an instrument no longer used.[17] This consisted of a very shallow concave-surfaced copper disk, set in a wooden frame supported by two angle-iron bars which were placed on pairs of iron studs set in the inner faces of the stone piers. The concave surface was coated with copper–mercury amalgam. Only a very small amount of mercury was needed in this trough, and any dust or other matter on the mercury surface could be easily swept away by running a glass rod across the trough.

4.7 The Collimators

In earlier instruments the line-of-collimation was determined from pairs of observations of a distant azimuth mark, the instrument being reversed in its bearings between the two observations. In larger, more massive instruments this was not considered practicable in Airy's time, and in any case it was unlikely that the error of collimation would remain unchanged during the reversal process. Airy therefore chose the alternative method of providing a pair of horizontal collimating telescopes set in the meridian plane with their objectives towards the TC, one north and one south of it.

The south collimator was provided with an illuminated fixed vertical wire, and the north collimator with a micrometer-controlled wire which was set coincident with the image of the fixed wire in the south collimator, the TC being raised out of its bearings to permit this. The TC was then set horizontal and its RA micrometer wire set on each collimator wire in turn; the difference between the mean of these settings and the centre of the field is a measure of the collimation error.

Simms suggested an improvement, unfortunately too late to be incorporated in the design of the cube castings, that apertures should be provided in the cube to enable the one collimator to be set on the other without raising the instrument.[18] This suggestion was adopted for the replica instrument constructed for the Royal Observatory at the Cape of Good Hope and worked well.[19] In 1865 the cube of Airy's original instrument was pierced, segmentally and not without some difficulty, and provided with shutters.[20] The following year new collimators with a larger aperture were provided[21], and routine measurements of the collimation error were thenceforth made without raising the instrument.

In order to monitor the accuracy of these measures, made through the partially obstructed cube, a comparison of collimation measured through the cube and with the TC raised was made weekly, normally on Monday mornings when the instrument was routinely raised for cleaning and lubrication. The systematic difference found was known as the 'Up–Down correction'. From 1874 January 1 a correction of $0^{r}.019$ (equivalent to $0''.28$) was applied to the collimation errors determined through the cube.[22]

4.8 The Pavilion and Piers

Airy housed the new TC by enlarging the existing circle room, extending it southward into the Astronomer Royal's private garden. A meridian opening three feet wide was protected by a set of four shutters along the roof ridge and vertical door-type shutters at each end. During the reconstruction of the building the Troughton circle was moved to a new temporary location and continued in use until the ATC came into full operation.[23]

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The stone piers that had supported the Troughton and Jones circles were dismantled and re-erected in new positions to support the ATC. Airy's design required 22 large holes, accurately inclined and positioned, to be bored right through one of the piers, eleven of them to carry the circle-reading microscopes and the other eleven to enable the circle under each microscope to be illuminated by the same gas-lamp that provided the field illumination (see section 4.3 above). The borings can be seen in plan in Figure 6. An unsuccessful attempt was made to bore the Troughton circle pier which proved to be of granite; the later pier of Jones' circle proved to be of Portland stone and was successfully bored, and therefore became the western pier of the ATC[24]. It clearly did not occur to Airy that re-using the existing piers might

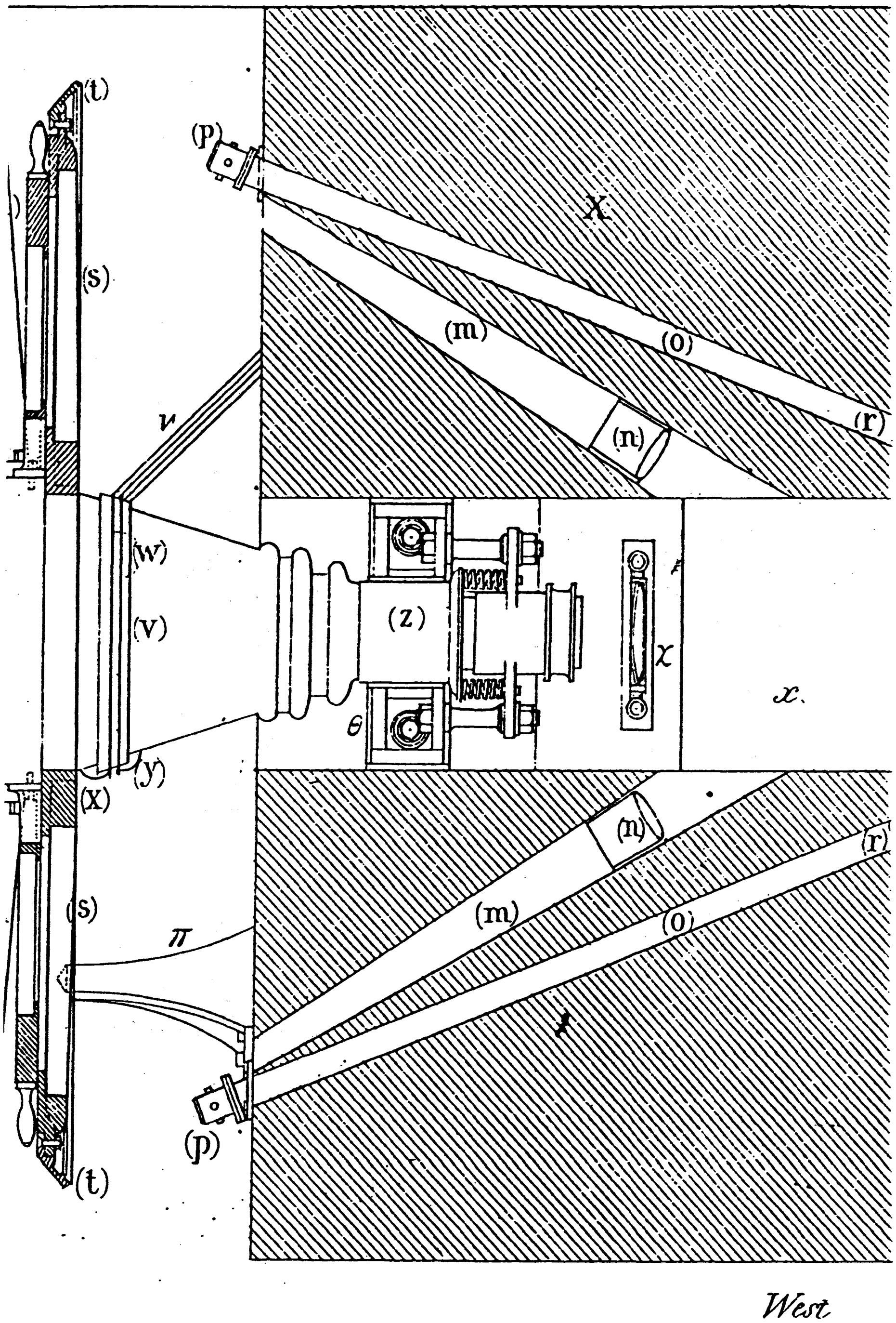

Figure 6. Section-plan of the western pier, showing the borings containing two of the circle-reading microscopes and illumination channels (after Airy, 1853:Plate XI).

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cause future problems, and the fact that they were of different materials appears to have been forgotten for many years. It was rediscovered in 1923 when it was suspected that the differing thermal properties of the piers might have been the cause of small, unexplained diurnal variations in collimation and azimuth. In fairness to Airy it must be pointed out however that these were so small as to have been unmeasurable until observations came to be made with greater accuracy than was possible in his time.

The TC was mounted with its axis approximately 1.6 m above the floor of the pavilion; between the piers the floor level was approximately 1.1 m lower, providing a space from which the observations were made. This sunken area was known to observers as 'the pit'. A padded couch on castors was provided, either end of which could be raised and held by a ratchet at a suitable position to support the observer's head whilst making the observation; handrails were provided on both piers to assist in positioning the couch. For observing lower altitude objects a set of steps was provided at each end of the pit, in which individual steps could be folded up to provide a comfortable stance at the appropriate height.

The wooden staircases which are such a prominent feature of the ATC (see Figure 3) had more than one role to play. Apart from their obvious purpose of giving access to the eye-end of the instrument for level and nadir-point measurements, and to the winding mechanism for raising the instrument, they provide screening to reduce the possibility of sunlight falling on the circle and its supporting iron ring-frame, and also to limit dust falling on the circle. Their design ingeniously provides for the upper steps to be removed and parts of the top platform hinged up, to permit passage of the circle assemblies when the instrument is raised.

5 MODIFICATIONS AND REPAIRS

In a working life of more than a century, routine repairs and replacement of parts were of course necessary from time to time, and minor modifications to the instrument were made to meet changing needs. The basic design and construction of the instrument were so satisfactory however that to the non-specialist eye it appears much the same today as it did 150 years ago. Only major modifications and important changes in its use are therefore documented here.

5.1 Recording ZD Micrometer

In June 1873 a new ZD micrometer was fitted.[25] Designed by W H M Christie, then Chief Assistant and later Astronomer Royal, it incorporated a small drum attached to the micrometer head and covered with a strip of paper. At each setting of the micrometer a pricking device could be used to puncture the paper so that it could be reset subsequently to the same position and the micrometer readings taken at leisure. This greatly facilitated taking several ZD readings as the star crossed each vertical wire in turn, especially for fast-moving stars close to the celestial equator. The new micrometer worked well, but was accidentally damaged and was replaced by a stronger version in 1875.[26]

5.2 Electrical Recording of Transits

As described elsewhere in this volume (Satterthwaite, 2001:110-112), Airy investigated the systems developed for the accurate recording of time in connection with longitude-difference determinations between observatories, and whilst accepting the validity of the principle decided to design his own form of chronograph for use with the new transit circle and altazimuth.

5.2.1 Airy's Barrel Chronograph

The chronograph is shown in this issue of the journal (see Satterthwaite, 2001:111, Figure 6). It was installed and 'galvanic' recording of transit times commenced on 1854 March 27. Subsequent investigations[27] showed that the probable errors of transit observations were only a third to a half of those made by the 'eye-and-ear' method (see section 6.1.1 below). The observer was provided with a small hand-tapper key-switch; depressing this as the star passed each wire automatically sent a signal to the chronograph and the time could subsequently be read against the clock-pulses on the chronograph sheets.

5.2.2. The Impersonal Micrometer

This was probably the most important modification made to Airy's instrument. In 1915 the entire eye-end of the telescope was replaced with one incorporating a moving-wire

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micrometer.[28] In the new micrometer the transit wire-frame carried a single wire which could be traversed across the field by smoothly rotating a two-handed drive spindle. By rotating the spindle at an appropriate rate the star's image was kept bisected by the moving wire and the instants when it passed certain predetermined positions in the field were recorded automatically by electrical pulses sent to the chronograph from a contact-ring attached to the micrometer head. The pulses were sent in sets of three per revolution of the micrometer drum, with a longer gap between sets. Figure 7 shows a small section of a barrel chronograph record. Compare the rapid motion of the near-equatorial star ε Serpentis (Dec. +4°) with stars of much higher declination, for example 51°2107.

The new eye-end (Figure 8) also incorporated a horizontal wire controlled by a ZD micrometer of the same pattern as had been introduced in 1873. To indicate approximate positions in the field the frame also carried nine fixed vertical wires. There were seven wires centred on the axis as in the previous eye-end, numbered 1 to 7, the axial wire 4 representing the meridian.[29] Additional wires were provided either side of wire 4, known as wires 3½ and 4½, to facilitate 'central' transits across the meridian. In 1919 a new set of fixed wires was fitted having no wire 4, which had been found to interfere with the recording of central transits.[30]

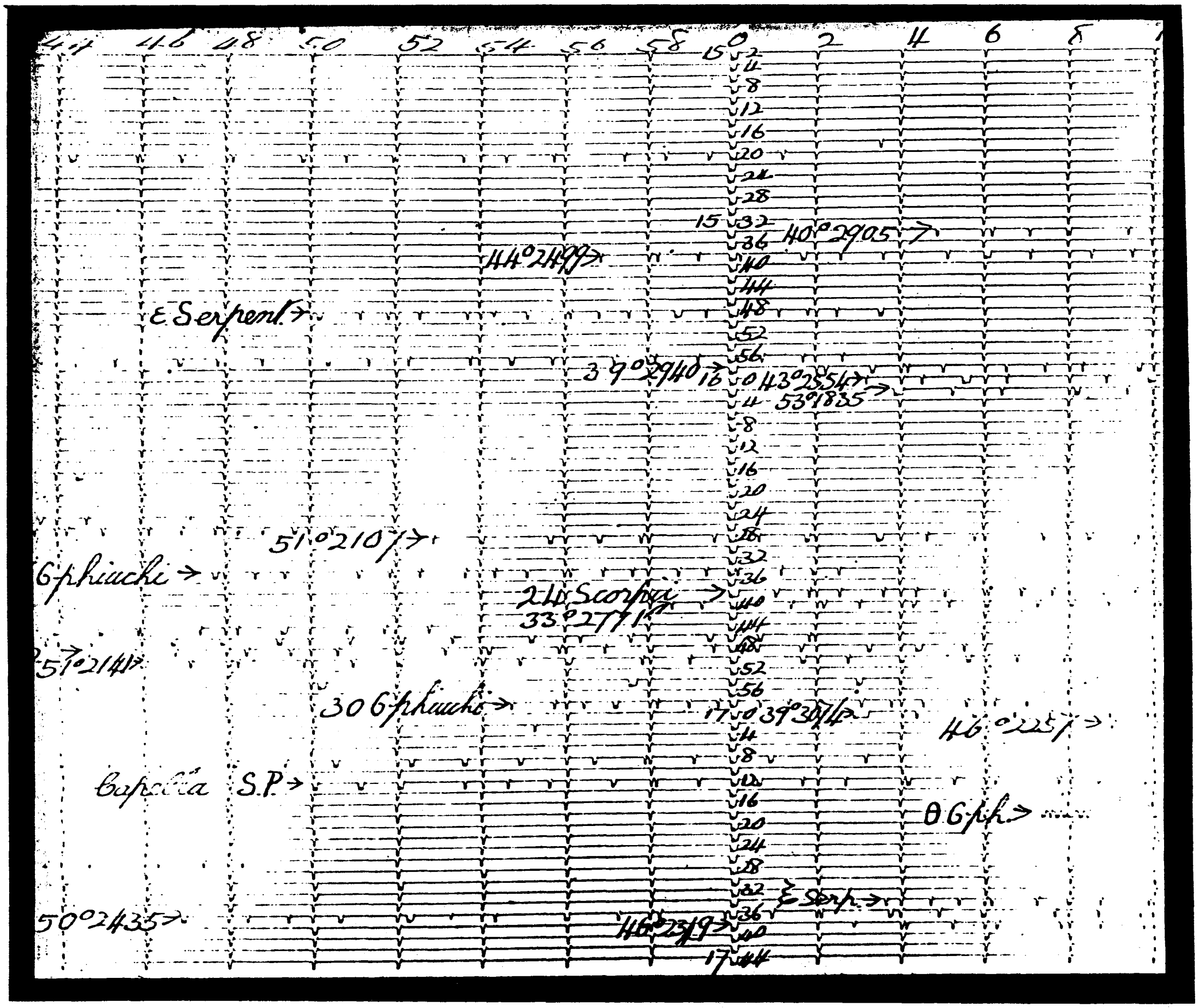

Figure 7. A small section of a barrel-chronograph sheet, with the recorded star transits and sidereal time pulses identified.

5.2.3 Tape Chronographs

The sheets of paper containing the records from the Barrel Chronograph were valuable throughout the remaining life of the ATC as a permanent record of transit observations made

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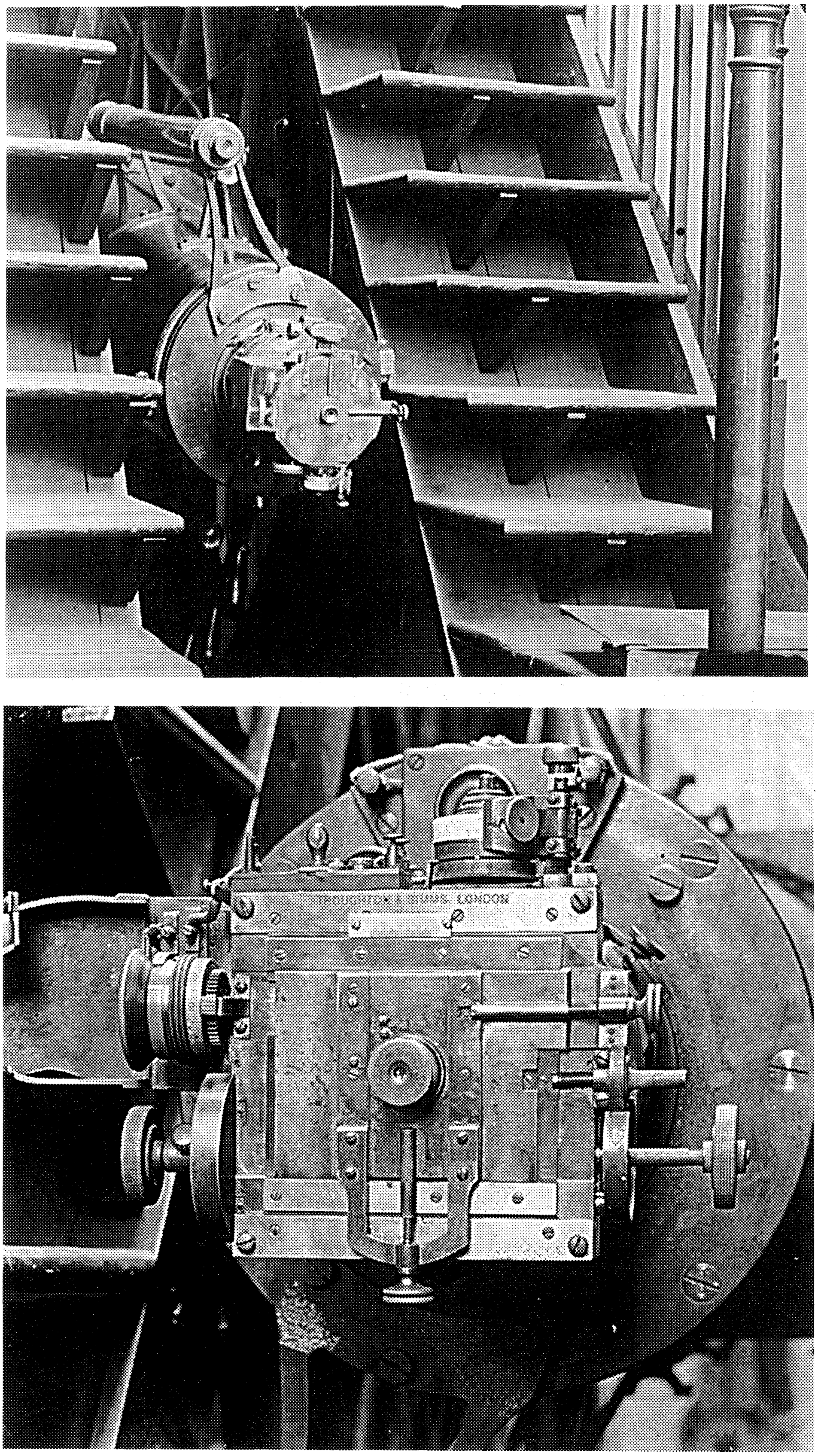

Figure 8. (a) The former eye-end. (b) The new eye-end with the impersonal micrometer (left) and recording ZD micrometer (top). The two-handed drive spindle can be seen below.

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with it. The chronograph was kept running throughout the observing watch, and they therefore constituted a complete record; in addition, they were easy to store in a plan-chest. The scale of about 1 cm per second was however insufficient as greater precision was required, and in 1934 a new siphon recording chronograph was brought into use which produced a record on paper tape at the much more satisfactory scale of 2.5 cm per second.[31] With the advent of quartz-crystal clocks even greater precision was required, and in 1952 a new tape chronograph operating at a scale of more than 5 cm per second was introduced.[32]

The tape chronographs permitted the transit times to be determined with much increased accuracy, but clearly they could only be run for the duration of the observation and necessarily had to be switched off between transits. Reels of tape were also inconvenient for both storage and access. They were therefore used for measurement and stored for a few years, but it was the sheets from Airy's Barrel Chronograph that were retained as a permanent record.

5.3 Accidental Damage

5.3.1 A Chain Failure

The ATC was fortunate to escape very serious damage in 1863 when the plate-chain carrying the western counterpoise broke. The counterpoise fell upon the pier, destroying the massive gun-metal wheels of the lifting machinery, but was prevented from falling further by the iron stay which supported the flue of the gas-lamp used to illuminate the circle. New chains and wheelwork were fitted, and subsequently the counterpoises were enclosed in strong iron box-sides.[33]

5.3.2 War Damage

On 1940 September 12 observations had to be suspended, following bomb damage to the TC Pavilion, "... bringing to an end the long series of fundamental observations made at Greenwich with this instrument ... the most important contribution from a single instrument to fundamental positional astronomy."[34] The Astronomer Royal's valediction proved to be premature, however, for following the serious loss to positional astronomy caused by the total destruction of the Pulkowa Observatory during the bombardment of Leningrad, it was decided to resume observations with the ATC in 1942 May, the damage to the instrument, its collimators and the chronograph, and to the Transit Pavilion and Chronograph Room, having been repaired.[35]

5.4 Bearing Problems and a Sinking Pier

5.4.1 New Bearings

In 1923 January the bearings were examined, following larger than usual annual variations in level and azimuth during the previous year. It was found that the western pivot was bearing only on its eastern edge.[36] The bearing was removed and a tinfoil shim removed, and tests were carried out to determine the correct thickness of shim required. It was during this exercise that the difference in materials of the piers was rediscovered: "Incidentally it was found that the Eastern pier of the transit circle is of granite and the Western pier of Portland Stone. This is a probable cause of the seasonal variation of the errors of the instrument."[37]

A new shim was fitted, but after further investigation it was concluded in October "... that constant adjustment would be required if the pivots were to have a good bearing over the 5 inches in the length of the Ys." It was therefore decided to have new bearings constructed which were installed at the end of 1924 March.[38] As the new form of bearing would require more of the weight to be borne by the counterpoises new bearings were also fitted to the counterpoise mechanisms.

5.4.2 Subsidence of the Eastern Pier

It soon became clear that replacement of the bearings had not solved the problem, which continued to require constant attention. In 1944, when the eastern bearing had to be raised twice within a year, the Astronomer Royal reported: "Until 1923 the level, apart from diurnal and annual variations, had remained very steady. In that year the east pier began to sink and from then to the present year it has been necessary to raise the east bearings 16 times, amounting in all to 250 seconds of arc; the east pier has thus sunk relatively to the west pier by approximately 1/12 inch in 21 years."[39] The need to constantly raise the bearing to counteract this tiny amount of subsidence is an indication of the precision of the observations now being made with the instrument.

6 OBSERVATIONS WITH THE ATC

By combining the functions of two instruments, the timing of meridian transits as with the transit instrument and the measurement of zenith distances as with the mural circle, observing with the transit circle is inevitably more complex. There is much to do and little time to do it in. The fastest moving stars – those on the celestial equator – cross the entire field of the ATC in less than two minutes. Observations are best made in the central part of the field, however, and an ideal observation of an equatorial star has to be carried out within half a minute.

Observations of the Sun, Moon, and planets are more complicated as two limbs may have to be observed in both co-ordinates; this has to be done over a larger proportion of the telescope field and can occupy up to two minutes.

6.1 Methods of Observation

As instrumentation and methods have developed during the lifetime of the ATC several different observing procedures have been used, three for the determination of RA and two for ZD.

6.1.1 Right Ascension Determinations

These were carried out for the first three years by the 'eye-and-ear' method as used with the previous transit instruments at Greenwich. Taking the time from the sidereal clock the observer mentally 'counted in' the star as it approached each fixed wire in the telescope field. By noting the position of the star either side of the wire at successive audible beats of the clock the time of its passage across the wire could be estimated (to a tenth of a second).

When the Barrel Chronograph came into use in 1854 a new technique was adopted. Pulses from the transit clock were sent by the observer using the tapping key as he judged the star to be passing each wire. The times of passage over the wires were then subsequently measured on the chronograph sheets.

The final change in transit observing came in 1915 with the introduction of the moving-wire impersonal micrometer. The observation now consisted of following the object with the transit wire, timing pulses being sent automatically to the chronograph (see section 5.2.2 above).

6.1.2 Zenith Distance Determinations

These were carried out by bisecting the star's image with the horizontal micrometer wire as it passed two of the fixed wires, ideally symmetrical either side of the transit measurement, recording the micrometer reading after each. While the TC was still clamped at the setting used, it was then necessary to read the circle micrometers.

This procedure was simplified in 1873 when the new micrometer described above (section 5.1) enabled the micrometer readings to be taken after the observation was completed.

6.2 Observing Procedures

It seems desirable to put on record the observing procedures used with the ATC. The procedures here outlined were used from 1915 when the last major modification to the instrument was made. Figure 9 shows diagrammatically the arrangement of wires as seen through the eyepiece with the telescope facing south, and the direction of motion of a typical equatorial star is shown. The telescope being an astronomical refractor inverts the image, and hence reverses the apparent direction of motion of the star. The eyepiece used for most objects gave a magnification of ×195; the special eyepiece used for observations of the Sun gave ×180.

Only part of the wire system is visible through the eyepiece at any one time; the eyepiece is tracked across the field automatically as the transit micrometer is turned so as to keep the transit wire always central in the field. The wires were known by the numbers shown; the former meridian wire '4' was removed in 1919 (see section 5.2.2 above). Note that the field wires were numbered in the observed direction of motion of the star, so that the wire here shown as wire 1 would be wire 7 for a star observed with the telescope facing north. The

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intervals between the fixed wires are equivalent to six revolutions of the RA micrometer; an ideal transit observation was made over the central six revolutions from wire 3½ to wire 4½. One revolution of the transit micrometer represents 36″.960, equivalent to $2^s.464$ of sidereal time.

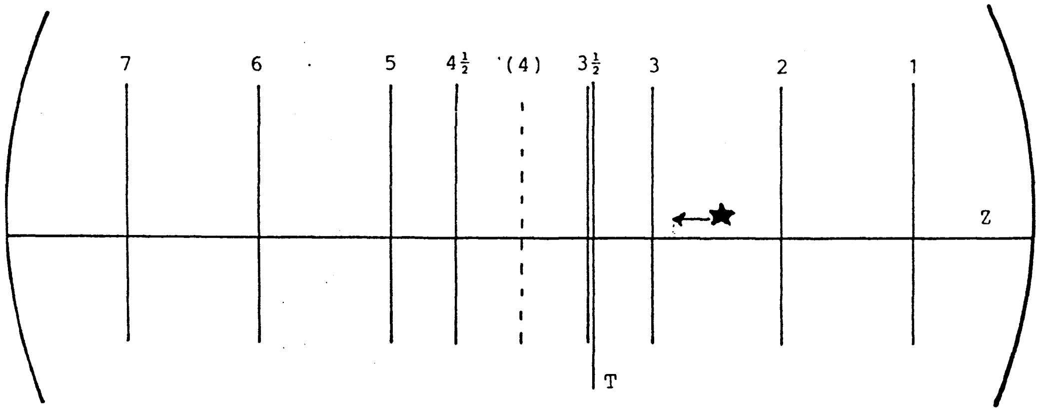

Figure 9. The ATC wire system.

'Z' is the horizontal wire controlled by the ZD micrometer. 'T' is the transit wire driven by the RA micrometer, shown in the starting position for a 'central' transit observation, close to wire 3½.

6.2.1 Observing a Star

In order to reduce transit observations of the Sun, Moon, planets, and minor planets it is necessary to observe also a number of stars, even if no stellar co-ordinates are being observed for a catalogue programme at the time. A number of stars culminating south of the zenith are required in order to determine the clock error, six being the desirable minimum; these are known as 'Clock Stars'. Stars culminating north of the zenith can of course be observed at both lower and upper culmination. Transits of these stars are used in the computation of azimuth error; the desirable minimum during a watch being two above and two below pole. These are termed 'azimuth stars'.

The telescopic image of a point source such as a star is, of course, the diffraction pattern known as the Airy disk. In practice its size will depend on the atmospheric conditions at the time, and its motion may appear unsteady due to atmospheric turbulence. The observer's task is to keep the image bisected as accurately as possible during the observation.

For a normal, symmetrical observation of a star: (i) set Z on star and tap on ZD drum as it passes wire 3; (ii) bisect and follow star with T from wire 3½ to wire 4½; (iii) set Z on star and tap on ZD drum as it passes wire 5; (iv) read circle microscopes.

In case of passing cloud or accidental failure, observations can be made 'off-centre', for example a transit observation could be made from wires 5 to 6 (stopping fractionally short of wire 6), and ZD taps obtained at wires 6 and 7. The appropriate corrections to centre can be made during reduction of the observations.

In the case of close circumpolar stars, within about 5° of the pole, the very slow motion renders observation with the impersonal micrometer impracticable. For these stars the procedure is: (i) switch off signal circuit from the RA micrometer to the chronograph; (ii) by rotating the micrometer drum move the transit wire with the star and stop with the star bisected, *simultaneously* tapping the hand key; (iii) record the reading of the transit micrometer; (iv) repeat stages (ii) and (iii) a further nine times; (v) switch on the RA micrometer circuit ready for the next normal transit.

6.2.2 Observing the Sun

For a full observation of the Sun transits are required of the preceding (1L) and following (2L) limbs, and three ZD taps on each of the north (NL) and south (SL) limbs. The procedure is: (i) set TC for the centre of Sun; (ii) observe transit of 1L from wires 3½ to 4½; (iii) reset TC for north limb; (iv) set wire Z tangential to limb and tap at wires 1, 2 and 3; (v) reset TC for south

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limb; (vi) set Z tangential to limb and tap at wires 5, 6 and 7; (vii) reset TC for centre of Sun and observe transit of 2L from wires 3½ to 4½. As it is necessary to read the circle micrometers twice, at stages (iii) and (v), a second observer is required to assist by 'reading the mics'.

6.2.3 Observing Planets and Minor Planets

For a major planet, or for Venus or Mars at full phase, the same procedure is used as for the Sun, but because of their much smaller diameter one setting of the telescope and set of circle readings is sufficient and no assistance is required. For a planet in crescent or gibbous phase only one limb can be observed in transit and one in ZD. The procedure for observing a minor planet is the same as for a star.

6.2.4 Observing the Moon

One limb is observed in transit and one in ZD. When visible the lunar crater Mösting A, which is close to the mean centre of the Moon's apparent disk, was also observed. This was introduced from the beginning of 1905 at Greenwich and the Cape, to improve determinations of the Moon's RA and parallax.[40]

6.3 Personal Equations

Personal equations are differences between individual observers making the same observations but obtaining different results. They affect the timing of meridian transits especially and have been a major preoccupation of transit observers since an assistant at Greenwich was dismissed in 1796 because his observations differed from those of the Astronomer Royal by $0^s.5$–$0^s.8$ (7–12 arcsec).[41] By Airy's time attitudes were more enlightened, it being recognized that personal equations were caused by variations in reaction speeds between observers. Differences in personal equation between pairs of observers were obtained from their observations of clock stars on the same day.[42] It had long been standard practice at Greenwich to analyse all observers' personal equations, and to relate them to one 'standard observer'. The change to galvanic recording in 1854 reduced observers' personal equations by about a half. The introduction of the impersonal micrometer in 1915 did not remove them entirely, but reduced them to very small values and it was no longer necessary to have a standard observer. There had been only six standard observers in the sixty years use of the ATC.: E Dunkin (1851-1860), G S Criswick (1870-1881), A M W Downing (1882-1891), T Lewis (1892-1895), W W Bryant (1896-1905) and W M Witchell (1906-1914).[43]

The residual personal equations with the moving-wire micrometer seem to be mainly 'bisection errors', that is differences between observers' interpretations of the mid-point of the image; there is some evidence that the amount of bisection error is related to the magnitude of the star observed. Later, personal equation machines were devised, in which observers could observe transits of an artificial star whose actual movement was precisely known: the results were usually in good accord with those deduced from real observations. It was also found that very small personal errors occurred in other aspects of TC observation, such as ZD measurements, reading of circle micrometers, etc..[44]

6.4 First and Last Observations with the ATC

6.4.1 The First Observations

Airy ensured that the erection of the ATC was completed before the end of 1850, and intended observations to commence on the first day of the new half-century. Due to the prevailing weather conditions, however, the first observation was not made until 1851 January 4 – a transit of a single second-magnitude star, α Ceti, by Thomas Ellis. The first full series of observations, (Figure 10a) including the first observation of Polaris and of a planet (Jupiter), were made on the following day by the Chief Assistant, Robert Main, and 'Mr Henry' – so known at the RO although his full name was actually Thomas Henry Belville.

Airy himself observed very little, probably due to his poor eyesight and his belief that the observing could be left to the Assistants and Junior staff while he busied himself with administrative and other matters. He was famously attacked by [illegible] Sir James South for not observing, but was exonerated by the Admiralty.[45] He did however observe with his transit circle on just one occasion, observing three stars on 1851 May 21 (see Figure 10b).

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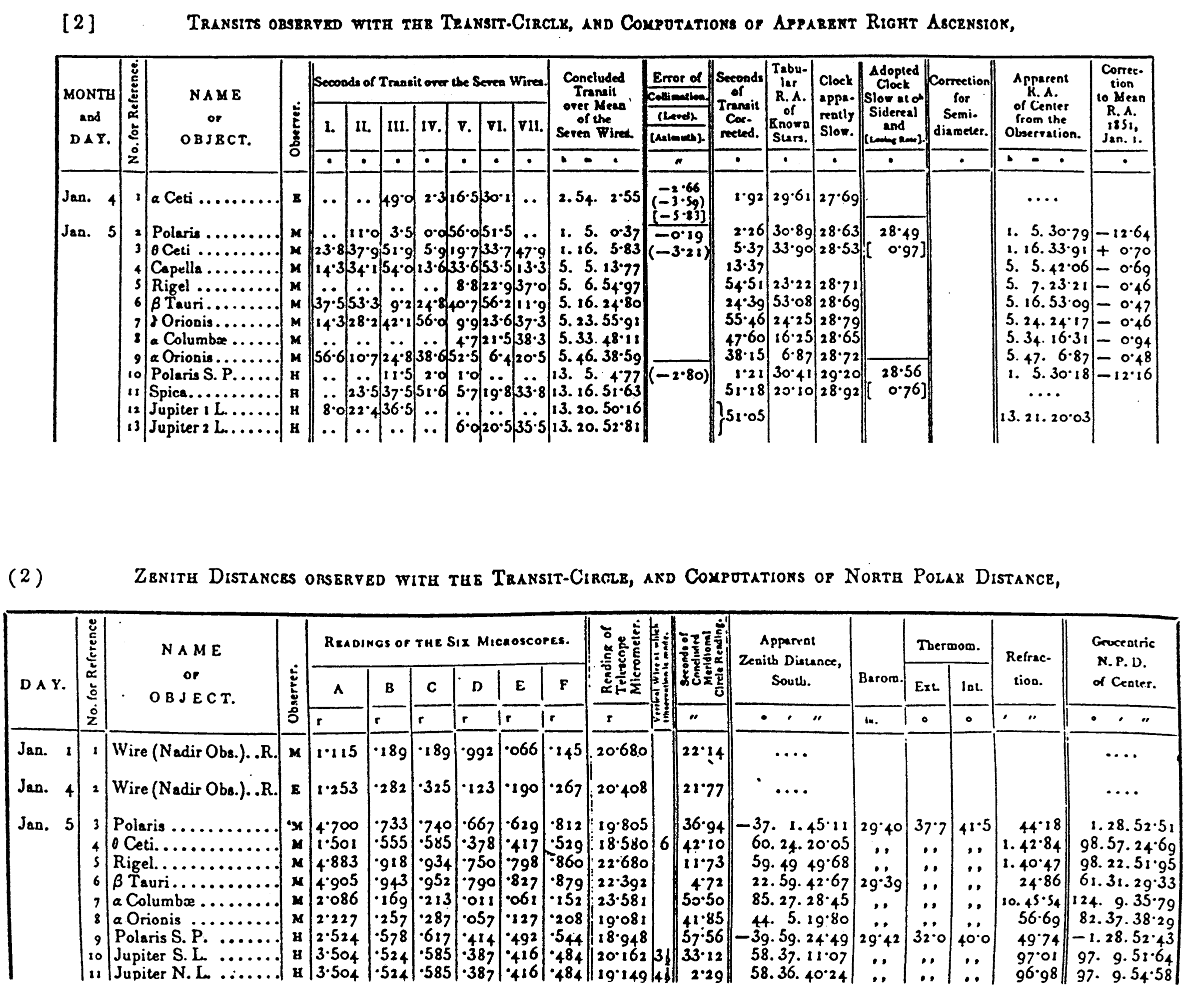


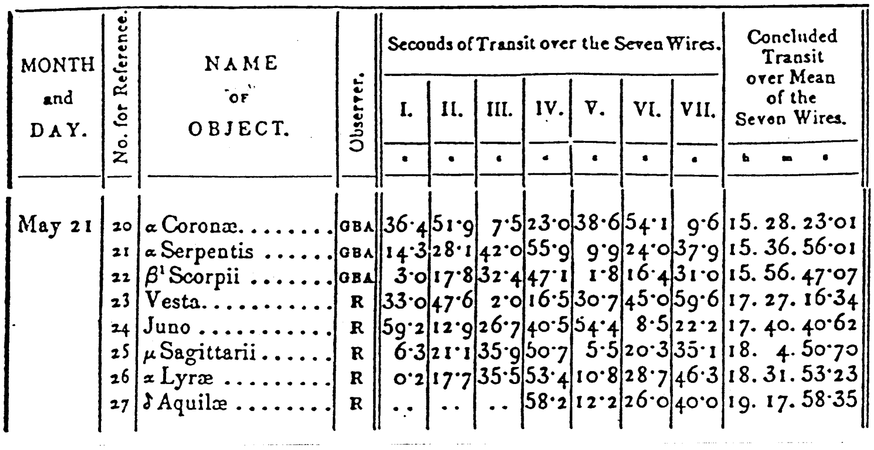
[2] TRANSITS OBSERVED WITH THE TRANSIT-CIRCLE, AND COMPUTATIONS OF APPARENT RIGHT ASCENSION,

MONTH and DAY.	No. for Reference.	NAME OF OBJECT.	Observer.	Seconds of Transit over the Seven Wires. I.	II.	III.	IV.	V.	VI.	VII.	Concluded Transit over Mean of the Seven Wires.	Error of Collimation. (Level). [Azimuth].	Seconds of Transit Corrected.	Tabular R. A. of Known Stars.	Clock apparently Slow.	Adopted Clock Slow at 0h Sidereal and [Losing Rate].	Correction for Semi-diameter.	Apparent R. A. of Center from the Observation.	Correction to Mean R. A. 1851, Jan. 1.
				s	s	s	s	s	s	s	h m s	″	s	s	s	s	s	h m s	s
Jan. 4	1	α Ceti	E	..	..	49·0	2·3	16·5	30·1	..	2. 54. 2·55	−2·66 (−3·59) [−5·83]	1·92	29·61	27·69			....	
Jan. 5	2	Polaris	M	..	11·0	3·5	0·0	56·0	51·5	..	1. 5. 0·37	−0·19	2·26	30·89	28·63	28·49		1. 5. 30·79	−12·64
	3	θ Ceti	M	23·8	37·9	51·9	5·9	19·7	33·7	47·9	1. 16. 5·83	(−3·21)	5·37	33·90	28·53	[0·97]		1. 16. 33·91	+ 0·70
	4	Capella	M	14·3	34·1	54·0	13·6	33·6	53·5	13·3	5. 5. 13·77		13·37					5. 5. 42·06	− 0·69
	5	Rigel	M	..	..	..	..	8·8	22·9	37·0	5. 6. 54·97		54·51	23·22	28·71			5. 7. 23·21	− 0·46
	6	β Tauri	M	37·5	53·3	9·2	24·8	40·7	56·2	11·9	5. 16. 24·80		24·39	53·08	28·69			5. 16. 53·09	− 0·47
	7	δ Orionis	M	14·3	28·2	42·1	56·0	9·9	23·6	37·3	5. 23. 55·91		55·46	24·25	28·79			5. 24. 24·17	− 0·46
	8	α Columbæ	M	..	..	..	..	4·7	21·5	38·3	5. 33. 48·11		47·60	16·25	28·65			5. 34. 16·31	− 0·94
	9	α Orionis	M	56·6	10·7	24·8	38·6	52·5	6·4	20·5	5. 46. 38·59		38·15	6·87	28·72			5. 47. 6·87	− 0·48
	10	Polaris S. P.	H	..	..	11·5	2·0	1·0	..	..	13. 5. 4·77	(−2·80)	1·21	30·41	29·20	28·56		1. 5. 30·18	−12·16
	11	Spica	H	..	23·5	37·5	51·6	5·7	19·8	33·8	13. 16. 51·63		51·18	20·10	28·92	[0·76]		....	
	12	Jupiter 1 L.	H	8·0	22·4	36·5	..	..	..	..	13. 20. 50·16		51·05					13. 21. 20·03	
	13	Jupiter 2 L.	H	..	..	..	..	6·0	20·5	35·5	13. 20. 52·81								

(2) ZENITH DISTANCES OBSERVED WITH THE TRANSIT-CIRCLE, AND COMPUTATIONS OF NORTH POLAR DISTANCE,

DAY.	No. for Reference	NAME OF OBJECT.	Observer.	Readings of the Six Microscopes. A	B	C	D	E	F	Reading of Telescope Micrometer.	Vertical Wire at which observation is made.	Seconds of Concluded Meridional Circle Reading.	Apparent Zenith Distance, South.	Barom.	Thermom. Ext.	Int.	Refraction.	Geocentric N. P. D. of Center.
				r	r	r	r	r	r	r		″	° ′ ″	in.	°	°	′ ″	° ′ ″
Jan. 1	1	Wire (Nadir Obs.). .R.	M	1·115	·189	·189	·992	·066	·145	20·680		22·14	....					....
Jan. 4	2	Wire (Nadir Obs.). .R.	E	1·253	·282	·325	·123	·190	·267	20·408		21·77	....					....
Jan. 5	3	Polaris	M	4·700	·733	·740	·667	·629	·812	19·805		36·94	−37. 1. 45·11	29·40	37·7	41·5	44·18	1. 28. 52·51
	4	θ Ceti	M	1·501	·555	·585	·378	·417	·529	18·580	6	42·10	60. 24. 20·05	,,	,,	,,	1. 42·84	98. 57. 24·69
	5	Rigel	M	4·883	·918	·934	·750	·798	·860	22·680		11·73	59. 49 49·68	,,	,,	,,	1. 40·47	98. 22. 51·95
	6	β Tauri	M	4·905	·943	·952	·790	·827	·879	22·392		4·72	22. 59. 42·67	29·39	,,	,,	24·86	61. 31. 29·33
	7	α Columbæ	M	2·086	·169	·213	·011	·061	·152	23·581		50·50	85. 27. 28·45	,,	,,	,,	10. 45·54	124. 9. 35·79
	8	α Orionis	M	2·227	·257	·287	·057	·127	·208	19·081		41·85	44. 5. 19·80	,,	,,	,,	56·69	82. 37. 38·29
	9	Polaris S. P.	H	2·524	·578	·617	·414	·492	·544	18·948		57·56	−39. 59. 24·49	29·42	32·0	40·0	49·74	−1. 28. 52·43
	10	Jupiter S. L.	H	3·504	·524	·585	·387	·416	·484	20·162	3½	33·12	58. 37. 11·07	,,	,,	,,	97·01	97. 9. 51·64
	11	Jupiter N. L.	H	3·504	·524	·585	·387	·416	·484	19·149	4½	2·29	58. 36. 40·24	,,	,,	,,	96·98	97. 9. 54·58

(a)



MONTH and DAY.	No. for Reference.	NAME OF OBJECT.	Observer.	Seconds of Transit over the Seven Wires. I.	II.	III.	IV.	V.	VI.	VII.	Concluded Transit over Mean of the Seven Wires.
				s	s	s	s	s	s	s	h m s
May 21	20	α Coronæ	GBA	36·4	51·9	7·5	23·0	38·6	54·1	9·6	15. 28. 23·01
	21	α Serpentis	GBA	14·3	28·1	42·0	55·9	9·9	24·0	37·9	15. 36. 56·01
	22	β¹ Scorpii	GBA	3·0	17·8	32·4	47·1	1·8	16·4	31·0	15. 56. 47·07
	23	Vesta	R	33·0	47·6	2·0	16·5	30·7	45·0	59·6	17. 27. 16·34
	24	Juno	R	59·2	12·9	26·7	40·5	54·4	8·5	22·2	17. 40. 40·62
	25	μ Sagittarii	R	6·3	21·1	35·9	50·7	5·5	20·3	35·1	18. 4. 50·70
	26	α Lyræ	R	0·2	17·7	35·5	53·4	10·8	28·7	46·3	18. 31. 53·23
	27	δ Aquilæ	R	..	..	..	58·2	12·2	26·0	40·0	19. 17. 58·35

(b)

Figure 10. (a) the first observations in RA and ZD. [Observers: E – Thomas Ellis; M – Robert Main; H – Mr Henry]. (b) The only observations with the ATC made by Airy himself [GBA], 1851 May 21 (after *Greenwich Observations*, 1851).

6.4.2 The Last Observations

The final observations with the ATC were scheduled for 1954 March 31, when appropriately the duty observer would be the Head of the Meridian Department, L S T Symms, who had joined the RO as a supernumerary computer in 1913 and became an established Assistant and a transit

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circle observer in 1921. Unfortunately history repeated itself and he was prevented from observing by bad weather, thus giving the writer the honour of having made the last observations on the previous day. These were of the Sun, Venus, Jupiter, Pallas, and Juno, together with the necessary clock and azimuth stars (Figure 11). The last published observation was that of Pallas; the last transit observed was of the fourth magnitude clock star o Leonis (see Figure 12).

GREENWICH TRANSIT-CIRCLE OBSERVATIONS, 1954. A 15

MAJOR PLANETS

Universal Time	Observer	Limb	Right Ascension		Limb	Declination		Diameter			
								Horizontal		Vertical	
			Observed	O − C		Observed	O − C	Observed	O − C	Observed	O − C
JUPITER											
Mar. 2 18	GS		5 4 1.78	−.10		+22 32 36.66	−1.14	2.80	−.08	38.04	+0.78
8 1r	GS		5 5 57.27	−.05		+22 36 9.22	−1.68	2.88	+.06	37.67	+1.13
10 18	GS		5 6 41.80	−.03		+22 37 25.87	−1.93	2.82	+.02	37.89	+1.59
11 18	LS		5 7 5.10	−.07		+22 38 6.00	−1.30	2.66	−.14	36.49	+0.29
30 17	GS		5 16 35.75	+.05		+22 51 57.95	−1.45	2.68	+.04	34.64	+0.46
SATURN											
Feb. 24 4	PG		14 30 59.89	−.20		−12 9 54.01	+0.39	1.20	−.02	18.96	+2.98

(a)

GREENWICH TRANSIT-CIRCLE OBSERVATIONS, 1954. A 17

MINOR PLANETS

Universal Time	Observer	Right Ascension		Declination	
		Observed	O − C	Observed	O − C
PALLAS					
Mar. 5 22	LS	9 20 39.52	−.32	− 7 55 36.61	−1.46
10 22	GS	9 18 54.71	−.37	− 5 41 39.53	−2.11
30 21	GS	9 19 6.70	−.36	+ 2 30 6.41	−1.60
JUNO					
Feb. 26 23	LS	8 58 (52)	..	+ 7 13 3.41	−0.67
Mar. 5 22	LS	8 55 23.45	−.14	+ 8 21 20.52	+1.76
10 22	GS	8 53 41.06	−.17	+ 9 6 32.64	−1.72
30 20	GS	8 53 39.86	−.14	+11 29 10.73	+0.19

(b)

Figure 11. The final observations with the ATC. (a) The last observations of Jupiter and Saturn; (b) the last observations of minor planets – that of Pallas on 1954 March 30 was the final published observation with the instrument. [Observers: LS – Mr Symms; PG – Dr Gething; GS – Mr Satterthwaite] (after *Greenwich Observations,. 1954*).

6.5 Some Noteworthy Observations

In his brief memoir Witchell (1952) recalls some remarkable observing feats, which must form part of the historical record of the instrument.

In 1896 W Bryant observed the re-appearance of an occulted fifth-magnitude star at the Moon's bright limb, and then registered the transit of both the star and the Moon's limb. On two successive days early in the twentieth century outstanding atmospheric transparency enabled the transit of a sixth-magnitude close polar star to be recorded less than two hours from noon. On at least one occasion the transit of Arcturus had been observed between the transits of the preceding and following limbs of the Sun. Witchell also describes how he, with the assistance of a 'mic-reader', observed all four limbs of the planet Mercury then in transit over the Sun's disk, as well as the four limbs of the Sun itself!

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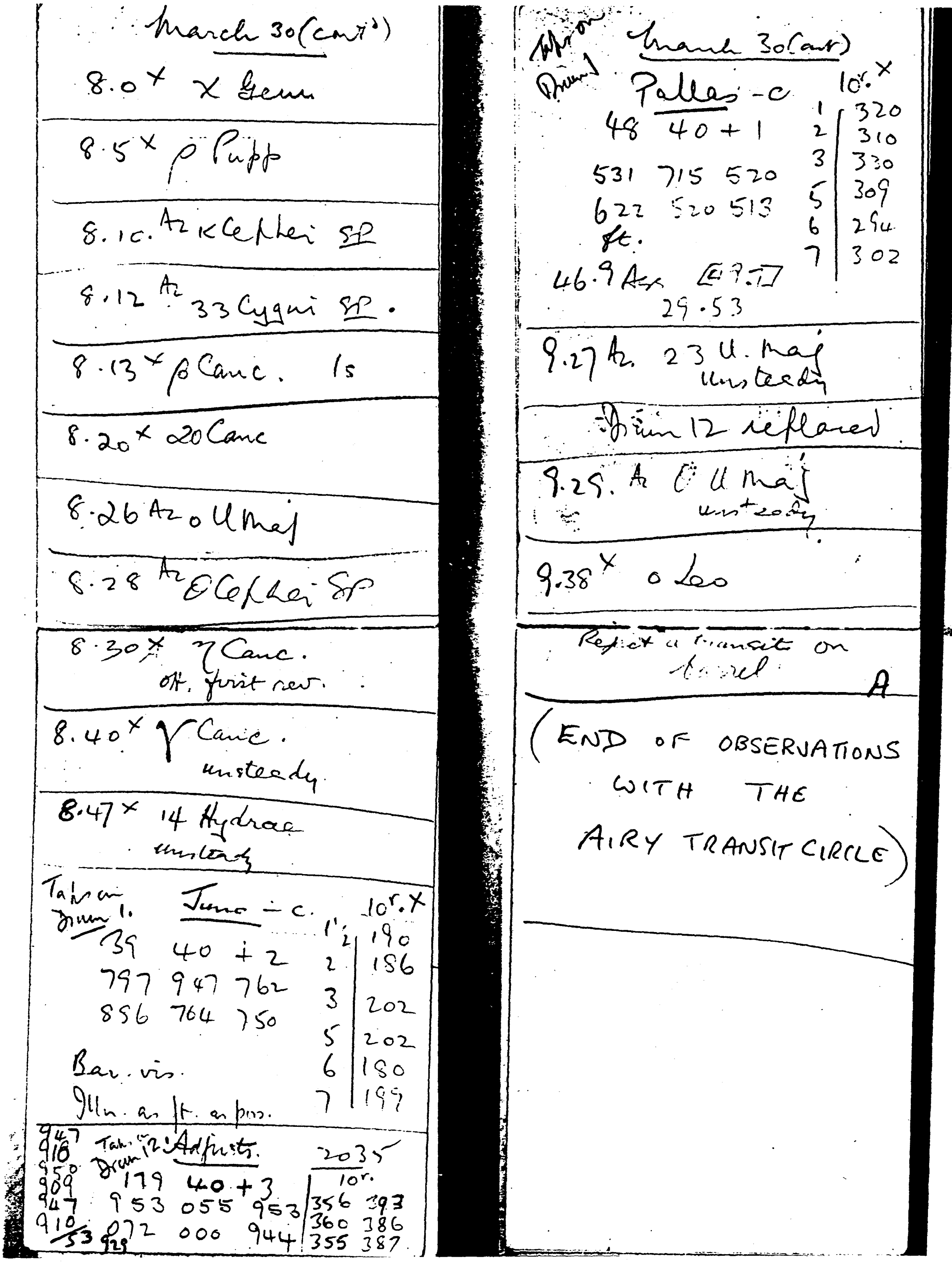

March 30 (cont^d)

8.0 × χ Gem

8.5 × ρ Pupp

8.10 Az κ Cephei SP

8.12 Az 33 Cygni SP.

8.13 × β Canc. 1s

8.20 × 20 Canc

8.26 Az o U Maj

8.28 Az θ Cephei SP

8.30 × η Canc.
off. first rev.

8.40 × γ Canc.
unsteady

8.47 × 14 Hydrae
unsteady

Taken on Drum 1. Juno – c. 10^r. ×
39 40 + 2
797 947 762
856 764 750
Bar. vis.
Illn. as ft. a pos.

	10^r. ×
1½	190
2	186
3	202
5	202
6	180
7	199

Taken on Drum 12 Adjusts. 2035

947 916 950 909 947 910 /53 929

179 40 + 3
953 055 953
072 000 944

10^r.	
356	393
360	386
355	387

Taken on Drum March 30 (cont) Pallas – c 10^r. ×
48 40 + 1
531 715 520
622 520 513
ft.
46.9 Asx [illegible]
29.53

1	320
2	310
3	330
5	309
6	294
7	302

9.27 Az. 23 U. Maj
unsteady

Drum 12 replaced

9.29. Az ζ U Maj
unsteady

9.38 × o Leo

Reject a transit on [illegible]
A

(END OF OBSERVATIONS
WITH THE
AIRY TRANSIT CIRCLE)

Figure 12. The last pages in my observing book. 'A' is the initial of Dr Atkinson, the Chief Assistant, who examined the observing books from each telescope every morning – a practice instituted by Airy.

Witchell also recounts that "an exercise in agility, occasionally performed, was the observation of γ Draconis (zenithal at Greenwich) with the Transit Circle and with the adjacent Reflex Zenith Tube by one and the same observer at the same culmination. The star passed

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through the field of view of the latter telescope in less than forty seconds, and this interval could just be spared from the larger instrument, situated about five yards to the east, still leaving time for a planned symmetrical transit observation to be made."

We should also record the devotion to duty of those who observed through two world wars; the ATC remained in service throughout WW1 and for much of WW2. When observing was resumed in 1942 the observers had to combine observing with fire-watching duties, and carry them out under constant threat of bomb attacks.

6.6 Statistics

Whilst it is generally agreed that the output of the ATC was unique, there is considerable disparity in the literature as to how many observations were made with it: "more than 667,000" (Witchell, 1952); "some 600,000" (Howse, 1975); "about 700,000 transits" (McCrea, 1975); "nearly 700,000" (Lowne, 1981). The writer has therefore endeavoured to make a reliable estimate. The task is complicated, for several reasons. After 1910 individual observations were no longer published, and the statistics given in *Gr.Obs*. (for calendar years) and *ARR* (for 'report years') vary in the detail given. After a careful attempt to harmonize these sources, and bearing in mind that large numbers of clock and azimuth stars would have been observed for reduction purposes, but are not published observations *per se*, the following totals are believed to be a realistic estimate of the output of the instrument:

Number of transits observed:	679,380
Number of ZD determinations:	632,040

7 PROGRAMMES CARRIED OUT WITH THE ATC

Throughout its service the ATC was used for the routine but vital purposes of a leading meridian instrument: observation of fundamental stars for the regulation of the standard clocks, and positional observations for the improvement both of star places and proper motions, and of ephemerides for objects in the solar system.

7.1 Time Determination

The ATC was used for the observation of clock stars to monitor the standard clocks and provide the basis of Greenwich Mean Time from 1851 to 1926. In 1880 the Statutes (Definition of Time) Bill received the Royal Assent; it stated:

> Whenever any expression of time occurs in any Acts of Parliament, deed, or other legal instrument, the time referred shall, unless it is otherwise specifically stated, be held in the case of Great Britain to be Greenwich mean time, and in the case of Ireland, Dublin mean time.

Thus time based upon observations made with the ATC became legal time for the whole of mainland Britain (Howse, 1980:114-115). In October 1884 the International Meridian Conference, meeting in Washington D.C., U.S.A., adopted the following resolutions:

> That it is the opinion of this Congress it is desirable to adopt a single prime meridian for all nations, in place of the multiplicity of initial meridians which now exist.
>
> That the Conferences proposes to the Governments here represented the adoption of the meridian passing through the centre of the transit instrument at the Observatory of Greenwich as the initial meridian for longitude.

The first resolution was adopted unanimously; the second, proposed by the United States, was adopted after lengthy discussion, San Domingo voting against and France and Brazil abstaining (Howse, 1980:138-142). This decision must have given great satisfaction to Airy, then in his 84th year and living a short distance from his now historic instrument.

A special series of observations for an international longitude programme carried out with a small reversible transit circle, ST 'B', revealed a systematic difference from the ATC of $0^s.09$.

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As the smaller reversible instrument was regarded as more suitable for time determinations, observations for this purpose were continued with ST 'B', which became the *de facto* basis of Greenwich Time from 1927 July, replacing the ATC in this role after 76 years.[46]

It was long suspected that the determination of the collimation error of the TC might be the cause of this difference. An extensive analysis of the measured collimation errors and deduced azimuth errors between 1922 and 1938 (Gething, 1954) finally confirmed that the adopted collimation errors of the ATC were subject to a systematic error of between $0''.2$ and $0''.5$; that there was a real annual variation in the collimation error; and that this systematic error would have been greater – approximately double – had the 'Up–Down' corrections not been applied throughout (see section 4.7 above).

7.2 Observation of Solar System Objects

Observations of the Sun, Moon, Mercury, Venus, Mars, Jupiter, Saturn, Uranus, and Neptune and many minor planets were made throughout the working life of the instrument. (Pluto, discovered in 1930, is too faint to be observed with the ATC). Observations of clock and azimuth stars are required for the reduction of these observations and were always part of the routine programme.

7.3 Stellar Observations

Observations of both fundamental and other stars were carried out to improve knowledge of their positions and proper motions. The observations made over a number of years were collated and published as Greenwich Catalogues. For inclusion in such a catalogue several good determinations of both RA and Dec were required for each star. The periods covered by Greenwich star catalogues were somewhat variable, as was the naming of them. Table 1 lists the catalogues based upon ATC observations.

Table 1. Catalogues based upon ATC observations.

Title	Epoch	Period comprised	Number of stars	Description
Seven-year Catalogue	1860	1854-1860	2022	Fundamental and miscellaneous stars.
New Seven-year Catalogue	1864	1861-67	2760	Fundamental and miscellaneous stars.
Nine-year Catalogue	1872	1868-76	2263	Fundamental and miscellaneous stars.
Ten-year Catalogue	1880	1877-86	4059	Fundamental and miscellaneous stars.
Five-year Fundamental Catalogue	1890	1887-91	258	Fundamental stars
Second Ten-year Catalogue	1890	1887-96	6892	Stars from Groombridge's Circumpolar Catalogue.
Second Nine-year Catalogue	1900	1897-1905	1541 10127	Fundamental and zodiacal stars; Reference stars for Greenwich Astrographic zones, Dec. +64° to +90°.
Catalogue for 1910	1910	1906-14	6179 12635	Miscellaneous stars; Reference stars for Oxford Astrographic zones, Dec. +24° to +32°.
First Greenwich Catalogue for 1925	1925	1915-21	2643	Stars from the Backlund–Hough list of brighter stars, down to ZD 80°.
Second Greenwich Catalogue for 1925	1925	1922-30	2111 10584	Fundamental stars; Stars brighter than $8^{\rm m}.0$ in zones Dec. +32° to +64°.
First Greenwich Catalogue of Stars for 1950.0	1950	1931-40	1399 6173	Fundamental stars; Harvard–Draper Catalogue stars.
Third Greenwich Catalogue of Stars, Sun, Planets and Moon for 1950.0	1950	1942-54	— 378 255	Sun, Moon and planets (re-reduction); Fundamental stars; Zenithal stars (for PZT).

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These observations were also combined with those from other observatories to produce major catalogues for various specialized purposes, and to improve still more the knowledge of fundamental stars. Notable among such catalogues to which the ATC contributed a great number of observations were the third and fourth fundamental catalogues, the 'FK3' (Kopff, 1937) and 'FK4' (Fricke & Kopff, 1963).

7.4 Contributions to Major Investigations

In addition to the routine programmes, observations made with the ATC often contributed to important work on a broader front. For example, investigations such as the determination of the solar parallax from astrometric observations of the minor planet Eros at its close approach to Earth in 1931 needed very accurate places for the field stars for the reduction of the plates (Jones 1941).

A very detailed analysis of the motions of the Sun, Moon, and inner planets, largely based on ATC observations, showed that fluctuations occurred which could only be explained by irregularities in the rotation of the Earth (Jones, 1939). Fourteen years later, with the greater accuracy of the quartz-crystal clocks then being used, such an irregularity was measured for the first time, a hesitation in the Earth's rotation of 1.3 ms.

7.4.1 The Final Investigation

The last special investigation carried out with the ATC was of considerable interest at the time. It is also very relevant to its history, and provided a very appropriate conclusion to its working life. It comprised a series of 'double azimuth' observations, that is measurements of successive transits of circumpolar stars at upper and lower culmination, combined with observations of a distant azimuth mark (Symms, 1953). This was the obelisk erected in 1824 on Pole Hill in Epping Forest, 11.1 miles (17.8 km) north of Greenwich.[47] On the meridian of Pond's 10-foot transit instrument (i.e. Bradley's meridian), it is approximately 19 feet (5.6 m) west of the Prime Meridian and was visible well within the field of the ATC. The obelisk had not been used as an azimuth mark since 1836, the trees of the forest having grown up behind so that it was no longer visible on the skyline, but Airy made arrangements for its preservation[48] and it can still be seen today. For this programme the Ordnance Survey supplied and manned a powerful beacon lamp mounted on the obelisk.

The programme, together with a gravity survey at both sites, was intended to determine astronomically the longitude difference between Greenwich and the new site of the Royal Observatory at Herstmonceux, as a check on the value determined by land survey. Two series of observations were made in 1953, from May 21 to August 6 and from September 11 to October 8. The results also provided additional information, especially in confirming the long suspected diurnal variation in azimuth error.[49] This was the first and only occasion when a distant azimuth mark was used with the ATC.

8 CONCLUSION

The writer has attempted to present a full and detailed history of the ATC from conception to retirement, in the context of its astronomical purpose and the procedures for error-determination necessary for the achievement of the positional accuracy demanded of a fundamental instrument.

There can be little doubt that its introduction marked the beginning of a new era in meridian astronomy. Many features of Airy's design were adopted in TCs built throughout the next century, and a direct lineage can be traced right through to the present. The ATC was copied, with minimal changes, for the TC erected at the Cape of Good Hope, South Africa, in 1855. From his experience with that instrument Sir David Gill designed a new, reversible TC for the Cape, which was completed in 1901. When it was decided in 1931 to replace the ATC at Greenwich with a new RTC, its design was based upon Gill's RTC. Following its transfer to Herstmonceux in 1954, the Greenwich RTC was modernized with the addition of cameras to read the circle, and later with facilities for producing its observations in computer-readable form.

The Carlsberg RTC built for the Copenhagen University Observatory in 1952 was developed from the Greenwich RTC design; this instrument was completely reconstructed and

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transferred to the island of La Palma in 1984, where it is now operated as the Carlsberg Automatic Meridian Circle (MC). Fully computer-controlled, it operates entirely automatically, selecting the objects to be observed from its built-in working catalogue, setting itself to the correct ZD at the appropriate time, carrying out the observation and transmitting the data straight to computer. The productivity of such an automated instrument in the clear skies of the Canary Islands is so great that the Carlsberg AMC passed the total number of observations made in 103 years with the ATC in about seven years! One feels Airy would have been impressed.

Airy's Transit Circle was transferred to the care of the National Maritime Museum[50], and remains in position marking the Prime Meridian (Figure 13). It had a lasting influence in the field of high-precision positional astronomy, which continued long after its own direct contributions came to an end. Truly it can be said to have met Airy's stated aim, that "Whatever we do, we ought to do well".[51]

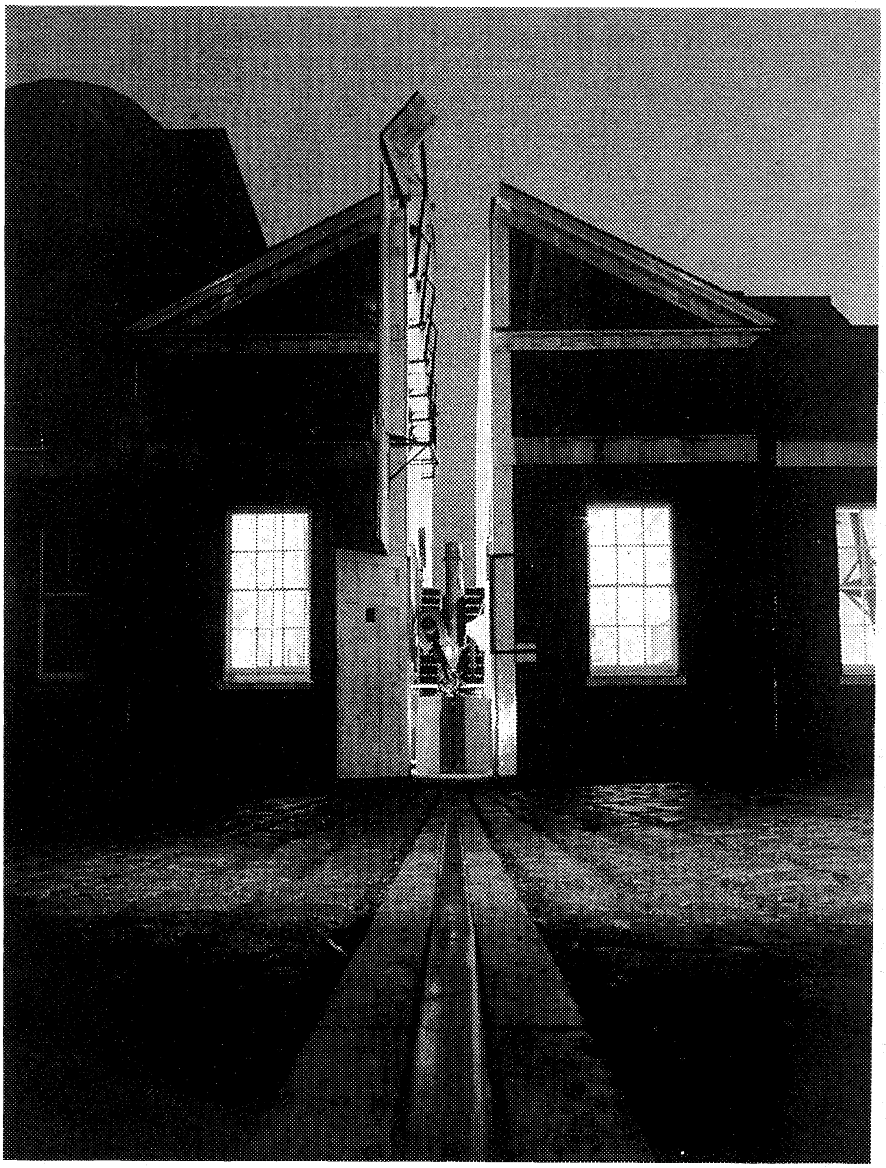

Figure 13. The Airy Transit Circle as it appears today, seen from the courtyard.

9 ACKNOWLEDGEMENTS

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Figures 1, 3, 4, 7, 8, and 13 are reproduced by courtesy of the National Maritime Museum. Figures 2, 5, 6, 10, 11, and 12 are reproduced from the RGO Archive, by courtesy of the Syndics of the University of Cambridge Library.

10 NOTES

Frequent reference is made to the annual *Reports of the Astronomer Royal to the Board of Visitors of the Royal Observatory*, a series begun by Airy on his taking office in 1835 and continued until the Board of Visitors ceased to exist in 1965. References to this valuable source are cited in the form (*ARR 19xx*).

References to the annual volumes of *Greenwich Observations* are similarly made in the form (*Gr. Obs. 19xx*).

1. Dyson, F.W., *ARR 1931*:16-17.
2. A more detailed, unpublished account of the design, history and use of the Airy Transit Circle is given in Satterthwaite (1995), upon which much of the content of this paper is based.
3. Airy, G.B., *ARR 1836*:1.
4. The errors of the transit circle and their correction are discussed in greater detail in Satterthwaite (1995). See also standard textbooks such as Campbell (1899), Smart (1962).
5. It is conventional to refer to 'wires', but by the mid-nineteenth century it was the practice to use threads of spider's web; this was certainly the case with the ATC.
6. The line of collimation (LOC) is defined as the line joining the optical centre of the object-glass to the point of intersection of the middle vertical wire with the fixed horizontal wire (Barlow & Brian, 1944:227).
7. Airy, G.B., *ARR 1848*:6.
8. This story was related at Airy's ninetieth birthday celebration by his cousin George Biddell, formerly of Ransome & May, who had been in charge of the installation of the ATC at Greenwich (Biddell, 1891).
9. Airy, G.B., *ARR 1848*:5.
10. Dyson, F.W., *ARR 1931*:16-17.
11. Jones, H. Spencer, *ARR 1946*:3.
12. Christie, W.H.M., *ARR 1908*:6.
13. Dyson, F.W., *ARR 1922*:9.
14. This can be seen in section in Plate V from Airy's original description (Airy, 1853).
15. Christie, W.H.M., *ARR 1890*:5.
16. Christie, W.H.M., *ARR 1891*:7.
17. Jones, H. Spencer, *ARR 1948*:10.
18. Airy, G.B., *ARR 1851*:5.
19. Airy, G.B., *ARR 1852*:3.
20. Airy, G.B., *ARR 1866*:9.
21. Airy, G.B., *ARR 1867*:7.
22. Airy, G.B., *ARR 1874*:6.
23. Airy, G.B., *ARR 1848*:3.
24. Airy, G.B., *ARR 1849*:3-4.
25. Airy, G.B., *ARR 1873*:7, *1874*:7.
26. Airy, G.B., *ARR 1875*:6.
27. See Dunkin (1860, 1864).
28. Dyson, F.W., *Gr .Obs. 1915*:Aiii-iv.

29. Dyson, F.W., *Gr. Obs. 1915*:Aiv-v.
30. Dyson, F.W., *Gr. Obs. 1930*:A7.
31. Jones, H. Spencer, *ARR 1934*:21.
32. Jones, H. Spencer, *ARR 1953*:4.
33. Airy, G.B., *ARR 1864*:7.
34. Jones, H. Spencer, *ARR 1941*:1,3.
35. Jones, H. Spencer, *ARR 1942*:3.
36. Dyson, F.W., *ARR 1923*:7.
37. Dyson, F.W., *ARR 1923*:8.
38. Dyson, F.W., *ARR 1924*:7.
39. Jones, H.Spencer, *ARR 1944*:3.
40. Christie, W.H.M., *Gr. Obs. 1915*:Axi.
41. The unfortunate assistant was David Kinnebrook, dismissed by Maskelyne. See Maskelyne (1799:339); Howse (1975:169-170).
42. Airy's observations with the ATC on 1851 May 21 differed from those of W Rogerson by $0^s.46$, comparable to the Maskelyne–Kinnebrook difference but no longer a sacking offence! (*Gr. Obs. 1851*). A detailed account of personal equations in astronomy is given by Duncombe (1945), and Schaffer (1988) examines two mutually supportive disciplines, astronomers' constant efforts to quantify and control personal equations and experimental psychologists' studies of reaction times.
43. Witchell, W.M. (1952:29).
44. For the major investigations see Airy (1856), Dunkin (1865), Stone (1866), Dunkin (1869), Christie (1891), Bryant (1898), Thackeray (1899), Bryant (1901).
45. Airy (1896:185).
46. Dyson, F.W., *Gr. Obs. 1927:*A86.
47. Witchell, W.M. (1934).
48. Airy, G.B., *ARR 1839*:2.
49. Jones, H. Spencer, *ARR 1954*:6, *1955*:9.
50. Jones, H. Spencer, *ARR 1955*:5.
51. Airy, G.B., *ARR 1847*:11.

11 REFERENCES

Airy, G.B., 1853. Description of the Transit Circle at the Royal Observatory, Greenwich. (Appendix, *Greenwich Observations 1852*). Her Majesty's Stationery Office, London.

Airy, G.B., 1856. Remarks upon certain Cases of Personal Equation which appear to have hitherto escaped notice, accompanied with a Table of Results. *Monthly Notices of the Royal Astronomical Society*, **16:**6-10.

Airy, W. (Ed.), 1896. *Autobiography of Sir George Biddell Airy*. Cambridge University Press, Cambridge.

Barlow, C.W.C. & Bryan, G.H., 1944. *Elementary Mathematical Astronomy* (fifth edition). University Tutorial Press, London.

Biddell, G., 1891. Reported in *Observatory*, **14:**291-292.

Bryant, W.W., 1898. On the "Two-Method" Personal Equation. *Monthly Notices of the Royal Astronomical Society*, **58:** 282-286.

Bryant, W.W., 1901. Further Investigation of the "Two Method" Personal Equation. *Monthly Notices of the Royal Astronomical Society*, **61:**408-414.

Campbell, W.W., 1899. *The Elements of Practical Astronomy* (second edition). Macmillan, New York.

Chapman, A., 1990. *Dividing the Circle*. Ellis Horwood, Chichester.

Christie, W.H.M., 1891. Preliminary Note on the Change of Personal Equation with Stellar Magnitude in Transits observed with the Transit Circle at the Royal Observatory, Greenwich. *Monthly Notices of the Royal Astronomical Society*, **51:**455-458.

Duncombe, R.L., 1945. Personal Equation in Astronomy. *Popular Astronomy*, **53:**2-13; 63-76; 110-121.

Dunkin, E., 1860. Comparison of the Probable Error of a Transit of a Star Observed with the Transit-circle by the "Eye and Ear" and Chronographic Methods. *Monthly Notices of the Royal Astronomical Society*, **20:**86-88.

Dunkin, E., 1864. On the Probable Error of a Meridional Transit-Observation, by the "Eye-and-Ear" and Chronographic Methods. *Monthly Notices of the Royal Astronomical Society*, **24:**152-160.

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Dunkin, E., 1865. On some Peculiar Instances of Personal Equation in Zenith Distance Observations. *Monthly Notices of the Royal Astronomical Society*, **25:**215-216.

Dunkin, E., 1869. On Personality in Observing Transits of the Limbs of the Moon. *Monthly Notices of the Royal Astronomical Society*, **29:**259-268.

Fricke, W. and Kopff, A., 1963. Fourth Fundamental Catalogue (FK4). *Veröffentlichungen des Astronomischen Rechen-Instituts, Heidelberg*, nr 10.

Gething, P.J.D., 1954. The Collimation Error of the Airy Transit Circle. *Monthly Notices of the Royal Astronomical Society*, **114:**415-432.

Howse, H.D., 1975. *Greenwich Observatory*, vol. 3: *The Buildings and Instruments*. Taylor & Francis, London.

Howse, H.D., 1980. *Greenwich Time and the Discovery of the Longitude*. Oxford University Press, Oxford.

Jones, H. Spencer, 1939. The Rotation of the Earth, and the Secular Accelerations of the Sun, Moon and Planets. *Monthly Notices of the Royal Astronomical Society*, **99:**541-558.

Jones, H. Spencer, 1941. The Solar Parallax and the Mass of the Moon from Observations of Eros at the Opposition of 1931. *Monthly Notices of the Royal Astronomical Society*, **101:**356-366.

Kopff, A., 1937. Dritter Fundamentalkatalog des Berliner Astronomischen Jahrbuchs (FK3). *Veröffentlichungen des Astronomischen Rechen-Instituts, Berlin*, nr 54.

Lowne, C.M., 1981. The Object Glass of the Airy Transit Circle at Greenwich. *Observatory*, **101:**43-50.

Maskelyne, N., 1799. *Astronomical Observations made at the Royal Observatory, Greenwich, from the year 1787 to the year 1798,* vol. III, p.339.

McCrea, W.H., 1975. *The Royal Greenwich Observatory*. Her Majesty's Stationery Office, London.

Newcomb, S., 1906. *A Compendium of Spherical Astronomy*. Macmillan, New York; reissued 1960, Dover Publications, New York.

R.A.S.Council, 1851. *In:* Report of the Council. *Monthly Notices of the Royal Astronomical Society*, **11:**94-99.

Satterthwaite, G.E., 1995. *The History of the Airy Transit Circle at the Royal Observatory, Greenwich.* MSc Dissertation, University of London.

Satterthwaite, G.E., 2001. Airy and positional astronomy. *Journal of Astronomical History and heritage*, **4**:101-113.

Schaffer, S., 1988. Astronomers Mark Time: Discipline and the Personal Equation. *Science in Context*, **2**(1):115-145.

Smart, W.M., 1962. *Text-Book on Spherical Astronomy* (fifth edition). Cambridge University Press, Cambridge.

Stone, E.J., 1866. On Personal Equation in Reading Microscopes. *Monthly Notices of the Royal Astronomical Society*, **26:**48-51.

Symms, L.S.T., 1953. Observations of the Old Meridian Mark at Chingford. *Observatory,* **73:**250-251.

Thackeray, W.G., 1899. The Greenwich Meridian Observations of Polaris, 1836-1893, with reference to Personality, the value of the Constant of Aberration, and the Star's Parallax. *Monthly Notices of the Royal Astronomical Society*, **59:**345-351.

Witchell, W.M., 1934. The Old Azimuth Pillar at Chingford. *Observatory*, **57:**283-264.

Witchell, W.M., 1952. The Story of the Greenwich Transit Circle. *Occasional Notes of the Royal Astronomical Society,* **2**(14):21-33; also in bound volume, **2:**147-159.

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