2003JAHH....6...13S

Journal of Astronomical History and Heritage **6**(1):13-26 2003

Airy's zenith telescopes and "the birth-star of modern astronomy"

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Abstract
When Sir George Airy (1801–91) became the seventh Astronomer Royal in 1835, the Royal Observatory at Greenwich already had a long history of zenith observations for monitoring aberration and nutation, and providing a zenith-point for the meridional instruments.

Continuing this programme, Airy designed two very successful instruments. His Reflex Zenith Tube succeeded where earlier instruments had failed, and his reflex principle was developed to provide the most successful zenith instruments over more than a century. His zenithal Water Telescope, developed for a specific experiment, was equally successful. The design and construction, operating procedures, and programmes carried out with these instruments are described.

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

1 INTRODUCTION

As Airy entered his second decade at Greenwich, having completed the massive re-reduction of all the Greenwich positional observations of the Moon and planets from the period 1750–1830, he turned his attention to the Observatory's positional instruments. Whilst the existing instruments were in good order, they had already been in use for more than three decades at a time of rapid development in positional astronomy, and Airy foresaw a need to extend his observing capability to fainter objects (not least because of the fast-growing numbers of minor planets), and also to achieve greater accuracy. This study resulted in a suite of four major new instruments which all entered service between 1847 and 1854, comprising three specialist telescopes and a chronograph. All were designed, and their construction supervized, by Airy himself. They would prove to have a combined useful life of 313 years, and the designs of two of them would remain influential for more than a century.

One of these instruments, the Reflex Zenith Tube, was an example of Airy's remarkable ability to select the best method of achieving a particular end, where many others had failed. Its performance eventually proved to be of such a high standard that it was hastily brought back into service after its intended retirement, and also provided the basis for a new generation of zenith instruments.

2 HISTORICAL BACKGROUND

By the beginning of the seventeenth century support was growing in favour of the heliocentric universe proposed by Copernicus half a century earlier, against the geocentric system still strictly advocated by the ecclesiastical authorities. An early supporter was Galileo, whose telescopic discovery of the phases of Venus and the satellites of Jupiter were demonstrations of the validity of the Copernican system. Galileo realized that if the annual parallax of a star could be measured it would effectively prove the Earth to be in motion. In 1632 he suggested a possible method of doing this in his *Dialogue Concerning the Two Chief World Systems.* By observing the parallactic angle between one star and another close by, the observation would be freed from the effects of atmospheric refraction. There is however no record of Galileo having attempted this himself.

As support for the Copernican system increased, the immediate need to observe stellar parallaxes in order to demonstrate the Earth's motion waned, but it was later realized that they would provide a means of directly measuring stellar distances. Early efforts were however doomed to failure, the stars being much farther away than the early observers imagined, and instruments would be needed capable of measuring parallactic angles to a fraction of one second of arc.

2.1 Early Observations

The first serious attempt to measure a stellar parallax was made by Robert Hooke in 1669. Hooke realised that the effect of atmospheric refraction is zero at the zenith, and that a second-magnitude star, γ Draconis, transited almost zenithally in London. Hooke had a telescope of 36 feet (10.97 m) focal length, and realizing that it would be necessary for it to remain stationary through months of observation he mounted it vertically within his rooms at Gresham College, London. Unfortunately his observations were terminated by illness and damage to the telescope lens, but as Hoskin (1997) has written, the construction of a telescope designed to measure the position of one single star, and that only when the star was near the zenith, was a brilliant conception at a time when telescopic astronomy was still in its infancy. Hooke did obtain a value of 27″ for the supposed parallax of γ Draconis, but this was not confirmed by other observers. Furthermore, Flamsteed and others had reported unexplained annual variations in the declination of Polaris over a range of some 40 arc-seconds.

This led Flamsteed, newly appointed as the first Astronomer Royal, to construct a zenith telescope in about 1676. This consisted of an objective nominally of 90 feet focal length, mounted horizontally at the top of a well at Greenwich, the eyepiece assembly being suspended beneath it as a plumb-bob, thus automatically establishing the vertical. There is only one recorded observation, on 1679 July 30: "Ego in puteo subterraneo transitum observavi lucidae in capite Draconis" [I, in the underground well, observed the star in the head of Draco], cited in Baily (1835:lix). There is no record of Flamsteed's well being specially dug, it is more probable that he made use of an existing well associated with Greenwich

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Castle [formerly known as 'Mirefleur'] which formerly stood on the site. Its exact location was in some doubt for many years, but was established by Airy in 1840; the upper 25 feet of the shaft were excavated in 1965. The well is shown in use as a telescope in a contemporary engraving by Francis Place (see Howse 1975, Figures 52, 53). Flamsteed's limited use of it may be explained by the unpleasant conditions, or by the poor quality of the object glass (by Borel of Paris) which still survives. It was presented to The Royal Society in 1737 by James Hodgson, an assistant to Flamsteed at Greenwich who married his niece and inherited some of his property; in the Society's records it is described as "that which Mr Flamsteed designed to have used in the well at the Observatory at Greenwich, but was prevented by the damp of the place" (Weld 1848, vol.I, p. 255). The lens, now in the care of the Science Museum, London, was examined and tested at Greenwich in 1955 where it was found to be of very poor quality. It is a very thin plano-convex lens, 9¾ inches (24.8 cm) in diameter and 0.36 inches (9 mm) thick at the centre, and the focal length was found to be 87 feet 5 inches (26.64 m) in sodium light (Hunter & Martin, 1956).

2.2 Observations by Molyneux and Bradley

The next significant attempt was made by the amateur astronomer Samuel Molyneux, using a zenith sector of 24 feet (7.3 m) radius by George Graham, one of the leading instrument-makers of the day. This instrument, built into the fabric of Molyneux's home in Kew, south-west London, was not a fixed telescope, but one pivoted at the top and therefore able to move in the meridian plane through a small arc north or south of the zenith, the motion being controlled by a micrometer screw and measured against a graduated arc. The vertical was established by a plumb-line. Molyneux was assisted in his observations by James Bradley, later to become the third Astronomer Royal. Observations of γ Draconis between 1725 December 3 and 12 had showed no change in the star's zenith distance (ZD), but observing again on December 17 Bradley found it had moved, and in a direction opposite to that predicted by the Earth's motion. During the next twelve months the displacement varied over a range of about 40″. This variation was not accounted for by either parallax or atmospheric refraction. Bradley decided that an instrument was required which could observe more stars, and commissioned from Graham a new zenith sector of 12½ feet (3.8 m) radius, which was erected at his aunt's home in Wanstead, Essex in 1727. The new instrument had a range of zenith distance of ±6°.25. Bradley found that each star traced out an apparent path whose size was related to its declination. He suspected that the annual movement was related to the Earth's motion, and in 1728 realized the cause. It was an effect of relative velocity, arising from the Earth's orbital motion and the finite velocity of light, which had been determined by Römer in 1675. Bradley had discovered the aberration of light. This explained the observed motions, but correcting for it did not reveal a measurable parallax due to the stars' great distances. Further observations with the same instrument did however enable Bradley to announce the discovery of nutation in 1748.

2.3 New Instruments Introduced by Pond

The story now moves back to Greenwich. After Bradley became Astronomer Royal in 1742 his zenith sector was purchased for the Royal Observatory, where it is still preserved, and continued to be used. Towards the end of his term of office Nevil Maskelyne had commissioned a mural circle to replace the quadrants which had been used for zenith distance determinations for more than half a century; it was installed in 1812. His successor as Astronomer Royal, John Pond, was very experienced in positional observation before his arrival at Greenwich in 1811. It had now become clear that the traditional plumb-line could no longer provide a sufficiently accurate zenith-point for ZD observations. Initially the mural circle was used differentially, using the direction of the pole (determined from observations of circumpolar stars) as a reference. In 1812 Pond installed a 9½-foot 'zenith micrometer' on the circle pier to provide the zenith-point. This was in effect a Newtonian reflector mounted as a zenith tube, but was never used successfully. In 1816 he replaced it with an 8-foot achromatic zenith telescope. The use of an achromatic object-glass was clearly a step forward, but no recorded observations exist. In any case, by 1822 Pond realized that the zenith-point could be determined using the mural circle itself, by combining observations of stars made directly and by reflection in a trough of mercury. This required the combination of observations made on different days, however, and in 1824 a second circle was erected so that the observations could be made directly and by reflection at the same transit.

Meanwhile, Pond's final zenith instrument was nearing completion. Originally intended to provide accurate zenith-point determinations, it had been commissioned in 1819 and a room constructed for it at the north-west corner of Flamsteed House, on the site once occupied by Halley's original transit instrument. After disputes and delays the 25-foot 'Great Zenith Tube', having an object-glass of 5 inches (12.7 cm) aperture and 24 feet 6 inches (7.47 m) focal length, was finally erected in 1831. It was found to be very unsatisfactory, largely due to the effect of convective air currents in its tall, narrow enclosure. The roof was replaced in 1834 in an unsuccessful attempt to cure the problem. The instrument was to prove yet another failure, but perhaps its greatest contribution was to engage the interest of the one person most capable of devising a solution to the problem.

2.4 Improvements by Airy

From his taking office in 1835 it is clear that Airy was anxious to get Pond's Zenith Tube into good order. In his very first report to the Board of Visitors he remarks:

> The Zenith Tube deserves particularly to be noted at present. I have reason to think that much of the difficulty of seeing stars well defined, &c. arose from the passage of currents of unequally-heated air near to the object-glass: possibly however a part might arise from defects of the object-glass ... With respect to the mechanical construction, it is in my opinion seriously defective.[1]

A year later he reports that the acting parts of the instrument have been completely remodelled, new micrometers fitted, and regular observations were about to commence[2]. Further modifications were reported in 1840. Although the instrument was designed to permit rotation of the telescope through 180°, this operation took a minimum of fifteen minutes and so direct and reversed observations at the same culmination were not possible. Airy makes an important statement in 1842:

> An inspection of the results of the Zenith Tube observations has convinced me that it will never be possible to obtain results quite satisfactory unless the double observation (in opposite or reversed positions of the instrument) can be made at one transit. I have therefore made some small alterations in its mounting for facilitating rapid observation (the principal novelty, as regards the observation, being that two wires are provided, one for the observation of γ Draconis in each position), and it is found that the double observation can be made without the smallest difficulty.[3]

In the following annual report Airy records that the results of the observations were more consistent since the change[4], but only four years later he is expressing doubts whether there is any advantage in the continued use of the instrument, "the irregularities of result ... exceeding those of the mural circles"[5]. The following year he reports that the final observation was made on 1848 May 1 and the instrument dismounted[6]. The major cause of the irregularities was no doubt the unsuitability of the room, and Airy refers in the same report to the expressed opinion of several members of the Board that the instrument should be remounted elsewhere[7]. He clearly had no intention of abandoning the observing programme, however, and records that a principle for a new instrument "first occurred to me in the spring of 1848 and was first described in a short Address to the Visitors"[8]. A month later, "if it be the object of the Visitors to obtain a continuous series of accurate observations of γ Draconis (a thing to which, in my opinion, too great importance cannot be attached), and to adopt ... a new construction", he submitted a proposal for a new form of zenith telescope[9]. Airy was clearly convinced of the importance of continuing observations of γ Draconis, which he was later to describe as "the birth-star of modern astronomy" (Airy 1872:cxix).

3 GAMMA DRACONIS

This star (HD164058) had now been an object of interest to English observers for 180 years. Also known as *Eltanin* (the Head of the Dragon), it appears to have been significant in ancient Egypt also, its rising *c.* 3500 BC being aligned with the central passages of the temples of Hathor at Denderah and of Mut at Thebes (Allen, 1963:208). It is an orange giant at a distance of 31 parsecs, equivalent to a parallax of only 0″.025, hence the inability of Hooke and his successors to measure it. Its position, for the epoch 2000.0, is $\alpha\ 17^h\ 56^m\ 36.2^s$, $\delta\ +51°\ 29'\ 20''$. Its declination, being very similar to the latitude of Greenwich (51° 28′ 38″.2N), and its relative brightness (visual magnitude 2.23) combined to establish its importance as 'the zenith star'. In Flamsteed's time it transited about 4′ north of the zenith, in Airy's time about 2′ north. With an annual proper motion of 0″.024 in an approximately south-west direction, its ZD at 2000.0 was 42″ north. Due to aberration its declination varies during the year over a range of ±40″.1, reaching its most northerly culmination in mid-September and its southernmost in mid-March. These figures demonstrate the accuracy Bradley had achieved with Molyneux's instrument in 1725.

4 AIRY'S REFLEX ZENITH TUBE

Airy's proposal for the new instrument, as set out in his report to the Board of Visitors in 1848, embodied the reflex principle that was to found a dynasty of highly-successful zenith instruments:

> Let the micrometer be placed close to the object-glass, the frame of the micrometer being firmly connected with the object-glass cell, and a reflecting eyepiece being used with no material tube passing over the object-glass: and let a basin of quicksilver be placed below the object-glass, but in no mechanical connexion with it, at a distance equal to half the focal length of the object-glass. Such an instrument would at least be free from all uncertainties of twist of plumb-line, viscosity of water, attachment of upper plumb-line microscope, attachment of lower plumb-line microscope, and the observations connected with them: and might be expected, as a result of this extreme simplicity, to give accurate results.[9]

Construction of the new instrument was delayed, pending a decision whether it should re-use the object-glass of the old Zenith Tube, or that of Pond's ten-foot Transit Instrument, which was about to be superseded by Airy's new Transit Circle. Airy did demonstrate the detailed construction of the proposed instrument at the Visitation in 1849 June, however, in the form of a model. He comments that:

> ... the Visitors will remember, that the micrometer and the object-glass are united, and that the only way of putting the telescope in focus is by altering the distance between the object-glass and the surface of the quicksilver. After careful consideration, I have determined on doing this by a vertical motion of the tube in which the object-glass is mounted; the weight of the tube, &c. being supported by a counterpoise, and the motion being effected by rack and pinion, with a clamp-screw for fixing when in the proper position.[10]

Airy further proposed "that the Observer should remain fixed in position while the object-glass and micrometer are reversed, his face being turned either to the East or to the West, in order that his hand may conveniently reach the micrometer head". He proposed that two wires be used, for observing the star in the two positions of the micrometer, and chose the object-glass from the old transit instrument. The optical arrangement of the instrument is shown schematically in Figure 1.

4.1 Design and Construction

This comparatively small instrument bears all the hallmarks of Airy's design principles. As in the case of the Altazimuth and the Transit Circle, stability was ensured by the use of iron castings, on which the optical and measuring parts were mounted. Manufacture of the instrument was entrusted to Airy's trusted collaborator William Simms (1793–1860) of Troughton & Simms, who was at the same time responsible for making the optical and precision-measuring parts of the Transit Circle.

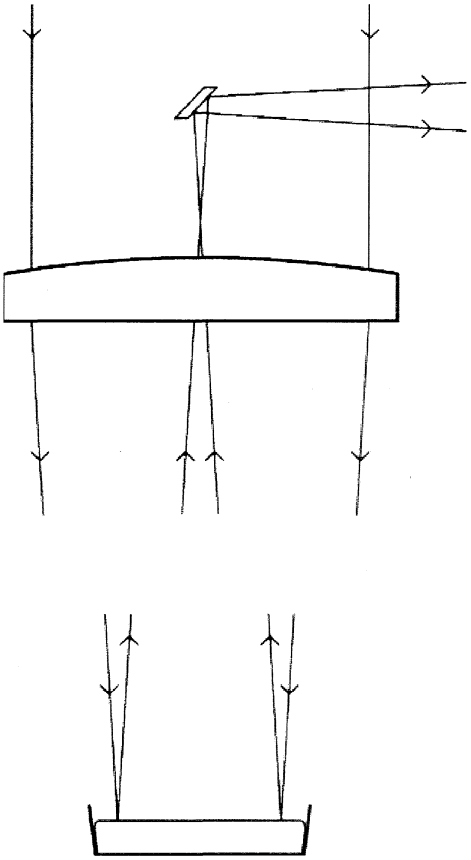

Figure 1. The optical arrangement of the Reflex Zenith Tube (middle section omitted).

Airy published a detailed description of the Reflex Zenith Tube (RZT), including four plates of detailed drawings (Airy, 1855). This account includes an extended statement of the optical principles and method of use of the instrument, and also the procedures used to determine the corrections to the micrometer readings to compensate for any slight inclination of the optical axis from the true vertical. Sectional drawings from Airy's description, showing the general construction of the instrument, are reproduced in Figure 2. The account concludes with a summary of the measures made to determine the constants of adjustment. A brief account of the instrument is given by Howse (1975:67–9).

4.1.1 Component Parts

The main parts of the instrument consist of three modules: (i) an outer tube on a pedestal base; (ii) an inner tube which can slide vertically within the outer tube and be clamped at the desired position, to which structures supporting the eyepiece tube and the diagonal reflector are attached and having a recessed and flanged upper end; (iii) the rotary, which sits in the recessed upper end of the inner tube and carries the object-glass and micrometer assembly. The exterior parts are shown in Figure 3.

The outer tube is of very solid construction and has an exterior pair of iron strengthening rings. The inner tube is provided with an interior pair of strengthening rings, and carries a counterbalancing stirrup arm with adjustable weight. A rack provides for vertical motion of the tube, activated by a pinion mounted on the outer tube and accessed through a slot; a clamping screw is also provided. Attached to its southern side is the upper end of a brass rod terminated with a wooden float in the mercury trough, to facilitate focussing. The arm attached to its eastern side to support the eyepiece, and the pair of arms on the west which support the diagonal reflector, are cranked in order to provide clearance for the rotary.

The eyepiece is constructed in two parts to avoid obscuration of the instrument's field of view, and has four optical components. The diagonal reflector is in the form of a 45° prism, whose lower surface is also figured to form the third lens. The fourth lens is mounted just below. The other part of the eyepiece comprises a horizontal tube, supported clear of the telescope aperture and containing the first and second lenses. In order to ensure that the observations of γ Draconis are made centrally in the field of the object-glass, the wire-frame and eyepiece diagonal are offset from the centre of the object-glass by an amount equivalent to the zenith distance of the star.

The rotary is equipped with handles and end-stops to facilitate the 180° rotation between observations. The object-glass is the achromatic objective by Peter Dollond, formerly used in the Troughton Ten-foot Transit Instrument from 1816-50; its aperture is 5 inches (12.7 cm) and its focal length 9 feet 8 inches (2.9 m). The micrometer assembly is attached to the object-glass cell, and hence rotates with it. A spirit level is provided on the cell, with a scale to measure any slight inclination of the optical axis from the vertical. The rotary (with handles), the eyepiece and the prism reflector can be seen in Figure 4.

There are two extraneous assemblies, (i) the mercury trough (described by Airy as the "quicksilver trough") and (ii) the field-illumination apparatus. The trough has two chambers, connected by a curved passage (Z) in the base of the trough, one to provide the horizontal reflecting surface (Y), and a smaller one (X) carrying the float used in adjusting the focus (see Figure 2). Airy points out in his description that "the surface of the quicksilver in Y may be made perfectly clean; the quicksilver being all poured from Y to X through Z, in such a manner as to carry the dirt with it, and being returned in such a manner that the upper stratum of the quicksilver in X never descends so low as the passage Z"[11]. The field-illumination apparatus comprises an inclined elliptic annular reflector, mounted above the mercury surface to direct the light from a gas lamp up the main tube, the brightness of the field being controlled by tilting the reflector with the control rod provided (see Figure 2).

4.1.2 Micrometer and Wire-frame

In his detailed proposal for the instrument Airy suggested a major detail of construction which would greatly facilitate the double observation:

> I propose to use a more complex micrometer; not a double micrometer in the ordinary sense, but an apparatus in which a micrometer A carries every part of a micrometer B; that A be read before beginning; that the first bisection be made by B; and that without altering or reading B the second

bisection be made by A, and that both be then read. This apparatus would possess two great advantages, viz., that no reading would be necessary between the observations, and the same hand would be used in both bisections; while the two observations would still be made upon two wires fixed to the same metallic frame, and no weakness, or new liability to friction, would be introduced.[12]

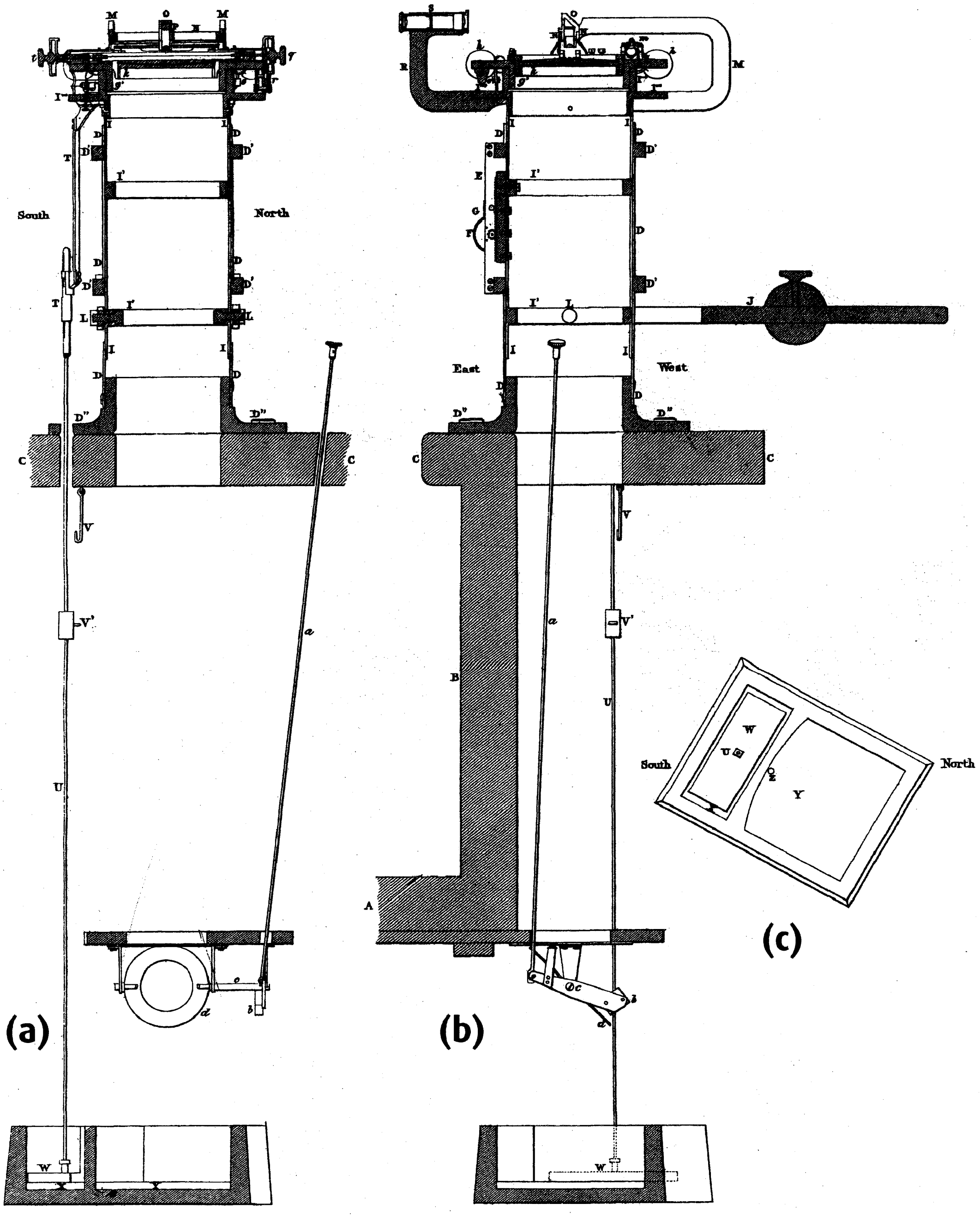

Figure 2. Vertical sections of the RZT, from Airy's description; (a) viewed from the east, (b) viewed from the north; (c) plan of the mercury trough (after Airy, 1855:plate I).

This passage demonstrates how thoroughly Airy had considered the procedure to be adopted in using the instrument, which was still only in the design stage. It is noteworthy too that Airy was concerned with the design and construction of both this instrument and his revolutionary and complex Transit Circle[13] at the same time, further evidence of his rare combination of supreme astronomical and engineering talents. The principle of the double micrometer is shown in schematic form in Figure 5. The values of one revolution of the micrometer screws expressed in arc, as re-determined in 1902 at the start of the latitude programme (see below), were 16″.79 for micrometer A and 16″.60 for B.

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The micrometer wire-frame carries two wires, called 15 and 16, separated by a distance equivalent to approximately twice the ZD of γ Draconis; these being centred in the field, if wire 15 is positioned on the image of the star in one position, a small adjustment will bring the other into coincidence with it in the reversed position. Wires 15 and 16 were the central pair of a series of thirty mounted on the frame, to provide pairs for the observation of other stars culminating at greater distances from the zenith. This provision was little used for many years, but was to prove essential to the success of the instrument in the latter phase of its working life. Although referred to as 'wires', as in all the positional instruments of the time they were in fact spider webs.

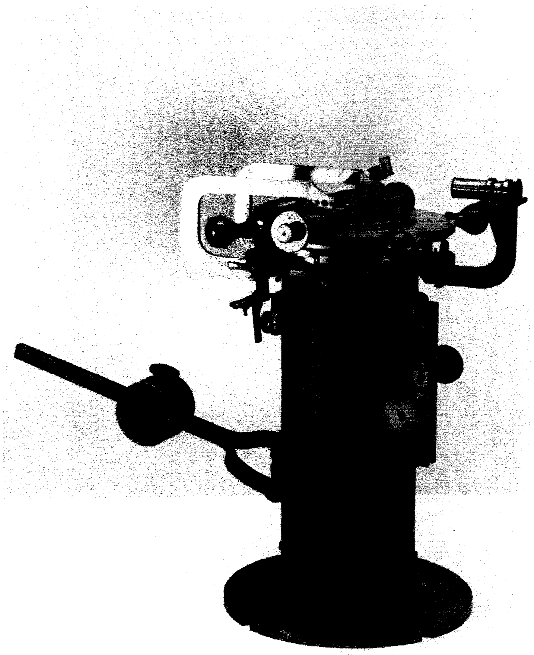

Figure 3. The RZT, photographed from the south-east.

In normal use the wires were oriented east–west, to make ZD measures as the star transited the meridian; the values of the wire intervals could be determined very easily, by rotating the instrument through 90° so that the wires were parallel to the meridian and timing the transit of the star across each wire in turn.

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4.1.3 Installation and Early Mounting Problems

Airy initially housed the new instrument by adapting a small room off the north-east corner of the former circle room, now extended southward to accommodate the new Transit Circle. The walls were raised, and a flap-shutter mounted in the roof. The RZT was erected, and initial determinations of the instrumental constants carried out, in the autumn of 1851. The mercury trough was mounted on a brick pier built over an old stove flue, but despite detaching it from all nearby structures it was found that the mercury surface was disturbed by frequent tremors. The brick pier was taken down and the trough mounted upon a bed of sand, but the disturbance persisted. Use of the instrument was also interrupted by an unfortunate accident when in November the wire-frame was removed for some broken wires to be replaced. Subsequent failure to record γ Draconis, which at the time transited in daylight, did not at first arouse suspicion. In the following spring, however, Airy returned from a visit abroad to find that night transits were also being lost, and found on investigation that when the wires were replaced the prism had been put back incorrectly. It was immediately corrected, but many possible observations had been lost and poor weather had also added to the problem.

By 1854 Airy had concluded that the tremors in the mercury surface were incurable, "proximity to the entrance gate rendering it liable to perpetual jars, and the hardness of the brickwork upon which its sand-bed is founded tending to propagate the tremors"[14]. He therefore proposed to construct a new building, "in the angle between the passage behind the Astronomer Royal's Room and the south projection of the Transit Circle room", that is adjoining the south-western corner of the ATC room. There was some delay, but the new RZT building was completed and the instrument moved at the end of 1855. On moving the instrument Airy modified it in the light of these experiences, by shortening the main tube and mounting it on a raised table. This provided easier access to the mercury trough, and the instrument was no longer standing on the same floor as the observer. The published account (Airy, 1855) describes the instrument in this revised form.

Before moving the RZT, Airy carried out some tests at the new site by erecting a collimating telescope vertically above the mercury trough, to examine the reflected image of its wires. The results were not pleasing:

> "A well was dug below to various depths, finally to the depth of ten feet below the surface, or seven feet below the deepest foundation; and stages were erected from time to time for support of the quicksilver trough, always resting on the bottom of the well without touching the sides. The tremor was not in the smallest degree diminished. Besides the great disturbances, causing the wire-comb of the Collimator to disappear, when a door was shut in any part of the Observatory, or when a person

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walked within many yards, there was a constant tremor which usually made the wire invisible. The experience of this investigation justifies me in believing that no practicable depth of trench prevents the propagation of tremor when the soil is like that of Greenwich Hill, a gravel, in all places very hard, and in some, cemented to the consistency of rock."[15]

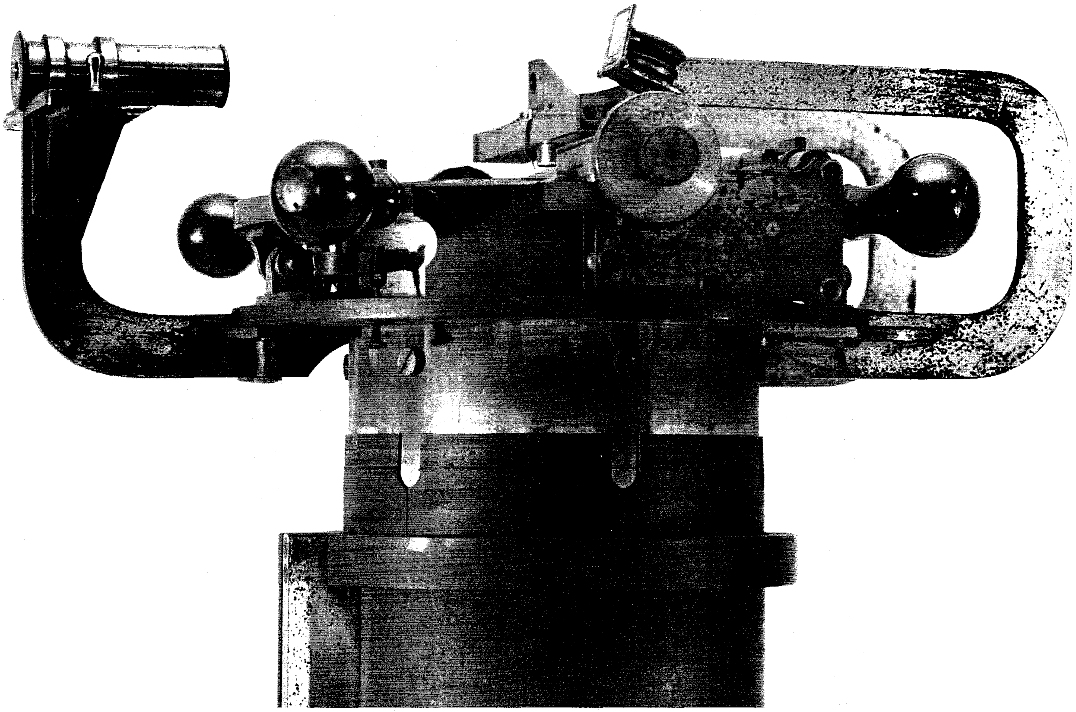

Figure 4. The upper part of the RZT, showing the reflecting prism and eyepiece above the rotary which carries the object-glass and microscope assembly.

Airy then adopted a plan which "was in some measure tried at the Paris Observatory, and was again urged by Sir John Herschel"[16], mounting the mercury trough on a stage suspended on strips of "vulcanized caoutchouc" [rubber]; after some adjustment the system worked, "leaving the image practically almost perfect". The following year Airy was able to report "the construction has been perfectly successful; the tremors are absolutely destroyed, and the star has been observed at all times of night and day. It so happened that it was observed on the very day on which it passed with the sun"[17], although "Frequent attention is necessary to correct the stretching of the straps of vulcanized caoutchouc".[18] Another problem in the tall, narrow room, described as "a little room of a most curious shape" (Maunder, 1900:304), was inadequate ventilation. This was cured by changing to an opening window: "The image of the star, since a free passage of air was allowed from the window, is almost always very good"[19]. Thus Airy had finally freed the observations of γ Draconis from the damaging effects of air currents on zenith observations which had plagued him since his arrival at Greenwich 22 years earlier.

5 OBSERVATIONS WITH THE RZT

5.1 Observing Programmes

5.1.1 The Original Programme, 1851–99

For almost half a century the RZT was used for its original purpose of determining the zenith distance of γ Draconis in order to monitor aberration and nutation, and to provide a reference zenith-point for the other meridian instruments. When it commenced operation in 1851 the mural circles hitherto used for the ZD observations of the Sun, Moon, planets, and stars had been superseded by Airy's Transit Circle, but like them the ATC was equipped with the means of observing stars both direct and by reflection, thus providing its own determined zenith-point. Airy was however very conscious of the fact that no instrument, however well engineered, can be entirely free from small errors of adjustment, and that these must be determined as accurately and frequently as possible and appropriate corrections made to the observations. He was clearly aware of the value of maintaining an independent means of determining the zenith point, using a simpler form of instrument which was not subject to those instrumental errors varying with the instrument's attitude which were an unavoidable complication in transit-circle observations, for example errors of collimation, level, azimuth, and flexure (see Satterthwaite, 2001). The RZT therefore continued to be used for this purpose until long after Airy's retirement.

Examination of the observations over several decades had revealed some unaccountable anomalies, however, and in the period 1882–86 ZD measures of the star were temporarily suspended and a long series of tests was carried out in an endeavour to relate these anomalies to thermal effects. A new focussing rod with a scale reading to 1/200 inch was fitted, and transits of γ Draconis, and occasionally 9 Aurigae, were observed over all 30 wires to determine variations in the scale value corresponding to different temperatures and slight variations in the focal length.[20] Unfortunately, analysis of these

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observations did not lead to a useful correlation. Normal ZD observations were resumed in 1886 April[21]. By the end of the century the Transit Circle was performing with such accuracy and its instrumental errors were so well determined that the need for an independent check was reduced, and because of the increased pressure on observers due to the programme of observations for a new Ten Year Catalogue, observations with the RZT were suspended at the end of 1899[22].

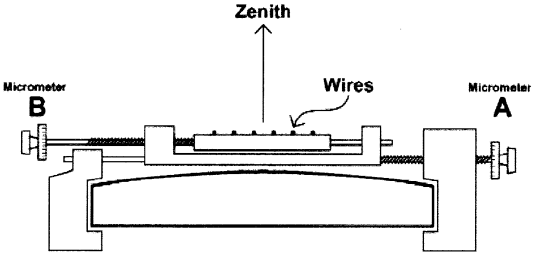


Figure 5. The principle of Airy's double micrometer, mounted on the OG-cell.

5.1.2 A New Programme, 1902–11

In the eighteenth century Euler had predicted that the axis of rotation of a body such as the Earth would not necessarily coincide with its axis of symmetry, in which case the latter would precess around the former which maintains a fixed direction in space. This would result in a wandering of the geographical pole around the pole of rotation, and consequently a variation in measured latitudes. The phenomenon was first observed by Küstner as a variation in the latitude of Berlin between 1886 and 1888. In a more extended analysis it was shown by Chandler (1891) that this would explain the anomalous results obtained with the RZT, which was therefore well suited to the task of monitoring the variation, and in 1902 "It was in consequence decided to resume the observations of γ Draconis without delay, and to observe such other stars as passed near enough to the zenith, and were sufficiently bright"[22].

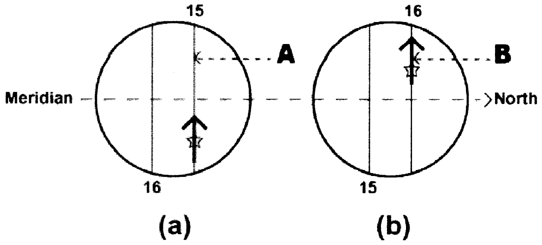
The provision for observing other stars which Airy had built in, little used hitherto, now became an important feature of the instrument. The first list of stars observed indicates its range of brightness and ZD:

Star	Magnitude	ZD (′)
Piazzi XIII.296	6.3	+3.5
9 Aurigae	5.5	0.0
Groombridge 1017	6.9	–0.4
Groombridge 1024	6.2	–0.6
γ Draconis	2.2	–1.4
Lalande 14549	6.6	–2.7
ι Bootis	5.3	–19.7
5 Canum Venaticorum	5.0	–36.7

It was found that stars could be observed with good definition down to magnitude 7.0 and up to 50′ north or south of the zenith; a considerable number of stars were therefore added to the list, and more than 9600 observations were made before the RZT was finally retired. The observations from the period 1906–09 were discussed by Eddington and "On the whole a fair agreement is shown with the results of the International Latitude determinations published by Professor Albrecht".[23] It appeared however that the instrument could no longer give the accuracy required in latitude work, and that the time had come when a new instrument was required. The RZT made its last observation on 1911 August 24, and was superseded by the Cookson Floating Zenith Tube, on loan from the Cambridge Observatory. This was a conventional 6½-inch, f/10 Cooke photographic refractor, supported vertically in an iron frame which floated in an annular trough of mercury, thus permitting rotation about the vertical. Airy's reflex principle was no longer used, but would soon make a triumphant return (see section 8 below).

5.2 Methods of Observation

The normal procedure was to start with micrometer A at the observer's right hand: (i) Read and record micrometer B; (ii) as star enters the field set wire 15 on its image using micrometer A; (iii) immediately reverse the instrument and set wire 16 on the star using micrometer B; (iv) read both micrometers and record; (v) read spirit level and record. The observer faced west during the observation, using his right hand to make the micrometer settings. His field of view is shown diagrammatically in Figure 6. (Note that the apparent path of the star is affected by telescopic inversion and by reflection at the prism).



(a) (b)

Figure 6. The observer's field of view, (a) before transit, micrometer A to the right, wire 15 set on the star; (b) after transit, instrument rotated 180°, micrometer B to the right, wire 16 set on star.

Reduction of the observations is carried out by combining the micrometer settings with the known separation of wires 15 and 16: first observation, reading of A + first reading of B; second observation, reading of A + second reading of B + separation of wires. A further correction is made for any slight inclination of the object-glass indicated by the spirit level. For stars further from the zenith a similar procedure was adopted, using the most convenient pair of wires, for example wires 11 and 20.

Although the complete observation required two bisections at the same transit, this was occasionally prevented, for example by passing cloud. As with other forms of positional work, however, for observations made regularly with the same instrument over a long period of time, the instrumental adjustments and variations become so well known that with care some value can be extracted even from a single observation.

Observing duties with the RZT were normally undertaken by the Transit Circle observers. The proximity of the RZT to the ATC was convenient, enabling the duty observer with the latter to make the observation of γ Draconis when its culmination occurred during his watch, absenting himself from the major instrument for only a very few minutes. One of the most experienced observers writes that

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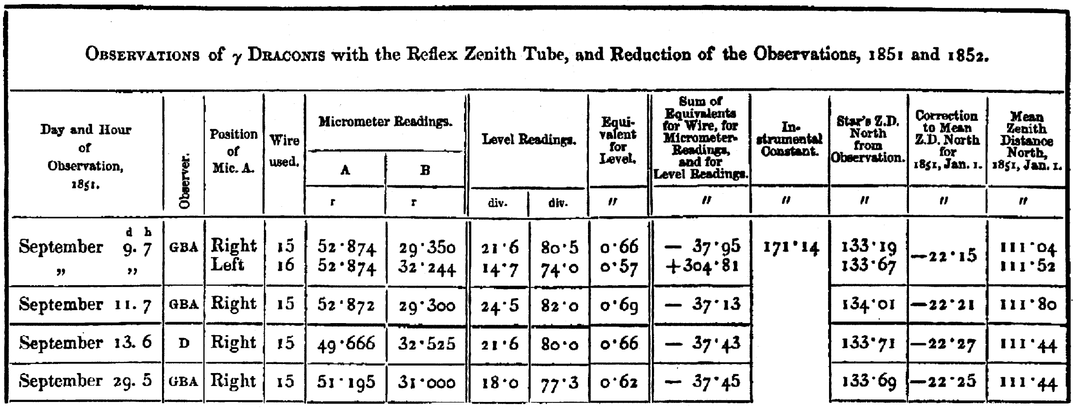
"an exercise in agility, occasionally performed, was the observation of γ Draconis ... with the Transit Circle and with the Reflex Zenith Tube by one and the same observer at the same culmination. The star passed through the field of view of the latter telescope in less than forty seconds, and this interval 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." (Witchell, 1952). This account clearly relates to the RZT in its original position, but access to its later position was only slightly less convenient and would not have precluded repetition of the feat.

5.3 First and Last Observations, and Statistics

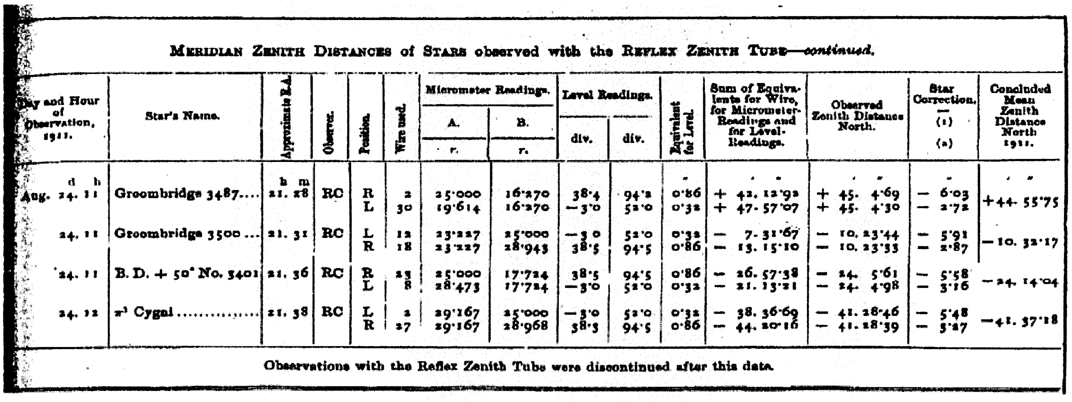
The first observation of γ Draconis was made by Airy himself on 1851 September 9 (see Figure 7). The last observation, at the end of the latitude programme, was made by R T Cullen on 1911 August 24 (Fig. 8).



Observations of γ Draconis with the Reflex Zenith Tube, and Reduction of the Observations, 1851 and 1852.

Day and Hour of Observation, 1851.	Observer.	Position of Mic. A.	Wire used.	Micrometer Readings. A	Micrometer Readings. B	Level Readings.		Equivalent for Level.	Sum of Equivalents for Wire, for Micrometer-Readings, and for Level Readings.	Instrumental Constant.	Star's Z.D. North from Observation.	Correction to Mean Z.D. North for 1851, Jan. 1.	Mean Zenith Distance North, 1851, Jan. 1.
d h				r	r	div.	div.	″	″	″	″	″	″
September 9. 7	GBA	Right	15	52·874	29·350	21·6	80·5	0·66	− 37·95	171·14	133·19	−22·15	111·04
” ”		Left	16	52·874	32·244	14·7	74·0	0·57	+304·81		133·67		111·52
September 11. 7	GBA	Right	15	52·872	29·300	24·5	82·0	0·69	− 37·13		134·01	−22·21	111·80
September 13. 6	D	Right	15	49·666	32·525	21·6	80·0	0·66	− 37·43		133·71	−22·27	111·44
September 29. 5	GBA	Right	15	51·195	31·000	18·0	77·3	0·62	− 37·45		133·69	−22·25	111·44

Figure 7. The first observations with the RZT. [Observers: GBA – G.B.Airy, D – E.Dunkin] (after *Greenwich Observations 1851*).



Meridian Zenith Distances of Stars observed with the Reflex Zenith Tube—*continued.*

Day and Hour of Observation, 1911.	Star's Name.	Approximate R.A.	Observer.	Position.	Wire used.	Micrometer Readings. A.	Micrometer Readings. B.	Level Readings.		Equivalent for Level.	Sum of Equivalents for Wire, for Micrometer-Readings and for Level-Readings.	Observed Zenith Distance North.	Star Correction. — (1) (2)	Concluded Mean Zenith Distance North 1911.
d h		h m				r.	r.	div.	div.	″	′ ″	′ ″	″	′ ″
Aug. 24. 11	Groombridge 3487....	21. 28	RC	R	2	25·000	16·270	38·4	94·2	0·86	+ 42. 12·92	+ 45. 4·69	− 6·03	+44. 55·75
				L	30	19·614	16·270	−3·0	52·0	0·32	+ 47. 57·07	+ 45. 4·30	− 2·72	
24. 11	Groombridge 3500 ...	21. 31	RC	L	12	23·227	25·000	−3·0	52·0	0·32	− 7. 31·67	− 10. 23·44	− 5·91	−10. 32·17
				R	18	23·227	28·943	38·5	94·5	0·86	− 13. 15·10	− 10. 23·33	− 2·87	
24. 11	B. D. + 50° No. 3401	21. 36	RC	R	23	25·000	17·724	38·5	94·5	0·86	− 26. 57·38	− 24. 5·61	− 5·58	−24. 14·04
				L	8	28·473	17·724	−3·0	52·0	0·32	− 21. 13·21	− 24. 4·98	− 3·16	
24. 12	π^1 Cygni	21. 38	RC	L	2	29·167	25·000	−3·0	52·0	0·32	− 38. 36·69	− 41. 28·46	− 5·48	−41. 37·18
				R	27	29·167	28·968	38·3	94·5	0·86	− 44. 20·16	− 41. 28·39	− 5·27	

Observations with the Reflex Zenith Tube were discontinued after this date.

Figure 8. The final observations with the RZT. [Observer: RC – R T Cullen] (after *Greenwich Observations 1911*).

The total number of published observations with the instrument is 11,844, more than 95% being double measures. Observations of γ Draconis during the period 1851–99 totalled 2051. Observations of all stars in the latitude variation programme, 1902–11, totalled 9793, approximately 660 of which were of γ Draconis; thus nearly 2500 observations of this star were made with the RZT during its working life.

6 AIRY'S WATER TELESCOPE

In the 1860s Hoch, Klinkerfues, and others, investigating the effects of the wave theory of light, pointed out that the passage of a ray through a refracting medium such as a telescope objective might affect the apparent value of aberration. To test this theory Klinkerfues had inserted a tube filled with turpentine in the telescope tube of a transit instrument and observed the transits of two groups of stars whose position suggested that the effect of aberration should be close to maximum and minimum respectively. His observations were not conclusive, but suggested that the theory might well be correct. This was clearly of concern to Airy:

> The question of dependence of the measurable amount of sidereal aberration upon the thickness of glass or other transparent material in the telescope (a question which involves, theoretically, one of the most delicate points in the Undulatory Theory of Light) has lately been agitated on the Continent with much earnestness. I have calculated the curvatures of the lenses of crown and flint glass (the flint being exterior) for correcting spherical and chromatic aberration in a telescope whose tube is filled with water ... I have not finally decided whether to rely on Zenith-distances of γ Draconis or on right-ascensions of Polaris. In any form the experiment will probably be troublesome.[24]

6.1 Design and Construction

Airy decided to use γ Draconis. He drew up a design for a vertical telescope and entrusted its construction to Troughton & Simms, this time in the care of the

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younger William Simms (1817–1907), nephew of Airy's former collaborator who had died in 1860. The new instrument was completed in 1870 and mounted in a building on 'the South Ground' of the Observatory, which had previously housed an instrument used by Struve as part of the Pulkowa–Altona–Greenwich longitude determination. Airy subsequently published an account of the instrument (Airy, 1872), including a detailed description, with drawings, of its design and construction. Figure 9(a), from Airy's description, shows a vertical section through the whole instrument, seen from the east. The telescope is shown after 90° rotation, that is mid-way between its two observing positions. Note the gas lamp (*I*) for field illumination via the inclined mirror (*Y*). Figure 9(b) is a section through the telescope alone; note the elbow eyepiece at the foot of the telescope.

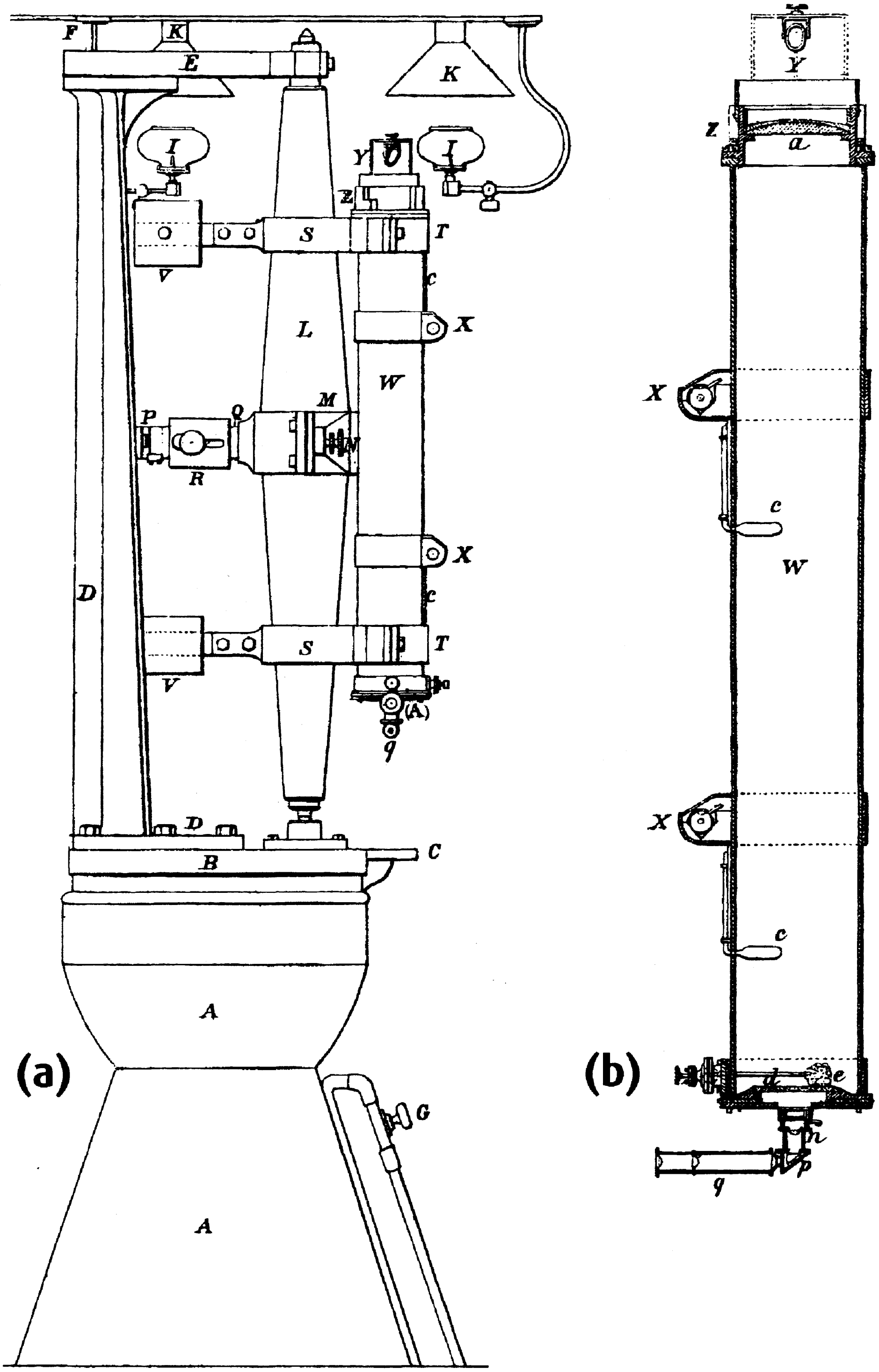

Figure 9. The Water Telescope, from Airy's description. (a) Vertical section from the east, showing instrument mid-way between its observing positions; (b) section through the telescope alone (after *Greenwich Observations 1871*).

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6.1.1 Component Parts

The instrument comprised a telescope clamped and parallel to a vertical axis, about which the whole could be rotated. The axis is of bi-conical construction, supported at top and bottom by substantial bearings built into a massive iron frame.

The objective Airy had designed was of a most unusual form. In his account of the instrument he gives full details of the calculations he had carried out in order to produce a lens capable of functioning normally in very abnormal conditions. The result was a two-element achromatic lens, free from spherical aberration, of 3 inches (7.5 cm) aperture and 36 inches (91.4 cm) focal length. Unusually the outer component is the flint glass element, to avoid direct contact with the water; the radii of curvature of its surfaces are 9.0 inches (22.9 cm) and 5.3 inches (13.5 cm). The inner component is a crown glass meniscus, radii 5.3 inches (13.5 cm) and 50.0 inches (1.27 m); the meniscus is cemented into the cell with a watertight cement.

A plane-parallel plate of crown glass closed the lower end of the tube. Provision was made for filling and draining the tube, the water column when full measured 35.3 inches (90.2 cm). Mounted below the bottom plate is the eyepiece, an elbow construction with a 45° prism and four lenses, one in the short vertical tube and three in the longer horizontal arm. The eyepiece can be rotated in its mount, so that the observer, sitting on the north side of the instrument and facing south, can make both observations. The construction of the instrument required "several unusual arrangements; amongst others, the means of cleaning the lower plate glass from mud, and of cleaning the internal surface of the object-glass from bubbles"[25]. The former was achieved by means of a sponge carried on a rod passing through the ball of a ball and socket joint. The tube was "so completely filled with water that there is a slight upwards-pressure against the object-glass. It is apparently impossible to prevent air bubbles from accumulating ... but a bent tube is inserted through [the filling aperture] and the bubbles are sucked out by a slight action of the observer's mouth."[26]

Figure 10 shows the instrument from the south-east, with the telescope in one of its observing positions south of the vertical axis. Note the two large spirit-levels mounted on the telescope tube, and the arms bearing adjustable end-stops for the 180° rotation. The eyepiece is not fitted.

6.1.2 Micrometer and Wire-frame

Mounted immediately below the plane glass window, the micrometer is of the same double construction used by Airy in the RZT. The wire-frame is carried by micrometer B, the supports for which are on the slide of micrometer A. There are 26 parallel wires, at intervals equivalent to about 250″. The fixed plate of the micrometer bears a system of crossed wires for reference. The value of one revolution of the micrometer was equivalent to 73″.77 for micrometer A and 73″.89 for B. The double micrometer and elbow eyepiece assembly are shown in Figure 11, from Airy's account.

7 OBSERVATIONS WITH THE WATER TELESCOPE

Observations of the ZD of γ Draconis were made "only at the times when aberration produces its greatest effect in north-polar-distance."[27]

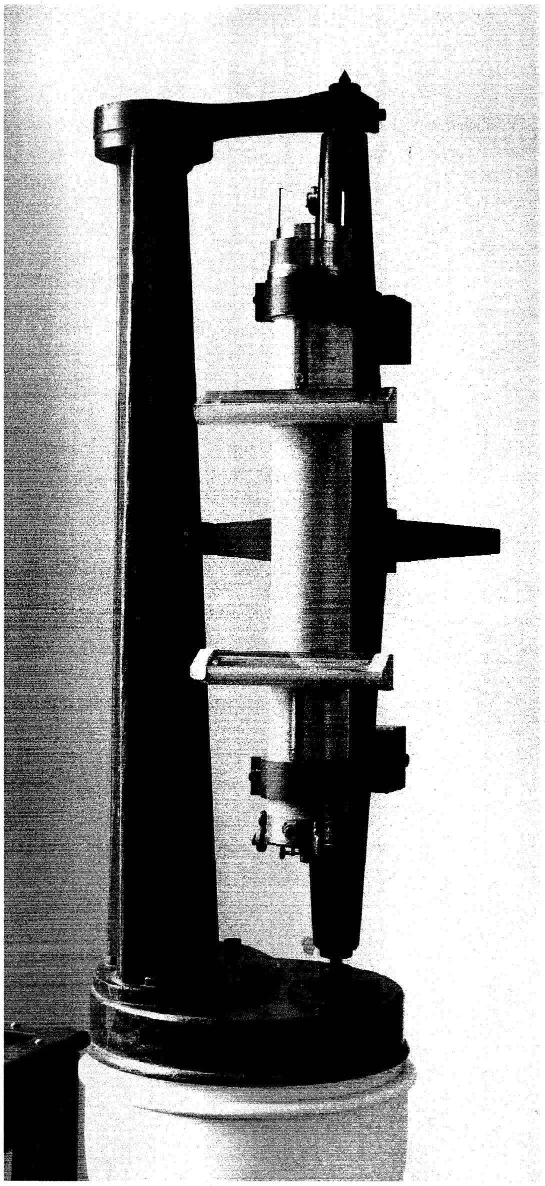


Figure 10. The Water Telescope in one of its observing positions, south of the vertical axis.

7.1 Method of Observation

This is essentially similar to that with the RZT, (see 5.2 above). Some impression of the observer's situation, and the pressures upon him, may be gained from extracts in Airy's own description:

> He reads micrometer (A), enters the reading in his book, places the instrument [at the first observing position] and reads the levels ... he turns the eyepiece to a convenient position, and, when the star has arrived near to the center of the field, he bisects it with the proper wire by the screw (B). Without leaving his place, and without reading the micrometer, he rapidly rotates the instrument [to the second observing position] and makes another bisection of the star ... by the screw (A). Then he reads the two levels. Finally, he brings the instrument to a convenient position, and takes the new readings of (A) and (B). Thus every element for a complete double determination in reversed positions of the instrument is obtained, by observations of the star occupying only a few seconds of time.[28]

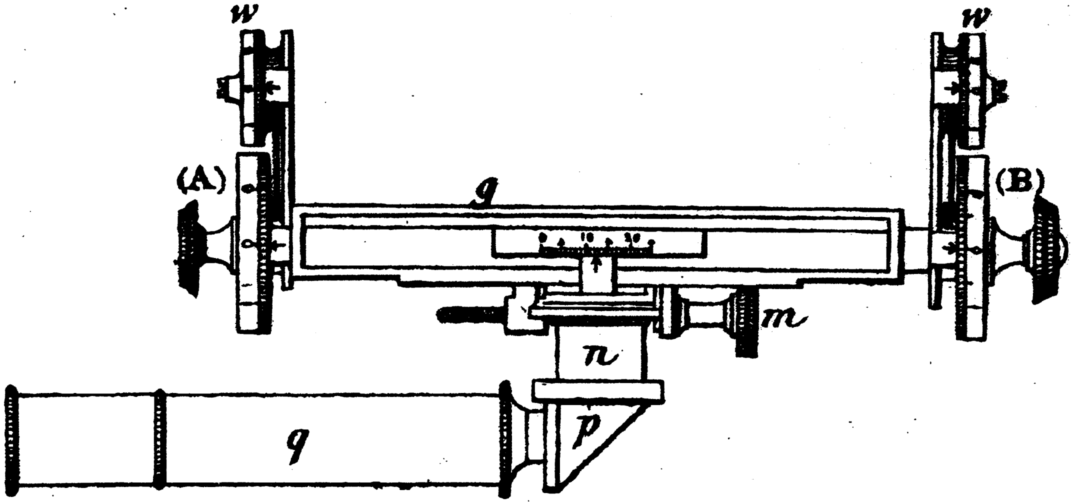


Figure 11.The double microscope and micrometer assembly of the Water Telescope (after *Greenwich Observations 1871*).

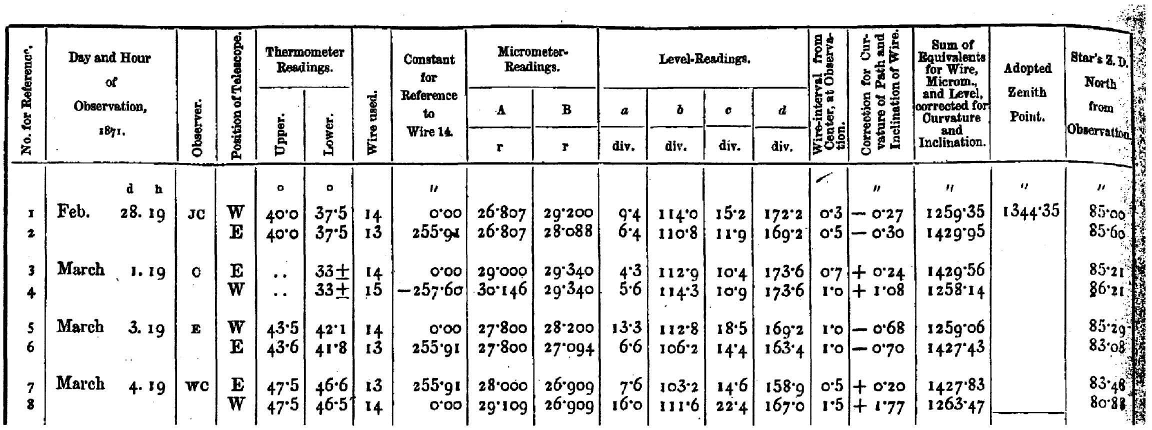
Reductions of the observations are similar to those for the RZT.

7.2 First and Last Observations, and Statistics

The first published observation was made on 1871 February 28 by J Carpenter (see Figure 12), and the last by G S Criswick on 1872 October 7. In 1871 Airy was able to record:

> "The new Water-Telescope has been got into working order, and performs most satisfactorily." He continues "As the astronomical latitude of the place of observation is not known, the bearing of these observations on the question of aberration cannot be certainly pronounced until the autumn observations shall have been made; but supposing the geodetic latitude to be accordant with the astronomical latitude, the result for aberration appears to be sensibly the same as with ordinary telescopes.[29] At the Annual Visitation in 1872 June he records "With the view of making its results less dependent on level-values, it has been carefully adjusted to verticality."[30] Finally, in 1874 June, he reports "The Water-Telescope was dismounted in August last, the observations with it having been brought to a satisfactory termination.[31]

In its short life the instrument was used for 51 double and 5 single observations of the zenith star. It is a mark of Airy's belief in the value of the experiment that he devoted so much effort and resources to the design and construction of an instrument for a single experiment, which could be achieved with so few observations over such a short time. He finally reports "The observations of γ Draconis with the Water-Telescope, made in the autumn of 1871, and the spring of 1872, are reduced" and concludes that the observations "absolutely negative the idea of any effect being produced on the constant of aberration by the amount of refracting medium traversed by the light."[32] Thus Airy, in little more than two years, had devised the means, constructed the instrument and made and reduced the observations necessary to solve a problem which had exercised the minds of numerous contemporaries for over a decade.



No. for Reference.	Day and Hour of Observation, 1871.	Observer.	Position of Telescope.	Thermometer Readings.		Wire used.	Constant for Reference to Wire 14.	Micrometer-Readings.		Level-Readings.				Wire-interval from Center, at Observation.	Correction for Curvature of Path and Inclination of Wire.	Sum of Equivalents for Wire, Microm., and Level, corrected for Curvature and Inclination.	Adopted Zenith Point.	Star's Z. D. North from Observation.
				Upper.	Lower.			A	B	*a*	*b*	*c*	*d*					
								r	r	div.	div.	div.	div.					
	d h			°	°		″							′	″	″	″	″
1	Feb. 28. 19	JC	W	40·0	37·5	14	0·00	26·807	29·200	9·4	114·0	15·2	172·2	0·3	− 0·27	1259·35	1344·35	85·00
2			E	40·0	37·5	13	255·91	26·807	28·088	6·4	110·8	11·9	169·2	0·5	− 0·30	1429·95		85·60
3	March 1. 19	C	E	..	33±	14	0·00	29·000	29·340	4·3	112·9	10·4	173·6	0·7	+ 0·24	1429·56		85·21
4			W	..	33±	15	−257·60	30·146	29·340	5·6	114·3	10·9	173·6	1·0	+ 1·08	1258·14		86·21
5	March 3. 19	E	W	43·5	42·1	14	0·00	27·800	28·200	13·3	112·8	18·5	169·2	1·0	− 0·68	1259·06		85·29
6			E	43·6	41·8	13	255·91	27·800	27·094	6·6	106·2	14·4	163·4	1·0	− 0·70	1427·43		83·08
7	March 4. 19	WC	E	47·5	46·6	13	255·91	28·000	26·909	7·6	103·2	14·6	158·9	0·5	+ 0·20	1427·83		83·48
8			W	47·5	46·5	14	0·00	29·109	26·909	16·0	111·6	22·4	167·0	1·5	+ 1·77	1263·47		80·88

Figure 12. The first observations with the Water Telescope. [Observers: JC – J.Carpenter; C – G.S.Criswick; E – W.Ellis; WC – W.H.M.Christie].

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8 CONCLUSION

Both the Reflex Zenith Tube and the Water Telescope still exist, in the care of the National Maritime Museum. Though no longer on permanent display, the RZT is in good order and was displayed in a temporary exhibition on Airy's life and work at the Royal Observatory during 2001.

Throughout his long term of office as Astronomer Royal (1835–81) Airy carried out observations of γ Draconis, continuing the interest shown by all his predecessors. Like Hooke, they all realized their good fortune in being able to observe a reasonably bright star passing almost exactly through the local zenith, with the consequent freedom from the loss of positional accuracy arising from the effects of atmospheric refraction. It was Airy, however, who finally devised instruments capable of realizing the full potential of the method. His design of the RZT was not just an improvement on the zenith instrument he had inherited and struggled with for so long, but was an entirely new concept that eventually provided the means of proving the existence of latitude variation, hitherto only a theoretical concept. His Water Telescope was the only effective instrument to disprove the possibility that the aberration of light might seriously affect positional observations. Only Bradley before him, with the discovery of aberration and nutation, had achieved comparable success with zenith instruments.

Airy's reflex design, using the normal to the horizontal surface of a dish of mercury to establish the vertical, combined with rotation of the instrument so that the quantity 'double ZD' could be measured, was the forerunner of a series of important instruments. The reflex principle was not used by Cookson in the design of the (photographic) Floating Zenith Tube which replaced the RZT at Greenwich, but it was used in the development of a photographic zenith instrument by F E Ross for the U.S. Naval Observatory in Washington. The prototype was used in Gaithersburg, Maryland from 1911 to 1914, before being installed in Washington in 1915.

A much more highly developed version, with many innovative refinements, was designed by D S Perfect for the Royal Greenwich Observatory. The Photographic Zenith Tube (PZT) was constructed by Grubb, Parsons & Co. and installed at Herstmonceux, Sussex, in 1955. It was used to determine the time of transit of fundamental stars which culminated close to the zenith, as well as to measure their ZD as with Airy's instrument. With an aperture of 25 cm, a large number of faint stars could be observed. Its operating sequence was entirely automatic, and initiated by remote control from a separate building so that there were no effects due to the body heat of an observer in the instrument pavilion.

In addition to monitoring latitude variation, the transit timings were used in the control of the time service; the PZT proved to be the most accurate telescope ever used for this purpose. Several similar instruments were set up at observatories around the world. Three-quarters of a century after Airy's death, instruments developed from his design were still in use for observations to a precision of which he could only have dreamed. They were a fitting memorial to the scientific and engineering genius of a remarkable man.

9 ACKNOWLEDGEMENTS

This paper is part of a series based on research carried out over many years, and the writer wishes to acknowledge the help of many friends and colleagues. In particular he would like to thank the late Derek Howse, Gloria Clifton, Maria Blyzynsky, Emily Winterburn and Janet Small of the National Maritime Museum, for facilitating his investigation of the zenith instruments and helping in so many ways.

Figures 3, 4, and 11 are reproduced by courtesy of the National Maritime Museum.

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 *ARR18xx*.

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