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Airy and positional astronomy

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Abstract
Sir George Airy (18011891), the seventh Astronomer Royal, made major contributions in numerous fields including many not directly concerned with astronomy. Throughout his life, however, he had a deep interest in fundamental aspects of astronomy, and constantly endeavoured to improve the instrumentation and procedures used for the measurement of astronomical positions.

His principal achievements in this field were the refinement of techniques for the mathematical reduction of positional observations and their timely publication, and the design of a new generation of positional instruments which revitalized the work of the Royal Observatory at Greenwich, and proved to be influential for the next hundred years.

Keywords: *positional astronomy, meridian instruments, reduction of observations, Cambridge Observatory, Greenwich Observatory.*

1 INTRODUCTION

The positions of objects in the sky are defined using two orthogonal co-ordinates, as are terrestrial locations. It is conventional to regard all celestial bodies as being situated on a sphere of infinite radius centred on the observer, the celestial sphere. All positions may then be expressed in angular measure, and are independent of the actual distance of the body concerned.

The position of an object at a given time is defined by its right ascension and declination; these are equatorial co-ordinates referred to the First Point of Aries and the celestial equator respectively. Observations of position are most conveniently made using the horizontal co-ordinates azimuth and zenith distance. Horizontal co-ordinates are specific to the observer's location, but can be simply converted to equatorial co-ordinates if that location is accurately known. The co-ordinate systems and the equations for converting between them can be found in standard texts of spherical astronomy, for example Green (1985). When observing in the meridian plane, the declination of an object may be obtained from its observed zenith distance and its right ascension from the local sidereal time of its transit.

Airy's contributions to positional astronomy fall mainly in two areas. Firstly, the reduction of observations on a standardized basis to ensure maximum accuracy, and their combination into usable form allied to prompt and regular publication. Secondly, the development of a new suite of positional instruments designed to improve the accuracy of measured positions and to broaden the range of possible observations.

2 EDUCATION AND EARLY INFLUENCES

The development of Airy's remarkable abilities, and the personal characteristics which enabled him to make such notable contributions to the design of astronomical instruments and the development of techniques for positional astronomy, can be traced throughout his early life. At school he excelled in an unusually wide range of subjects including arithmetic, algebra, and double-entry book-keeping, quite apart from Latin and Greek which were to provide him with spare-time interests throughout his life. He regularly spent school holiday periods with his uncle Arthur Biddell, a wealthy farmer and valuer who owned an extensive library. By self-study among his uncle's books Airy developed a number of new interests, which included navigation and various aspects of engineering. He also developed practical skills, becoming notable among his school friends for the construction of guns to fire peas and arrows, and other mechanical devices.[1]

As to his interest in astronomy, Airy (1896) recalls his father giving him a pair of 12-inch globes, and he comments "The first stars which I learnt from the celestial globe were α Lyrae, α

Aquilae, α Cygni: and to this time I involuntarily regard these stars as the birth-stars of my astronomical knowledge". He does not give a date, but we may deduce that he was aged about 12 or 13 at the time.

With encouragement from several of his uncle's influential friends, Airy applied to and was accepted by Trinity College, Cambridge, to read the Mathematical Tripos. It is typical of him that in the months preceding the start of his undergraduate career he read (and "understood perfectly") a number of advanced mathematical texts, including part of Newton's *Principia*.

3 AT CAMBRIDGE

3.1 As Student and Tutor

Soon after beginning his studies Airy began a lifelong habit of keeping quires of scribbling paper sewn into pads, in which he systematically noted everything he undertook – a presage of his lifelong passion for order. He kept these as a permanent record of his activities, which proved very useful in later years when he began to compile his autobiographical notes. As an undergraduate he soon gained a reputation for excellence and made the acquaintance of a number of Cambridge men who were to remain influential and valued friends thereafter, not least the mathematician George Peacock. The texts he used would certainly have included that of Robert Woodhouse, then the Plumian Professor of Astronomy at Cambridge. He also began to develop a particular interest in optics, and experimented with a small telescope. He records being given his first *Nautical Almanac* in 1821 November (Airy, 1896). In 1822 he graduated as Senior Wrangler, and in 1823 January was awarded the First Smith's Prize. He was the outstanding mathematics student of his year.

He tutored undergraduates to support himself whilst pursuing his own research, which was increasingly directed towards problems in optics and theoretical astronomy. An important event was a visit to London at the end of 1823 as the guest of James South, who introduced him to Sir Humphrey Davy "and many other London savants, and shewed me many London sights and the Greenwich Observatory." (Airy,1896:54). John Herschel, with whom Airy was already acquainted, visited South to observe double stars and Airy remarks that "This was the first time that I saw practical astronomy." (ibid.)

In 1824 Airy was elected a Fellow of Trinity College and appointed Assistant Mathematics Tutor. In 1826 he was elected Lucasian Professor of Mathematics, but following the death of Woodhouse applied for the Plumian Professorship of Astronomy, to which he was elected in 1828 February.[2] This Chair carried with it the direction of the Cambridge Observatory, then only three years old, and this, together with the provision of accommodation for the Director within the Observatory, was seen by Airy as an ideal way to further both his professional career and his personal life.[3]

3.2 As Director of the Cambridge Observatory

3.2.1 Management of the Observatory.

When Airy took over the Observatory, only one of the instruments ordered for it had been installed and commissioned, a ten-foot transit instrument of five inches aperture by Dollond. Even before assuming the Directorship Airy was busy devising procedures for correcting transit observations for instrumental errors, and "... began a book of proposed regulations for observations." (Airy, 1896:82). The second positional instrument, an eight-foot mural circle by Troughton, was installed at the end of 1832.

3.2.2 British Association Report and the Planetary Reductions

Airy was asked to prepare a 'Report on the Progress of Astronomy' for presentation at the second meeting of the British Association for the Advancement of Science at Oxford in 1832 June. He completed this in typically thorough and detailed manner, the resulting 65-page paper (Airy, 1833) proving to be of seminal importance and much quoted for many years. Whilst covering all aspects of the subject, Airy gave particular prominence to fundamental matters. Beginning with a survey of instruments then in use, he concentrates especially on those used for positional astronomy. He surveyed existing star catalogues, and considered specifically the problems of correcting positional observations for atmospheric refraction, the determination of nutation, the observation of stellar proper motions and attempts to measure stellar parallaxes.

Towards the end of his report Airy made an important proposal. The Greenwich observations of star positions made by Bradley between 1742 and 1762 had been published in 1818 in a new reduction by Friedrich Bessel, Director of the Königsberg Observatory. Bessel had spent many years systematically investigating the causes of inaccuracy in positional observation, and devising procedures for their reduction to correct for these errors. He was also the first to recognize the need to correct for the effects of personal equation – the small differences between measurements made by individual observers. He had himself established accurate positions for 50,000 stars, corrected for instrumental errors, nutation, and atmospheric refraction. His work provided the basis for a new era of improved positional work, the measurement of stellar proper motions and, eventually, of stellar parallaxes. His reduction of Bradley's stellar observations to the same accuracy had greatly increased their value – indeed in his report Airy wrote that "Bradley's observations of stars were nearly useless till Bessel undertook to reduce them." (Airy, 1833:187).

Airy had engaged in correspondence with Bessel in this matter, and had devised similar reduction procedures for the Cambridge observations. He now realized that the unbroken series of meridian observations of the Sun, Moon, and planets made by Bradley and his successors would be similarly enhanced in value if reduced in the same way, and using the constants recently published by Bessel in his *Tabulae Regiomontanae* (Bessel, 1830). The General Committee of the British Association supported the proposal and sent a deputation to the Treasury which included both Airy and Sir John Herschel, and funds were allocated for the purpose of carrying out the reductions of all the observations obtained since the introduction at Greenwich of Bradley's improved instruments in 1750, up to and including 1830.

3.2.3 Use of Printed Reduction Forms

Airy firmly believed that the routine calculations of an observatory, such as the reduction of positional observations, were best carried out by computers working on pre-printed skeleton sheets. This ensured total adherence to the prescribed order and method of computation, and the work was readily susceptible to checking at every stage by a supervising computer. He had already introduced such forms for the reduction of the Cambridge observations, but first had the idea as an undergraduate in 1822 when, faced with the reduction of lunar distances observed with a sextant: "I prepared a printed skeleton form, I believe my first." (Airy, 1896:37).

He records ordering from the University Press 12,000 copies of printed forms for the planetary reductions. Sets of the forms used in the computations were bound into the published volumes; there were nineteen separate forms for the planetary reductions and fifteen for the subsequent volumes of lunar reductions.

3.2.4 Reduction of Groombridge's Observations

Airy had been impressed by the positional observations of circumpolar stars obtained by Stephen Groombridge from his home in Blackheath, using a small transit circle by Troughton. Due to a stroke Groombridge was unable to complete their reduction and the compilation of a catalogue himself, and the Astronomer Royal John Pond had arranged to have this done. The reductions were being undertaken by a computer whose efforts proved on investigation to be very unsatisfactory, and he was dismissed. Airy agreed to take over the supervision of the work, to be carried out by supernumerary computers, and to see the volume through the press. Groombridge's catalogue (Airy, 1838), with its later revision (Dyson & Thackeray, 1905), became the standard reference for northern circumpolar stars.

3.2.5 First Telescope Design

At Cambridge Airy undertook his first design of a major telescope. The Duke of Northumberland, Chancellor of the University, provided funds for a large equatorial refractor, with an 11¾-inch objective by Cauchoix. The design was a version of the English yoke mounting, the polar axis consisting of two triangular-sectioned components with the telescope pivoted between them by its declination axis. The six main members were larch poles. The design proved so successful that Airy later built a larger version in steel for the great equatorial at Greenwich in 1859. Although the Northumberland telescope was not designed for positional work, Airy gained experience in its construction that was to prove invaluable when he came to design positional instruments later.

3.2.6 Departure from Cambridge
In 1835 Airy accepted the appointment of Astronomer Royal following the retirement of Pond. He took charge of the Royal Observatory with effect from 1835 October 1, but typically made arrangements to deliver his planned lectures, supervise the completion of the Northumberland equatorial, and complete the reduction of every observation made during his tenure at Cambridge before finally handing over to his successor.

4 AT GREENWICH

4.1 Initial Programmes and Existing Instruments

On arrival at Greenwich Airy continued the programmes of observation that had been undertaken by Pond. He did however immediately institute changes in daily routine: "With the beginning of 1836 my new system began. I had already prepared skeleton forms (a system totally unknown to Mr Pond) which were now brought into use." (Airy, 1896:123). Airy's system continued in use until after the removal of the Royal Observatory from Greenwich to Herstmonceux Castle in Sussex in the 1950s, printed 'ledgers' of the reduction sheets for transit and zenith distance observations being still essentially based upon Airy's original forms (Figure 1), and similar workbooks were used for the calculation of, for example, azimuth and clock errors. The use of such ledgers was only superseded when meridian observations came to be fed directly to a computer for immediate reduction.

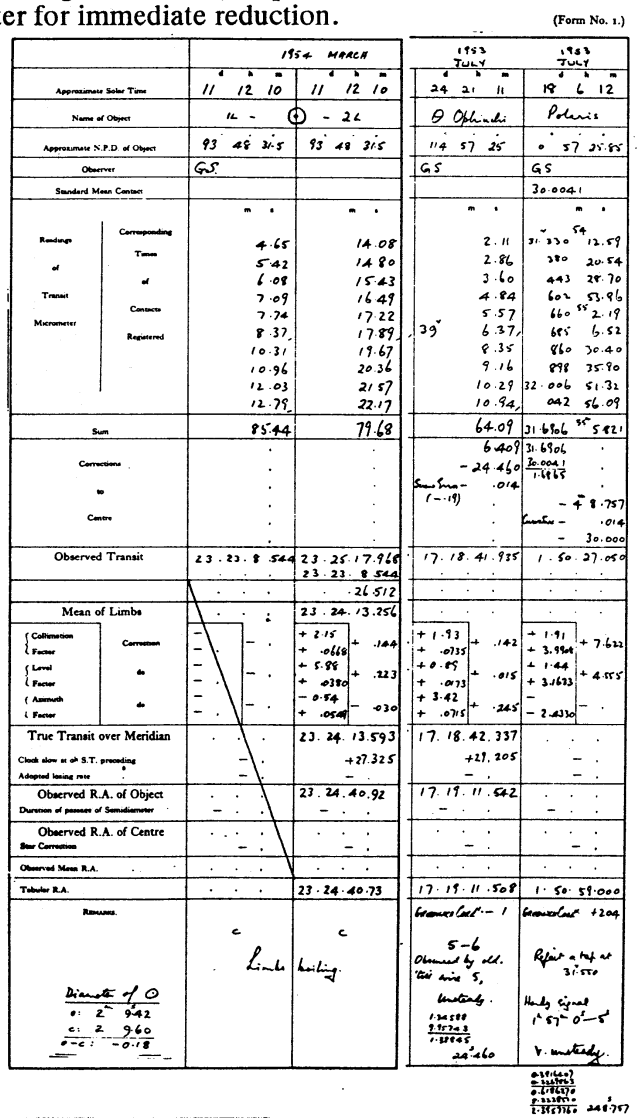

Figure 1. Part of a ledger sheet used for the reduction of RA determinations made with the Airy Transit Circle at Greenwich, showing specimen reductions of transits of the preceding and following limbs of the Sun on 1954 March 11.

Determinations of right ascension (RA) had been made at Greenwich with a sequence of transit instruments installed by Halley, Bradley, and Pond in 1721, 1750, and 1816 respectively. Zenith distance (ZD) was formerly measured with quadrants installed by Halley and Bradley in 1725 and 1750; these were replaced by a mural circle commissioned by Maskelyne but completed after his death and installed by Pond in 1812. A contemporary account of these instruments may be found in Pearson (1829). Detailed descriptions of all the instruments used at Greenwich are given by Howse (1975).

The principal meridian instruments in use when Airy arrived at Greenwich were the Troughton six-foot mural circle, installed in 1812, and the ten-foot transit instrument of five inches aperture, also by Troughton, which had replaced Bradley's eight-foot instrument in 1816. In his first Report to the Board of Visitors of the Royal Observatory in 1836 Airy remarked "The state of the meridian instruments is most satisfactory."[4] He was therefore able to concentrate his efforts on matters other than instrument design during his first few years of office. The routine meridian observations of the Sun, Moon, planets, and fundamental stars, and their reduction and publication, remained of prime importance.

The massive programme of reducing the planetary observations of 1750–1830 was now under way at Greenwich under Airy's immediate supervision; James Glaisher, who had been one of his assistants at Cambridge, was brought in to lead the team of computers engaged in the task. The computations were completed in 1841 April, and the task of preparing them for the press began. The volume, comprising over 700 quarto pages, was finally published thirteen years after Airy's original proposal (Airy, 1845). Work then commenced on the reduction of the lunar observations over the same period, and these were completed and published three years later in two volumes totalling over 1500 pages (Airy, 1848a).

4.2 Need for New Instruments

The positional instruments at Greenwich continued to perform satisfactorily. Even as late as 1849, in his annual report to the Board of Visitors, Airy comments "The Transit appears to be in every respect in an excellent condition."[5] Nevertheless, a number of factors had persuaded him to review the Observatory's positional instruments. As early as 1843 he records "In November I was enquiring about an 8-inch object-glass. I had already in mind the furnishing of our meridional instruments with greater optical powers." (Airy, 1896:157-8), and in his report of 1847 he put forward his concerns:

> I think it worthy the careful consideration of the Visitors, whether meridional instruments carrying larger telescopes should not be substituted for those which we possess. Whatever we do, we ought to do well. Our present instruments were, at the time of their erection, the best in the world; but they are not so now: and we actually feel this in our observations. It is with the utmost difficulty that we have observed Astraea a few times, though she has been observed repeatedly on the Continent. We frequently are unable to observe, on the meridian, stars which have been compared with Comets in equatoreal observations.[6]

Tenth-magnitude Astraea was the fifth minor planet to be discovered, in 1845, and the first for 38 years. Airy immediately foresaw the probability of more faint planetary bodies being discovered, and indeed three more were found within five months of his penning the above words. He later came to regard the rapidly proliferating 'small bodies' as a nuisance, and arranged to share meridian observations of them with the Paris Observatory. It was clearly an embarrassment, however, that the national observatory was unable to monitor the motions of newly discovered bodies, or supply accurate positions of stars used to define the motions of comets observed with larger aperture telescopes.

4.3 Types of Instrument and Design Considerations

It is apparent that during these years Airy was undertaking a very detailed review of the positional observations the Royal Observatory was required to make, and examining the various types of instrument that could be introduced for them. There were several possibilities to consider. The quadrants formerly used had been successfully replaced by the mural circle, which, when it was commissioned, Maskelyne had thought might be used as a transit instrument also. Its rather unbalanced design, however, with the telescope and attached circle fixed at one end of the horizontal axis, did not prove to be suitable for this purpose, hence Pond's decision to use it for ZD observations only (for which it performed well) and to commission a new transit instrument.

Measurements of ZD require the zenith point of the circle to be accurately defined; with the earlier instruments this was achieved with the aid of a plumb-line, but a more accurate determination was now required. Pond had favoured the use of a second mural circle, one observing the star's ZD direct and the other by reflection in a mercury surface. This procedure ceased when the second circle was transferred to the Royal Observatory, Cape of Good Hope, for which it had originally been intended. Airy found, however, that with appropriate corrections to the centre a star could be observed with one circle both direct and by reflection at the same transit; this was a considerable advantage since it obviated the need for a separate determination of the zenith point at the time of observation.

Two circle instruments of a quite different design, mounted with provision for observing in other azimuths as well as the meridian plane, had been constructed by Troughton and successfully used by Piazzi at the Palermo Observatory and by John Pond before he became Astronomer Royal. Despite the failure of the mural circle to make sufficiently accurate observations in RA, it was clear that an instrument combining the functions of the mural circle and the transit instrument was possible. One had been built for the English observer Wollaston in 1793, but its construction was insufficiently sturdy to give good results. In 1806 Troughton had manufactured the small transit circle (aperture 3½ inches, circles four feet in diameter) so successfully used by Groombridge for his catalogue of circumpolar stars, but otherwise the combined instrument had not found favour in Britain. Abroad, notably in Germany, some larger transit circles were in use. Airy was very familiar with the accuracy achieved by Groombridge with his small transit circle, and after a thorough examination of all the possibilities he concluded that he could design a transit circle, of significantly larger aperture than the existing transit instrument, to replace both the transit instrument and the mural circle.

Airy was also interested in continuing the long sequence of zenith telescopes, which not only provided another means of measuring the zenith direction, but had contributed considerably to fundamental astronomy by Bradley's discovery, with his zenith sector, of the aberration of light in 1728 and nutation in 1748. The second-magnitude star γ Draconis, which transits very close to the zenith in the latitude of Greenwich, had long been observed for this purpose, and also in the hope of determining its annual parallax. It is now known that this was too small to be detectable with the instruments available, although the first determinations of stellar parallax had recently been made elsewhere (in 1838).

During this time Airy was formulating his basic design principles, which were to contribute very significantly to the success of his positional instruments. He had realized that even with the best engineering techniques it is not possible to build such instruments free from very small errors of construction and adjustment, and that such errors would not necessarily remain constant in constantly changing ambient conditions. He therefore approached his designs with the intention of not only keeping these errors as small as possible, but also building into the instruments provision for regularly measuring them so that their effects could be included in the subsequent reduction of the observations. He designed his instruments with the precision parts mounted on a massive and rigid superstructure of cast iron, made in as few pieces as possible and bolted together not screwed, and with the minimum of *in situ* adjustments.

Airy finally determined on a set of three positional instruments and an associated chronograph, all completed within a period of seven years. They were:

The Altazimuth, completed in 1847;
The Transit Circle, 1851;
The Reflex Zenith Tube, 1851;
The Barrel Chronograph, 1854.

4.4 The Altazimuth

Airy's first decision was to acquire an instrument specifically designed to double the number of positional observations of the Moon obtained each year. Because of its complex motion, frequent determinations of the Moon's position are required to refine the theory of its motion and so permit accurate prediction of its future movements. Due to the lunar phases, and the close proximity of the Moon to the Sun for part of every month, a continuous sequence of observations is impossible. A meridian observation can be lost if the Moon is temporarily obscured by cloud for only a few minutes, but it is frequently visible before and after meridian transit. Airy therefore proposed an 'Altitude and Azimuth Instrument' – later abbreviated to 'Altazimuth' – designed to measure the Moon's position with comparable accuracy to that possible with the best meridian instruments.

His proposal was considered at a special meeting of the Board of Visitors in 1843 September; they approved it and Admiralty sanction was given for the construction of the instrument and the building to contain it. Airy (1896:159) saw this as "... the most important addition to the Observatory since its foundation."

The instrument comprised a four-foot refracting telescope, aperture 3.7 inches, mounted like a transit instrument on a three-foot axis suspended in Y-bearings. These were supported by a pair of vertical 'cheek' pieces, connected by top and bottom plates, all massive iron castings. The whole structure was free to rotate about a vertical axis, supported by a top bearing carried on a framework of welded iron bars, and a bottom bearing mounted on the central plinth (Figure 2). The entire structure was on a three-rayed foundation pier 26 feet high, not connected to the walls of the building or the observing floor. The base-plate carried a 3.0-feet divided horizontal circle, with circle-reading microscopes attached to the telescope bottom plate to read the azimuth setting (Figure 3); a similar 3.0-feet divided circle was attached to one side of the telescope axis, with circle-reading microscopes attached to the cheek-plate. The massive parts were made by the agricultural engineering firm of Ransome & May of Ipswich, and the precision parts by Troughton & Simms of London (Airy, 1848b).

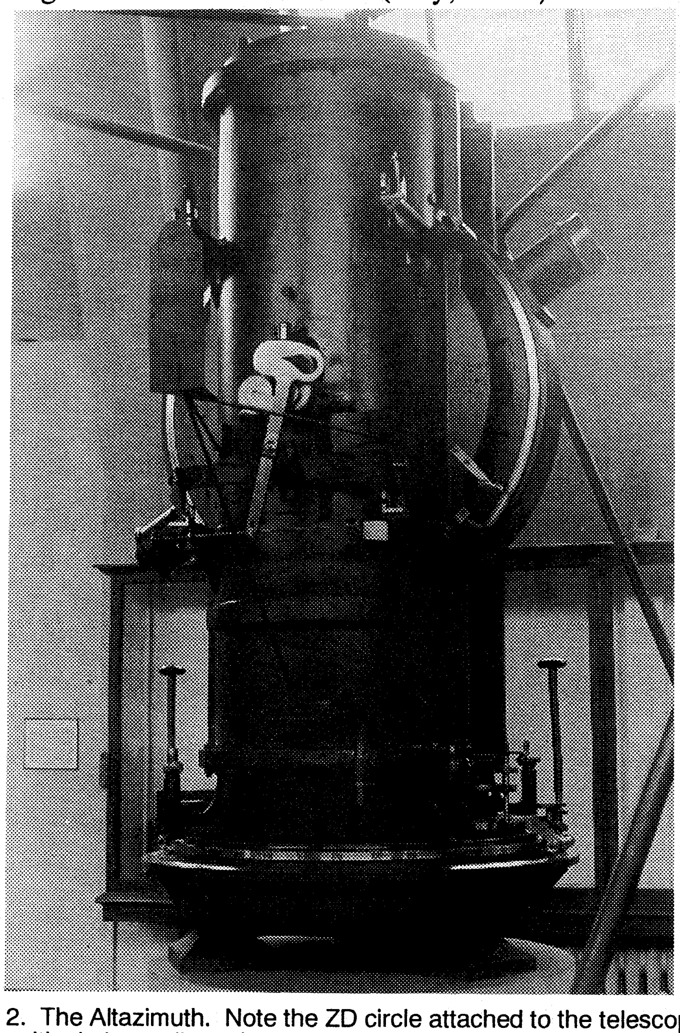

Figure 2. The Altazimuth. Note the ZD circle attached to the telescope axis, with circle-reading microscopes mounted on the cheek-piece.

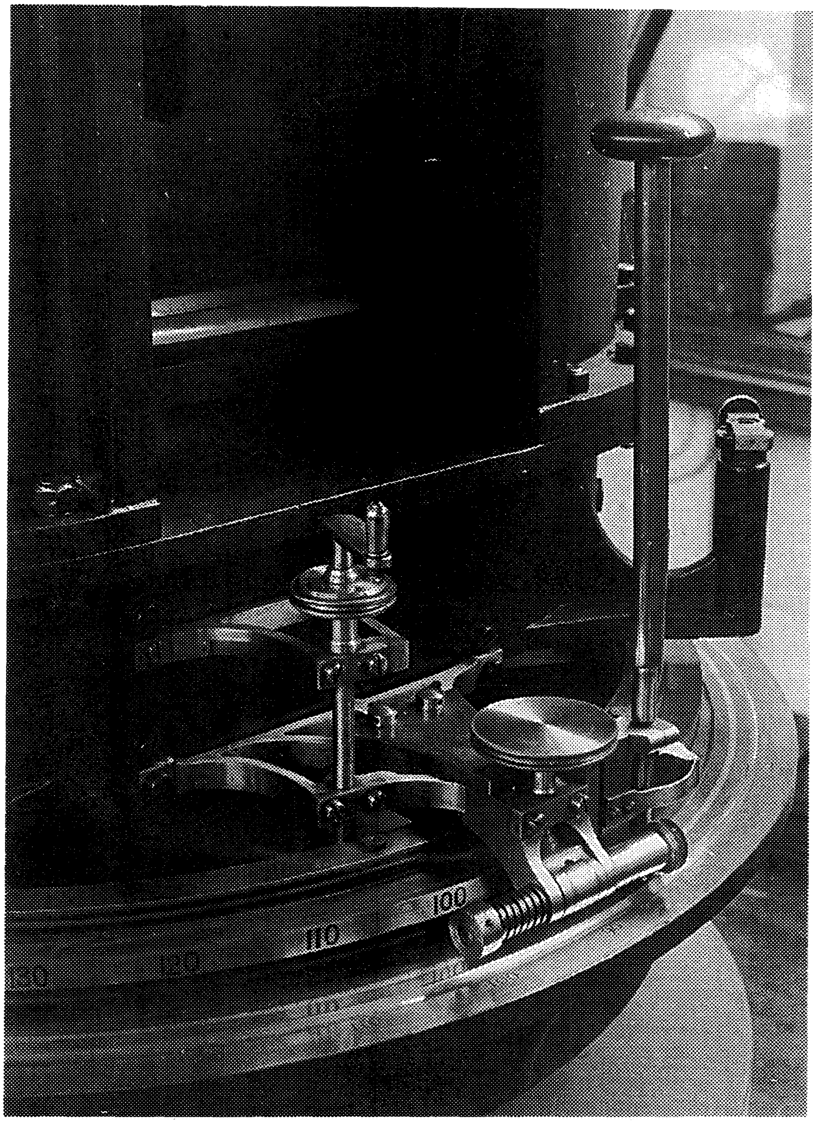

Figure 3. The base of the Altazimuth, showing the azimuth circle and slow-motion controls.

A building to house the instrument, topped by a drum-shaped 'dome', was erected on the foundations of Flamsteed's equatorial sextant house. After a thorough series of tests the instrument came into use in 1847 May. Airy's expectations were fully realized; in the first five years of its existence the Moon's position was measured on an average of 209 days a year, compared with 107 days with the meridian instruments. Despite its success, regular observations with the instrument ceased after 50 years, when in 1897 November it was replaced by a new altazimuth designed by the then Astronomer Royal, William Christie, which was used sporadically for 30 years but never matched the success of Airy's instrument.

4.5 The Transit Circle

Following his suggestion in 1847 that meridian instruments of larger aperture would be required, and having concluded that a transit circle would be the best means of obtaining both transit and ZD observations, Airy spent some time in formulating a design for one. His instrument would provide for full determination of errors, including monitoring the effects of changing temperature and pressure on the precise alignment of it during an observing watch. It would also have provision for making observations both direct and by reflection. Airy used the same manufacturing companies as for the Altazimuth, and his design embodied the same principles of massive construction allied to precision engineering. The instrument was erected during 1850 and came into use in 1851 January; it was to have a working life of over a century and exert a seminal influence on the design of meridian instruments for even longer. The history of this instrument is detailed elsewhere in this volume (see Satterthwaite, 2001).

4.6 The Reflex Zenith Tube

Airy continued to be concerned at the lack of a zenith instrument. In addition to providing a determination of the zenith point for use in the reduction of ZD observations, a satisfactory instrument would also provide a useful means of re-determining from time to time the constants of aberration and nutation.

Pond had introduced three zenith instruments which all proved to be failures. These included a 9½-foot Newtonian reflector mounted as a 'zenith micrometer' in 1812, and an eight-foot achromatic refractor in 1816. For some years Pond relied on the use of two mural circles for the determination of zenith point, but in 1833 erected a 25-foot 'Great Zenith Sector' from Troughton & Simms, with a 5-inch objective by Dollond, which was mounted vertically within a cast-iron tube. Even this giant instrument failed, however, and Airy decided to create a new design from first principles, and to eschew the use of a plumb-line to define the vertical which had contributed to the failures of all these instruments.

Airy's instrument (Figure 4) utilized the 5-inch objective by Peter Dollond, formerly part of the Troughton ten-foot transit instrument now no longer in use. The lens was mounted with its axis vertical, almost half its focal length above a dish of mercury. Light from the observed object would therefore be reflected back through the objective, where a small inclined plane mirror mounted over the centre of the lens diverted it into an eyepiece placed just outside the aperture (Figure 5). The normal to the mercury surface automatically provided a true vertical.

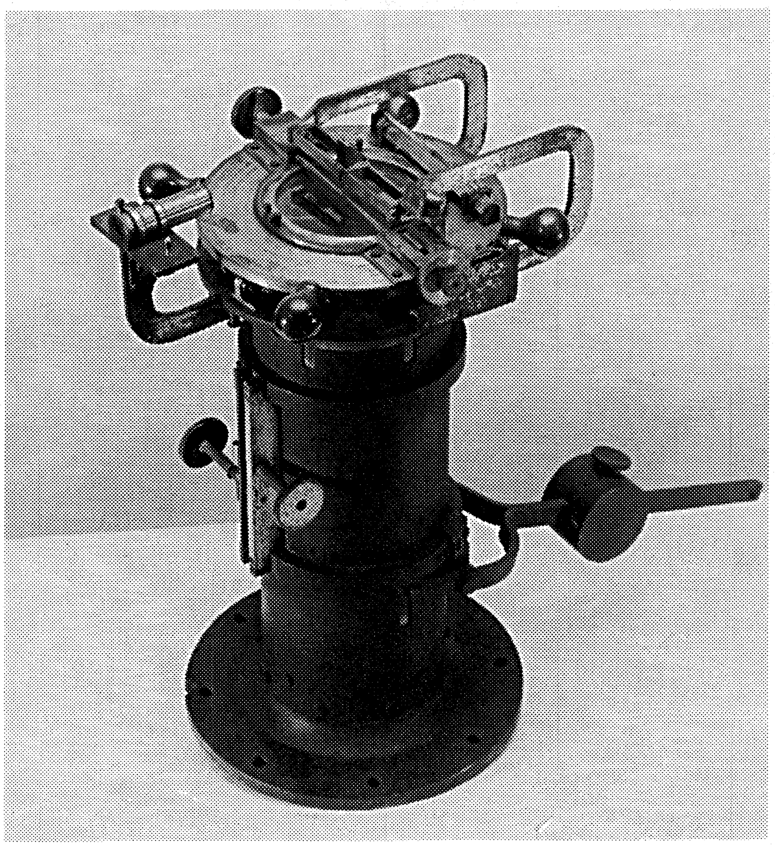

Figure 4. The Reflex Zenith Tube. The counterweight-lever is to balance the mercury container (within the tube), which can be moved vertically to adjust the focus.

The objective cell and eyepiece were mounted on a rotary mechanism, so that the observation of a star could be made in two parts. A frame carrying reference wires in the focal plane of the eyepiece could be moved across the field of view by micrometers, and by setting a wire on the star as it approached the meridian, then reversing the instrument and repeating the setting with another wire after the star had transited, the value of twice the ZD of the star could be calculated from the micrometer settings and the known separation between the wires used (Airy, 1855).

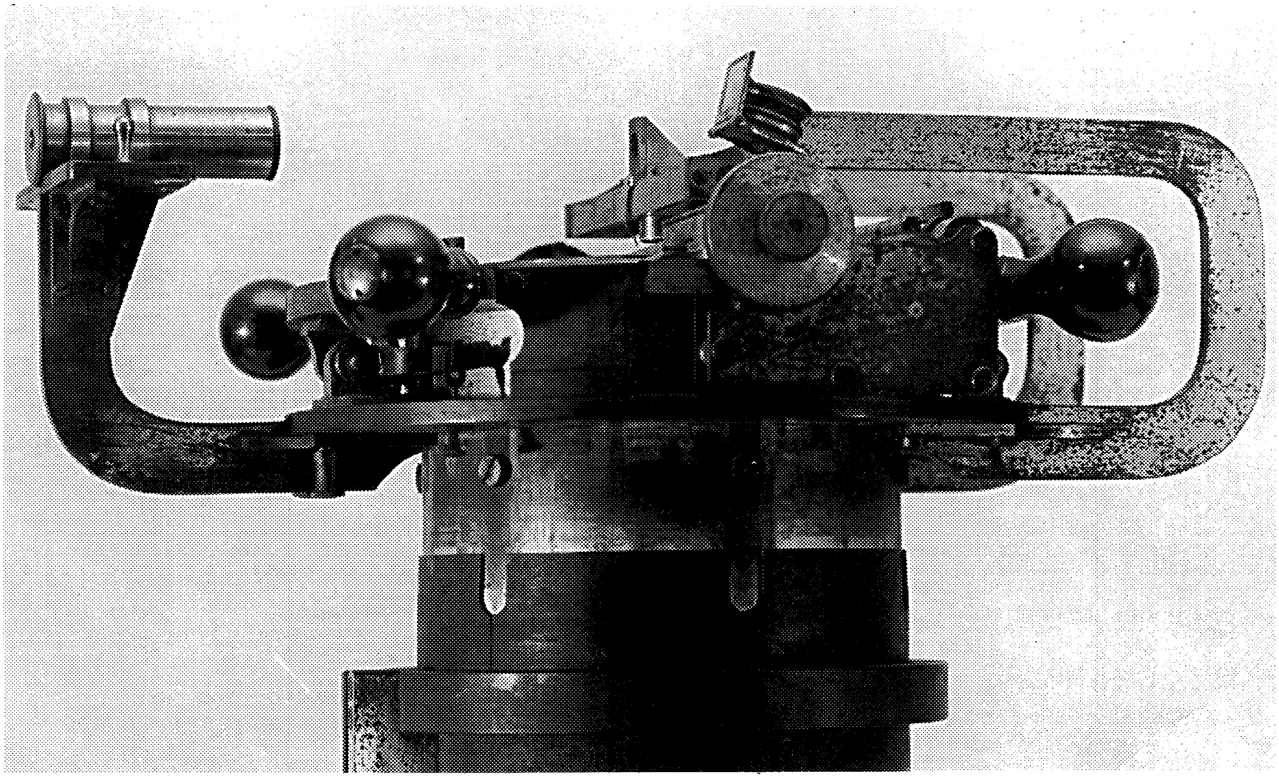

Figure 5. The upper part of the RZT, showing the reflecting prism and eyepiece above the rotor which carries the microscope wire-frames.

The instrument was initially set up in a small room adjoining the north-east corner of the Transit Circle pavilion, but due to its proximity to the courtyard and main entrance gate of the Observatory the mercury surface was often disturbed. At the end of 1855 the instrument was rehoused in a room specially constructed close to the south-west corner of the transit pavilion, which proved quite satisfactory. Although suitable only for stars transiting close to the zenith, principally γ Draconis, the instrument proved to be very successful, and was used for 60 years, from 1851 September to 1911 August.

In 1902 the reflex zenith tube (RZT) was to enter a new lease of life. It had been predicted by Euler in the eighteenth century that variations in latitude would result from the inclination between Earth's axis of rotation and its axis of symmetry, but the phenomenon was not detected until 1888 in Berlin. Confirmation was obtained by further analysis, notably of the observations made with Airy's instrument between 1882 and 1886. A programme was therefore instituted of routinely observing about 60 stars down to magnitude 7 that transited within 50′ of the zenith. This continued until 1999 August when the RZT was superseded by the Cookson floating zenith telescope formerly used at the Cambridge Observatory.

The influence of Airy's reflex design continued, however, with its later embodiment in the design of a series of instruments culminating in the photographic zenith tube (PZT) erected in 1955 at the Royal Greenwich Observatory, Herstmonceux, which proved to be the most accurate instrument ever developed for this work and also for the astronomical determination of time (Howse, 1975).

4.7 The Barrel Chronograph

When the transit circle came into use in 1851 January, transit timings were still made by the traditional 'eye and ear' method of listening to the beats of the transit clock and interpolating mentally, to a tenth of a second, the instants when the star image crossed fixed wires in the field of view. Whilst it was being constructed, however, telegraphs were being used in the United States to transmit signals between observatories for the determination of longitudes, and it was soon realized that they could be of use in recording time-related astronomical observations also. Two chronographic systems had been devised, which Airy discussed in a lecture to the Royal Astronomical Society (Airy, 1850). At first sceptical, he soon became convinced of the potential value of 'galvanic recording', but did not consider either of the American systems ideal and resolved to design his own. It was manufactured by the eminent clockmaker E J Dent of London.

The chronograph consisted of a large brass barrel covered with felt, around which a sheet of cartridge paper could be pasted, rotated by a clock mechanism at a uniform rate of one rotation every two minutes. Regularity was achieved by the use of a conical pendulum as governor (Figure 6). A set of 'prickers' operated electromagnetically by impulses from the transit clock and from a tapping key at the telescope, tracked along the barrel on a screwed rod. The prickers and an accompanying ink pipette to draw a continuous line thus followed a helical path around the barrel. The barrel could be lifted off when full and replaced by another. When the paper was removed and opened out, the times indicated by the punctures sent by the observer at the telescope could be measured against the clock-time punctures (Airy, 1857).

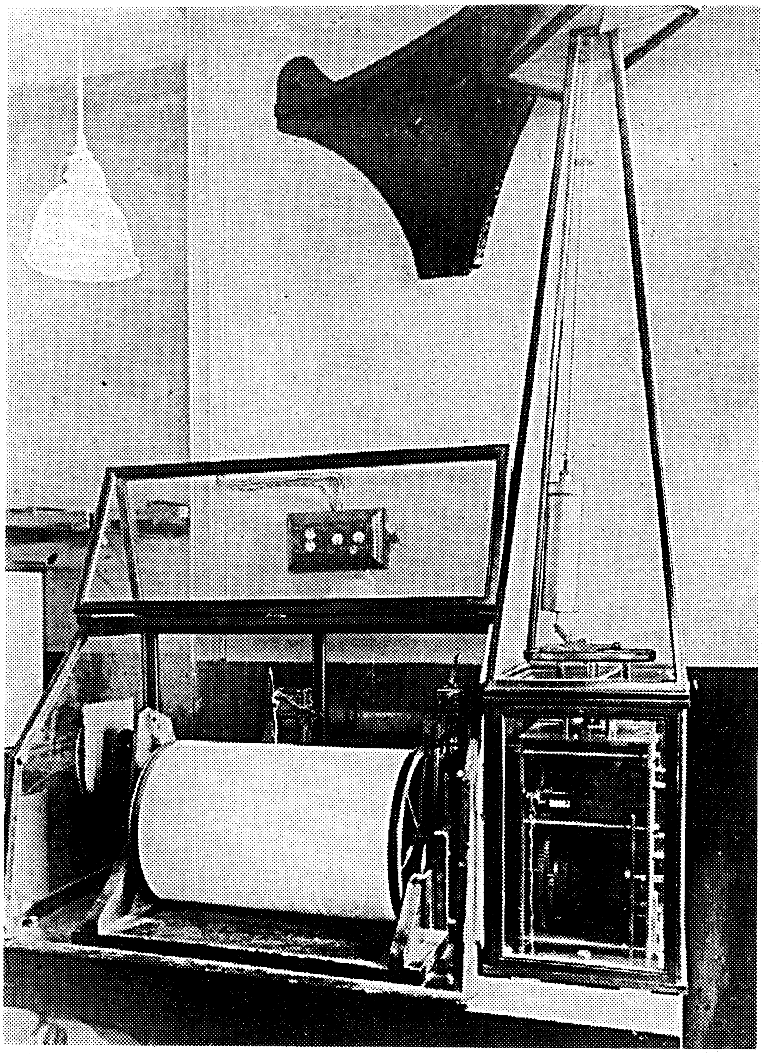

Figure 6. Airy's Barrel Chronograph. Note the clock drive mechanism at right, with the conical pendulum above.

An investigation showed that the probable errors of transit observations made with the chronograph were only a third to a half those made by the eye-and-ear method. Later modifications were the addition of water/glycerine damping of the pendulum, and substitution of a fountain pen for the prickers and pipette (as shown in Figure 6).

The barrel chronograph was used to record observations made with both the transit circle and the altazimuth. It had a useful life of 100 years, which only ended when the transit circle ceased to be used in 1954. Further reference to its use with the transit circle is made in the description of that instrument, elsewhere in this volume (see Satterthwaite, 2001).

4.8 A Successful Set of Designs?

These four instruments, conceived, constructed, and commissioned during a few remarkably productive years, were an unparalleled achievement. Their introduction enabled the Royal Observatory to remain at the forefront of positional astronomy for the second half of the nineteenth and well into the twentieth century. Their combined working lifetimes total 313 years, two of them having been in use for a century, and at the time of writing there are still instruments in use which are in direct line of descent from Airy's designs.

5 SUMMARY AND CONCLUSIONS

From his early days in Cambridge, during his direction of the Cambridge Observatory, and throughout his 46-year service as Astronomer Royal, Airy made notable contributions to positional astronomy. He maintained it at the forefront of astronomical activity, recognizing that without accurate positional work other kinds of astronomical research would be difficult or impossible to pursue. He ensured the reduction and publication of a great quantity of valuable positional data, including important work carried out at other institutions not under his personal supervision.

Due to his influence, the best possible techniques for reduction were used, and by his skilful use of computers working on skeleton forms of his design, he ensured a standard of accuracy and excellence that was to continue until all such work was taken over by main-frame computers. By the design of his suite of positional instruments, he not only revitalized the work of the Royal Observatory, but set a pattern for its future development, and he stimulated later instrument designers to make further improvements.

To understand the extent to which positional astronomy developed during Airy's lifetime it is instructive to compare two textbooks of practical astronomy, one published eleven years before his birth (Vince, 1790), and one published by his successor at Cambridge, two years before he finally retired at the age of eighty (Challis, 1879). Another volume reveals not only that Airy was an excellent communicator of complex astronomical matters to a lay audience, but also the overriding importance he placed on positional astronomy as the foundation of all astronomical work (Airy, 1849).

Among his many achievements, surely nothing Airy did can outrank what he did for positional astronomy.

6 ACKNOWLEDGEMENTS

Figure 1 is reproduced by courtesy of the Syndics of the University of Cambridge Library (RGO Archives). Figures 2-6 are reproduced by courtesy of the Trustees of the National Maritime Museum.

The author would like to record his thanks to his former colleagues at the Royal Observatory, Dr P J D Gething and Mr C A Murray, and especially the late Mr L S T Symms, for introducing him to the fascinating realm of positional astronomy.

7 NOTES

Frequent reference is made to the annual Report of the Astronomer Royal to the Board of Visitors of the Royal Observatory, 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 (*AAR 19xx*)

1. Airy compiled autobiographical notes, mainly relating to his scientific endeavours but not exclusively so, up to his sixtieth year (1861). Thereafter he kept much briefer notes. After

his death in 1891 his son Wilfrid examined them, together with his official files and much personal correspondence, and edited them into the autobiography (Airy, 1896), from which these remarks are culled.

2. The Plumian Chair at Cambridge was endowed in 1704 by Revd Dr Thomas Plume, who served as Vicar of Greenwich for 46 years; he was also Archdeacon of Rochester. The terms of the endowment were remarkably apposite for the latest incumbent of the Chair, who was later to serve in Greenwich himself for 46 years: "... the promotion of practical astronomy, especially to describe the parts and uses of astronomical instruments, and to prove and exemplify the mathematical formulae required for the reduction of observations".
3. Airy gave up his College rooms and moved into the Observatory in 1828. When negotiations with the University authorities regarding his emoluments were satisfactorily settled, he left immediately for Derbyshire to propose to Richarda Smith, whom he had wished to marry for six years. They were married in 1830 March.
4. Airy, G.B., *ARR* 1836:1
5. Airy, G.B., *ARR* 1849:6
6. Airy, G.B., *AAR* 1847:11

8 REFERENCES

Airy, G.B., 1833. Report on the progress of astronomy during the present century. In *Report of the First and Second Meetings of the British Association for the Advancement of Science.* John Murray, London, pp. 125-189.

Airy, G.B. (ed.), 1838. *A Catalogue of Circumpolar Stars, Deduced from the Observations of Stephen Groombridge (1810.0).* John Murray, London.

Airy, G.B., 1845. *Reduction of the Observations of Planets, made at the Royal Observatory, Greenwich, from 1750 to 1830.* John Murray, London.

Airy, G.B., 1848a. *Reduction of Observations of the Moon made at the Royal Observatory, Greenwich, from 1750 to 1830.* John Murray, London.

Airy, G.B., 1848b. *Description of the Altitude and Azimuth Instrument of the Royal Observatory, Greenwich.* (Appendix, *Greenwich Observations, 1847*). Her Majesty's Stationery Office, London.

Airy, G.B., 1849. *Six Lectures on Astronomy, delivered at the Meetings of the Friends of the Ipswich Museum.* Simpkin & Marshall, London.

Airy, G.B., 1850. Address to the R.A.S., 1849 December 14. *Monthly Notices of the Royal Astronomical Society,* **10:** 26-34.

Airy, G.B., 1855. *Description of the Reflex Zenith Tube of the Royal Observatory, Greenwich.* (Appendix, *Greenwich Observations, 1854*). Her Majesty's Stationery Office, London.

Airy, G.B., 1857. *Description of the Galvanic Chronographic Apparatus of the Royal Observatory, Greenwich* (Appendix, *Greenwich Observations, 1856*). Her Majesty's Stationery Office, London.

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

Bessell, F.W., 1830. *Tabulae Regiomontanae*. Königsberg.

Challis, J., 1879. *Lectures on Practical Astronomy and Astronomical Instruments.* Deighton, Bell, Cambridge.

Dyson, F.W. and Thackeray, W.G., 1905. *New Reduction of Groombridge's Circumpolar Catalogue for 1810.0.* His Majesty's Stationery Office, Edinburgh.

Green, R.M., 1985. *Spherical Astronomy.* Cambridge University Press, Cambridge.

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

Pearson, W., 1829. *An Introduction to Practical Astronomy.* Longmans, Rees, Orme, Brown & Green, London.

Satterthwaite, G.E., 2001. Airy's transit circle. *Journal of Astronomical History and Heritage*, **4**:115-141.

Vince, S., 1790. *A Treatise on Practical Astronomy.* J Archdeacon, Printer to the University, Cambridge.

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