Airy's Altazimuth

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When considering the instrumental needs of the Royal Observatory, Greenwich soon after becoming Astronomer Royal, George Airy decided that the difficulty of refining the theory of the Moon's motion required some means of obtaining accurate positional observations additional to those traditionally made with meridian instruments. His Altazimuth, completed in 1847, was to prove the most successful means of attaining this end and added significantly to our knowledge of lunar theory. The design, construction, operating procedures and results obtained with this instrument are described.

Introduction

When George Biddell Airy (1801–1891) came to Greenwich in 1835 as the seventh Astronomer Royal he took over an establishment that had become rather run down, mainly due to the ill health of his predecessor and incompetent members of staff. Positional astronomy, always one of Airy's major interests, was still the Observatory's main function, and Airy immediately reviewed the performance of the main positional instruments then in use. These were the six-foot mural circle and the ten-foot transit instrument, both constructed by Edward Troughton and in use since 1812 and 1816 respectively. In his first Report to the Board of Visitors in 1836 he confirmed that "The state of the meridian instruments is most satisfactory."[1] He was therefore able to concentrate for his first few years in office on the necessary improvements to the functioning of the Observatory, including staff restructuring, and reorganisation of the procedures for the reduction and publication of observations.

1.1 Need for lunar positions

Determinations of the Moon's position had been a major task since the foundation of the Royal Observatory in 1675, because then the only means of determining longitude at sea was by measuring the distance of the Moon from fixed stars and calculating the longitude difference from a comparison with the Moon's tabulated positions as seen from a fixed station. The task assumed by John Flamsteed, the first Astronomer Royal, and his successors was therefore the constant improvement of the co-ordinates of a large number of fixed stars, and frequent measurement of the Moon's position to facilitate the formulation of a theory to predict its future movement. Over the next 160 years the first of these tasks had been carried out very satisfactorily, but predicting the Moon's position had proved to be a different matter.

Due to the complexity and rapidity of its motion against the background of the fixed stars, circling the sky more than twelve times a year but not exactly retracing its path for about 18.6 years (230 lunations), far more position measurements were required than for any other celestial body, but paradoxically the Moon's position could be satisfactorily determined far less often than that of other bodies. For a period of about four days either side of New Moon the thin crescent cannot be observed with meridian instruments owing to its proximity to the Sun and the consequent glare; the fact that a positional measurement can be lost by the passing of a small cloud at the moment of transit is therefore much more serious in the case of the Moon. A further problem in obtaining really accurate positions of the Moon arises from the fact that due to its changing phases, except at times close to Full Moon only one limb each in Right Ascension and Zenith Distance can be observed, so that an estimated value of the apparent semi-diameter has to be applied to derive the position of the Moon's centre.

By Airy's time the lunar ephemeris was no longer needed by navigators, since the successful development of the marine chronometer and the annual publication of the *Nautical Almanac* provided better means of longitude determination. By then, however, the Royal Observatory had established itself as one of the world's leading stations for the provision of positional observations of fundamental stars as a fixed frame of reference, and of the motions of the Sun, Moon and planets for the purposes of refining orbital theory and improving ephemerides. In other words, the requirements of the navigator had been superseded by those of the world's astronomical community. This is apparent from the huge undertaking of re-reducing all the Greenwich observations of the Moon and planets made since the introduction of improved instrumentation by James Bradley, the third Astronomer Royal, in 1750. Suggested by Airy in 1832, and involving the use of improved constants derived by Friedrich Bessel, this government-funded enterprise was now being carried out by a team of supernumerary computers under Airy's supervision, and would lead to publications a few years later which would prove to be of great and lasting value (Airy 1845, 1848a).

1.2 Airy's proposed solution

Despite his initial satisfaction with the performance of the meridian instruments, Airy was considering their eventual replacement as early as 1843 (Satterthwaite 2001a). In particular he contemplated replacing the transit instrument with one of larger aperture − prompted by the discovery of new, faint, minor planets − and of combining its function with that of the mural circle in a single instrument. This he achieved with the inauguration in 1851 of his uniquely successful transit circle (Satterthwaite 2001b). Whilst considering the matter of improved instrumentation for positional work, however, Airy was also acutely conscious of the need to provide some means of increasing the number of lunar position measurements, and so made this the first priority of his review.

In an address to a specially convened meeting of the Board of Visitors of the Royal Observatory on 1843 November 10 Airy presented his proposed solution. He summarized the lunar positions that had been determined during his seven years in charge at Greenwich, remarking that "one-fourth of the Moon's course is absolutely lost, and one-half is very imperfectly observed" and that "the uniform suppression of observations during the Moon's passage through entire portions of her orbit of great extent is, in reference to theory, extremely injurious." Noting that the number of complete observations of the Moon's position currently being made was under one hundred a year he estimated that given the means to make off-meridian observations "the number of nights of efficient observation might be made to exceed two hundred". He continued:

> "After careful consideration of the ways in which these observations might be made, I have come to the conclusion that there is but one instrument with which observations could certainly be made possessing the required accuracy, and that with it the observations certainly could be made. This instrument is the Altitude and Azimuth Instrument. No form, however, in which I have seen this instrument appears to me to be sufficiently firm for this purpose (in which the azimuths are as important as the altitudes). I should propose to construct a new instrument, with circles of three feet diameter, in general form resembling the Palermo or Dublin circle, but framed on the same principles of massiveness and strength, and with the same exclusion of adjusting power, which I have adopted in the Ordnance Zenith Sector." [2]

The Zenith Sector was a new instrument designed by Airy and used by the Ordnance Survey for star observations in connection with its on-going re-triangulation of the British Isles.

The Palermo circle referred to was the highly successful 5-foot vertical circle constructed by Jesse Ramsden and used by Giuseppe Piazzi from 1789; with it, Piazzi compiled a catalogue of nearly 8000 stars, discovered the large proper motion of 61 Cygni, and in 1801 discovered Ceres, the first minor planet. The Dublin circle, also by Ramsden, was originally intended to be ten feet in diameter, but this was later reduced to eight feet. Unfinished when Ramsden died in 1801, it was eventually completed by Matthew Berge and installed at Dunsink Observatory in 1808, although observational records exist only for the period 1812−1839. These instruments are basically transit circles, but mounted so as to permit observation in azimuths other than the meridian plane. It was entirely characteristic of Airy to design his own version of the instrument, rather than to have another Ramsden copy made, and to incorporate his own carefully thought out principles of design. His instrument achieved the required stability and precision with far less interruption of its field of view that was the case with any of its predecessors.

It is worthy of note that initially the new instrument was known as the Altitude and Azimuth Instrument. This rather cumbersome title would clearly have beneffited from abbreviation, and occasional references to the 'Alt-Azimuth' are found. Airy finally resolved this himself; in his Annual Report in June 1851 he for the first time refers to the instrument as the Altazimuth, by which name it has been known ever since. A concise description of the instrument is included in the Tercentenary History of the Royal Observatory (Howse, 1975:53-5).

2. Design principles

Airy was considering the design of three instruments simultaneously at this time (the Altazimuth, the Transit Circle and the Reflex Zenith Tube), and applied the same principles to each. He believed it unrealistic to expect that a precision instrument could be so well engineered that when fully adjusted it would remain free from instrumental errors, and knew that such errors would in any case vary with ambient conditions; he therefore aimed at making the structure as massive and rigid as possible, with no provision for delicate adjustments, and relied on determining the necessary corrections for instrumental errors by measurement at the time of observation. In his own words:

> " That in all the moving parts of the instrument the fundamental principles of construction have been:— to form as many parts as possible in one cast of metal,— to use no small screws in the union of parts,— and to leave no power of adjustment in any part; it being intended that the observations shall be so arranged that every instrumental error shall be deduced from the ordinary observations, and that numerical corrections shall be applied in the reduction of the observations." [3]

This approach, unusual for the time, was to be triumphantly vindicated by the success of these instruments, and would be used as the basis for the design of a large number of instruments worldwide during the next hundred years.

Whilst the designs were entirely his own, Airy did consult with two trusted friends during their formulation: Charles May, engineering director of the firm of Ransomes & May who were to manufacture the massive parts of each instrument, and William Simms of Troughton & Simms who would be responsible for the optics, graduated circles and other precision components. It is clear that he regarded the proposed Altitude and Azimuth Instrument as the greatest priority, and following the acceptance of his proposal by the Board of Visitors he was able to report to them six months later that:

> " The Board of Admiralty at once sanctioned the principle of this proposal; and, on their application, the Lords Commissioners of the Treasury without hesitation sanctioned the estimated expense." [4]

3. Housing and support

3.1 Building

In addition to the construction of the instrument it was also necessary to provide a building to house it. Airy chose to build on the walls of the Advanced Building, in effect on the site where Flamsteed's Equatoreal Sector had once stood, a few feet to the south of the Halley/Bradley Quadrant Room. The western wall had been constructed by Flamsteed as a meridian wall for his Mural Arc, whereas the other walls aligned with the original buildings, approximately 14° off-meridian; the new building, in effect a tower, was therefore an irregular quadrilateral in section. The instrument was mounted three storeys high in order to have a clear horizon for the lunar observations. Airy records that:

> "… the Deputy Ranger of the Park consented, on my application, to cut off the top of the only tree which interfered materially with our view near the horizon." [5]

A revolving 'dome' with opening shutters, in fact a flat-topped cylinder of ten feet internal diameter, covered the instrument. This became known as the New South Dome (Figure 1).

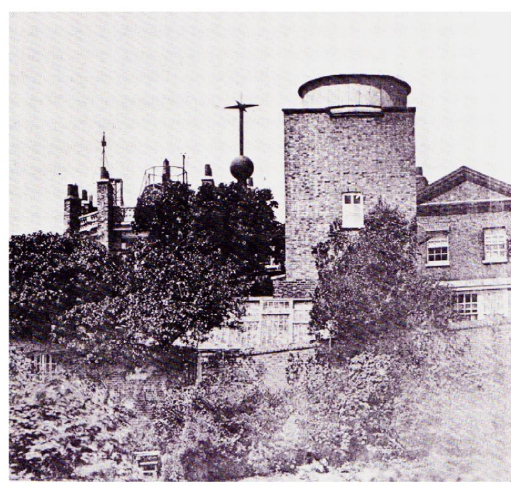

Figure 1

The Altazimuth dome, from the south in 1857.

Courtesy of the National Maritime Museum.

3.2 Supporting Pier

The proposed massive construction of the instrument required a very firm foundation; for this Airy specified a three-rayed pillar of brickwork, unconnected with the surrounding building and topped by blocks of Portland stone, rising some 26 feet above the foundation. The central part of this pillar was triangular in section, of side approximately 5 feet, with rays one foot wide extending five feet from the centre at each corner. At the centre of this structure an upward extension, a cylindrical brickwork column 3 feet in diameter and approximately

4½ feet high, was provided to support the actual instrument, the lower rayed pier providing support for the framework bearing the upper pivot bearing.

The floor of the observing room was independently supported some two feet above the top of the rayed pillar, having no contact with the mounting or any part of the instrument.

4. Design and construction

The basic design of such circles comprises a telescope mounted on a horizontal axis with a vertical circle attached, contained within a framework which can be rotated around a vertical axis and provided with a horizontal circle to measure the azimuth setting. A major difference from the design of earlier vertical circles, however, was the need for the measurements in azimuth to be made with the same accuracy as those in altitude in order for lunar positions to be computed from them; hence the horizontal circle needed to be graduated to the same accuracy as the vertical circle, and similarly read by microscopic micrometers. This imposed a further requirement, that the upper pivot of the vertical axis be very firmly supported, and engineered to maintain accurate verticality at all settings. Airy achieved this by a characteristically simple but effective design.

4.1 Upper bearing support

In addition to providing for this verticality and rigidity, it is also necessary to minimise obscuration of those parts of the sky where observations were required to be made. Airy achieved this by mounting the upper bearing at the centre of a horizontal triangular frame, which was supported by three vertical triangular frames bolted to a horizontal triangular base. These welded triangular frames, of iron rods 1½ inches in diameter, fastened together by means of strong bolts in welded supports, provide a very rigid structure without the need for massive components which would obscure more of the sky. The radial arms which locate the upper and lower bearings at the centre of the two horizontal frames are also welded, and the radial arms of the lower triangle rest in grooves cut in the stone blocks which cap the three rays of the supporting pier. Airy further provided for the framework to be orientated so as to minimise the area of useful sky obscured by the framework:

> " The single bars offer no material interruption to the telescope; the only part which deserves consideration is the angle of the upper triangle, where five bars unite, and where there are also a fork, nuts, &c. Now it was obvious that, if the frame were so placed that one of these angles should be exactly South; then the two remaining angles would be in positions in which the Moon could never pass them; and the southern angle, though it would undoubtedly interrupt the sight of the Moon, would do so in a position of the Moon which is not favourable to observations with this instrument, and in which she would infallibly be observed with the meridional instruments. That position was therefore adopted for the frame; and every arrangement of the building, staircase, &c., was made in subordination to this choice." [6]

This arrangement can be seen in Figure 2, which is extracted from the published description of the instrument (Airy 1848b). It shows the brick pillar *C* bearing the horizontal circle *Q*, and is drawn from the perspective of an observer standing north of the instrument and facing south; notice that the lower horizontal triangle is viewed from above and the upper from below. *N* is the upper bearing for the vertical axis.

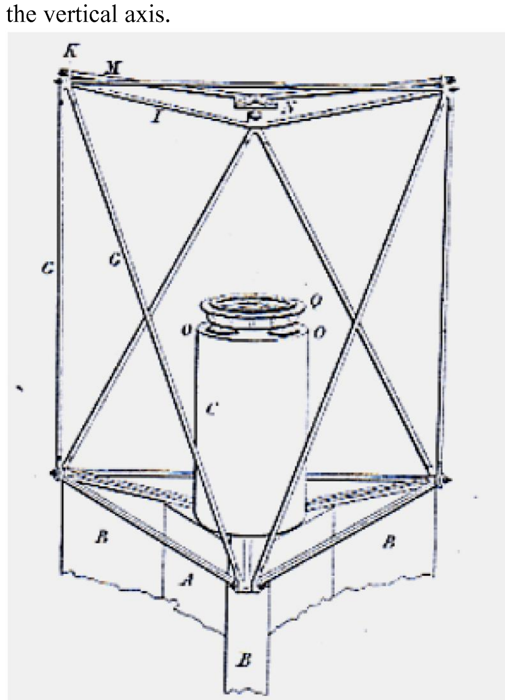

Figure 2

The supporting structure for the Altazimuth

This shows, in particular, the upper azimuth bearing *N*, and the column *C*, which supports the base plate *Q*, seated on top of the 26-foot high, three-rayed supporting pier.

This image is from Airy 1848b, Plate I, Figure 4.

4.2 The telescope and circle

The telescope and vertical circle are constructed as a single unit, comprising two gun-metal castings bolted together. One casting forms the central drum with a set of spokes and one pivot, the objective and eye-ends of the telescope, and carries the vertical circle; the other casting forms the second pivot and set of spokes. The combined unit is supported with the axis horizontal, each pivot resting in a counterpoised bearing in the 'cheek' pieces of the rotating frame. The telescope objective is an achromatic doublet of 3.7 inches aperture, approximate focal ratio 12. This unit is shown in Figure 3.

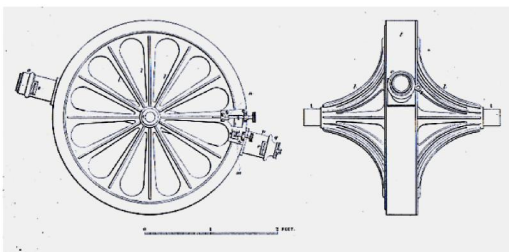

Figure 3

The telescope and vertical circle unit

This image is from Airy 1848b, Plate III, Figures 18 and 19.

4.3 The Rotating Frame

This frame is basically comprised of four parts in cast iron, two vertical side or 'cheek' pieces and upper and lower connecting plates carrying the pivots of the vertical axis. Each cheek piece is a single casting, over 4½ feet high and 2 feet wide; both carry a pivot bearing for the horizontal axis, and one carries the four microscopes for reading the vertical circle. The other cheek piece carries a toothed circle, which engages with a pinion attached to the telescope and circle drum to provide adjustment in altitude. The upper connecting plate carries the upper pivot of the vertical axis, and is bolted to the two cheek pieces. The lower connecting plate, also bolted to the cheek pieces, carries the lower pivot and also four microscopes for reading the horizontal circle. The spherical gun-metal pivot rests in a counterpoised gun-metal cone and has an oil-channel bored through it for lubrication of the bearing.

In his description of the instrument Airy gives the weights of these various components: the total weight of the rotating frame together with the telescope and vertical circle is almost 2000 lb (907 kg). That such a mass can be rotated whilst preserving verticality to the accuracy required is confirmation of the excellence of the design of the supporting framework. The massive construction of the rotating frame, with the telescope/circle unit mounted within it, is well shown in Figure 4.

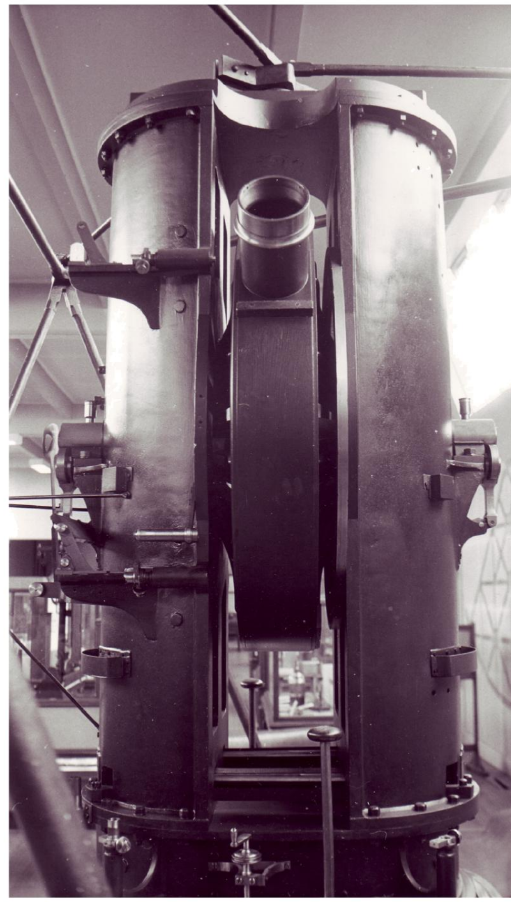

Figure 4

The rotating frame and telescope/circle unit

Photographed when displayed in the Science Museum, London, *circa* 1965.

Courtesy of the National Maritime Museum.

4.4 The base plate

The base plate is located by three of its spokes seating in grooves cut in iron blocks set in the stone capping of the brick column, each furrow being filed to the exact depth to ensure horizontality. It carries the horizontal circle, and also a toothed circle engaging with a pinion attached to the lower plate of the rotating frame, to provide for adjustment in azimuth.

4.5 The divided circles and microscopes

Both circles are of silver and 3 feet in diameter, with graduations every 5 minutes of arc. The graduations were engraved using William Simms's self-acting dividing engine, his improvement on Troughton's excellent machine. His nephew, also William Simms, who had joined the business in 1836, records in his memoirs that his Uncle had entrusted him with the graduation of several important instruments:

> " Amongst the instruments I graduated upon this machine may be named the Transit Circle at Greenwich, that at the Cape of Good Hope, … the large Equatorial at Greenwich, the Alt-Azimuth instrument there also." [7]

The circles produced by Troughton & Simms at this time were to remain some of the finest examples of machine-divided circles for many decades. Each circle has four reading microscopes with micrometers, and a low-power 'pointer' microscope for identifying the whole number of degrees.

4.6 Ancillary equipment

Additional fittings included levels to confirm horizontality of the altitude and verticality of the azimuth axes, and an illumination system enabling the circles to be read by the microscopes. This was provided by a single lamp, with a series of reflectors to direct the illumination to those parts of the circles beneath the microscopes.

At each end of the horizontal (altitude) axis was affixed a small plate bearing a small dot, and microscopes were provided to enable the position of these dots to be measured and thus to determine any pivot errors.

Some of these additional components can be seen in the drawing of the assembled instrument (Figure 5). Figure 6 shows in close up part of the base plate with the setting circle, azimuth circle and slow-motion controls.

4.7 Construction

The construction of the new instrument was not without difficulties and delays. Airy reported in 1845 that the instrument was:

> "... not yet out of the engineer's hands, but I am assured that its principle parts will be transferred to Mr Simms in a few days. It is almost unnecessary to remark, that the work was, in several respects, different in some degree from that to which engineers are accustomed, and this has caused greater delay in its construction than I had anticipated." [8]

A year later he records that construction had been delayed "by a singular accident":

> " The parts cast by Messrs Ransome and May … had been sent to Mr Simms, and several fittings of micrometers and other small parts had been adapted to them. Some levels also having been adapted, I was much surprised to find that the end of the telescope would not pass them, although the calculations of height, &c., had been expressly arranged in order to permit it to pass. On examination it appeared that, in attaching some small portions of the pattern to the principal

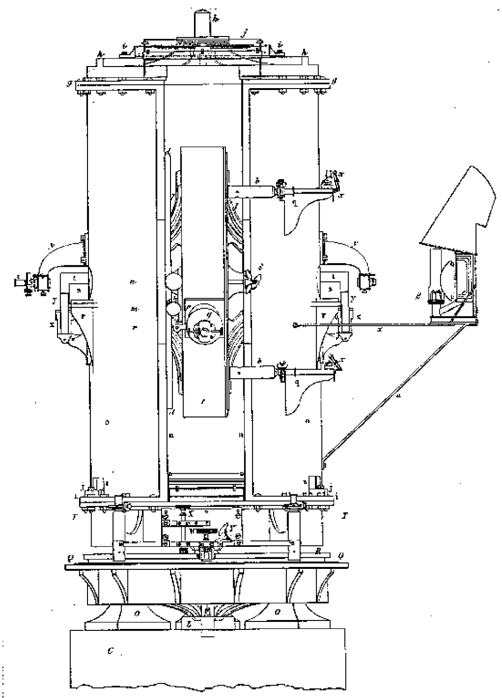

Figure 5

Drawing of the complete Altazimuth assembly

From Airy's published description (Airy 1848b, Plate IV, Figure 22). Notice the microscopes for examining the pivots of the horizontal axis, two of the microscope micrometers for reading the vertical circle, and the light source that illuminated the circles via a system of mirrors.

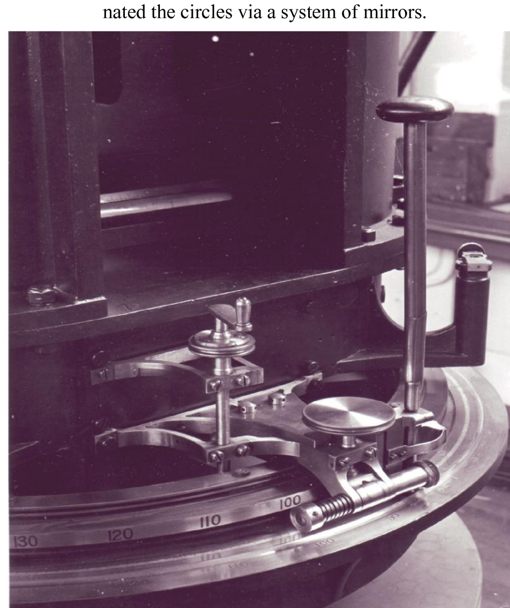

Figure 6

Close-up view of part of the base plate and horizontal circle structure

Also shown are the setting circle and slow-motion controls. Courtesy of the National Maritime Museum.

parts, these portions had been attached on the wrong side of the hole for the horizontal axis, so that, in the casting, what was intended for the upper part of the vertical axis became the lower part. The engineers, upon hearing of this mistake, immediately undertook to prepare new sides without expense to the Observatory, and with as little delay as possible; but as the completion of these parts requires not only skilful casting, but also careful turning and planing, there is necessarily considerable delay." [9]

In his next report, in June 1847, Airy records that "The Altitude and Azimuth Instrument has been completed several weeks." [10] In the light of the complexities of the design and the difficulties encountered in its construction, completion just 3½ years from the initial proposal seems very commendable. Airy records his satisfaction with the work of both the engineers and the instrument-maker, and especially with the graduation of the circles with Simms's dividing engine:

"… my first care was to examine the graduations … in no instance is the mean of the four microscopes of either circle half a second in error."

(A positional accuracy better than one part in 600.) The form of the pivots of the horizontal axis was also "examined most severely", by measurement of the dots placed at each end of the axis with the micrometer microscopes provided for the purpose (see Section 4.6 above) and the effect of any irregularity "does not amount to half a second." Airy comments:

" I think it extremely creditable to the engineers that pivots which have not been touched by the tool of the instrument-maker should possess this accuracy."

The completed instrument is shown in situ in the New South Dome in Figure 7.

5. Modifications and repairs

During its working life of half a century, normal maintenance procedures were carried out from time to time, such as repolishing pivot surfaces, replacing damaged webs, repairing or replacing levels, but few major repairs were necessary.

5.1 Major repairs

In 1856 Airy altered the bearings of the horizontal axis, which had been introducing slight errors in its orientation relative to the azimuth circle. He substituted "a pair of anti-friction wheels (carried by one frame) instead of a single wheel." [11] The original single-wheel bearing is visible in the engraving featured on the cover of this issue; the two-wheel bearing can be seen in Figure 10, on page 93, behind a tapered shutter used to control the illumination (from a lamp, which is not present in the photograph).

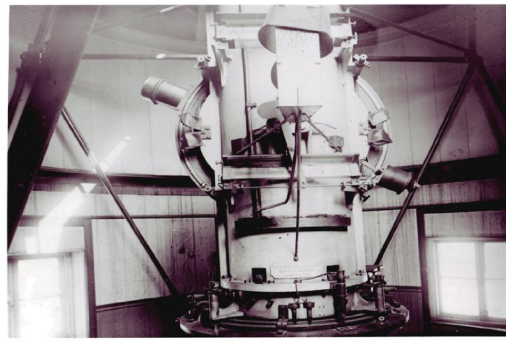

Figure 7

The Altazimuth photographed by E.W.Maunder *circa* 1900

This is the only extant photograph of the instrument in its working position.

Courtesy of the British Astronomical Association.

In 1873 Airy reports that he had become dissatisfied with the bearings of the horizontal axis, and had the Y-bearings replaced with circular segments (a system that he had used successfully in the Transit Circle). Oil-lubricators were also fitted and the pivots re-turned.[12] The instrument was out of use from 1872 September 9 to 1873 January 5 whilst this work was carried out, the only closure of such length ever allowed by Airy. In 1874 October the counterpoises of the horizontal axis were removed, "the object being to insure the stability of that axis." [13] In 1876 he reports that:

"… a little trouble has been occasioned lately by stiffness in the azimuthal motion. As the lower bearing of the vertical axis appears never to have been cleaned since the erection of the instrument, I have had the whole instrument raised, under the superintendence of Mr. Simms, and the accumulation of oil cleaned out. Small channels are now made, to permit the oil to reach the bearing-parts more readily." [14]

Airy records in 1877 that:

" To relieve the lower bearing of the vertical axis more effectually from the weight of the instrument a more powerful lever-counterpoise has been applied … with very beneficial results as regards the azimuthal motion of the instrument." [15]

And in 1880:

" The horizontal circle of the Altazimuth has been regraduated by Mr. Simms, the divisions having been nearly rubbed out in course of years; and improved compound object-glasses, with adjustment for focus, have been supplied to the reading microscopes. Two supplementary microscopes have been mounted for examination of the division errors of the horizontal circle and of the errors of the micrometer-screws. The instrument is now in thorough working order." [16]

In 1895, W.H.M. Christie, who had succeeded Airy as Astronomer Royal in 1881August, reports that:

> " In 1894 June it was noticed that the level error of the instrument was very unsteady; on searching for the cause, it was found that the upper pivot of the vertical axis of the instrument and its bearing were much worn. The bearing was removed, and a new bearing of phosphor-bronze, made by Messrs Troughton and Simms, was inserted and the pivot was re-ground." [17]

5.2 Collimation marks

Observations of zenith distance, made with the 'altitude' circle, are of course referred to the true vertical, the zenith point being checked by means of the levels provided to confirm verticality of the axis. Observations in azimuth are less simple, unlike meridian observations the azimuth in which the instrument is set needs to be referred to a fixed datum. To provide for this it was usual to accompany lunar observations with azimuth measurements of a pair of bright stars of accurately known position, one high and one low in the sky. In 1850, however, whilst confirming his confidence in both the instrument and its methods of use, Airy reports "an occasional change … in the apparent Zero of Azimuth." [18] In order to examine if the change was real he decided to erect a collimating mark.

> " The interference of buildings has compelled me to do this in an unusual way. The 25-feet object-glass of the old Zenith Tube is fixed in the North wall of the New South Dome staircase. The mark is fixed … upon the cross wall which rises from the western side of the Computing Room, and just below the ridge of the Quadrant Room".

The 5-inch lens, by Dollond, had been the objective of Pond's unsuccessful zenith tube, dismantled in 1848 and about to be replaced by Airy's Reflex Zenith Tube (Satterthwaite 2003). The mark consisted of a metal plate with a round hole $^{1}/_{50}$ of an inch in diameter, illuminated by a gas flame. An image of the hole about $^{1}/_{300}$ inch in diameter made by a short-focus lens was then formed in the focal plane of the collimating lens; when observed through this with the Altazimuth telescope it was seen "as a beautifully defined circle, subtending an angle of 2¼"."

The problem of the wandering zero point was found to affect observations with the Transit Circle as well, and remained a constant preoccupation for decades. From time to time new marks were set up, notably in 1880 when a mark consisting of a small plane mirror was set up on the parapet of the south-east building of the Royal Naval College, some 1700 feet distant. In order to observe this a circular hole was cut in the brick wall between the courtyard and the terrace of the Wren building.[19] The new mark was used successfully. After many years of study it was concluded that the variations in the azimuth zeros were caused by actual movement of the ground on which the supports of the instruments stood, small in extent but enough to be detected with such sensitive telescopic instruments, and were linked to variations in the ambient temperature.

6. Observations with the Altazimuth

To obtain accurate positions of the Moon the azimuth of the visible 'preceding' or 'following' limb, depending on the phase, and the zenith distance (Z.D.) of at least one of the 'upper' and 'lower' limbs, are measured. At, or very close to, Full Moon all four limbs can be measured, and at large gibbous phases both the upper and lower limbs can be measured in Z.D., appropriate corrections being applied for 'defective illumination' in these cases. In order to average out instrumental effects, observations are made in symmetrical pairs, the instrument being rotated through 180º in both planes between them; these orientations are defined as 'graduated face of the vertical circle facing left' (i.e. to the east) or 'right' (west). Airy laid down strict rules for the use of the instrument:

> " The Moon is to be observed if visible, and the observer is bound to watch if necessary while the Moon is above the horizon, and the Sun is not more than an hour above the horizon. One Azimuth and one Altitude are to be observed, and, if possible, two Azimuths and two Altitudes in reversed positions of the instrument: and if the night is fine, a low star and a high star are to be observed in azimuth, both in reversed positions of the instrument, and one star in altitude, in reversed positions. Thus a complete set includes ten observations." [20]

6.1 Methods of observation

In principle, the observation is similar to that made with a transit instrument. If the object is being observed in an azimuth other than the meridian plane it will of course be seen to cross the field diagonally. For azimuth, the sidereal times of passage of the object across six vertical wires[21] in the focal plane of the telescope are recorded. Between each wire the telescope is rotated slightly around the horizontal axis using a slow-motion control, so that the object crosses each wire approximately centrally. Similarly for Z.D., the times of passage across six horizontal wires are recorded.

During its early years, observations were made by the traditional 'eye-and-ear' method, wherein the observer noted down the hour and minute, then listened to the second beats of the sidereal clock and estimated (to one tenth of a second) the time of passage over the wire. In 1854 March Airy's Barrel Chronograph came into use, enabling the observed times to be electrically recorded and subsequently measured (to about one hundredth of a second) against time pulses transmitted from the sidereal standard clock. This system increased the accuracy and considerably reduced personal errors (Satterthwaite 2001a). Both the Altazimuth and the Transit Circle were wired into the chronograph circuit, 'morse-keys' being provided to enable the observer to send the signals. Thus a typical procedure for the observation of a star might be as follows:

1. Switch on chronograph.
2. Set instrument ahead of star, circle facing east.
3. As star crosses field, tap key as it crosses each of six vertical wires, adjusting to mid-wire position for each (first azimuth observation).
4. Read four microscope micrometers and pointer on horizontal circle, read levels.
5. Reset; as star crosses field, tap key as it crosses each of six horizontal wires (first Z.D. observation).
6. Read microscopes and pointer on vertical circle.
7. Reverse instrument to face west.
8. Reset, repeat 5 and 6 (second Z.D. observation).
9. Reset, repeat 3 and 4 (second azimuth observation).

6.2 First and last observations

The first observation, of just one limb of the Moon in both co-ordinates, was made by Hugh Breen Jr on 1847 May 10 (Figure 8). The first symmetrical pairs of observations were made three days later, but were clearly experimental with two observers sharing the task; on May 20, however, routine observations began with accompanying stars observed. Airy himself did not normally observe, his responsibilities being such that regular night duties would clearly be impracticable, and in any case he suffered from poor eyesight (both myopia and astigmatism) and preferred not to observe but to delegate that task to others. Nevertheless, as with the Transit Circle (with which he had observed just three stars on a single night!) he clearly wished to try out his instrument personally, observing a limb of the Moon on May 21, and on two more occasions during that first week.

[ii] OBSERVATIONS OF AZIMUTH WITH THE ALTITUDE AND AZIMUTH INSTRUMENT

DAY.	Observer.	No. for Reference.	NAME OF OBJECT.	Position of Graduated Face of Vertical Circle.	Seconds of Horizontal Transit over Vertical Wires.						Concluded Clock Time of Horizontal Transit over Mean of Vertical Wires.	Clock Slow.	Sidereal Time.	Readings of Microscopes of Horizontal Circle.			
					I.	II.	III.	IV.	V.	VI.				a	b	c	d
					s	s	s	s	s	s	h m s	s	h m s	rev.	rev.	rev.	rev.
May 16	H B	1	☽ 1 L.	Left	24·8	47·7	9·9	32·6	55·0	17·8	12. 7. 21·30	69·15	12. 8. 30·45	5·045	5·035	5·095	5·405
May 19	D	2	☽ 1 L.	Left	25·8	47·8	9·7	31·5	53·4	15·1	12. 9. 20·55	74·26	12. 10. 34·81	7·343	7·441	7·600	7·940
	H B	3*	☽ 1 L.	,,	48·6	10·7	32·5	55·0	17·5	38·9	12. 39. 43·87	74·26	12. 40. 58·13	0·035	0·297	0·147	0·357
	H B	4*	☽ 1 L.	Right	48·8	10·5	33·4	56·0	18·2	40·5	13. 23. 44·57	74·27	13. 24. 58·84	3·510	3·594	3·700	4·013
	H B	5	☽ 1 L.	,,	14·3	36·5	58·8	21·5	43·8	6·2	13. 45. 10·18	74·28	13. 46. 24·46	4·055	4·207	4·375	4·522
May 20	H B	6	☽ 1 L.	Right	58·7	16·9	35·8	54·7	13·8	32·2	11. 6. 45·35	75·94	11. 8. 1·29	0·003	0·069	0·052	0·273
	H B	7	☽ 1 L.	,,	47·5	6·4	25·8	45·5	5·1	24·4	11. 33. 35·78	76·00	11. 34. 51·78	3·435	3·487	3·710	4·056
	H B	8	☽ 1 L.	Left	14·7	34·9	55·6	16·5	36·8	56·9	12. 19. 5·90	76·11	12. 20. 22·01	5·773	5·906	6·093	6·172
	H B	9	☽ 1 L.	,,	36·6	57·8	18·8	40·0	1·8	22·8	13. 0. 29·63	76·19	13. 1. 45·82	3·936	4·193	4·085	4·332
	H B	10	Arcturus.	,,	7·5	24·7	41·8	59·7	17·2	34·5	13. 24. 50·90	76·24	13. 26. 7·14	7·075	6·973	7·407	7·617
	H B	11	α Aquilæ.	,,	2·7	23·5	44·5	4·6	25·7	46·3	14. 50. 54·55	76·41	14. 52. 10·96	6·892	6·887	7·197	7·532
	H B	12	α Aquilæ.	Right	54·6	14·7	35·8	56·7	17·3	38·3	15. 3. 46·23	76·44	15. 5. 2·67	3·752	4·036	3·815	4·212
	H B	13*	α Lyræ	,,	40·7	13·5	47·6	22·0	55·5	29·5	15. 36. 4·80	76·51	15. 37. 21·31	7·445	7·705	7·835	7·952
May 21	G B A	14	☽ 1 L.	Right	41·5	58·2	15·0	32·2	49·6	6·7	8. 41. 23·87	78·22	8. 42. 42·09	3·901	4·050	3·865	3·974
	G B A	15	☽ 1 L.	Left	37·4	54·1	10·7	27·4	44·6	0·7	9. 19. 19·15	78·32	9. 20. 37·47	0·476	0·605	0·808	0·898
	D	16	☽ 1 L.	,,	16·1	33·8	50·9	8·8	26·0	43·2	11. 11. 59·80	78·52	11. 13. 18·32	4·265	4·438	4·492	4·669
	D	17	☽ 1 L.	,,	52·7	10·1	27·7	45·6	3·0	20·7	11. 18. 36·63	78·53	11. 19. 55·16	3·281	3·420	3·423	3·531
	D	18	☽ 1 L.	Right	37·8	55·3	13·5	31·5	49·7	7·7	11. 38. 22·58	78·54	11. 39. 41·12	3·548	3·569	3·624	4·005
	D	19	☽ 1 L.	,,	17·3	35·0	53·5	11·9	30·0	48·1	11. 47. 2·63	78·55	11. 48. 21·18	6·654	6·635	6·687	7·108
	D	20	Arcturus.	,,	50·5	8·1	25·8	44·0	2·0	19·8	13. 3. 35·03	78·61	13. 4. 53·64	4·881	4·930	4·865	5·062
	D	21	Arcturus.	Left	45·7	3·2	21·0	38·6	56·0	13·5	13. 17. 29·07	78·64	13. 18. 48·31	6·430	6·458	6·749	7·030
	D	22	α Aquilæ.	,,	46·7	7·5	28·3	49·2	10·2	30·8	13. 56. 38·78	78·67	13. 57. 57·45	1·378	1·498	1·537	1·859

Figure 8

The first observations in azimuth with the instrument (only part shown)

Observers: HB − Hugh Breen Jr; D − Edwin Dunkin; GBA − G.B.Airy.
From *Greenwich Observations 1847*.

[x] OBSERVATIONS OF AZIMUTH, WITH THE ALTAZIMUTH,

Day and Hour		Observer.	No. for Reference.	Name of Object.	Position of Graduated Face of Vertical Circle.	Seconds of Transit over Vertical Wires. First.	Second.	Third.	Fourth.	Fifth.	Sixth.	Seventh.	Correction for Personal Equation.	Clock Slow.
d	h					s	s	s	s	s	s	s	s	s
Oct. 20.	12.6	HF	1	ν Piscium	Right	23.3	27.4	31.4	35.9	39.7	43.7	48.0	−.13	8.15
	12.8	HF	2	ν Piscium	Left	56.0	0.3	4.4	8.4	12.5	16.8	20.8	−.13	8.15
	13.5	HF	3	☽ 2 L.	Right	53.5	59.2	4.2	9.5	15.0	20.6	25.9	−.13	8.15
	13.7	HF	4	☽ 2 L.	Left	58.7	4.1	9.3	14.8	20.5	25.9	31.1	−.13	8.15
Oct. 30.	5.3	AC	5	☽ 1 L.	Right	29.8	34.7	39.3	43.8	48.6	53.1	57.9	+.04	7.63
	5.5	AC	6	☽ 1 L.	Left	26.0	30.6	35.2	39.9	44.7	49.1	54.0	+.04	7.63
	5.7	AC	7	α Aquilæ	Left	40.9	44.8	49.0	53.1	57.2	1.1	5.2	+.04	7.63
	5.9	AC	8	α Aquilæ	Right	35.7	39.9	43.6	47.8	52.1	56.1	0.5	+.04	7.63
Oct. 31.	5.4	HF	9	α Aquilæ	Right	47.2	51.4	55.3	59.4	3.3	7.5	11.6	−.13	7.67
	5.6	HF	10	α Aquilæ	Left	37.1	41.2	45.2	49.4	53.5	57.5	1.8	−.13	7.67
	6.0	HF	11	☽ 1 L.	Left	38.9	43.1	47.9	52.2	56.9	1.2	5.8	−.13	7.67
	6.3	HF	12	☽ 1 L.	Right	42.4	47.0	51.3	55.7	0.2	5.0	9.4	−.13	7.67
Nov. 29.	4.3	H	13	☽ 1 L.	Right	40.0	44.5	48.6	52.8	57.2	1.4	5.8	−.23	5.75
	4.7	H	14	☽ 1 L.	Left	30.6	34.9	39.0	43.3	47.6	51.7	56.1	−.23	5.75
	5.4	H	15	β Ceti	Right	57.4	2.1	6.5	11.2	15.9	20.8	25.3	−.23	5.75
	5.7	H	16	β Ceti	Left	50.9	55.3	0.1	4.5	9.4	13.6	18.4	−.23	5.75

[xviii] OBSERVATIONS OF ZENITH DISTANCE, WITH THE ALT

Day and Hour		Observer.	No. for Reference.	Name of Object.	Position of Graduated Face of Vertical Circle.	Seconds of Transit over Horizontal Wires. First.	Second.	Third.	Fourth.	Fifth.	Sixth.	Seventh.	Correction for Inequality of Motion.	Correction for Personal Equation.
d	h					s	s	s	s	s	s	s	s	s
Sept. 20.	14.0	AC	1	☽ L. L......	Right	46.0	50.0	53.9	58.4	1.8	5.7	9.7	...	+.04
	14.4	AC	2	☽ L. L......	Left	28.6	32.6	36.1	40.0	44.0	48.0	52.1	...	+.04
Sept. 21.	14.9	H	3	☽ L. L......	Left	25.3	30.0	33.3	37.0	40.9	45.2	48.9	...	−.23
Oct. 19.	17.5	H	4	☽ L. L......	Right	36.4	43.1	50.4	57.3	3.9	10.5	17.2	...	−.23
	17.8	H	5	☽ L. L......	Left	50.5	58.9	6.1	13.6	22.0	30.0	37.9	...	−.23
Oct. 20.	13.6	HF	6	☽ L. L......	Right	...	...	16.0	20.0	23.9	27.9	32.1	...	−.13
	13.8	HF	7	☽ L. L......	Left	10.9	15.1	18.8	22.9	27.1	30.5	34.8	...	−.13
Oct. 30.	5.4	AC	8	☽ L. L......	Right	9.2	26.9	43.0	...	16.9	33.8	50.9	+ .18	+.04
	5.6	AC	9	☽ L. L......	Left	8.6	22.7	37.1	49.9	4.0	17.6	31.7	+ .08	+.04
Oct. 31.	6.2	HF	10	☽ L. L......	Left	...	12.4	33.3	51.2	10.4	28.8	...	+ .11	−.13
	6.4	HF	11	☽ L. L......	Right	40.9	57.1	12.8	27.1	42.7	58.0	14.0	+ .12	−.13
Nov. 29.	4.4	H	12	☽ L. L......	Right	...	50.2	13.9	37.3	1.3	25.4	50.9	− .48	−.23
	4.6	H	13	☽ L. L......	Left	27.2	56.2	27.6	57.7	32.7	4.6	40.0	− 1.69	−.23

Figure 9

The final observations with the Altazimuth

Observations in azimuth are in the left panel; those in zenith distance are in the right panel. Only part of both is shown.
Observers: HF − Henry Furner; AC − Andrew Crommelin; H − Henry Hollis.
From *Greenwich Observations 1897.*

The final lunar observations were made on 1897 November 29 by Henry Hollis (Figure 9). The instrument thus had a working life of 50 years and six months. During most of this time it had been out of use only for brief periods of maintenance, etc., rarely exceeding a few days and normally at a time when observations of the Moon could be undertaken using the Transit Circle. Even when the dome was damaged in 1872, the roof shutter being blown off in a heavy gale, it was soon replaced and observations continued.[22]

6.3 Record of lunar observations

From an examination of the annual volumes of *Greenwich Observations* and the summaries published in the *Annual Reports of the Astronomer Royal* it is possible to see how successfully the Altazimuth achieved Airy's stated goal of increasing the number of positional observations of the Moon, especially during the period between Last Quarter and First Quarter. Whilst he remained in office Airy required the Moon to be observed, together with the necessary observations of stars and the collimation mark, on every possible occasion.

Following his retirement his successor, William Christie, did not continue this practice, being concerned to reduce the demands of positional astronomy, including staff time devoted to both observations and reductions, in favour of the development of astrophysical work. In his first *Annual Report*, in 1882, Christie comments that:

> "… important economy of force would result from the restriction of the altazimuth observations of the Moon to the period from last to first quarter. The other half of the lunation is provided for by the transit-circle" [23].

This ignores, of course, the possibility of meridian observations being lost due to passing cloud, but became the standard practice from July 1882. However, the instrument was occasionally used to measure the Moon's diameter in both co-ordinates at Full Moon.

Christie also suspended observations for 5½ months from May to October 1892 "during great pressure of longitude and other work" [24] - the longest period of inactivity in the life of the instrument.

In order to demonstrate Airy's success in achieving his aims, the statistics in the Table below are presented separately for the periods of full and reduced use.

The number of lunar diameters measured during a sample period of seven years, 1875−1882, when both instruments were being used also demonstrates the value of the Altazimuth (next page):

The number of Moon positions obtained and the average number per lunation

	With Altazimuth			With Transit Circle	
	1847−1882	6549	(15.7 per lunation)	3602	(8.6 per lunation)
	1882−1897	1261	(6.3 per lunation)	1784	(8.5 per lunation)
Total	1847−1897	7810	(12.6 per lunation)	5386	(8.5 per lunation)

With Altazimuth		With Transit Circle	
in Azimuth	78 (11.1)	in R.A.	17 (2.4)
in Z.D.	263 (37.6)	in N.P.D.	6 (9.0)

Figures in parentheses are the annual means.
Z.D. zenith distance; R.A. right ascension; N.P.D. north polar distance.

Airy records a quite exceptional, possibly unique, achievement in lunar positional observation:

> " The Moon was observed with the Altazimuth on every one of the 20 consecutive days from 1863, April 21 to May 10." [25]

6.4 Other Observations

The Altazimuth was also used occasionally for other purposes, such as the observation of comets, lunar occultations of stars, and Jupiter's satellite phenomena, and on 1870 April 19 it was used to observe an occultation of Saturn by the Moon. Airy also records that:

> " The Earthquake of 1863, October 5, $15^h.23^m$. was seen with the Altazimuth Telescope by Mr Ellis, who happened to be observing the Collimator. The mark appeared to descend, to rise rather more, and to descend a little to its original position." [26]

The instrument was brought out of retirement very occasionally for the observation of lunar occultations in the period 1900−1910.

7. Conclusion

The Altazimuth is a very unusual example of a large and expensive instrument, requiring experienced observers to operate it and constructed to carry out a programme of necessarily restricted observations, but in doing so to meet a major astronomical need. That it fulfilled the hopes of its designer clearly gave him considerable satisfaction; after only three years' use he felt able to express to the Board of Visitors his opinion that:

> "… the erection of this instrument is the most important innovation that has been made in the Royal Observatory for many years." [27]

A decade later, discussing the improvement in lunar theory and consequent improvement of lunar ephemerides, he commented that:

> "… the introduction and vigorous use of the Altazimuth for observations of the Moon is the most important addition to the system of the Observatory that has been made for many years. The largest errors of Burckhardt's Tables were put in evidence almost always by the Altazimuth observations, in portions of the Moon's orbit which could not be touched by the meridional instruments; they amounted sometimes to nearly 40″ of arc, and they naturally became the crucial errors for distinction between Burckhardt's and Hansen's Tables" [28]

Hansen's Tables (published in 1857) were, with later amendments by Newcomb, to remain the basis of lunar ephemeris calculation until the publication of Brown's Tables (Brown 1919).

Airy's Altazimuth was clearly of seminal importance in positional astronomy. When Christie terminated its long observational life in 1897, it was to be succeeded by a new instrument, which he described as a universal transit circle, but which soon became known as an altazimuth. It was in effect a large, non-reversible transit circle, mounted on a turntable base so that it could be used in azimuths other than the meridian. Already erected in a new building in 1896, major problems, including significant flexure of the massive telescope tub, delayed its use; the first observation were not made until February 1899. It was used sporadically until 1929, but was never a success.

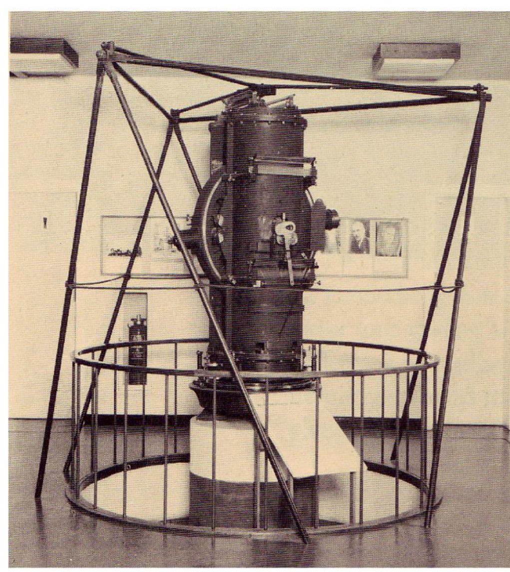

Figure 10

Airy's Altazimuth on display in the Pond Gallery at the Royal Observatory, Greenwich, *circa* 1967

Airy's Altazimuth was dismounted in 1910 and transferred to the Science Museum, London, in 1929, where it was exhibited until 1965. From 1967 it was displayed in the Pond Gallery in the meridian building of the Observatory, close to its original position (Figure 10). When removed from display in 1993, it was returned to the Science Museum, where it remains in store. It is to be hoped that this historic instrument will one day again be exhibited for the interest of future generations.

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Notes

Frequent reference is made in this paper to the annual *Reports of the Astronomer Royal to the Board of Visitors of the Royal Observatory*, a series begun by Airy on his taking office in 1835 and continued until the Board of Visitors ceased to exist in 1965. References to this valuable source are cited in the form (*ARR 18xx:*Page number).

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2. Airy (1843:1).
3. Airy (1848b:v).
4. Airy, G.B., *ARR 1844*:13.
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6. Airy (1848b:vii).
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10. Airy, G.B., *ARR 1847*:4.
11. Airy, G.B., *ARR 1856*:9.
12. Airy, G.B., *ARR 1873*:7-8.
13. Airy, G.B., *ARR 1875*:7-8.
14. Airy, G.B., *ARR 1876*:7.
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16. Airy, G.B., *ARR 1880*:6.
17. Christie, W.H.M., *ARR 1895*:8.
18. Airy, G.B., *ARR 1850*:5.
19. Airy, G.B., *ARR 1880*:6-7.
20. Airy, G.B., *ARR 1848*:7.
21. It is conventional to refer to 'wires', but by the mid-nineteenth century it was the practice to use threads of spider's web; this was the case with the Altazimuth.
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23. Christie, W.H.M., *ARR 1882*:17-18.
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25. Airy, G.B., *ARR 1863*:8.
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