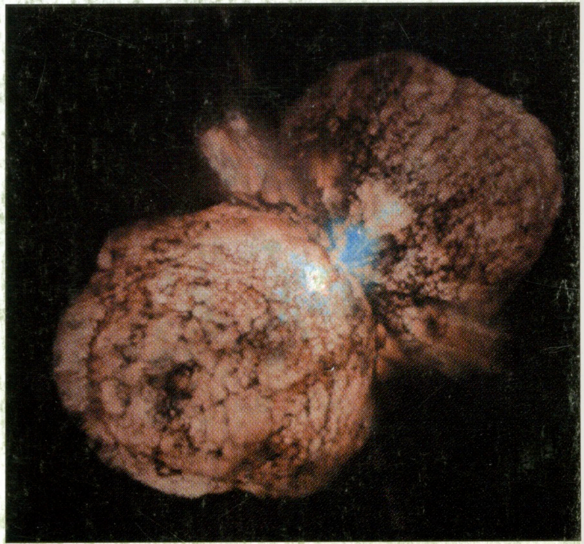
Journal of Astronomical History and Heritage



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E-mail: astral@iinet.net.au
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The life and times of Sir George Biddell Airy: a symposium

Papers presented at an Open Museum meeting held on 2001 January 4 and 5 at the National Maritime Museum, Greenwich, U.K., in association with Goldsmiths College, University of London, to celebrate the sesquicentenary of Airy's Transit Circle.

The Transit Circle designed by Airy, the seventh Astronomer Royal, was erected at the Royal Observatory, Greenwich, during 1850 and was scheduled to come into use on 1851 January 1. In the event no observations were possible until January 4, when the transit of a single star was obtained, and January 5. The symposium was thus held exactly on the 150th anniversaries of the first observations. Among those present were members of the Airy family and several former observers with the transit circle.

Airy's design for the transit circle was to have a lasting influence on the design of instruments for positional astronomy. The instrument itself was to have a working life of more than a century, for much of that time providing the basis for Greenwich Time, and in 1884 it came, by international agreement, to define the Prime Meridian of longitude for the world. Airy's design of this and other instruments formed but a part of his total overhaul of the Royal Observatory, which ensured its continuance at the forefront of fundamental astronomical work for a further century and beyond. His influence was still felt long after the Royal Observatory moved from Greenwich in the 1950s.

Sir George Biddell Airy (Royal Astronomical Society Library).

Airy held the post of Astronomer Royal for 46 years, and continued to reside in Greenwich until his death ten years later. He and his family were notable figures in Greenwich life at a time of considerable social change. The symposium was arranged to examine his contributions to astronomy, and positional astronomy in particular, and also the vast contributions he made in other fields of science and technology, especially as a trusted government advisor. It also sought to assess him as a man, and place him in the context of his family, his colleagues and his peers, against the background of Victorian Greenwich, as illustrated in water-colours by his talented daughter Christabel. Due to the pressure of other commitments all the symposium papers were not available for publication at this time; however, readers may find the references listed below useful. These cover much of the missing material presented at the symposium.

During the symposium a reception was held in the Octagon Room of the Royal Observatory, part of the original building designed by Sir Christopher Wren and the scene of Airy's presentation of his Annual Reports to the Board of Visitors of the Royal Observatory. A small exhibition in one of the adjoining buildings included Airy's Reflex Zenith Tube and his Barrel Chronograph, beautifully refurbished for the occasion.

The Transit Circle was demonstrated to all the participants at the symposium. It is still in place on the Prime Meridian, a source of much interest to the many visitors from all nations who come to stand with a foot in each hemisphere. It also serves as a fitting memorial to the man who led the Royal Observatory through almost half a century of its distinguished history, and who was such an outstanding man of his time.

References

Chapman, A., 1988. Science and the public good: George Biddell Airy (1801-92) and the concept of a scientific civil servant. In Nicolaas A. Rupke (Ed.), *Science, Politics and the Public Good.* Macmillan, London.

Chapman, A., 1998. *The Victorian Amateur Astronomer. Independent Astronomical Research in Britain 1820-1920*. Chichester, Wiley.

Chapman, A., 1988. Private research and public duty: George Biddell Airy and the search for Neptune. *Journal for the History of Astronomy* **19**:121-139.

Gilbert Satterthwaite
Guest editor for the symposium papers

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Airy and positional astronomy

Gilbert E Satterthwaite
Department of Physics, Imperial College, London SW7 2BH, UK
E-mail: g.satterthwaite@ic.ac.uk

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

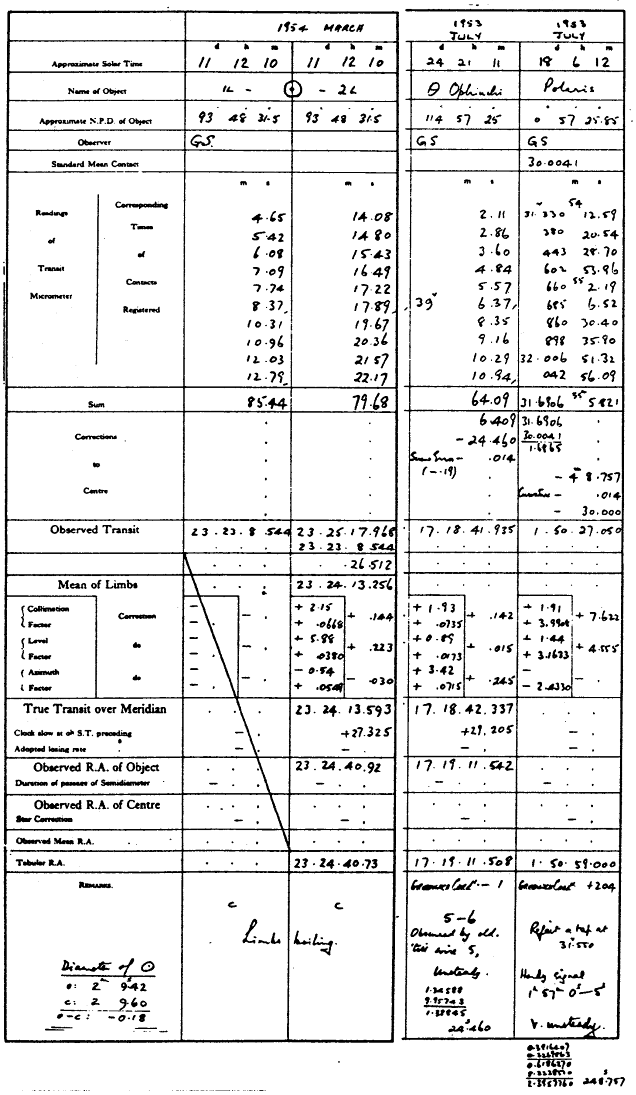
At Cambridge Airy undertook his first design of a major telescope. The Duke of Northumberland, Chancellor of the University, provided funds for a large equatorial refractor, with an 11¾-inch objective by Cauchoix. The design was a version of the English yoke mounting, the polar axis consisting of two 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.


(Form No. 1.)

	1954 March		1953 July	1953 July
Approximate Solar Time (d h m)	11 12 10	11 12 10	24 21 11	18 6 12
Name of Object	1L - ⊙	- 2L	θ Ophiuchi	Polaris
Approximate N.P.D. of Object	93 48 31.5	93 48 31.5	114 57 25	0 57 25.85
Observer	GS		GS	GS
Standard Mean Contact				30.0041
Readings of Transit Micrometer / Corresponding Times of Contacts Registered (m s)	4.65 5.42 6.08 7.09 7.74 8.37 10.31 10.96 12.03 12.79	14.08 14.80 15.43 16.49 17.22 17.89 19.67 20.36 21.57 22.17	39 2.11 2.86 3.60 4.84 5.57 6.37 8.35 9.16 10.29 10.94	31.330 54 12.59 380 20.54 443 28.70 602 53.96 660 55 2.19 685 6.52 860 30.40 898 35.90 32.006 51.32 042 56.09
Sum	85.44	79.68	64.09	31.6906 55 58.21
Corrections to Centre			6.409 - 24.460 .014 (-.19)	31.6906 30.0041 1.6865 - 4 8.757 - .014 - 30.000
Observed Transit	23.23.8.544	23.25.17.968 23.23.8.544	17.18.41.935	1.50.27.050
		.26.512		
Mean of Limbs		23.24.13.256		
Collimation Factor / Correction		+ 2.15 + .0668 + .144	+ 1.93 + .0735 + .142	+ 1.91 + 3.9904 + 7.622
Level Factor / do		+ 5.88 + .0380 + .223	+ 0.85 + .0173 + .015	+ 1.44 + 3.1633 + 4.555
Azimuth Factor / do		- 0.54 + .0549 - .030	+ 3.42 + .0715 + .245	- - 2.4330
True Transit over Meridian		23.24.13.593	17.18.42.337	
Clock slow at 0h S.T. preceding / Adopted losing rate		+27.325	+29.205	
Observed R.A. of Object / Duration of passage of Semidiameter		23.24.40.92	17.19.11.542	
Observed R.A. of Centre / Star Correction				
Observed Mean R.A.				
Tabular R.A.		23.24.40.73	17.19.11.508	1.50.59.000
Remarks. Diameter of ⊙: 2 9.42; c: 2 9.60; o-c: -0.18	c Limbs	c boiling.	5-6 Observed by old. 'till wire 5, unsteady.	Repeat a tap at 31.550. Hardly signal 1h 57m 0s-5s. V. unsteady.

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).

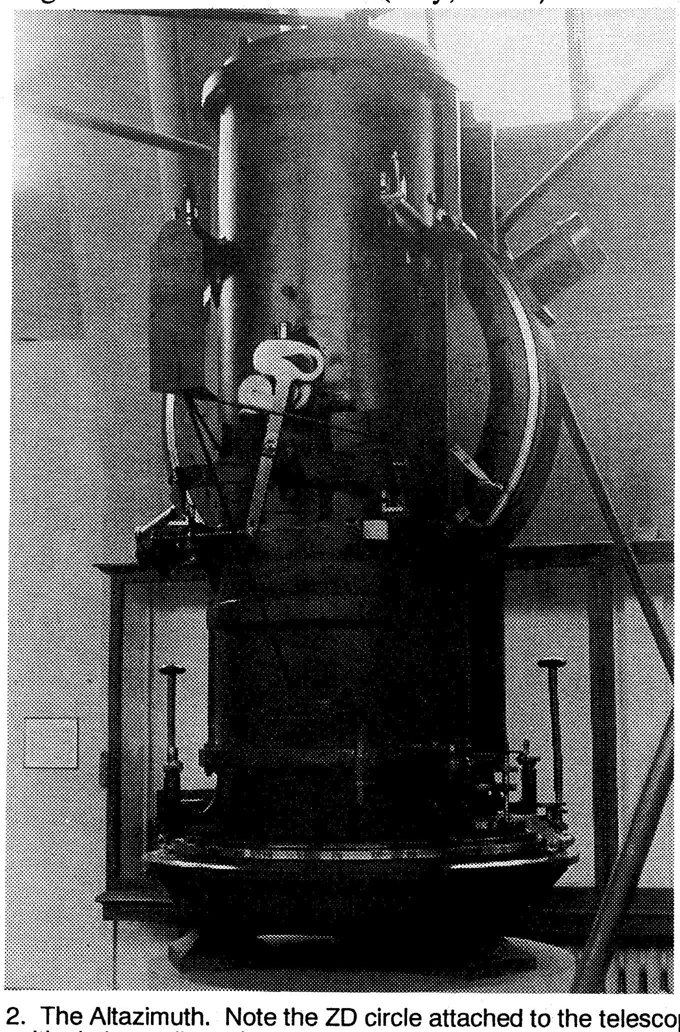


Figure 2. The Altazimuth. Note the ZD circle attached to the telescope axis, with circle-reading microscopes mounted on the cheek-piece.

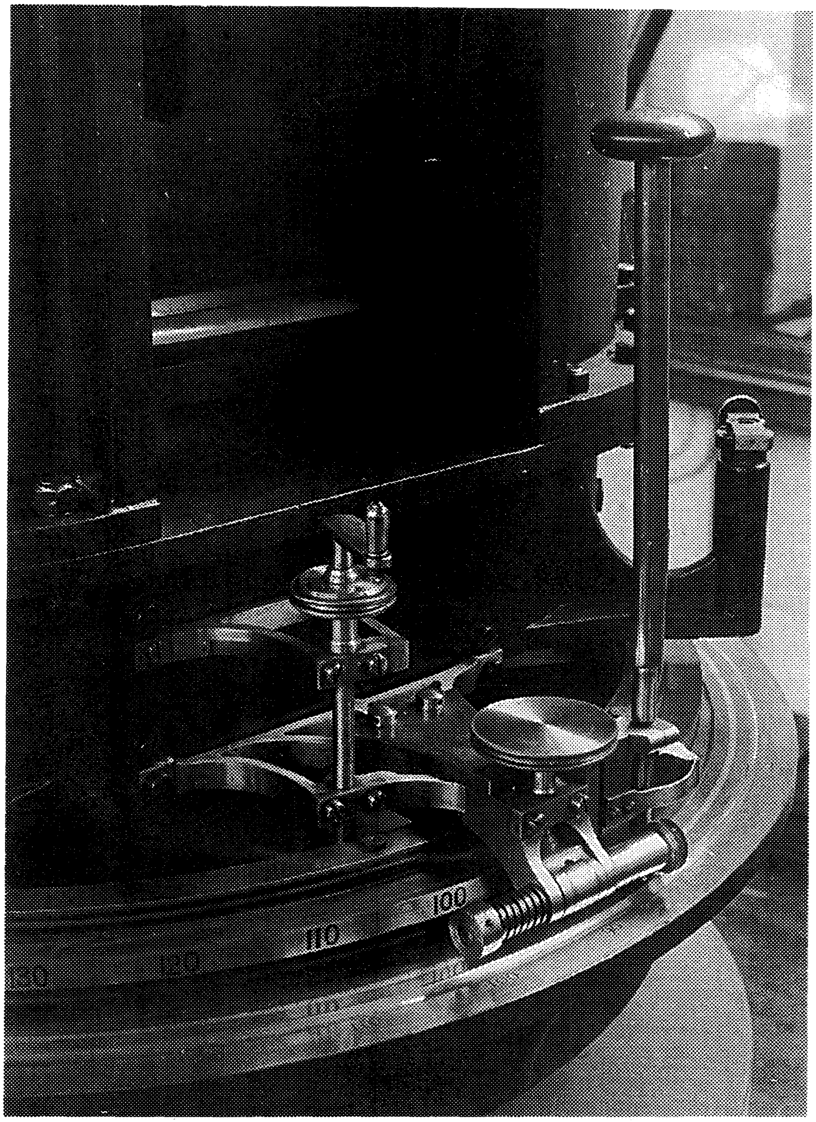


Figure 3. The base of the Altazimuth, showing the azimuth circle and slow-motion controls.

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.

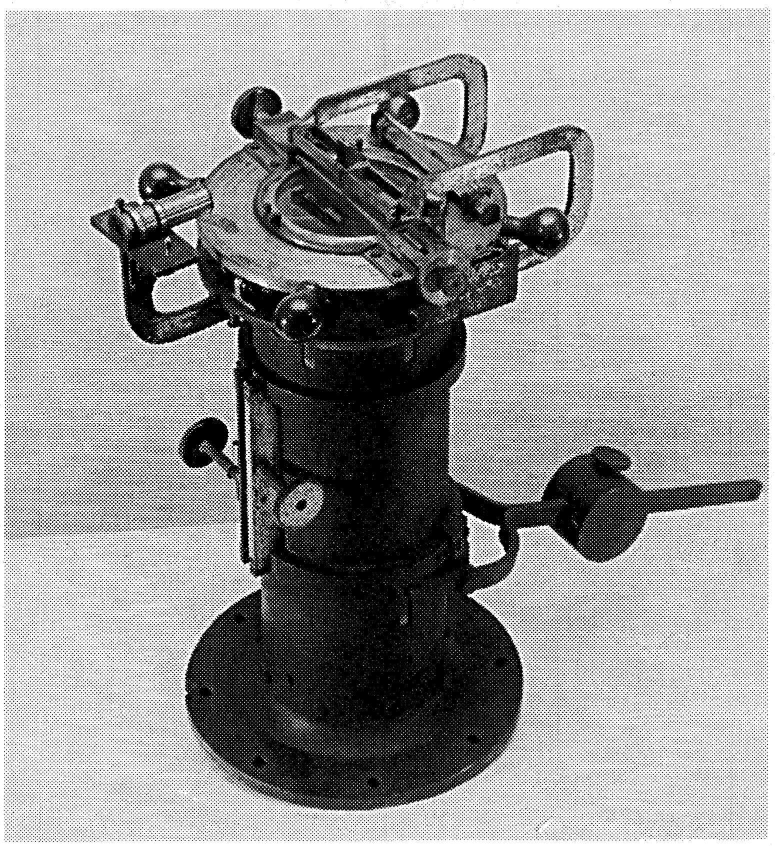


Figure 4. The Reflex Zenith Tube. The counterweight-lever is to balance the mercury container (within the tube), which can be moved vertically to adjust the focus.

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).

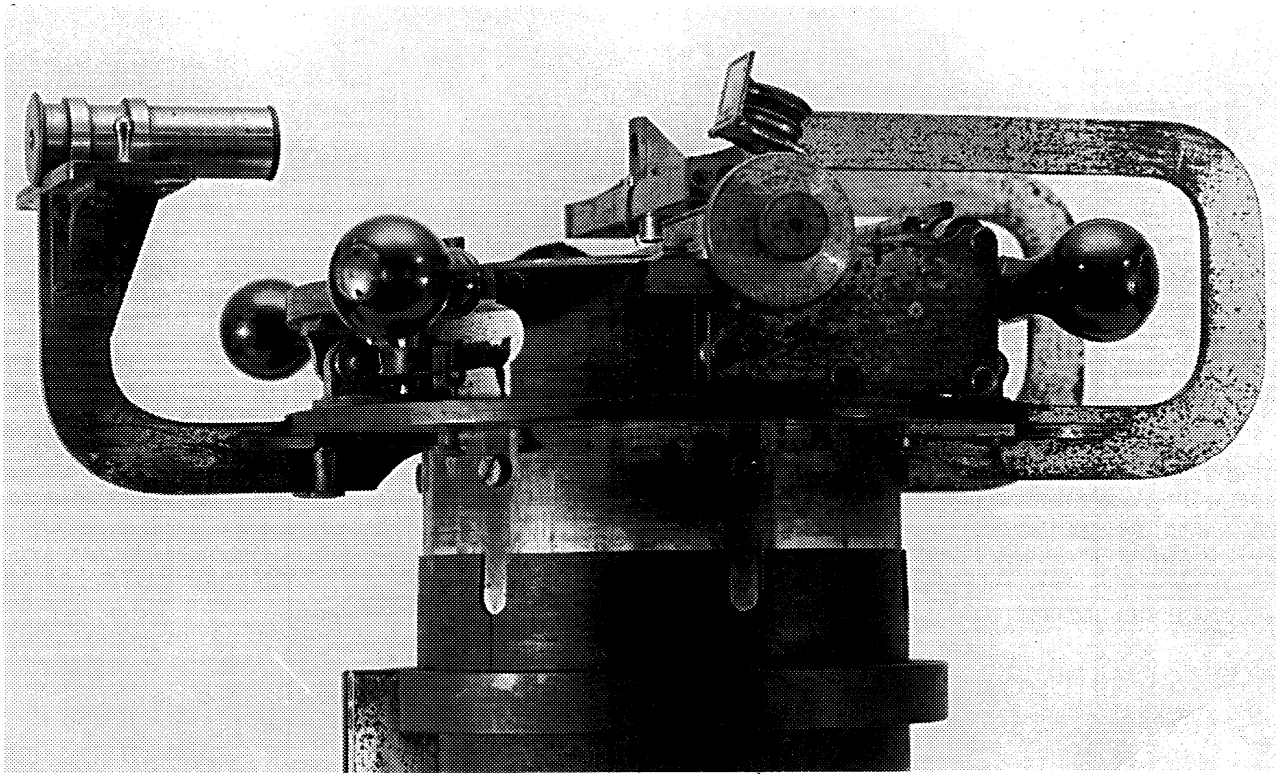


Figure 5. The upper part of the RZT, showing the reflecting prism and eyepiece above the rotor which carries the microscope wire-frames.

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).

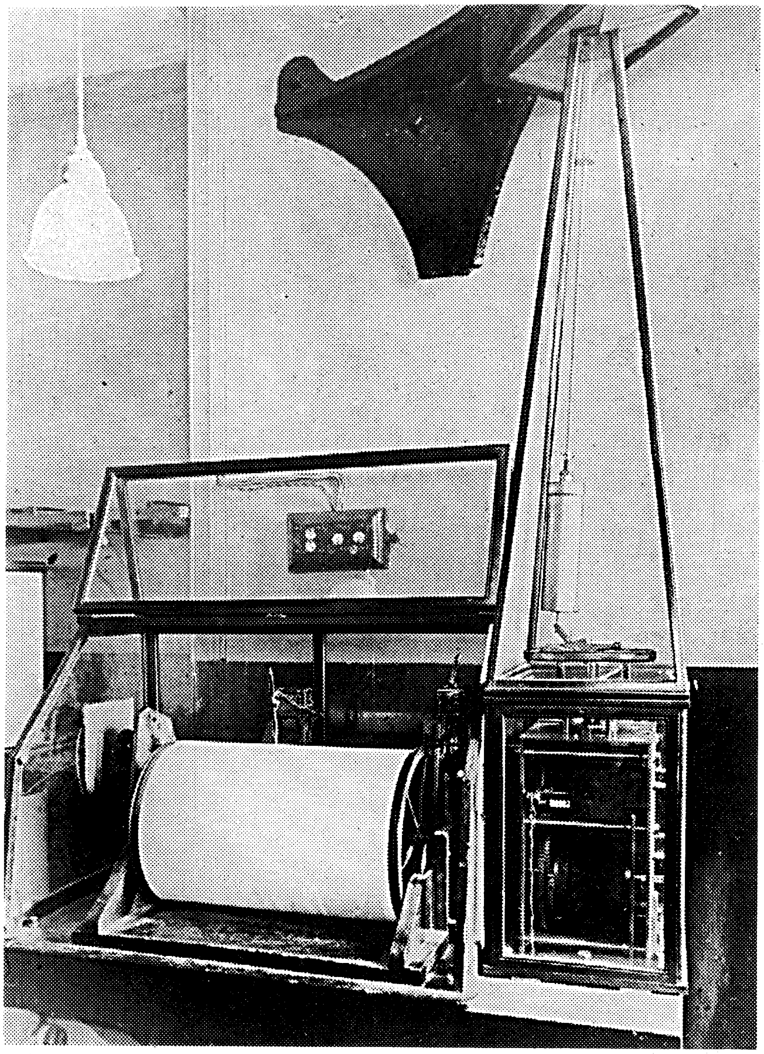


Figure 6. Airy's Barrel Chronograph. Note the clock drive mechanism at right, with the conical pendulum above.

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.

Gilbert E Satterthwaite has recently retired from the Optics and Photonics Group of the Physics Department, Imperial College, London, but is currently retained on a part-time basis. He began his working life in the Meridian Department of the Royal Observatory at Greenwich, where he is still a volunteer consultant on the history of the RO and advises on the care of the old instruments, especially Airy's Transit Circle. In 2000 he was elected a consultant member of IAU Commission 41 (History of Astronomy).

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Airy's transit circle

Gilbert E Satterthwaite
Department of Physics, Imperial College, London SW7 2BH, UK
E-mail: g.satterthwaite@ic.ac.uk

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

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

1 INTRODUCTION

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

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

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

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

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

2 AIRY'S DESIGN CONCEPTS

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

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

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

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

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

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

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

3 ERRORS OF THE TRANSIT CIRCLE

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

3.1 Errors Which Affect Right Ascension

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

3.1.1 Level Error

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

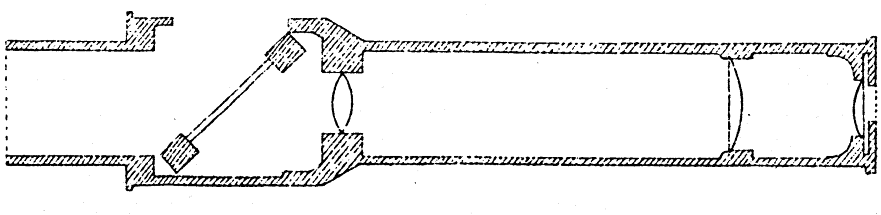

Figure 2. Diagram of the Bohnenberger eyepiece, described by Airy as the 'nadir eyepiece' (after Airy, 1853:Plate XVI, fig. 32).

3.1.2 Azimuth Error

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

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

3.1.3 Collimation Error

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

3.2 Errors Which Affect Zenith Distance

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

3.2.1 Flexure

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

3.2.2 Zenith Point

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

4 CONSTRUCTION

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

4.1 The Telescope and Axis

One of the most important considerations in the design of a transit instrument is the rigidity of the joint between the telescope tube and the east–west mechanical axis. Troughton had achieved this in the design of the existing transit instrument, but Airy's proposed instrument was very much larger and heavier, and required a correspondingly massive construction. He settled for a central 'cube' constructed as part of the axis, to which the telescope half-tubes could be rigidly bolted: "I propose that the whole be made of cast-iron: the axis being in two parts (which enables the founder to make the pivots of hard chilled iron while the rest is of soft iron) and each end of the telescope being in one part".[7] Airy required the pivots, of diameter 6 inches and bearing length about 5 inches, to be perfect cylinders to within 1/30,000 inch; it was found impossible to achieve this accuracy by mechanical means, and each pivot required six weeks of 'hand-finishing'.[8]

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

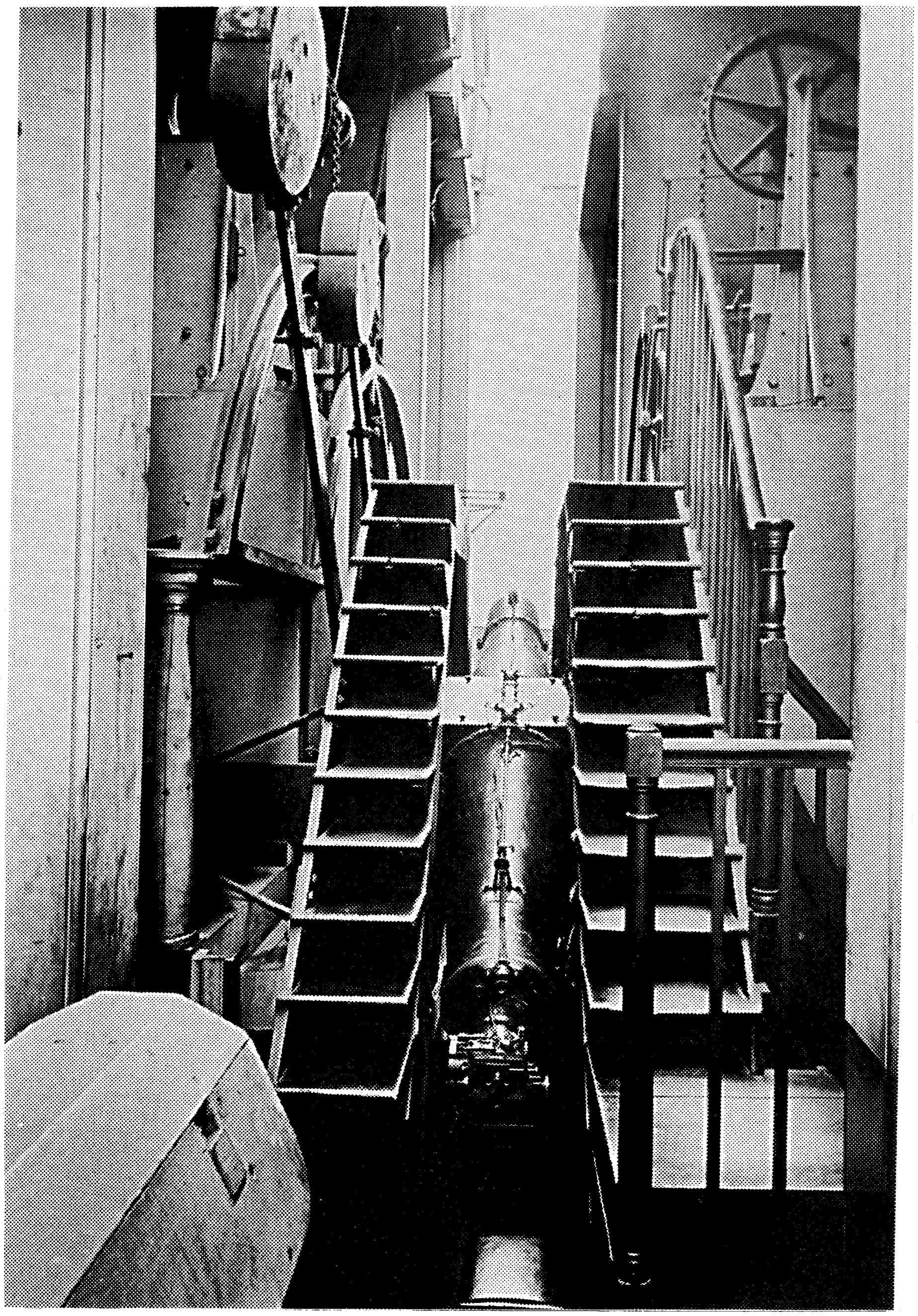

Figure 3. The Airy Transit Circle. The north collimator housing has been tilted to the east, a position that permitted observation of objects low on the meridian.

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

4.2 The Objective

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

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

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

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

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

4.3 Field Illumination

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

In 1908 a new field illumination system was fitted, in which light from a small, low-voltage electric lamp mounted on the centre of the objective illuminated a small, finely ground glass disk and was scattered uniformly down the axis of the telescope.[12] This provided a considerable advantage in that the intensity of the lamp could be controlled by the observer by means of a rheostat, and hence the field illumination could be minimized when observing very faint objects.

4.4 The Circles and Microscopes

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

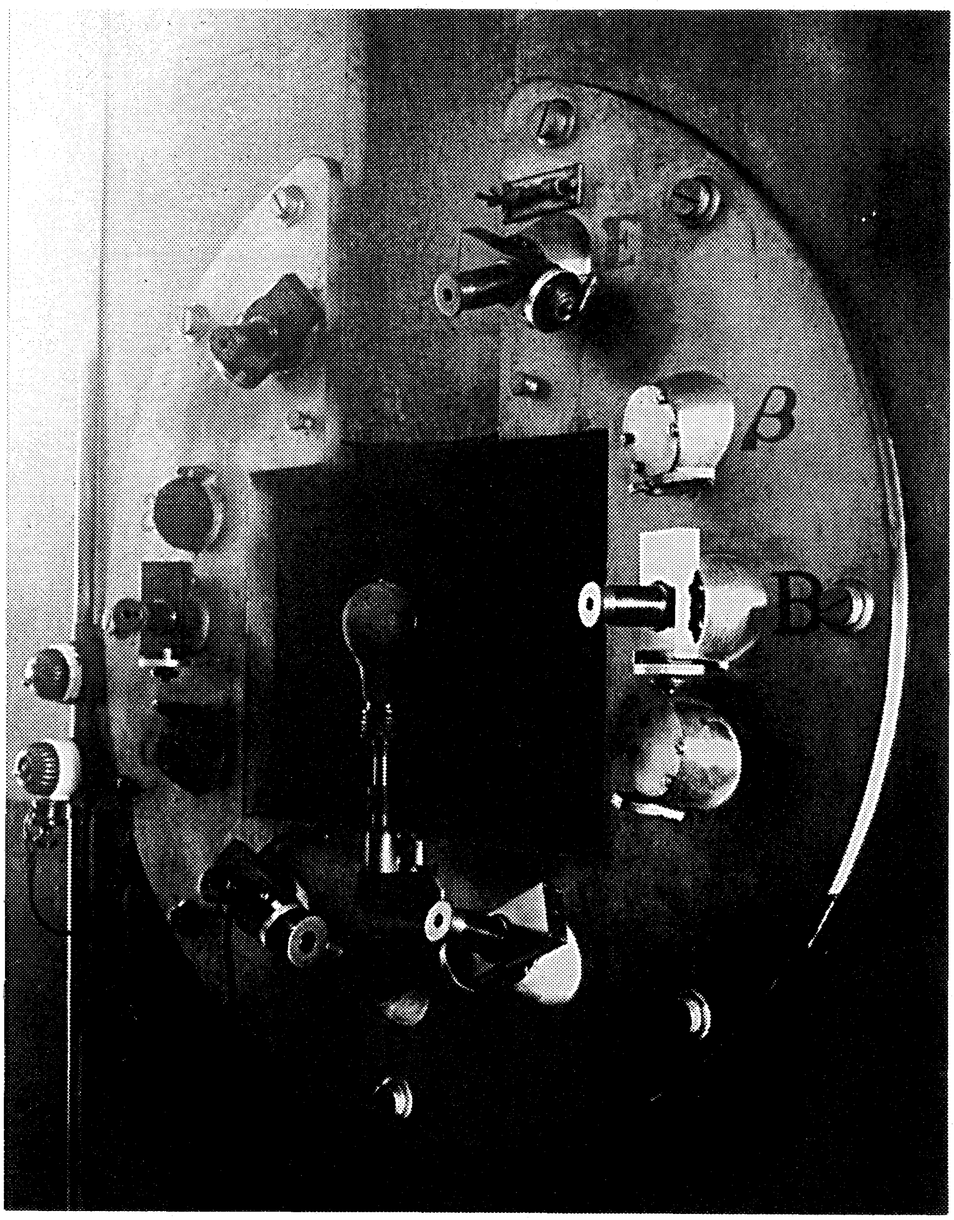

Figure 4. The six circle-reading microscopes and pointer microscope P. The single lamp illuminates the circle under each microscope.

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

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

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

4.5 The Eye-end Micrometers and Wire systems

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

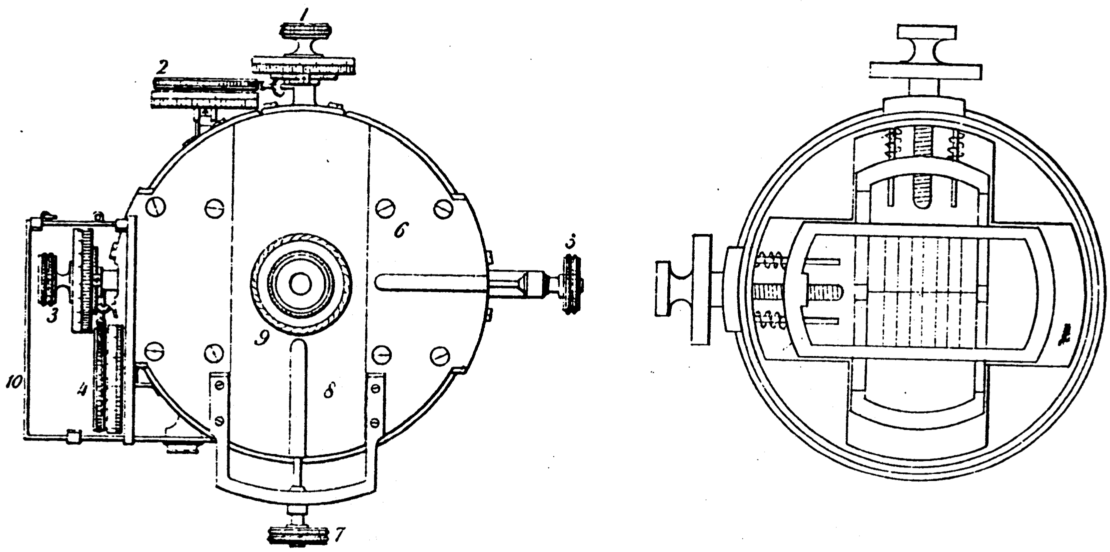

Figure 5. (a) The RA and ZD micrometer assembly. Note the provision to track the eyepiece across the field in both co-ordinates (after Airy, 1853:Plate XIV, Figure 7. See, also, Figure 8(a) below). Figure 5. (b) The wire-frame assemblies (after Airy, 1853: Plate XVI, Figure 27).

4.6 The Mercury Trough

Airy intended to observe stars with the TC both directly and by reflection, and therefore built into his design a mercury trough which could be used for this purpose, as well as for the determination of level and zenith point errors as described above. The trough was mounted on two iron bars in a parallel motion assembly which ensured that it was horizontal when used with the telescope at any altitude setting. The weight of the trough was counterpoised by large oval weights carried at the upper ends of the bars (see Figure 3), and a cistern was mounted at the north end of the pit to store and supply the mercury. An alternative position for a small mercury trough for use with the telescope in the nadir position was also provided, located beneath a removable panel in the floor of the pit.[14]

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

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

4.7 The Collimators

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

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

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

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

4.8 The Pavilion and Piers

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

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

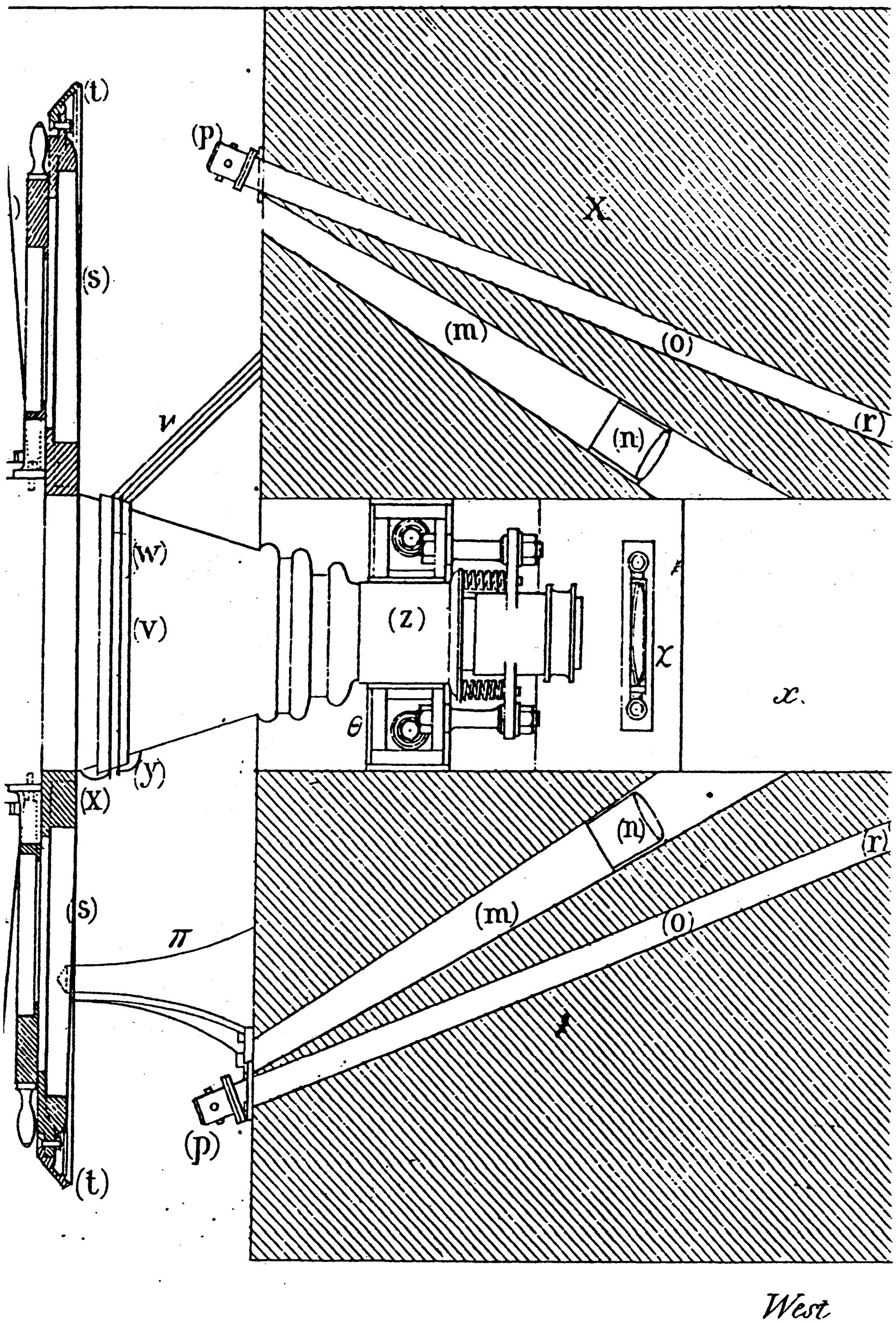

Figure 6. Section-plan of the western pier, showing the borings containing two of the circle-reading microscopes and illumination channels (after Airy, 1853:Plate XI).

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

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

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

5 MODIFICATIONS AND REPAIRS

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

5.1 Recording ZD Micrometer

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

5.2 Electrical Recording of Transits

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

5.2.1 Airy's Barrel Chronograph

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

5.2.2. The Impersonal Micrometer

This was probably the most important modification made to Airy's instrument. In 1915 the entire eye-end of the telescope was replaced with one incorporating a moving-wire micrometer.[28] In the new micrometer the transit wire-frame carried a single wire which could be traversed across the field by smoothly rotating a two-handed drive spindle. By rotating the spindle at an appropriate rate the star's image was kept bisected by the moving wire and the instants when it passed certain predetermined positions in the field were recorded automatically by electrical pulses sent to the chronograph from a contact-ring attached to the micrometer head. The pulses were sent in sets of three per revolution of the micrometer drum, with a longer gap between sets. Figure 7 shows a small section of a barrel chronograph record. Compare the rapid motion of the near-equatorial star ε Serpentis (Dec. +4°) with stars of much higher declination, for example 51°2107.

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

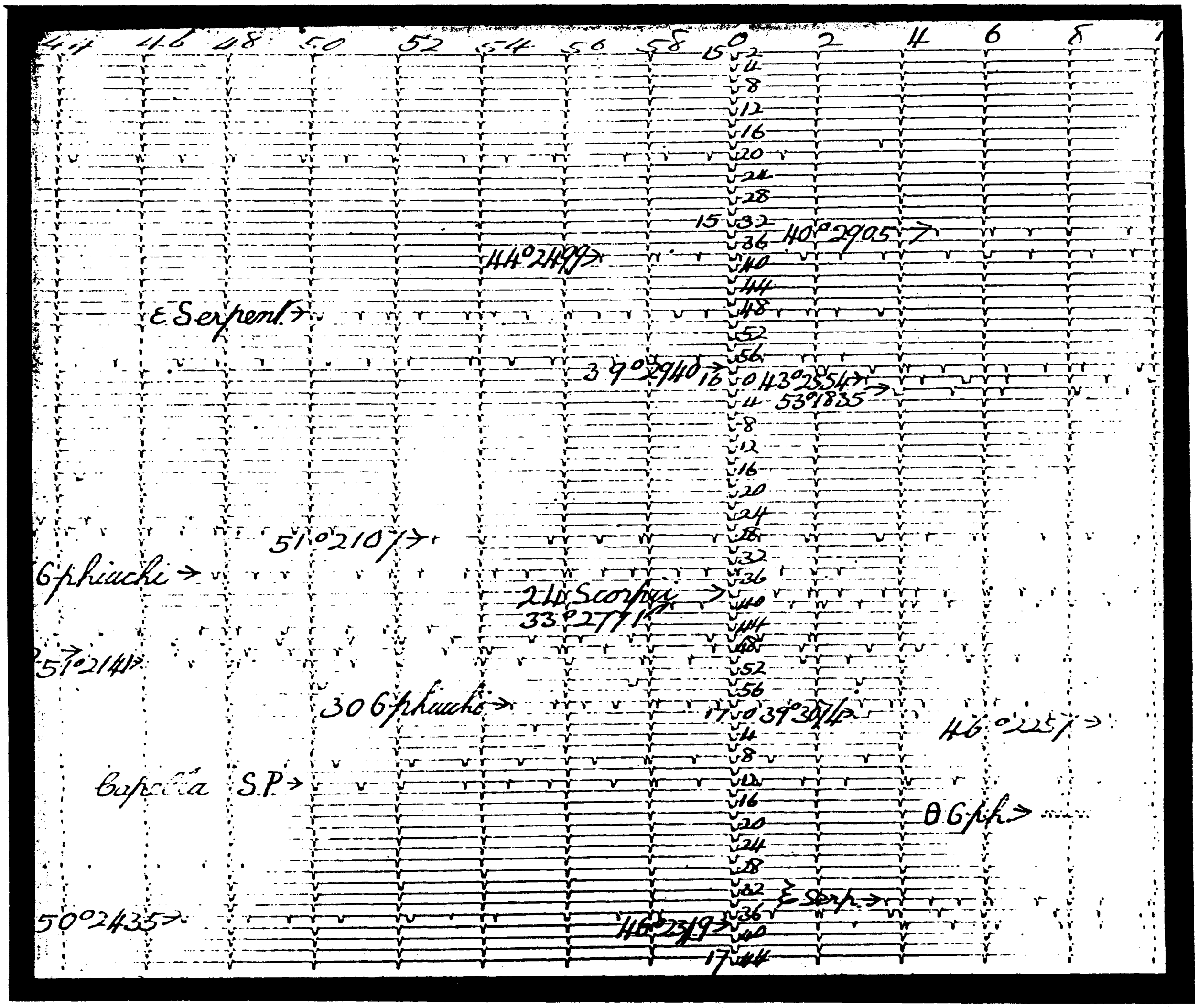

Figure 7. A small section of a barrel-chronograph sheet, with the recorded star transits and sidereal time pulses identified.

5.2.3 Tape Chronographs

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

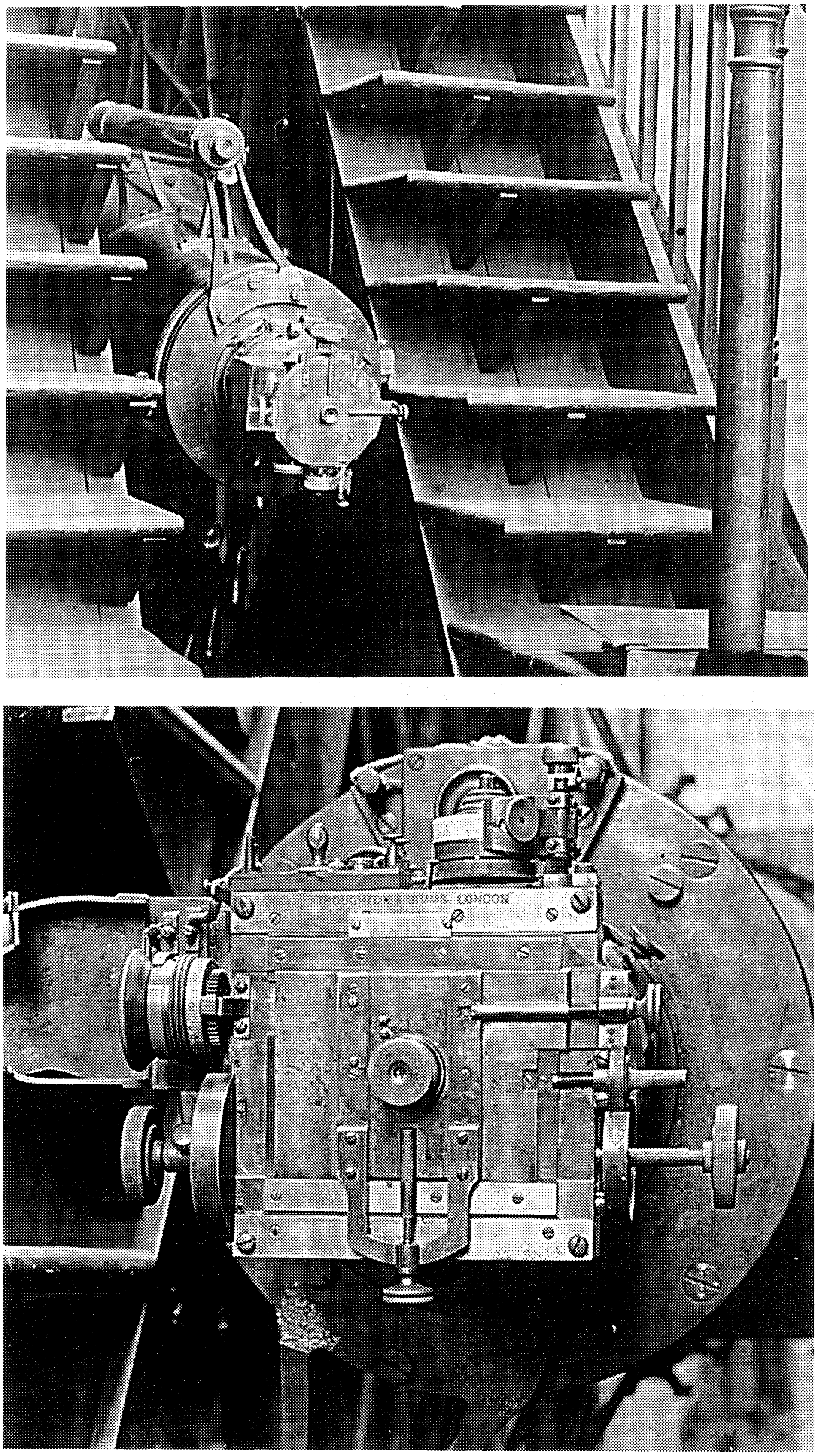

Figure 8. (a) The former eye-end. (b) The new eye-end with the impersonal micrometer (left) and recording ZD micrometer (top). The two-handed drive spindle can be seen below.

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

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

5.3 Accidental Damage

5.3.1 A Chain Failure

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

5.3.2 War Damage

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

5.4 Bearing Problems and a Sinking Pier

5.4.1 New Bearings

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

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

5.4.2 Subsidence of the Eastern Pier

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

6 OBSERVATIONS WITH THE ATC

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

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

6.1 Methods of Observation

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

6.1.1 Right Ascension Determinations

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

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

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

6.1.2 Zenith Distance Determinations

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

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

6.2 Observing Procedures

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

Only part of the wire system is visible through the eyepiece at any one time; the eyepiece is tracked across the field automatically as the transit micrometer is turned so as to keep the transit wire always central in the field. The wires were known by the numbers shown; the former meridian wire '4' was removed in 1919 (see section 5.2.2 above). Note that the field wires were numbered in the observed direction of motion of the star, so that the wire here shown as wire 1 would be wire 7 for a star observed with the telescope facing north. The intervals between the fixed wires are equivalent to six revolutions of the RA micrometer; an ideal transit observation was made over the central six revolutions from wire 3½ to wire 4½. One revolution of the transit micrometer represents 36″.960, equivalent to $2^s.464$ of sidereal time.

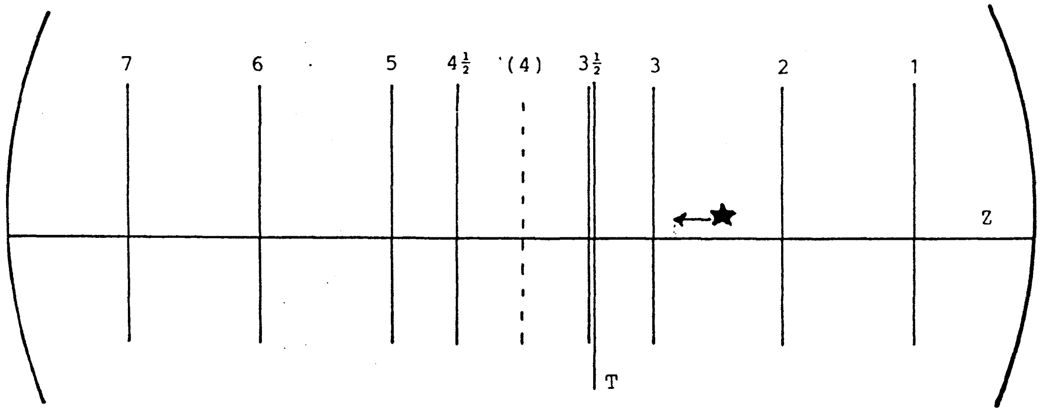

Figure 9. The ATC wire system.

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

6.2.1 Observing a Star

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

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

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

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

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

6.2.2 Observing the Sun

For a full observation of the Sun transits are required of the preceding (1L) and following (2L) limbs, and three ZD taps on each of the north (NL) and south (SL) limbs. The procedure is: (i) set TC for the centre of Sun; (ii) observe transit of 1L from wires 3½ to 4½; (iii) reset TC for north limb; (iv) set wire Z tangential to limb and tap at wires 1, 2 and 3; (v) reset TC for south limb; (vi) set Z tangential to limb and tap at wires 5, 6 and 7; (vii) reset TC for centre of Sun and observe transit of 2L from wires 3½ to 4½. As it is necessary to read the circle micrometers twice, at stages (iii) and (v), a second observer is required to assist by 'reading the mics'.

6.2.3 Observing Planets and Minor Planets

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

6.2.4 Observing the Moon

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

6.3 Personal Equations

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

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

6.4 First and Last Observations with the ATC

6.4.1 The First Observations

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

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

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

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

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

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

(a)

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

(b)

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

6.4.2 The Last Observations

The final observations with the ATC were scheduled for 1954 March 31, when appropriately the duty observer would be the Head of the Meridian Department, L S T Symms, who had joined the RO as a supernumerary computer in 1913 and became an established Assistant and a transit circle observer in 1921. Unfortunately history repeated itself and he was prevented from observing by bad weather, thus giving the writer the honour of having made the last observations on the previous day. These were of the Sun, Venus, Jupiter, Pallas, and Juno, together with the necessary clock and azimuth stars (Figure 11). The last published observation was that of Pallas; the last transit observed was of the fourth magnitude clock star o Leonis (see Figure 12).

GREENWICH TRANSIT-CIRCLE OBSERVATIONS, 1954. A 15

MAJOR PLANETS

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

(a)

GREENWICH TRANSIT-CIRCLE OBSERVATIONS, 1954. A 17

MINOR PLANETS

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

(b)

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

6.5 Some Noteworthy Observations

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

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

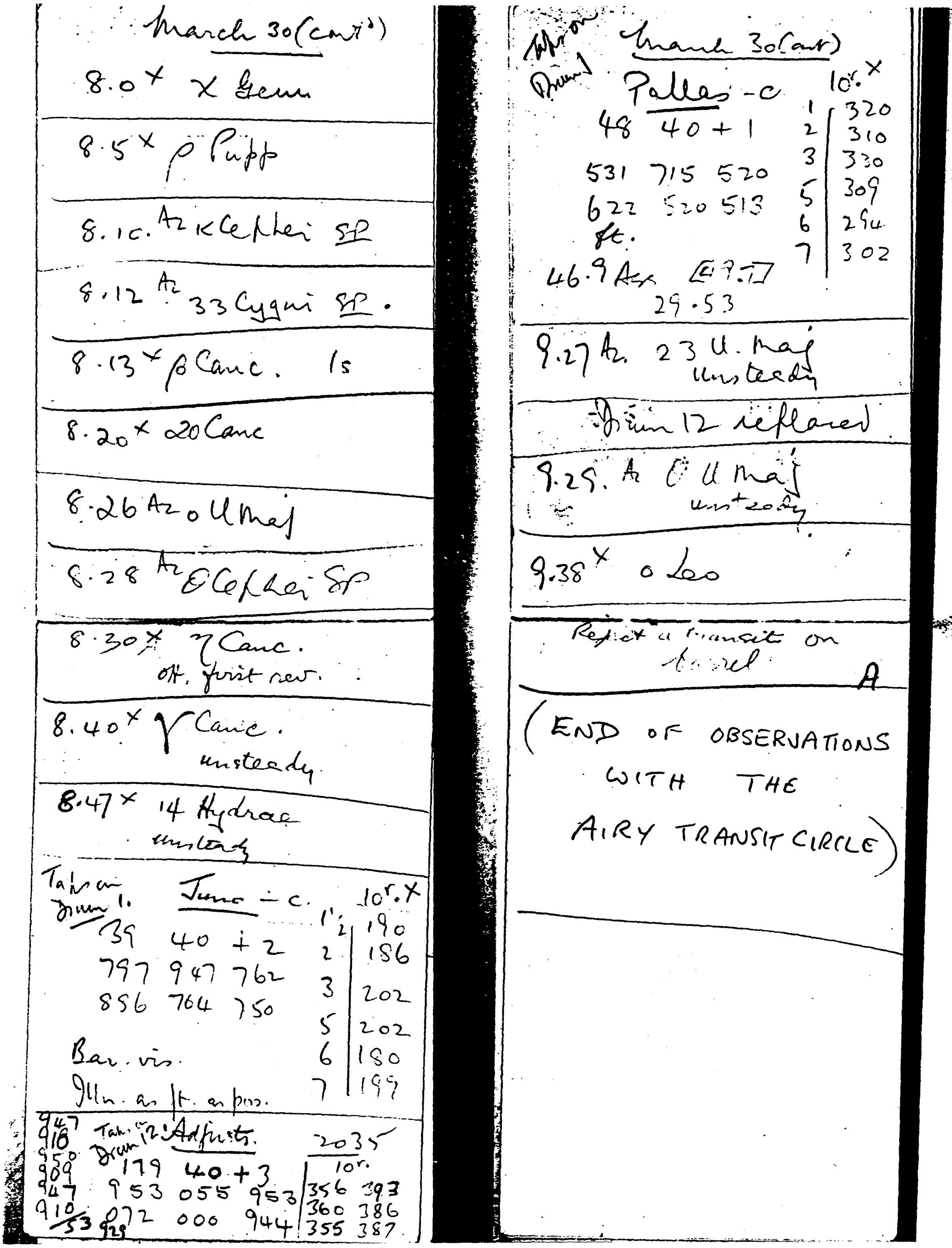
March 30 (cont'd)
8.0x χ Gem
8.5x ρ Pupp
8.10 Az κ Cephei SP
8.12 Az 33 Cygni SP.
8.13x β Canc. 1s
8.20x 20 Canc
8.26 Az o UMaj
8.28 Az ε Cephei SP
8.30x η Canc. Ott. first rev.
8.40x γ Canc. unsteady
8.47x 14 Hydrae unsteady
Juno - c. 10r.x
39 40 + 2
797 947 762
856 764 750
Bar. vis.
March 30 (cont)
Pallas - c 10r.x
48 40 + 1
531 715 520
622 520 513
9.27 Az 23 U. Maj unsteady
Drum 12 reflared
9.29 A U Maj unsteady
9.38x o Leo
A
(END OF OBSERVATIONS WITH THE AIRY TRANSIT CIRCLE)

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

Witchell also recounts that "an exercise in agility, occasionally performed, was the observation of γ Draconis (zenithal at Greenwich) with the Transit Circle and with the adjacent Reflex Zenith Tube by one and the same observer at the same culmination. The star passed through the field of view of the latter telescope in less than forty seconds, and this interval could just be spared from the larger instrument, situated about five yards to the east, still leaving time for a planned symmetrical transit observation to be made."

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

6.6 Statistics

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

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

7 PROGRAMMES CARRIED OUT WITH THE ATC

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

7.1 Time Determination

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

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

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

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

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

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

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

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

7.2 Observation of Solar System Objects

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

7.3 Stellar Observations

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

Table 1. Catalogues based upon ATC observations.

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

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

7.4 Contributions to Major Investigations

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

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

7.4.1 The Final Investigation

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

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

8 CONCLUSION

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

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

The Carlsberg RTC built for the Copenhagen University Observatory in 1952 was developed from the Greenwich RTC design; this instrument was completely reconstructed and transferred to the island of La Palma in 1984, where it is now operated as the Carlsberg Automatic Meridian Circle (MC). Fully computer-controlled, it operates entirely automatically, selecting the objects to be observed from its built-in working catalogue, setting itself to the correct ZD at the appropriate time, carrying out the observation and transmitting the data straight to computer. The productivity of such an automated instrument in the clear skies of the Canary Islands is so great that the Carlsberg AMC passed the total number of observations made in 103 years with the ATC in about seven years! One feels Airy would have been impressed.

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

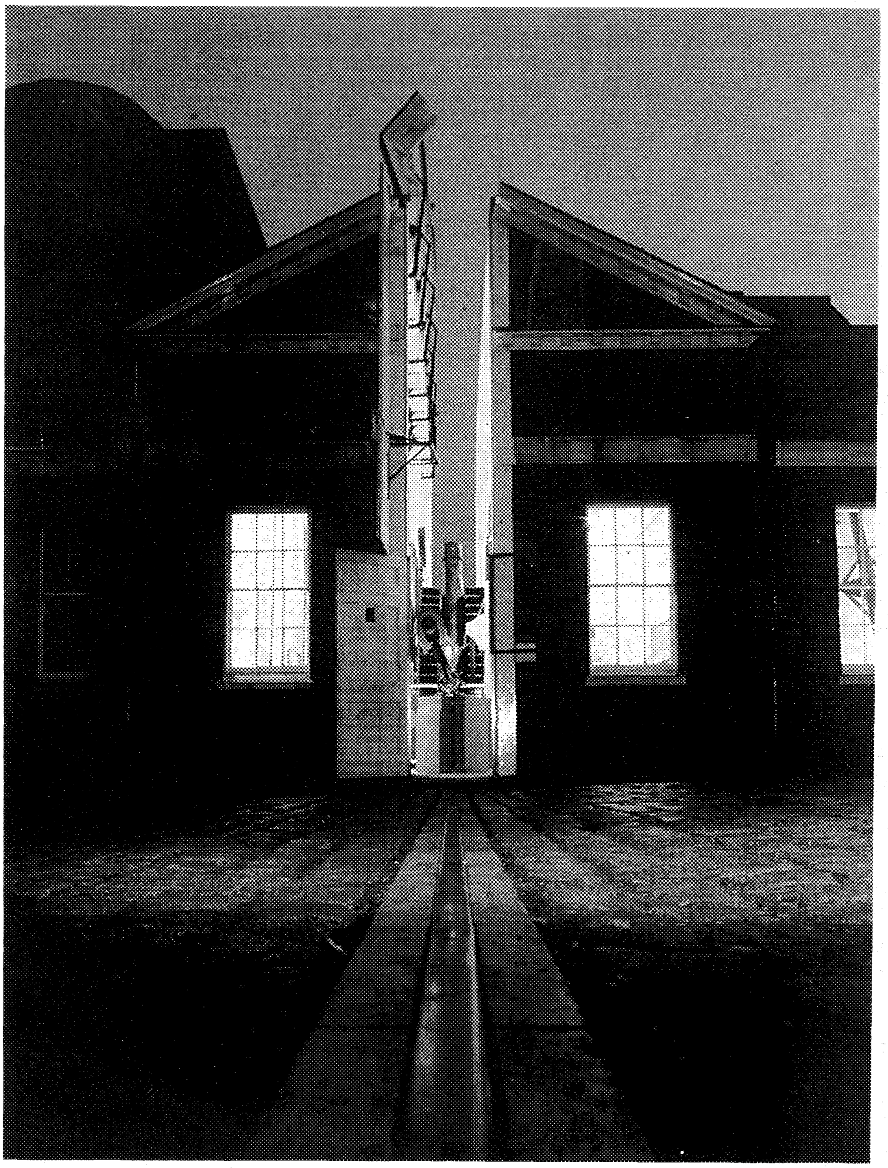

Figure 13. The Airy Transit Circle as it appears today, seen from the courtyard.

9 ACKNOWLEDGEMENTS

The research upon which this paper is based has been carried out over many years, and the writer wishes to acknowledge the help of many more people than can be listed here. He particularly wishes to acknowledge his debt to former colleagues at the RO, Phillip Gething, Andrew Murray, and the late L S T Symms and Phil Laurie. At the National Maritime Museum Gloria Clifton, Maria Blyzynsky, Jonathan Betts and Emily Winterburn have greatly assisted my research, as did the late Derek Howse. Allan Chapman of Wadham College, Oxford, who knows more about Airy than anyone else I know, has always been unfailingly helpful and encouraging. I have been much helped also by Peter Hingley, Librarian of the Royal Astronomical Society; Adam Perkins, RGO Archivist at the Cambridge University Library; and among many colleagues at Imperial College I would especially mention Chris Dainty, Jonathan Maxwell, and Andy Warwick.

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10 NOTES

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

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

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

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

11 REFERENCES

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

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

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

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

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

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

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

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

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

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

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

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

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

Dunkin, E., 1865. On some Peculiar Instances of Personal Equation in Zenith Distance Observations. *Monthly Notices of the Royal Astronomical Society*, **25:**215-216.
Dunkin, E., 1869. On Personality in Observing Transits of the Limbs of the Moon. *Monthly Notices of the Royal Astronomical Society*, **29:**259-268.
Fricke, W. and Kopff, A., 1963. Fourth Fundamental Catalogue (FK4). *Veröffentlichungen des Astronomischen Rechen-Instituts, Heidelberg*, nr 10.
Gething, P.J.D., 1954. The Collimation Error of the Airy Transit Circle. *Monthly Notices of the Royal Astronomical Society*, **114:**415-432.
Howse, H.D., 1975. *Greenwich Observatory*, vol. 3: *The Buildings and Instruments*. Taylor & Francis, London.
Howse, H.D., 1980. *Greenwich Time and the Discovery of the Longitude*. Oxford University Press, Oxford.
Jones, H. Spencer, 1939. The Rotation of the Earth, and the Secular Accelerations of the Sun, Moon and Planets. *Monthly Notices of the Royal Astronomical Society*, **99:**541-558.
Jones, H. Spencer, 1941. The Solar Parallax and the Mass of the Moon from Observations of Eros at the Opposition of 1931. *Monthly Notices of the Royal Astronomical Society*, **101:**356-366.
Kopff, A., 1937. Dritter Fundamentalkatalog des Berliner Astronomischen Jahrbuchs (FK3). *Veröffentlichungen des Astronomischen Rechen-Instituts, Berlin*, nr 54.
Lowne, C.M., 1981. The Object Glass of the Airy Transit Circle at Greenwich. *Observatory*, **101:**43-50.
Maskelyne, N., 1799. *Astronomical Observations made at the Royal Observatory, Greenwich, from the year 1787 to the year 1798,* vol. III, p.339.
McCrea, W.H., 1975. *The Royal Greenwich Observatory*. Her Majesty's Stationery Office, London.
Newcomb, S., 1906. *A Compendium of Spherical Astronomy*. Macmillan, New York; reissued 1960, Dover Publications, New York.
R.A.S.Council, 1851. *In:* Report of the Council. *Monthly Notices of the Royal Astronomical Society*, **11:**94-99.
Satterthwaite, G.E., 1995. *The History of the Airy Transit Circle at the Royal Observatory, Greenwich.* MSc Dissertation, University of London.
Satterthwaite, G.E., 2001. Airy and positional astronomy. *Journal of Astronomical History and heritage*, **4**:101-113.
Schaffer, S., 1988. Astronomers Mark Time: Discipline and the Personal Equation. *Science in Context*, **2**(1):115-145.
Smart, W.M., 1962. *Text-Book on Spherical Astronomy* (fifth edition). Cambridge University Press, Cambridge.
Stone, E.J., 1866. On Personal Equation in Reading Microscopes. *Monthly Notices of the Royal Astronomical Society*, **26:**48-51.
Symms, L.S.T., 1953. Observations of the Old Meridian Mark at Chingford. *Observatory,* **73:**250-251.
Thackeray, W.G., 1899. The Greenwich Meridian Observations of Polaris, 1836-1893, with reference to Personality, the value of the Constant of Aberration, and the Star's Parallax. *Monthly Notices of the Royal Astronomical Society*, **59:**345-351.
Witchell, W.M., 1934. The Old Azimuth Pillar at Chingford. *Observatory*, **57:**283-264.
Witchell, W.M., 1952. The Story of the Greenwich Transit Circle. *Occasional Notes of the Royal Astronomical Society,* **2**(14):21-33; also in bound volume, **2:**147-159.

Gilbert E Satterthwaite has recently retired from the Optics and Photonics Group of the Physics Department, Imperial College, London, but is currently retained on a part-time basis. He began his working life in the Meridian Department of the Royal Observatory at Greenwich, where he is still a volunteer consultant on the history of the RO and advises on the care of the old instruments, especially Airy's Transit Circle. In 2000 he was elected a consultant member of IAU Commission 41 (History of Astronomy).

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'Extraneous government business': the Astronomer Royal as government scientist: George Airy and his work on the commissions of state and other bodies, 1838-1880

Adam Perkins
Royal Greenwich Observatory Archivist, University Library, West Road, Cambridge CB3 9DR, U.K..
E-mail: ajp21@cam.ac.uk

Abstract
In the absence of a scientific civil service the governments of Victoria's reign had few public servants to consult when it came to the requirement for specialist scientific and technological advice – and this was at the height of the industrial revolution when the enormous changes wrought were affecting the whole population of Britain. So governments turned to one man of cast-iron probity and unparalleled credentials: George Airy. Though his formal scientific training was in mathematics and astronomy, not the engineering and thermodynamics that the industrial age might have called for, Airy gave of his time and energy to the full. But what were the purposes of the commissions? When did they sit? Who ran the Royal Observatory in Airy's absence? Only recently have the original papers in the RGO Archives been plumbed in any depth and the answers to these questions make an intriguing story.

Keywords: *Astronomer Royal, commissions of state, government science, Royal Observatory.*

1 INTRODUCTION: HISTORY AND BIOGRAPHY

The first result of research is the discovery that there is much more to the subject than the researcher had anticipated. Even given a background of 19 years familiarity with Airy and all his works, this was certainly the case with the present author and this paper. Close professional association with the Royal Observatory records means that few days pass without reference to George Airy's papers in Cambridge University Library. However, it was the research into the subject of this paper that amply demonstrated just what Airy had achieved in this sphere.

When the Royal Greenwich Observatory [RGO] was about to close at Herstmonceux and move to Cambridge in 1990, Sir William McCrea gave the last lecture to the joint RGO/Sussex University astronomical society that he had helped to found soon after the establishment of the astronomy institute at Sussex. He commented light-heartedly, though addressing a plain truth, "Sir George Airy single-handedly undertook duties fulfilling which today collectively occupies the resources of several entire research councils".

History is a continuous cloth; to look at the biography of one person is to take a small fragment of a different sort of material and hold it against the cloth from the broad loom. One must question how much holding the fragment against the seamless fabric tells you about the whole broad pattern around your patch of cloth; how well the patterns of the cloths match indicates how well the person fits into the character of his age. In some cases only a complete mismatch is achieved, of someone who clashes with the spirit and culture of their time. In the case of the seventh Astronomer Royal, George Biddell Airy, you find that the biographical fragment melds effortlessly into the broader pattern of his period.

No doubt it is a cliché to say that the nineteenth century was a period of unprecedented social, political, and technological change. Nevertheless this is the case. The end of the wars with France in 1815 ended the post-medieval modern era for Britain. The religious divisions of the sixteenth and seventeenth centuries were behind the country and no longer governed matters of state. These matters were taken as settled. The stirrings of the industrial revolution were already manifest with the primitive use of steam-power in the mines, the laying of tracked roadways for mine wagons, the smelting of metal by coal-fired furnaces, and the introduction of spinning and weaving machinery were harbingers of a new age. Erasmus Darwin and the luminaries of the Lunar Society were the fresh minds of this new age in what would in a few decades become the heart of industrial Britain.

George Airy, born shortly before Erasmus Darwin died, grew up in the years of the Napoleonic War; he was fourteen when the Battle of Waterloo settled European affairs of state for a century. In Britain the peace lead to social upheaval with the demobilization of the army and navy and the movement for the emancipation of the working man which was a background to Airy's Cambridge years. The 'Peterloo' massacre on St. Peter's Fields in Manchester at a meeting to promote the extension of the franchise occurred in 1819, the year that Airy went up to Cambridge. The foiling of the 'Cato Street' conspiracy took place in the following February.

Airy's family was not a wealthy one, his father being an excise collection officer. It was through George's uncle Arthur Biddell that George met Thomas Clarkson, the anti-slavery associate of William Wilberforce, who in turn introduced the very gifted young Airy to a fellow of Trinity College. Airy tells the story in his *Autobiography*,[1] a work described by an assistant from Airy's later period of office, Walter Maunder, as "... to anyone not personally acquainted with Airy ... heavy and monotonous".[2] This is a moot point and some disagree with Maunder, who was perhaps too personally close to his subject as he had been an assistant under Airy for eight years before the Astronomer Royal retired. Though indeed the *Autobiography* tells little of Airy as a person, it is an invaluable source that relates the activities of a remarkable career, as the endnotes to this paper amply demonstrate.

Thus Airy became a Cambridge mathematician and as a consequence of his studies, his profession became astronomy. In his university career he progressed from the Lucasian chair in mathematics, once held by Isaac Newton, to the Plumian chair in astronomy. Airy applied his mathematics to the sciences, was appointed Astronomer Royal, reformed every facet of the Royal Observatory to such an extent that his direct influence was remembered by staff still in post when the RGO was closed in 1998. Airy became something of an engineer in the design and construction of the Greenwich telescopes of his tenure and improved the regulators of the Royal Observatory. He was the astronomer *par excellence* of his day.

However this paper is not, by its very title, about Airy the astronomer but Airy the professional government scientist as he served the governments of his country. That Airy did not take the view his duties should include the 'nitty-gritty' work of nightly observation and daily reduction is well recognized. Allan Chapman has drawn our attention to Airy's attitude to his work and duty[3] and shows clearly that central to Airy's perception was the royal warrant of appointment to his office:

> Victoria, by the Grace of God of the United Kingdom of Great Britain and Ireland, Queen, Defender of the Faith. To our trusty and well beloved George Biddell Airy Professor of Astronomy in the University of Cambridge. We, being well satisfied of your learning and your industry and great skill and ability in the science of astronomy by these Presents constitute and appoint you Our Astronomical Observatory at Greenwich during our pleasure; requiring you forthwith to apply yourself with the most exact care and diligence to the rectifying the Tables of the motions of the heavens and the place of the fixed stars in order to find out the much desired Longitude at sea for perfecting the Art of Navigation ...[4]

For all but two years, Airy was Astronomer Royal under Queen Victoria. Victoria issued the last formal Royal Warrant for any Astronomer Royal; William Christie and his successors were offered the post of Astronomer Royal by the Admiralty without a warrant from the sovereign[5]. Airy had first been offered, and had provisionally accepted, the post of Astronomer Royal in 1834. A change of government had put the offer into abeyance but when the administration of Robert Peel took office the offer was once more made and then accepted by Airy[6].

Walter Maunder, the contemporary observer of Airy's *modus operandi* was not at all an uncritical observer. He assessed Airy's character in the following terms "It is most difficult to give any adequate impression of his far-reaching ability and measureless activity. Perhaps the best idea of these qualities may be obtained from a study of his autobiography ..." though Maunder goes on to call that volume, as already, noted "heavy and monotonous"[7]. It is worth quoting in the context of the Royal Observatory records some more of Maunder's remarks about Airy himself; "... great as Airy was, he had the defects of his qualities ... His love of method and order was often carried to an absurd extreme, and ... one of the greatest intellects of the century was often devoted to doing what a boy at fifteen shillings a week could have done as well, or better" and reports Wilfrid Airy's comment "in his last days he seemed to be more anxious to put letters ... into their proper place ... than even to master their contents"[8].

Wilfrid Airy also tells us of his father "In all his views and opinions he was strongly liberal ...", Wilfrid going on to cite two instances of Airy's opposition to religious bigotry in the University of Cambridge, and proceeds "... he was opposed to every kind of narrowness and exclusiveness ... But all his views were in the liberal direction ..."[9] which assessment might be compared to the comment by Maunder on Airy's personal administration of Greenwich Observatory in the words "his regulation of his subordinates was ... despotic in the extreme – despotic to an extent which would scarcely be tolerated in the present day ..." concluding that "A regime so personal ... was almost avowedly intended to militate against the growth of real zeal and intelligence in the staff ..."[10]

The assessment of Airy as "...one of the greatest intellects of the century ..." would bear some examination but in the context of Maunder's world is no doubt adequate. Maunder only briefly refers to the commissions of state and similar activities in his observations about Airy's work; he was an astronomer and Airy, by virtue of his position and abilities, one of the great astronomers of his age. But Maunder summarizes the extraneous work "... he was confidential adviser of the Government in a vast number of subjects: lighthouses, railways, standard weights and measures, drainage, bridges – he yet always kept the original objects of the Observatory in the very first place"[11] and makes another telling remark: "Airy had ... the true spirit of the public servant; his sense of duty to the State was very high. He was always ready to undertake any duty which he felt to be of public usefulness, and many of these he discharged without fee or reward".[12]

The royal warrant was all-important to Airy. The wording had barely changed since Charles II addressed his well-beloved John Flamsteed. To Airy the meaning was plain; he was to do what the governments of his day wanted him to do; it was a new interpretation of the warrant, but not by that token incorrect. Clearly, however, Flamsteed, Halley, Bradley, Bliss, Maskelyne, and Pond had not taken quite this view, or had assumed that the direction of the warrant was the literal interpretation, to undertake astronomical observations and reductions and the publication of tables of results, all for the betterment of navigation. Airy directed that this was the purpose of the foundation at Greenwich but did not apply that direction to his personal duties.

Flamsteed was perfectly clear about the meaning of the warrants of Charles II and Anne, the celebrated quarrel with Newton and Halley springing partly from that interpretation. Halley perhaps came to sympathize with Flamsteed's view when he took over at Greenwich and clearly Bradley and Bliss understood their duties in this way. Perhaps with Nevil Maskelyne we begin to see the work at Greenwich rather less as though it was prosecuted on an astronomical island. Much of Maskelyne's work he undertook in his *ex officio role* on the Board of Longitude, a body which had existed since Flamsteed's time but which Maskelyne found very important to his Greenwich operations. That work was still as specified literally in the warrants, however.

Working with inadequate funding and few staff all of whom do more than one job is not a new phenomenon. The story of the Astronomers Royal over the centuries is a case in point. Vital to the history of the development of the work at Greenwich in the nineteenth century is the trend begun by Pond and extended by Airy to increase the number of staff working at the Royal Observatory. Until Pond's time, Greenwich operated with the Astronomer Royal and his assistant, as laid down by another warrant of Charles II in 1675. If Maskelyne was away at a Board meeting, there was just one astronomer left at Greenwich. If Pond increased the staff working under him, he quite clearly remained of the opinion that his place was at Greenwich, however irksome he came to find the work.

The Board of Longitude remained in being until 1828 and as Plumian Professor at Cambridge, George Airy sat on the Board. Pond's relationship with the Board was different to Maskelyne's though the Board remained of great importance to the work at Greenwich until its dissolution. Airy observed the Astronomer Royal's relationship to the Board of Longitude but more importantly observed Pond's dealings with the Board of Visitors to the Royal Observatory, and these observations led to the way Airy, after his acceptance of the post of Astronomer Royal, approached his directorship.

While the Astronomers Royal before Pond were working in the pre-industrial age, at a pre-industrial pace, the social changes of the early part of the nineteenth century were responsible in part for the pressures that mounted on Pond. These tended to bear him down; there was the production of the almanac, the routine work on chronometers and the difficulties with his assistants, problems with administration and staff that are familiar enough to us today. There are distant echoes of the way there is now between research establishments and the universities the tension created by competition for funding, staff and projects and by fine professionals gradually diverting their energies away from their professional expertise into the administration of their establishments.

There are horses for courses. Pond's course was essentially laid down by Maskelyne and his predecessors but the tenor and requirements of his time meant that Pond began to alter the *modus operandi* of the Greenwich Observatory. Airy took up where Pond left off and forged a completely new course for Greenwich in the modern Victorian era, though Airy for one was always quite clear on how much the Royal Observatory owed John Pond.

Airy started as he meant to go on. Where Pond had been dragged down by the weight of care Airy, a younger, more dynamic and more forceful personality, was dealing from a position of strength. The government of the day positively wanted him in the post and his bargaining position was thus enhanced. Airy thrived on the modern way of proceeding. From this starting point, Airy made his own interpretation of the terms of the warrant; his duty was to direct his minions, to whom Pond famously referred as "drudges", to achieve this aim. The Astronomer Royal was above, or at any rate aside, from the daily astronomical work at Greenwich. So Airy took to be the direction of his sovereign Queen Victoria. James South wrote in a letter to the Admiralty in 1847 that of the 69,204 observations made at Greenwich between 1836 and 1844, only 164 had been made by Airy himself.[13] Which was just how Airy intended it should be.

This hardly left Airy at a loose end. He was a man of enormous industry, industry attested by only a casual inspection of the manuscripts stacks in Cambridge. A century and a half of the Royal Observatory's history, the papers of the Astronomers Royal from Flamsteed to Pond, occupies some 30 metres of shelving. Then Airy's papers begin and do not end for another 110 metres of shelving. The papers are contained in eight hundred and thirty-five substantial volumes of correspondence and papers associated with all aspects of the work at Greenwich and the work of George Airy. This includes copies of the complete outgoing as well as incoming correspondence and copies of all Airy's own work. To quote from the *Autobiography* "... having seen the utility of the Copying Press in merchants' offices, I procured one. From this time my correspondence, public and private, is exceedingly perfect",[14] though the perfection of the correspondence and papers arises directly from Airy's method rather than the copying press. It has been said that Airy was "methodical beyond belief".[15]

The offer of knighthood was made to Airy on several occasions before his accepting the honour in 1863; Airy had been offered this first on 1835 December 08, only a few months from taking over the Greenwich directorship and in his letter declining the offer written a couple of days later he made a telling remark in conclusion "I have only to add that my services will always be at the command of the Government in any scientific subject in which I can be of the smallest use".[16]

The new cataloguing of the papers at Herstmonceux undertaken in the 1980s naturally followed the archival 'best practice' of maintaining the contemporary arrangement of the original records. It needs little reflection to realize that to have tried to alter in some way Airy's arrangement of his Greenwich records would have been folly indeed; Airy was following 'best practice' one hundred and fifty years before the Herstmonceux archivists followed and put that same practice into operation. Airy's own arrangement of his records was maintained and few new readers of the papers fail to be amazed by the sheer size of the catalogue, let alone the actual collection.

This readiness on Airy's part to serve the government leads on to his involvement with the commissions of state. The appointment of commissioners arose out of the needs of governments in a more modern age and it was the time to be someone considered one of 'the great and good'. Airy was available as a government-employed scientist, yes; and social and technological history converged to make him the right man at the right time, a Cambridge educated academic as well as the Astronomer Royal, a practical man with knowledge of engineering. The needs for guidance in the fields of science and engineering by the governments of the industrial age were many.

The commissions had begun their history in the early years of the century and had advised governments on such subjects as working and living conditions in the new cities, sanitation and emancipation; they have since become a pillar of the prosecution of government in this country, as the complexity of society, science, and technology, and the cultural environment have increased.

Another of Allan Chapman's papers[17] illustrates much of this background. There was no scientific civil service, no research councils, no Department of Scientific and Industrial Research. From 1820 it had been the Admiralty who controlled the Royal Observatory, which was funded through the annual navy votes. The 'interface' between Airy's Greenwich and his government masters was the Hydrographer's Office. To this day, the Public Record Office in its institutional history of the RO and its offspring the Royal Greenwich Observatory takes the view that the Observatory was a department under the Hydrographic Office, until the RGO was transferred to the auspices of the new Science Research Council in 1965. Thereby hang other tales. Greenwich was unique in the Britain of the nineteenth century, and indeed of the seventeenth and eighteenth centuries, though they do not concern the subject of this paper, in being a government funded scientific establishment. It was not a research establishment, at least in Airy's time, but Airy was the senior 'scientific' civil servant – and his assistants were the only others of the day.

Airy filed away the warrants of George IV and Victoria in their proper places in the early portion of the seven volumes, about two feet of shelf-space, which Airy classified as *Government superintendence*, essentially how he dealt with his masters at the Admiralty and how the Admiralty dealt with the Royal Observatory. Seven, even hefty, volumes are not such a great deal for 46 years of 'superintendence' – six or seven years per volume. The Admiralty was hardly breathing down Airy's neck, issuing continual orders to the Observatory and Astronomer Royal. What the Admiralty wanted was someone who would get on with the job without requiring too much superintendence.

Perhaps it would be more apt to say 'jobs'. The "extraneous government business" and the subjects covered by this paper Airy classified under other titles:

Volume titles	Range of dates	Classmarks
Railway Gauge Commission	1845-1848	MSS.RGO.6/284-321
Metropolitan Commission of Sewers	1846-1849	MSS.RGO.6/322-324
Ordnance Survey Commission	1858	MS.RGO.6/325
Lighthouse Commission	1860-1861	MS.RGO.6/326
Sale of Gas Act	1858-1863	MSS.RGO.6/327-334
University of Melbourne	1854-1856	MSS.RGO.6/335-336
University of Sydney	1851-1852	MS.RGO.6/337
Standards Commission	1838-1857	MSS.RGO.6/338-367
Great Exhibition of 1851	1850-1852	MS.RGO.6/441
Paris Exhibition	1854-1857	MS.RGO.6/442
Extraneous government business	1854-1880	MSS.RGO.6/443-445
International Coinage Commission	1852-1868	MS.RGO.6/446
Gold Standard Table - Bank of England	1870	MS.RGO.6/447
Railways	1840-1848	MS.RGO.6/448
Steam engine propellers, ship building	1838-1848	MS.RGO.6/449
Sawmills for ship's timbers	1842-1849	MS.RGO.6/450
Atlantic submarine cable	1858	MS.RGO.6/455
Greenwich charities/Blue Coats School	1839-1878	MSS.RGO.6/492-498
Tidal harbour commission	1839-1842	MSS.RGO.6/499-518
Navigation on the River Dee	1849-1853	MSS.RGO.6/519-522
Construction of the Westminster Clock	1845-1861	MS.RGO.6/607-609
Compass correction in iron ships	1838-1875	MSS.RGO.6/682-692
Meteorological commission	1875-1878	MS.RGO.6/704

This adds up to 212 pieces, whilst the total in whole Airy class is 835 pieces, indicating that this business occupies papers equivalent to about 25% of the Royal Observatory record over his tenure in office, 1835-1881.

In the words of Sir William McCrea "Airy became the national oracle on all technological matters".[18] Allan Chapman has estimated that Airy served upon or gave advice to at least three dozen commissions and government inquiries of a non-astronomical character during his 46 years as Astronomer Royal.[19] To pursue the theme of how the 'percentage of effort expended' by Airy has been regarded previously, it should be noted that in his short account of the Royal Observatory, McCrea (a celebrated and gifted astrophysicist) devotes nine pages to Airy's tenure of office and only a few lines to his work on the commissions, other bodies and the extraneous work. Professor Jack Meadows[20] hardly mentions the work and a later Astronomer Royal, Sir Harold Spencer Jones[21] only briefly refers to all this effort, which demonstrates how Airy's work on behalf of his country, but away from Greenwich, has not always been fully recognized.

There are several matters to note from this list with its huge range of activities. There is the span of dates, almost from Airy's appointment until his retirement, at least forty years of continual effort in fields that were not directly connected with, or were quite unconnected with, the astronomy done at Greenwich. Consequently this miscellaneous collection of subjects made a miscellaneous set of demands on Airy's time and ability.

Airy's concerns in his first years of office were however directly related to Greenwich and the associated work. He established the observing procedures he required, provided for the regular and retrospective reductions to be tackled, and looked to the printing of Groombridge's catalogue. There was the matter of the testing of chronometers and agreement with the Admiralty on the priority of the work as well as the new magnetic and meteorological observatory. In addition, the manuscripts had to be put in order and a place made for them while in Cambridge there was the University Observatory and the work on completion of the Northumberland Telescope which Airy wanted to oversee, as well as the work of the observatory at the Cape of Good Hope. All these required his attention and this work occupied the first years of his tenure to 1838.

Perhaps by this date the writing was on the wall. In fact it was an enquiry from Thomas Maclear at the Cape Observatory to the Admiralty that was the connecting thread from astronomy, to geodesy, to the standards commission. Captain Francis Beaufort of the Hydrographic Office passed to Airy Maclear's request for a standard of length to be used in the trigonometric survey of southern Africa. Airy wrote to Charles Wood, the Secretary to the Admiralty on 1838 March 13 pointing out that the national standard of length was wanting.[22] The answer brought Airy closer to an appointment as a commissioner.

With Airy working so much away from the Observatory on government work, selection is necessary in such a brief study as this. Only some aspects can be considered. The remainder of this paper will examine the following; (a) the work; (b) the records; and (c) the conclusions of two important commissions, first the standards of weights and measures commission and second the railway gauge commission. Reference will also be made to some of the other commissions of lesser importance, though Airy gave his fullest attention to the detail of every study he carried out for the governments of the day.

2 THE STANDARDS COMMISSION

With the exchange of correspondence over Maclear's enquiry, the wedge had its thin end inserted into Airy's work of astronomical superintendence in 1838. On May 11[23] Mr Spring Rice[24] wrote to Airy to ask him to be the chairman of the committee being established to report on what should be done to restore the national standards of weights and measures, which had been destroyed in the fire at the Houses of Parliament on 1834 October 16. Airy received the letter the next day[25] accepted and, in the manner of the times, did not let the matter hang on his hands. Just ten days later the commission of Airy as chairman, Francis Baily, J E Drinkwater Bethune, Davies Gilbert, J G S Lefevre, J W Lubbock, G Peacock and Richard Sheepshanks[26] had their first meeting.

A significant source of information on the extent of Airy's work extraneous to the functions of the Observatory are the four *Astronomer Royal's Journals* which Airy kept, covering the years 1836-1881, his complete period in office.[27] It is salutary to quote from the

Journal for the day of this first meeting as it is so characteristically Airy speaking: "May 22 Tuesday Rain in the morning, fine in the evening, wind W. A meeting of the Standards Commission was held at the Observatory".[28]

The commission began a prodigious amount of work, mainly meeting at the Royal Astronomical Society, with Airy not only Chairman but "as working secretary".[29] The recommendations of the commission were enacted on 1855 July 30[30] but Airy's related work went off and on for thirty-eight years in all, until 1876, and the international commission on the metre.[31]

The records consist of the official correspondence and minutes of the commission,[32] correspondence with commission members,[33] correspondence on the 'decimalization' of weights and measures,[34] general correspondence on standards,[35] acts of parliament,[36] the papers of Airy, Francis Baily, Richard Sheepshanks, and others on comparisons of length,[37] formal printed accounts of the work,[38] work on decimal coinage[39], thermometer experiments[40] and further official and semi-official correspondence.[41] Airy gives a full account of the work in the *Philosophical Transactions* for 1857.[42] It was Airy's involvement with the standards and particularly that work recorded on decimal coinage that lead William Gladstone to ask for his advice to the Coinage Commission in 1853,[43] an example of how the cycle of Airy's involvement in giving governments advice was perpetuated.

It is worth noting that after discussions early in 1838, by July Airy had at the instance of Beaufort, the Hydgrographer, begun his intensive series of experiments and calculations on the effects of iron hulls on ships' compasses using the iron built steamer *Rainbow*[44] owned by the General Steam Navigation Company. Again the work involved was rigorously conducted, vigorously prosecuted and protracted, taking place at much the same time as the standards work between 1838 and 1855.[45]

In his obituary of Airy,[46] H H Turner notes that the work of the commission "... included the preparation and comparison of a large number of copies of the standards for distribution to public bodies in England and to foreign Governments, thus securing the legal standards against future loss from any possible accident to the national standards".[47] A second standards commission under Airy's chairmanship was appointed in 1843 and it must be noted that much of the practical work on the actual determinations and the production of copies was the work of W H Miller, who worked on the standard of weight, and Francis Baily who was engaged on the length standard. Sir John Herschel relates that Baily had copied the standard yard by John Bird of 1758 onto a five feet scale for the Royal Astronomical Society six months before the disastrous fire of 1834[48] and before his death in 1844 Baily had expended much effort in recreating the standard. Richard Sheepshanks took over the work that Baily had commenced and made nearly ninety thousand measurements in the basement of the Royal Astronomical Society at Somerset House in perfecting the standard before 1855.[49]

Much was happening in England, Europe, and the wider world and it is suitable at this point to recall once more the historical context of Airy's work. That it was a time of great technological change, the age of the 'Industrial Revolution', can be seen plainly from the list of titles of the commissions. That Spring Rice first communicated with Airy about the Standards commission is significant enough, though given the role of the Astronomer Royal it was not unlikely that Airy would be at the least consulted on the subject of mensuration and standards. The tenor of the times really resounds in the subject matter of this paper with Airy's appointment to the royal commission on the railway gauge.

3 THE RAILWAY GAUGE COMMISSION

An interesting note is made by Airy in his journal for 1836 February 4; "Returned to Greenwich [from Cambridge]. In the evening wrote a report to the Admiralty upon the railroad".[50] The interest in this note stems from it demonstrating that Airy was considering the subject and using his official position to communicate on the subject of the railways, or at least the roadways themselves, only a few months after taking office and nearly ten years before the gauge commission was convened. At this date, Airy was plainly thinking about the effect that the vibrations from the trains passing over the railroads proposed for the environs of Greenwich Park would have on the Royal Observatory instruments,[51] but nonetheless the connection was made in some government mind between the Astronomer Royal and the railways.

The *Autobiography* relates that Lord Dalhousie, then President of the Board of Trade, approached Airy about his membership of the commission to enquire into the two different permanent way gauges employed in this country. On the one hand the Great Western Railway used the broad, seven feet, gauge while on the other the rest of the country's railways used a gauge of 4 feet 8½ inches. The difference of the gauges being, in Airy's words, "... of enormous inconvenience to the public".[52] Of the proposal to him Airy wrote "The Government determined to interfere ... I would act as second ... [with] Col. Sir Frederick Smith [and] Prof. Barlow ... I assented to this: and very soon began a vigorous course of business." Smith had been the Inspector General of Railways; Peter Barlow was professor of mathematics at the Woolwich military academy and the commissioners were appointed on 1845 July 9, a day on which Airy notes he saw Lord Dalhousie himself.[53]

Dalhousie plainly had confidence in Airy's ability to absorb extra responsibilities, and well-placed confidence it was. On the previous April 5 Airy had begun work with the tidal harbour commission, the first report of which is dated July 21, in the middle of the initial flush of activity with the railway gauge commission, and on the day Airy saw Dalhousie about the gauge commission he had earlier attended a meeting of the harbour commission.

There are still divided opinions about the rights and wrongs in deciding what was the better standard gauge for Britain's railways. Isambard Kingdom Brunel is an engineer and character who opposed the steam-roller of government and has his personal champions rather in the way that Barnes Wallis, another engineer who has challenged and opposed the received opinions of his day, is championed. A biographer of Brunel, L T C Rolt comments of Airy and Barlow "... the other two seem somewhat oddly chosen ... But ... it would have been impossible to find a distinguished engineer who was not an interested party".[54] Rolt continues "Knight, astronomer and mathematician, set to work with a will, devoting thirty days to the protracted examination of 48 witnesses, a total which included such seemingly irrelevant characters as Her Majesty's Inspector General of Fortifications".[55]

One thing to note from the archival record is the immense amount of effort and detail of examination that went into what was, after all, a small commission of three people. There are thirty-eight large volumes of correspondence and records relating to the gauge commission in the Airy papers of the Royal Greenwich Observatory Archives. All this was the labour of the three commissioners working, without the customary modern secretariat. The volumes commence with the commission correspondence,[56] continue with the written and printed minutes of interviews,[57] railway company replies to circulars,[58] correspondence and papers supplementary to the interviews,[59] booklets and printed material in support of one or other of the parties,[60] maps,[61] further booklets,[62] a G.W.R. directors' report,[63] related acts of parliament,[64] and further minutes, correspondence, circulars, and booklets.[65]

Though the taking of evidence took up the first intense work period of the commissioners a practical demonstration, in the form of a contest between a broad gauge and a narrow gauge locomotive that Brunel proposed, gave a rather comic turn to the proceedings. Rolt suggests that "Evidently this challenge appealed to the sporting instincts of the commissioners for they agreed ..."[66] to the contest. The broad gauge locomotive *Ixion* on a course between Paddington and Didcot returned an average speed of 53.9 m.p.h. hauling 60 tons whilst a narrow gauge locomotive running between Darlington and York could only manage a maximum speed of 53¾ m.p.h. pulling 50 tons.

On 1846 January 1 another narrow gauger named *Stephenson* ran off the rails during its run and a modern commentator on the event, E L Ahrons, has quipped "...the astronomer was not on board at the time or he might ... have seen some constellations such as he had never observed from Greenwich.[67] Airy's *Journal* version reads "1846 Jan 1 Thursday At York. Day not perfectly favourable, and a train was run merely for experiment on evaporation. The engine ran off the rails (at a broken joint-chain), the train was upset, and the fireman dangerously hurt. I left York by the night mail train".[68]

Of the New Year's Day entry it might be noted that from it is known (1) the purpose of the *Stephenson* run, (2) the weather conditions and (3) that someone was injured, information otherwise rarely available. It is typical of Airy's thoroughness. Early on the Friday morning Airy was back at Greenwich, working of course, and it was a very fine day. The Astronomer Royal's *Journal* certainly gives an immediacy to the events that is lacking in the other accounts.

Airy and the other commissioners were not deterred by the clear superiority of the broad gauge engines and the lack of success of the narrow gauge locomotives. Plainly the evidence they had heard from a majority of their forty-eight witnesses and other documentary evidence swayed them. No doubt there is much more to be culled from the Observatory records on quite what happened during the commission hearings and why the report was as it was. Whatever those details the important matter was that by 1846 January 29 the three commissioners had signed their report at Greenwich[69] and "... the business was concluded by the end of April. Our recommendation was that the narrow gauge should be carried throughout".[70] Though as Airy's further comment in the *Autobiography* makes clear, the business was not concluded as the recommendation was in practice ignored. The dual gauge solution, the broad and the narrow gauges both set side-by-side on the roadway, was run on the Great Western until the later years of the 19th century.

With the beginning of the gauge commission's activities in the summer of 1845, the vigorous course of business had unforeseen consequences. Within a year or eighteen months Airy's distraction with the gauge business would lead to the greatest criticism of his management of the Greenwich Observatory to which he would be subjected in his career. Though the incidents surrounding the discovery of the planet Neptune in 1846 are the subject of a scholarly paper by Allan Chapman, it is nonetheless proper to outline some of the circumstances to illustrate the tensions under which Airy was placed as director of the Royal Observatory and as a public servant.

The circumstances surrounding the discovery of the new planet in 1846 and why this was certainly not discovered from Greenwich, nor indeed from Airy's Alma Mater the Cambridge Observatory, but from Berlin are germane to this subject because the discovery was one of the triumphs of nineteenth century mathematical astronomy, the very stuff of Airy's qualifications. Yet Airy declined the chance to look for the planet at the place John Couch Adams predicted. Perhaps the Greenwich instruments were not ideal and the Northumberland telescope in Cambridge was better suited, but at the core, Airy did not consider his paid duty to be to look for new planets, however exciting this might be. Nor, indeed, how much this aroused public interest and public passion; "I was abused most savagely by both English and French." Airy commented.[71] With so much business being prosecuted on the gauge commission, with a heavily pregnant wife and a senior assistant arraigned for the murder of a child conceived in an incestuous relationship, Airy's eye was off the ball, in the modern phrase. In fact, Airy was on a continental 'rest-cure' holiday when he heard of the discovery of the new planet in 1846 September, so arduous had the previous year been, even for George Airy.

4 THE EXTRANEOUS GOVERNMENT BUSINESS

From the list of subjects of this paper, naturally the title was self-selective. It will be noticed whence it comes, Airy's own title for a group of three volumes of papers. This was really Airy's 'catch-all' title to cover just about everything else that he had been asked to do in the years 1854-1880. This included various national and international exhibitions, lectures, work on examinations for South Africa, interviews for the public schools commission, correspondence on the 1870 education act, on a possible physical observatory, and his evidence to the Tay Bridge enquiry of 1879.

Already reference has been made to the tidal harbour commission. Other commissions that Airy served upon were:

4.1 Ordnance Survey Commission

There is, of course, a natural connection between the Astronomer Royal and the geodetic survey of the country and it is hardly surprising that Airy served in this capacity.

4.2 Lighthouse Commission

In Airy's papers there is one volume dated 1860-1861, including correspondence with Michael Faraday and William Gladstone, and the report of the commission as well as Airy's report on the Start Point lighthouse is dated 1860, Airy's involvement following an application for advice by Admiral Hamilton.

The 'utilities' commissions on which Airy served may be summarized as follows, really as an indication of his industry and the breadth of application of his skills that was required.

4.3 Sale of Town Gas Commission

There are eight volumes of papers preserved by Airy, dated 1858-1864, including correspondence, acts of parliament, circulars, plans, gas-holder designs, the parliamentary bills dated 1860 June 28 and 1863 March 17, papers on gas meters, and on the definition of a cubic foot of gas. Lord Mounteagle (formerly Thomas Spring Rice) had applied to Airy for assistance because of his work on the standards, and the latter definition as it related to the sale of gas.

4.4 Metropolitan Commission of Sewers

Public sanitation was a critical matter in the great cities of Britain as they grew enormously in the industrial age. The commission commenced work on 1848 October 28 and in the *Autobiography* Airy referred to the constitution as "... the most foolish that I ever knew – consisting of, I think, some 200 persons, who could not possibly attend to it. It came to an end the next year".[72] Nonetheless, Airy accumulated a further three volumes of papers, dated 1846-1849, including proceedings, reports, plans, correspondence, and suggested improvements in relation to the disposal of London's sewage. Airy had, as usual, practical ideas to put forward.

5 CONCLUSION

In this paper, reference is made on more than one occasion to the 25% of the Airy papers taken up by his 'extraneous' work. Of course, the corollary of this is that 75% of his time was taken up with doing everything else.

As Allan Chapman has written, in a fitting tribute "Looking at Airy's career during the mid-1840s in particular, it is astonishing to find one man called upon to fulfil so many exacting tasks all at the same time. In 1845-46 alone, he was providing meteorological data for the Registrar General, advising the Tidal Harbour Commission on the design of breakwaters at Plymouth and Cherbourg, suggesting improved sawing machines for Chatham Dockyard, and undertaking preliminary enquiries leading to the construction of the new Westminster Clock. He was also involved in correcting compasses for Admiralty postal vessels, advising on the design of the Menai tubular bridge, and, of course his work on the Railway Gauges Commission. None of these heavy demands were in the least concerned with astronomy, and it should also be remembered that at the Observatory, he was considering the introduction of a range of electrical self monitoring devices which in themselves amounted to a revolution in practical instrumentation. And when all the other extraneous demands had been met, he still faced the relentless task for which the state paid him; the collection, reduction and publication of the flawlessly accurate Greenwich Observations."[73]

6 NOTES

All references to MSS.RGO are from the Royal Greenwich Observatory *Handlist of the papers of George Biddell Airy in R.G.O.Archives* [unpublished catalogue to the manuscripts collection], Herstmonceux, 1985.

1. Airy (1896), chapter II.
2. Maunder (1900), p.108.
3. Chapman (1988a).
4. MS.RGO.6/1:f.195^r.
5. Lovell (1994).
6. See for his account Airy (1896:104-109).
7. Maunder (1900:108).
8. Maunder (1900:116-117).
9. Wilfrid Airy: *In* Chapter I, Personal sketch of George Biddell Airy (Airy 1896:6-7).
10. Maunder (1900:118-119).
11. Maunder (1900:114).
12. Maunder (1900:118).
13. James South to the Lords Commissioners of the Admiralty, 1847 March 12, MS.RGO.6/2; quoted in Meadows (1975:3).

14. Airy (1896:123).
15. McCrea (1975:21).
16. Airy (1896:111-113).
17. Chapman (1988b).
18. McCrea (1975:28).
19. Chapman (1988b).
20. Meadows (1975).
21. Jones (1943:27).
22. Airy (1896:133); *Astronomer Royal's Journals* MS.RGO.6/24:f.24^r.
23. Airy (1896:134).
24. Thomas Spring Rice, later Lord Monteagle, at this time Chancellor of the Exchequer.
25. *Astronomer Royal's Journals* MS.RGO.6/24:f.26^r.
26. Airy (1896:134).
27. *Astronomer Royal's Journals* MSS.RGO.6/24-27.
28. *Astronomer Royal's Journals* MS.RGO.6/24:f.26^r.
29. Airy (1896:134).
30. Clerke (1909).
31. MS.RGO.6/367.
32. MSS.RGO.6/338-339.
33. MSS.RGO.6/340-341.
34. MS.RGO.6/343.
35. MS.RGO.6/344.
36. MS.RGO.6/345.
37. MSS.RGO.6/346-347, 350-354.
38. MSS.RGO.6/348, 363-365.
39. MS.RGO.6/349.
40. MS.RGO.6/355.
41. MSS.RGO.6/356-359, 361, 366-367.
42. Airy (1857).
43. Chapman (1988b), and Airy's papers relating to the Coinage Commission, MS.RGO.6/446.
44. See entries for the dates in *Astronomer Royal's Journals* MS.RGO.6/24:f.28^r *et seq*.
45. Airy (1839) and Airy (1855).
46. Turner (1892).
47. Turner (1892:223).
48. Herschel (1844).
49. Clerke (1909).
50. *Astronomer Royal's Journals* MS.RGO.6/24: f.1^r.
51. See for this period Airy (1896:126).
52. Airy (1896:171).
53. Ibid.; MS.RGO.6/24:f.100^v.
54. Rolt (1957:199).
55. Rolt (1957:199).
56. MS.RGO.6/284.
57. MSS.RGO.6/285-290.
58. MS.RGO.6/291.
59. As if there were not enough already, see MS.RGO.6/292.
60. MSS.RGO.6/293-299.
61. MS.RGO.6/300.
62. MSS.RGO.6/301-306.
63. MS.RGO.6/307.
64. MS.RGO.6/308.
65. MSS.RGO.6/309-321.
66. Rolt (1957:200).
67. Ibid. p.201.
68. *Astronomer Royal's Journals* MS.RGO.6/24:f.106^r.
69. *Astronomer Royal's Journals* MS.RGO.6/24:f.106^v.

70. Airy (1896:180).
71. Airy (1896:181).
72. Airy (1896:196).
73. Chapman 1988b.

7 REFERENCES

Airy, G.B., 1839. Account of experiments on iron-built ships, instituted for the purpose of discovering a correction for the deviation of the compass produced by the iron of the ships. *Philosophical Transactions of the Royal Society of London*, 1839 April 25.

Airy, G.B., 1855. Discussion of the observed deviations of the compass in several ships, wood-built and iron-built: with a general table for facilitating the examination of compass deviations. *Philosophical Transactions of the Royal Society of London*, 1855 November 22.

Airy, G.B., 1857. Account of the construction of the new national standard of length, and of its principal copies. *Philosophical Transactions of the Royal Society of London*, 1857 June 18.

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

Chapman, A. 1988a. Private research and public duty: George Biddell Airy and the search for Neptune. *Journal for the History of Astronomy*, **19**:121-139.

Chapman, A., 1988b. Science and the public good: George Biddell Airy (1801-92) and the concept of a scientific civil servant. *In:* Nicolaas A. Rupke (Ed.), *Science, Politics and the Public Good.* Macmillan, London.

Clerke, A.M., 1909. Richard Sheepshanks. In *Dictionary of National Biography*, vol. 18. Smith Elder, London.

Herschel, J.F.W., 1844. Memoir of Francis Baily, Esq. *Monthly Notices of the Royal Astronomical Society* **6**:22-23.

Jones, H. Spencer, 1943. *The Royal Observatory, Greenwich*. The British Council & Longmans, London.

Lovell, A.C. Bernard, 1994. The Royal Society, the Royal Greenwich Observatory and the Astronomer Royal. *Notes and Records of the Royal Society of London* **48**:283-297.

Maunder, E .Walter, 1900. *The Royal Observatory, Greenwich: a Glance at its History and Work.* Religious Tract Society, London.

McCrea, W.H., 1975. *The Royal Greenwich Observatory: an Historical Review Issued on the Occasion of its Tercentenary*. Her Majesty's Stationery Office, London.

Meadows, A.J., 1975. *Greenwich Observatory* vol. 2: *Recent History (1836-1975).* Taylor & Francis, London.

Rolt, L.T.C., 1957. Isambard Kingdom Brunel. Longmans Green, London.

Turner, H.H., 1892. Obituary notice of Sir George B. Airy. *Monthly Notices of the Royal Astronomical Society* **52**:212-229.

Adam Perkins graduated in physics from City University, London, in 1973. After a period working in industry and as director of a company manufacturing thermal insulation materials, in 1983 he joined the Royal Greenwich Observatory, Herstmonceux, to lead a team cataloguing the archival collection there. He was appointed archivist in 1987 at a time when the imperative was to move the archives from Sussex to the new home of the collection, Cambridge University Library. This move was completed on schedule as a parallel project to the move of the RGO itself to Cambridge in the spring of 1990. Adam then transferred to the staff of CUL to remain as RGO Archivist. Over the intervening decade, his work has expanded to cover responsibility for the manuscript collections of Cambridge scientists held at the Library such as the papers of Newton, Maxwell, Darwin, Kelvin, Stokes, and Rutherford. His primary responsibility, however, remains the archival collection of the Royal Greenwich Observatory.

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The Airys at Greenwich

Frances Ward
Greenwich Local History Library, Woodlands, 90 Mycenae Road, Blackheath, London SE3 7SE

Abstract
George Airy and his immediate family lived in Greenwich for over half a century, and were much involved in local affairs. A selection of water-colours by his daughter Christabel show the surroundings amid which he lived and worked.

Key words: *Airy family, Greenwich Observatory.*

Professor George Airy was 34 when he was appointed Astronomer Royal in 1835 and took up residence with his family in the Royal Observatory, and 80 when he retired. Six of his nine children were born there, and for most of that time his sister Elizabeth also lived there. When he retired he moved with his two unmarried daughters into the White House, just outside one of the gates of Greenwich Park. His son Wilfrid records that "The house suited him well and he was very comfortable there: he preferred to live in the neighbourhood with which he was so familiar and in which he was so well known, rather than to remove to a distance. His daily habits of life were but little altered: he worked steadily as formerly, took his daily walk on Blackheath ..." (Airy, 1896:347). His daughters continued to live there after his death ten years later; the Airy family were thus prominent citizens of Greenwich for over half a century.

Christabel Airy was born at Greenwich Observatory in 1842, the third daughter of the Astronomer Royal and his wife Richarda. With her younger sister, Annot, she devotedly nursed her mother after a paralytic stroke until her death in 1875 when she assumed the duties of housekeeper and companion to her father, moving with him on his retirement in 1881 to the White House at the top of Crooms Hill. With him she travelled extensively all over the British Isles but still found time to be actively involved in church activities and many of Greenwich's good causes. At the Provident Dispensary in Nelson Road, she was described as a powerful influence and was responsible for much valuable work. She was also involved with the Children's Country Holiday Fund, the Boys' Orphanage on Blackheath Hill, the Metropolitan Association for Befriending Young Servants (which always commanded her sympathy), the Bluecoat School and the Roan Schools, the YMCA Hut for Soldiers on Blackheath, the Jubilee Almshouses and the Miller Hospital. Most important however was her work on the Greenwich Board of Guardians where she took a close interest in the Calvert Road Children's Home and the schools at Sidcup. Her hobbies included campanology, cycling, gardening, and sketching. She died after an apoplectic fit in 1917 June.

The 12 water-colours reproduced below are drawn from a collection of 22 now held by Greenwich Local History Library. They were all executed by Christabel Airy when the Observatory was her home, and were painted between 1866 and 1880. They all portray scenes that her father knew well, whether looking out from the Observatory or on his daily walks in Greenwich Park or Blackheath. They have been reproduced by courtesy of the Greenwich Local History Library.

Figure 1 is the view to the west from Observatory Hill, showing the spot where, today, the Meridian Line emerges into the park. The fence borders the path which the young Martial Bourdin took in 1894 when the home-made bomb he was carrying exploded. It was widely believed at the time that he was an anarchist bent on blowing up the Observatory, but the real reason for the tragedy will probably never be known. The event did inspire Joseph Conrad to write *The Secret Agent*, published in 1907.

Figure 2, Greenwich Observatory from One Tree Hill. When Christabel painted this, it was really No Tree Hill , the great tree for which it was named having been blown down in the terrible gale of 1848 August, but the original name is still used today. Until its suppression in 1857, Greenwich Fair would have disturbed the Astronomer's family when thousands flocked to spend the Easter and Whitsun holidays in Greenwich Park. One Tree Hill was a favourite spot for the dangerous game of "tumbling" in which lines of boys and girls raced down the steep slopes in the Park to the great amusement of onlookers.

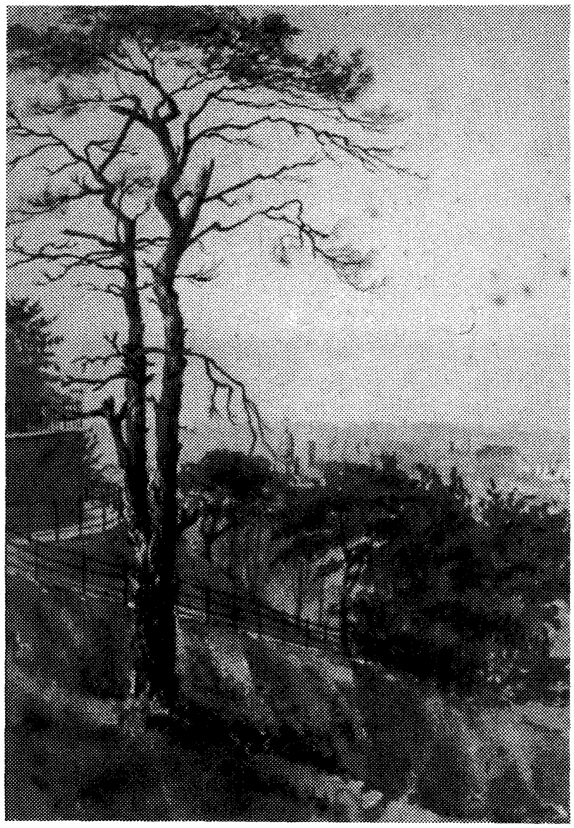

Figure 1.

Figure 2.

Figure 3 shows Greenwich Observatory from the north in 1873 with, on the left (beyond the tree), the wooden drum dome built in 1857 to house the Great Equatorial Telescope. This dome can also be seen at left in Figure 2. It was replaced by the more familiar onion dome for the new 28-inch refractor in 1893. The Great Equatorial was a 12¾-inch refractor in a massive mounting designed by Airy, based upon his design for the Northumberland refractor at the Cambridge Observatory. The success of the mounting may be judged from the fact that it was re-used for the much larger 28-inch telescope. The present dome was erected in 1975, the previous one having been severely damaged in the Second World War.

The main building is the original Observatory of 1676 built by Wren "for the observator's habitation and a little for pomp". The upper floor, with the deep windows, was the famous Octagon Room, the original observing area. The dwelling house, on ground and basement levels, was several times extended on the far side. The final extension, in 1835-6, was to accommodate Airy and his growing family.

Airy's Transit Circle of 1851, which defines the Prime Meridian, is behind the trees approximately mid-way between the drum dome and the Wren building. The Meridian runs down the park towards the bottom left-hand corner of the picture.

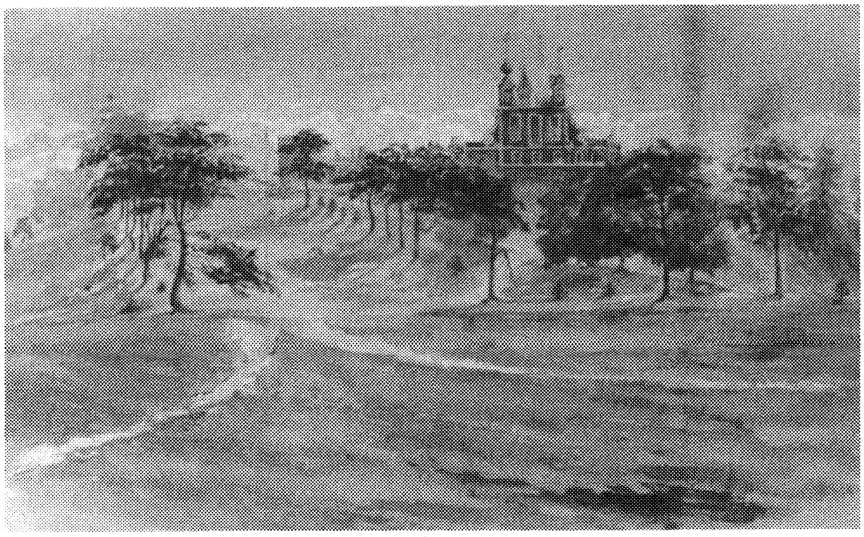

Figure 3.

Figure 4, a view from the Observatory north to Greenwich Peninsula (1866). In the foreground can be seen the east wing of the Royal Hospital School with its own observatory on the right. The small tower in the centre is Trinity Hospital, almshouses founded in 1614 by Henry Howard, Earl of Northampton, for the relief of poor and indigent men. Today the attractive buildings are overshadowed by Greenwich Power Station. Further north can be seen the factories on the Isle of Dogs to the left, and to the right on Greenwich Peninsula, its tip still undeveloped – awaiting the arrival of, first, the South Metropolitan Gas Company and, more recently, the Millennium Dome. The Prime Meridian crosses the extreme tip of the peninsula.

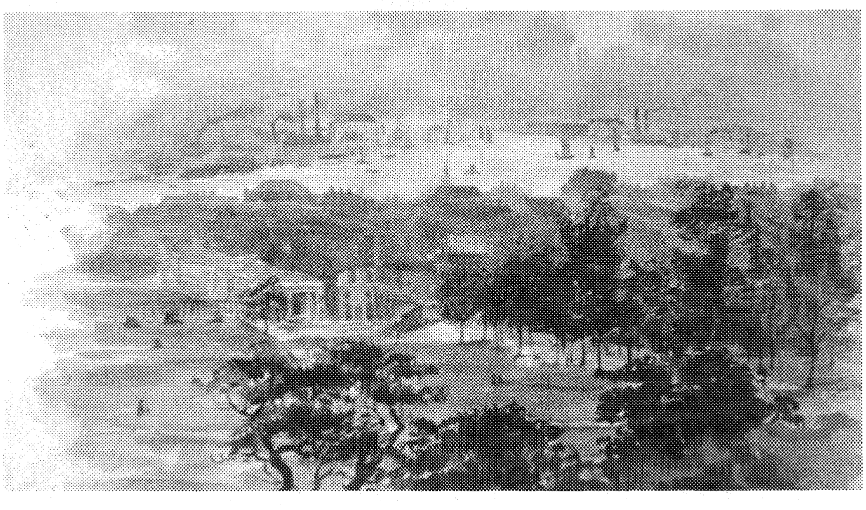

Figure 4.

Figure 5, a similar view painted in the same year (1866). Christabel (like many other Victorians) may have had a special interest in this area as among the factories are the premises of Glass, Elliot and Co. who, combined with the Gutta Percha Co. to form the Telegraph Construction and Maintenance Co., made the transatlantic cable which was finally successfully laid by the *Great Eastern* in 1866. George Airy had taken a great interest in the development of the electric telegraph and was a pioneer in its use, notably for the distribution of time; he was consulted during the planning of the transatlantic cable.

The forest of tall chimneys on the north bank of the river stand testament to the increasingly rapid eastward progress of riverside industries (and pollution) in the mid nineteenth century. It must have already been clear that the location was becoming less favourable for astronomical observation.

Figure 5.

Figure 6. Another view to the north, but painted four years later on 1870 February 15 when the bitterly cold weather caused the Thames to freeze. Christabel inscribed the picture "Showing the ice in the Greenwich Reach". Earlier in the month, continuous rain and a succession of high tides on the river had caused flooding on both banks, and a sudden drop in temperature during the second week brought snowstorms and widespread misery as flooded roads and fields turned to ice.

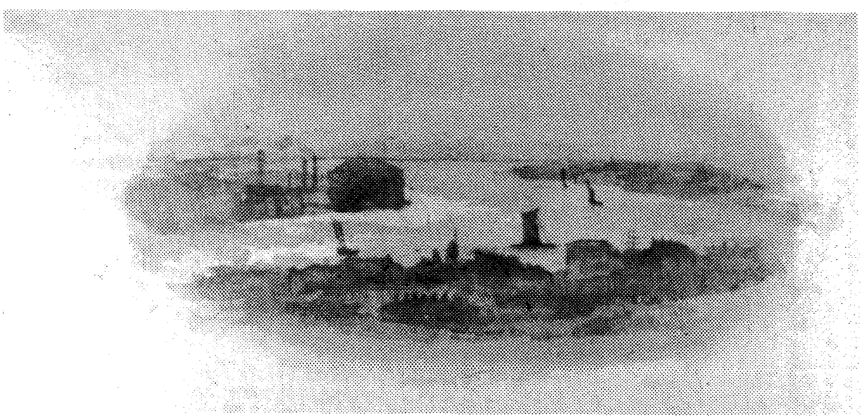

Figure 6.

Figure 7. View over a wintry Greenwich Park to the town, painted in 1866 February. The tower on the left belongs to the parish church of St. Alfege, traditionally said to stand on the site of the martyrdom of Alfege, Archbishop of Canterbury, by the Danes in 1012. The church, rebuilt by Hawksmoor in 1714 with a steeple by John James (1730), is the burial place of James

Wolfe, hero of Quebec, and Thomas Tallis, the Tudor musician. Christabel had a lifelong association with this church. On the evening of his ninetieth birthday, 1891 July 27, Sir George was invited to turn on the gas-lighting which illuminated the church clock for the first time, and spoke for about a quarter of an hour on the importance of time and its dissemination.

Figure 7.

The other tower is that of St Mary's Church, built as a chapel of ease by George Basevi in 1825. It stood by the Park gates in King William Walk, closed in 1919 and was demolished in 1936. A fine statue of William IV marks the site.

Figure 8, a view north-west from the Observatory towards the river with the hospital ship, *Dreadnought*, in the centre of the picture. The hospital, for sick seamen, was moored off Greenwich for nearly half a century, originally on board the *Grampus* and from 1831 on the *Dreadnought*, until it came ashore in 1870 when it moved into the old Greenwich Hospital Infirmary. It closed in 1986 March. The dome of St Paul's Cathedral can be seen against the sky – one of Wren's masterpieces seen from another.

Figure 8.

Figure 9 is a view in the west side of Greenwich Park with the tower and steeple of Our Lady Star of the Sea above the trees. This was the first Roman Catholic church built in Greenwich since the reformation, and was erected in 1851 on a piece of land given by the North family in Crooms Hill. The architect was W.W.Wardell and the beautiful interior is by Augustus Pugin. The Sacred Heart Chapel with its magnificent ceiling is by Edward Pugin. The water-colour is dated 1868.

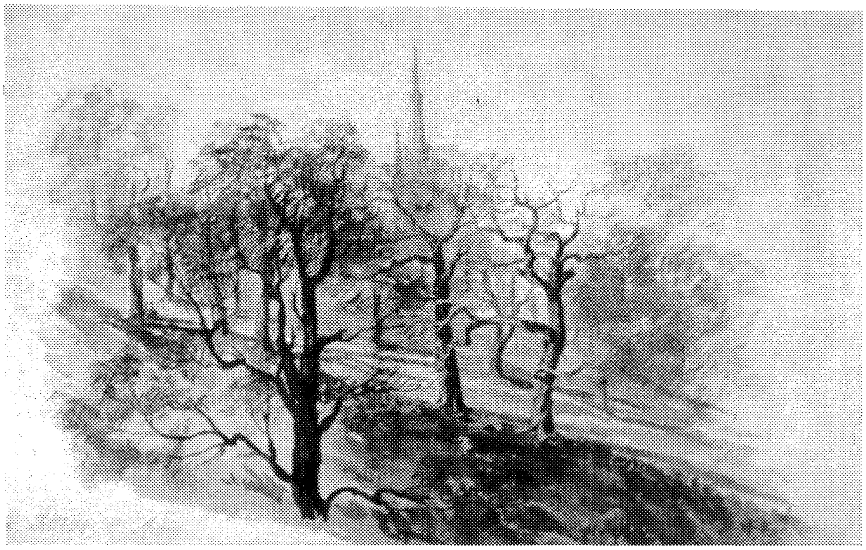

Figure 9.

Figure 10. Blackheath from the south-west corner of Greenwich Park, the wall of which can be seen on the left, painted in the summer of 1880. A very short walk from the White House, and only half a mile from the observatory, Airy must have passed this spot almost daily for many years. Blackheath Village and All Saints Church occupy the middle distance with the wooded slopes of Shooters Hill beyond. This is one of the very few of Christabel's drawings to include figures; the man on the penny farthing may reflect her own interest in cycling. The Heath would have been very familiar to her too, as for many years she and her sister Annot exercised their dogs here.

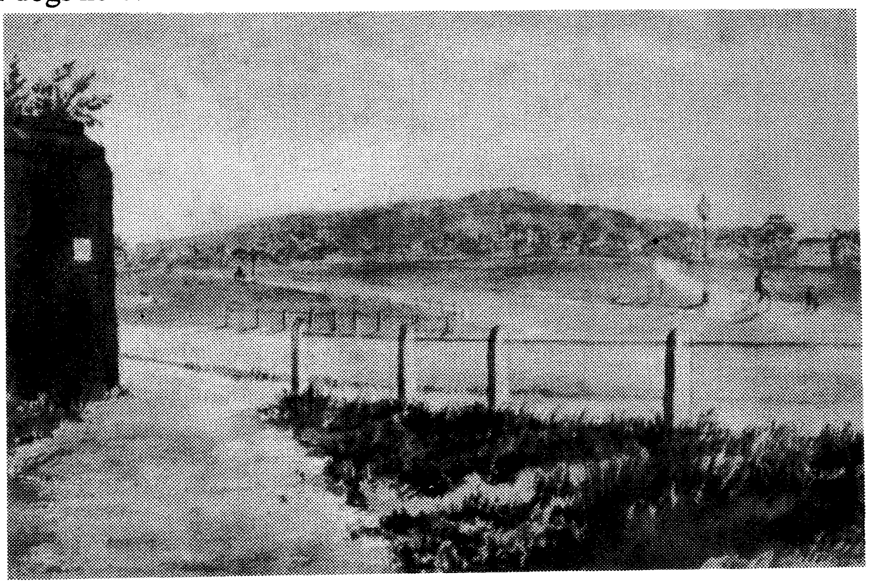

Figure 10.

Figure 11. Another view of Blackheath looking west to the grand houses in Dartmouth Row. In the foreground are Whitefields Pond and Mount. The Mount is almost certainly an ancient burial mound but has never been the subject of an archaeological excavation. The Pond is the result of digging gravel from the Heath. Both are named for the great Wesleyan preacher, George Whitefield, who, with other prominent Methodists, regularly gave open air sermons to vast crowds on Blackheath.

Figure 12. Another view of the Observatory, from the south. The structure in the bottom left is probably the Standard Reservoir which supplied water to Greenwich Hospital and the Hospital Schools. The beautiful old tree on the right may be one of the horse-chestnuts planted

in the 1660s when the Park was landscaped for Charles II. Many have been lost to weather and disease but a good number of the original trees still stand. Beyond is the Observatory with Pond's time ball, erected in 1833 to provide the first public time signal. It is surmounted by a wind vane. The ball was a wooden frame covered with canvas and leather, five feet in diameter; it was replaced in 1919 by the present aluminium one. The structures to the left, on the roof of the Wren building, carried other meteorological instruments.

Behind the tree was the area termed by Airy the 'Magnetic Ground', where he erected a magnetic observatory in 1836, and an office building for the Magnetic Department in 1862. The latter building was demolished in 1885 to make way for the 'new physical observatory', now known as the South Building, erected between 1894 and 1899. Airy died in 1892, but this typically Victorian terracotta building, designed by the architect Frank Crisp, would have been very familiar to his daughters. The largest building on the site, it is cruciform in plan, three storeys high with a basement, and surmounted by a telescope dome which since 1965 has housed the Greenwich Planetarium. All round the building are prominently carved the names and dates of the astronomers and instrument makers who had contributed to the success of the Observatory over two centuries – including Airy.

Figure 11.

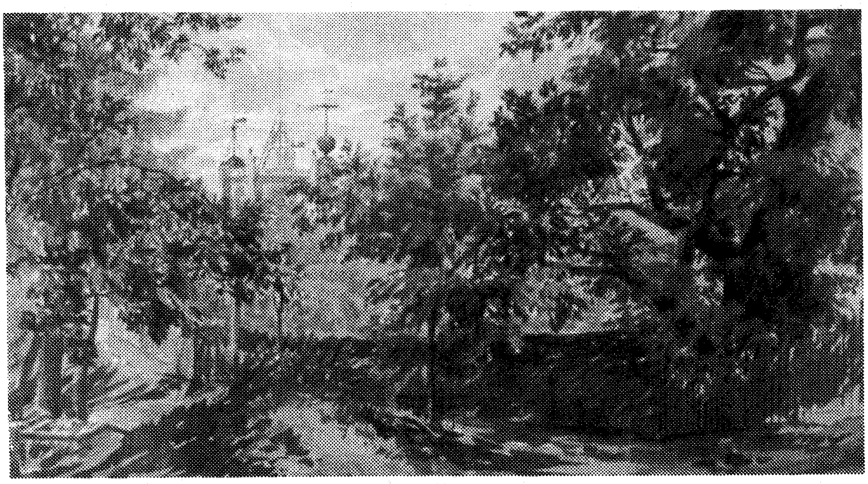

Figure 12.

REFERENCE

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

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Bertil Lindblad's early work: the two-dimensional classification of stellar spectra at low dispersion

Per Olof Lindblad
Stockholm Observatory, SE-133 36 Saltsjöbaden, Sweden
E-mail: po@astro.su.se

Abstract
This paper[1] describes the work of Bertil Lindblad (1895-1965) up to the time when he took an increasing interest in galactic dynamics and when he also became director of the Stockholm Observatory with the task of creating a new observatory in Saltsjöbaden.

The paper relates how the two-dimensional classification of stellar spectra at very low dispersion in terms of temperature and luminosity developed out of measurements of effective wavelengths of stars. From this emanated the scheme of quantitative classification of objective prism spectra by which Lindblad's collaborators derived important results concerning the structure of the Milky Way galaxy.

The paper ends when Lindblad's main research took new directions and tasks within national and international science gave new directions to his life.

Keywords: *B. Lindblad, Uppsala Observatory, Stockholm Observatory, spectral classification*

1 INTRODUCTION

At the northernmost end of the large lake Vättern in central Sweden, on the shore of a protected bay, lies the little pastoral town of Askersund. If you cross the bridge over the small stream that limits the town to the west, you will pass a seventeenth century church, and one mile further on you will reach a farm named Lind, very likely because an impressive lime-tree (in Swedish, "lind") is shadowing the yard. In the first half of the eighteenth century this farm was owned or leased by a market-gardener who adopted the family name Lindblad. For almost two hundred years the Lindblads lived in Askersund as merchants and magistrates.

Bertil Lindblad's father, Birger, was an army officer. He had married Sara Waldenström, daughter of the mayor of Askersund. The mayor's father was a renowned country doctor in the far north of Sweden and one of his brothers was a Congregational theologian, Paul Petter Waldenström, who on one of his world-wide travels even may have visited the Lick Observatory.

When Bertil Lindblad was born in 1895 the family lived in the city of Örebro where his father's regiment was stationed. At the gymnasium in Örebro the young Lindblad was a very successful student, and his teacher put in his hands books on astronomy.

In the spring of 1914 Bertil Lindblad graduated from school and prepared to enter the university in Uppsala. In the summer of that year the path of a solar eclipse swept past the northern part of Sweden. Lindblad equipped himself with a 2-inch telescope and set out for an eclipse expedition of his own. In the fall of 1914 he went to Uppsala and begun his studies of astronomy, complemented with mathematics, physics and latin. To support his studies he assisted the medico-optician and Nobel Prize winner A Gullstrand as head of his computing office, and at some moment he may also have felt inclined to enter studies in medicine.

2 PHOTOGRAPHIC EFFECTIVE WAVELENGTHS

In the first two decades of the last century stellar photometry, spectral photometry, and spectral classification were still in their infancy. Visual photometry, that had culminated with the Potdamer Photometrische Durchmusterung (1894-1907) and the Revised Harvard Photometry (1908), was being replaced by photographic photometry. Although this was far superior to visual photometry, the calibration of photographic plates to set up a universal photometric system was in no way an easy problem. In the beginning of the second decade of the twentieth century the first experiments using the photoelectric effect for stellar photometry were made. The first use of the photoelectric cell was made by Guthnick (1913) in Germany in 1912, subsequently followed up by Stebbins in Illinois.

One particular problem that could be tackled by photographic photometry, but with difficulty, was the determination of colours of stars. A particular method to measure colour, or rather the so-called effective wavelength, of stars in a single exposure that could be extended to very faint magnitudes had been developed by Hertzsprung in Copenhagen and Bergstrand in Uppsala. In this method a coarse grating was placed in front of the objective of a refractor when a star field was being photographed. The distance between the two almost point-like images of the first order spectra, amounting to some millimetres on the photographic plate, is a function of the effective wavelength of the stellar spectrum and could be used as a "colour equivalent". Thus, the measure of colour was, in principle, reduced to a measure of relative positions on the plate, whereby several of the effects that introduce severe systematic errors in the determination of colours, particularly for faint stars, could be avoided.

On the other hand, spectral classification at a large scale with the help of objective prisms was developed at the Harvard Observatory by Mrs Fleming, Miss Maury, and Miss Cannon under the directorship of Pickering, beginning with the first catalogue in 1890 and culminating with the Henry Draper Catalogue, the first volume of which was published in 1918.

Lindblad's first research project at the Uppsala Observatory was to join Bergstrand in determining the photographic effective wavelengths of stars [1], a work that Lindblad soon developed in his own direction.

One of the main problems, and also the aim of Lindblad's work, was to find out to what extent the colour of a star is given by its spectral class and to establish the relation between colour and temperature, a problem which also had its bearing on the unsolved question of whether there exists a selective absorption of light in space. For bright stars Lindblad derived a close relation between effective wavelength and spectral class, but he also investigated the dependence of colour on absolute magnitude for stars of similar apparent magnitude [3]. The increasing reddening of a star with absolute magnitude either could be due to selective absorption in space, as suggested by Kapteyn and van Rhijn, or be an effect of luminosity, or both. However, investigations by Hertzsprung and Shapley of globular clusters and by Lundmark and Lindblad [2, 5] on the effective wavelengths of globular clusters and spiral galaxies had indicated, in particular when applying the immense distances to spirals derived by Lundmark, that the selective absorption *per parsec* in space was exceedingly small. In retrospect, we now can see the true explanation for this. As Oort has pointed out (private comm.), at that time astronomers were not fully aware of the strong concentration of dust in the Milky Way itself and, in particular, in its plane of symmetry. Thus, Lindblad favoured the view that the colour of a star was intrinsically dependent upon its absolute magnitude and concluded that it should be possible to distinguish between late-type giants and dwarfs using spectral types and colours and so derive distances for such stars. This would complement and extend to fainter stars the method of Adams and Joy (1917) for determination of absolute magnitude from spectral criteria.

To separate temperature and luminosity two parameters obviously were needed, and Lindblad was looking for a second colour equivalent. As such he choose the position of the inner edge of the first order spectrum on his plates, or in other words the short wavelength cut-off, which was rather sharply defined in his spectra. In a diagram of cut-off wavelength versus effective wavelength he found giant and dwarf stars to be separated [4]. Thus, it was possible to determine both spectral type and absolute magnitude directly from two colour equivalents. This hypothetical possibility first seems to have been pointed out to Lindblad by von Zeipel [6, Preface].

Having arrived at these empirical results Lindblad now entered on a thorough theoretical investigation of radiative transfer in the solar atmosphere in order to get a clearer view of how photospheric temperature and the dimensions of a star are reflected in the spectral energy distribution. This work occupied him throughout 1919, and formed the first part of his thesis [6]. Starting from the work of K Schwarzschild (1906, 1914) on the integral radiation, Lindblad treated the radiative transfer for each wavelength separately, considering both absorption and scattering in a solar atmosphere that was in radiative equilibrium. In this way he derived equations by which the temperature of successive layers as a function of optical depth, the effective temperature of the total radiation, and the spectral energy distribution of the radiation could be derived from the centre-limb variation of the solar radiation at a set of different wavelengths.

In the second part of his thesis Lindblad proceeded to discuss the dependence of effective temperature and the absorption line spectrum upon atmospheric mass above the photosphere for stars of the same spectral type, that is when going from dwarfs to giants. He concluded that by combining a colour equivalent determined at rather long wavelengths with a relative ultraviolet intensity it should be possible to determine both the spectral type and the absolute magnitude of a star.

The third part of the thesis aimed at an empirical verification of these conclusions following the methods he had published as a preliminary notice in the *Astrophysical Journal* [4]. The instrument used for the observations was the twin 15-cm astrograph at the Uppsala Observatory, equipped with a coarse objective grating consisting of wires with diameters of 0.62 mm. With this instrument he measured effective wavelengths and cut-off wavelengths for 63 stars of known spectral type and absolute magnitude. From this material he was then able to construct diagrams of effective wavelength and cut-off wavelength versus spectral type. Both diagrams, but particularly the one containing the cut-off wavelength, showed luminosity effects for the later-type stars. The strong luminosity effect for the cut-off wavelength was attributed to the circumstance that the absorption of the lenses of the astrograph caused a sharp boundary of the images to fall in a region of groups of luminosity-sensitive ultraviolet absorption lines. Again, Lindblad demonstrated that in a diagram of effective wavelength versus cut-off wavelength it was possible to separate later-type giants and dwarfs.

This later part of his thesis was criticized by Lundmark and Luyten (1922), with an ensuing discussion in the *Monthly Notices of the Royal Astronomical Society* [11, 13, Lundmark & Luyten, 1923]. However, Lindblad had already taken the next important step towards a spectrophotometric method for luminosity classification of stars from objective prism spectra.

3 TWO-DIMENSIONAL CLASSIFICATION OF OBJECTIVE PRISM SPECTRA

After he had obtained his doctoral degree in the spring of 1920, Lindblad was awarded a fellowship from the Swedish-American Foundation to spend one and a half years in the United States, mainly at the Mount Wilson Observatory [7]. There Adams and Joy and their collaborators were developing the spectrographic criteria for luminosity introduced by Kohlschütter and Adams. These methods used rather faint luminosity-sensitive lines and required fairly large spectral dispersions. Inspired by the discovery by Adams (1914) of the A0 type spectrum of the absolutely very faint star o_2 Eridani (which we today would call a white dwarf) and a comparison of the spectrum of that star with the spectrum of Sirius, Lindblad set out to investigate luminosity criteria for early-type stars that could be seen at very low dispersion. At the same time he continued his investigations of the luminosity criterion for later-type stars that had been found in his cut-off wavelengths. The results were published under the title "Spectrophotometric methods for determining stellar luminosity" in the *Astrophysical Journal* [10]. The method was to find narrow spectral regions that varied in intensity with luminosity, and the instrument used for this quest was a 10-inch Cooke refractor with a 6° objective prism. For a more detailed study of some spectra he used the 60-inch reflector and, during a month's stay at the Lick Observatory, a slitless quartz spectrograph on the Crossley reflector.

For the first part of the investigation Lindblad used early-type stars in the Hyades, Ursa Major, Praesepe, and Pleiades clusters, and he found a very good correlation between the intensity ratio of the regions $\lambda\lambda$ 3895-3907 and $\lambda\lambda$ 3907-3925 and the absolute magnitude, a correlation that would be useful for luminosity estimates for the spectral types B8–A3. This effect was ascribed to a widening of the Hζ line with decreasing luminosity as well as to some lines of Fe and Si.

Spectra of later-type stars obtained with the Crossley reflector showed that the luminosity sensitivity of the cut-off wavelength as used earlier was obviously due to variation in the strength with stellar luminosity of a cyanogen band with its first head at λ 3883. Other such bands at λλ 4216 and 3590 were also detected. Of these, the band at λ 4216, although weaker than the others, was the most favourable not being situated so far in the violet, where for the redder stars the exposures had to be very long.

Thus Lindblad was able to set up a two-dimensional classification scheme for objective prism spectra based upon the appearance and relative strengths of the hydrogen lines, the K-line and λ 4227 line of calcium, the titanium-oxide bands as well as on the cyanogen absorption.

On his way home from the United States Lindblad visited the Harvard Observatory. The possibility of using Lindblad's spectral classification in the analysis of existing Harvard objective prism spectra interested Harlow Shapley, and resulted in a joint paper [9]. Lindblad declined, however, the offer of a position at the Harvard Observatory.

After his return from the United States Lindblad continued to develop the spectral criteria. The instrument used for the observations was the Zeiss-Heyde astrograph at the Uppsala Observatory, equipped with an objective prism. The dispersion gave a separation between Hγ and Hε on the plates of 1.4 mm. The relative spectrophotometry was carried out by comparing spectral regions in a series of exposures of varying length on the same plate. In 1925 he published a detailed two-dimensional scheme of classification and spectrophotometric measurements [20], which was a development of the Harvard classification. Earlier work had shown the wings of the hydrogen lines to increase with decreasing luminosity. For stars of spectral type B8–A3 the sharpness of the hydrogen lines was now introduced as a luminosity criterion. For the stars of spectral type G–M the jump in intensity at the G-band was used as an indicator of spectral type, and the cyanogen absorption at λ 4184 and the line absorption at λ 3900 were used as a measure of luminosity.

Lindblad applied his classification to a study of the velocity distribution of Greenwich Polar Zone stars with known proper motions [20, 27]. In the analysis of this material he found the same asymmetric drift in stellar motions and its relation to velocity dispersion as discovered by the Swedish astronomer Strömberg (1924, 1925), who for several years had been based at the Mount Wilson Observatory. From the same material he also demonstrated the difference between stars of spectral types B8–A3 and giant stars of types gG0–gK2 in their distribution perpendicular to the galactic plane. In further refinements of this work he and Schalén determined the characteristics for the velocity ellipsoid of the A stars [33], and he checked on the absolute magnitudes determined by the cyanogen criterion [34, 36].

4 NEW DIRECTIONS

While in front of a black-board at the Uppsala Observatory, Lindblad pondered on the meaning of the asymmetric drift, the direction of which was almost perpendicular to the direction towards the central point of Shapley's (1918) system of globular clusters, and the reasons for the relation between drift motion and velocity dispersion, and he suddenly realized the true explanation. He applied the analysis of Jeans (1922) to suggest that the Milky Way galaxy was built up by a number of sub-systems with different velocity dispersions and different flattening rotating around a distant centre [21, 22, 24-26, 28, 30, 32, 35, 37-39, 41]. The development of the theory for the rotation of the Milky Way galaxy by Lindblad and Oort in the later half of the 1920s has been described by the present author in the volume, *Oort and the Universe* (see P.O. Lindblad, 1980). Thereby Bertil Lindblad entered into a life-long study of galactic dynamics and problems associated with the formation and maintenance of spiral structure.

In 1927 Lindblad (Figure 1) was appointed "Astronomer of the Royal Swedish Academy of Sciences", which also implied the directorship of the Stockholm Observatory. The Observatory had been founded in 1748 and was situated near the centre of the city, but at the time of Lindblad's appointment the Academy already had plans to erect a new observatory. It was the task of the new director to decide on completely new instrumentation for this relocated facility, and to identify a location with far better observing conditions (see Lindblad, 1931).

One of the research objectives for the new Stockholm Observatory in Saltsjöbaden was to mount a large-scale attack on the distribution and motions of stars in the Milky Way. Among the first tasks was to find and calibrate spectral criteria suitable for the new instrumentation. The instruments to be used for this work were the 40-cm Zeiss astrograph with objective prism and the 1-m Grubb reflector with a Zeiss quartz-spectrograph mounted at the newtonian focus. The scheme of two-dimensional classification of low dispersion spectra which was developed there (Lindblad & Stenquist, 1934) originated from the earlier work by Lindblad and his Uppsala collaborators, Schalén (1926, 1928) and Öhman (1927, 1930a, 1930b), but was based upon quantitative measurements of densitometer recordings of the spectra. For photometric calibration a coarse grating was placed in front of the objective prism on the astrograph.

Figure 1. Bertil Lindblad in his office at the Stockholm Observatory in Saltsjöbaden

For the early-type stars (B2–F8) the lines measured were Hγ and Hδ and for the late-types (F8–M) mainly the G-band, the line λ 4227, and the strength of the cyanogen absorption at λ 4180. The slope of the spectrum was measured from a series of points in the continuum.

This scheme was the foundation of further work on low dispersion spectra and stellar statistics carried out at Saltsjöbaden with the 40-cm astrograph. One intriguing result of this project was the density distribution of stars across the local spiral arm in Lacerta (see Ramberg 1957), a result that is interesting and puzzling in view of the strong concentration of A stars and later-type giants to the spiral arms. This finding should be confirmed by modern photometric methods. Another important outcome of this research was the derivation of the density distribution of normal stars perpendicular to the galactic plane by T. Elvius (1965), a result which is supported by more recent results (see Gilmore, 1989:12).

Lindblad's early work up to 1940 has been put into the context of Swedish astronomy by Holmberg (1999) and his work on stellar photometry and spectrophotometry has been discussed by Hearnshaw (1986, 1996). Bertil Lindblad died in Stockholm on 1965 June 26.

5 NOTES

1 The author of this paper is the son of Bertil Lindblad.

6 BIBLIOGRAPHY

This bibliography for B Lindblad is complete up to the year 1927.

[1] Bergstrand, Ö. and Lindblad, B., 1916. Om bestämningen af de fotografiskt effektiva våglängderna i fixstjärnspektra. *Arkiv för Matematik, Astronomi och Fysik*, Bd **11**, No. 17.

[2] Lundmark, K. and Lindblad, B., 1917. Photographic effective wave-lengths of some spiral nebulae and globular clusters. *Astrophysical Journal*, **46**:206-218.
[3] Lindblad, B., 1918. Die photographisch effektive Wellenlänge als Farbenäquivalent der Sterne. *Arkiv för Matematik, Astronomi och Fysik*, Bd **13**, No. 26.
[4] Lindblad, B., 1919. On the use of grating spectra for determining spectral type and absolute magnitude of the stars. *Astrophysical Journal*, **49**:289-302.
[5] Lundmark, K. and Lindblad, B., 1919. Photographic effective wave-lengths of nebulae and clusters (second paper). *Astrophysical Journal*, **50**:376-390.
[6] Lindblad, B., 1920. On the distribution of intensity in the continuous spectra of the sun and the fixed stars, and its relation to spectral type and luminosity. *Uppsala Universitets Årsskrift 1920, Matematik och Naturvetenskap*, **1**.
[7] Lindblad, B., 1921. Några intryck från Mount Wilson. *Populär Astronomisk Tidskrift*, **2**:10.
[8] Lindblad, B., 1921. Ett nytt fält för undersökningar med objektivprisma. *Nordisk Astronomisk Tidsskrift*, **2**:85-87.
[9] Shapley, H. and Lindblad, B., 1921. The distances of fifty stars determined from objective prism spectra. *Harvard Observatory Circular 228*.
[10] Lindblad, B., 1922. Spectrophotometric methods for determining stellar luminosity. *Astrophysical Journal*, **55**:85-118.
[11] Lindblad, B., 1922. Note to Dr. Knut Lundmark's and Dr. W.J. Luyten's paper on the determination of the colour-equivalent of a star. *Monthly Notices of the Royal Astronomical Society*, **83**:97-98.
[12] Lindblad, B., 1922. De spektroskopiska metoderna för bestämning av stjärnornas avstånd. *Populär Astronomisk Tidskrift*, **3**:33-42.
[13] Lindblad, B., 1923. On the intensity-distribution in short grating spectra and objective-prism spectra as a function of spectral type and absolute magnitude. *Monthly Notices of the Royal Astronomical Society*, **83**:503-510.
[14] Lindblad, B., 1923. Radiative equilibrium and solar temperature. *Nova Acta Regiae Societatis Scientiarum Upsaliensis, Ser. IV*, **6**(1).
[15] Lindblad, B., 1923. Om solskivans strålning. *Nordisk Astronomisk Tidsskrift*, **4**:129-135.
[16] Lindblad, B., 1924, Note on the distances of the cluster-type variables. *Astrophysical Journal*, **59**:37-44.
[17] Lindblad, B., 1924. Note on the spectroscopic parallaxes of A-type stars. *Astrophysical Journal*, **59**:305-309.
[18] Lindblad, B., 1924. Stjärnornas rörelser. *Populär Astronomisk Tidskrift*, **5**:89-101.
[19] Lindblad, B., 1924. Hur avspeglar sig en stjärnas konstitution i dess spektrum? *Svenska Fysikersamfundets Årsbok 1924*:222-243.
[20] Lindblad, B., 1925. Spectrophotometric determinations of stellar luminosities—the distances and tangential velocities of stars in the Greenwich Polar Zone. *Nova Acta Regiae Societatis Scientiarum Upsaliensis, Ser. IV*, **6**(5).
[21] Lindblad, B., 1925. On the cause of star-streaming. *Astrophysical Journal*, **62**:191-197 (= Upsala Observatoriums Meddelanden, No. 2).
[22] Lindblad, B., 1925. Star-streaming and the structure of the stellar system. *Arkiv för Matematik, Astronomi och Fysik*, Bd **19** A, No. 21 (= Upsala Observatoriums Meddelanden, No. 3).
[23] Lindblad, B., 1925. Om bestämning av stjärnornas yttemperaturer. *Populär Astronomisk Tidskrift*, **6**:13-24.
[24] Lindblad, B., 1925. Stjärnströmningen och universums struktur. *Populär Astronomisk Tidskrift*, **6**:92-98.
[25] Lindblad, B., 1926. On the dynamics of the system of globular clusters. *Arkiv för Matematik, Astronomi och Fysik*, Bd **19** A, No. 27 (= Upsala Observatoriums Meddelanden, No. 4).
[26] Lindblad, B., 1926. Star-streaming and the structure of the stellar system (Second paper). *Arkiv för Matematik, Astronomi och Fysik*, Bd **19** B, No. 7 (= Upsala Observatoriums Meddelanden, No. 6).
[27] Lindblad, B., 1926. Researches based on determinations of stellar luminosities (Second paper). *Nova Acta Regiae Societatis Scientiarum Upsaliensis, Volumen extra ordinem editum 1927* (= Upsala Observatoriums Meddelanden, No. 11).

[28] Lindblad, B., 1926. Cosmogonic consequences of a theory of the stellar system. *Arkiv för Matematik, Astronomi och Fysik*, Bd **19** A, No. 35 (= Upsala Observatoriums Meddelanden, No. 13).

[29] Lindblad, B., 1926. On the decrease of star-density with distance from the galactic plane. *Arkiv för Matematik, Astronomi och Fysik*, Bd **19** B, No. 15 (= Upsala Observatoriums Meddelanden, No. 14).

[30] Lindblad, B., 1926. On the evolution of stellar systems. *Vierteljahrsschrift der Astronomischen Gesellschaft*, **61**:265-267.

[31] Lindblad, B., 1926. Spektralfotometriska undersökningar vid Upsala observatorium. *Nordisk Astronomisk Tidsskrift*, **7**:41-52.

[32] Lindblad, B., 1926. Kosmogoniska problem i samband med nyare föreställningar om stjärnsystemets natur. *Populär Astronomisk Tidskrift*, **7**:125-134.

[33] Lindblad, B. and Schalén, C., 1927. The luminosities, individual parallaxes, and motions of B and A type stars. *Arkiv för Matematik, Astronomi och Fysik*, Bd **20** A, No. 7 (= Upsala Observatoriums Meddelanden, No. 17).

[34] Lindblad, B., 1927. *Summary of Results Concerning the Determination of Absolute Magnitudes by the Cyanogen Criterion*. Almqvist & Wiksell, Uppsala (= Upsala Observatoriums Meddelanden, No. 18).

[35] Lindblad, B., 1927. The small oscillations of a rotating stellar system and the development of spiral arms. *Arkiv för Matematik, Astronomi och Fysik*, Bd **20** A, No. 10 (= Upsala Observatoriums Meddelanden, No. 19).

[36] Lindblad, B., 1927. On the absolute magnitudes and parallaxes of bright stars determined by the cyanogen criterion. *Kungliga Svenska Vetenskapsakademiens Handlingar, Ser.3*, Bd **4**, No. 5 (= Upsala Observatoriums Meddelanden, No. 28).

[37] Lindblad, B., 1927. On the nature of the spiral nebulae. *Monthly Notices of the Royal Astronomical Society*, **87**:420-426 (= Upsala Observatoriums Meddelanden, No. 23).

[38] Lindblad, B., 1927. On the state of motion in the galactic system. *Monthly Notices of the Royal Astronomical Society*, **87**:553-564 (= Upsala Observatoriums Meddelanden, No. 24).

[39] Lindblad, B., 1927. On the cause of the ellipsoidal distribution of stellar velocities. *Arkiv för Matematik, Astronomi och Fysik*, Bd **20** A, No. 17 (= Upsala Observatoriums Meddelanden, No. 26).

[40] Lindblad, B., 1927. Flashspektrum vid den totala solförmörkelsen den 29 juni 1927. *Populär Astronomisk Tidskrift*, **8**:136-139.

[41] Lindblad, B., 1927. On the spiral orbits in the equatorial plane of a spheroidal disk with applications to some typical spiral nebulae. *Kungliga Svenska Vetenskapsakademiens Handlingar, Ser. 3*, Bd 4, No. 7 (= Upsala Observatoriums Meddelanden, No. 31).

7 REFERENCES

Adams, W.S., 1914. An A-type star of very low luminosity. *Publications of the Astronomical Society of the Pacific*, **26**:198.

Adams, W.S. and Joy, A.H., 1917. The luminosities and parallaxes of five hundred stars. *Astrophysical Journal*, **46**:313-339.

Elvius, T., 1965. Distribution of common stars in intermediate and high galactic latitudes. In Blaauw, A. and Schmidt, M., (eds.). *Galactic Structure, Stars and Stellar Systems, Volume 5*. University of Chicago Press, Chicago. Pp. 41-60.

Gilmore, G., 1989. The distribution of stars in space. In Gilmore, G., King, I. and van der Kruit, P. (eds.). *The Milky Way as a Galaxy*. Geneva Observatory, Geneva. Pp. 9-40.

Guthnick, P., 1913. Nachweis der Veränderlichkeit des kurzperiodischen spektroskopischen Doppelsterns β Cephei mittels photoelektrischer Messungen. *Astronomische Nachrichten*, **196** (4701):359-366.

Hearnshaw, J.B., 1986. *The Analysis of Starlight. One Hundred and Fifty Years of Astronomical Spectroscopy*. Cambridge University Press, Cambridge.

Hearnshaw, J.B., 1996. *The Measurement of Starlight. Two Centuries of Astronomical Photometry*. Cambridge University Press, Cambridge.

Holmberg, G., 1999. *Reaching for the Stars. Studies in the History of Swedish Stellar and Nebular Astronomy 1860-1940*. Lund Studies in the History of Science and Ideas, 13.

Jeans, J.H., 1922. The motions of the stars in a Kapteyn-universe. *Monthly Notices of the Royal Astronomical Society*, **82**:122-132.

Lindblad, B., 1931. *Observatoriet i Saltsjöbaden. Minnesskrift vid invigningen av Stockholms observatorium i Saltsjöbaden fredagen den 5 juni 1931*. Kungliga Vetenskaps-akademien. Pp. 20-55.

Lindblad, B. and Stenquist, E., 1934. On the spectrophotometric criteria of stellar luminosity. *Astronomiska Iakttagelser och Undersökningar å Stockholms Observatorium*, Bd **11**, No. 12.

Lindblad, P.O., 1980. Early galactic structure. In van Woerden, H., Brouw, W.N. and van de Hulst, H.C. (eds.). *Oort and the Universe*. Reidel Publication Company. Pp. 59-64.

Lundmark, K. and Luyten, W.J., 1922. On the determination of the colour-equivalent of a star, with special reference to the effective wave-length, and its relation to spectral class: a review of the different methods. *Monthly Notices of the Royal Astronomical Society*, **82**:495-509.

Lundmark, K. and Luyten, W.J., 1923. Note on the determination of absolute magnitude from λ_e and λ_m. *Monthly Notices of the Royal Astronomical Society*, **83**:470-474.

Öhman, Y., 1927. Photometric studies of effects of luminosity and colour in short stellar spectra. *Arkiv för Matematik, Astronomi och Fysik*, Bd **20** A, No. 23 (= Upsala Observatoriums Meddelanden, No. 33).

Öhman, Y., 1930a. The intensity of the hydrogen lines as a criterion of luminosity for B, A and F type stars. *Arkiv för Matematik, Astronomi och Fysik*, Bd **22** B, No. 3 (= Upsala Observatoriums Meddelanden, No. 47).

Öhman, Y., 1930b. Spectrophotometric studies of B, A and F type stars. *Nova Acta Regiae Societatis Scientiarum Upsaliensis, Ser. IV*, **7**, No. 3 (= Upsala Observatoriums Meddelanden, No. 48).

Ramberg, J.M., 1957. The space distribution of stars in selected Milky Way regions derived from photometric and spectrophotometric data. *Stockholms Observatoriums Annaler*, Bd **20**, No. 1.

Schalén, C., 1926. Spectrophotometric determinations of absolute magnitudes of B and A type stars. *Arkiv för Matematik, Astronomi och Fysik*, Bd **19** A, No. 33 (= Upsala Observatoriums Meddelanden, No. 10).

Schalén, C., 1928. The space distribution of B and A type stars in bright and dark galactic regions. *Kungliga Svenska Vetenskapsakademiens Handlingar, Ser. 3*, Bd 6, No. 6 (= Upsala Observatoriums Meddelanden, No. 37).

Schwarzschild, K., 1906. Über der Gleichgewicht der Sonnenatmosphäre. *Nachrichten von der Königlichen Gesellschaft der Wissenschaften zu Göttingen, Mathematisch-Physische Klasse*, **13**:41-53.

Schwarzschild, K., 1914. Über Diffusion und Absorbtion in der Sonnenatmosphäre *Sitzungsberichte der Königlischen Preussischen Akademie der Wissenschaften*, **112**:1183-1200.

Shapley, H., 1918. Studies based on the colors and magnitudes in stellar clusters. Seventh paper: The distances, distribution in space, and dimensions of 69 globular clusters. *Astrophysical Journal*, **48**:154-181.

Strömberg, G., 1924. The asymmetry in stellar motions and the existence of a velocity-restriction in space. *Astrophysical Journal*, **59**:228-251.

Strömberg, G., 1925. The asymmetry in stellar motions as determined from radial velocities. *Astrophysical Journal*, **61**:363-388.

Per Olof Lindblad was the Astronomer of the Royal Swedish Academy of Sciences 1966-73 as successor to his father, Professor at the Stockholm University 1973-93, and is Emeritus Professor from 1994. He was Director of the Scientific Division of the European Southern Observatory (ESO) 1979-81 and President of the ESO Council 1988-90. His main work has been in the field of galactic kinematics.

Reviews

Great Comets, by Robert Burnham (Cambridge University Press, Cambridge, 2000), x + 228 pp., £14.95, $US21.95 paperback, 253 x 202 mm.

For those of us living in the southern hemisphere the term 'Great Comet' immediately conjures up images of a number of nineteenth century favourites: C/1843 D1 with a tail that stretched almost the full length of the sky and was visible in broad daylight; our old friend 1P/Halley which was conspicuous in 1835; C/1858 L1 (Donati) and C/1874 H1 (Coggia) with their impressive tails; C/1861 J1 and C/1881 K1 that were both discovered by Australia's foremost nineteenth century astronomer, John Tebbutt; and successive sun-grazers of the 1880s, C/1880 C1, C/1882 R1 and C/1887 B1. I also have memories of those dual visitors, C/1956 R1 (Arend-Roland) and C/1957 P1 (Mrkos), which left such a vivid visual impression on my teenage mind back in 1957. With the arrival of Burnham's book I was expecting to see vivid accounts of all of these comets, and others, so it was a little surprising to discover instead a book that skipped over these and other Great Comets, in order to focus instead on two much more recent, yet spectacular, visitors, C/1996 B2 (Hyakutake) and C/1995 O1 (Hale-Bopp).

Once over the initial shock I began wading into Burnham's book, and found it to be very readable – and so it should be, for the author is no newcomer to astronomy. An active amateur astronomer since the mid-1950s, Robert Burnham was an editor-in-chief of *Astronomy* magazine between 1992 and 1996, and is the author of many books, including *Comet Hale-Bopp: Find and Enjoy the Great Comet* which was published in 1997. Perhaps it was this volume which inspired him to spread his net wider, resulting in his latest book.

Great Comets is entertainingly written, and its 238 pages are packed with excellent illustrations, many of them in colour. This, indeed, is one of the great strengths of the book. Another is the final chapter, "Staying Current With Comets", which not only provides a basic sample of published works for those seeking further information but also a liberal listing of relevant web sites.

So what else does *Great Comets* offer? In his "Introduction", Burnham identifies three themes that he wishes to pursue: to celebrate the beauty of comets (and particularly Great Comets); to introduce the "... new knowledge that Great Comets have brought to planetary scientists and ... all of mankind ..."; and to "... explore mankind's relationship with comets, which has long been troubled."

Chapter 1, titled "Great Comets and Astronomy", is by far the longest chapter in the book (at 46 pages), and it needs to be as it sets the scene for what follows. In it we review mankind's changing views on comets from ancient times through to the present day, examine current thinking on the composition and behaviour of comets, discuss where comets fit in to the overall picture of the solar system's formation and evolution, and learn about the naming of comets. All this leads up to an interesting chapter on what makes a comet 'Great', and Burnham opts for David Hughes' five familiar criteria plus one added by Don Yeomans. A Great Comet must

(1) have a large nucleus and coma,
(2) have a large active surface area,
(3) reach perihelion near the Sun,
(4) pass close to the Earth,
(5) provide good viewing opportunities for observers, and
(6) be conspicuous to the naked eye in the night sky.

Sometimes a Great Comet can make a major contribution to cometary astronomy by appearing at a particularly auspicious time in astronomical history. Hyakutake and Hale-Bopp both fall into this category, as Burnham clearly demonstrates, but an earlier comet for which such credit is generally not given is C/1881 K1, one of Tebbutt's two discoveries. This Great Comet just happened along at a time when important developments were taking place in astronomical photography and spectroscopy, and as a result it was the first comet for which successful photographs and spectrograms were obtained. In addition, the behaviour of its head and tail built on data provided earlier by C/1858 L1 (Donati) and C/1874 H1 (Coggia). That famous nineteenth century chronicler of astronomical history, Agnes Clerke (1893:425-426), reports that "Tebbutt's comet ... was, in the opinion of some, the finest object of the kind since 1861." More recently, ways in which this 1881 Great Comet aided our understanding of cometary science have been detailed in a paper published in the *Irish Astronomical Journal* (see Orchiston, 1999).

Burnham concludes chapter 2 with an all too briefly examination of one of the key topics in contemporary solar system astronomy: "When is a comet not a comet?" He points out that "... some objects follow comet-like orbits but show no evidence of cometary activity. And other objects, traveling in asteroid-like orbits, have developed gas and dust comas and even display small tails. Finally, there is at least one inert object whose orbit matches that of a meteor stream ..." (p. 74). His discussion of Centaurs, asteroid-comets and comet-asteroids occupies a mere two-and-a-half pages and provides but a tantalizing taste – how I yearned for more.

Our two most recent Great Comets, Hyakutake (1996) and Hale-Bopp (1997), occupy chapters 3 and 4 respectively, and collectively span 59 pages filled with all sorts of interesting information and a succession of stunning photographs. C/1996 B2 (Hyakutake) offered two main surprises: unexpected X-ray emission, and an abundance of methane, acetylene and ethane. Not to be outdone, C/1995 O1 (Hale-Bopp) entertained professional and amateur astronomers for almost two years, revealing an unusually large nucleus, the first-ever sodium tail and the first cometary detections of eight different molecules.

If we wish to engage in really close-up investigations of comets then we must rely on space missions, and this is the topic of Chapter 5. Not only are we told about the five different space craft that provided invaluable information on 1P/Halley in 1986 and earlier space craft and orbiting observatories that supplied data on other comets, but there is a very useful diagram on page 140 that lists the different probes that are due to rendezvous with various comets over the next eleven years. The coming decade promises to be an exciting era for cometary astronomy.

With chapter 6, Burnham leads us on a new path, to explore the ways in which comets – and particularly Great Comets – have impacted on cultures over the ages. Beginning with Greek, Roman and Chinese perceptions, including the 'harbinger of doom' scenario, we speed past familiar names like Newton and Halley and enter the nineteenth century, with its never-ending cavalcade of Great Comets. Burnham reminds us that in 1910, "Regular doses of Halleyana became a feature of public discussion." (page 183) as 1P/Halley assaulted the human psyche. Editors, cartoonists, music publishers, advertisers and telescope-salesmen had a field day, but then public panic set in when it was realised that the Earth would pass through the tail of the comet, with its deadly cyanogen gas. However, as Burnham could have pointed out, to set their minds at rest all people had to do was reflect on Tebbutt's Great Comet of 1861 (C/1861 J1) when exactly the same situation occurred yet no-one perished (see Orchiston, 1998). Today's public is supposedly more scientifically literate, yet in March 1997 we read with dismay of the Heaven's Gate disaster with its tenuous link to Comet Hale-Bopp.

Burham's final chapter also focusses on Great Comets and culture, but in a totally different context: the potential they have to end culture as we know it here on planet Earth. In "Danger From the Sky" he regurgitates the now-familiar 'nuclear winter' scenario associated with a major cometary or asteriodal impact, lists recent near misses, discusses the annual incidence of meteorite falls and introduces us to the Spaceguard Survey. Despite this somewhat pessimistic stance I finished the book feeling somewhat reassured, for Burnham points out on page 215 that the probability of my meeting death through a major celestial impact event is comparable to my chances of dying in an aeroplane crash, that is, about 1 in 20,000. But despite these rather favourable odds, it is reassuring to know that increasing numbers of observatories worldwide are taking up the search for NEOs (Near Earth Objects). This is money well spent; it may prove to be an investment in our very future.

So to a final assessment. I believe that Burham has achieved all of the goals that he spelled out in his "Introduction". But he has done more than this: notwithstanding the somewhat misleading title, he has produced an excellent general introductory work, with plenty of historical perspectives for those of us with a penchant for astronomical history. There are many books about comets on the shelves of my library, but this particular volume proved to be one of the most readable and enjoyable. And at just US$21:95 it is very affordable, so why not add it to your library.

Wayne Orchiston

References

Clerke, A.M., 1893. *A Popular History of Astronomy During the Nineteenth Century*. Adam & Charles Black, London.

Orchiston, W., 1998. Illuminating incidents in Antipodean astronomy: John Tebbutt and the Great Comet of 1861. *Irish Astronomical Journal* **25**:167-178.

Orchiston, W., 1999. C/1881 K1: a forgotten "Great Comet" of the nineteenth century. *Irish Astronomical Journal* **26**:33-44.

Sur les traces des Cassini, Astronomes et observatoires du sud de la France, actes du 121[e] Coongrès des sociétés historiques et scientifiques, section d'histoire des sciences et des techniques, Nice, octobre 1996, sous la direction de Paul Brouzeng et Suzanne Débarbat (Sodis, Editions du CTHS, Ministère de l'éducation nationale, de la recherche et de la technologie, France, 2001), 360 pp., ISBN 2-7355-0425-5, FR 203,35 €31, soft cover, 240 × 160 mm.

The Dark or Medieval Ages (5th to 15th centuries – Europe) was notable for a crushing of cultural progress and stagnation of trade and commerce. However a rebirth or Renaissance of human endeavour commences with intellectual awakening – scientific knowledge and experience of the divine arise, as a great creative effort of a new era of Humanism. Copernicus (1543) publishes *De Revolutionibus*, asserting the Sun as centre of the solar system, orbited by planets. New optics technology yields the telescope (1609), microscope (1610) and their application to scientific research develops human insight of the infinitesimal and the infinity of the Cosmos. Printing in the sixteenth century with vernacular teaching and discourse, vastly enriches literature and the sciences.

With this material readers embark in the footsteps (*"Sur les traces des Cassini"*) of the Cassini family dynasty and since several generations of Cassinis occupied key positions at the Observatory of Paris, a national observatory established in the years 1667 to 1671, their history also describes well that of the institution and astronomy itself in France. As a matter of interest, Leiden Observatory, Holland, began in 1637, Copenhagen 1657 and the Royal Greenwich Observatory (RGO) was established 1675.

The Golden Age of Science, first evident in Italy, crosses borders to other states to flourish throughout Europe and is based on observational confirmation of theoretical models and not mysticism nor astrological predictions. Universities and other institutions arise to teach science, medicine and philosophy. Art and technology are important for revival of knowledge. In France observatories and universities yield intellectual awakening and new knowledge in astronomy. The Cassini dynasty arises and contributes vastly.

An Italian-born French astronomer, Giovanni Domenico Cassini was born 1625 June 8 in Parinaldo near Nizza (Nice) and died 1712 September 14 in Paris. In 1650 he became professor at Bologna and from 1669, summonsed by Louis XIV, he took charge of the observatory in Paris, then under construction and organized its activities. Cassini was a zealous and successful astronomical observer. He discovered (among other things) the rotation of Jupiter, the division named after him in the rings of Saturn and four of the moons of Saturn, determined the rotation of Mars, co-operated in determining the solar parallax, and is claimed to have made the earliest systematic observations of the zodiacal light. Cassini's son, Jacques (1677-1756), his grandson, Caesar Francois (1714-1784), and his great-grandson Jacques Dominique (1748-1845) succeeded him in turn as Directors of the Paris observatory.

At the 121[st] Congress of the National Society for history of science and technology at Nice, France, 1966 October 26-31, 32 presented papers by different authors honour the achievements of French astronomers, their research and astronomical facilities. Edited by Paul Brouzeng and Suzanne Débarbat, *In the footsteps of the Cassinis* is five Chapters of rich and original archival material, arranged as themes:

1. **Astronomy at the Cassinis, a family affair:** Three natives of Perinaldo, Astronomers of the Paris Observatory; G. D. Cassini, Pupil of the Jesuits; Perinaldo, countryside of astronomers

(who) rediscover their Cassinis; Jean-Dominique Cassini, the last director of Paris Observatory under L'Ancien Régime, told by himself.
2. **The contributions of Cassini to the science of Astronomy:** Astronomical Research by G.D. Cassini at Bologna, 1649-1669; J.-D. Cassini and his English Colleagues; J Cassini, J Gregory, C Huygens – their distance determinations, Sirius to Earth; The Perfect Engineer, author Cassini III.
3. **Use of fruitful heritage, the Cassini school:** The Chart of Cassini, Scientific Work and the Exigencies of its Use; On Correspondences received by the Cassinis and the Maraldis; Notara, a Pupil of Cassini; A descendant of the sister of Jean-Dominique Cassini (1625-1712); The wealth of the Library of the Observatory of Paris.
4. **Research and discovery:** The first astronomical discoveries made at Marseilles: Pythéas le Massaliote; A Marseilles astronomer travels: Father Louis Feuillé in the South Seas 1704-1771; The scientific voyage in Italy of G Rayet and the establishment of Bordeaux Observatory; Voyage to South Sea by Amédée Frézier: navigation rules and longitude correction; Francis Xavier of Zach and astronomy in Southern France; Work & observational results on the solar diameter at Côte d'Azur Observatory.
5. **Site selection and establishment of observatories:** Astronomy and astronomers in Languedoc in the eighteenth century; The erudite astronomers of Provence: Peirese and Gassendi; G. Rayet, Founder and First Director of the Observatory of Bordeaux; establishment and history of the Observatory of Bordeaux at Floirac; Observatory at Pic du Midi of Bigorre: Men and missions; The birth of the Observatory of Nice.

An interesting and typical example is the paper by Christiane Demeulenaere-Douyère, "The Cassini Family and the Academy of Sciences", being their successive association over several generations in the French Royal Academy of Sciences. The Cassini-Maraldi family merits particular examination and the study begins, naturally enough, with the foundation of the dynasty. And that by F. Grossi, Engineer: Three natives of Perinaldo, astronomers of the Paris Observatory, "At Perinaldo, a community located 20 kms north of Vintimille, there is a dwelling above whose door one reads an inscription: here were born G.D. Cassini on the 8th of June 1625, died in Paris 14th September 1712, G-F Maraldi on the 17th April 1709, died at Perinaldo on the 14th November 1788". The castle Maraldi of Perinaldo, as it is called, was the birthplace of three astronomers who in the second half of the seventeenth century and the first half of the eighteenth century, have illumined the observatory of Paris. The study relies upon the archives of the Maraldi and Scribani Rossi which allow the tracing of the sister of Cassini I, become Maraldi then Grossi and Manuel-Gismondi, up to 1854." Another example is that written by J. Casanovas, Astronomer, Vatican: "G. D. Cassini, Pupil of the Jesuits: Following an experimental period, the teaching of mathematics in Jesuit schools was fixed by the *Ratio Studiorum*. Mathematics comprised geometry, arithmetic, music and astronomy. It was in this context that G.D. Cassini was a student of the Jesuits at Genes."

Colloquium participants visited the actual birthplace of the Cassinis and Marinaldos courtesy of the Compte de Nice, also viewing their town and two churches, town hall, as well as the Exposition which the community of Perinaldo installed during 1994 as a homage to one of their most illustrious sons, Jean-Dominiques Cassini (1625-1712) and to his descendants. Their previously unpublished documents reveal the role played by the prestigious dynasty of the Cassini family in the appointment of explorers, navigators, and scientists whose initiatives and projects – exploration, construction of observatories (particularly in the South of France) – were inspired by methods used by the greatest figures of science. They are of immense value to students of history and science alike. Indeed this 121st Congress of the Historical and Scientific Society was convened at Nice, at the invitation of the group for history and techniques, to acknowledge the scientists and the institutions of this region.

This book will be well appreciated by those for whom French is a first or second language. It may well be promptly translated to English, however note the delay of four years from the Congress at Nice to production as text in the original tongue. The style is elegant and clear, as befits the original language of science.

Importantly, the name of Cassini remains honoured by science. In 1655 Huygens discovered Titan, the second largest moon (only Jupiter's Ganymede is bigger) in our solar system. Launched 1997 October 15, ESA/NASA jointly will use an orbiter (Cassini) and a probe (Huygens) to investigate Saturn's giant moon Titan – commencing 2004 July 1, four centuries after Cassini the Elder developed Paris Observatory for King Louis X1V. [*note: Cassini's first and second flybys of Titan occur 26 October and 13 December. As the Cassini Orbiter orbits Titan's cloud tops at an altitude of 65 000 km the Huygens Probe will be released towards Titan 25 December for an entry into the moon's atmosphere 22 days later, 2005 January 14. While Cassini continues to explore Saturn and its rings, the Huygens probe is now released to parachute through Titan's thick orange atmosphere – considered to resemble that of the very early Earth*]

Isobel Nikoloff

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"ASTRONOMICAL INSTRUMENTS AND ARCHIVES FROM THE ASIA-PACIFIC REGION"

CALL FOR PAPERS

An international conference on "Astronomical Instruments and Archives from the Asia-Pacific Region" will be held in Cheongju, Korea, between 2-5 July 2002 to commemorate the inauguration of the Nha Il-Seong Museum of Astronomy.

This Conference is organized by IAU Commission 41 and the newly-formed Inter-Union Commission for History of Astronomy (ICHA), and will constitute the first formal conference and meeting of the ICHA. In Korea, the Conference will be sponsored by the City of Cheongju, the Korea Astronomy Observatory and the Ministry of Science and Technology. Meanwhile, the following Scientific Organizing Committee has been set up:

Professor Il-Seong Nha (Korea: Chairman), Professor Richard Stephenson (UK: Deputy-Chairman), Dr Wayne Orchiston (Australia: Secretary), Dr Christine Allen (Mexico), Dr Suzanne Débarbat (France), Dr Kwan-yu Chen (USA), Dr Steven Dick (USA), Professor Alexander Gurshtein (Russia), Dr Bambang Hidayat (Indonesia), Professor Rajesh Kochhar (India), Dr Lui Ciyuan (China), Dr Tsuko Nakamura (Japan), Professor Boonraksar Soonthornthum (Thailand)

The programme will include paper sessions, C41/ICHA business meetings, a city tour and a visit to the Korea Astronomy Observatory, one or two dinners and a banquet. For the paper sessions we are seeking papers about individual or small groups of related archives or historic astronomical instruments that are either from, or relate to, the Asian region, any of the Pacific nations, or American countries that have Pacific Ocean coastlines. Most of those selected by the SOC to deliver papers will be assigned 20-30 minutes (including question time); other titles offered will be accepted as poster papers. If you would like to offer a paper, please forward your title and abstract to all three under-signed by 2002 April 30, or to either Il-Seong Nha (The Nha Il-Seong Museum of Astronomy, San-133 Gamcheon-myon, Yechon-gun, Kyungbuk 757-910, Korea) or Wayne Orchiston (Anglo-Australian Observatory, PO Box 296, Epping, NSW 2121, Australia) if using ordinary airmail.

The plan is to publish all papers in a conference proceedings, and Professor Nha and Drs Debarbat and Orchiston have agreed to serve as co-editors.

This Conference will be held in the city of Cheongju, which is 128 km south-east of Seoul. Cheongju has an international airport, and is also accessed from Incheon International Airport (with a connecting shuttle bus). Accommodation will be in tourist hotels, with a nightly room rate of between US$50 and US$70 depending on the number of bookings. The Conference registration fee is US$100 if paid by 2002 May 1 and US$120 thereafter. This fee includes a copy of the conference proceedings, the welcome banquet and one or two dinners, the city tour and the Observatory excursion. There is a registration fee of US$70 for accompanying guests.

For further details please consult the Conference Web site:

http://www.nhamuseum.org/conference2002

This contains a registration form, plus travel and accommodation details. Those seeking additional information should contact Professor Nha.

We look forward to seeing a good turnout of C41/ICHA members at this Conference, our last before the Sydney General Assembly in July 2003.

Il-Seong Nha (SLISNHA@chollian.net)
Richard Stephenson (f.r.stephenson@durham.ac.uk)
Wayne Orchiston (wo@aaoepp.aao.gov.au)

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Cover illustrations show a series of images of the η Carinae area beginning with a drawing by John Herschel published in 1847, a black and white photograph taken by Ben Gascoigne with the MSSSO 40-inch reflector at Siding Spring, a colour photograph taken by David Malin with the AAO 150-inch at Siding Spring, and a view taken with the Hubble Space Telescope, courtesy J Morse (U. CO), K Davidson (U. MN), and NASA.