The Royal Greenwich Observatory

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[Plates 1 to 4]

The Royal Observatory was established by King Charles II in the year 1675 for the specific practical purpose of 'rectifying the tables of the motions of the heavens, and the places of the fixed stars, so as to find out the so-much-desired longitude of places for the perfecting the art of navigation'. At that time the most accurate star catalogue available was the catalogue of 1000 stars, prepared by Tycho Brahe about 1598; only 777 of the stars had been properly observed, and the star places, whose average errors were of the order of 1′ to 2′, were not sufficiently accurate for the purpose of determining longitudes. The best tables for giving the position of the Moon were liable to errors as great as 20′. Flamsteed, who was appointed the first Astronomer Royal, realized that a good stock of observations, continued for many years, was needed in order to provide star places with all the accuracy that was attainable and to furnish positions of the Sun, Moon and planets which could serve as the basis for the construction of satisfactory tables of their motions. So, from its very foundation, the Observatory started upon systematic and long-continued programmes of observation which, throughout its history, have formed its most significant and important contribution to astronomy.

Meridian astronomy

Until after the middle of the eighteenth century, when William Herschel embarked upon his studies of the structure of the sidereal system and upon his observations of star clusters, nebulae and double stars, astronomical observation was concerned almost entirely with the positions and motions of the heavenly bodies. But long after Herschel's pioneer work had opened up new fields of investigation, the observations at Greenwich continued to follow closely the lines originally laid down. There were improvements, of course, in the design and construction of instruments and in their optical quality; there were progressive refinements in technique and progressive improvements in accuracy, which in turn opened up new fields of investigation. The observations which Bradley made at Greenwich between 1750 and 1762, amounting to about 60,000 in all, were of a higher accuracy than any made previously and are, in fact, the earliest observations which are precise enough to be of use to the astronomers of to-day. Bradley was particularly careful in examining the errors of his instruments and in keeping the instruments in the best adjustment; he was the first to introduce corrections to atmospheric refraction for the temperature of the air and for the height of the barometer.

Halley in 1718 called attention to the fact that three of the bright stars, Sirius, Procyon and Arcturus, had changed their positions since Greek times, and that Sirius had perceptibly changed its position since the time of Tycho Brahe; the fixed stars were not, in fact, fixed, and the study of their proper motions added a new interest to the determination of stellar positions. Bradley himself discovered the two phenomena of stellar aberration and of nutation. William Herschel, by analyzing the proper motions of fourteen stars which had been determined with accuracy by Maskelyne at Greenwich was able to show that the Sun itself had a motion relative to the stars. The improvements in the tables of the motions of the Sun, Moon and planets, which resulted from the progressive increase in accuracy of observation and from the fact that observations were made all round their orbits, enabled the great Continental mathematicians of the eighteenth century, Euler, Clairaut, D'Alembert, Lagrange and Laplace, to prove that within the limits of accuracy of observation the movements of the bodies in the solar system could be accounted for in detail on the sole hypothesis of the Newtonian theory of gravitation.

These facts are mentioned to emphasize that the determination of the positions and motions of the Sun, Moon, planets and stars is work of fundamental importance in astronomy. It demands continuity of observations over a long period, made with the greatest care and precision. It was the work for which the Observatory was founded; it is the work which must always be its first concern, for it is work that is never completed but that will always go on. In 1875 Airy, after reviewing the work of 40 years at Greenwich since his appointment as Astronomer Royal, in the course of which he had expanded the work into various new directions, remarked:

'Turning now from the past to the future, I see little in which I could suggest any change. If it should ever be necessary to make any reduction, I should propose to withdraw Meteorology, Photoheliography, and Spectroscopy; not as unimportant in themselves, or as ill-fitted to the discipline of the Observatory, but as the least connected with the fundamental idea of our Establishment.'

Until well into the nineteenth century, meridian telescopes for the determination of position formed essential equipment of most observatories. Many amateurs even made regular meridian observations and provided significant contributions to positional astronomy. But as new fields of investigation in astronomy have been developed, meridian observations have been discontinued at most observatories. They make heavy demands on observing resources and involve much computational work. For this branch of astronomy, continuity of observations with the same instruments over a long period is of the greatest value. Such observations are therefore not well fitted for University or private observatories. It is proper that they should be undertaken almost entirely, as in fact they are to-day, by the national observatories. In recent years the systematic pursuit of meridian observations has tended to be restricted more and more in the northern hemisphere to three observatories, Greenwich, Washington and Pulkowa. During the war the Pulkowa Observatory was completely destroyed, though it is now being rebuilt on a larger scale, and meridian observations will continue to form an important portion of its work. At the end of 1940 meridian observations at Greenwich had to be discontinued for the first time in the history of the Observatory; the complete discontinuance was not for long, but until after the end of the war it was possible to carry on the observations only on a small scale.

The purpose of meridian astronomy is to provide a fundamental system of reference, defined by the positions and proper motions of a network of stars distributed with reasonable uniformity over the whole sky, together with the numerical value of the constant of precession. The observations are made from a moving and rotating earth and it is convenient to use the equator as a plane of reference and the equinox as a zero point. Both the equator and the equinox depend upon the motion of the Earth and the motion of its axis; they can therefore be determined by observations of the Sun which, in effect, fix the orbit of the Earth, or by observations of the bright inner planets, which involve the elements both of the orbit of the planet and of the orbit of the Earth. Observations of the Sun are peculiarly liable to errors of a systematic nature, while observations of the inner planets, showing perceptible disks and phases, are liable to personal errors which are different from those that affect star observations. There is the further difference that observations of the Sun and planets are made by day, while the star observations are mostly made at night.

The position of the pole can be determined from observations of circumpolar stars, and the position of the nadir can be determined from observations with a mercury horizon. The two together will fix the equator point. There are normally systematic differences between the equator point fixed in this way and the equator point deduced from Sun and planet observations. The circumpolar observations, above and below pole, are made 12 hr. apart; they may be affected by systematic diurnal effects, by errors in the corrections applied for refraction, by changes in the instrumental adjustments, by instrumental flexure, which is different for the two observations, and by errors in the adopted figure of the instrumental pivots. There are consequently many possibilities of errors of a systematic or quasi-systematic nature. When observations of stars in the equatorial belt made at a northern and at a southern observatory are compared, systematic differences are generally found. The observations can be brought into agreement by adjusting the coefficients of refraction used in the reductions of the observations at the two observatories, but the corrections so obtained are usually found to be quite inadmissible.

The observations made with the conventional type of transit circle are, in fact, liable to many sources of error which are difficult to control adequately. If the same stars are observed with two different transit circles and the derived positions are compared, it is found that, in addition to random errors of observation, there are systematic errors in both right ascension and declinations which vary with right ascension and also with declination. Magnitude error in right ascension, which affected observations made by the old methods of eye and ear and of hand-tapping, have been practically eliminated by the use of the impersonal micrometer.

The sources of error with the conventional transit circle are numerous. The errors of instrumental adjustment—of level, of azimuth, and of collimation—are continually varying. The variations are difficult to control adequately. If the meridian opening in the transit pavilion is narrow, refraction anomalies are inevitable; with a wide opening, the instrument is fully exposed to the wind and to temperature changes. The errors of azimuth are particularly difficult to control, unless the site is one which permits of fixed azimuth marks of high stability. Corrections must be applied for any departure of the figures of the pivots from perfect cylindricality; the determination of the figures of the pivots with accuracy and with freedom from spurious elliptical terms is not easy. Instrumental flexure can be determined only in the horizontal position of the telescope, so that a law of variation with zenith distance must be assumed. The telescope is turned in the course of observation into all sorts of positions, with possibilities of displacements of objective or of the mechanical parts of the micrometer, which may be sufficiently small to escape easy detection but which can introduce serious errors of a systematic nature.

The difficulty of eliminating systematic errors of instrumental origin can be illustrated by the reversible transit circle of the Cape Observatory, which was designed by Sir David Gill with much thought and care. The telescope can be reversed in its bearings, giving two positions for observation, denoted by E and W; the object glass and eye-end are arranged to be interchangeable, giving two arrangements denoted by I and II. Four separate combinations are therefore possible. After allowing for the difference in horizontal flexure in the two conditions I and II, the difference in the declinations measured in the two conditions has a regular run amounting to $0''\cdot 4$ from dec. $+40^\circ$ to the south pole. The difference between the two positions E and W in both conditions has a range of $0''\cdot 18$, but the difference is systematically larger in condition II than in condition I, the extreme differences being $0''\cdot 3$ and $0''\cdot 2$ respectively. The mean of the observations in the four separate combinations is adopted as likely to provide the closest approximation to the truth.

Because of these systematic errors of instrumental origin, the proper motions of stars must be based largely upon series of catalogues observed over many years with the same instrument, whereby the instrumental peculiarities are to a large extent eliminated. The observations made at Greenwich are of special importance for this purpose, as the Airy transit circle, which defines the prime meridian of longitude, has been used continuously since 1851. With this instrument more than 650,000 observations have been made. The last three programmes consisted of the observations of all the stars down to about the 8th magnitude in the zones of declination 0° to $+32^\circ$, $+32^\circ$ to $+64^\circ$, $+64^\circ$ to $+90^\circ$, supplemented by fainter stars in regions of high galactic latitude, together with numerous observations of a large number of fundamental stars. Thus the whole of the northern sky has been covered. The proper motions of the stars have also been investigated. The Airy instrument does not accord with modern ideas for the construction of a transit circle; it is not reversible in its bearings; it is housed in a pavilion which has buildings on each side with a narrow opening and liability to refraction anomalies; the terrain is asymmetrical to north and south, with the possibility that the atmospheric refractions north and south of the zenith may not be equal. The instrument has now reached the end of its useful life. A new transit circle, reversible and housed in a pavilion of semi-cylindrical shape, with a wide aperture and a fairly symmetrical terrain to north and south, was installed shortly before the war. Before bringing this instrument into regular use, it has been subjected to a lengthy series of investigations, in the course of which the errors of the circle graduations and of the figures of the pivots have been determined with great accuracy. These investigations have thrown much light upon various ways in which the observations can be affected by systematic or quasi-systematic errors of instrumental origin.

These remarks have been made to illustrate the difficulties and complexities of meridian astronomy and to explain why observations of position must still be continued. The observations made at different times and with different instruments at different observatories are combined, by a process of adjustment which is to a large extent empirical, to form what is termed a fundamental system, so providing a system of reference that is more accurate than it is possible to obtain from observations with a single instrument and, moreover, covering the whole sky. The more effectively the various sources of error can be eliminated or controlled with each particular instrument, the more reliable the fundamental system will be. Both the places of the stars and their proper motions, as given in the fundamental system, are affected by errors; the errors of the star places increase with the lapse of time from the epoch of the system, so that successive revisions of the system become necessary. A process of gradual approximation, which still continues, is involved.

With the realization of the serious difficulties involved in the use of a large movable telescope for the accurate determination of positions, it is natural that consideration should be given to alternative designs of instruments in which the movable parts are reduced as much as possible. The use of a fixed telescope in conjunction with a moving plane mirror has more than once been suggested; a design of such a mirror transit circle has been developed at Greenwich. It is proposed to employ two fixed horizontal telescopes, with their axes in the meridian and their objectives facing a movable mirror, whose plane is parallel to the east-west axis of rotation. Stars would be observed in one or the other telescope according to whether they transit north or south of the meridian, while the two telescopes would serve also as collimators. Such an arrangement reduces moving parts to a minimum. The fixed telescopes can be of longer focal length than is convenient for a movable telescope, and they can be effectively insulated against rapid temperature changes. Observations of nadir, of level and of near-zenith stars can be taken in either telescope. Flexure effects are reduced to a minimum, while troubles arising from small displacements of micrometer parts or of objectives are entirely eliminated. The adaptation of a variable-speed motor drive to the micrometer wire is simplified. A small model of the proposed design has been constructed and the theory of the instrument has been investigated. The instrument appears to have great possibilities and it is hoped to try it out in practice.

Closely related to the meridian astronomy is the determination of the variation of latitude caused by the movement of the Earth's axis of rotation relative to the Earth. The pole has an irregular motion within a circle of about 30 ft. radius; it contains two principal components, of periods 12 and 14 months, but the motion is not sufficiently regular to predict ahead. The component of the motion along the meridian of a place causes a change of latitude; the component in the perpendicular direction affects time determinations. The complete motions can be determined by observations of the variations of latitude at two places whose longitudes differ by about 90°. The variation of latitude was first established in 1888; Chandler afterwards found it clearly exhibited in observations back to 1750. Determinations were first made at Greenwich with the Airy reflex zenith tube, but the observations were not entirely satisfactory. A long series of observations was commenced in 1911 with the Cookson floating zenith telescope, the observations being made photographically. Pairs of stars at nearly equal distance north and south of the zenith are observed at meridian passage; each star makes a trail across the plate, the telescope being rotated through 180° between the observations of the two stars. The separations of the pairs of trails are measured, and the variations in latitude are deduced from the changes in these separations. Meridian observations of declination are corrected for the variation of latitude. A new photographic zenith tube, now under construction, will be used, when completed, for the determination of the variation of latitude as well as for time determination. The study of the polar motions raises many interesting problems and provides a means for the determination both of the constant of nutation and of the constant of aberration.

Time Department

The provision of a time service is a normal function of a national observatory and is closely related to the work of the meridian department. The right ascension of a star is the sidereal time of meridian transit of the star. In positional astronomy a selected number of the brighter stars in the equatorial belt, suitably distributed round the sky, are selected as 'clock stars'. The positions and proper motions of the clock stars, as used at Greenwich, have been derived from the long series of meridian observations and are progressively refined as the observations continue. Observations extending from 6 to 12 hr. serve to control periodic errors in the right ascensions of the clock stars. Using these adopted right ascensions, the observations of the clock stars determine the errors of the standard sidereal clock night by night. The right ascension of any other star is derived by correcting the observed sidereal time of its transit for the clock error, interpolated for the time of transit.

Before 1927 the time determined at the Royal Observatory was based upon observations with the Airy transit circle. In 1926 a world programme of longitude determinations, in which a large number of observatories in all parts of the world participated, was undertaken under the auspices of the International Astronomical Union. For this special programme, a small reversible transit circle was used at Greenwich, the telescope being reversed near the middle of each transit, thereby eliminating the correction for collimation error. For such a programme it is necessary to adopt a common system of star places, in order to ensure that the derived longitudes are as free as possible from systematic errors in star positions determined with different instruments; in this particular programme the star places in Eichelberger's *Fundamental Catalogue* were used. It was found that the clock errors derived from these observations had a much smoother run than the clock errors derived concurrently from observations with the Airy transit circle. The latter are affected by obscure instrumental errors, to which reference has already been made. It was found, moreover, that when the smoother clock errors provided by the small transit observations were used for the reduction of the Airy transit circle observations, the derived right ascensions of the stars became discordant; but that when the more irregular errors given by the transit circle observations were used, the derived right ascensions became accordant. The instrumental peculiarities of the transit circle are evidently involved.

Since 1927, therefore, the time determinations have been based entirely upon observations with small transit instruments, which are reversed in the middle of each transit. By resolution of the International Astronomical Union the revised Auwers fundamental system, known as the FK3, is used for the system of star places. The apparent places of the stars are taken from the annual volume *Apparent Places of Fundamental Stars*, published by the Nautical Almanac Office.

Prior to 1923 the standard clocks employed in the Royal Observatory were regulator clocks with Graham dead-beat escapements. A Cottingham clock, fitted with a Riefler escapement, installed after the first World War, was expected to give a higher standard of performance, but failed to come up to expectations. The development of the Shortt free-pendulum clock introduced a new standard of precision in time-keeping. In this type of clock a master pendulum, mounted in an airtight case, exhausted to a pressure of about 1 in. of mercury, and placed in a constant-temperature room, synchronizes a slave clock of commercial type. The master pendulum swings freely, except when given a small impulse once each half-minute, and is relieved of the work of moving a train of wheels to show the time on dials and of sending out signals. The first clock of this type, Shortt no. 3, was installed at the Observatory in November 1924 and soon showed its superiority over other types of pendulum clock. Other clocks of this type were therefore installed and used both as sidereal and as mean time standards in the Observatory.

The introduction of the new standards resulted in an important change in the system of time employed. The transit of the first point of Aries or the vernal equinox defines the beginning of the sidereal day, 0 hr. sidereal time. But the precessional motion of the true equinox is not uniform, being affected by irregularities, due to solar and lunar perturbations, which are known as *nutation*. In consequence the sidereal day varies slightly in length. If we imagine a point moving uniformly along the equator, with a motion equal to the mean motion of the true equinox, and so that its extreme distances from the true equinox on both sides are equal, we may term this point the *mean equinox*. The sidereal time determined by observation is *apparent sidereal time*. A *mean sidereal time* can be defined by reference to the mean equinox, in which all days are of equal length; it is obtained by subtracting the nutation from the apparent sidereal time. Apparent sidereal time was good enough before the introduction of the Shortt free-pendulum clocks; their superior precision made it necessary to introduce the concept of mean sidereal time, which has been universally adopted. The detailed study of the performance of the Shortt clocks at Greenwich, which proved their superiority over other types of pendulum clocks, stimulated their introduction into observatories in many parts of the world.

The Royal Observatory is responsible for the distribution of time to the public. The first steps in the distribution outside the Observatory became possible with the development of telegraphic communications. In 1852 an electric clock was installed at the Observatory, which transmitted a signal each day that caused a time-ball, on the offices of the Electric Telegraph Company in the Strand, to drop. In 1865 signals were sent hourly to the Electric and International Telegraph Company's office, whence they were distributed over the railway network of the country. After the telegraph system was taken over by the Post Office, in 1870, a complete system for the hourly distribution of time through the Post Office was gradually developed, which made Greenwich time widely available. A further step in the widespread dissemination of accurate time followed naturally upon the development of broadcasting. Two of the Dent regulator clocks were modified to run as synchronized clocks under the control of one of the mean time free pendulums, and were provided with a system of contacts to enable time signals to be transmitted automatically every quarter of an hour to the British Broadcasting Corporation. The signals were in the form of six dots at intervals of a second, the last coming exactly at the hour, the quarter, or the half hour. These signals are the familiar B.B.C. 'six pips' Greenwich time signal, which, since 5 February 1924, have been transmitted on all B.B.C. wave-lengths several times daily.

A further service, designed to be of value for navigation, was commenced on 19 December 1927. From that date radio time signals have been sent out on a frequency of 16 kc./sec. twice daily, at 10 and 18 hr. G.M.T., from the Observatory, via the Rugby wireless station. These signals, which last for 5 min., are of the so-called vernier type, spaced 61 to the minute, enabling the error of a chronometer to be accurately determined by observing the instants of coincidence between the signals and the ticks of the chronometer. Corrections to the times at which the signals were emitted are published by the Observatory at approximately monthly intervals, for use where higher precision is required, as, for instance, in survey operations. For the distribution of these signals a special 'diminished seconds' slave clock was installed, whose pendulum swings 61 times in a minute, and which is kept in synchronization by the mean-time master pendulum. The service has more recently been extended by simultaneous transmission of the time signals on several short wave-lengths. The introduction in 1936 by the Post Office of the 'speaking clock', designed by the Post Office engineers and constructed at the Post Office Research Station, which is automatically controlled by hourly time signals from the Observatory, has made accurate time continuously available.

It is necessary that the Observatory should keep abreast of developments in precision horology so that the time service can meet all demands for precision that are made upon it. After the development of the quartz crystal clock, it soon became evident that a new standard of precision in time-keeping had been reached. It was therefore decided to instal a clock of this type at the Observatory in order that some direct experience could be gained of its performance in comparison with the performance of the free-pendulum clocks. A clock, using a Dye-Essen ring crystal, was constructed under the supervision of the National Physical Laboratory and installed in 1939. The quartz vibrator was adjusted to have a frequency of 100 kc.

per sidereal second; demultiplier circuits provided an output with a frequency of 500 cycles per sidereal second, which was used to drive a phonic motor. Although the performance of this clock was not altogether satisfactory, experience showed that it was free from the small erratic changes of rate to which the pendulum clocks were liable and which made prediction uncertain; it was found also that it would be more convenient, when additional quartz clocks were installed, to employ a fundamental frequency of 100 kc. per mean solar second instead of per mean sidereal second.

The outbreak of war stopped for a time developments which had been planned for an improved time service. A skeleton time service was at once installed at the Abinger Magnetic Station as a safeguard against the possibility of the service from Greenwich being put out of action. Towards the end of 1940 when the frequent air raids made night observations impossible at Greenwich, the time service was moved in its entirety from Greenwich to Abinger. Shortly afterwards a second time service was installed at the Royal Observatory, Edinburgh, with the co-operation of the Astronomer Royal for Scotland. For the remainder of the war, the two time stations, at Abinger and Edinburgh, were in use; the two stations were connected by direct land line with teleprinter communication, enabling clocks at either station to be recorded at the other station.

Plans were proceeded with for the installation of quartz-controlled frequency standards. The first group of three clocks was installed in 1943. These clocks, which were constructed at the Post Office Research Station, were of the Post Office Group IV type, in which a GT-cut plate of quartz is maintained in oscillation at 100 kc. per mean time second, by a bridge drive circuit, which reduces to a minimum the effect of variation in the supply voltages. The crystals are mounted in thermostatically controlled ovens, and the temperature range permitted by the modified Turner circuit employed ensures that variations in frequency from this cause are small. Regenerative frequency dividers are used to provide an output at 1000 c./sec., which can operate phonic motors, provided with contacts from which signals can be taken off.

The installation has since been considerably extended and the time service is now based upon six groups of three quartz crystal clocks, four of the groups being at Abinger, where the main time-service station has remained, and two at Greenwich, enabling a time service of much higher precision to be provided than was possible with pendulum clocks. The quartz clocks have the further advantage that relative errors and rates can be obtained much more readily and with much greater accuracy than with pendulum clocks. For measuring time and frequency differences, decimal counter chronometers are used, embodying scale-of-ten counter circuits. The 100 kc./sec. output from one of the primary standards is fed into the counting unit. A seconds impulse from one clock can be applied to start the count and a seconds impulse from another clock to stop it. A single reading of the time difference between the two clocks is obtained, being shown on five dials reading successively in units of tenths, hundredths, thousandths, ten-thousandths, and hundred-thousandths of a second. To provide a check, the roles of the two clocks can be interchanged. Alternatively, by throwing over a switch, a series of successive readings may be obtained, when the results are added in the counter. This procedure is of value when the intervals are nominally constant but are subject to small erratic variations, as when comparing a clock with a time signal; ten consecutive readings can then be obtained with advantage. For frequency comparisons, the nominal 100 kc./sec. outputs from two clocks are fed into a comparator, where the levels are adjusted to a standard value. The adjusted outputs are then combined and the resultant beats are shown on a meter. By means of a trigger circuit, a pulse is sent to the decimal counter when the beat-frequency voltage passes through zero. The intervals between the beats are thus accurately timed, enabling frequency differences to be determined with an accuracy of at least one part in 10^{10}. The quartz clocks are provided in addition with automatic beat counters; by automatic counting of the number of beats between each pair of oscillators in a 24 hr. period, the change in the time difference between each pair of clocks in the course of a day is recorded in units of 10^{-5} sec. The intercomparisons between each pair of clocks, in each group of three, provides an automatic check against incorrect action of any of the beat counters.

An additional advantage of the quartz crystal clocks is that though they are rated approximately to mean time they can serve all purposes. Separate sidereal time clocks and diminished seconds transmitters for the rhythmic time signals are no longer required. The phonic motors, driven by the 1000 c./sec. output from one of the clocks, can be adapted to these additional requirements. In the phonic motors used at the Royal Observatory, the rotor consists of a laminated iron ring with 100 teeth cut on its inside surface. The six-pole stator within the rotor has corresponding teeth cut on its pole faces. The motor runs synchronously at 10 revolutions per second, driving by gearing a commutator wheel at one revolution per second. A contact spring, bearing on this wheel, closes an electrical circuit for one-tenth of each second. In order to obtain sidereal seconds, a special gearing is used. The gearing ratio employed is $\frac{119}{114} \times \frac{317}{330}$, which is about four parts in 10^9 smaller than the correct ratio. This small error in the gear ratio is immaterial, for when the rate of the clock in mean-time milliseconds has been determined, the rate of the sidereal impulses, in sidereal-time milliseconds, can be at once inferred.

The rhythmic time signals consist of a long dash at the minute, followed by a series of dots spaced at intervals of $\frac{1}{61}$ min. These signals are derived from a contact drum, which is driven through a 60/61 gear from a phonic motor. In order that the signals may be sent out at the desired instants, a phasing adjustment is provided for the signal transmitter. There are day-to-day variations in the time lag introduced by the land-line joining the Observatory to the Rugby wireless station. Some test signals are transmitted a few minutes before the time signals themselves; these test signals are received and recorded at the Observatory and by comparing the times with those of the outgoing signals, the land-line lag is deduced. An adjustment to correct for the lag is made by rotating the phonic motor stator, thus advancing or retarding the phase of the rotor. A rotation of the stator housing by 360° advances or retards the contact time by one-tenth of a second.

The most recent phonic motor equipment installed at the Observatory provides a complete contact assembly for the control of all the time signals sent out, including not only the rhythmic signals but also the B.B.C. 'six pips' time signals and the hourly signals for the control of the Post Office speaking clock.

The use of quartz clocks has resulted in a much improved precision in the time service. Their freedom from small erratic changes of rate makes accurate short-term prediction possible. This is of importance for the control of precision frequency standards, which can be checked against a 24 hr. time interval of high precision. The Rugby 10 hr. time signals are transmitted so as to give an accuracy in the 24 hr. interval between the signals on consecutive days which does not normally exceed 1 msec. The difficulties of accurate long-term prediction, which is needed to carry over periods during which no time determinations can be obtained, are much greater. The quartz crystal oscillators are subject to an ageing effect, which causes a drift in frequency, more rapid at first and gradually decreasing, though never, as far as present experience is a guide, completely disappearing. Time determinations extending over some months are needed in order to derive the frequency drift with the accuracy needed for prediction. But a complication is introduced by the motion of the Earth's poles, which causes small displacements of the meridian; the result is that a perfect clock, compared with absolutely accurate time determinations, would appear to have a small variable error, which at Greenwich can amount to about ± 25 msec. As the polar motion has two principal components, with periods of 12 and 14 months, an incorrect determination of frequency drift is inevitable unless the effects of polar motion can be allowed for. The motion of the pole along the meridian can be determined by observing the changes of latitude which result from it; the motion in the perpendicular direction can be determined only from observations of latitude variation at another observatory, differing by about 90° in longitude. The determinations of latitude variation at Washington, longitude 77° W, are communicated regularly to Greenwich and are used to correct for the effects of polar motion and thereby to derive more accurate values of the frequency drifts of the clocks. It is noticeable that the application of these corrections has appreciably smoothed the apparent errors of the clocks.

The introduction of quartz crystal clocks has demanded an improvement in the precision of the time determinations. The period of several months, which is required for a satisfactory determination of frequency drift with the relatively large errors inherent in the time determinations with the small transit instruments, could be much reduced if an appreciable reduction in the errors of observation were achieved. Much consideration has therefore been given in recent years to the design of new instruments for time determinations.

A photographic zenith tube, which is expected to reduce the probable error of a time determination to a few milliseconds, is now in an advanced stage of construction. This instrument is based on Airy's design of the reflex zenith tube at Greenwich, with modifications to adapt it for photographic observation due to F. E. Ross and incorporated in his photographic zenith tube, now in Washington. The essential principle is the employment of a zenith telescope, whose tube contains a mercury horizon to reflect the light and to bring it to a focus in the second Gaussian point of the objective, thereby making the observations practically independent of any error of level. The important modification introduced by Ross was the inversion of the objective, placing the flint component uppermost, whereby, with an appropriate separation between the two components, the second Gaussian point is brought a few millimetres below the lower face of the crown component. The observations are made photographically, the photographic plate being mounted in the Gaussian plane. The instrument was designed originally for the measurement of the variation of latitude; the upper portion of the instrument, which carries the objective and the photographic plate, is in the form of a rotary, which can be turned through exactly 180°. If two exposures are made on a star, the rotary being turned through 180° between them, the separation between the two images in the direction of the meridian is twice the zenith distance of the star. In practice, exposures of finite length are given, the plate carriage being travelled along during each exposure with the speed of motion of the star image. If the two exposures are accurately timed and are approximately symmetrical about the instant of meridian transit, the time of transit can be inferred from the small relative displacement of the images in the direction perpendicular to the meridian.

The advantages of this type of instrument for time determination are considerable. The observations being photographic, personal equations are eliminated. Errors of level do not affect the observations; there is no collimation correction to trouble about; observations in the zenith are independent of azimuth error. As the instrument is fixed, the various sources of error to which a moving instrument is liable cannot occur. A longer focal length can be used than is possible with a moving instrument, with the advantage of a correspondingly greater scale. Observations are restricted to the zenith, where atmospheric transparency is highest and refraction effects are at a minimum.

The instrument which has been designed at Greenwich differs in a number of important respects from the Washington instrument:

(i) It has a larger aperture (10 in.) and longer focal length (135 in.).

(ii) A plain ball-bearing is used for constraint of the rotary, in place of conical bearing, in order to reduce friction and to facilitate construction.

(iii) An autocollimation method is used as a criterion of the angle of reversal of the rotary.

(iv) As a fixed axis of rotation is not required for (iii), a definite constraint in the horizontal plane is not needed. The two working orientations are each defined by a pair of stops instead of by a single stop.

(v) Adjustments to the objective are provided for squaring-on and for coincidence of the nodal plane and photographic plate.

(vi) Automatic reversal is accomplished by means of a system of wires which exert a pure torque on the rotary and therefore no tilting torque on the tube. The system is such that unidirectional rotation of the driving shaft is converted into reciprocating rotation of the rotary.

(vii) The plate carriage is annular and the plate-holder mount is circular so that symmetry of diffraction pattern is secured. The carriage constraints are external to the aperture.

(viii) Relative motion of the carriage and rotary is made to approximate to pure translation by means of a compensating system of flexed rods, which constrain the carriage in the horizontal plane to which the motion is restricted by means of three balls that roll between horizontal planes.

(ix) Uniformity of rate in the relative translation of carriage and rotary is obtained by a specially designed system comprising a differential roller and metallic tapes.

(x) The time scale is produced photographically by means of a clock-controlled lamp giving flashes of very short duration. An independent chronograph is not required.

(xi) The height of the mer ury surface is accurately adjustable and, as criterion of adjustment for constancy of scale value, an optical null method has been introduced for use in conjunction with a suspended silica rod.

Some consideration has also been given to the design of a new type of transit instrument, designated as the Horizontal Transit Instrument. The essential feature is that the telescope system remains fixed (though adjustable) with its axis horizontal and in an east-west direction. The light from a star of any declination, near the position of meridian transit, is directed along the optical axis by a subsidiary optical system of constant deviation, which can be rotated about an east-west axis and can be set to the appropriate declination. The effect on time determination of its positional errors (whether due to maladjustment of the axis of rotation or to pivotal errors) is reduced to the second order. Level and azimuth errors of the telescopic system have the same effect on the observed time of transit as they do with the ordinary transit instrument; but since the telescopic system is not deliberately subjected to gross mechanical disturbances and suffers from no pivotal errors, these level and azimuth errors should be far more stable than in the reversible instrument. The collimation error is dealt with by duplication of the telescopic system and reversal of the subsidiary system, so that the essential advantage of the reversible instrument is not sacrificed. Observation is made at the common focal plane of the duplex telescopic system, from the two sides successively. The fixity of the telescopic system avoids errors due to flexure, and permits of the use of a focal length considerably greater than can profitably be used in the ordinary reversible instrument. The level is determined with reference to two mercury surfaces, one at each end of the instrument, by means of an autocollimation method.

Instead of following the star image with a movable micrometer wire, a variable-deviation system is used by which the light in the telescopic portion of the instrument is kept always axial as the direction of the incident starlight rotates. In this way the tolerances of certain essential adjustments are greatly increased. Further, this variable-deviation system acts also as a micrometer and as the means by which signals are sent to the chronograph. An additional advantage of this axial method is that the fiducial line that bisects the star image is not required to move in order to follow the star's image or to be linked to the signalling system as at present. Thus no mechanical errors are introduced at this point. An optical method is contemplated for defining the position of the variable-deviation system in such a way that in its performance as a micrometer or signal emitter the system will be effectively free from the effects of mechanical errors. A thorough examination of the theoretical aspects of the design has been completed.

Magnetic and Meteorological Department

The first extension of the work of the Observatory beyond that laid down in the Royal Warrant for its foundation came with the setting up by Airy in 1840 of a magnetic and meteorological department. Certain meteorological data are of importance for the astronomical observations; atmospheric refraction depends upon the barometric height and the temperature; atmospheric transparency, an important factor in photometric observations, is correlated with horizontal visibility; the measured variation of latitude depends to some extent upon the direction of the wind; the amounts of sunshine, of rainfall, and of clear sky at night give some indication of the general observing conditions. The astronomer has to make his observations at the bottom of a dense atmosphere, and it is only to be expected that atmospheric conditions can influence the observations in many different ways. The effects are often unsuspected and obscure in origin and may not be discovered until results are analyzed; it was, for instance, quite unsuspected in advance that the measured latitude would depend upon the direction of the wind, though not upon its velocity. With a complete record of meteorological data, the basic data are available for any purposes of subsequent analysis. The Observatory makes continuous records of wind direction and pressure, of the total flow of air, of dry- and wet-bulb temperatures, of barometric height, of rainfall, of sunshine by day and of clear sky at night—the last being recorded by the trails of Polaris and of δ-Ursae Majoris obtained with a small fixed camera pointing to the pole. Daily eye observations are made of the barometer, dry-bulb and wet-bulb thermometers, radiation and earth thermometers, of the amount of cloud and of visibility. Some of the instruments used, such as the anemometers, are not of the most modern type, but the long series of observations made according to a uniform plan and with the same instruments is of special value for climatology. The Greenwich series of observations does, in fact, hold a unique place in British climatology. The data are of importance for various statistical purposes, such as questions of public health, the occurrence of epidemics, etc.; the meteorological results are therefore sent weekly to the Registrar-General. Observations are communicated daily to the Meteorological Office.

Magnetic observations were commenced in 1840 at the same time as the meteorological observations. Though not closely related, the magnetic and meteorological observations have always been in the charge of one department of the Observatory. This was primarily a matter of administrative convenience, to keep the non-astronomical work separate from the astronomical.

When the magnetic observations were started, they were made visually every 2 hr. throughout the day and night, but on one day each month they were made at 5 min. intervals throughout the 24 hr. This severe and trying labour was eliminated by the introduction in 1848 of continuous photographic registration, which has been maintained ever since, though with various changes and improvements in the recording instruments. A century of photographic registration has therefore been completed; the records are stored at the Observatory and are of great value in a variety of investigations.

In 1923 it became necessary to remove the magnetic observations from Greenwich because of the plans for the electrification of the local railway system. A site was selected near Abinger, on the slopes of Leith Hill, in Surrey, where a new magnetic observatory was built and observations were commenced in 1924. At that time the absolute observations of horizontal intensity were made with the Kew magnetometer, and those of dip with the dip inductor, which had superseded the dip circles in 1913. A few years later coil magnetometers were introduced as the standard instruments for the absolute measurement of horizontal and vertical intensity. The Schuster-Smith coil magnetometer for the measurement of horizontal intensity was installed in 1927, and the Dye coil magnetometer for the measurement of vertical intensity in 1928. Both these instruments were constructed at the National Physical Laboratory and are on loan to the Observatory from the Laboratory. The potentiometers used in conjunction with them are checked from time to time at the National Physical Laboratory.

The Schuster-Smith coil magnetometer has proved greatly superior to the Kew unifilar magnetometer in both speed and accuracy. The speed of observation is particularly valuable when conditions are at all disturbed. The base-line values of the horizontal intensity magnetograph deduced from the absolute observations have an uncertainty of not more than 1γ. The scatter of the base-line values of the vertical intensity magnetograph, deduced from the absolute observations with the Dye coil magnetometer is a little greater, but the uncertainity is only about 2γ or 3γ. This instrument is adopted as the standard for vertical intensity, the dip being deduced from the observed values of the vertical and horizontal intensities.

Absolute observations of declination are made several times every weekday, using for reference an azimuth mark whose azimuth is controlled by observations of Polaris; those of horizontal and vertical intensity are made daily, except Sundays. Frequent observations of horizontal intensity are made with the Kew magnetometer and of dip with the dip inductor; these observations serve as a general check on the observations with the coil magnetometers and are not otherwise used.

The Royal Observatory was the pioneer in using electrical coil instruments as standards; it is of interest to remark that a small systematic difference between the dip inferred from these observations, and the dip measured directly with the dip inductor was traced to an unsuspected defect in the inductor, arising from slight play in the bearings of the rotating coil.

The recording variometers, which record declination, horizontal intensity, and vertical intensity, are of the well-known la Cour type. They include both slow-run and quick-run variometers. Records are also obtained with declination and horizontal intensity magnetographs of low sensitivity, which are of value in following the field changes during great magnetic storms when the large rapid movements cannot always be followed with certainty on the normal records. The published data include the hourly means of each element throughout the year, together with the monthly mean hourly values and the means for the five international quiet days and the five international disturbed days each month; the daily mean and daily extreme values for each element, with the corresponding monthly means for all days, for the quiet days, and for the disturbed days; the mean diurnal inequalities for each month, for the year, and for winter, equinox, and summer, of declination, dip, horizontal intensity and for north, west, and vertical components, for all days, for international quiet days, and for international disturbed days separately; the harmonic components of the diurnal inequalities of north, west, and vertical components, for each month, for the year, and for the three seasons, for all days, quiet days, and disturbed days; together with mean monthly and annual values for all elements.

The daily magnetic character figures, and the 3-hourly range indices are assigned on the basis of the daily records and are communicated regularly to the international centre at De Bilt. As opportunity offers, the estimation of the 3-hourly range indices is being carried backwards through the long series of Greenwich records, providing data of fundamental importance in many geophysical investigations.

The Royal Observatory has for some 30 years assumed the responsibility for the preparation of the world magnetic charts which are published by the Hydrographic Department of the Admiralty. Charts of declination are prepared at 5-yearly intervals; of horizontal intensity and of dip at intervals of 20 years. During the war, in connexion with the degaussing of ships as a protection against magnetic mines, a world chart of vertical intensity was prepared. It has been decided that charts of horizontal intensity, of dip, of vertical intensity, and of total intensity will be prepared in future at intervals of 10 years, in accordance with a recommendation of the Association of Terrestrial Magnetism of the International Union of Geodesy and Geophysics. The preparation of these charts involves the collection and examination of magnetic observations and surveys made in all parts of the world; from these observations the secular change and the rate of change of secular change have to be inferred in order to reduce the observations to a common epoch and to extrapolate to the epoch for which the charts are prepared.

Since the untimely loss of the non-magnetic ship, the *Carnegie*, put an end to the long series of ocean magnetic observations undertaken by the Department of Terrestrial Magnetism of the Carnegie Institution, Washington, the magnetic data over some of the ocean regions, and particularly over the southern Indian Ocean, have become increasingly uncertain. Reports received from vessels of the mercantile marine were sufficiently concordant to justify some empirical corrections to the charts. The matter was discussed with the Hydrographer of the Navy and, as a result of representations made to the Board of Admiralty, the construction of a non-magnetic ship was decided upon. The ship, known as the R.R.S. *Research*, was in an advanced stage of construction at the time of the outbreak of war, when work had to be suspended. The possibility of completing the ship, except for the auxiliary engines, and of putting her into commission as a sailing ship is under consideration, though no decision has yet been reached.

The harmonic analysis of the world magnetic charts and the comparison between the observed and computed field at various points on the earth's surface can give some indication of areas where the charts are seriously in error. The charts for 1922 and 1942 were analyzed in this way, and in each case it was found that the computed position of the north magnetic pole was not in agreement with the adopted position, which was determined by Amundsen in 1904 and was in close agreement

FIGURE 1. View of Flamsteed's original observatory (Wren building) looking north.

FIGURE 2. View from the 26-inch dome, looking towards the Wren building (circa 1930).

(*Facing p.* 156)

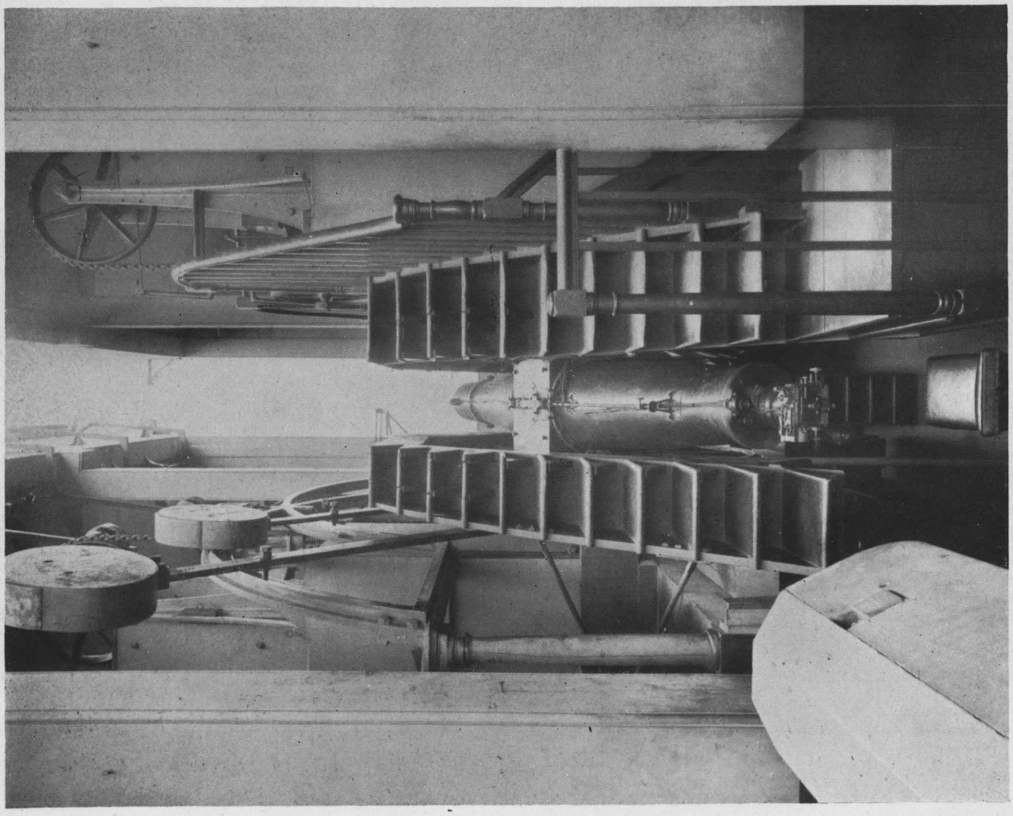

FIGURE 3. Airy transit circle.

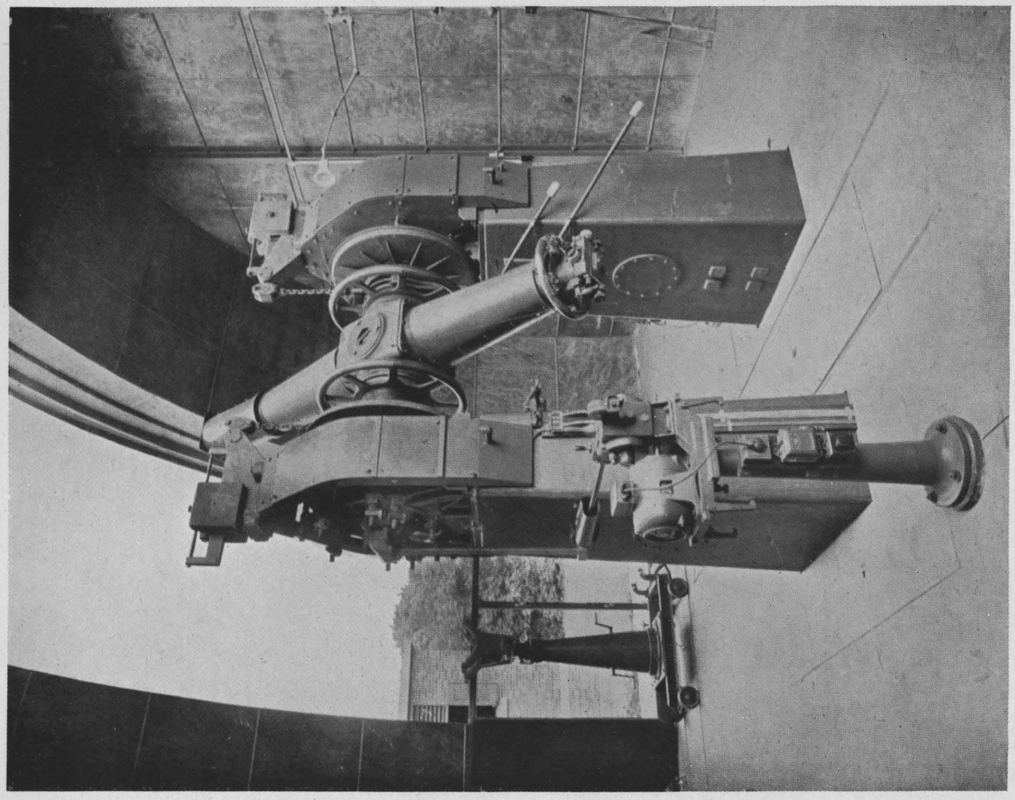

FIGURE 4. Reversible transit circle.

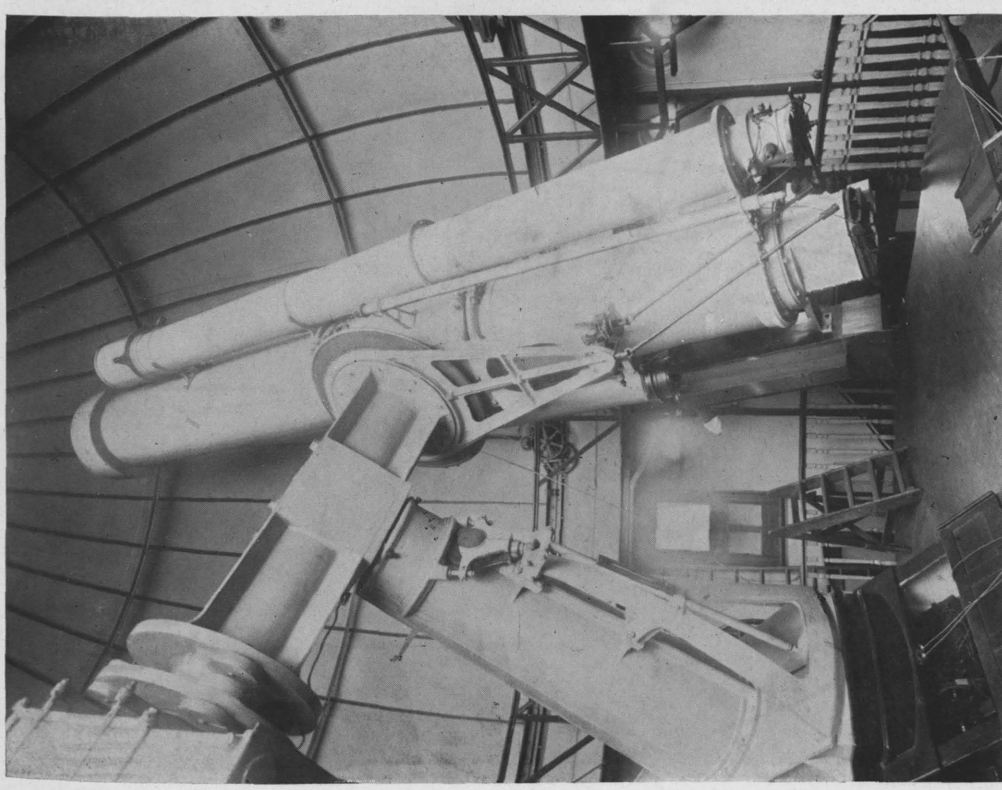

FIGURE 5. Thompson 26-inch refractor.

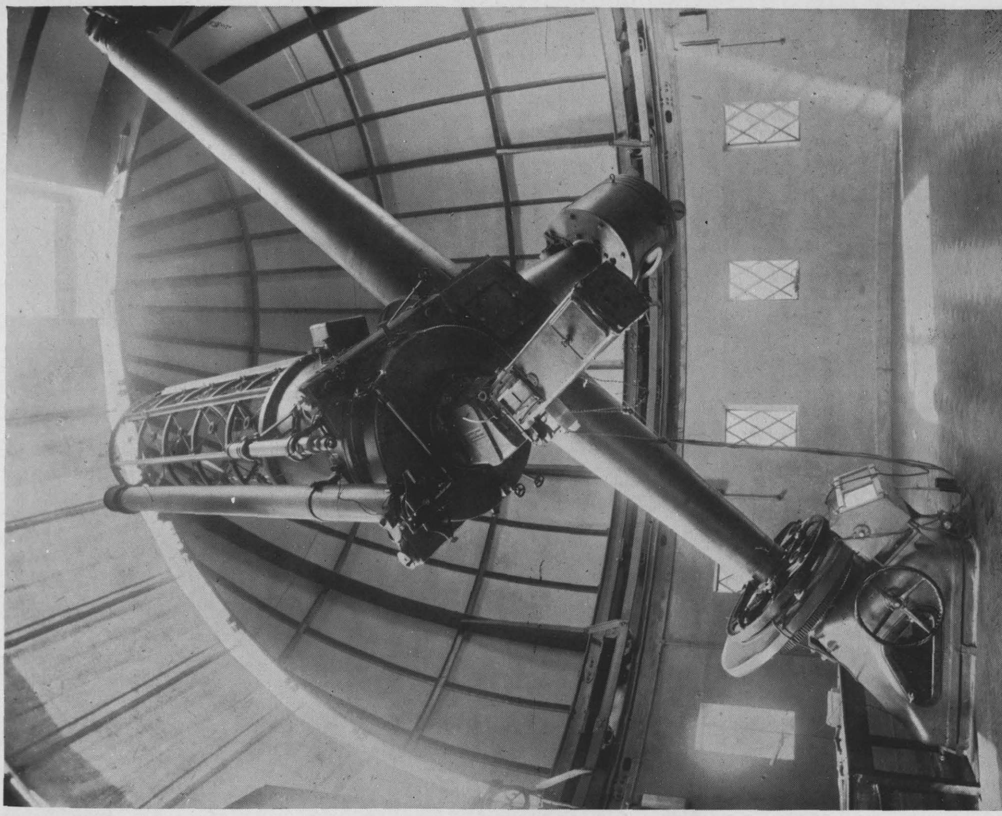

FIGURE 6. Yapp 36-inch reflector.

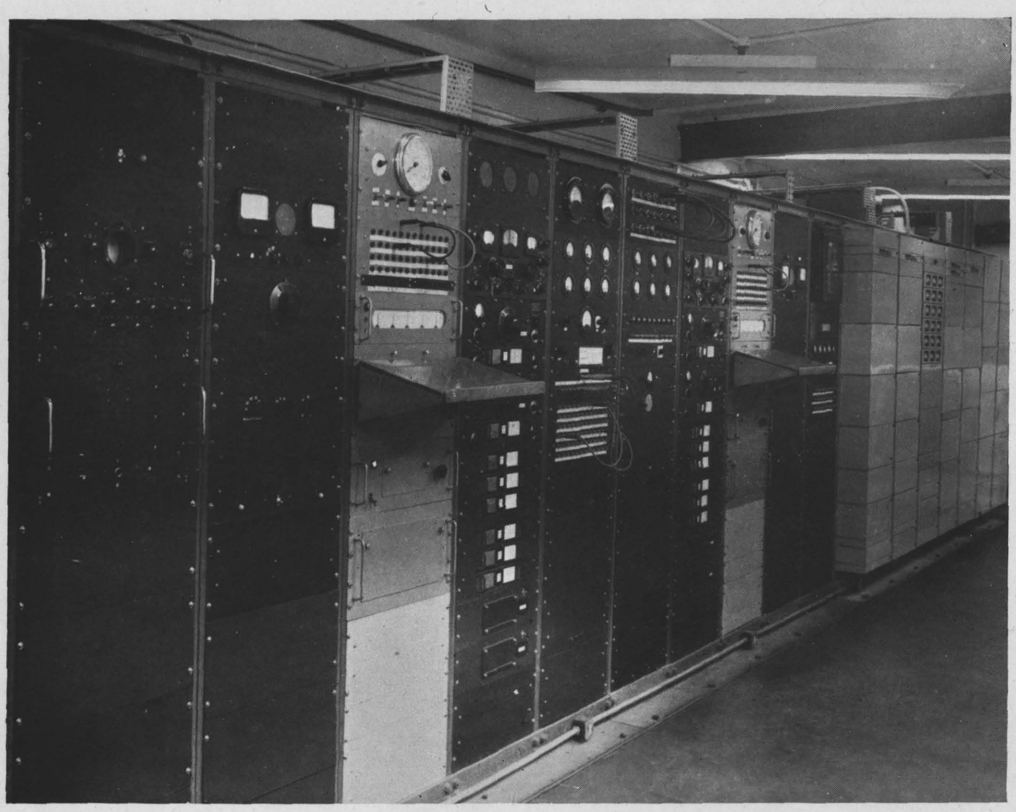

FIGURE 7. Control-room of Time Department.

FIGURE 8. General view of Herstmonceux Castle.

with the position assigned by Ross in 1831. The discordance appeared to be too great to be attributable entirely to errors in the charts, and it appeared probable that the magnetic pole had moved appreciably from its position in 1904, in a direction somewhat to the west of north. When in 1945 a series of polar flights by the Lancaster aircraft *Aries* was being planned by the Empire Air Navigation School, there seemed to be an opportunity for obtaining some evidence on this question. The Commandant of the Empire Air Navigation School agreed that such observations as were possible in conjunction with the other objects of the flight should be undertaken. One of the flights actually made passed over the Amundsen position of the magnetic pole and another passed near the computed position. The results of these flights provided strong supporting evidence for the movement of the magnetic pole. More recent observations made by the Canadian Eastern Arctic Patrol have fully confirmed the displacement, though not by so large an amount as the harmonic analysis had suggested.

Since the termination of magnetic observations at the Kew Observatory, the Royal Observatory has taken over the responsibility for the testing and certification of magnetic instruments of different types. This work is undertaken not only for Government Departments and Colonial Governments, but also for various institutions and commercial firms.

THE SOLAR DEPARTMENT

The magnetic observations, which are of some importance for navigation, led to a further development, which has no connexion with navigation. About the middle of the nineteenth century it was discovered independently by Sabine, Lamont and Wolf that magnetic phenomena have a period similar to the 11-year sunspot period, which had been announced shortly before by Schwabe. It was also found that magnetic storms often occurred when there was a large spot near the centre of the Sun's disk. The relationship suggested the need for supplementing the magnetic observations by solar observations. The solar department was accordingly established by Airy in 1873. A photo-heliograph, in which the primary image of the Sun is magnified by an enlarging lens to give an image 8 in. in diameter, was installed, and the regular daily photography of the Sun, whenever conditions permitted, was commenced. These observations have been continued without interruption. Photographs with a similar instrument are made at the Cape Observatory and are forwarded to Greenwich. There are normally but a few days in the year which are not represented in the combined Greenwich and Cape series; photographs for the missing days can usually be obtained on request from either the Kodaikanal Observatory or the Mount Wilson Observatory. The positions and areas of sunspots and faculae appearing on each photograph are measured. A general catalogue of sunspots and ledgers both of recurrent and of non-recurrent groups are prepared from the measures. The total areas of umbrae, of whole spots, and of faculae for each day are computed, as well as the mean areas and heliographic latitudes for spots north of the equator, for spots south of the equator, and for all spots. The collected results provide the most complete information that is available about sunspots and faculae, and one of importance in the study of the relationships between solar and terrestrial phenomena.

The sunspot data have been used at Greenwich in a variety of investigations. The position of the Sun's axis was determined from the observations of sunspots in the period 1874 to 1912, using both recurrent groups and groups observed for eight or more days; the data were analyzed for three complete spot cycles separately, for four different phases of the cycle, and for the three chief zones of heliographic latitude. The inclination of the Sun's axis of rotation to the ecliptic was found to be $7^\circ\ 10'\cdot 5$, and the longitude on the ecliptic of the ascending node to be $73^\circ\ 46'\cdot 8$ (epoch 1850·0). The motions of recurrent spots observed in five complete spot cycles, from 1878 to 1933, have been analyzed to determine the Sun's rotation period and its dependence upon heliographic latitude. The rotation periods derived from the five separate cycles were in excellent agreement, in contrast to the large secular change given by spectroscopic observations; the sunspots, however, because of their cyclic fluctuation in frequency, cannot be used to determine the rotation period year by year.

Many investigations have been made at Greenwich of the relationships between sunspots and terrestrial magnetic disturbances. The general statistical relationship between the occurrence of magnetic storms and the sunspot state of the central region of the Sun at the times of occurrence of the storms has been fully established. The largest storms tend to be associated with the largest spots; on the other hand, though the largest spots have a strongly marked tendency to persist for several rotations, the largest storms show little or no tendency to recur after 27 days—the period of the solar rotation—whilst moderate storms show a marked recurrence tendency. When a spot appears to be the source of a magnetic disturbance, the spot is usually situated, at the moment when the storm begins, between 2 days east and 4 days west of the Sun's central meridian.

In 1929 solar observations were extended to include visual observations of the Sun's disk in Hα light, using a spectroheliscope lent by the Mount Wilson Observatory. The initial purpose of these observations was to detect any special disturbances on the Sun that might be related to the occurrence of magnetic storms. Measurements are made, with the line-shifter, of the radial velocities of dark markings and, in particular, of those in the neighbourhood of sunspots. The intensities of bright Hα flocculi and of prominences relative to the adjacent background are determined with a simple form of wedge photometer fitted with a comparison lamp. Visual measures of the contour of the normal Fraunhofer line Hα at the centre of the disk are also made.

A special study has been made of the bright chromospheric eruptions or solar flares. The sunspot activity was on the wane when the spectrohelioscope was installed. By 1936 sunspot activity, having passed a minimum, was increasing rapidly. The number of flares showed a correspondingly rapid increase. By 1937, when the number of flares had still further increased, the association between the flares and sudden fadings of short-wave radio transmissions, more particularly in the case of the larger and brighter flares, had been fully established. The simultaneity of the two phenomena implied that the radio fadings were due to a solar agency travelling with the speed of light. A direct comparison photometer to enable the peak intensities of the flares to be rapidly measured in relation to the adjacent continuous spectrum at 15Å from Hα was constructed in the workshop and installed in 1939.

The flares are found to occur mainly in the vicinity of large sunspots when in the stage of active development. In a number of instances the full sequence of phenomena has been observed; the brilliant eruption with the synchronous radio fade-out, accompanied by a typical bay or crochet on the magnetic trace, followed at an interval of the order of 1 day by a great magnetic storm. The solar influence on geomagnetic disturbance has led to the study of various geomagnetic phenomena. It is found that there is a marked diurnal variation in the times of sudden commencements, with a minimum at about 8 to 9 hr. G.M.T. A small proportion of sudden commencements have the initial movement in a direction opposite to the normal; these 'reversed' sudden commencements show an entirely different diurnal frequency, with a maximum at the time when the normal sudden commencements show minimum frequency.

The Brentwood radio station of Cable and Wireless Ltd. reports direct to the Royal Observatory any radio fade-out while it is in progress. Ionospheric data are sent regularly to Greenwich by the Superintendent, Radio Research Station, Slough, the Engineer-in-Chief, Radio Branch, G.P.O., and the Controller (Engineering), B.B.C. Information about sunspots and flares observed at Greenwich is supplied to various radio research centres, while an informal liaison over solar observations in general has been maintained with the Radio Group of the Cavendish Laboratory, Cambridge; the Radio Research Station, Slough; and the operational Research Group of the Ministry of Supply. It is of interest to note that though the solar observations were commenced at Greenwich purely because of the scientific interest in the possible relationship between solar phenomena and geomagnetic disturbance, the observations have become of practical value for the forecasting of ionospheric conditions. At the same time, they are of increasing importance for the theoretical investigation of the processes involved.

Astrometry and Astrophysics Department

In this department is included a wide range of investigations in astronomy which have developed from the application of photography to astronomy. It includes two main sections: (i) astrometry, involving precise measures of positions of star images on photographic plates, which may be purely differential, involving small displacements in position between two different epochs, or may be used to derive absolute positions, by using a number of stars as reference points whose positions have been separately determined by meridian observations; (ii) astrophysics, which is concerned with physical characteristics, brightness, colour, spectra, etc.

The first development of the work at Greenwich in this direction was the participation in the great international project, proposed in 1887, of a photographic chart and catalogue of the entire sky. A large number of observatories shared in this project, which included the preparation of a catalogue, giving the positions of all stars down to a certain brightness, and the publication of star charts showing all the stars to a fainter limit of magnitude. To each observatory there was allotted a certain region of the sky, the Greenwich Observatory assuming responsibility for the cap of 25° radius around the north celestial pole. 13 in. photographic refractors of the same focal length, having a scale on the plates of 1 mm. to 1′ of arc, each plate covering a field of $2 \times 2°$, were to be used. The astrographic refractor for Greenwich was made by Grubb of Dublin, similar telescopes being made for a number of other observatories. For the determinations of position, all the stars in the Greenwich zones down to the limit of magnitude $9^{m}.0$ were observed with the transit circle in the years 1897 to 1905, while the measurement of the rectangular co-ordinates of the star images on the photographic plates was in progress. During these measurements, the diameters of the star images on the photographic plates were estimated in order to derive photographic magnitudes of the stars by the use of an empirical relationship connecting diameter and magnitude. In addition, the photographic magnitudes of all the stars brighter than $9^{m}.0$ were determined with a Cooke triplet lens camera of 6 in. aperture and 27 in. focus, covering a large field without appreciable distortion. Each region was photographed when at the altitude of the pole, the polar region being also photographed on the plate, so that the magnitudes of the field stars could be derived by comparison with the standard north polar sequence of magnitudes, which had been determined at the Harvard Observatory. The sequence of exposures was arranged so that the mean time of exposures on the field was in close agreement with the mean time of exposures on the pole, the assumption being made that the atmospheric absorption was equal under these circumstances for the two regions at the same altitude. This very large programme of work was spread over a number of years. The project was an ambitious one and proved to be beyond the power of some of the co-operating observatories, so much so that it has not even now been brought to completion after the lapse of more than half a century. The Greenwich section, both of the chart and of the catalogue, was one of the first to be completed. The results are published in rectangular co-ordinates, with sufficient data to enable the right ascension and declination of any star to be readily derived. For all the stars, however, down to magnitude 9·0 on the scale of the *Bonn Durchmusterung*, together with all fainter stars included in the catalogues of the Astronomische Gesellschaft and in Carrington's circumpolar catalogue, 16,780 stars in all, right ascensions, declinations, and photographic magnitudes were published in a separate volume.

Many programmes of observation undertaken at Greenwich since the completion of this work have been planned in order to make the available information about the stars in the polar cap, from dec. +64° to the north pole, more complete. The proper motions of the stars for which more than one position had been determined were derived by the comparisons of all available catalogues, each catalogue being reduced to a common basis by the application of systematic corrections. Then, commencing in 1923, the whole region was rephotographed with the astrographic telescope for the determination of relative proper motions of the stars. This second series of plates were exposed through the glass, so that by placing the corresponding plates of the two series of photographs film to film, the two images of each star were brought into close proximity. It was necessary only to measure the small displacements between corresponding images differentially, and to apply corrections for differences in scale and orientation of the two plates in order to derive the relative proper motions. Comparisons between the photographic proper motions and proper motions based on meridian observations, where the latter were available, provided the data for converting from relative to absolute proper motions. The probable error of the derived proper motions was about $\pm 0''\cdot 8$ per century in each co-ordinate. The value of the Greenwich *Astrographic Catalogue* as a source of stellar positions was greatly enhanced by the determination of the proper motions.

The astrographic telescope has been used for a variety of other investigations. Mention may be made of a special determination of the magnitudes of the stars in the standard north polar sequence, using a coarse wire grating to give sensibly round first diffracted images, with a calculable difference in magnitude from the central image. The magnitudes of the sequence had been determined at the Harvard and Mount Wilson Observatories, but there was an appreciable difference in scale between the two determinations. The investigation at Greenwich proved that the Mount Wilson scale was correct. The telescope also co-operated, along with the 26 in. refractor, in the two international programmes of observation of Eros at the favourable oppositions of 1901 and 1931 for the determination of the solar parallax.

The main programme of observation with the 26 in. photographic refractor, which was presented to the Observatory by the distinguished surgeon, Sir Henry Thompson, has been the measurement of stellar parallaxes. Such observations demand great care and precision and, before the commencement of the work at Greenwich, had been made mostly in the United States with telescopes of much greater focal length. The high latitude of Greenwich is not favourable for stellar parallax work, because the short nights in the summer make it impossible to secure observations near the times when the parallax factors are at a maximum; more photographs are needed for the same weight in the parallax determinations than in lower latitudes. The weather at Greenwich, moreover, makes it difficult to obtain a proper balance in the observations at the several epochs at intervals of about six months which are required. By special care in the adjustment of the lenses of the objective, controlled by photographs at intervals to detect any tilt or eccentricity, and by other precautions, the results have proved to be of an accuracy comparable with that given by longer focus telescopes.

The observations have been confined to stars in the Greenwich astrographic zones. The observing lists include all stars in this region of magnitude 5·5 or brighter; stars down to 7^{m} with annual proper motions greater than $0''\cdot 10$; stars down to 8^{m} with proper motions greater than $0''\cdot 15$; fainter stars with proper motions greater than $0''\cdot 20$, together with stars of type K0 with proper motions greater than $0''\cdot 05$, the latter being included to obtain information about the distribution of these stars in absolute magnitude. The photographs are obtained with the use of one of a series of rotating sectors, the aperture being chosen to reduce the magnitude of the parallax star to about $11^{\mathrm{m}}\!\cdot 5$, the magnitude of the stars selected as comparison stars. For the brightest stars sufficient reduction in magnitude cannot be obtained by using a rotating sector; local desensitizing of the central region of the plate with copper sulphate was tried for a time, in combination with a rotating sector, but the magnitude reduction produced by the desensitizing was uncertain. A neutral filter, giving a magnitude reduction of about 5^m was therefore employed, in combination with a suitable sector.

The observations were at first made by Kapteyn's method, in which the plate is exposed at one epoch, then stored undeveloped, and exposed again at the next epoch, the small displacements between the two series of images being measured. The method resulted in much loss of weight; good definition at one epoch might be followed by bad definition or exposures interrupted by cloud at the second. There were difficulties in balancing the different epochs. The method was therefore abandoned and each plate developed after exposure at the one epoch. For the measurement of the series of plates for the determination of the parallax of a star, suitable comparison stars were selected; a blank glass plate was then ruled with short fine parallel lines near the position of each comparison star, and of the parallax star. A plate was placed film down on the ruled plate, and the small displacements between each star and the rulings were measured. The ruled plate served as a dummy, which permitted of accurate setting of the micrometer wire and with which each stellar photograph was compared, thereby making possible the intercomparison between the stellar photographs themselves. Three separate exposures were normally given on each plate during the first series of observations. The practice was then introduced of giving two exposures, the plate being turned through 180° between the exposures; this procedure reduces any errors that may be caused by small local film distortions. It has been found that two exposures, with intermediate reversal, give the same accuracy as three exposures without reversal and with the advantage of saving time at the telescope. About 750 determinations of stellar parallax have been made since observations were commenced.

The 26 in. refractor has been used for a number of smaller programmes. Several series of photographs of Jupiter's satellites were obtained at the request of Professor de Sitter, to provide material for his determination of the elements of the orbits of the satellites and for his investigation into the theory of their motions. Photographic magnitudes of stars down to magnitude 14 in a number of Kapteyn's Selected Areas, zones $+15°$, $+30°$, $+45°$, and $+60°$ declination, were determined by comparison with the north polar sequence; the magnitudes of 395 stars within 1° of the north pole were also measured.

A 30 in. reflector is mounted on the same mounting as the 26 in. refractor; the arrangement is not convenient, as it is never possible to use the two telescopes at the same time and there can be inconvenient competition between the demands on the same mounting for different programmes of work. The reflector has been used for the photography of comets and other celestial objects; in particular, a very fine series of photographs of Comet Morehouse 1908, whose tail changed markedly from night to night, was secured. On photographs taken with it, the eighth satellite of Jupiter was discovered by Melotte. The reflector was used also for a programme of determination of effective wave-lengths of stars in the north polar cap. Using a coarse wire diffraction grating over the end of the telescope, the distance between the two first diffracted images depends upon the grating interval, upon the focal length and upon the wave-length of the light. The first diffracted images are really short spectra. The distance between the points of maximum photographic intensity determines the colour or effective wave-length of the star. The points of maximum intensity depend upon the distribution of light in the spectrum of the star, and upon the intensity curve of the photographic plate. The use of a reflector avoids difficulties from chromatic aberration. The growth of the diffracted images is not the same for stars of different colours, so there is an exposure-time effect, which must be allowed for. The image given by a 10th magnitude star with an exposure of 10 min. was used as standard. The change of effective wave-length with spectral type of the star depends upon the type of plate employed; with panchromatic plates and a yellow screen the change was found to be approximately linear, whereas with blue-sensitive plates there was little change between A0 and F8. The dispersion in the first diffracted images in this investigation was comparable in amount with atmospheric dispersion at a zenith distance of about 60°; the results obtained throw much light on the relative displacements for stars of different types due to atmospheric dispersion, which may introduce systematic errors into the determination of the solar parallax from observations of the minor planet Eros or of any other asteroid.

In 1931, Mr William Johnston Yapp offered to present a large telescope to the Observatory. A 36 in. reflector was decided upon. The telescope was brought into use in 1934 for the continuation of a programme of observations of the colour temperatures of stars which had been commenced with the 30 in. reflector. The programme was a particularly difficult one to undertake at Greenwich, where the atmospheric transparency is poor, variable, and not uniform in amount in different directions. The colour temperature of a star is the temperature of a black body which has the same relative distribution of energy throughout the spectrum as the star. The determination of colour temperature involves comparison with a terrestrial source whose colour temperature is known; it is convenient, however, to divide the investigation into two parts, intercomparing the stars and then making comparisons with the terrestrial source. A selection was made of twenty-five stars, of spectral types A and B and fairly evenly distributed, to serve as standard stars. These standards were intercompared one with another, when at the same altitude. Other stars were then compared with one or more of the standard stars.

The reflector was employed with a slitless spectrograph. At first a coarse wire diffraction grating with dispersion at right angles to that of the spectrograph was used to provide a photometric scale. But this was wasteful of observing time. A scale spectrograph was therefore used with multiple slits, whose breadths were closely in the ratio of 1:2:4, the dispersion being approximately the same as that of the slitless spectrograph. The exact ratios of the light passing through the three slits were determined by a half aperture method. A Lummer-Brodhun cube microphotometer was used for measuring the spectral intensities, measurements being made at eight points in the blue and at eight in the red, free from absorption lines.

As standard source of comparison, a standard acetylene burner, with a nominal colour temperature of 2360° K, was used. The burner was specially calibrated at the National Physical Laboratory. The difference of colour from the stars was reduced by the insertion of a blue filter in the beam from the burner, whose absorption was measured with the scale spectrograph. The burner was placed at a distance of about 600 ft. on the Octagon Room roof. The horizontal reddening of the acetylene flame in this distance was determined by special observations.

The colour temperatures of most northern stars brighter than $4^{m}.5$ and of spectral type A or earlier, as well as of many fainter stars of these types and of a selection of bright F- and G-type stars have been determined.

A slit spectrograph for use with the 36 in. reflector was completed in 1937. The optical parts are made of ultra-violet glass, and one-prism or three-prism dispersion can be used. The spectrograph was mounted towards the end of 1939, on the completion of the colour-temperature programme and various tests were made. But circumstances at that time made it impossible to commence any definite programme of observation. Since the war it has been employed in attempts to detect faint blue companions in late-type spectroscopic binary systems.

Miscellaneous programmes

Some items of the work of the Observatory do not come definitely within the scope of any particular department, but depend to some extent upon the personal interest of individual members of the staff. Expeditions have been sent from time to time to various parts of the world to make observations of total eclipses of the Sun, the programmes being determined by the problems of current importance. It was the expedition from Greenwich to Brazil for the observation of the total eclipse of 29 May 1919 which provided the first evidence to confirm Einstein's predicted displacement of stars in the vicinity of the Sun. The most recent expedition was a small expedition to Mombasa for the eclipse of 1 November 1948, to test a method of accurate determination of the position of the Moon, designed to be used on the occasions of a total eclipse at two widely separated centres, for the purpose of providing an accurate geodetic connexion.

The 28 in. refractor, installed in 1886, has been employed for many years for the observation of close double stars with a filar micrometer. The measures obtained up to 1919 were collected and published in a single volume. The observations were used, in conjunction with observations made elsewhere, for the determination of the dynamical parallaxes of 576 double stars. The parallax of a binary system of known period and angular dimensions of orbit can be calculated if the combined mass is known; in the absence of a knowledge of the mass, the error introduced by assuming the combined mass to be twice that of the Sun is relatively small, as the mass enters only to the power of $\frac{1}{3}$. The parallax so deduced is called the dynamical parallax. When the binary star has not been observed for a complete period, the parallax can be estimated, though with less certainty, from the rate of change of angle and distance.

A marked improvement in the accuracy of the measures followed from the introduction of a comparison image micrometer, constructed in the Observatory workshop. A Wollaston prism is used to give a double image of an artificial star, the separation of the two images being varied by altering the distance of the source from the prism. Rotation of the prism rotates the position angle of the artificial binary. Crossed nicols permit the brightness of either image to be varied. A blue filter is used to give a colour temperature of about 5500° K, so that the artificial images appear of about the same colour as the stellar images. The position angle, separation and magnitudes of the two images are adjusted to be comparable to those of the binary star; the four images, two real and two artificial, are set to form the corners of a parallelogram. The eye is sensitive to any slight lack of symmetry, even under unsteady conditions when the use of a filar micrometer is difficult. The comparison image micrometer is particularly advantageous in the measurement of close pairs and, because no field or wire illumination is required, it enables fainter stars to be observed.

Chronometer Department

In 1821, soon after the control of the Royal Observatory passed from the Master-General of the Ordnance to the Board of Admiralty, the charge of chronometers used in H.M. Navy was transferred to the Royal Observatory. In the following year public trials of chronometers were instituted. Makers were invited to submit chronometers for trial, with a view to purchase by the Admiralty, and money prizes of considerable value were offered for the best chronometers. This system of annual trials was continued up to the beginning of the World War of 1914–18, though the giving of special prizes was discontinued after a few years. These trials had a considerable influence in stimulating improvements in the design and construction of chronometers.

Because increasing difficulty was found in getting chronometers and navigational watches satisfactorily repaired and adjusted by the trade, a Repair Shop was started in connexion with the Chronometer Department in 1937, where repairers and adjusters could be trained to the high degree of skill essential for work on precision time-pieces. The Repair Shop proved invaluable during the war, when the numbers of repairs to be dealt with was very large and when the Chronometer Department was testing and issuing an average of from 25,000 to 30,000 chronometers and watches a year. It is expected that the amount of repair work undertaken will gradually expand, and a scheme has recently been introduced for the indenturing and training of apprentices. The facilities of the Repair Shop are available also for any fine precision work required in connexion with the construction and modification of instrumental equipment.

Optical and Electronic Laboratories

The progressive expansion in the scope of the work of the Observatory has involved the employment of much specialized equipment, which has had to be designed in the Observatory and made in the Workshop. The slitless spectrograph, the scale spectrograph, and the Lummer-Brodhun cube microphotometer, employed in the colour-temperature programme, and the comparison image micrometer for double-star observations are a few of the many items of equipment which have been made at the Observatory. The satisfactory design of new equipment not infrequently requires a considerable amount of preliminary investigations and tests, and the need for a definite laboratory section has progressively increased. The introduction of quartz crystal vibrators as standard clocks required the use of much ancillary electronic equipment; because much of the special equipment needed was not available commercially, it became necessary to design and construct it in the Observatory. A laboratory section has accordingly been formed, comprising both an optical and an electronics laboratory. Started initially for the special needs of the Time Department at the time when the work of that department was expanding rapidly, the laboratories can meet the requirements of all departments of the Observatory. Amongst the electronic equipment which has been designed and constructed, mention may be made of a special radio receiver for the reception of radio time signals transmitted on the long-wave band with low carrier frequency, designed to secure constant lag, a high degree of selectivity, and a steep build-up curve, and with provision for selecting any particular point on the build-up curve and for securing constant output voltage; of a 2 Mc./sec. standard frequency transmitter, controlled by one of the 100 kc./sec. oscillators; of a receiver for comparing the frequency of the Droitwich 200 kc./sec. transmissions with any of the Abinger standards; of a number of double current electronic send relays; and of a great deal of switching, modulating, and monitoring equipment.

Nautical Almanac Office

In 1766, the year after his appointment as Astronomer Royal, Maskelyne published the first number of the *Nautical Almanac* (for the year 1767). The *Almanac* was designed for the use of seamen and particularly to facilitate the employment of the method of lunar distances for determining longitude. It proved to be a most valuable aid to navigation. Maskelyne continued to produce it annually for 44 years, until his death in 1811. The computations for the *Almanac* were performed in duplicate by computers, mostly working at home, and it acquired a very well-deserved reputation for high accuracy. In 1781 Maskelyne published a volume of *Tables Requisite to be Used with the Nautical Ephemeris*, which was in effect a handbook for use with the *Almanac*. Pond, who succeeded Maskelyne as Astronomer Royal, did not take the same interest in the *Nautical Almanac*, though he remained nominally responsible for it. The *Almanac* lost its reputation for accuracy, and eventually in 1831 a separate Nautical Almanac Office was established with its own Superintendent and having no formal connexion with the Observatory.

In 1937, the Nautical Almanac Office was again placed under the direction of the Astronomer Royal and became a branch of the Royal Observatory, though retaining its own identity and its Superintendent. The *Almanac* at that time was responsible for the production and publication of the standard edition of the *Nautical Almanac* and of the *Abridged Nautical Almanac*, designed for navigational purposes. Shortly afterwards the office undertook the production of an *Air Almanac*, adapted to the special requirements of air navigation. The airman does not need to know his position as accurately as the sailor, but, because of the high speed of modern aircraft, he requires to deduce his position with the minimum of delay after making the observations. To meet these requirements, the data in the *Air Almanac* are presented in a special way, Greenwich hour angle being used instead of right ascension, and to a lower degree of accuracy than in the *Abridged Nautical Almanac*. Special *Air Navigation Tables* were also prepared in the office and published, for use with the *Air Almanac*, to facilitate the rapid derivation of the position of the aircraft.

In 1940 the publication (for the year 1941) of an annual volume of *Apparent Places of Fundamental Stars* was commenced. This volume gives the apparent places, at 10-day intervals, for most stars, but at daily intervals for close circumpolar stars, of the 1535 stars in the FK3 Fundamental Catalogue; the time determinations at all observatories are based upon these positions. The computations of the apparent places are shared by the United States, France, Germany, and Spain; the Nautical Almanac Office is responsible for the co-ordination of the work, for the collation of the data, and for the preparation and publication of the volume.

At the Conference of Commonwealth Surveys in London in August 1947, a strong desire was expressed for a special almanac to be prepared and published to meet the needs of topographical surveyors. Detailed proposals were therefore prepared in the office for a *Star Almanac for Land Surveyors* and have been approved. The first issue will be made in 1950 for the year 1951.

The experience gained with the *Air Almanac* has confirmed the advantages of the method of tabulation of data according to Greenwich hour angle, and has given rise to a desire for the revision of the *Abridged Nautical Almanac*. Various alternative arrangements of presentation of the data have been considered, and, after much detailed consultation with all classes of users, the final form has been settled. In its revised form, which will be issued in 1951 for the year 1952, the *Almanac* will tabulate Greenwich hour angle in arc directly, instead of right ascension.

Special investigations into methods and tables for both sea and air navigation have been made, including a comprehensive survey of tables for astronomical polar navigation. The office has also been responsible for the preparation and publication of various tables, including *Seven-Figure Trigonometrical Tables for Every Second of Time* (1939), *Five-Figure Tables of Natural Trigonometrical Functions* (1941), *Planetary Co-ordinates for the Years* 1800–1940, *Referred to the Equinox of* 1950·0 (1933), and of a continuation volume for the years 1940–60 (1939).

The office has been a pioneer in the adaptation of computations, formerly performed by logarithms, to machines. Because of its wide experience in methods of numerical computation and its machine equipment, it was able to provide a computing service to deal with a great variety of problems for various Government departments, which presented themselves during the war. Much preliminary investigation was often needed to discover the best method of solving special problems, with the least expenditure of labour and of time. Approval has recently been given for the installation of a complete range of Hollerith punched-card equipment, suitable for general computational work. It is intended to extend the use of the equipment, where suitable, to the work of the Observatory as a whole, as well as to the more routine work of the office. It is also hoped, eventually, to produce copy for some of the office publications automatically on card-operated machines.

The office has a close link with navigational problems and maintains a complete library of the navigational almanacs and tables of all countries. It is at present engaged on the computational work necessary for the latticing of charts required for the Decca system of navigation.

Removal of the Observatory from Greenwich

The conditions at Greenwich for astronomical observations have progressively deteriorated as London has grown outwards beyond the Observatory. The increasing pollution of the atmosphere and the increasing brightness of the sky at night have combined to affect adversely the quality and nature of the observations. Photometric and spectrophotometric observations, which require a uniform transparency in different directions and freedom from rapid variations of transparency, are practically impossible when clouds of smoke from nearby power stations and factories drift over the Observatory. But every type of observation is affected—meridian, solar, visual and photographic; in the exacting work of double star observations it has become impossible to observe close doubles which were observed with relative ease half a century ago. Under such conditions, the removal of the Observatory from Greenwich was essential if the Observatory was to continue to make useful contributions to astronomy. With the strong support of the Board of Visitors, proposals to remove the Observatory to a new site were submitted to the Board of Admiralty shortly before the outbreak of war. The war started before a decision was reached, and the question of removal had then to be deferred. During the war the principal instruments were partially dismantled, the Time Department was transferred to Abinger, and the Chronometer Department, with the Repair Shop, was moved first to Bristol and then to Bradford-on-Avon. The work of the Magnetic Observatory was becoming hampered by disturbances from the extension of railway electrification, and proposals for its removal to a site remote from railways were made. Widespread search for suitable new sites was carried out. After the termination of the war, the question of removal was again taken up. A short list of the most promising sites was prepared, and these sites were visited by a Committee of the Board of Visitors. Finally, it was announced on 11 April 1946 that Herstmonceux Castle in Sussex had been chosen as the future home of the Royal Observatory, and approval was given for the transfer of the Magnetic Observatory to a site to be selected in north Devon at a distance of at least 10 miles from any railway.

Some 372 acres of ground were acquired with the fifteenth-century castle, providing adequate space for erecting the various telescopes and for future additions to the equipment, and a safeguard against near encroachment by undesirable developments. A first stage of the removal is in progress. The Chronometer Department and the Secretariat have moved to Herstmonceux. A solar building to house the photoheliograph, two spectrohelioscopes, and spectrographic equipment for solar research is nearing completion. The transfer of the Solar Department, of the Magnetic and Meteorological Department, and of the Nautical Almanac Office should be possible during the course of the present year. Further stages of the removal, involving the erection of buildings and domes for telescopes, are under consideration. The 26 and 28 in. refractors, whose domes were seriously damaged during the war, have been dismantled; the opportunity is being taken for some alterations to be made to these telescopes before re-erection takes place. The work of some departments of the Observatory is necessarily on a reduced scale during the present period of transition. There are, however, great hopes for the future, when the Observatory has been fully established in its new home and can reap the advantage of the good observing conditions. A selection of several possible sites in north Devon for the Magnetic Observatory has been made, and tests of their freedom from magnetic anomalies have been made. Some further sites will be examined before a definite selection is made.

On the occasion of the commemoration of the tercentenary of the birth of Sir Isaac Newton, held in London in July 1946, the President of the Royal Society announced that the Chancellor of the Exchequer had agreed to provide funds for the construction of a reflecting telescope of 100 in. aperture, to be associated with the name of Sir Isaac Newton and to be available for use by qualified astronomers from all observatories in Great Britain. It has been decided that the telescope will be erected in the grounds of the Royal Observatory at Herstmonceux. The telescope will be under the administrative control of the Astronomer Royal; a special Board of Management will be responsible for the scientific direction, including the designing of the telescope, the supervision of its construction, the consideration of programmes of observation, and the allocation of observing time between the various users of the telescope. The Board of Management will consist of the Astronomer Royal (Chairman), the Astronomer Royal for Scotland, and the Directors of the Cambridge and Oxford University Observatories as *ex-officio* members, together with four Fellows of the Royal Society and four Fellows of the Royal Astronomical Society. The telescope will enable British astronomers to undertake many programmes of observations which have hitherto been impossible because of the restricted light-gathering power of the largest telescopes at present in use in Great Britain, while the library, workshop, and other facilities of the Royal Observatory will be available to all users.