PRELIMINARY RESULTS OF TESTS OF AND OBSERVATIONS WITH THE REVERSIBLE TRANSIT CIRCLE OF THE ROYAL OBSERVATORY, GREENWICH

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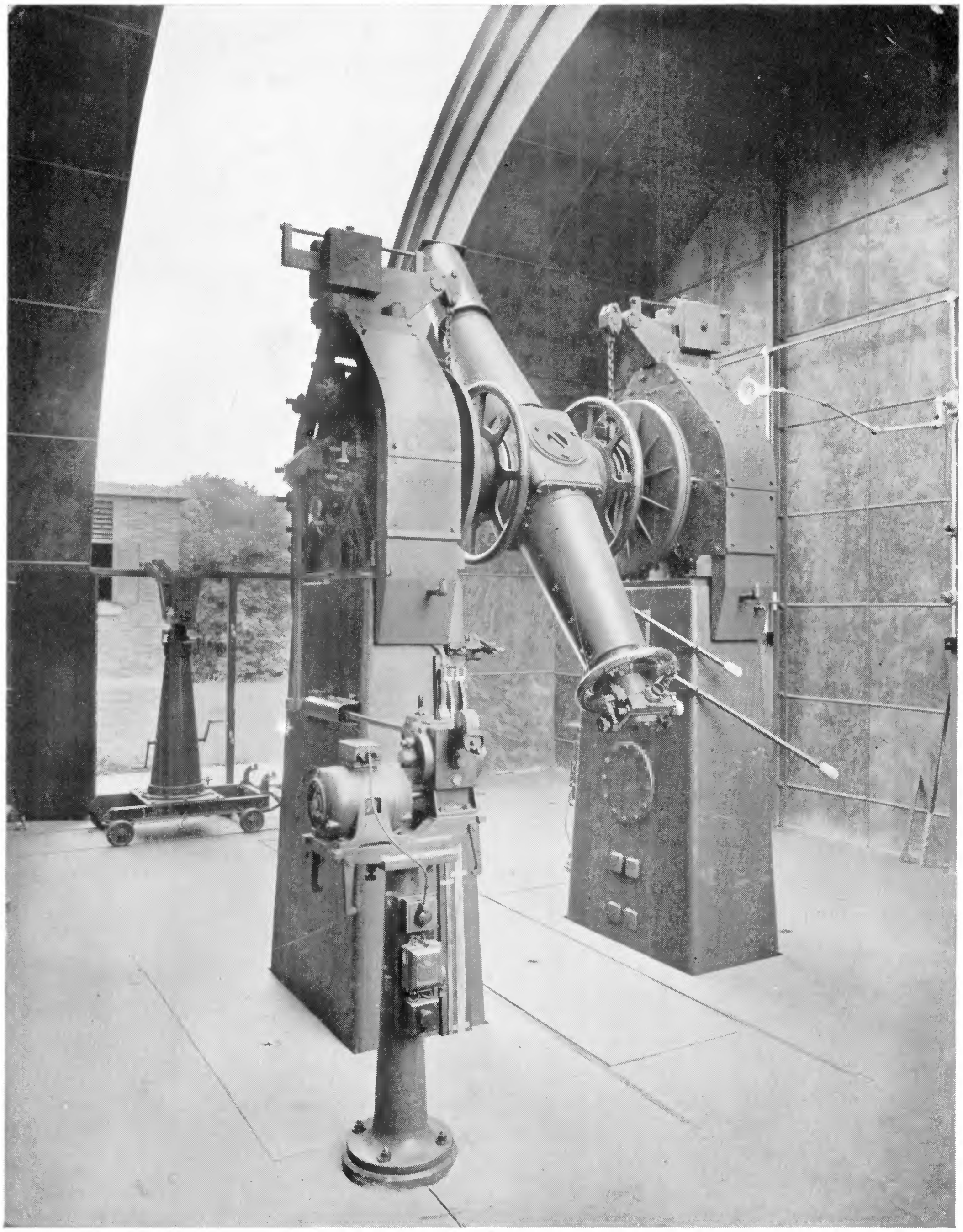
Summary

The principal features of the new reversible transit circle of the Royal Observatory, Greenwich, are described, and an account is given of the preliminary tests of the instrument, including the figure of the pivots and the construction of the micrometer eye-end. The diurnal and seasonal changes of the instrumental errors of adjustment have been investigated, and the importance of a close control over the error of collimation is emphasised. A correlation between the observed azimuth error and wind direction has been found. The investigations lead to some conclusion about the housing of meridian instruments.

With the installation of the reversible transit circle in 1936, a new era in meridian astronomy at the Royal Observatory, Greenwich, commenced. The transit circle, designed by Airy and installed in 1851, which defines the prime meridian of longitude, had remained the fundamental instrument for meridian observations since that date. No instrument in the history of astronomy has had such a record of work, and the value of the Greenwich meridian observations is due, in large measure, to the continuity of observation with the same instrument. The object-glass has been twice refigured to get rid of stains; although the surface is so badly stained that there is a considerable loss in transparency, the lenses have become too thin for a further refiguring to be contemplated. The graduated silver circle has become worn, through constant cleaning to remove the tarnishing produced by the polluted atmosphere of Greenwich, so that many of the divisions are only read with difficulty; some had completely disappeared and were recut at the Observatory. In addition, the instrument is non-reversible and is so housed that refraction anomalies are troublesome.

The new instrument, constructed by Messrs. Cooke, Troughton & Simms, Ltd., is a reversible instrument, which follows closely in design the reversible transit circle of the Cape Observatory, designed by Gill, of which a detailed description is given in the *History and Description of the Cape Observatory*. The objective has an aperture of 7 inches and a focal length of 102 inches. The travelling wire of the impersonal micrometer is driven by a synchronous motor, with a continuously variable gear, the drive passing up the outer face of one of the piers, through one of the pivots and then inside the tube to the eye-end. A reversing gear is fitted at the eye-end, together with a differential sun and planet gearing to enable the observer to maintain an accurate bisection of the star image during transit.

The principal feature in which the design differs from that of any previous instrument is the adoption of glass circles, with etched graduations, to eliminate the trouble of tarnishing to which graduations on silver are liable. It may be mentioned that in the Cape instrument the graduations of the fixed circle are made upon an inlaid band of iridio-platinum (30 per cent. iridium and 70 per cent. platinum), those of the movable



Reversible Transit Circle, Royal Observatory, Greenwich.

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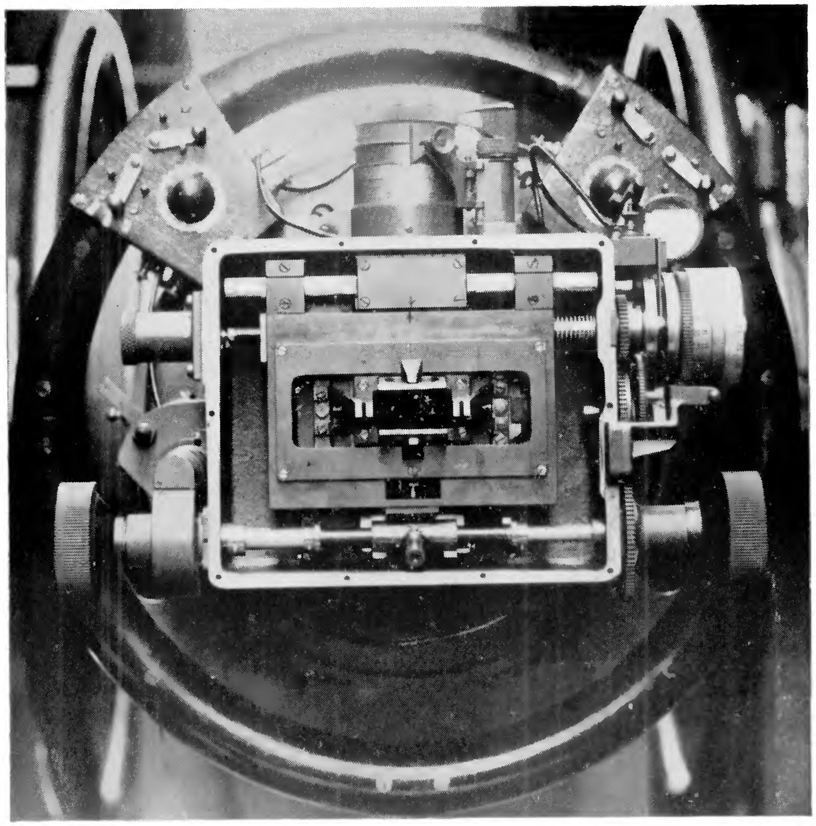
A



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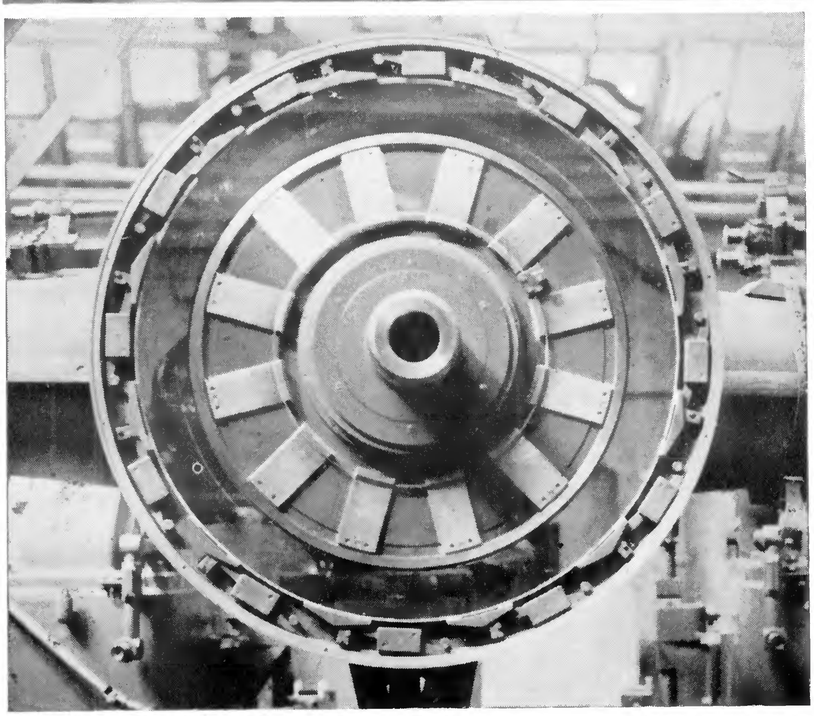

A. Transit Micrometer, with cover plate removed.

B. Glass Circle, showing method of mounting and counterpoising.

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circle being made upon an inlaid band of silver. The design and construction of the glass circles required considerable care. The circles are of 28 inches diameter, and the etched graduations are spaced at intervals of 5 minutes of arc around an annulus of 24 inches diameter. Each circle is supported on a spigot formed by 12 gunmetal arms, which are in turn attached to a cast-iron bracket fixed to the central casting. The spigot was turned in place after the arms were fitted. The coefficients of expansion of samples of the cast iron, gunmetal and glass were determined at the National Physical Laboratory; the dimensions of the supporting gunmetal arms were chosen so that the difference of expansion of the cast iron and glass is compensated. The rotation of the circle is prevented by a single stop-pin. The weight of each glass disk is approximately 16 lb. Flexure in the plane of the disk is minimised by a system of twelve counterpoises, bearing on the outer edge of the disk. Each counterpoise consists of a lever arm, weighted at one end and carrying at the other end a self-aligning arm; leather pads at the end of this arm bear on the edge of the circle. In any position of the circle the six lower counterpoises are in operation. The weight on each arm is adjusted so that the maximum pressure of each counterpoise is the same, and so that the total weight relieved is slightly less than the weight of the circle. Each circle is protected by a cover disk, so that only the graduated annulus is exposed. The etched graduations are sharp and excellent for setting upon.

The instrument is supported from two hollow cast-iron piers, which are mounted upon a strong cast-iron framework, which is adjustable for level. This framework is carried by a strong cast-iron base plate, which is adjustable in azimuth. Thus adjustments to the level and azimuth of the instrument can be made without upsetting the alignment of the bearings. The base plate is mounted in a hollow cast-iron tank, filled with Rubrex Oil No. 40 to prevent rusting of the screws which control the level and azimuth adjustments. The hollow piers are filled with a solution of ethylene glycol in water, containing 25 per cent. by volume of ethylene glycol. The freezing-point of this mixture is $-12^\circ{\cdot}5$ C. $7\frac{1}{2}$ cwt. of ethylene glycol were used.

As originally constructed, the weight of the instrument was relieved from the pivots by means of springs and rods acting through self-aligning swivel stirrups, which pressed upwards on to the axis, ball journal races making line contact with a fitting on each axis to reduce friction. The springs were adjusted, calibrated, and fitted with a scale and pointer to indicate the amount of weight relieved. Both supporting rods and springs were carried from the azimuth adjustment plate. Tests on the instrument, mounted at the contractor's works, showed that the readings given by the instrument were not consistent. When, for instance, the instrument was set on the nadir and the microscopes were read, then on rotating the instrument through 360° and again setting on the nadir, a different reading was obtained on the microscopes. The readings varied, moreover, with the direction in which the instrument was rotated. The cause of the inconsistencies was either torque in the axis casting or constraint exerted by the weight-relieving device. The results became more capricious as the weight on each bearing was reduced, pointing to the counterpoise gear as the cause of the trouble. Some modifications to the gear were made, which reduced, but did not entirely eliminate, the inconsistencies; these still amounted to one or two seconds of arc with a weight of 50 lb. on each pivot. This method of relieving the weight from the bearings was therefore abandoned. A new counterpoise system was made in which the instrument is supported within anti-friction collars by two chains, attached to the ends of counterpoised lever arms. Each counterpoise consists of a large fixed weight and a smaller adjustable weight, which can slide along a calibrated arm; by the adjustment of this weight, the weight on the corresponding bearing can be varied within a range from 0 to 50 lb. The weight-relieving gear is supported from the piers, below the block which carries the micrometers for reading the circle, so that there is no tendency for these blocks to be strained. With this self-equilibrating method of relieving the weight from the pivots, the inconsistencies in reading are no longer obtained. The instrument is used with a weight of 30 lb. on each bearing.

The instrument was erected at the Royal Observatory in February and March 1936. Researches of various kinds were initiated, concurrently with observations for the establishment of a fundamental system of right ascensions. These were continued until the air attacks on London in the autumn of 1940. The objectives of the instrument and of the two collimators and the micrometer eye-end were then dismounted and removed to a place of safety. Enough material has been obtained and conclusions formed to guide the planning of post-war observations with the instrument, and the performance of the instrument has been improved. The investigations have revealed various ways in which systematic discordances of instrumental origin can enter into meridian observations, and the results may be helpful to others in possession of, or planning the design of, similar equipment.

The transit pavilion is semi-cylindrical in shape, the axis of the cylinder coinciding with that of the instrument. The interior diameter of the cylinder is 30 feet. The internal width of the pavilion is 20 feet. Two shutters, of semi-cylindrical shape, can slide back in the E.–W. direction to give an aperture of 8 feet along the meridian. Thermal insulation of the pavilion is provided by slabs of granulated cork, 3 inches in thickness. The housing is covered externally with copper sheets, lapped together. The reversing carriage, when placed in position under the instrument and raised, lifts the instrument from its bearings. The carriage is then run along steel rails to the north of the piers and the instrument is turned through 180°, after which the carriage is run back and the instrument is lowered into its bearings. A platform is fitted to the carriage, which is employed for making observations on the nadir. When not in use the carriage is run to a position at the side of the pavilion to the west of the turntable, a turntable being provided for this purpose.

The foundation which carries the instrument is of concrete, extending to a depth of 9 feet and weighing 75 tons. It had been intended to carry the foundations to a depth of 15 feet, but the subsoil of hard compacted gravel was so firm that 9 feet was judged sufficient.

The pavilion is surrounded by a surfacing of concrete, measuring 50 feet from north to south and 55 feet from east to west, to carry rain-water away from the foundations. About 4 feet from the edge of this surround is an isolation trench, 3 feet deep, to keep the upper portion of the foundations dry; this trench is covered with slabs of reinforced concrete $2\frac{1}{2}$ inches in thickness.

The collimators, which are of the same aperture and focal length as the transit instrument, are mounted on substantial foundations, inside brick houses, roofed with concrete, to the north and south of the instrument. The distance between the centre of the instrument and the centre of each collimator is 50 feet.

One revolution of the R.A. micrometer screw is equivalent to $55''\cdot7$ or $3^{s}\cdot7$ for an equatorial star. The R.A. micrometer carries with it a metal contact wheel, into which five studs are inserted to break the contact. One of these studs corresponds to zero reading of the micrometer head. The motion of the travelling wire is very uniform; in order to prevent an inaccurate bisection of the star image being maintained throughout a transit it was decided, after some experience had been gained, that five successive bisections on this stud should be retained for a normal transit observation. The moving wire is deliberately removed from the star after each bisection, so that the observation of a transit is based on five completely independent bisections, whose mean time corresponds to the time of the centre one. A loud speaker has been installed to give audible signals when the studs break the contact. The five studs on the wheel are not equally spaced; the observer knows by the rhythm of the pips from the loud speaker the correct stud at which the bisection must be made, and is able to concentrate on an accurate bisection of the star image just before the appropriate instants. This relieves the observer of the necessity of maintaining bisection throughout a transit and results in increased accuracy. It is found that the probable error of a single transit is less than one-hundredth of a second of time.

The detailed investigation of the equipment and the results derived from observational data will first be described. The effect on the observations of the buildings housing the equipment will then be discussed.

Instrumental Errors

These may be divided into two distinct groups:

I. Errors that are constant or nearly so.
II. Those which are variable with diurnal and seasonal fluctuations in temperature.

The present investigation is concerned primarily with right ascension observations.

The errors in group I comprise:

(*a*) Errors due to inequalities of the pivots.
(*b*) Errors produced by a faulty fixture of the frame carrying the moving wire, called "frame correction".
(*c*) Errors due to the moving wire lagging behind the micrometer screw reading when in motion, termed "lag".
(*d*) Division errors of the circle graduations.

Those in group II comprise:

(*e*) Errors of collimation.
(*f*) Errors of level.
(*g*) Errors of azimuth.

The errors in group I can be determined and allowed for; when possible, it is preferable to reduce them to negligible quantities.

(*a*) *Pivot Errors.*—Errors due to irregularities of the pivots should be determined with extreme accuracy, as such errors are not eliminated by reversal of the instrument, except for stars in the zenith. Pivot errors affect the determination of collimation and the times of transit of stars across the meridian. It is desirable that they should be sufficiently small in amount for the effect on collimation to be insensible.

The pivot errors are determined by the method introduced by Airy in the Greenwich transit circle. In this method the horizontal axis of the telescope is converted into a horizontal collimator. An object-glass, mounted into a slightly cone-shaped tube, fits into a correspondingly conical hole in one pivot. Into a similar hole in the other pivot is fitted an apparatus carrying a fine mark, with provision for adjustments for focus and centring. The object-glass and mark can be interchanged in the two pivots. The mark is focused in the principal focus of the object-glass in the other pivot and viewed by a telescope, provided with micrometer eyepiece, mounted on the external face of the pier with its axis parallel to and nearly coincident with the axis of the transit circle. The displacements of the mark as the instrument is rotated are measured. Thus the combination of the effects of the inequalities of the two pivots, with which alone we are concerned, is directly measured.

When the telescope was first erected, preliminary tests of the pivots, whose diameter is 4·6 inches, were made with the pivot-testing telescope. These showed that one or both pivots were definitely oval. Determinations of collimation were made by three methods: (1) by observing north and south collimators, without reversal of the telescope; (2) by observing north or south collimator and reversing the telescope; (3) by observing the nadir and reversing the telescope. The determinations by the first two methods were in agreement; those by the third method showed a systematic difference of about

$0''.6$. The effect of the observed pivot errors on the determination of the line of collimation by methods (1) and (2) were negligible; they accounted for not more than 15 per cent. of the discordance by method (3). This indicated a difference in diameter of the two pivots of 0·0003 inch. The pivots had been tested at the works by ring tests; it was therefore probable that the smaller pivot was the more oval, as ring tests can only compare the greatest diameters of the two pivots. It was decided that the pivots should be lapped *in situ*, with the telescope mounted on the reversing carriage, by a representative of the contractors, starting with the pivot of larger diameter.

The pivot-testing telescope was not suitable for rapid testing of the figure of the pivots during lapping. To mount the equipment and obtain the observations takes a considerable time, and no information is provided about the figure of each pivot separately. A Krupp mikrotast gauge was therefore obtained to enable the figure of the pivots to be rapidly tested. This gauge consists of a pair of plane jaws inclined to one another at an angle of 39°, between which is mounted a movable foot. The displacements of the foot are magnified mechanically and read from a circular dial to an accuracy of a micron by direct reading, or to a decimal of a micron by estimation. The difference of the readings obtained with the mikrotast gauge, when placed on two truly cylindrical pivots of slightly different diameter, gives at once the difference in diameter of the pivots, because the cosecant of $19\frac{1}{2}°$, half of the angle between the jaws, has the value 3. When the gauge is moved round a pivot which is not truly cylindrical, the errors of figure are shown by the variations in the reading of the dial. The reading for any position of the gauge represents a combination of the errors of figure at three points: the two points where the jaws touch the pivot, and the intermediate point where the movable foot is in contact with the pivot. It can be shown that with the commonest types of error of figure, elliptical or pseudo-cylindrical, the mikrotast readings determine the error of figure with a magnification somewhat greater than 3.

The first tests with the mikrotast gauge were made after some preliminary lapping of the pivots with emery and rouge, and showed a variation in the readings on each pivot of about 4 microns and a difference in diameter of about 2 microns. The gauge indicated the portions of the pivots where lapping was chiefly required and the figure of each pivot was rapidly improved. As the accuracy of figure was improved, it was found necessary to allow the pivots to stand for at least an hour to equalise their temperature before tests were made. Readings were taken at intervals of 10° round the pivots. The figure was considered satisfactory when the variations in reading on each pivot showed no departure at any point from the mean exceeding 0·25 μ; the difference in the mean diameters of the two pivots was 0·28 μ.

Observations were then made with the pivot-testing telescope equipment in order to obtain the relative pivot errors. The errors so determined were larger than could be accepted as correct, in view of the consistency of the readings obtained with the mikrotast gauge. It was noted that the definition of the dot was not the same for all positions of the transit instrument, suggesting an aberrational effect such as might be introduced by the tilt of a lens. Repeat series were therefore made, turning the collimating lens into different positions, but keeping the pivot-testing telescope in the same position; then further series, keeping the collimating lens in the same position but turning the pivot-testing telescope into different positions. The apparent errors were altered by the first change but not the second, pointing to the collimating lens as the cause of the discordance. Investigation showed that its axis is not coincident with the axis of the pivots; it is probable that the conical holes in the pivots are not exactly coaxial with the pivots. Taking observations in four positions of the collimating lens at 90° apart, the true pivot errors could be separated from the spurious errors introduced by the tilt of the lens. The spurious errors were in the form of a double harmonic wave with a total amplitude of about $0''.5$ in each co-ordinate, corresponding in linear measure to 3 microns. When the spurious errors were allowed for, it was found that true pivot errors were appreciably less than one-tenth of a second of arc, in agreement with the conclusions derived from the mikrotast gauge observations.

(*b*) *Frame Correction.*—This error was detected by setting the R.A. moving wire on one of the fixed wires; it was found that the micrometer readings for the position of coincidence varied with the position of the telescope. In other words, the reading corresponding to the line of collimation varied with the circle reading or declination. Observations were also made by setting the movable wire on a speck of dust on the horizontal wire, with similar results. The effect was found to be greatest at one end of the field, diminishing to a minimum at the other end. The fixed wires are mounted on an immovable frame, and the existence of the effect therefore indicated a looseness of the frame carrying the moving wire.

Similar variations in reading depending upon the position of the telescope were obtained when the Z.D. wire was set on a fine speck of dust on a fixed vertical wire and

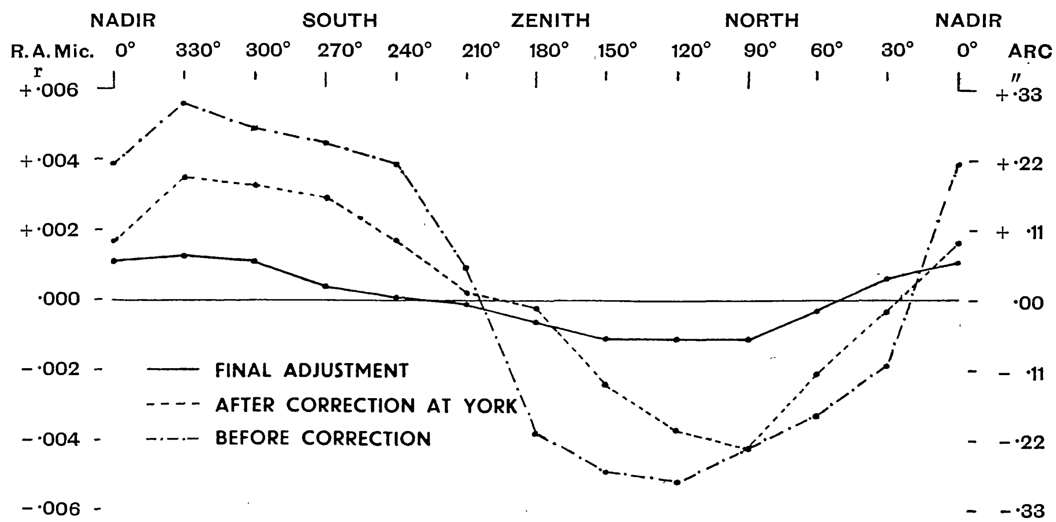

FIG. 1.—*Frame correction for position of micrometer slide showing maximum effect.*

the reading of the Z.D. micrometer was taken. The maximum displacements were of the order of 0″·6 for both the R.A. and the Z.D. movable wires.

The motion of the R.A. slide is guided by a guide rod of rustless steel, 18 cm. in length and 1 cm. in diameter. The central portion of the rod fits into a V-shaped groove, $5\frac{1}{2}$ cm. in length, in a cast-iron block, forming a part of the micrometer box casting; it is clamped into position by a flat plate, which bears on a flat on the central portion of the rod. The R.A. slide is guided by two bearings, 2 cm. in width; the portion of each bearing, which forms an integral part of the slide, is partially cleared away, to leave two segments, each of about 60° angle, bearing on the rod. The upper part of the bearing is clamped to this by two screws, and bears along a segment of about 120° angle.

The micrometer eye-end was returned to York for correction of this trouble and also of the trouble from lag of the moving wire, referred to below. After return from York, it was found that though the effect had been reduced in magnitude, it still persisted and showed the same general features. Much time was spent in investigating the cause of the trouble. It was finally reduced to negligible amount by a careful adjustment of the screws clamping the guide rod to the main casting and of the screws holding the bearing surfaces of the wire frame against the guide rod. In making these adjustments the slide was moved backwards and forwards to test the ease of motion and the freedom from constraint. The final adjustment has been tested at intervals and has been found to remain satisfactorily constant.

The diagram shows the nature of this error at different pointings of the telescope, for the position of the slide at which the effect was a maximum; the observed effects when first detected, after the eye-end had been returned from York, and after final adjustment at Greenwich, are shown separately. The plottings are micrometer readings in the sense mean *minus* observed values, for the circle east position of the instrument. At the centre of the field, where most transits are observed, the corrections are smaller and are negligible in amount.

Similar adjustments were made to the Z.D. micrometer frame. It was not found possible to reduce the range of the effect below about $0''\cdot 2$, the extreme values being found when the telescope is in the north and south horizontal positions. It may be noted that an undetected discordance of this nature would enter directly into the determination of horizontal flexure and would give a spurious result for the flexure.

(*c*) *Lag of Travelling Wire.*—Preliminary observations of right ascension were compared with the R.A.'s given in the FK3 fundamental catalogue. It was found that the stars near the pole, whether observed above or below pole, appeared to transit too early as compared with equatorial stars. The order of magnitude of the discordance was about half a second of time at 7° from the pole. The discordances were the same whether the observations were made with the moving wire hand driven or motor driven, and were the same in the two positions of the instrument.

Observations of right ascension were then made by tapping transits across the fixed wires. The R.A.'s so obtained showed no appreciable deviations from the catalogue places. This definitely located the trouble in the micrometer. The discordance could be explained by supposing that the moving wire lagged behind the screw when the micrometer is in motion by about one second of arc, or 12 microns.

There are two methods of observing close polar stars: (*a*) by a normal transit, using the slowest possible motor drives; (*b*) by setting the motor to equatorial speed, running the wire alternatively backwards and forwards and tapping by hand the instants of its transit over the star. If there were a lag in the wire, the two methods would not give the same result and the difference could be used to infer the amount of lag. On observing by the two methods a selection of circumpolar stars, a difference between the R.A.'s obtained by the two methods was revealed, amounting to $0^s\cdot 44$ at $6\frac{1}{2}^\circ$ from the pole. This gives $0''\cdot 7$ as the lag of the wire behind the screw reading.

The lower bearing of the micrometer slide consists of a slot in which runs a tail-piece on the slide. It appeared possible that this exerted a frictional constraint, tending to twist the moving frame when the micrometer is in motion.

When the micrometer eye-end was tested at York, it was set up with the Z.D. head at the top and the slides vertical. A sensitive bubble was attached to the main slides; it was found that the bubble would travel undisturbed in one direction, but on reversal it ran through $20''$ and showed a tendency gradually to correct itself. On removal of the main lead-screw, the motion of the slide in this direction was found to be uneven and harsh. This was corrected by easing the slide which guides the tail-piece. The guiding rod for the R.A. slide was found to be slightly convex to the eyepiece and the Z.D. slide showed a tendency to jump on reversal of the motion. These faults were attributed to settling down of the metal parts after machining and were cured by the removal of very small amounts of metal. After return of the micrometer eye-end from York, further tests showed that the error of lag had been eliminated.

The absence of lag is now checked at intervals by the following purely instrumental method. The moving wire is motor driven backwards and forwards at equatorial speed and the instants of transit across a fixed wire are tapped off. The same is done with the wire driven at a slow speed corresponding to that of a star with high declination. These tests have shown that the lag has remained negligibly small.

(*d*) *Division Errors of the Fixed Circle.*—The determination of the error of every division is essential for accuracy. The method used and an analysis of the results will be given in a further communication. It is sufficient here to mention that the determination involved over 200,000 microscope pointings. The most noticeable feature is a cyclic error, recurrent every $2\frac{1}{2}°$, ranging from $+0''.19$ to $-0''.18$. Superposed on this cyclic error are periodic errors with periodicities of 15°, 30° and 60°, and semi-amplitudes of $0''.022$, $0''.023$ and $0''.077$ respectively. The total range in the division errors is about $0''.7$.

Coming now to the second group of errors, the instrumental errors of collimation, level and azimuth are subject to both rapid and slow variations. It should be noted that with an instrument in which the level observation involves the use of the R.A. micrometer, an error in the assumed value of the collimation enters directly into the error of level and further produces an error in azimuth. Also, if azimuth marks are used, an error in the assumed value of the collimation will also enter into the determination of the azimuth of the instrument relative to the marks.

(*e*) *The Error of Collimation.*—The usual procedure in meridian observations is to determine the error of collimation at most once daily and to assume that the error varies very slowly. The preliminary observations of transits showed that the instrument was capable of very high precision, and it became clear that more attention must be given to the determination of instrumental errors, especially of the error of collimation. The observations were reduced in the first instance assuming a constant value of the collimation error throughout the day, and interpolating the level error from a smoothed curve drawn to represent the level errors determined from the nadir observations. It was found that, in general, the observations gave a spurious drift in clock error in the course of a night's observations. This appeared to indicate that an apparent drift in level, possibly arising from a drift in the collimation error, was superimposed on the real variations in level.

In the summer of 1938 intensive observations of both collimation and level errors, together with transit observations of clock and azimuth stars, were commenced. Starting at 9^h in the morning, continuous observations were made, when conditions were favourable, throughout the day and into the night, with the exception of about one hour on each side of apparent noon, when the Sun shines directly on the telescope. Marked diurnal changes of the error of collimation, which often exceed $0''.5$, were soon apparent. These changes were associated with temperature variations. Thermometers were later introduced and readings of the temperatures in the dome, inside and outside the eye-end, and inside the tube at the object-glass end, were made at the time of each observation of the collimation error.

The variations in the collimation error are of two types. The first observation of collimation in the morning is taken under what may be termed steady temperature conditions, when the instrument has been left with the dome closed for several hours. Under these conditions the collimation error correlates closely with temperature, showing satisfactory stability and a slow annual variation with temperature.

Plotting the readings of the micrometer screw for the position of collimation against temperature, it is found that the reading decreases by 0·00022 revolution of the micrometer screw for each 1° F. rise in temperature. The micrometer screw has 36 threads to the inch. The screw is of mild steel and bears at one end against a diamond bearing, mounted on the cast-iron micrometer box. The distance from the end bearing to the centre of the field is 3·6 inches. As the micrometer readings increase when the wire moves towards the end bearing, the collimation changes can be accounted for on the assumption that the coefficient of expansion of the steel micrometer screw is 3×10^{-6} per degree C. greater than that of the cast-iron box. The amount is of the right order of magnitude, though somewhat larger than would be expected. Samples of the steel and cast iron are not available for measurement of the coefficients of expansion.

When the observations are continued throughout the day, however, under conditions of changing temperature, the collimation reading changes by amounts that are too great to be accounted for by expansion effects within the micrometer box. The changes correlate *qualitatively* with the temperature differences outside and inside the micrometer, with the differences between the dome and the eye-end, and with the differences between the dome and the objective. These various temperature differences usually correlate very closely with one another, though they differ in range, so that it is not possible to associate the changes in collimation reading with any particular set of temperature changes. The correlation between changes in collimation reading and the various temperature differences is not, however, quantitative; similar temperature differences may be obtained on two days, but the variations in collimation reading may be much smaller on one day than on the other.

The sequence of temperature changes usually observed is as follows: in the morning, when observations normally commence, the temperature in the dome rises more rapidly than the temperature within the tube at either end; the differences become greatest near the time of maximum dome temperature. As the dome temperature falls, the other temperatures lag behind, so that the dome in the evening falls to a lower temperature than the interior of the tube. The temperature differences usually reach a minimum value at some time in the evening, though the dome temperature is still falling, and then begin to increase again.

As an example of the changes that occur, the collimation and level readings for 1940 May 13–14 are shown in Fig. 2, together with the differences of temperature between the outside and inside of the micrometer box. This day has been selected as one on which the true variations in level were very small. The true level error is the difference between the collimation and level readings; it will be noticed that the level readings closely reproduce the fluctuations in the collimation reading. Thus undetected fluctuations in collimation would be thrown into the level readings and spurious corrections for level would be adopted.

Generally speaking, large temperature changes correspond to large collimation changes and conversely. The changes in collimation are thus appreciably greater in the summer months than in the winter months. The correlation is not, however, sufficiently close for the collimation changes to be inferred from the temperature changes and the time devoted to the collimation observations to be thereby reduced.

During the course of a day the observed range in collimation may amount to as much as 0·018 rev., corresponding to 5×10^{-4} inches. Such a change is much too great to attribute to differential thermal expansions in the micrometer box. There must be some other cause which produces a relative change between objective and eye-end. Displacement of the objective itself cannot occur; the objective is held against two fixed stops, 120° apart and symmetrical with respect to the meridian, by a small spring-loaded plunger in the meridian, the spring being of sufficient strength to keep the objective against the fixed stops when its weight is acting against the spring.

The manner in which displacements of the eye-end relative to the objective, of the order of magnitude observed, might most readily be produced seems to be through temperature differences between some parts of the telescope tube and other parts. The design of the telescope is intended to prevent such differences of temperature occurring. The tube is in the form of two truncated cones of cast iron, each about 38 inches in length, with a central cube of 20 inches side. The cube has short flanged cylinders, forming the means of attachment for the truncated cones. Each of the truncated cones is surrounded by a conical copper sheathing, attached at the base of the cone, where it is fixed to the central cube, and free at the other end, so that no strain can be introduced by the different thermal expansions of iron and copper. Between the copper sheathing and the tube is an air space of about one inch. The purpose of the sheathing is to protect the tube itself from local heating and to prevent differences of temperature in different parts of the tube being created.

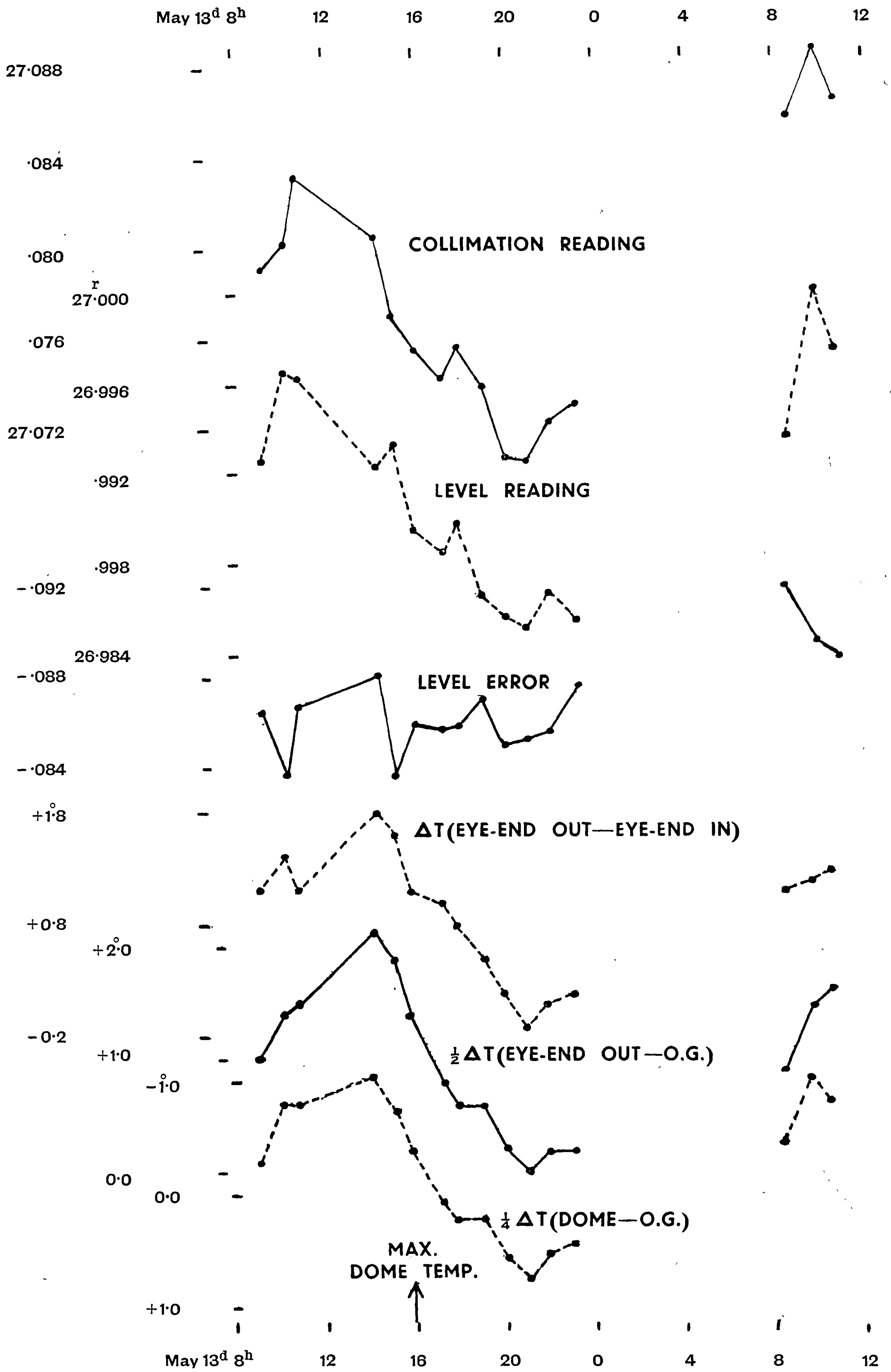

FIG. 2.—*The diagrams give the observed collimation and level readings, the inferred level error; the differences of temperature outside and inside the eye-end, between the eye-end (outside) and the object-glass (half scale) and between the dome and object-glass (quarter scale).*

But if, in spite of the copper sheathing, some parts of the tube could be at a different temperature from others by amounts depending on recent history, as well as on immediately prevailing conditions, displacements that would account for changes in collimation reading, of the order of magnitude that are actually observed, might occur. At the same time, though the changes would be expected to show some qualitative connection with temperature inequalities, they would not repeat exactly on different occasions. If, for instance, a temperature gradient across the tube were to exist, it can easily be shown that a difference in temperature between the east and west sides of the tube over the lower half of its length of a few tenths of a degree Centigrade, causing a slight bending of one-half of the tube, would be sufficient to account for the maximum observed changes of collimation reading. Variable differences in temperature between the two piers of the order of 1° C. have frequently been observed in the summer months. It might be supposed that the side of the tube adjacent to the warmer pier might be at a somewhat higher temperature than the other side, and that the difference in temperature between the two sides would be greater for the portion of the tube carrying the eye-end than for that carrying the objective; for the objective-end during star observations is at a higher level than the eye-end and therefore less likely to be affected by the piers. An equal bending of the two halves would not affect the collimation reading; it is only a differential bending that would produce any effect. If this were the cause of the diurnal changes in collimation, the effect on the collimation reading produced by a given difference of temperature between the two piers would be reversed by reversing the instrument. But such a reversal in the effect is not found; the general changes in collimation reading are qualitatively the same whether the instrument is in the position clamp east or the position clamp west. The changes are therefore not related to any tendency of the west pier to be systematically at a higher or lower temperature than the east pier.

The cause of the variations in collimation reading under conditions of changing temperature remain for the present obscure, and further investigations will be required, when the instrument is brought into use again, in order to find the cause. Unless it proves possible to trace the variations in collimation to their origin and to eliminate them, frequent observations of collimation will be needed in order that the instrumental errors can be sufficiently controlled to give results of the highest precision. This will necessarily slow down the observing appreciably, because frequent determinations of collimation consume considerable time.

(*f*) *Level Error.*—The daily variations in level at times exceed $1''\cdot 0$. They are caused by variations in temperature affecting the piers, and possibly also the pivots, unequally. The direction and velocity of the wind are important factors in producing rapid changes of level. When the dome is open the wind, unless directly from the north or south direction, will blow on one pier more than the other, causing a fall in temperature of that pier. During the daytime the varying position of the Sun is also an important factor.

When the instrument was first brought into use, the variations in level were considerable and sometimes very rapid. This was particularly so on clear nights in the winter with a wind from a north-easterly direction. The west pier would then cool much more rapidly than the sheltered east pier and there would be a quick run off in the level.

A number of thermometers were therefore introduced, some of which were placed in direct contact with the metal surface of the piers. On each pier one thermometer was mounted about a foot below the pivots and another about two feet above the floor. A thermometer was placed in the oil in the base trough, and two others were mounted to give the air temperature on the piers at each end of the axis of the instrument.

It soon became apparent that the changes in level were closely correlated with the differences in temperature between the two piers. It was found possible to express the level error, with a probable error of about $0''\cdot 1$, by the following formula:—

$$\text{Level error} = A + BT + C(T_E - T_W) + D(T'_E - T'_W),$$

where T is the temperature of the oil in the trough;

T_E and T_W are the temperatures of the east and west piers, measured on the inside about a foot below the pivots;

T'_E and T'_W are similar temperatures measured about 2 feet above the ground;

A, B, C, D are constants.

In order to reduce the rapid changes of temperature it was decided to try the effect of screening the piers from direct air currents. For this purpose felt was used, being a good thermal insulator and the material most readily available at the time.

The Greenwich instrument differs from the Cape instrument in that the circle-reading microscopes are not water-jacketed. The superstructure and the bearings of the Greenwich instrument are open to direct contact with the air. Those exposed metal surfaces were jacketed, as far as possible, with the felt. To shield the piers from direct sunlight, portable screens had been constructed. These were made of sheets of "masonite"—a wood pulp compressed on to a canvas backing—mounted on an aluminium framework. Each screen was in two sections, easily fixed together by means of clips; they protected not only the piers, but also the microscopes, both circles and the pivots. As further protection against rapid changes of temperature, the screens were modified and their inner surfaces were lined with felt. This work was carried out by 1939 November. Data available under these conditions extend only to 1940 September, when observations were discontinued. Observations during this period have shown that the mean daily variation in level has been about halved by this incomplete thermal insulation. It is therefore intended, when the instrument is brought into use again, to provide the piers and the micrometer boxes with a much more efficient thermal insulation. The piers will be protected with slabs of granulated cork, about one inch in thickness, with an external covering. If the diurnal variations in level can be reduced to a negligible amount, the nadir observations will provide a useful check on the variations in collimation.

The level error shows a small seasonal change, with a total range of about $1''\cdot5$ during the year. The extreme values occur about the end of March or early April and the end of September or early October, and therefore show a lag, relative to the extremes of air temperature, of six weeks or two months. The ground temperature on the west side of the pavilion is higher during the summer months than that on the east side. It is probable that the small seasonal change in level is caused by a differential expansion between the east and west sides of the foundations which support the instrument.

The direction of the seasonal variation in level corresponds to the west bearing being slightly higher during summer than during winter, relatively to the east bearing. The seasonal change in level is determined from the first observations of level each day, when the instrument is under steady temperature conditions and the temperatures of the two piers are equal.

The mercury trough used for the determinations of level error by means of nadir observations is placed directly on the pier base, below the floor level. A portion of the flooring is removed when the nadir observation is to be made, and a cylindrical screen is placed round the trough to prevent air currents from disturbing the surface of the mercury. When the temperature of the dome is higher than that at the base of the instrument below the floor level, the definition of the wire images is satisfactory. When, however, the temperature of the dome is lower than that at the base of the instrument the nadir observation becomes increasingly difficult the greater the difference of temperature.

With frequent determinations of collimation and level errors, smoothed curves were drawn through the values given by the observations and the adopted collimation and level errors were read off from these smoothed curves. The drift in clock error in the course of a night, which had previously been observed, was then practically eliminated.

(*g*) *Error of Azimuth.*—As the subsoil at Greenwich is not suitable for stable azimuth marks, such as are used for the control of the azimuth of the transit instrument at the Cape Observatory, the azimuth error of the Greenwich transit instrument must be derived from transits of stars. The main purpose of the instrument being to provide fundamental star places, the most satisfactory method of determining the azimuth is by observations of consecutive transits of the same star above and below pole, termed "double azimuths". Any error that may exist in the adopted R.A. of the star cannot affect the azimuth error, as the place of the star is eliminated. This is the ideal and fundamental method of deriving the azimuth of the instrument, but it assumes that the stability of the azimuth can be relied upon over the period of 12 hours between the upper and lower culminations. The effects of any diurnal variation in azimuth can be minimised by selecting stars whose upper culmination lies near the zenith, so that the azimuth factor is small. With the exception of the close polars, the stars used for double azimuths have been situated between 45° and 78° N. Dec.; in general, the upper culmination is observed during the daytime and the lower culmination at night, either 12 hours earlier or later. The derived azimuth error is then applicable to the night observations. The observations are made with the motor-driven impersonal micrometer, with a speed of drive corresponding to the declination of the star, with the exception of the close polars, *Polaris* and δ Ursæ Minoris. These stars have been observed by travelling the moving wire backwards and forwards at equatorial speed and using the hand tapper to record the instants of its passage over the star image.

Double azimuths are not easily observed at Greenwich where, throughout the year, observations are much interfered with by clouds, mist and smoke. Observations of azimuth stars at lower transit are often impossible because of the smoke over London to the north. There is also a period of some weeks in midsummer when a high Sun and a paucity of bright stars reduces the opportunities of obtaining double azimuths.

When double azimuths have not been observed, the azimuth error must be derived by other methods. The two methods used have been:

(1) A close circumpolar star, either *Polaris*, 51 Cephei, δ or λ Ursæ Minoris, is observed in conjunction with a clock star.

(2) Two circumpolar stars north of declination +70° are observed, one at upper culmination and the other at lower culmination.

Whichever method is used, the transits of the two stars are observed as near together in time as possible.

The azimuth error derived by either of these methods is not independent of the positions of the stars and it is necessary to adopt R.A.'s for the stars. In the preliminary investigations, the R.A.'s of the stars given in the FK3 catalogue were used. The smaller the available azimuth factor, the greater will be the effect of accidental and periodic errors of the adopted R.A.'s on the determination of the azimuth error. These additional methods must be used, in order to supplement the less frequent observations of double azimuths. By comparison between the azimuth errors obtained by the three methods of determination, it is possible to derive corrections to the azimuth errors, in whose determination the star places are not eliminated, in order to reduce them to the fundamental system provided by the double azimuths. This enables all the determinations of azimuth to be used and at the same time to be based on the double azimuth system. The adopted azimuth error for the night is thereby strengthened and the R.A.'s derived from transits become more accurate.

For the nights during the period 1937 September to 1940 September on which azimuth errors were derived by more than one method, the separate determinations of azimuth have been compared in order to find what measure of accordance is given by the different methods. The comparisons are given in the table below compared under the two headings and grouped as follows:—

(1) Doubles *minus* circumpolars north of +70°,
(2) Close polars *minus* circumpolars north of +70°,

from which can be inferred the difference Doubles *minus* Close polars. The R.A.'s of the two circumpolars, in the circumpolar-star methods, and of the close polar and associated clock star in the close-polar method, have been adopted from the FK3 catalogue.

Azimuth Errors

1937–1940	(1) Doubles – Circumpolars			(2) Close Polars – Circumpolars			(1)–(2) Doubles – Close Polars
		Wt.	No. of Nights		Wt.	No. of Nights	
	″			″			″
Jan., Feb.	−·33	93	14	−·20	93	23	−·13
Mar., Apr.	−·21	97	18	−·09	67	18	−·12
May, June	−·09	155	27	+·05	144	38	−·14
July, Aug.	·00	17	5	+·01	75	22	−·01
Sept., Oct.	+·23	109	22	+·35	94	23	−·12
Nov., Dec.	+·06	115	19	+·08	86	22	−·02
Mean	−·05	586	105	+·04	559	146	−·09

The results indicate that, compared with the azimuths from both doubles and close polars, the azimuths from circumpolar stars north of declination +70° show variations of a periodic nature. There is also a small systematic difference between the azimuths from doubles and from close polars, which may be caused by the different method of observing close polars and stars at a greater difference from the pole. This can be checked in further investigations by observing suitable stars by both methods. Apart from this small systematic error, the accordance between the azimuths from doubles and close polars is very satisfactory; it should be noted that double azimuths are entirely free from errors of the adopted R.A.'s, whilst, in the close-polar method, the effects of such errors on the derived azimuth errors are greatly reduced by the large azimuth factors.

The question arises to what extent the comparisons may be affected by diurnal changes in the azimuth of the instrument. As it is impossible to obtain observational data for azimuth determinations at all hours of the day and night, diurnal changes in azimuth error cannot be controlled as closely as the diurnal changes in collimation and level. From the data available at present, it appears that any diurnal changes in azimuth must be small. Thus, for instance, the double azimuths may be based on observations of a bright close polar, which would be affected by diurnal change in azimuth, or on the observations of a circumpolar whose upper culmination is near the zenith, which would not be appreciably affected by any such change. The azimuths derived in the two cases are in close agreement. Again, in the course of a night's observations, several determinations of azimuth error may be available, extending over several hours. There is no definite evidence of any systematic tendency for the azimuth error to change in a particular direction. From the design of the mounting of the telescope rapid changes in azimuth would not be expected.

The possibility of a systematic drift in azimuth during the day was investigated in another manner. The differences in observed R.A.'s of clock stars and the R.A.'s of the FK3 catalogue were collected according to the U.T. of the observation. The means of such differences for a complete year, for each hour of U.T. covered by the observations, were formed. Such means are practically independent of any errors in the FK3 places. The means were found to be practically constant up to 18^h U.T., but then showed a slight progressive drift up to 1^h U.T., which could be interpreted as the effect of a drift in azimuth amounting to $0''{\cdot}2$. But on treating stars transiting within 10° of the zenith in the same manner, a similar drift, of equal amount when expressed in time, is shown by north and south zenith stars separately. The drift cannot therefore be produced by diurnal change in azimuth. Though its cause is obscure, it can be concluded that the mean diurnal change in azimuth is satisfactorily small.

Errors of a periodic nature in the right ascension system of the FK3 catalogue would not affect the determinations of azimuth by the double-azimuth method, as errors of star places do not enter into these, nor the determinations by the observation of a close polar and associated clock star, as the R.A.'s of the two stars are nearly the same. But they would affect the determinations of azimuth by the circumpolar method, for the R.A.'s of the two stars—one of which is observed at upper and the other at lower culmination—differ by approximately 12 hours. It is possible therefore that the systematic variation through the year between the azimuths given by the circumpolar observations and those given by double azimuths or close polar observations are caused by periodic errors in the R.A. system of the FK3 catalogue.

The determinations of azimuth by the double-azimuth method are adopted as the fundamental basis of the azimuth. But to discard all transits of azimuth stars for position on nights when no double azimuths are observed would be wasteful. All determinations of azimuth will therefore be reduced to the basis of the double azimuths by the application of the following corrections, which are of a provisional nature:—

(1) To azimuths from a close polar and an associated clock star, a systematic correction of $-0''{\cdot}10$.

(2) To azimuths from circumpolar stars north of declination +70° corrections of $-0''{\cdot}30$ in Jan., Feb.; $-0''{\cdot}20$ in Mar., Apr.; $-0''{\cdot}10$ in May, June; $0''{\cdot}00$ in July, Aug.; $+0''{\cdot}20$ in Sept., Oct.; $+0''{\cdot}05$ in Nov., Dec.

Future observations will provide data for the revision, if necessary, of these corrections.

The azimuth errors show a small systematic annual variation, with a total range of about $1''{\cdot}5$, approximately equal to the annual variation in level. The extreme values occur at about the end of April and the end of October.

The seasonal variation in azimuth having been allowed for, the individual azimuth errors for the period 1938·80 to 1940·68 were arranged according to the direction of the wind, under the headings N, NNE, NE, ENE, etc. The wind directions are only approximate and are liable to variations during the course of a few hours. The weighted means by threes were therefore formed and adopted as the values for the mean direction. The results are given in the following table:—

Corrections to be applied to Observed Azimuths depending on Direction of Wind

Direction	Correction	Wt.	Direction	Correction	Wt.
	″			″	
N	+·33	25	S	−·05	23
NNE	+·26	20	SSW	−·27	45
NE	+·19	18	SW	−·28	49
ENE	+·14	19	WSW	−·32	40
E	+·14	15	W	+·03	25
ESE	+·09	20	WNW	+·05	18
SE	+·06	12	NW	+·22	20
SSE	+·03	10	NNW	+·27	22

A pronounced effect depending upon the direction of the wind is clearly apparent. It should be mentioned that as winds from N. to E. tend to be more frequent in the spring than at other times of the year, the wind effect on azimuth and the annual variation in azimuth are partially correlated. The two effects are not completely separated in the results given above. A more complete separation could have been effected by a second approximation, but this has not seemed worth while for the present discussion, which is of a preliminary nature.

It may be recalled that the observations with the Cookson zenith telescope have clearly shown a close correlation between the direction (but not the strength) of the wind and the position of the zenith. The extreme effects are obtained with N.E. and S.W. winds, the displacement in the zenith between N.E. and S.W. winds being $0''.11$. The observations with the Airy transit instrument have also shown a displacement of about the same amount in the zenith point with winds in these directions.

It is probable that the effects of the wind on the azimuths determined with the reversible transit instrument, and on the zenith point in the observations with the Cookson floating telescope and the Airy transit circle, are due to a tilting of the layers of equal density or temperature in the atmosphere.

It may be as well to stress that, if stable azimuth marks are available for the control of the azimuth of a transit instrument, spurious results will be obtained unless the fluctuations in the collimation are accurately controlled.

Housing of the Telescope and Collimators.—The experience gained in the various investigations with the instrument, which have extended over four years, leads to some comments on the general installation, which may be helpful in the consideration of the design of similar equipment elsewhere.

Observations of the Sun, Venus and Mercury, and of clock and azimuth stars during the daytime are essential in fundamental astronomy. It soon became apparent that the copper-covering of the transit pavilion was heated by the direct rays of the Sun sufficiently to impair the definition of the images in day observations, even when the shutters were open to their maximum extent. Further, the concrete surfacing of the area around the pavilion, and the two collimator houses in the line of the meridian, became heated by the direct rays of the Sun and had a further harmful effect on the seeing.

The importance of a close control over the collimation error is of great importance. Any error in the adopted collimation directly affects the observed right ascensions, but has a further indirect effect because it enters into the determination of the level error by nadir observations and of azimuth by observations of azimuth marks. The collimation is usually assumed to be free from rapid changes, and it is customary for collimation to be determined at infrequent intervals, perhaps once daily or even only once or twice a week. The collimation of the new reversible transit instrument has been found to change appreciably in the course of a day; though the cause of these changes has not yet been found, it is improbable that the instrument is unique in this respect.

The observation of collimation, when the collimators are housed separately from the telescope, is often difficult. The best conditions for observation are obtained with a completely overcast sky. With intermittent cloud they are fairly satisfactory. With a clear sky and the Sun shining, conditions are at their worst. The hot air rising from the heated surface of the concrete surround made the images of the collimator wires diffuse. The collimator housings developed an oven effect, the internal temperatures being different from the outside temperature. This caused diffusion and unsteadiness of the wire images, which was more troublesome the greater the difference between inside and outside temperatures. The effects were particularly noticeable at night after a hot sunny day.

The determination of horizontal flexure for use in the declination observations depends upon observations with the collimators. The accuracy of the result depends almost entirely on the stability of the collimating telescope throughout the period of observation. Experience showed that reliable observations could be obtained only when the sky was overcast and when the temperatures inside and outside the buildings were the same and remained constant. If an observation had been commenced and the clouds broke and the Sun shone before it had been completed, unsteadiness and bad definition resulted and the observation had to be abandoned.

At the end of 1939 louvred wooden screens, painted white, were fitted to the roofs and to the south and west walls of the collimator houses, in order to improve the conditions and to reduce the oven effect. The screens have helped to give substantially better definition than before, but when internal and external temperatures vary greatly, the observations are still difficult.

Experience with the instrument has clearly shown the great advantages that would be gained if the two collimators were housed in the same building as the telescope. Considerations of expense would no doubt be of some importance if this would entail appreciable increase in the size of the telescope pavilion. But it would have been possible without increase in size of the reversible transit circle pavilion to mount the two collimators in the pavilion by making them in the form of bent telescopes, with mirrors placed at a distance of about 18 inches behind the objectives to turn the rays of light through a right angle. There would be sufficient space between the north collimator and the pier for the turntable for the reversing carriage. The cost of separate houses for the collimators would be eliminated; time would be saved in the observation of collimation, because the observer would not have to go outside the pavilion and because of the improvement in definition; and the collimation would be determined with increased accuracy.

The purpose of the concrete surround was to carry rain-water from the pavilion away from the concrete pier on which the instrument is mounted and to keep the surrounding ground dry. These are not unimportant considerations and undoubtedly reduce the seasonal changes in instrumental errors. The small seasonal variations in level and azimuth are evidence of this. On the other hand, the concrete surfacing is detrimental to definition. It is a question for consideration whether this disadvantage does not outweigh the advantage of the stability in level and azimuth. In any similar future installation, it is suggested that the concrete surfacing should be at least one foot below the ground and possibly sloping outwards in the form of a ramp, so that the ground almost up to the pavilion could be covered with turf.

Radiation from the heated copper-covering of the pavilion is troublesome for the day observations. The copper-covering is economical from the point of view of maintenance, as it does not require painting, and is attractive in appearance when the green patina has formed. The development of this patina has been much slower than had been expected, but it is now proceeding satisfactorily. The patina should be beneficial to some extent, but it remains for future observations to show how much is gained by it. If radiation from the covering still proves troublesome, it will be necessary to consider whether the covering should not be painted white and, possibly, the moving shutters covered with light louvred wooden screens, painted white.