III. An Account of some Experiments with the Torsion-rod, for determining the Mean Density of the Earth. By F. Baily, Esq.

This paper was in part read, and will be resumed at the next ordinary meeting.

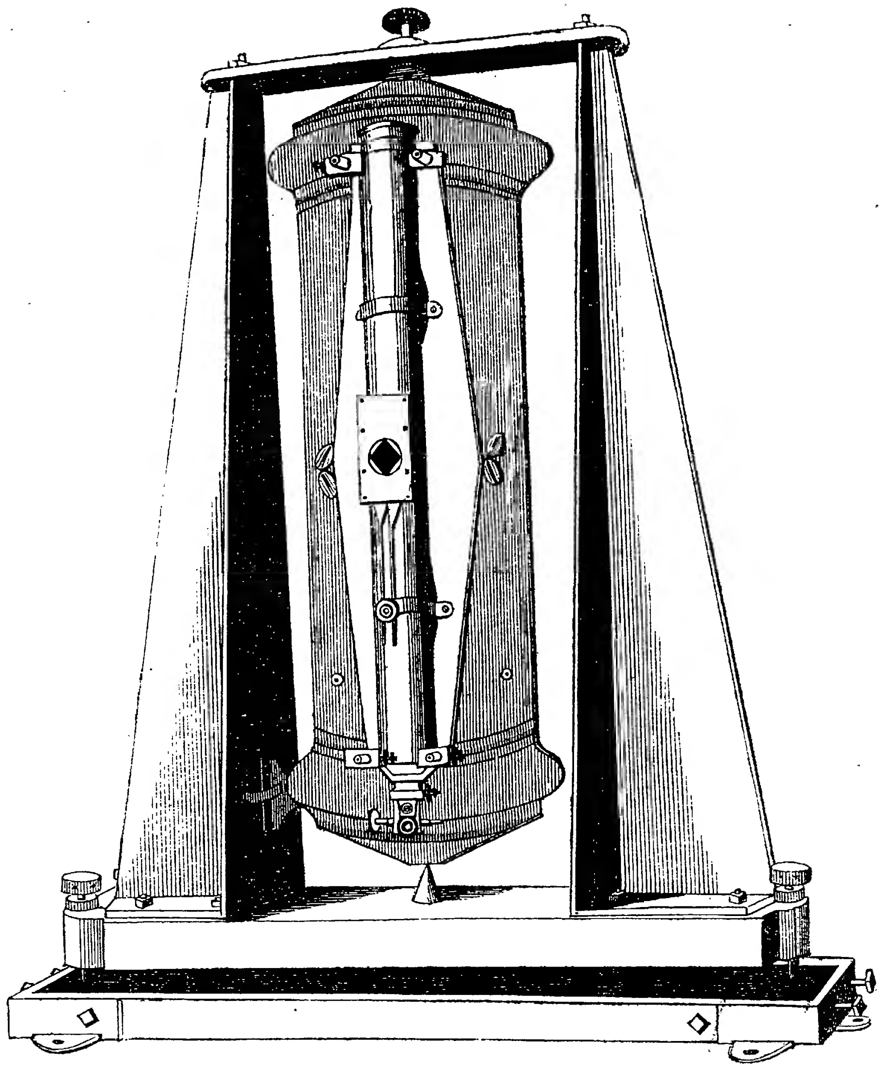
Mr. Airy gave a verbal account, illustrated by a full-sized model, of a zenith sector, now in the course of construction by Messrs. Troughton and Simms, under his direction, for the use of the Trigonometrical Survey. The instrument itself he considered to deserve attention in no remarkable degree except as illustrating principles of construction, which, as speculative principles, possessed no particular novelty, but whose practical importance he had felt so strongly as to have determined, at the first opportunity, on departing from the modes of construction usual among English instrument-makers. The construction of this sector originated in a request of Col. Colby to Mr. Airy to furnish him with a sketch of an instrument by which absolute zenith-distances might be determined with great accuracy by a single night's observations. The necessity for securing the last condition has been frequently felt in the course of the survey (the sectors arranged on the received construction requiring observations with the instrument in reversed positions on successive nights; and the unsettled weather, especially of hilly countries, rendering this a source of most vexatious delay): and in the event of extending the determination of astronomical latitudes in the survey, it would be indispensable that means should be provided for obtaining zenith-distances in a single night. The construction of the instrument was actually begun when the fire at the Tower occurred, in which Ramsden's zenith sector was destroyed. There was now urgent necessity for the completion of the new instrument.

The first principle in the new instrument is the arrangement for obtaining in one night zenith-distances cleared of instrumental reductions. For this purpose it is necessary to have the means either of making observations equally inclined on opposite sides to a horizontal surface, or of making observations equally inclined on opposite sides (as regards the graduations of the instrument) to a vertical axis, or to an axis whose inclination to the vertical could be accurately obtained. The former method was practically introduced by Mr. Airy (at the suggestion of Mr. Sheepshanks, though Dr. Robinson had independently proposed the same plan) at the Cambridge Observatory, and is now continued at the Royal Observatory of Greenwich: the practical process is, to set the circle properly for the observation by reflexion in mercury, to clamp it firmly, and to read the microscopes, before the object enters the field of view: then the reflexion observation is completed in a very short time by bringing upon it the micrometer wire of the telescope; and there is ample time for making the direct observation in the usual way. The latter method had been adopted by Dr. Brinkley in the use of the Dublin Circle: it was also applied (in a somewhat different manner) in the use of the repeating circle, which probably owed much of its value to this circumstance; and Mr. Airy himself had lately made some small modifications in the 25-feet zenith-tube of the Royal Observatory for the same purpose. The practical application of it consists in using every possible contrivance to make the first observation (before reversing the instrument round its vertical axis) as rapid as possible, as, for instance, by reading previously any levels, verniers, or plumb-line microscopes, by which the position of the telescope for the moment is determined, and then making the completion of the observation to depend only on the turning of a micrometer or other screw through a very small space (in the Greenwich zenith-tube an additional wire has been inserted, so that one wire is used for γ *Draconis* with the instrument in one position, and another for the same star with the instrument in the opposite position), and by making the reversion, by means of definite stops, &c., as rapid as possible.

The second principle in the new instrument is, the abandonment of plumb-lines (which have been used in all former zenith sectors) and the reliance upon levels in their stead. Mr. Airy pointed out as a very serious objection to the use of plumb-lines in all instruments which are reversed rapidly, that the bob of the plumb-line will not revolve in the same manner as the instrument, and therefore the lower part of the wire will be twisted relatively to the instrument. And as no wire is ever quite straight, an error is introduced by this twist (the wire not being observed in the same manner, with relation to the parts of the instrument, before and after reversion). In the zenith-tube of the Royal Observatory, to which allusion has been already made, this danger is removed by suspending the plumb-bob to a horizontal bar several inches long, and supporting the two ends of this bar on two plumb-lines, of which one is that which is observed with the microscopes; but this method is not wholly free from objection. In good levels, Mr. Airy expressed great confidence generally: and these it is evident are exposed to no particular error in rapid reversion.

The third principle is, to have each portion of the instrument cast in one piece, as far as possible, and not composed of a great number of pieces connected together by screws and stop-pins. Mr. Airy insisted strongly upon this, as the most important departure from the practice of London instrument-makers. The experience of the engineer-officers employed in our surveys, as well as that of observing astronomers, has shewn that the usual failure of instruments does not arise from want of accuracy of graduation (a few instances of extreme carelessness excepted), but from want of firmness of frame. In some instances (for example, in a part of the East Equatoreal at the Royal Observatory) a partial inaccuracy of division has been produced by the weakness of frame, which required extraordinary precautions to enable it to bear properly the pressure of the dividing apparatus. But the mere process of division, in Troughton's method, appears to be as nearly perfect as it can be made by human powers. Mr. Airy, therefore, had not thought it necessary to attempt any new arrangement for increasing the accuracy of the divisions, or the accuracy of the methods of reading them (the micrometer-microscope scarcely admitting of improvement), but had given much attention to the subject of firmness. The usual plan of construction, he remarked, might be considered as one of *trussing*. This plan possesses the advantage of lightness: it is also strong for supporting a pressure always in one direction, but it can scarcely be trusted when the pressure is sometimes in one direction and sometimes in another. It was adopted by Mr. Airy in the large equatoreal frame of the 20-feet Northumberland telescope at the Cambridge Observatory; but even there it was thought necessary to have powerful screw-bolts, acting in various ways, so as to put it in the power of the astronomer to insure the firmest contact at every joint. Trussing also, in general, has respect to one plane only. For instruments which never change their position, or which are held by hold-fasts in the direction perpendicular to that plane, this principle may be exceedingly good; an excellent instance of this is in Graham's and Bird's mural quadrants, in which such trussing is properly applied, because they are held by proper bolts acting perpendicularly to the plane of the truss, and because the direction of the pressure is always the same. But it fails sometimes in its proper direction from weakness in the perpendicular direction. An instance of this occurred several years ago in the failure of the trussed iron roof of the Brunswick Theatre. The truss was amply strong enough to bear a weight considerably greater than that under which it failed, had it been maintained firmly in its own plane; but the ruin occurred in consequence of the rafters first bending sideways. Mr. Airy then called attention to the construction of the circle called (improperly perhaps) a mural circle. He pointed out that it consisted of thirty-three pieces, entirely in one plane, fitted together with very great manual labour, yet weakly connected; and he inferred that it would be extremely weak without some other principle of strength. Upon examination it was obvious that the strength depended entirely upon the external rings, which were in one piece. The suggestion immediately followed,—Why not make the whole circle in one piece? So strongly had Mr. Airy felt this, that, in mounting the great Northumberland equatoreal, he had caused its hour-circle (five feet in diameter) to be cast in one piece; and Mr. Simms, who had the immediate charge of the further operations, division, &c., was fully satisfied with it. The same remarks as to weakness apply to the zenith sector.

Mr. Airy then proceeded to describe the instrument; a representation of which, in its observing state, is given in the following view:—



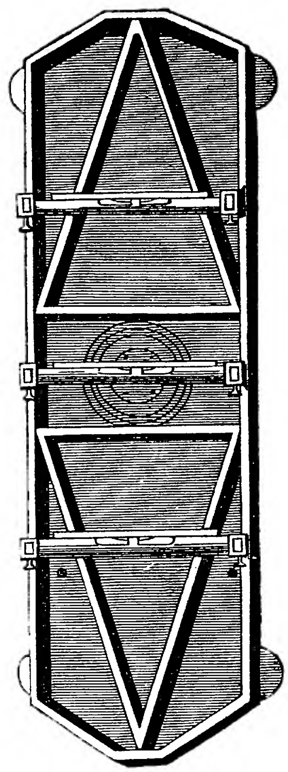
The instrument essentially consists of three portions:—1. The Stand; 2. The Frame, revolving in azimuth; 3. The Telescope-Frame. These were described in order.

1. The Stand.—In conformity with the spirit of Mr. Airy's remarks, the Stand ought, if possible, to have been made in one piece. This was found, however, to be very difficult. Partly for providing for the coarse adjustments necessary in the erection of an instrument, and partly for the sake of portability, it was made of the following parts. The lowest part of all is a large tray of cast-iron, with upright sides. This tray is intended to be fixed upon the pier which will be built up at each station, and is provided with several projecting ears in the plane of its base, pierced with holes, through which screws or bolts may be passed for the purpose of fixing it to such pier. Each of the sides of the tray has tapped in it two strong screws, in a horizontal position, which pass through the sides, and are intended to press the widened edges of

the flat piece next to be mentioned, for the purpose of giving it, if necessary, a part of a revolution (of small extent) in azimuth, and there fixing it. The second part is the flat piece, which is a thin plate of cast iron, having its edges widened in eight places (two on each edge), for receiving the action of the points of the screws, which are tapped in the sides of the tray. The width of the flat piece is less than that of the inside of the tray by about two inches, and its length is less by about one inch; and to this extent it can be turned in azimuth by the screws. The flat piece has three bosses on its lower side, and three others (exactly corresponding to the former) on its upper side. The bosses on the upper side are channelled for receiving the points of the foot-screws of the next part of the stand. The lower bosses are to give definite points of bearing on the horizontal plate of the tray. As these bosses correspond, the bearing of the foot-screws is immediately transmitted to the tray, without any dependence on the strength of the thin plate, which serves merely to connect the bosses on which the foot-screws rest with the widened edges on which the side-screws act. The third part is the Stand proper, consisting of a base and two uprights. The base is an inverted tray of cast iron, strongly ribbed below, the sides and ribs being three inches deep. At the sides, near to one end, it has two brass foot-screws; and at the middle of the other end it has one foot-screw. These screws rest in the channelled bosses of the thin plate. Each upright consists of a broad bearing piece; of a broad upright diminishing in breadth to the top (whose plane in observations will be east and west nearly); and of a broad edge-bar diminishing in breadth to the top (whose plane will be north and south). In order to give to the two uprights a connexion with the base nearly as firm as if they had been cast in one piece, the bearing surfaces of the base and the uprights are planed with the planing engine, and each bearing piece is screwed upon the base with four bolts and nuts. Mr. Airy here took occasion to observe, that he considered the tools of instrument-makers to be extremely defective in regard to their total want of a planing-engine; no other operation giving plane surfaces admitting of the same solidity of contact which is given by that machine: and no instrument having contributed so much, in the opinion of all engineers, to the perfection of modern workmanship, as the planing-engine. For completing the description of the Stand, it is only necessary to add that a cone fixed on the base gives the lower bearing for the Revolving-Frame: and that a cross bar at the top is fastened by nuts upon the two uprights (whose ends are cut as screws), and that a screw in the centre of the bar, with a conical point directed downwards, and a tightening nut, gives the upper bearing for the Revolving-Frame.

2. The Revolving Frame.—This part is of bell-metal, cast entirely in one piece. Its front is represented in the first figure, and its back (with its levels mounted) is shewn in the second figure. It consists of a hexagonal tray, with sides and ribs about

two inches deep. In the central part of its front (on that face shewn in the first figure, but concealed by the Telescope-Frame) is a ring of about eight inches diameter, turned on the lathe. This ring serves as the bearing by which the position of the Telescope-Frame is determined; the Telescope-Frame being drawn to contact by a spring-clutch. The parts at which the Revolving-Frame turns upon the two conical points, mentioned in the description of the Stand, are simply two conical holes, with cylinders of small diameter drilled in continuation of the vertices of the cones. In order to make the workmanship true, the centres of these holes ought to have been marked while the frame was on the lathe for turning the bearing ring; but, from some confusion in transmitting directions through two persons (no instrument-maker having any lathe except of very small dimensions, and the turning of this frame having consequently been intrusted to Messrs. Maudslay and Co., by whom the castings were made) it was forgotten. It is believed, however, that by a subsequent process they are correctly marked; this will be discovered in the use of the instrument. In the second figure are seen the three levels carried by the Revolving-Frame. These can be removed by slipping their ends (which have oblong holes) from the supporting pieces (which are cast with the Revolving-Frame). When in use, the levels are held firmly upon the supporting pieces by screws tapped through the lower sides of the oblong holes, which by pressing with their points the lower sides of the projecting pieces enforce the bearing of the levels upon the upper sides. It is necessary to make the levels moveable, because, in order to determine from observation the want of parallelism between the azimuthal-axis and the bearing-ring, it is necessary to have the power of reversing the Revolving-Frame. The revolution of the Frame in azimuth is checked by a stop attached to one of the uprights of the stand, to which the Frame approaches without much of jar by being compelled to rub along a spring. Near each end of the Revolving-Frame, on the face seen in the first figure, is a divided limb, viewed by the micrometer-microscopes of the Telescope-Frame: and near each end there is also a clamping-limb, for attaching the clamp of the Telescope-Frame; only one of these clamping-limbs (namely, that which happens to be lowest) is used at a time.



3. The Telescope-Frame.—This consists of a ribbed frame of considerable strength, widest in the middle (where its surface is turned to bear properly upon the bearing-ring of the Revolving

Frame), and having a pivot of large size which passes through a corresponding hole in the centre of the Revolving-Frame, and is drawn up by a spring-clutch to give the proper contact of the Telescope-Frame with the bearing ring. The telescope-tube is merely a protection from dust, and carries no essential part of the telescope. Near the object glass are two micrometer-microscopes, and near the eye-end are two opposite to the former. In considering what parts ought to be cast in one piece, it was laid down as absolutely necessary, that the screw for holding the object-glass-cell and its neighbouring microscopes should be in one cast; and that the eye-piece and its microscopes should be in one cast. It was then found easiest to cast the whole in one piece. The microscopes were bored. The following parts are therefore entirely in one cast; the screw for the object-glass-cell, the screws for the object-glasses of the four microscopes, the bearing-parts for the micrometer-screws of the four microscopes, and the bearing-part for the micrometer-screw of the eyepiece. The field of view is to be illuminated by a lamp at a distance; the same lamp throws light upon two reflectors on each side of the Telescope-Frame, which reflect the light to the microscope-reflectors.

General Remarks, and Method of Observing.—It will be perceived, from this description, that very little power of adjustment is left to the observer. The telescope may not describe a great circle; the plane of that circle may not be parallel to the azimuthal axis, the microscopes may have great error of runs, the levels may be not centrally adjusted; but for these errors the observer has no remedy, except in numerical calculation. Mr. Airy stated that he considered this to be a most important principle; that firmness was thereby insured; and that, whether there was or was not a power of adjustment, every instruction for observation, and every skeleton form for calculation, ought to be drawn out on the supposition that there may be, and usually will be, such errors. It is only necessary in the construction of the instrument that means should be provided for measuring the amount of the various errors; and in the instrument in question sufficient means existed, either by the observations of transits in different positions of the revolving frame (both as regards up and down, and as regards face east and face west), or by ordinary instrumental observations. The only adjustment to which these remarks do not apply is that for focal length; and this must be left to the instrument-maker. A small error in this point does not much affect the accuracy of observations which are confined to stars.

The consideration which determined the magnitude of the instrument was this. It was thought that it would be convenient to choose such a length of telescope, that a person of ordinary stature might be able, sitting upon a bench, to observe at the eye-end with a reflecting eyepiece; and that he might be able, standing upon the same bench, to read the upper micrometer-microscopes. It was found that the length of forty-six inches satisfied this condition pretty well; and, as Mr. Simms had by him several good object-glasses of this focal length, one was selected, after trial, by Mr. Airy, and the instrument was adapted to it.

In describing the method of observing, it is to be premised that, though the divisions of the graduated limbs are read as if those limbs were interrupted parts of a complete circle, in which the degrees are read in continued sequence from 0 (at the beginning of one limb) to 359 (which does not appear, being upon the imaginary completion of the circle), yet for convenience a coarse graduation was provided on each end of the revolving frame, upon the clamping limb, giving zenith-distance both ways from the zenith, and used in conjunction with a small indicating mark carried by the telescope-frame. A small setting-piece was also provided, sliding on the opposite side of the clamping limb, and having upon it a strong mark; the use of this is, to be previously set to a zenith distance, in order that the observer may in an instant bring the telescope-frame to its proper position without the trouble of reading the divisions.

The method of observing then is this. There must be two observers, one on each side of the instrument. No. 1 (who is supposed to be on the same side as the Telescope-Frame at commencing) must set the telescope as nearly as possible for the star which is to be observed, and must also fix the small setting-piece for the same zenith distance on the opposite side; he must then read the four microscopes. No. 2, at the same time, must read the three levels. As soon as the star has entered the field, and has arrived at that part at which it is thought proper to observe it (before reaching the centre of the field), No. 1 must bisect it with the micrometer wire; and it will be prudent, though not necessary, for him to read the micrometer. He must immediately turn the Revolving-Frame in azimuth: No. 2 must then loosen the clamp and bring the indicating mark of the Telescope-Frame to the mark on the small setting-piece, when he will find the star in the field of view: he must then bisect it, either by means of the tangent-screw, or by the micrometer (if it has been read); then he must read the four microscopes, and No. 1 in the meantime must read the levels. This completes the double observation. The method of reduction will be, for each position of the instrument, to add together the mean of microscopes, the correction for runs, the mean of equivalents for the three levels, and the equivalent for the micrometer reading (the whole of these ought to be so arranged that there will never be negative quantities); the mean between these two sums for the opposite positions will be the quantity corresponding to a zenithal observation; and it will be prudent to deduce this separately from each star observed in the same evening, and to compare all. The difference between the adopted zenith-point and the sum for each observation, is the true zenith-distance from that observation. The whole of the preceding process requires no fixed wire in the field of view; and it is thought best that there should be no fixed wire (except wires parallel to the meridian, to indicate the part of the field in which the star may be observed).

Mr. Airy then stated that he had no improvement to suggest in the construction of the instrument, except that it might, perhaps, have been a little wider at the base (in the east and west direction), and that the whole might have been made of cast iron. He had been induced to use bell-metal on the belief that, with sufficient soundness, it might be cast thinner than cast iron; but he now had reason to think that he had been misinformed. He stated his intention, if he should again superintend the construction of an important instrument, of constructing it entirely of cast iron, unless some inconvenience at present unknown to him should present itself.

Mr. Airy concluded with some remarks on the tools and methods of instrument-makers, which, though well adapted to work on the small scale, are, in his opinion, inefficient for the construction of large instruments. He instanced particularly the want of powerful lathes with sliding rests, of planing machines, and of fixed drill-frames: and he expressed his opinion that the method of cutting micrometer-screws by dies held in the hand, adopted by instrument-makers, is inferior to the method of cutting them by machinery without reference to manual skill, adopted in the cutting of larger screws in the establishments of modern engineers.

Erratum in last Monthly Notice (*April* 8, 1842).

Page 180, line 11 from the bottom, *for* node, *read* note.