

Terrestrial Magnetism *and* *Atmospheric Electricity*

VOLUME XVI

MARCH, 1911

NUMBER 1

TWO NEW TYPES OF MAGNETOMETERS MADE BY THE
DEPARTMENT OF TERRESTRIAL MAGNETISM
OF THE CARNEGIE INSTITUTION
OF WASHINGTON.

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The land operations of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington especially in regions more or less difficult of access, have emphasized the need of more portable and more compact instrumental outfits than heretofore in general use, without at the same time sacrifice in requisite accuracy. For the regions here considered, in which the greater part of our work must be done, travel is usually difficult and a bulky and heavy equipment is, accordingly, a serious obstacle to safe transportation and rapid work. The conditions imposed make imperative also the omission of complicated and intricate mechanical devices, the adjustments of which are generally difficult to make and maintain, as well as the avoidance of a great number of loose accessory parts, the loss of any one of which may mean at times either the discontinuance or at least the serious interruption of a campaign. Another essential feature in work of this kind is that the outfit be such to admit advantage being taken of every opportunity for observations; the construction therefore should permit practically *immediate* use and not require what may be the best part of the available time for setting up and assembling various parts.

The controlling conditions in the designs and constructions of the present instruments, as carried out under the direction and in consultation with the Director of the Department, have therefore been: (a) portability; (b) compactness; (c) simplicity; (d) minimum loose accessories; (e) readiness for immediate use; (f) the

attainment of an absolute observational accuracy equal to that of the best field instruments now in use. The execution of the Director's instructions fell to the writer, who planned the general instrumental designs and details, and under whose supervision the magnetometers were ably and skillfully constructed by the chief mechanician of the Department, Mr. Adolf Widmer.

The new instruments are of two types. The first is a theodolite magnetometer for astronomical work and the determination of declination and horizontal intensity, in general principles along usual lines but differing greatly in details. Mascart had already designed a very portable and ingenious instrument of this kind;¹ an instrument of his type has been used by the Department but the accuracy attained has not been equal to that of the heavier magnetometers owing perhaps largely to the extreme lightness of the essential parts and especially the very close proximity of the metal portions to the magnet. The second type of instrument of the Department is a universal magnetometer with which the three magnetic elements may be determined as well as the astronomical elements. Wild's² universal theodolite for magnetic surveys is too heavy to admit of ready portability, is rather complicated in its construction, has too many accessory parts, and is not readily adapted to quick work. The magnet and suspension systems of the new instruments are of like design and the following details apply for both.

Magnet System and Suspension.

The *magnet system* for either instrument consists of a long and of a short magnet, each a true cylinder, the dimensions being respectively: length 56 and 26 millimeters, outside diameters 7.9 and 6.5 millimeters, and inside diameters 5.6 and 4.5 millimeters. The ratio of the lengths is such as to theoretically eliminate the second distribution coefficient. The magnets are made of a special permanent magnet steel manufactured by the Crucible Steel Company of America. The method of magnetization was substantially that given by Barus³. The cylinders of steel were ground down to size, next tem-

¹ MASCART, EMILE. *Traité de magnétisme terrestre*. Paris, 1900 (206-219).

² WILD, H. *Theodolith für magnetische Landesaufnahmen*. Vierteljahrsschrift der Naturforschenden Gesellschaft in Zürich. Vol. 41, 1896 (25).

³ BARUS, CARL. The effects of hardness on the electrical and magnetic constants of steel, with particular reference to the tempering of the magnetic parts of instruments. *Jour. Terr. Mag.*, Vol. 2, 1897 (1 to 10). Also *Bulletin of the U. S. Geological Survey*, No. 14.

pered "glass hard," and then subjected alternately to the annealing effect of a steam bath at 100° Centigrade for periods of five to six hours, and magnetization in a solenoid for intervals of one to two minutes, each operation being repeated five times. The solenoid consists of 24 layers of 63 turns each of double cotton wound copper magnet wire 1.3 mms. in diameter; length of solenoid is 10.2 cms., outer diameter 8.8 cms., and inner diameter 1.3 cms. A small dynamo supplies current at 20 volts; the resistance of the coil is 3.7 ohms. The magnetic moments of the long magnets so far made average between 280 and 300 C. G. S. units, the intensity of magnetization thus being of the order 210 to 220 C. G. S. units. The loss in the magnetic moments during the past year has averaged but little over one per cent. The induction coefficients average between 0.0094 and 0.0101; the temperature coefficients between 0.00046 and 0.00060.

Each *long magnet* is encased in a heavily gold-plated brass cylindrical sheath which prevents rusting and provides means for mounting the collimating optical system and balancing. The magnet is centered in position by a projecting pin in the bottom of the stirrup which fits snugly in a rectangular groove properly placed in the brass sheath. The reticle consists of two engraved intersecting lines at right angles on a piece of plano-parallel glass mounted at the south end of the sheath so that when using the magnetometer the observer sights towards the magnetic south. The magnet is erect when the numbered and lettered side of the sheath is east; in order to place the magnet quickly the stirrup is provided with a beveled edge a line on which agrees with a corresponding mark on the magnet sheath when the magnet is erect or inverted as the case may be.

Each *short magnet* is similarly encased and provided with the same optical collimating system so that outwardly both long and short magnets are of the same length, diameter, and appearance; the sheaths and balance are also so adjusted as to make both magnets with their attachments of equal weight. The long magnet can therefore be distinguished from the short magnet only by the lettering on the sheaths, *e. g.*, for magnetometer number 12 the lettering is 12L and 12S at the south ends with the letter N at the north ends respectively. Figure 1 shows one of the magnets mounted in its suspension stirrup.

The entire *suspension system* is comparatively free from complex or intricate parts. The devices for clamping the phosphor

bronze ribbon used for the suspension are such that a new ribbon may be very easily and quickly inserted whenever necessary. In replacing the ribbon the entire suspension head including the graduated circle for setting of line of no torsion (see figure 2) may be removed by unscrewing the lower clamp, *A*, at the top of the brass suspension tube below the graduations. It is not really necessary to remove the head as the ribbon may be dropped through it. The hinged clamp plate at the top is loosened by unscrewing its set screw, *B*, better shown in figure 5, and the new ribbon inserted; the new ribbon must be somewhat longer than finally necessary in order to allow clamping at the stirrup end. The clamp plate at the stirrup (see figure 1) may be loosened by its clamp screw, *C*; the new ribbon is then put in place and the clamping plate turned into its proper position and clamped—the screw *C* is so made that it may not be removed and accordingly the clamping plate is always in place. The length of the suspension is then suitably adjusted by drawing it up through the clamp at the top of the tube. It is to be noted that in these arrangements there are no removable parts and therefore no chance of loss of any essential portion.

The *phosphor bronze ribbon* used ordinarily is 0.013 by 0.188 mm. in section; for inertia determinations a grade twice as thick is used. The *torsion* effect for the smaller ribbon amounts to about nine minutes of arc for ninety degrees of twist for the suspension length of these instruments as used at Washington; a lighter ribbon will be used subsequently if it can be supplied by the makers. The effect of torsion can be quite accurately eliminated by the arrangements for the determination of the line or rather plane of no torsion. It will be noted that there is attached permanently to the stirrup (see figures 1 and 5) a graduated circle; this graduation is brought in focus of the telescope (which is previously focused on a distant mark) by interposing an auxiliary lens mounted at the telescope end of the magnetometer house, operated by the milled head, *D*, into the optical axis of the system. The 180-degree division of the two-degree graduation is the division which, when torsion has been removed, being in the axis of the stirrup should be in the line of sight of the magnetometer telescope. The angle of line of detorsion from the axis of the instrument may be quickly determined by noting extreme swings on the graduation of the stirrup when the round brass torsion weight, equal in weight to the long magnet (and also the short one), is suspended; the suspension head may be shifted

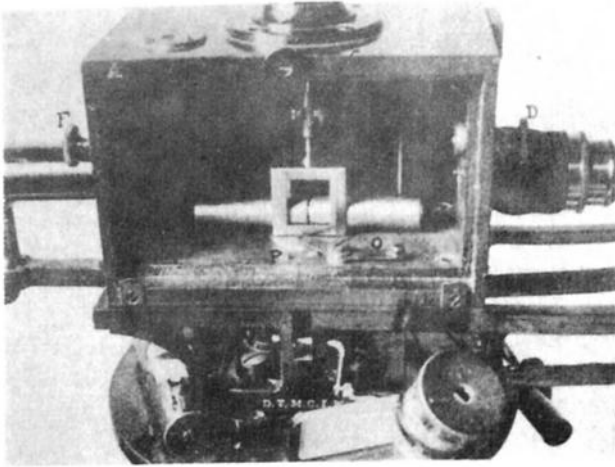


FIGURE 1.

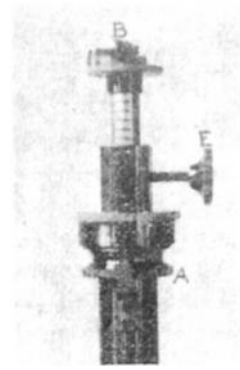


FIGURE 2.

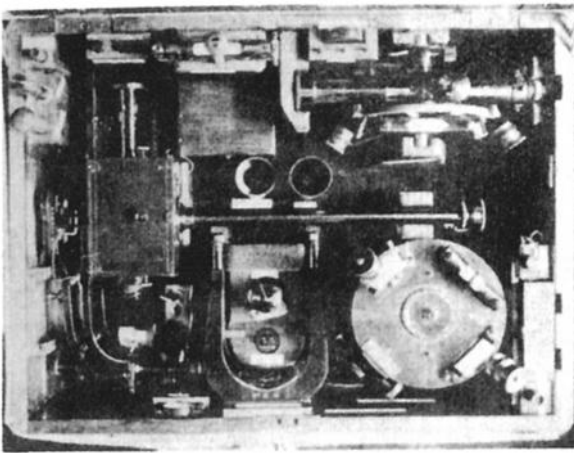


FIGURE 3

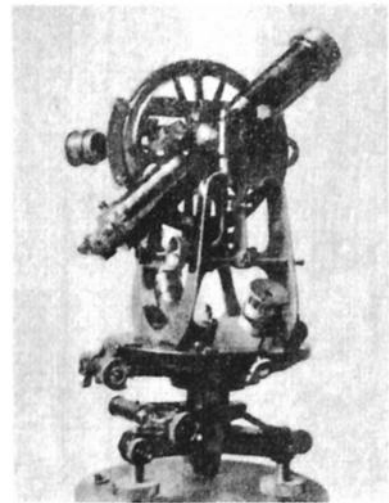


FIGURE 4.

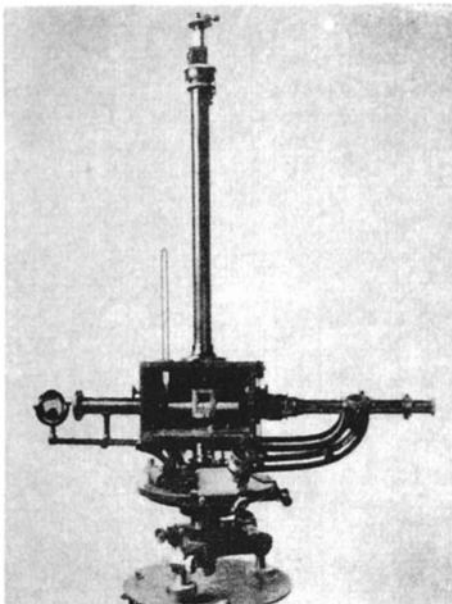


FIGURE 5

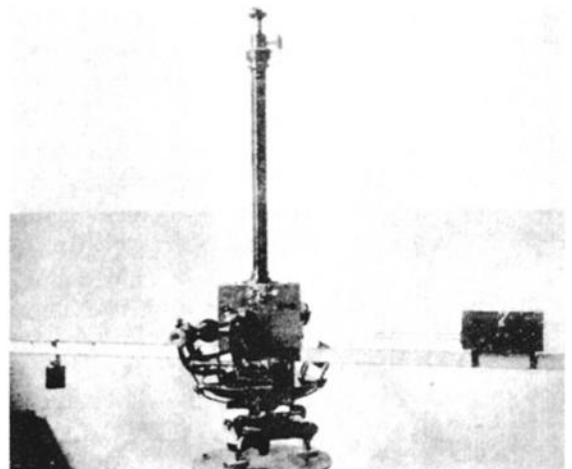


FIGURE 6

through this angle after loosening its clamp, *A* (see figure 2); this operation may be repeated until the mean reading on the graduated circle of the stirrup is 180° when the head is clamped in position. For the measurement of torsion effect a graduated circle with fixed index is provided at the suspension head; the graduation is for intervals of ten degrees and such that one degree may be readily estimated. For the determination of detorsion for inertia observations there is provided a brass torsion weight in the shape of a rectangular parallelepiped of suitable size and weight and with a groove for centering in the stirrup.

The *stirrup* is of brass heavily gold-plated to prevent oxidation. It is of rectangular cross section with portions of its sides cut out to reduce its moment of inertia. The width of the stirrup is made equal to the diameter of the magnet sheaths and the length sufficient to insure accurate orientation of the magnets. The height has been made so that an inertia bar, also of the same diameter as the completed magnets, may be mounted in the stirrup on top of the magnet. The inertia bars provided are of the finest grade drawn phosphor bronze rod; they are 56 mms. long and 9.1 mms. in diameter, the moment of inertia being of the order 82 C. G. S. units at 20° Centigrade. The moment of inertia of the long magnet together with stirrup, the attached graduated circle for torsion work, and the suspension is of the order 66 C. G. S. units at the same temperature. To prevent oxidation the inertia bars are gold-plated; for the purpose of centering in the stirrup there is a very light line engraved on the surface and the bar set accordingly by means of the beveled edges of the stirrup. The edges of the stirrup are beveled in order to prevent parallax when inserting inertia bars or magnets. For determining the proper elevation of the stirrup there are two small holes drilled in the deflection box so that when the latter is mounted on the deflection bar the stirrup, and accordingly the suspended magnet, is at the proper elevation when the lower edge of its rectangular opening in the side is centered in the resulting line of sight. These holes are so small as to be in no way detrimental to protection by the box against sudden changes in temperature of the deflecting magnet. The stirrup is readily raised or lowered by means of the rack and pinion arrangement operated by the milled head, *E* (see figure 2), at the top of the suspension tube; to facilitate setting at the proper point there is a graduation provided on the movable centering tube of the suspension head.

There is an *arrester* for the purpose of quieting the motion of the suspended magnet although such an arrangement is not deemed absolutely necessary by experienced observers who make use of the fingers instead. The device (partially shown in figure 1) consists of two arms attached to a bar operated by means of a slow motion mounted on the outside of the magnetometer house (see figure 6, upper right hand corner of telescope end of house). There is only one adjustment provided for the arrester, *viz.*, that of its axis by means of a set screw in collar at the slow motion end; in case the position of the arms relative to the axis must be altered, this may be readily done by slightly bending one or the other arm until the position is such that when the magnet system is released there will be no vertical motion or "bobbing" and the vertical line of the reticle of the magnet will be near the middle division of the telescope scale.

The *scale* by which the position of the collimation lines of the magnets are referred to the horizontal circle setting is composed of sixty divisions engraved on the plano-parallel glass reticle of the magnetometer telescope. The value of one scale interval is two minutes of arc, the line of sight or reference of the magnetometer as regards the horizontal circle being the middle or thirtieth division of the scale. Particular attention has been paid to the engraving of these scales to insure accurate graduations and that the width of the engraved lines are suitably selected to make possible sharp, definite readings and estimations; this is a point frequently overlooked in instruments of otherwise fine construction.

The Theodolite Magnetometer.

The essential units of the instruments are four, *viz.*: (a) the base, center, and horizontal circle; (b) telescope standard frame; (c) telescope and vertical circle, and (d) magnetometer. These are shown in figure 3 which gives a view of the instrument in its packing case. The theodolites are from selected non-magnetic materials carefully tested by the Department and made by the Messrs. C. L. Berger and Sons, of Boston, Massachusetts; the magnetometer parts and appliances, with some slight modifications in the theodolites, were constructed in the instrument shop of the Department.

The *base* is supported by three leveling foot screws. The graduation of the horizontal circle is for thirty minute intervals; there are two verniers the least count of each being one minute of arc, but

one-half minute is quite definitely and easily estimated. The diameter of the graduated circle is 101 mms.

The *telescope standard frame* is made in one U-shaped piece. Two pins are mounted in the base and corresponding holes placed in the bottom of the standard frame to insure invariably the same relation between the two parts when mounted the surfaces in contact being carefully and accurately fitted. The standard frame fits over a threaded projection of the center and is clamped firmly in place by means of a clamping screw plate (partially shown in figure 1) about 5 centimeters in diameter—a loose thin brass washer is interposed to prevent sticking—suitable depressions are made in the upper surface of the screw flange for its operation by the fingers. The same arrangement is used to clamp the magnetometer unit to the base. In setting up for astronomical work the standard frame is placed on the base in its proper position (indicated by corresponding marks on the two parts) and the clamping flange screwed down lightly—no great pressure is needed as the device is very effective.

The *vertical circle and telescope* are then mounted in the standards and the instrument approximately leveled by the base level the sensitiveness of which is about sixty seconds of arc. A stride level is provided for the final leveling; the sensitiveness of this level is from 18 to 20 seconds for the various instruments. The vertical circle is of the same diameter and has the same graduation as the horizontal and is read directly to one minute by two verniers and by estimation to one-half minute. The circle is attached to the telescope, the verniers being fixed in reference to standards. Suitable arrangements are provided for the usual adjustments. The magnifying power of the telescope is 20; the reticle is a simple cross of two fine fibres at right angles. The instrument as used for astronomical work is shown in figure 4.

It will be noted from figure 3 that the *magnetometer* attachment including its telescope and suspension is packed assembled and may be mounted on the base in one operation. Figure 1 shows the device for clamping the stirrup when the instrument is packed away (the magnet is of course first removed). After the magnetometer is set up and properly leveled, the stirrup is quickly unclamped by pushing over the lever, *O*, until stopped by the pin, *P*, and at once raised into position for the insertion of torsion weight and the determination of the plane of detorsion. In order to prevent any wearing action on the top of the graduated circle of the stirrup it should be

noted that the clamp is so arranged that it touches the circle only in its holding position and not while being removed or put in place. The magnetometer house is of wood; this permits observations of oscillations and of deflections in the same housing. The magnetometer telescope, magnifying power 8, is supported by wyes made in the extension of the magnetometer supports carried directly from the base. A *hood*, as in figure 1, attached to the house and fitting over the objective end of the telescope is provided in place of a window to shut out air currents. At the south end of the house there is a plano-parallel glass window which may be turned out of the way, when reading the mark, by means of a milled head, *F*, as in figure 1; this window is of course kept closed while making magnet readings to exclude air currents.

For the *illumination of the magnet* reticle and telescope scale an iris diaphragm and tube (see figure 5) are provided; the opening in the iris diaphragm may be made larger or smaller by motion of a small lever and so regulate the illumination according to the light conditions. A mirror which may be rotated in both the vertical and horizontal planes, with a white reflector on its reverse side, serves to reflect light through the iris diaphragm and tube; it is mounted at the end of the support of the diaphragm tube as shown in figure 5. These illuminating appurtenances are all made removable so that in case it is necessary to use a mark which is not in the horizon they can be taken off and so not interfere with sightings; the telescope end of the hood is provided with a brass collar so that it may be removed from the end of the telescope and the latter have greater vertical motion as may be necessary under the same circumstances. Figure 5 shows the magnetometer with one of the two doors removed and with a magnet suspended in place. The total length of the suspension, *i. e.*, the distance from the bottom of the ribbon clamp at the suspension head to the center of the magnet when in place is from 314 to 364 mms., depending upon the length of ribbon between the upper and lower clamps; ordinarily the total length is about 340 mms. The distance from the top of the clamp of the stirrup to the center of the magnet when suspended is 35.5 mms.

The *deflection bar* for the deflection observations is of rectangular cross section, 5 mms. thick by 15 mms. deep, and is mounted just below the magnet house; the detail of this mounting is shown by figures 1 and 6. The bar is centered and securely held in place by two slightly tapered pins, one at each side of the house. For

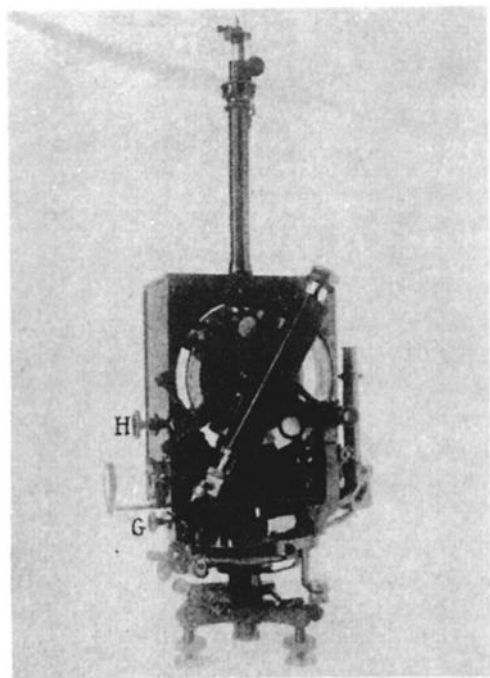


FIGURE 7

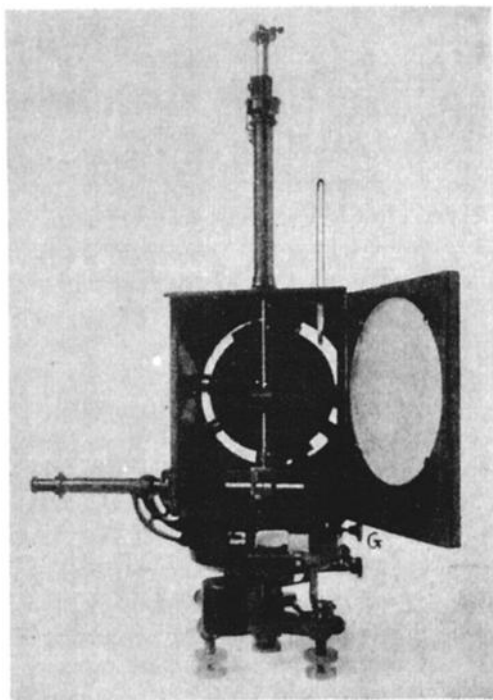


FIGURE 8.

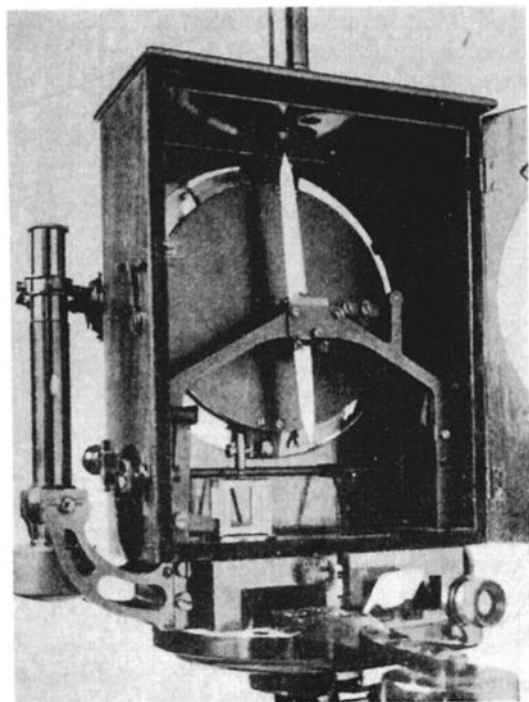


FIGURE 9.

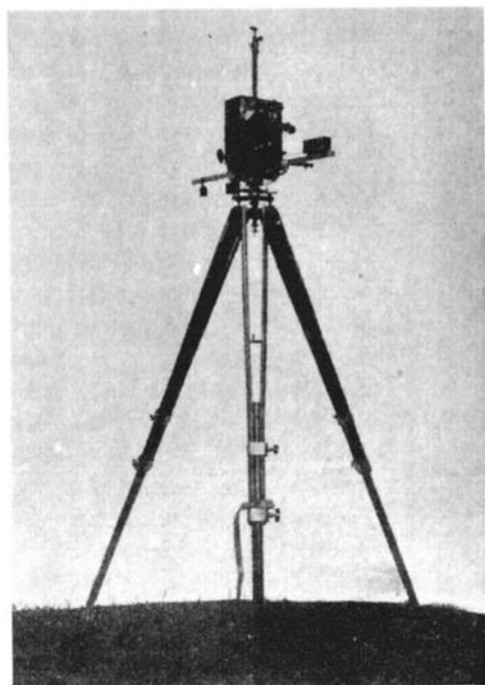


FIGURE 10.

UNIVERSAL MAGNETOMETER.

centering and protecting the magnet against sudden changes of temperature there is a wood box; the metal supports, wyes, and centers of this housing are complete in themselves, the metal surface bearing on the bar being of sufficient length to insure horizontality of the magnet when mounted in the wyes and centered by a pin fitting snugly in the rectangular groove of the magnet sheath. The lower end of the magnet centering pin of the deflection box is finished to fit snugly in rectangular grooves in the deflection bar at deflection distances 20, 25, and 28 centimeters; the rectangular grooves for centering deflection box have been adopted as they seem somewhat better than the old form of slightly tapering circular holes. For maintaining the vertical plane of the center two broad arms extend down from the metal base the full depth of the deflection bar, against which a heavy spring on the rear side presses them. A suitable counterweight is provided to maintain the level when observing deflections. The instrument as mounted for deflection work, and as seen from the telescope end, is shown in figure 6.

The inside measurements of the *packing case* (see figure 3) are: depth 15 cms. when closed; width 30 cms.; length 42 cms.; the dimensions over all are about 2 cms. greater each way; the *total weight of the instrument and case* is 11 kilograms; that of the older forms of theodolite magnetometers used by the Department twice as much. When account is taken also of the much heavier shipping cases required for the older form of instrument the material reduction in total weight for transportation in the case of the present instrument is made still more apparent. The tripod for the new theodolite magnetometer, as made by Messrs. Berger and Sons, is of the telescoping kind as figure 10, with the exception that the head is somewhat modified to provide means for mounting the Dover dip circle used in connection with this instrument. The deflection bar when in transportation is mounted in its tube case in a hand strap with the tripod; the weight of the tripod and bar is four and one-fourth kilograms against seven and one-half for the tripod and bar of the older form.

The Universal Magnetometer.

This instrument is completely assembled in one unit, comprising astronomical telescope and magnetometer for the determination of magnetic declination and horizontal intensity, and dip circle for determination of inclination and total intensity, and therefore always

ready for immediate use upon mounting on its tripod. The advantage of being able to proceed with the determination of any one of the observations desired at the magnetic station, without first assembling a number of parts, is evident and of peculiar value in taking advantage of every available opportunity for work.

The *base, horizontal circle, and center* are practically identical as regards diameter, graduation, and verniers, with those of the theodolite magnetometer, except a heavy top plate attached to the base to provide means for the securing of the heavier upper works of this instrument. The level attached to the base has a sensitiveness of 30 seconds of arc.

The *astronomical telescope*, magnifying power 18, is mounted eccentrically the distance between the center of the instrument and its vertical plane of collimation being 63 mms. It is provided with a swivelled prismatic eye-piece and suitable shade-glasses for sun work. The single heavy telescope standard is securely mounted on the heavy base casting supporting the magnet house; the bearing for the axis of the telescope is 18 mms. long. This standard also carries the various attachments for dip circle microscopes, vertical circle, reading lenses, clamps, etc. The graduated circle and counterpoise are on the opposite side of the bearing from the telescope and behind a plano-parallel glass window, somewhat greater in diameter than the circle, suitably mounted in the magnet house.

The *vertical circle* is 101 mms. in diameter and graduated for 30 minute intervals, the least count on the two verniers being one minute of arc, but estimations being easily and definitely made for one-half minute. The vertical circle in this instrument is fixed in position, while the verniers move with the telescope. Figure 7 gives a view of the instrument showing various details of the astronomical telescope, vertical circle, magnet house, etc.

The *magnet house* is of old well-seasoned mahogany, carefully finished, polished, and reinforced as necessary to prevent any warping. Figure 8 shows the interior of the house when the instrument is used for magnetic declination and oscillation work. The *magnetometer telescope*, magnifying power 8, is supported in two wyes secured to the base in such a way that its line of sight is central. As will be noted in the figure the wyes are, for economy in packing space, quite near the object end of the telescope which is suitably counterweighted. The counterweight serves the additional purpose of making possible the elimination of the hood arrangement as in the

theodolite magnetometer and which has some objectionable features. The end surface of the counterweight is part of a sphere of large radius; there is a spherical surfaced depression of like size and radius in the outer face of the end of the house; the depression is lined with velvet and so made that when the telescope is horizontal, or nearly so, the two surfaces make a neat fit, thus preventing any currents of air entering the house (see figure 9). The window and illumination device at the south end of the house are somewhat modified over those of the theodolite magnetometer. The plano-parallel glass for keeping out currents of air that might interfere with the suspended magnet, the iris diaphragm, and the mirror and reflector are assembled together, the whole being attached to the box and swinging on a hinge, so that when mark readings are desired the clamping pin may be removed and the system thrown over to prevent interference; when observations are being made it is of course put back into position and clamped. The total length of the suspension, *i. e.*, from the bottom of the clamp of the suspension head to the center of the magnet when mounted is from 326 to 375 mms., depending upon the length of the phosphor-bronze ribbon used. Ordinarily the total length is about 360 mms. The distance between the upper end of the stirrup clamp and the center of the magnet when in position is 32 mms.

The *deflection bar*, box, and counter weight are similar to those above described for the theodolite magnetometer, with the exception of the centering and clamping arrangements for the deflection bar. The casting supporting the magnet house is much heavier than for the theodolite magnetometer and therefore allows of much broader and better bearings, so that the bar for this instrument is firmly held in place by means of but one tapered pin mounted in the center of the instrument; this pin is operated by the milled head *G* (figures 7 and 8). In order to have the center of the house free for the dip work (see figure 9) the stirrup is clamped in one corner and the suspension head sufficiently elevated to make the bronze ribbon nearly taut, and so out of the way. The detail of the clamping arrangement by knee lever and spring is shown in figures 8 and 9 in lower left-hand inside corner of house.

The supports for the agates of the *dip circle*, used for the needle bearings (figure 9), are attached securely to the heavy base independently of the house. They are made of similar shape with the telescope standard in order that there may be as little interference of parts as possible in sighting on the needle points. The needle lifter is operated by means of an eccentric and lever, by a milled head on the south end of the house (see *H*, figure 7). The dip needles were made by Dover, and are of the usual land pattern, except as regards length, being somewhat longer in order that the ends may project beyond the vertical circle. The sighting microscopes are a little unusual in that the object lenses are mounted inside of the house fixed permanently to the counterpoise plate so as

to move with the verniers, while the remainder of the optical arrangements are mounted outside; this has been found quite satisfactory. It should be noted that no matter what position the needle may take it is always possible to read the upper end; it is a comparatively easy matter to supply the data for those parts of the circle where the lower end is obscured by interference of supports by observations made on either side.

Total intensity arrangements according to Lloyd's method are also provided, the deflecting needle being mounted on suitable supports attached to the telescope, which is at right angles to the line of sight of the microscopes. The instrument is equipped with two pairs of dip needles and two pairs of intensity needles, together with all necessary appurtenances, as reversing block, bar magnets, etc.

Figure 10 shows the magnetometer mounted on its *tripod*. The latter has legs of a telescoping pattern; this style, unless carried in the hand, is rather inconvenient for packing, as the numerous screws and nuts are quite likely to be bent. It is therefore expected in the next universal magnetometer to provide a tripod somewhat similar to the pattern usually supplied with the Dover dip circles, which is not much heavier and of simpler construction than the one shown.

The inside measurements of the *packing case* are: depth with door closed, 21 cms.; width, 25 cms.; height, 49 cms.; the dimensions over all are about 2 cms. greater each way. The weight of the instrument with all of its appurtenances, but exclusive of the case is $7\frac{1}{4}$ kilograms. That of the case about 6 kilograms, the total weight being about 13 kilograms. The weight of the instrumental outfit consisting of dip circle and magnetometer usually supplied is more than twice as much; when account is taken of the transportation cases, three to four times as great. The weight of the tripod as in figure 10, with deflection bar, is $4\frac{1}{4}$ kilograms; the new form referred to above will be of about the same weight.

The *corrections* of the new instruments on the provisional International Magnetic Standards of the Department have been carefully determined by the method of simultaneous intercomparisons with standard field instruments. The type of standard instrument of the Department has been subjected to a peculiarly severe test as regards accuracy in the numerous intercomparison observations that have been made at various observatories; the results have been such as to indicate *absolute* accuracy in magnetic determinations of the order of 0.5 minute in declination, 0.02 per cent in horizontal intensity ($.0002H$), and about one-half minute in inclination. The results of the comparisons of the new instruments have clearly shown that their accuracy is of the same order.

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