

Determination of
the Horizontal Component
of the Earth's Magnetic
Field.

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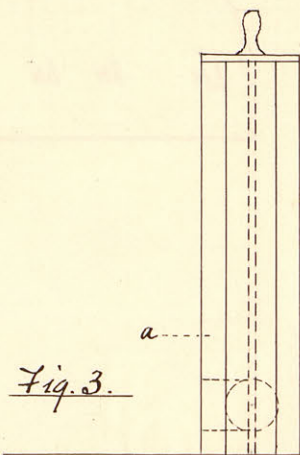


Fig. 3.

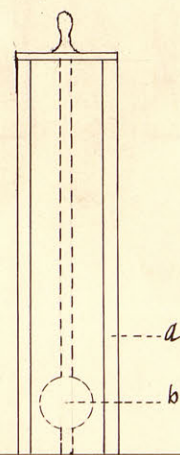


Fig. 2.

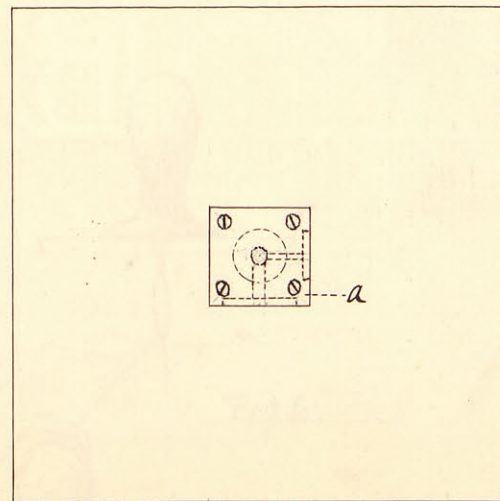


Fig. 1.

PLATE I.

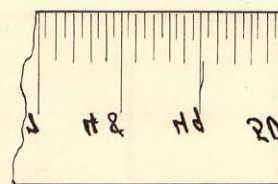
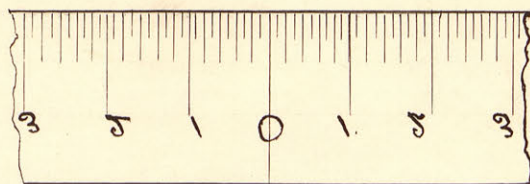


Fig. 7.

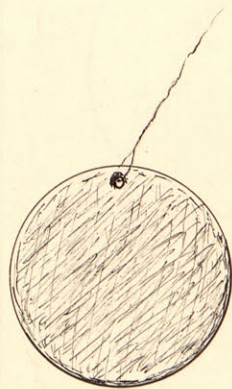


Fig. 4.

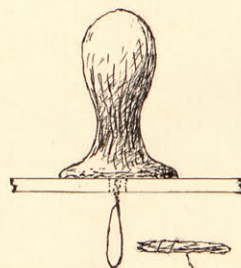


Fig. 5.

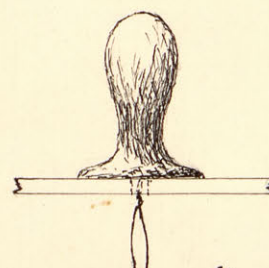
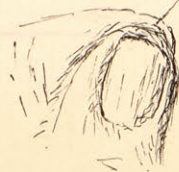


Fig. 6.



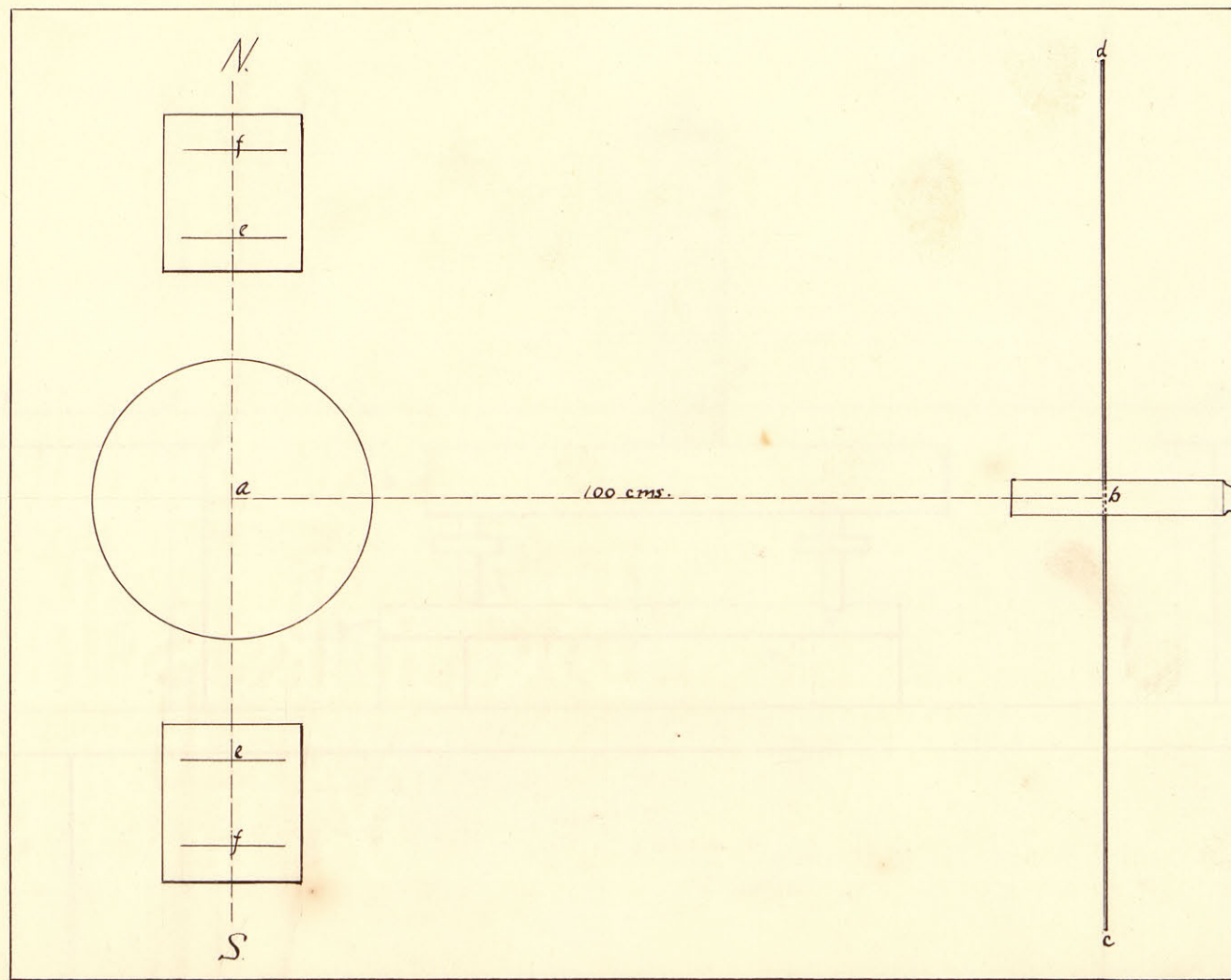
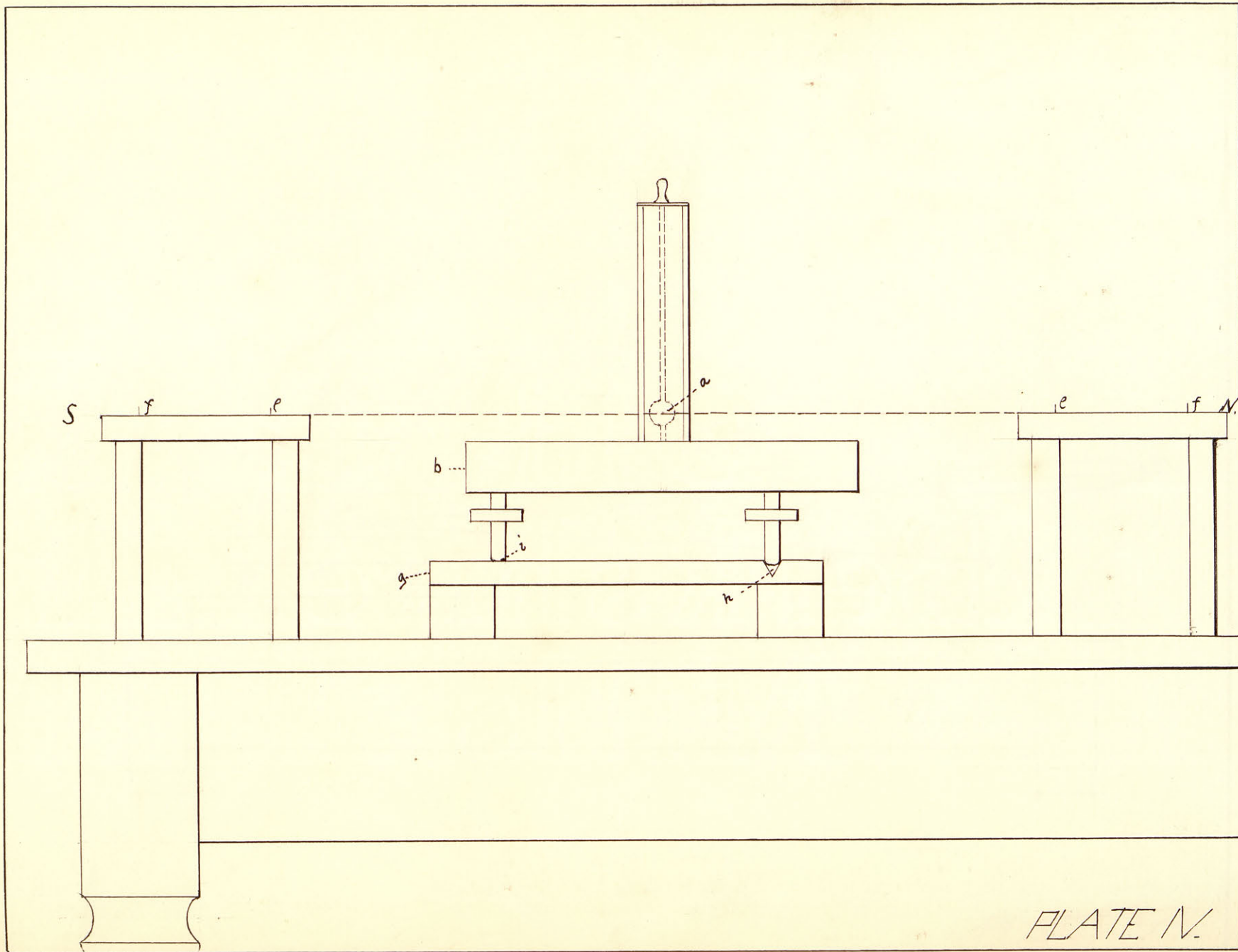


PLATE III.



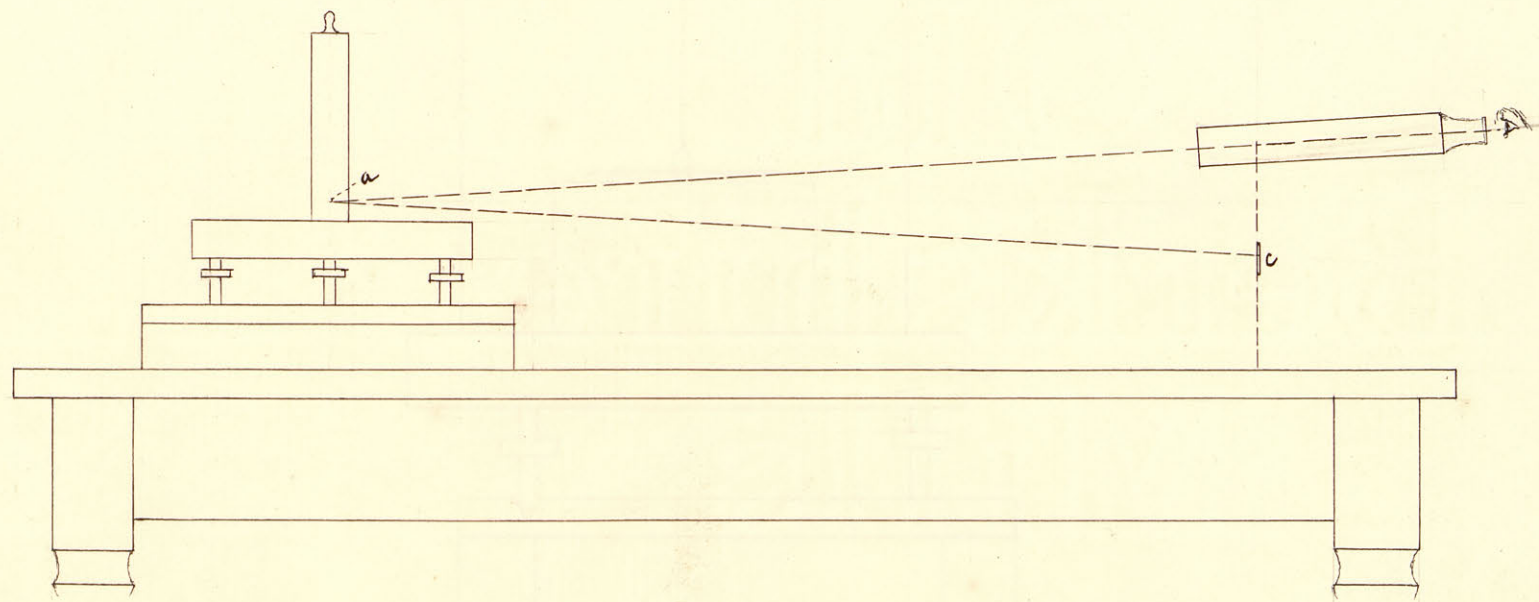
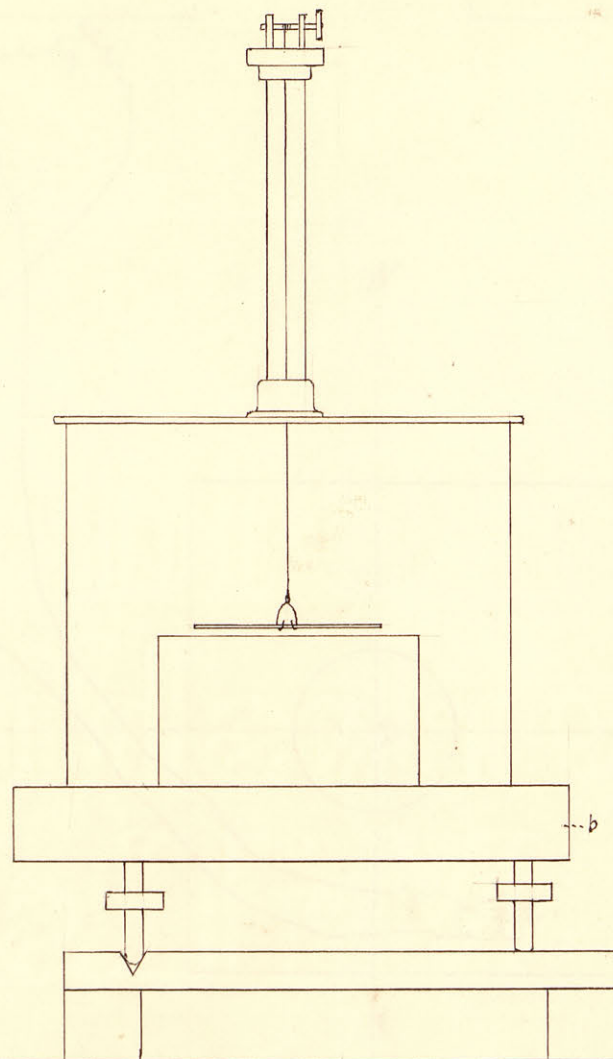
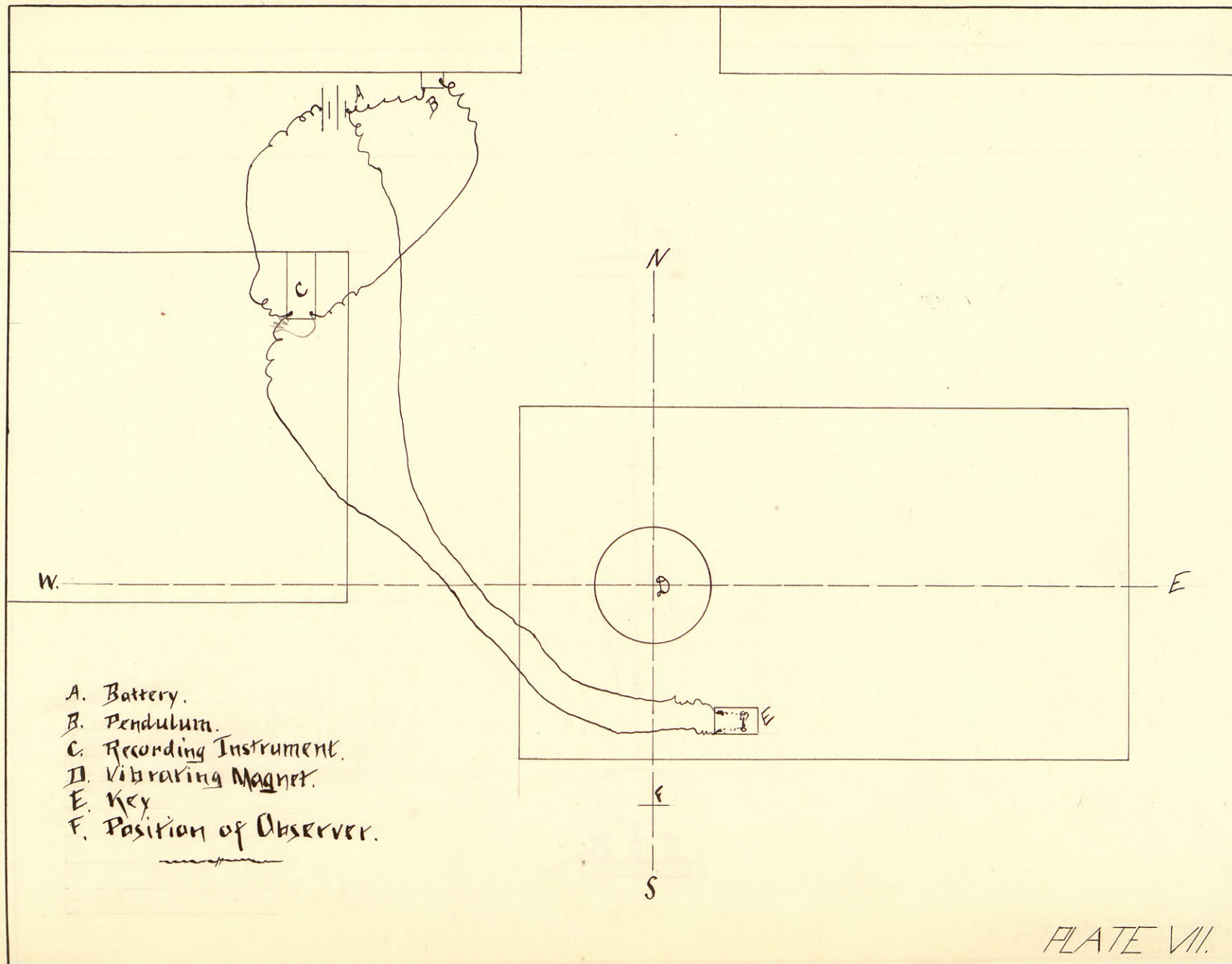


PLATE V





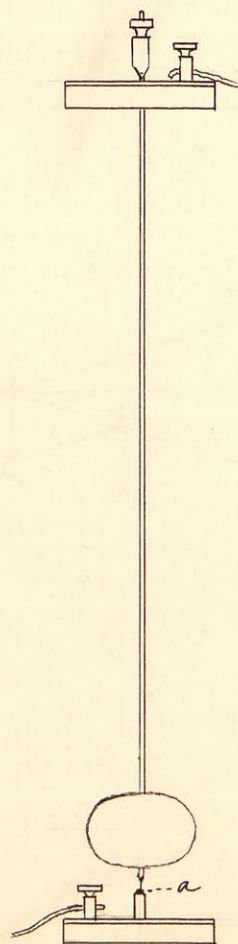
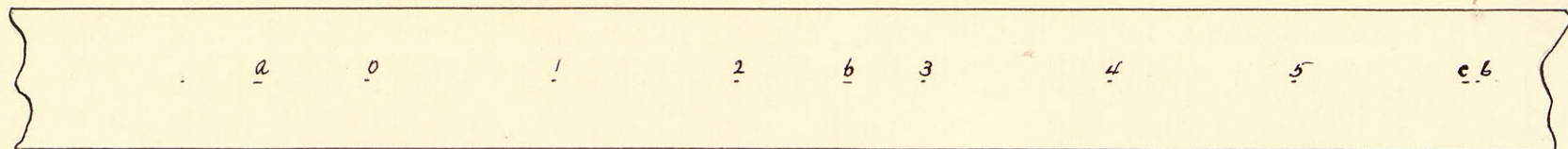


PLATE VIII.

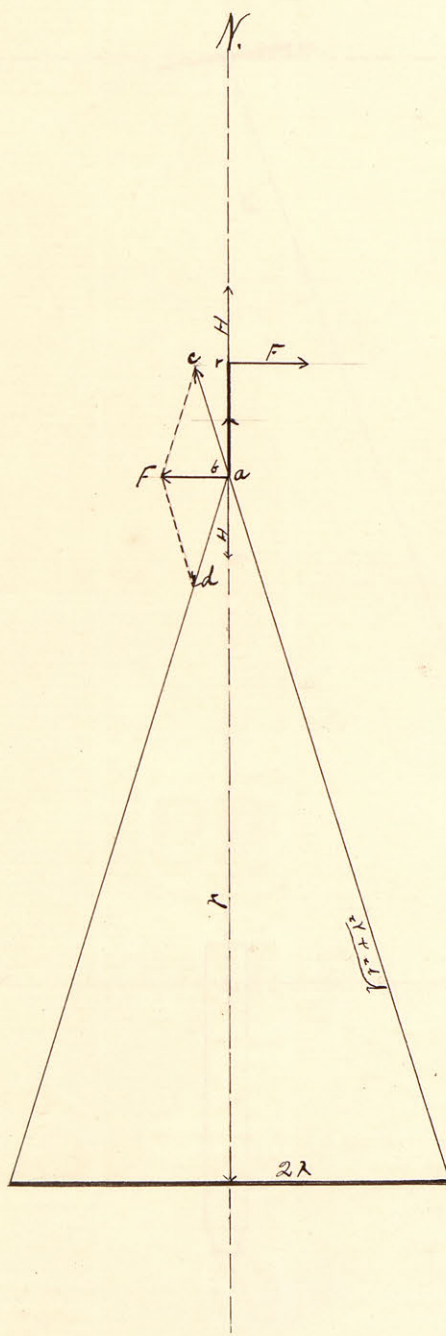
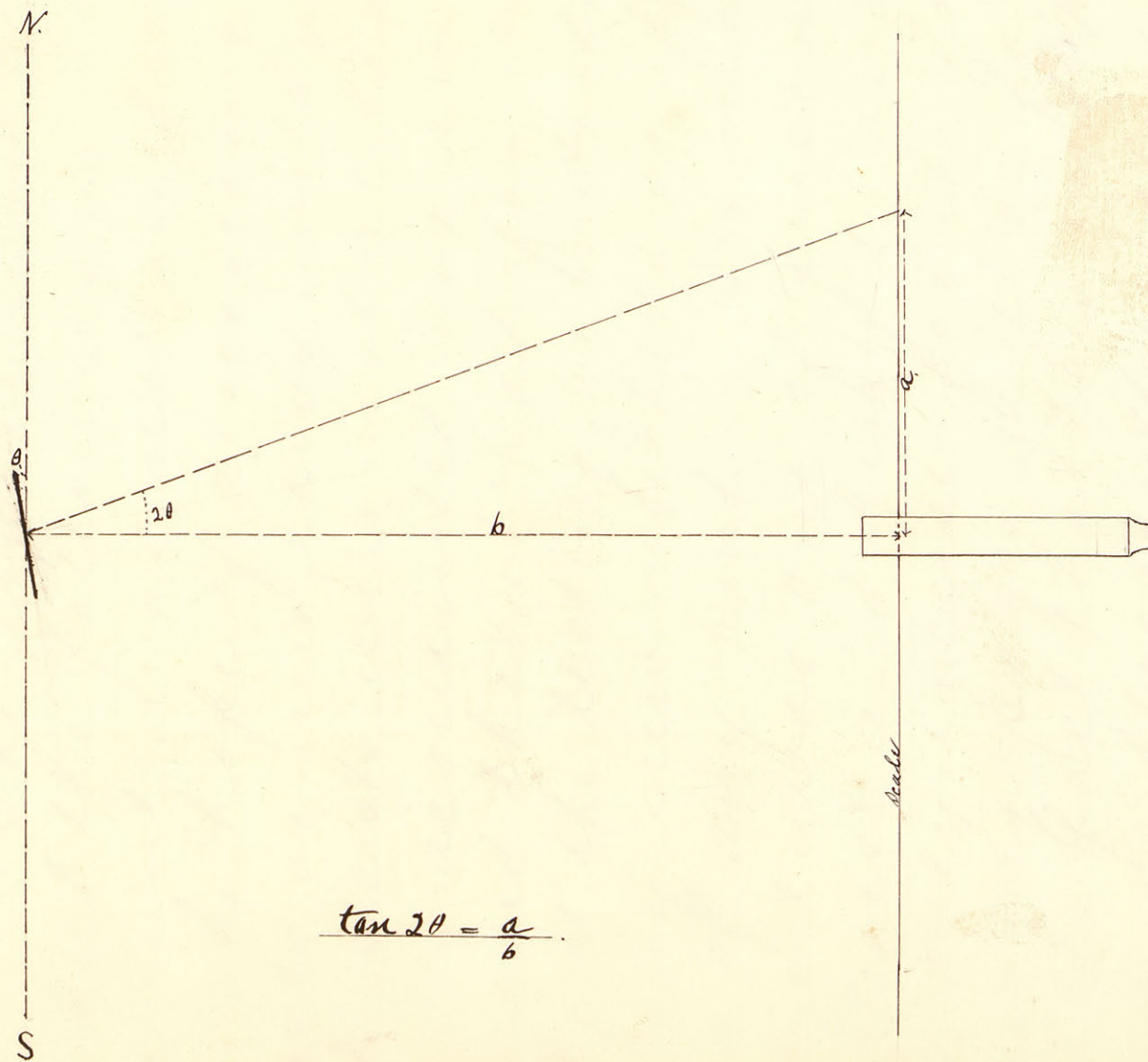


PLATE IX

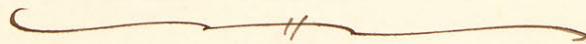


$$\tan 2\theta = \frac{a}{b}$$

PLATE X

Plates—

- I. The Magnetometer.
- II. Telescope Scale, etc.
- III. Deflection Experiment
- IV. " "
- V. " "
- VI. Oscillation Experiment
- VII. " "
- VIII. " "
- IX. "Side-on" Position.
- X. Angle of Deflection.



The experiment of which the following is an account, was not undertaken in the hope of discovering new facts or new laws with which physicists were not already fully acquainted, nor can it be said that it had for its object the testing or introduction of any new methods or apparatus of any kind. Its main object was one of personal interest and benefit; and the only excuse for the following pages, will be found in the fact that this end has been so pleasantly realized, and in the hope that a record of the experiment and the results reached, including a description of the apparatus used and an account of the difficulties encountered,

may not be without some interest to students at the College who in after years may undertake a similar experiment.

"The absolute system of units, introduced by Gauss and Weber," says Prof. Andrew Gray, "has changed experimental electricity and magnetism into sciences of which the very essence is the most delicate and exact measurements, and enables their results to be expressed in units which are altogether independent of the instruments, the surroundings, and the locality of the investigator."

More attention is constantly being given to the expression of electric and magnetic forces in absolute measure because of its importance as a basis for

the practical units, and perhaps, also, because of the interest such experiments draw forth on account of the great accuracy of results that may be attained with proper precautions.

The determination in absolute measure of the intensity of the horizontal component of the earth's magnetic field, commonly denoted by H , is the subject of the following experiment.

It often becomes necessary in magnetic and electrical measurements, to know the value of H .

The method used here is that first introduced by Gauss, and which according to the statement of Prof. Gray" consists in finding (1.) the angle through which the needle of a magnetometer is deflected by a magnet placed in a given position,

at a given distance, (2.) the period of vibration of the [same] magnet when suspended horizontally in the earth's field so as to be free to turn about a vertical axis."

From these two experiments, as we shall see later, equations are obtained involving the ratio of the horizontal component of the earth's magnetic field (H) to the magnetic moment (M) of the magnet, in the one case, and their product in the other.

Before entering upon the details of the experiment, a brief description of the apparatus used, will be given.

The magnetometer was constructed as shown in plate I. of wood, brass, and glass. It consists of a wooden base made to fit into the wooden base of

a torsion balance (b. plate VI) (also b. plate IV.) having three leveling screws. In the centre of the base is a standard also of wood, about 20 cms. high, having a hole from the top down through the centre, with an enlarged chamber, b., near the bottom—just large enough to permit the free movement of a polished circular magnet, such as is used in Thompson's reflecting galvanometers. The front side of the chamber (Fig. 2. b.) is cut out and covered with glass so that the light may be reflected from the "mirror-magnet" within. One of the adjacent sides has a narrow opening (Fig. 3. and 1.) also covered with glass. This is to permit the suspended magnet of being seen from that side, and will be found useful in leveling the instru-

ment, and in laying off the magnetic meridian passing through the magnet. The top of the standard is covered with a brass plate in the centre of which, is a knob having a wire loop passing through a hole in the plate. The corner piece a of the standard, may be removed by taking out the screw at the top, in order to facilitate the hanging of the reflecting magnet. The magnet is suspended by a single fiber of unspun silk, from the loop in the knob at the top. This is done by first fastening one end of the fiber to the magnet (Fig. 4.) and passing the other through the loop (Fig. 5.), and then carefully pulling the magnet up by means of the fiber till it hangs in the chamber (b plate I.) without touching top or bottom.

Then at just the right height, apply a little mucilage to the fiber just below the loop (c), and then give the knob a few turns. If very little mucilage was used, it will dry in a moment, and the magnet will be properly suspended.

Replace the corner piece of the standard, and the glass covers, and the magnetometer is complete. The object of having the magnet suspended within a closed chamber is to eliminate the disturbing effect of currents of air, and to make the magnet as nearly "dead beat" as possible.

It was necessary to have some way of resetting the instrument, should it be disturbed during the experiment, and a hollow and V groove was found useful for this purpose. A board (q. plate IV) was fastened to the table upon which the instruments used

in the experiments, were placed. The board had a hollow in which one of the leveling screws rested, and a V groove, h, with its axis in line with the hollow, in which another screw found secure lodgment, while the third screw rested upon the plane surface, i. The instrument could thus be leveled without disturbing its position, or it could be removed and replaced at will.

For determining the angle of deflection, a reading telescope and scale was used. The scale was one meter in length and was made by gluing heavy manilla paper to the face of a smooth, dry stick, about one inch wide by three-eighths of an inch thick. The scale was then laid off on the paper as shown in

Fig. 7, plate II., placing the zero point in the middle, and numbering in cms. in both directions. It will be noticed that the numbering is in "reversed" characters, this will make them appear "right" when reflected in the mirror.

The deflecting magnets were all made from knitting needles by cutting off the tapering ends, and then grinding them smooth, and square with the sides. It is convenient to make all the magnets of a series exactly of the same length, as this will simplify the calculation of results. The exact length was measured by means of a micrometer scale. The bars were magnetized between the poles of a powerful dynamo, and their weight was determined by means of a pair of very accurate chemist's balances.

Plate III. shows the arrangement of the apparatus for the deflection experiments.

NS is the magnetic north and south line in which the magnetometer needle is suspended at a. At b, in a line perpendicular to NS at a, is placed a reading telescope with the scale cd attached at right angles to the instrument. It was found convenient to make the distance of the scale, cd, from a just one meter, as this greatly simplified the calculation necessary in determining the angle of deflection. The places marked e and f (see also plate IV) on the line NS, are the "side on" positions of the magnets.

The distances used in this experiment, were 30 cms. for e and 40 cms. for f, from the centre of the magnetometer needle. It was at first

intended to use the "end-on" positions also, which are on either side of a in the line ab prolonged; but the limited time that could be devoted to the experiment forbade the use of more than one position.

Plate IV. shows in elevation, the magnetometer in place and the positions e and f in the same horizontal plane as the centre of the magnetometer needle, as viewed from the east end of the table, with the telescope removed.

Plate V shows in elevation, the position of the magnetometer and the reading telescope, as viewed from the south, the south stand for holding the deflectors being removed.

It was found that with this arrangement, readings

could be taken most readily when the telescope was shaded and the only source of light was from the west and above. The light would then strike the scale ed, illuminating it so that its reflection in a could be easily seen with the telescope.

The line NS was laid off by means of a surveyor's transit.

Eight readings were taken for each magnet—four for the 40cm. distance and four for the 30cm distance. For instance, if the magnet was placed in the 40cm. position south of the magnetometer, the deflection would be noted, and then by reversing the magnet, a deflection in the opposite direction, would take place which, if the instruments were properly placed, and the

conditions are right, ought to be the same in amount as the former. By reversing the magnet in this way, however, any errors one way or the other would be dreadfully diminished by the equalizing effect of the average of the two readings. In the same way two readings were taken for each of the other three positions, making eight in all for each magnet. The object of taking so many readings for each magnet was to reduce the chances of error to a minimum.

Below is a table giving the eight readings for each of the fourteen magnets used. The deflections are expressed in cms. of the scale on the telescope. Those marked N, appeared north on the scale as one would see it in the telescope, and con=

respond to an eastward deflection of the north end of the magnetometer needle.

Those marked S, are, of course, the opposite.

Table No. 1. —

Date and Time. 1894.	No. of Magnet	Kind of Deflection →	40 cms.		30 cms.		Average.	
			South position	North position	South position	North position	40 cms. —	30 cms. —
4/7-11: am.	A1.	N.	.65	1.20	1.20	2.50		
" "	"	S.	.45	.70	1.20	2.70	.75	1.90
" 12: m.	A2.	N.	.70	1.15	1.40	2.92		
" "	"	S	.50	.95	1.25	2.75	.82½	2.08
" 2:30 pm.	A4	N	.65	1.35	1.65	2.95		
" "	"	S	.65	.95	1.05	2.50	.90	2.03½
" 3:15 "	A3.	N	.63	1.10	1.10	2.55		
" "	"	S	.47	.63	.85	1.65	.70¾	1.53¾
" 4: - "	D1	N	1.15	1.45	2.05	3.75		
" "	"	S.	.52	.60	1.37	2.95	.93	2.53
4/21-11: a.m.	D2.	N	.67	1.30	1.63	3.20		
" "	"	S	.82	1.32	1.45	2.92	1.02¾	2.30¾
" 12: m.	D3.	N	1.07	1.73	2.08	3.95		
" "	"	S	.68	1.25	1.50	3.28	1.18¾	2.70¾
" 12:30 pm.	D4	N	.90	1.60	1.95	3.70		
" "	"	S	.73	1.30	1.62	3.40	1.13¾	2.66¾

Table No. 1. (Concluded)

4/21-1: p.m.	D 5	N.	.75	1.75	1.55	3.00		
" "	"	S.	.67	1.15	1.43	2.93	.95 1/2	2.22 3/4
" 1:45 p.m.	C 1.	N	.40	.63	.75	1.70		
" "	"	S	.42	.73	.92	1.75	.54 1/2	1.28
" 2:15 p.m.	C 2.	N	.55	.90	1.05	2.15		
" "	"	S	.55	.90	1.13	2.25	.72 1/2	1.64 1/2
" 3:30 p.m.	C 3.	N	.55	.87	1.05	2.13		
" "	"	S.	.50	.85	1.05	2.13	.69 1/4	1.59
" 4:1- p.m.	C 4.	N	.50	.85	1.05	2.10		
" "	"	S.	.50	.83	1.03	2.00	.67	1.54 1/2
" 4:15 p.m.	C 5.	N	.40	.63	.75	1.50		
" "	"	S.	.40	.63	.80	1.60	.51 1/2	1.16 1/4

It is interesting to note, in the above table, that almost without exception, the north readings are greater than the south readings for the same position, while the readings of the "north side" positions are greater in every instance, than the corresponding readings of the "south-side" position. The reasons for this, I am unable to give. It is, however, probably due to some local influence.

These readings were taken, as the table shows, on two different days — the first on April 7th and the latter ~~portion~~ on April 21st. To eliminate as far as possible errors due to change in the earth's magnetic condition, the oscillation experiment, described below, should have been performed as soon after the deflection experiment as possible, at least on the same day. This, however, was not done and for that reason there is doubtless considerable error in the results due to this cause. The oscillation experiments for all the magnets were performed on April 23^d.

The oscillation experiment consists in noting the time required in seconds, for each of the magnets before used as deflectors, to perform a

complete oscillation when free to move about a vertical axis under the influence of the earth's magnetism alone. The apparatus used is shown in elevation in plate VI. The glass case of a torsion balance was placed in the base before used for the magnetometer, and at the end of a single fiber of unspun silk, attached to the hoisting screw at the top of the centre glass standard, was fastened a little copper-wire stirrup. In this stirrup the magnets were placed in a horizontal position. In order to facilitate the balancing of the magnets, a box having a hole about an inch in diameter in its top side, was placed in the glass case with its hole directly under the stirrup, so that when the magnet was lowered,

by means of the hoisting screw, it would rest on the box while the stirrup would drop into the hole. The stirrup could then be moved back and forth by means of a stick until a perfect balance of the magnet was secured. Two strips of paper were then pasted on the glass sides in line with the magnet when at rest, and hence, in the magnetic meridian. These were to enable the observer to note the moment in which the magnet had finished a complete oscillation—i.e. back and forth once—by observing the moment in which the nearer end of the magnet passed through the magnetic meridian.

Plate VII. gives a plan view of the apparatus as arranged for the oscillation

observations. D is the deflector stand shown in plate VI. At B is a pendulum, shown in elevation in plate VIII. so connected with the circuit of a battery at A, and a recording instrument at C, that every time it passes the point a (see plate VIII), it completes the circuit, and the recording instrument at C, places a dot upon a strip of paper that is moving through the instrument at a uniform rate. Since the pendulum makes one complete oscillation in just two seconds; and, in so doing, passes the point a, two times, making two dots on the paper in the recording instrument; the distance between the dots on the paper, may be taken to represent seconds in time. Fractions of this distance would then be fractions of a

second. A.K., is a key also in circuit with the battery and recording instrument, but not connected with the pendulum. When the key is pressed, it completes the circuit and a record is made upon the paper in the recording instrument.

Everything is now ready for observations. The magnet in the deflector stand at D may be set in motion by bringing another magnet toward it, being careful to keep it in the East and West line passing through the middle point of the suspended magnet, as otherwise it may produce a pendulum-like motion instead of a vibratory, or rotary motion about a vertical axis. The magnet should then be allowed to so far come to rest that the arc of oscillation does not

exceed three degrees on either side of the meridian.

The observer now takes his place at *F*. and with one hand on the key at *E*, he presses the key every time the magnet passes through the meridian in the same direction.

A record is thus obtained on the strip of paper in the recorder from which the exact period of oscillation may be determined.

The upper figure, plate VIII, represents a fragment of such a record. If 0, 1, 2, 3, 4, etc. be the dots marking seconds in time; and *a*, *b*, and *c* be dots made by pressing the key, and hence, marking the period the period of oscillation, it is evident that the period of oscillation for the magnet in question, is 5 sec. + the fraction of a second

represented by the distances between a and o, and between b and c, and the whole divided by 2, the number of oscillations.

In this way the period of oscillation for all the magnets was determined with results as shown in Table No. 2.

Table No. 2. — Oscillation Experiment

No. of Magnet	Number of Oscillations	Total time in seconds.	Average time per Oscillation	No. of Magnet	Number of Oscillations	Total time in seconds.	Average time per Oscillation
A1.	11	67.3	6.118	C4	13	57.7	4.438
A2	11	64.9	5.88 $\frac{1}{3}$	C5	14	72.	5.142
A3	10	64.8	6.48	D1	14	99.	7.071
A4	10	56.8	5.68	D2	13	98.2	7.554
C1	11	53.1	4.827	D3	13	91.9	7.07-
C2	16	70.2	4.375	D4	12	84.6	7.05
C3	14	62.3	4.45	D5	8	63.1	7.88 $\frac{1}{4}$

From plate X. it will be readily seen how the angle of deflection of the magnetometer needle is found from the readings in Table No. 1, page 14. For a given angle of deflection

θ , a reading a is obtained measuring an angle of twice θ . If b is the distance of the scale from the magnetometer needle, we have the expression,

$$\tan 2\theta = \frac{a}{b}.$$

Reduction of Results.—
In the reduction of the results of the observations, the formula for the "side on" position as given by Prof. Gray was used. In plate IX let NS be the magnetic north and south line; $\underline{bn}$ the needle of the magnetometer; $\underline{BR}$ the deflector; $\underline{r}$ the distance from $\underline{BR}$ to the centre of $\underline{bn}$; 2λ , the distance between the poles of $\underline{BR}$; $2\lambda'$, the distance between the poles of $\underline{bn}$; $2l$, the length of $\underline{BR}$; $2l'$, the length of $\underline{bn}$; and θ , the angle of deflection. R and B , and r and b in each case denote the positive and neg-

active poles, respectively, of the magnets.

For the long thin magnets used, the distance between the poles was taken as equal to the length of the magnets. This assumption with the magnets used would not introduce any great error. It was also considered that the magnetic effect was concentrated at the poles.

B will then repel b with a force that may be represented in amount and direction by the line ac ; but B will attract b with an equal force, similarly represented by the line ad . The resultant of these two forces is a force, F , parallel with the deflector, BR .

Now let m equal the magnetic strength of a pole of the deflector, and m' that of a pole of the magnetometer

needle, and M and M' respectively the magnetic moments of the deflector and the magnetometer needle.

$$\text{Then } 2m\lambda = M$$

$$m = \frac{M}{2\lambda}$$

$$\text{and } 2m'\lambda' = M'$$

$$m' = \frac{M'}{2\lambda'}$$

Since the force decreases with the square of the distance, we have,

$$\underline{ac} = \frac{M}{2\lambda} \times \frac{M'}{2\lambda'} \times \frac{1}{r^2 + \lambda^2}$$

But from the similarity of the triangles $\underline{aPK}$ and $\underline{cPa}$, we have

$$Pa : ac :: PB : aP$$

From which by substituting and solving we get

$$P = \frac{MM'}{2\lambda'(\lambda^2 + \lambda'^2)^{\frac{3}{2}}}$$

Similarly it may be shown that the action of the deflector on the other end of the magnetometer needle

is a force equal and opposite to F_x . $\underline{OA}$ is thus under the influence of a couple tending to produce rotation clockwise. The total effect of this couple is

$$\frac{MM'}{(r^2 + \lambda^2)^{\frac{3}{2}}} \times \cos \theta.$$

θ = angle of deflection.

But $\underline{OA}$ is also under the influence of the horizontal force of the earth's magnetism, the value of which is $M'H \sin \theta$, and which opposes that due to the deflector. When the needle comes to rest under the influence of these two forces, they (the forces) must be equal and hence, we have the following equation:

$$\frac{MM'}{(r^2 + \lambda^2)^{\frac{3}{2}}} \cos \theta = M'H \sin \theta$$

$$\frac{M}{H} = (r^2 + \lambda^2)^{\frac{3}{2}} \tan \theta. \quad (1)$$

For a reduction of the

oscillation observations, the following formula as derived by Prof. Gray was used:

$$MH = \frac{4\pi^2 l^2 H}{3 t^2} \quad (2.)$$

H = weight in grams of the magnet

t = period of oscillation in seconds.

$\pi = 3.14159 \text{ etc.}$

Combining (1.) and (2.), we have

$$H^2 = \frac{4\pi^2 l^2 H}{3(\lambda^2 + \lambda'^2)^{\frac{3}{2}} t^2 \tan \theta}$$

$$H = \frac{2\pi}{13} \times \frac{l}{(\lambda^2 + \lambda'^2)^{\frac{3}{4}}} \times \frac{1}{8} \sqrt{\frac{W}{\tan \theta}} \quad (3.)$$

Formula (3.) was used and the labor of calculation was greatly reduced by taking advantage of constant quantities. Thus $\frac{2\pi}{13}$ is a constant in the formula for all the observations, and $\frac{l}{(\lambda^2 + \lambda'^2)^{\frac{3}{4}}}$ is a constant in the formula for a series of magnets of the same length in a given position. These

Two constants were combined for a new constant for each series in a given position.

Below is a table of constants used.

Table No. 3. - Constants.

Formula: $H = \frac{2\pi}{13} \times \frac{l}{(r^2 + \lambda^2)^{3/4}} \times \frac{1}{t} \sqrt{\frac{\mu}{\tan \theta}}$

Series of magnets	Distance in cms. of magnet from magnetometer needle.	Constant.	Logarithm of Constant.
A	40	$\frac{2\pi l}{13(r^2 + \lambda^2)^{3/4}}$	8.844251 - 10
A	30	"	9.027894 - 10
Q	40	"	8.798432 - 10
Q	30	"	8.982795 - 10
D	40	"	9.053187 - 10
Q	30	"	9.230710 - 10

It will be noticed from Table No. 4 that the results vary considerably for different magnets and for different series of magnets. This is perhaps what should be expected under the circumstances. In the first place no corrections have been made

Table No. 4.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
No. of Deflector	Length of Deflector in cms.	Diameter of Deflector in cms.	Height of Deflector in millimeters.	Average time of oscillation in seconds (from Table No. 2.)	Angle (θ) of deflection with deflector in 40-cm. position	Angle (θ) of deflection with deflector in 30-cm. position	Horizontal intensity in 40-cm. position	Horizontal intensity in 30-cm. position	Mean intensity for each deflector - 30 and 40-cm. positions	Mean intensity for each series of deflectors	Mean intensity of all magnets and all observations.	Mean intensity of Series C. and D.	Mean of results in column 8 - 40-cm. position	Mean of results in column 9 - 30-cm. position
A1	9.855	.20065	2.4567	6.118	12' 54"	32' 37"	.29222	.28044	.28633					
A2	"	.20593	2.5455	5.88 $\frac{1}{3}$	14' 10"	35' 45"	.29511	.28356	.28933					
A3	"	.20339	2.4781	6.48	12' 9 $\frac{1}{4}$ "	26' 25 $\frac{1}{4}$ "	.28540	.29551	.29045					
A4	"	.20065	2.4057	5.68	15' 28"	34' 59"	.28420	.28864	.28657	.28817				
C1	8.849	.1524	1.2619	4.827	9' 22"	22' 0"	.28047	.27961	.28004					
C2	"	.155	1.3351	4.325	12' 28"	28' 16 $\frac{1}{2}$ "	.27903	.28315	.28109					
C3	"	"	1.3137	4.45	12' 24 $\frac{1}{4}$ "	27' 29"	.27591	.27690	.27641					
C4	"	"	1.2960	4.438	11' 30"	26' 33"	.27895	.28058	.27976					
C5	"	"	1.2940	5.142	8' 50 $\frac{1}{2}$ "	19' 58 $\frac{1}{2}$ "	.27436	.27894	.27665	.27879				
D1	16.25	.134	1.7828	7.071	15' 59"	43' 30"	*21300	*.28554	# —					
D2	"	.133	1.7180	7.554	17' 39 $\frac{1}{4}$ "	39' 38"	.27366	.27457	.27411					
D3	"	.134	1.7878	7.07	20' 19"	46' 27 $\frac{1}{2}$ "	.27809	.27673	.27741					
D4	"	"	1.7815	7.05	19' 27 $\frac{1}{2}$ "	45' 51"	.28448	.27885	.28167					
D5	"	.1342	1.8239	7.88 $\frac{1}{4}$	16' 25"	38' 17"	.28011	.27600	.27805	.27782	.28137	.27835	.28171	.28104

* These figures were not used in the calculation of the mean intensity in any instance. See page 33 for explanation.

for induction, distribution, or variation in the earth's field. The daily variation was quite perceptible and was corrected to some extent by frequently resetting the telescope so that the cross-hairs were over the zero point on the scale. Frequently, however, there were more or less violent disturbances due to local statical effects which doubtless affected results considerably. For instance, the mere opening and closing of doors, sometimes in a distant part of the building, or the sweeping of a carpet in an adjoining room set the magnetometer needle into violent spasms. Of course no readings could be taken at such times until the needle came to rest, but as the normal equilibrium

was restored more or less gradually, it is probably that errors often arose by taking readings after such a disturbance. On March 30th, no readings could be taken at all as there seemed to be no stability in the direction of the magnetic force. It was afterward learned that on that day, and the day previous, there was a violent magnetic storm. This accounts for the peculiar actions of the magnetometer needle on that day. April 21st was a fine day and there were no disturbances. The gradual change in declination during the day was quite perceptible.

The presence of an abundance of iron in the room in which the experiment was performed, though not movable, doubt-

less influenced the result greatly, and made it higher than it should be for this locality.

It is interesting to note that the mean intensity for series A is considerably greater than that for series C or D. This is perhaps largely due to variations in the intensity of the earth's magnetism, as the deflection observations for series A were made on April 7th while those of C and D except in the case of D1 were all made on April 21st. The reasons for supposing this to be the case will be found in the fact that the intensity for D1 which was determined on the same day as series A is so much greater than that for any of the other magnets of series D, that it seems

as though the earth's field must have been stronger on that day, or possibly there may have been an error in observation for D1 which would account for its greater result. Another reason, however, for supposing that there was a change in the earth's magnetism is found in the close resemblance of the results of series C and D (nos 2 to 5) all of which were taken on the same day. D1 has not been included in the mean results as its results seem to be of a rather doubtful character, and it was thought that if an other reading had been taken for it on April 21st, it would have shown entirely different results. Windy weather proved

to be an annoying interference. On windy days the building trembled from the effects of the wind so that no observations could be made.

The means in columns 14 and 15, Table No. 41, differ by only .00067 of a dyne. The mean in column 13 is perhaps the most reliable since in the case of series C and D, the oscillation experiment followed the deflection experiment more closely.
