10

U. S. DEPARTMENT OF COMMERCE

COAST AND GEODETIC SURVEY

Washington 25, D.C.

BY

J. H. Nelson, R. E. Gebhardt, J. L. Bottum

SUBJECT

THE CONSTANT-FIELD COIL HOUSE AT THE FREDERICKSBURG MAGNETIC OBSERVATORY

THE CONSTANT-FIELD COIL HOUSE

AT THE

FREDERICKSBURG MAGNETIC OBSERVATORY

J. H. Nelson, R. E. Gebhardt, J. L. Bottum

Geophysics Division, U. S. Coast and Geodetic Survey

Abstract. When plans were made for the construction and operation of the Fredericksburg Magnetic Observatory and Laboratory, they included the installation of a set of large coils with which it would be possible to duplicate the geomagnetic field at any place on the earth. For this purpose two sets of coils were constructed, having a common center--one set for control of the Z field, the other with its axis horizontal and approximately in the mean magnetic meridian. Each coil form has a main, or primary, winding and an auxiliary, or secondary, winding. A Helmholtz coil was later installed with its axis in the magnetic east-west direction.

Automatic control circuits are provided for maintaining steady currents in the primary windings of the H and Z coils, constant to about ± 5 microamp, which is equivalent to about 3 parts in 10^6.

Other automatic controls provide currents in the east-west (D) coils, and in the secondary windings of the H and Z coils, that vary in amplitude and polarity so as to produce component fields that just neutralize the variations of the earth's field, thus maintaining within the coils a constant field.

During planning and design of the facilities for the new Fredericksburg Magnetic Observatory, it was considered essential that some provision be made for the calibration and testing of magnetic instruments in magnetic fields other than the normal field at the observatory site. Coils similar to those in use at the Wingst Observatory seemed to be the best suited for the type of work planned at Fredericksburg. The coils described here are similar to those at Wingst except for a few minor differences. The Fredericksburg coils are slightly smaller, the coil forms and supporting framework are constructed of aluminum alloy, and the number of turns of wire and its arrangement on the coil forms is different.

When the coils were being constructed a secondary winding was placed on each coil form for use in compensating for the normal daily changes and storm activity inside the coils. This type of control is quite independent of the steady currents used for modifying the mean total field and its direction within the coils. A Helmholtz pair was added to the system to afford means of controlling diurnal variation in the east-west direction.

The physical dimensions and computed constants of the coils are summarized in Table 1:

Table 1 - Coil Data

	H coils	Z coils	D coils
Diameter, large inner pair (cm)	520.6	538.5	417.4
Diameter, small outer pair (cm)	396.6	410.9	- -
Separation, inner pair (cm)	141.6	148.1	208.7
Separation, outer pair (cm)	431.6	450.9	- -
Number of turns, primary (per coil)	20	100	- -
Number of turns, secondary (per coil)	5	5	7
Coil constant, primary (γ/ma)	12.60	60.5	- -
Coil constant, secondary (γ/ma)	3.15	3.03	3.02

The entire coil system is built of non-magnetic aluminum, including the framework, coil forms, and all supporting members. Each coil form is supported at twelve to sixteen points on the circumference.

In order to align and adjust the coils for proper spacing and orientation, it was first necessary to measure the actual diameters of each coil. This was done by using a length of aluminum tubing cut to a few centimeters less than the inside diameter of the coil to be measured. An inside micrometer was used to measure the small additional increment to be added to this fixed length. The individual measurements were repeatable to a few thousandths of an inch. Twelve diameters of each coil were measured, at intervals of about 15 degrees. The lower Z coil could not be measured in any simple way because of the central concrete pier that intervened, and therefore, because of the close agreement between the two coils of the other three pairs, the dimensions were assumed to be the same as those of the topmost Z coil. Diameter measurements are summarized in Table 1.

The best spacing for the coils of each set (H or Z) was computed from expressions for the third-order and fifth-order terms of the harmonic expansion for the potential of a four-coil symmetric set. Using the measured diameters, the spacing was computed (for each set) that would eliminate these two terms. (This computation was made necessary because the ratio of diameters of large and small coils, as they were finally constructed, was not precisely the ideal ratio given by Braunbek [Chapman and Bartels, 1940].) The separations were then adjusted to the computed values. At the same time the coils were aligned in horizontal and vertical planes, as described in the next paragraph.

A vertical reference was established by dropping a plumb line from a point at the top of the framework and permanently marking the lower point on the pier. A mean magnetic meridian, magnetic prime vertical, and a horizontal axis for the coil system were also established and permanently marked on the walls of the coil house. The three coil axes intersect at a common point 120 cm above the concrete pier, the top of which is at floor level.

A surveyor's level and theodolite were used to orient the coils and to adjust the alignment and spacing. All of the adjustments were made with respect to the three axes previously established. The planes of the Z coils were made horizontal. The planes of the H coils and of the D coils were made vertical and parallel. The coils of each set were made concentric with respect to the appropriate axis. Computed coil constants, as finally adjusted, are summarized in Table 1.

A few small errors are known to exist in the setting and adjustment of the coils. These errors are:

1. With a finite number of points of support for the coil form, it was not possible to make each coil exactly circular. Small scallops exist, reflecting a slight variation in the radius from point to point. These differences in the radii of a given coil are of the order of ± 2 millimeters from the mean radius.

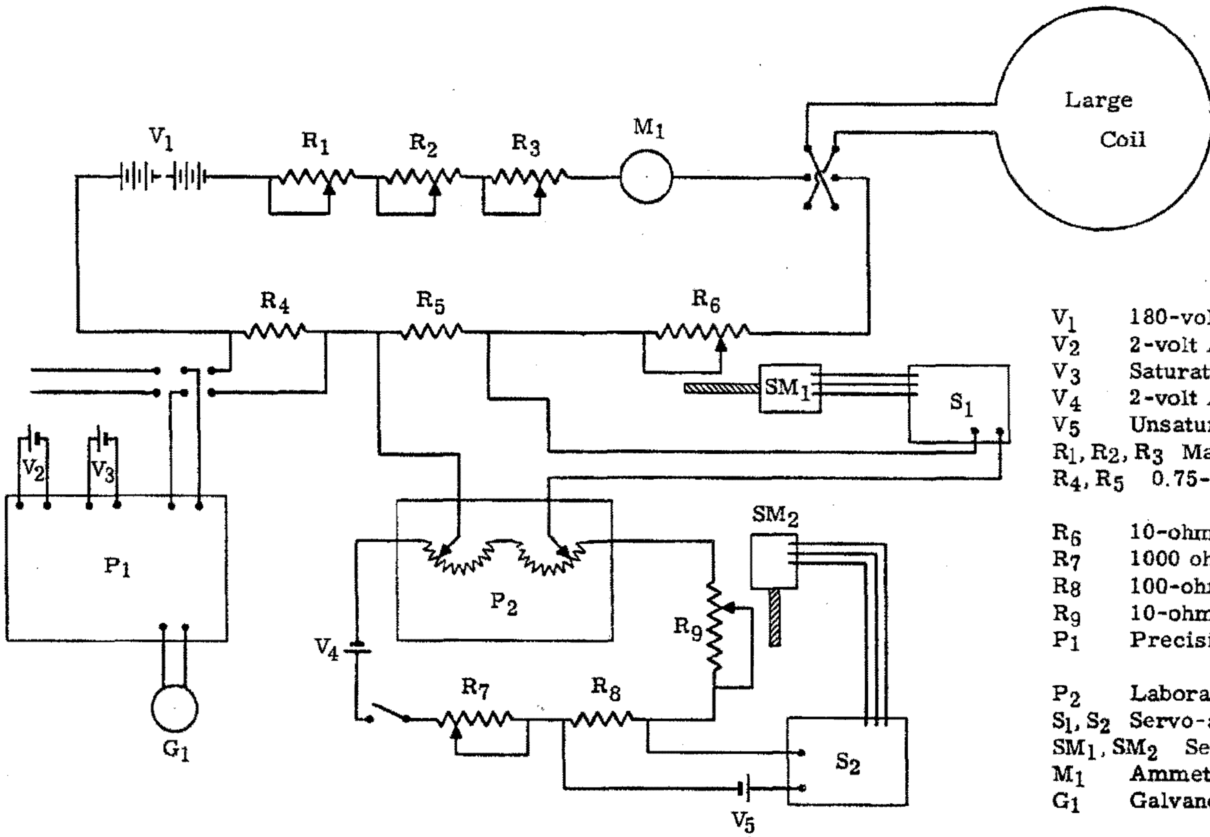
2. The coils for the vertical field, being supported at a finite number of points, show a sagging of approximately 1/4 millimeter between the points of support.

3. The spacing of the coils was done quite accurately. The errors in this dimension are not greater than 1/4 millimeter.

The geometric defects listed above will introduce small gradients in the working space, but they have not been intolerable. The measurement of the actual gradients will be done in the near future. In fact, it was hoped that the results of the survey would be available at this time. Due to the number of urgent experiments that have kept the coils in almost continuous use, it has not been possible to do the necessary experimental work.

Two types of electrical controls are required: first, for the primary windings, in which a steady current of selected value must be held constant with great precision; second, for the secondary windings, in which the current must vary in polarity and amplitude in such a way that the field due to this current will exactly neutralize within the coils the daily variation and storm activity so that the resultant field will be constant.

The schematic diagram of the constant-current circuits for H and Z is shown in Figure 1. The current for the primary windings is supplied by a 180-volt storage battery V_1. Manual adjustments for approximate current are made with variable resistances R_1, R_2, and R_3. An indication of the current is given by the 0-2 ampere ammeter M_1. A multiple-turn variable resistance, R_6, driven by servo-motor SM_1, automatically adjusts the coil current to compensate for changes of the battery voltage and changing resistances of all parts of the power circuit. The voltage drop across the 3/4-ohm resistor R_5 is balanced against a constant voltage (which may be set at any value) from potentiometer P_2, so that when there is a change of current in the coils a small d.c. signal appears at the input of the servo-amplifier S_1, causing motor SM_1 to operate and modify the setting of R_6 and thus readjust the coil current to the desired value. A d.c. signal of less than 3 microvolts will cause the servo-motor to operate, this corresponding to less than 0.3γ change in the Z coil field, less than 0.05γ change in the H field.



V_1	180-volt Battery
V_2	2-volt Aircell
V_3	Saturated standard cell
V_4	2-volt Aircell
V_5	Unsaturated standard cell
R_1, R_2, R_3	Main resistance bank
R_4, R_5	0.75-ohm precision resistor
R_6	10-ohm Helipot
R_7	1000 ohms
R_8	100-ohm precision resistor
R_9	10-ohm Helipot
P_1	Precision laboratory potentiometer
P_2	Laboratory potentiometer
S_1, S_2	Servo-amplifiers
SM_1, SM_2	Servo-motors
M_1	Ammeter, 0-2 amps.
G_1	Galvanometer

Fig. 1. Schematic diagram of constant-current control circuits.

The reference voltage supplied by the potentiometer P_2 is adjustable from zero to 1.6 volts. That voltage in turn is maintained constant by holding the potentiometer working current constant with an independent servo-motor and amplifier, SM_2 and S_2, which use a Weston standard cell V_5 as a reference. Again the sensitivity of the servo-amplifier is better than 3 microvolts.

Direct measurement of the primary current in the coils is made in conventional manner with the precision laboratory potentiometer P_1 employing a bank of saturated standard cells V_3 which are kept in a temperature-controlled housing.

The laboratory potentiometer P_1 is switched from the H circuits to the Z circuits as needed, but duplicate sets of all the other control equipment are provided for the H and Z coils so that both may be operated at the same time.

At the present, the field in the main coils (primary) can be changed in increments of 8γ in Z and 2γ in H, corresponding to one wire turn on the slide-wire of the potentiometer P_2. However, any selected value of the Z field can be maintained constant to about 0.4γ; of the H field, to about 0.1γ.

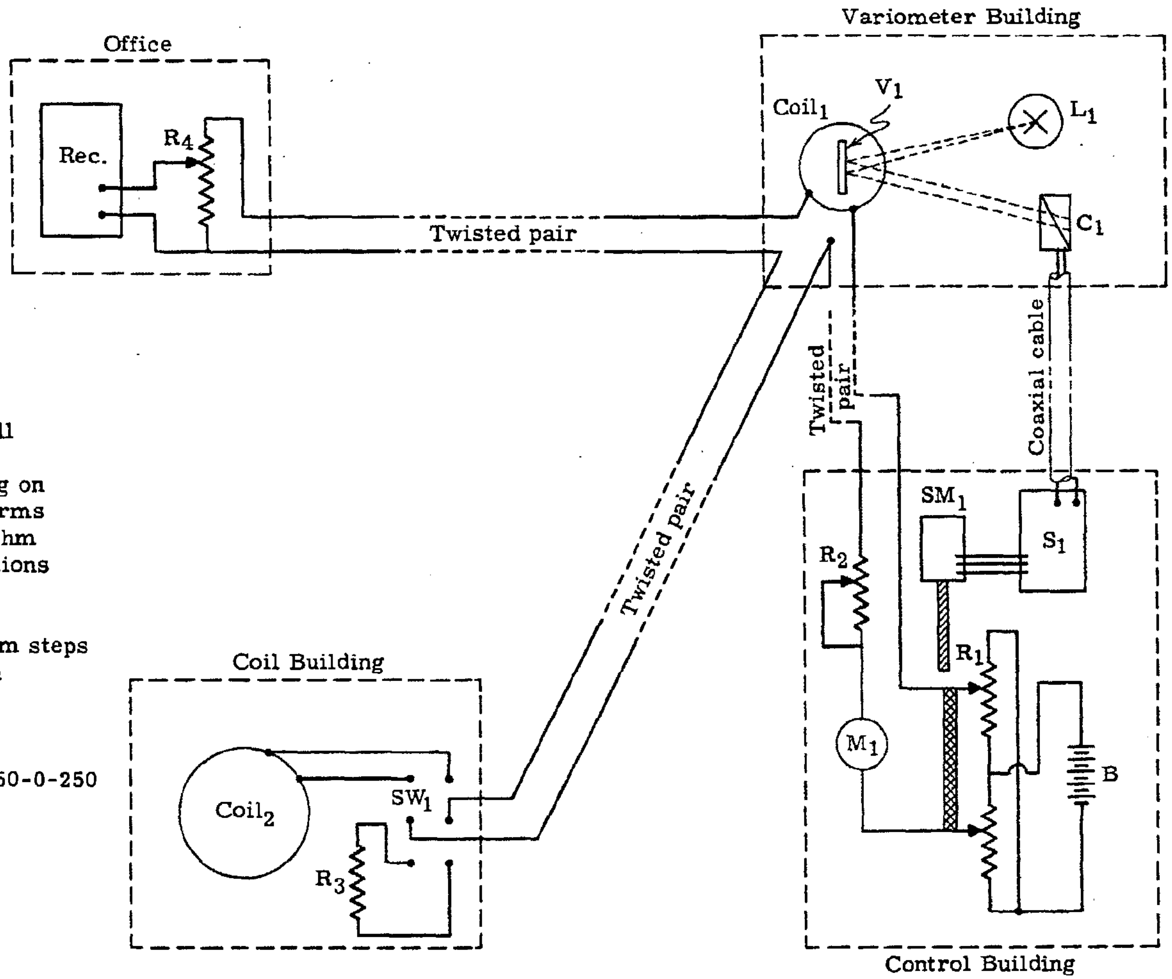
The system described above will generate and control fields of about $27,000\gamma$ in the horizontal component and $130,000\gamma$ in the vertical component, and it can be directed to add to the ambient field of $19,000\gamma$ in H and $55,000\gamma$ in Z, or it can be directed oppositely. Thus the ranges of intensities that can be obtained in the coils with the specified circuit constants are:

H: $-8,000\gamma$ to $+46,000\gamma$

Z: $-75,000\gamma$ to $+185,000\gamma$

Figure 2 is a schematic diagram of the circuits used for control of diurnal variation within the large coils. The basic principle of the system is that used in the Differential Magnetograph at the College (Alaska) Magnetic Observatory during the IGY. [Nelson, 1957]. In the College installation the master station eliminated, from the recording at the outpost station, the d.v. and storm changes that occurred at the master station. In the present installation the "master station" (that is, the control variometers) senses the d.v. changes and eliminates them from the field in the large coils.

Referring to Figure 2, $Coil_1$ is a small pair of coils mounted on a standard Ruska observatory-type variometer (D, H, or Z); $Coil_2$ is the secondary winding on the large coil forms. The variometers are located in a building some 100 meters or more from the large coils. The amplifiers and power sources are located in a third building, well removed from the other two. $Coil_1$ and $Coil_2$ have the same coil constants (in gammas/milliamp), and are connected in series. Their power source is the voltage drop across the two multiple-turn variable resistances R_1. These resistances are so connected to a 12-volt storage battery that by turning the resistances from one limit to the other the voltage applied to the coils can be varied continuously from +12 volts to -12 volts. The resistances are mechanically adjusted by the servo-motor SM_1 operated by the servo-amplifier S_1. The amplifier is energized by a split selenium photocell, C_1, mounted near the variometer in such a way that the variometer mirror reflects a beam of light on the cell. When natural change of the earth's field deflects the light beam to either side of the null position on the cell, a voltage generated in the cell will cause the servo-system to adjust the current in the variometer coil so as to bring the suspended variometer magnet and light beam back to the null



L_1	Light source
V_1	Variometer
C_1	Split selenium cell
$Coil_1$	Variometer coil
$Coil_2$	Secondary winding on large coil forms
R_1	Helipot, two 50-ohm sections
R_2	35 ohms
R_3	4 ohms
R_4	10 ohms, in 1-ohm steps
SW_1	D. P. D. T. switch
S_1	Servo-amplifier
SM_1	Servo-motor
Rec.	Recorder
M_1	Milliammeter, 250-0-250
B	12-volt battery

Fig. 2. Schematic diagram of constant-field control circuits.

position, thus maintaining a constant field within the variometer coil. Since the secondary winding on the large coil forms has the same coil constant as the variometer coil, and since it carries the same current, the field within the large coils will also be held constant by the changing current. Three independent sets of control equipment -- for the elements D, H, and Z -- are able to maintain the field at a constant value both in magnitude and direction.

A secondary advantage of this system derives from the use of three recording milliammeters which record the currents flowing in the three coil systems at all times. These records constitute a 3-component "magnetogram", so that there is at all times a reliable up-to-the-minute, visible record of the changes in the earth's field. In Figure 2, the recorder, Rec., is installed in the observatory office. The fixed resistor, R_4, is an adjustable shunt, so that the scale value of the visible recorder may be varied as desired.

Under normal conditions, the diurnal variation in the working area of the coil house can be controlled to about 0.5γ or better. There is a limitation, however, on the speed with which the servo motors can respond to a short period changes (periods of less than about 10 seconds). At these times, there is a slight lag in the control of the diurnal variation. In actual practice, during a severe magnetic storm when the field changed by several hundred gammas during a two-hour period, the diurnal variation was held constant to about 0.6γ.

The installation of the diurnal-variation controls was accomplished with financial assistance from the National Aeronautics and Space Administration to make available the required facilities for testing geomagnetic instrumentation for use in satellites and space probes. Special mention should be made of the excellent work done by J. B. Townshend and L. L. Posey in

setting up the three variometers and adjusting them so that the orientation was identical with the standard meridian previously established in the coil building. L. Hurwitz assisted materially by analyzing the coil measurements and determining the proper positioning of the coil forms.

References

Chapman, S., and J. Bartels, Geomagnetism, vol. I, p. 84, Oxford 1940

Nelson, J. H., A Preliminary Report on a Differential Magnetograph, Annals of IGY, vol. IV, part IV, pp. 240-242, 1957

Nelson, J. H., The Differential Magnetograph for the College (Alaska) Magnetic Observatory, Annals of IGY, vol. IV, part IV, pp. 242-245, 1957.