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18. A Differential Proton Magnetometer.

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Summary

A magnetometer that records differences in total geomagnetic intensity between two points is described. By mixing the signals caused by free precession of protons from the two detecting coils, the beat signal is recorded on a pen-writing oscillograph. According to the test of the apparatus at the Oshima Geophysical Observatory, the accuracy of the differential magnetometer is found to be about $0.2\,\gamma/10\,m$ at the moment. Since it is easy to increase the distance between the two coils, the sensibility of the apparatus can be increased. The purpose of the present apparatus is to detect very accurately local anomalous changes in the earth's magnetic field which might be accompanied by activities of Volcano Mihara.

1. Introduction

A number of attempts have been hitherto made to design and construct magnetic gradiometers or differential magnetometers by which we can measure the space gradients of the geomagnetic field. A few types of such instruments have been advanced in relation to magnetic prospecting[1),2),3)]. Meanwhile, S. Chapman[4)] emphasized the importance of measuring the time rate of change of the space gradients in polar regions. On the occasion of the International Geophysical Year 1957–58, J. H. Nelson[5)] developed a differential magnetograph following S. Chapman's suggestion[6)]. Being designed for close observations of auroral electrojet over Alaska, the magnetograph records the differences between

1) A. BERROTH and A. SCHLEUSENER, *Zeits. f. Geophys.* **9** (1933), 355.

2) I. ROMAN and T. C. SERMON, *Trans. Amer. Inst. Mining Metall. Eng.*, **110** (1934), 373.

3) T. NAGATA and K. WATANABE, *Chishitsu Kosho to Butsuri Tanko*, No. 2 (1950), 106.

4) S. CHAPMAN, *Terr. Magn.*, **41** (1936), 127.

5) J. H. NELSON, *IGY Instruction Manual*, No. 3, Part 1 (1956), 37 and 39.

6) S. CHAPMAN, *IGY Instruction Manual*, No. 3, Part 1 (1956), 35.

the values of a certain component of the earth's magnetic field at a master and auxiliary stations, several kilometers apart with one another. Some careful adjustment of orientation of recording magnets as well as of electric device are necessary for a reliable observation.

The differential magnetometer that will be described in this paper differs very much from those developed so far. It is made so as to measure the difference in the total geomagnetic intensity between two points by counting the beat frequency which is produced by mixing the proton precession frequency at the respective points. Since M. Packard and R. Varian[7] proposed a method for measuring the absolute value of the earth's magnetic field by counting the free precession frequency of protons in the water, many researchers[8)-14] have attempted to construct practicable proton magnetometers based on the principle. Even the use of the magnetometers on balloons[15], and rockets[16] has been successful. Seaborne proton magnetometers have been also developed by the Research Group for Proton Magnetometers[14], M. N. Hill[17] and others[18].

T. Rikitake, who has been in charge of the geomagnetic observation on Oshima Island in collaboration with I. Yokoyama and others since 1950, equipped the Oshima Geophysical Observatory, which was built in 1959, with a station-use proton magnetometer constructed by the Research Group for Proton Magnetometers[14]. Although no detailed analysis of the results observed by it has been worked out yet, it is expected that we can accurately trace changes in the earth's magnetic field relevant to activities of Volcano Mihara by the apparatus. In view of the local anomalous geomagnetic changes associated with the volcanic activities as have been reported in a series of papers in this bulletin[19)-21] and

7) M. PACKARD and R. VARIAN, *Phys. Rev.*, **93** (1954), 941.

8) G. S. WATERS and G. PHILLIPS, *Geophys. Prosp.*, **4** (1956), 1.

9) G. S. WATERS and P. D. FRANCIS, *Journ. Sci. Instr.*, **35** (1958), 88.

10) I. TSUBOKAWA, M. TAZIMA and T. SETO, *Sokuchi Gakkai-shi*, **4** (1957), 24.

11) I. TSUBOKAWA, *Kagaku*, **28** (1958), 73.

12) S. KOZIMA, K. OOI, S. OGAWA and K. TORIZUKA, *Kagaku*, **27** (1957), 255.

13) S. KOZIMA, S. OGAWA, K. TORIZUKA and K. OOI, *Keisoku*, **7** (1957), 456.

14) RESEARCH GROUP FOR PROTON MAGNETOMETERS, *Bull. Earthq. Res. Inst.*, **36** (1958), 433.

15) L. J. CAHILL JR. and J. A. VAN ALLEN, *Journ. Geophys. Res.*, **61** (1956), 547.

16) L. J. CAHILL JR., *Journ. Geophys. Res.*, **64** (1959), 489.

17) M. N. HILL, *Deep Sea Res.*, **5** (1959), 309.

18) D. CHRISTOFFEL, *Annual Report, Geophys. Lab., Univ. of British Columbia* (1959), 3.

19) T. RIKITAKE, *Bull. Earthq. Res. Inst.*, **29** (1951), 161 and 499.

20) T. RIKITAKE, I. YOKOYAMA, A. OKADA and Y. HISHIYAMA, *Bull. Earthq. Res. Inst.*, **29** (1951), 583.

elsewhere[22], it is thought to be of further advantage for presuming the internal conditions of the volcano to add some geomagnetic observations of a different sort to those which have been hitherto conducted. As has been already suggested by I. Tsubokawa[11], the values of geomagnetic total force at two points can be simultaneously compared with one another quite easily and accurately by providing two detector coils of proton magnetometer and counting the beat frequency produced by mixing signal frequencies from them. The writers constructed a differential proton magnetometer of this sort and set it up at Oshima Geophysical Observatory in the hope of observing changes in the gradient of the geomagnetic total force that might be accompanied by grows and decays of the volcanic activity of Volcano Mihara.

2. Expected changes in the gradient of the geomagnetic total intensity

From the analyses of repeated magnetic surveys over Oshima Island, the local anomalous changes in the earth's magnetic field have been apparently interpreted as the magnetic fields due to hypothetical magnetic dipoles. The positions and strengths of the dipoles have been obtained by T. Rikitake[19] and I. Yokoyama[21] as reproduced in Table 1. The dipoles are directed to the same (+) or reverse (−) directions of the geomagnetic field according to the decaying or developing periods of volcanic activity.

Table 1. The hypothetical dipoles for various periods of the activities of Volcano Mihara

Period	Intensity of dipole (*e.m.u.*)	Depth of dipole (*km*)
July. 1950—Sept. 1950	-6.3×10^{14}	5.5
May. 1951—Aug. 1953	$+8.6\times10^{13}$	4.7
Aug. 1953—Jan. 1954	-1.2×10^{13}	1.6
Jan. 1954—June. 1954	$+1.2\times10^{13}$	1.6

Let us here estimate the gradient of the total magnetic force caused by a magnetic dipole of which the magnetic moment amounts to 10^{13} $\sim10^{14}$ *e.m.u.* Suppose a dipole at the origin of cartesian coordinates, the magnetic potential due to the dipole can be given as

21) I. YOKOYAMA, *Bull. Earthq. Res. Inst.*, **32** (1954), 17, 169; **33** (1955), 251; **34** (1956), 21.

22) T. RIKITAKE and I. YOKOYAMA, *Journ. Geophys. Res.*, **60** (1955), 165.

$$W=\frac{M_x x+M_y y+M_z z}{r^3}, \tag{1}$$

where

$$r^2=x^2+y^2+z^2, \tag{2}$$

while M_x, M_y and M_z denote respectively the moment projected to the x, y and z directions. Differentiating (1) with respect to x, y and z, the three components of the magnetic field become

$$X=M_x\frac{y^2+z^2-2x^2}{r^5}-3M_y\frac{xy}{r^5}-3M_z\frac{zx}{r^5}, \tag{3}$$

$$Y=-3M_x\frac{xy}{r^5}+M_y\frac{z^2+x^2-2y^2}{r^5}-3M_z\frac{yz}{r^5}, \tag{4}$$

$$Z=-3M_x\frac{zx}{r^5}-3M_y\frac{yz}{r^5}+M_z\frac{x^2+y^2-2z^2}{r^5}. \tag{5}$$

If we further differentiate (3), (4) and (5) with respect to x, we have

$$\frac{\partial X}{\partial x}=M_x\left(15\frac{x^3}{r^7}-9\frac{x}{r^5}\right)+M_y\left(15\frac{x^2y}{r^7}-3\frac{y}{r^5}\right)+M_z\left(15\frac{x^2z}{r^7}-3\frac{z}{r^5}\right), \tag{6}$$

$$\frac{\partial Y}{\partial x}=M_x\left(15\frac{x^2y}{r^7}-3\frac{y}{r^5}\right)+M_y\left(15\frac{xy^2}{r^7}-3\frac{x}{r^5}\right)+M_z\left(15\frac{xyz}{r^7}\right), \tag{7}$$

$$\frac{\partial Z}{\partial x}=M_x\left(15\frac{x^2z}{r^7}-3\frac{z}{r^5}\right)+M_y\left(15\frac{xyz}{r^7}\right)+M_z\left(15\frac{xz^2}{r^7}-3\frac{x}{r^5}\right). \tag{8}$$

Since the total magnetic force F is defined by

$$F^2=X^2+Y^2+Z^2, \tag{9}$$

the gradient to the x direction becomes

$$\frac{\partial F}{\partial x}=\frac{1}{F}\left(X\frac{\partial X}{\partial x}+Y\frac{\partial Y}{\partial x}+Z\frac{\partial Z}{\partial x}\right). \tag{10}$$

We can therefore calculate the gradient of F to any direction with expressions from (3) to (10) provided the direction of the coordinate axes are chosen suitably.

For an order-of-magnitude estimate, let us here consider a simple case in which $M_x=M_y=0$, $y=z=0$. In that case, we simply obtain

$$\partial F/\partial x=-\frac{3M_z}{x^4},$$

so that, if $M_z=10^{13}$ $e.m.u.$, $\partial F/\partial x$ amounts to 3.0×10^{-2}, 1.9×10^{-3}, 3.7×10^{-4} and 4.8×10^{-5} γ/cm for $x=1$, 2, 3 and 5 km respectively. In other words, these gradients are 30, 1.9, 0.37 and 4.8×10^{-2} $\gamma/10$ m.

Since the distance between the two detecting coils is about 10 m for the present apparatus and the accuracy of counting the beat frequency amounts to 0.01 c/s or 0.2γ, the dipole having a moment of 10^{13} $e.m.u.$ cannot be detected provided it appears at a distance farther than 2 km or so. Even if the moment becomes 10 times larger, the detectable distance would not exceed 4 km.

From the above estimate of $\partial F/\partial x$, we see that it would be rather difficult to catch the dipoles supposed at some depth under the central part of the island because the observatory where the differential magnetometer has been installed is about 4 km distant from the crater. It will not be utterly hopeless, however, that we might catch the local anomalous changes in the magnetic field with the instrument provided the magnetized or demagnetized regions within the interior of the volcano have some volume. The gradient depends largely on the distance between the instrument and the magnetic matter.

According to the previous observations, there is some evidence that we sometimes have very localized changes which can be detected at stations only a few hundred meters distant from one another though no detailed investigation of such changes has been carried out. If we had changes of this sort, the differential magnetometer would certainly catch them. If they were once caught, we would be quite sure that some anomalous changes occurred because no correction whatever is necessary for the result unlike usual magnetometers.

It is also intended in the future to increase the distance between the two detecting coils by a factor 10 or so. In that case, the sensibility of the apparatus might be sufficient for observations of the supposed local anomalous changes.

3. Apparatus

As the principle on which a proton precession magnetometer works is well known, no detailed explanation of the proton magnetometer itself is necessary. The writers would here like to describe only some brief outline of the differential proton magnetometer.

As can be seen in the block-diagram in Fig. 1, the apparatus consists of a pair of detecting coils, electric sources for magnetization and voltage amplifiers and also a power amplifier, a standard frequency oscillator, and a recorder.

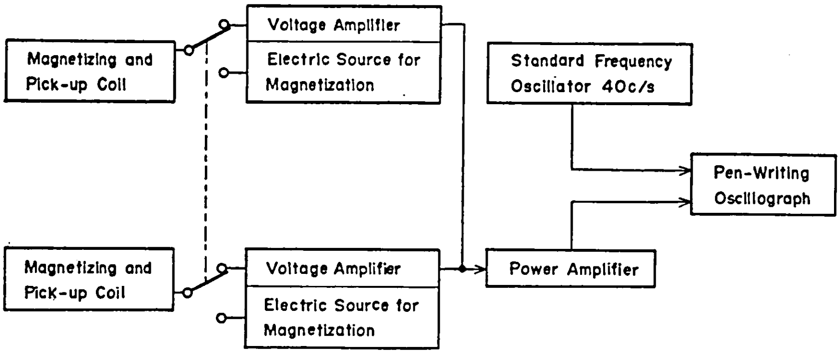

Fig. 1. Block-diagram of the differential proton magnetometer.

Detecting and magnetizing coils

Enamelled copper wire of 1 *mm* in diameter is wound about 500 *turns* on glass or vinyl bottles of about 7 *cm* in diameter and 8 *cm* in length. The bottles contain some 200 *cc* of distilled water.

In order to direct the magnetic moments of protons in the water to a direction approximately perpendicular to the geomagnetic field, electric currents of about 5 *amperes* are supplied to these coils from the electric sources. If the magnetic fields produced by the electric currents are removed suddenly, gyromagnetic motions of protons take place around the flux of the earth's magnetic field. In that case, the coils can be also used as pick-up coils for the induced voltage due to the rotating resultant magnetic moment provided the coils are switched to the amplifiers at the same time. The relation between the precession frequency $f(c/s)$ and the intensity of magnetic field $F(\gamma)$ is $F=23.4865f$.

Voltage amplifiers

The voltages that are induced in each coil are introduced to the coupling transformers of the respective voltage amplifiers. Through a preamplifier and a 2 *kc/s* narrow-band amplifier with two 50 *c/s* rejectors, the signal voltage is amplified attaining a gain of 130 *db* or so.

The amplifier of the station-use proton magnetometer[14] (amplifier 1) that has been reported previously is used as one of the voltage amplifiers. The electric circuit of the newly constructed amplifier (amplifier 2) is shown in Fig. 2 together with the power supply, mixing part and power amplifier. The circuit of amplifier 1 is more or less the same as that of amplifier 2.

Mixer and power amplifier

As can be seen in Fig. 2, the signal voltage that is amplified by amplifier 1 is mixed with that from amplifier 2 through terminal *J*. The beat waves thus produced are detected by means of grid detection and then introduced to the push-pull power amplifier.

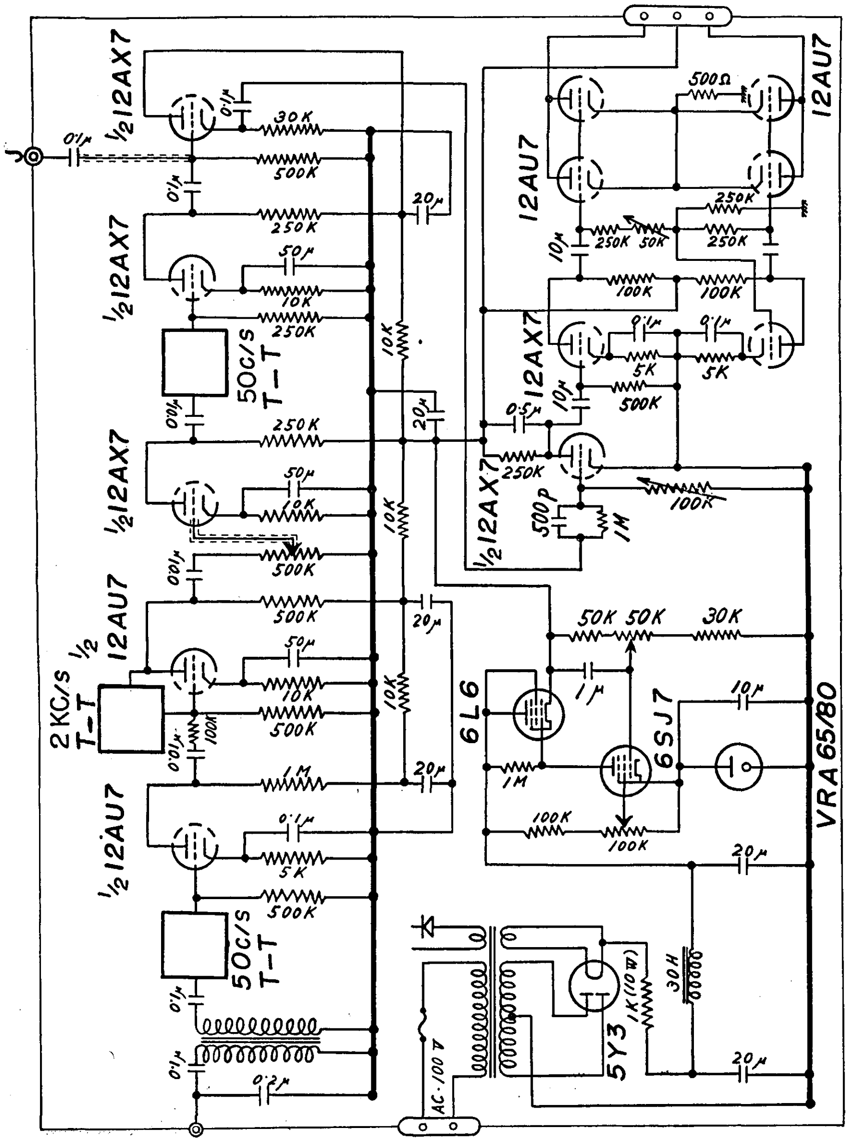

Fig. 2. Electric circuits of amplifier 2, power supply, mixing part and power amplifier.

Standard frequency oscillator

A 40 c/s standard frequency is provided as the time reference. The standard oscillator of the station-use proton magnetometer is used for that purpose. We may refer to the previous paper[14] for the details. Since the 40 c/s is used only for the time reference, a time marking watch can be utilized for the same purpose.

Recorder

A two-component pen-writing oscillograph is used for recording. With the aid of the 40 c/s standard frequency, the beat frequency, which is 2–3 c/s in this case, can be readily counted with an accuracy of 0.01 c/s. The paper speed of recording is usually 12.5 cm/sec.

4. Test at the Oshima Geophysical Observatory

In order to look for a suitable site where one of the detecting coils was to be set, a survey of total magnetic intensity was made on the premises of the Oshima Geophysical Observatory by the station-use proton magnetometer of which the detecting coil is usually set in the absolute measurement room. There was found a considerable anomaly in the geomagnetic field as can be seen in Fig. 3, where the isodynamics are shown in units of c/s. Since 1 *cycle* of precession frequency is approximately equal to 20 γ, it is seen that there exists a very localized anomaly having a range of 500 γ within such narrow grounds. The anomaly is probably caused by strongly magnetized lava flows beneath the ground.

The coils are put at points A and B as shown in Fig. 3. The distance between the two points amounts to 11.8 m. The straight line connecting A to B points towards the crater of Volcano Mihara. The coil at A is also used for routine observations of the values of total magnetic intensity.

The operation of the apparatus is very simple. The operator first puts on the switches for magnetizing both the coils. After several seconds' magnetization, the switches are suddenly turned off and the coils are connected to the voltage amplifiers at the same time. Since the signal waves do not last long because of the marked inhomogeneity of the magnetic field, we can record only a few numbers of strongly damped beat waves as can be seen in one of the examples of record shown in Fig. 4.

A series of observation was made with the differential magnetometer on Dec. 23 and 24, 1959. The results are summarized in Table

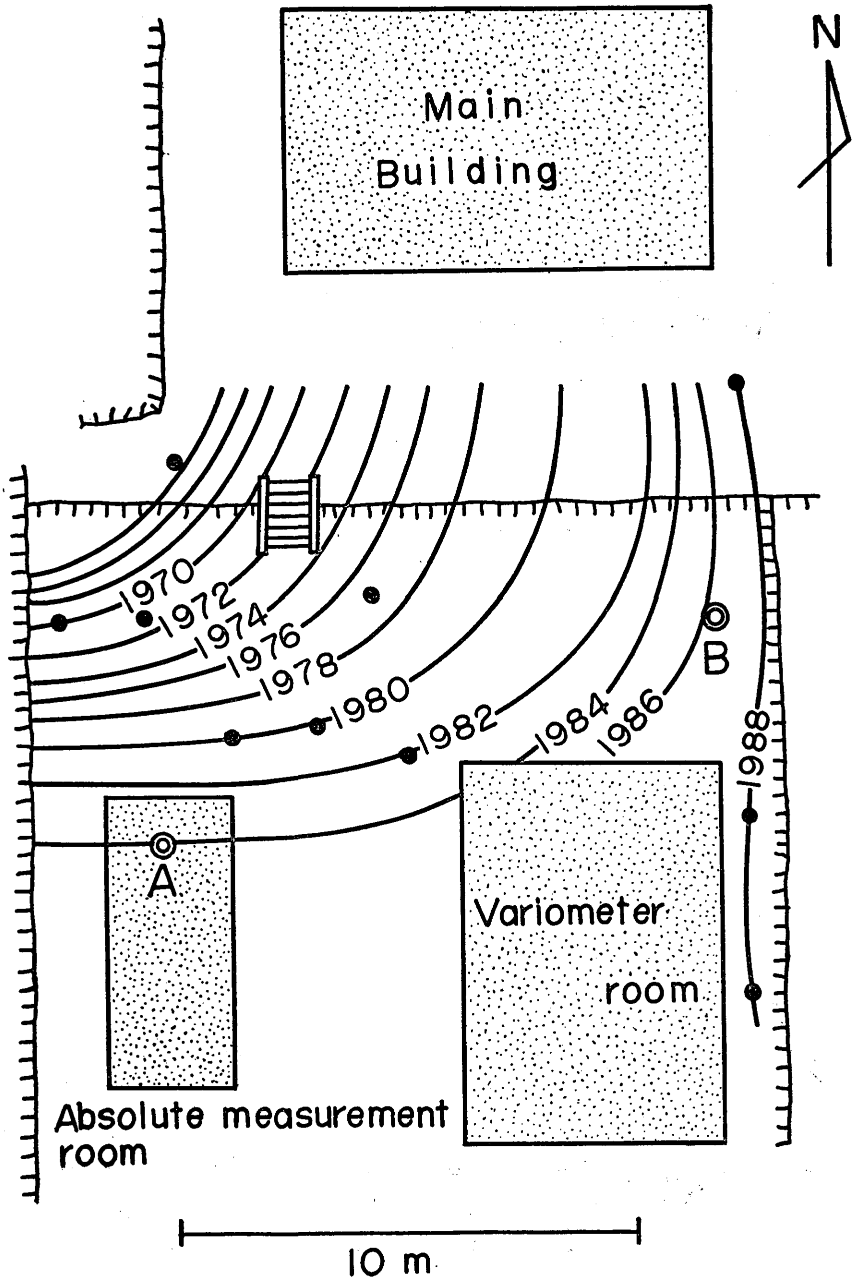

Fig. 3. The distribution of the proton precession frequencies (c/s) in the Oshima Geophysical Observatory. The detecting coils of the differential proton magnetometer are set at points A and B. The coil at A is also used for the routine observations of the total geomagnetic field by the station-use proton magnetometer.

1 and shown in Fig. 5 together with the total geomagnetic intensity at point A. It is seen that the differential magnetometer does not show significant changes in spite of the appreciable changes in the geomagnetic field itself. The results seem to be quite natural because those changes are probably caused by some agency outside the earth and consequently they are so uniform that nothing should be recorded by the present apparatus.

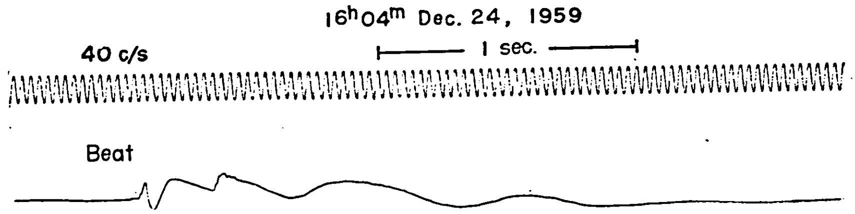

Fig. 4. One example of the records.

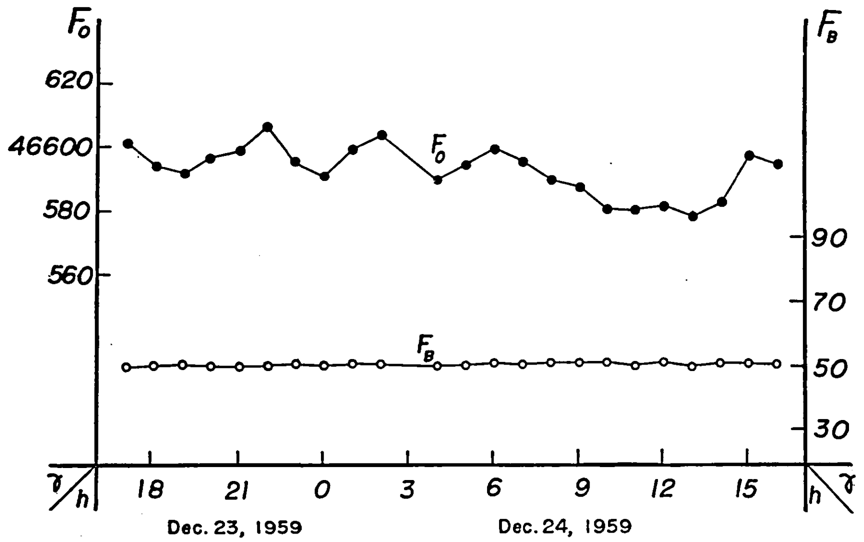

Fig. 5. Results of the observation by the station-use proton magnetometer (F_0) and the differential proton magnetometer (F_B) on Dec. 23 and 24, 1959.

5. Concluding remarks

A differential magnetometer was constructed by mixing the signal waves from two proton magnetometers. According to the test at the Oshima Geophysical Observatory, it was proved that the differential proton magnetometer could record the difference in the total geomagnetic intensity between two points apart 11.8 m with an accuracy of about 0.2 γ. Observations with the apparatus will be continued there in the hope of detecting local anomalous changes in the earth's magnetic field that might be associated with the activity of Volcano Mihara.

Table 1. The results of the observation by the station-use proton magnetometer and the differential proton magnetometer on Dec. 23 and 24, 1959.

Time (J.S.T.)	Beat Freq.	Difference in total force	Signal Freq. at Point A	Total force at Point A
Dec. 23, 1959				
h m	c/s	γ	c/s	γ
17 01	2.20	51.7	1985.0	46620.7
18 01	2.20	51.7	1985.0	46620.7
19 01	2.22	52.1	1984.6	46611.3
19 58	2.20	51.7	1984.8	46616.0
21 02	2.18	51.2	1984.9	46618.4
21 56	2.19	51.4	1985.2	46625.4
22 57	2.22	52.1	1984.75	46614.8
23 58	2.20	51.7	1984.55	46610.1
Dec. 24, 1959				
0 58	2.22	52.1	1984.9	46618.4
2 04	2.22	52.1	1985.1	46623.1
3 59	2.18	51.2	1984.5	46609.0
4 58	2.20	51.7	1984.7	46613.7
6 00	2.22	52.1	1984.9	46618.4
6 59	2.20	51.7	1984.75	46614.8
7 58	2.22	52.1	1984.5	46609.0
8 58	2.22	52.1	1984.4	46606.6
9 58	2.22	52.1	1984.1	46599.6
11 00	2.17	51.0	1984.1	46599.6
11 58	2.22	52.1	1984.15	46600.7
12 58	2.15	50.5	1984.0	46597.2
14 00	2.20	51.7	1984.2	46601.9
15 04	2.20	51.7	1984.8	46616.0
16 04	2.18	51.2	1984.7	46613.7

18. プロトン磁力計による地磁気傾度計

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プロトン磁力計の 2 個の検出器からの信号周波数を混合して得られる唸周波数を計数して，2 地点の地磁気全磁力の差を 0.2γ 程度の精度で測定する装置を考案した．

この器械は地震研究所伊豆大島観測所に設置され，三原山の火山活動に伴なうと予想される地磁気変動の精密観測に使用される予定である．