NASA TN D-358

TECHNICAL NOTE
D-358

THE VECTOR FIELD PROTON MAGNETOMETER FOR IGY SATELLITE GROUND STATIONS

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON October 1960

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SUMMARY

The application of homogeneous-bias fields to a proton precessional magnetometer allows the measurement of the vector field by measuring the absolute scalar field F, declination variations ΔD, and inclination variations ΔI. The absolute scalar field can be measured to an accuracy of ± 1 gamma and absolute declination and inclination to an accuracy of ± 2 minutes. This paper describes a vector proton magnetometer that has been in operation at nine Minitrack stations since the spring of 1958.

CONTENTS

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INTRODUCTION

Measurements from the Vanguard III magnetic-field satellite* yield information on currents in and beyond the ionosphere, depending on surface measurements taken near the geographical locations where the satellite was interrogated (References 1 and 2). During satellite flight, the surface measurements provided: (1) immediate information on the existence of a magnetic disturbance; (2) highly accurate values of the scalar and vector field variations at the surface during disturbances, to permit interpretation of simultaneous satellite measurements in terms of currents; and (3) absolute drift-free measurements of diurnal variations during quiet periods, to permit selection of those satellite measurements to be used in establishing the undisturbed field at satellite altitudes over each station.

The merits of vector rather than scalar measurements at the earth's surface are not immediately apparent but become so if one considers a variety of disturbance conditions. An obvious example is that of obtaining an estimate of local ionospheric effects: adjacent stations could, for example, observe similar variations in the scalar field even though a large change in declination occurs at only one of the stations. When it is known that this is occurring, one can assign reasonable limits to the form of the local ionospheric current. Where a multiplicity of interpretations might be possible with only scalar measurements, the vector details will in many cases be useful in eliminating some of the possibilities.

The establishment of stations to satisfy these requirements was a major problem at the outset of the satellite experiment. Considerations of cost and ease of operation by station personnel inexperienced in magnetic-field measurements were as important as accuracy requirements. Existing instruments did not meet these requisites, and this led to the development of the F-ΔD-ΔI magnetometer. It was designed to measure the total scalar field F as well as the declination and inclination variations ΔD and ΔI, relative to the surveyed setting of the instrument. The quantities F, D, and I define the vector field.

Lt. F. W. Bacon, while working with Varian Associates, demonstrated that vector measurements could be made with a proton precessional magnetometer (Reference 3). The inherent advantage of this instrument is the high accuracy which is achieved without calibration, temperature corrections, and corrections for instrumental drifts. Although the electronic system described here is quite different from that used by Bacon, his work was a good foundation for rapid development of an operational instrument. Ten magnetometers were constructed. Nine of these were put in operation during the spring and early summer of 1958 at Fort Stewart, Georgia; San Diego, California; Havana, Cuba; Antigua, British West Indies; Quito, Ecuador; Lima, Peru; Antofagasta and Santiago, Chile; and Woomera, Australia.

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*1959 Eta, launched September 18, 1959

†Material presented herein has also been presented in the Journal of Geophysical Research, Vol. 65, No. 3, March 1960, pp. 913-920.

PRINCIPLES OF MEASUREMENT

Total Scalar Field F

The absolute total scalar field F is the field normally measured with a proton precessional magnetometer; details have been published previously (Reference 4). The free precession of a proton in an external magnetic field F has an angular frequency ω given by $\omega = \gamma_p F$, where γ_p is the proton gyromagnetic ratio equal to $2.67513 \pm 0.00002 \times 10^4$ seconds^{-1} gauss^{-1} in the latest determination by the National Bureau of Standards (Reference 5). Absolute field values are obtained by measuring the frequency

$$f = \frac{\omega}{2\pi} = 4257.6(F). \tag{1}$$

In order to obtain a precession signal of sufficient amplitude to measure this frequency accurately, the proton sample is first polarized by passing a strong current through a coil surrounding the sample. When this current is cut off, a small but significant fraction of the protons are in phase in their precession and thus induce a detectable voltage at a frequency f in the surrounding coil. Maximum amplitude of the precession signal is obtained by orienting the polarizing coil perpendicular to the magnetic field. However, the frequency of the induced signal is not a function of the orientation angle, and a non-perpendicular orientation will cause only a reduction in amplitude. The signal amplitude decays exponentially with a time constant which is a function of the proton sample and polarizing time.

In the instrument described here, n-heptane is used for the proton sample. Although alcohol and even water can be used as samples, the high boiling point and low freezing point of n-heptane made it more desirable for field use. About 6 amperes from a 12-volt battery is applied for 5 seconds for polarization. This produces a precession signal visibly above noise for 4 to 5 seconds. As frequency counting is practically unaffected by noise for about 2 seconds, a large number of cycles can be referred to a 100-kc standard to obtain very high accuracy.

Declination Variations ΔD

To obtain measurements of declination variations ΔD, the proton precession frequency is measured in the manner described above. However, the field measured is the vector sum of the earth's field and a bias field created at right angles to the earth's field in the horizontal plane by passing current through a vertical Helmholtz coil. To make the measurement independent of the coil current, two measurements with opposite bias fields are taken as illustrated in Figure 1a. The change in declination measured, ΔD, is relative to the orientation angle of the Helmholtz coil. When the coil orientation is accurately known, this also gives the absolute declination D through the algebraic addition of D_o and ΔD, where D_o is the "zero" orientation of the Helmholtz coil (Figure 1a).

The precession frequency

$$f_d^+ = 4257.6\ (F + B_d^+) = 4257.6\ (F_d^+)$$

is measured when current is passed through the Helmholtz coil in the sense producing an axial bias field B_d^+ in the easterly direction. The precession frequency

$$f_d^- = 4257.6\ (F + B_d^-) = 4257.6\ (F_d^-)$$

is measured next with the coil current reversed, thus producing an axial bias field B_d^- in the westerly direction.

(a)
DECLINATION MEASUREMENT
(North of the Magnetic Equator)

(b)
INCLINATION MEASUREMENT
(North of the Magnetic Equator)

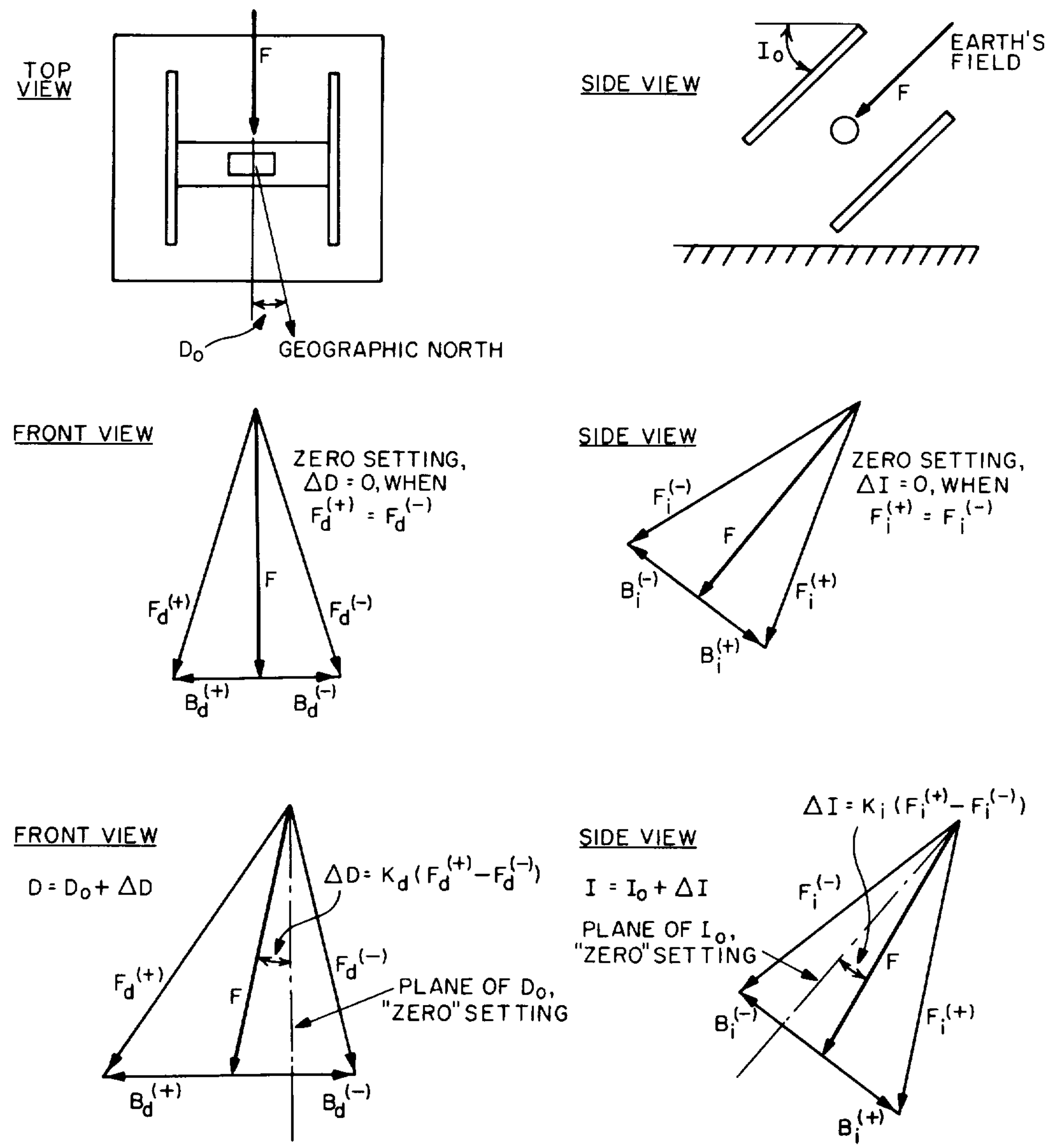

Fig. 1 - Graphic representation of component measurements

Although the "zero" orientation is not critical, there are advantages to making it such that f_d^+ and f_d^- are nearly equal. When ideally oriented, the readings over a period of the diurnal variation will be such that the amount of time when $f_d^+ > f_d^-$ is roughly equal to the amount of time when $f_d^+ < f_d^-$; i.e., such that D_o is close to the mean declination. Possible errors due to small-angle assumptions leading to Equation 2 below are then negligible, and there is the additional convenience of working with small numbers in the difference $F_d^+ - F_d^-$.

The equation, with ΔD in minutes of arc,

$$\Delta D = \frac{1.719 \times 10^3 \, (F_d^+ - F_d^-)}{\left[F(F_d^+ + F_d^- - 2F)\right]^{1/2} \cos I}, \qquad (2)$$

where

F = the absolute scalar field,

I = the inclination of the field, $I_o + \Delta I$, and

1.719×10^3 is the conversion from radians to minutes,

was derived by Bacon (Reference 3) from the cosine law with the assumption that $(F_d - F)/F << 1$ and several small angle assumptions having considerably less effect. Errors from the assumption $(F_d - F)/F << 1$ are a function of bias-field intensity B_d and the magnitude of F at a particular station. Although declination sensitivity is proportional to bias-field intensity, the latter is limited by the above assumption.

Equation 2 is easily programmed into computing machines in terms of frequency count. When computers are not used, data handling is simplified with little loss of accuracy by using simply

$$\Delta D = K_d(F_d^+ - F_d^-),$$

in which the lumped constant K_d is computed by using mean values for F, I and $F_d^+ + F_d^-$. Mean values for F and I can, of course, be considered valid for periods of months. The constancy of $F_d^+ + F_d^-$ is, however, a function of current in the Helmholtz coil. In general, the changes in current over a period of a day or so are not easily measured, and it is simpler to check the constant by occasional use of Equation 2.

Inclination Variations ΔI

The method of measuring inclination variations ΔI is basically the same as for ΔD. The Helmholtz coil for the ΔI bias fields is perpendicular to the ΔD coil, with the coil axis perpendicular to the earth's field. The field inclination (dip angle) I is the algebraic sum of I_o and ΔI, where I_o is the "zero" or fixed orientation (Figure 1b).

In a manner analogous to the ΔD measurement, the two frequencies

$$f_i^+ = 4257.6\ (F + B_i^+) = 4257.6\ (F_i^+)$$

and

$$f_i^- = 4257.6\ (F + B_i^-) = 4257.6\ (F_i^-)$$

are measured. The I_o setting is determined after the D_o setting by rotating the coil until f_i^+ and f_i^- are nearly equal when averaged over a diurnal cycle.

The equation for ΔI in minutes (analogous to Equation 2 for ΔD),

$$\Delta I = \frac{1.719 \times 10^3 \, (F_i^+ - F_i^-)}{\left[F \, (F_i^+ + F_i^- - 2F)\right]^{1/2}} , \qquad (3)$$

is subject to the assumption $(F_i - F)/F \ll 1$ as was previously noted for ΔD. The corresponding simplified expression is

$$\Delta I = K_i \, (F_i^+ - F_i^-) .$$

DESCRIPTION OF INSTRUMENTATION AND DATA

The magnetometer is illustrated in block form in Figure 2 and in the photograph of Figure 3. To isolate the sensing unit from artificial fields while keeping cable lengths for battery power at a minimum, the instrumentation occupies three locations separated as indicated by the cable breaks in Figure 2.

Programming

The sequence of measurement is F, F_d^+, F_d^-, F_i^+ and F_i^-. This set constitutes one vector measurement. To minimize the number of readings with little chance of missing significant field variations, it was decided that one set would be taken every 3 minutes. A one-third rpm, 60-cycle synchronous motor-timer is used as a master timer for sequencing three other synchronous motor-timers on the programming timer chassis. Cam switches on these motors sequence relay power to four relays in the field electronics box, which in turn switch the bias-field current, battery-charge current, and the polarize-read relays. The readings for F, F_d^+ and F_d^-, F_i^+ and F_i^- are taken on successive minutes and spaced such that a battery trickle charge occurs between all readings; thus there is little chance of battery voltage drop causing any difference in successive bias-field currents.

The programming timer also operates a relay (located on the input-filter subchassis) which shorts the signal input circuit to the counter between readings so that noise transients cannot cause false triggering of the counter.

Sensing Head and Preamplifier

The proton sensing head, polarize-read relay circuit, and tunable preamplifier were designed and built by Varian Associates. Storage batteries supply the 12-volt polarizing and 6-volt filament power, while four 45-volt dry cells connected in series are used for plate voltage and normally last for three months of continuous operation. The input precession signal to the preamplifier is roughly 10 microvolts. This is amplified to 200 to 500 millivolts for transmission by cable to the recording electronics. For noise elimination, the preamplifier has variable tuning in bandwidth steps of 67 cycles. Signal-to-noise ratios at the preamplifier output are between 10:1 and 30:1.

Helmholtz Coils

The interlocking aluminum Helmholtz coils were cast, machined, assembled, and wound in the shops of the Naval Research Laboratory. The Helmholtz condition, that the separation of paired turns equal the coil radius, was maintained by sloping the coil winding

I_o values can influence the overall accuracy of the declination and inclination measurements. The accuracy of the survey of the field coils will, generally, be limited by imperfection in the machined surfaces of the coil assemblies and the relatively small dimensions of the coil diameters. With care, the coils can be surveyed to an accuracy of ± 1 minute.

CONCLUSION

Considering the various station locations and the errors noted above, the scalar field inaccuracy is within ± 0.7 to ± 1.3 gammas. The ΔD and ΔI inaccuracies are probably within ± 1.3 and ± 0.5 minutes respectively. To obtain the absolute accuracy of declination D and inclination I the surveying errors must be added to these figures. It should be emphasized that the particular counter described here is not an irreplaceable component of the system and, consequently, the variations it gives rise to are not inherent to the proton magnetometer. Specifically, values of greater accuracy than the above can be obtained by using a counter with an internal time-base stability of ± 1 part in 10^6. Such a stability, though not warranted in this experiment, would reduce the overall variations in F, ΔD and ΔI by approximately ± 0.4 gammas, ± 0.6 and ± 0.2 minutes, respectively.

There are no further corrections to be made, such as those for temperature and drift, nor are any calibrations required. Therefore it can be seen that the proton precessional magnetometer measures total field to an accuracy several times greater than that obtained by the magnetic observatories, and that declination and inclination measurements are at least comparable to those obtained in the best observatories. A record taken near the Naval Research Laboratory is shown in Figure 4 compared with that of a standard observatory instrument located about 50 miles away. The observatory records horizontal and vertical intensities so that only the declinations are directly comparable. Large errors in the vertical component which normally limit the accuracy of conventional observatory instruments do not, of course, appear in the proton magnetometer.

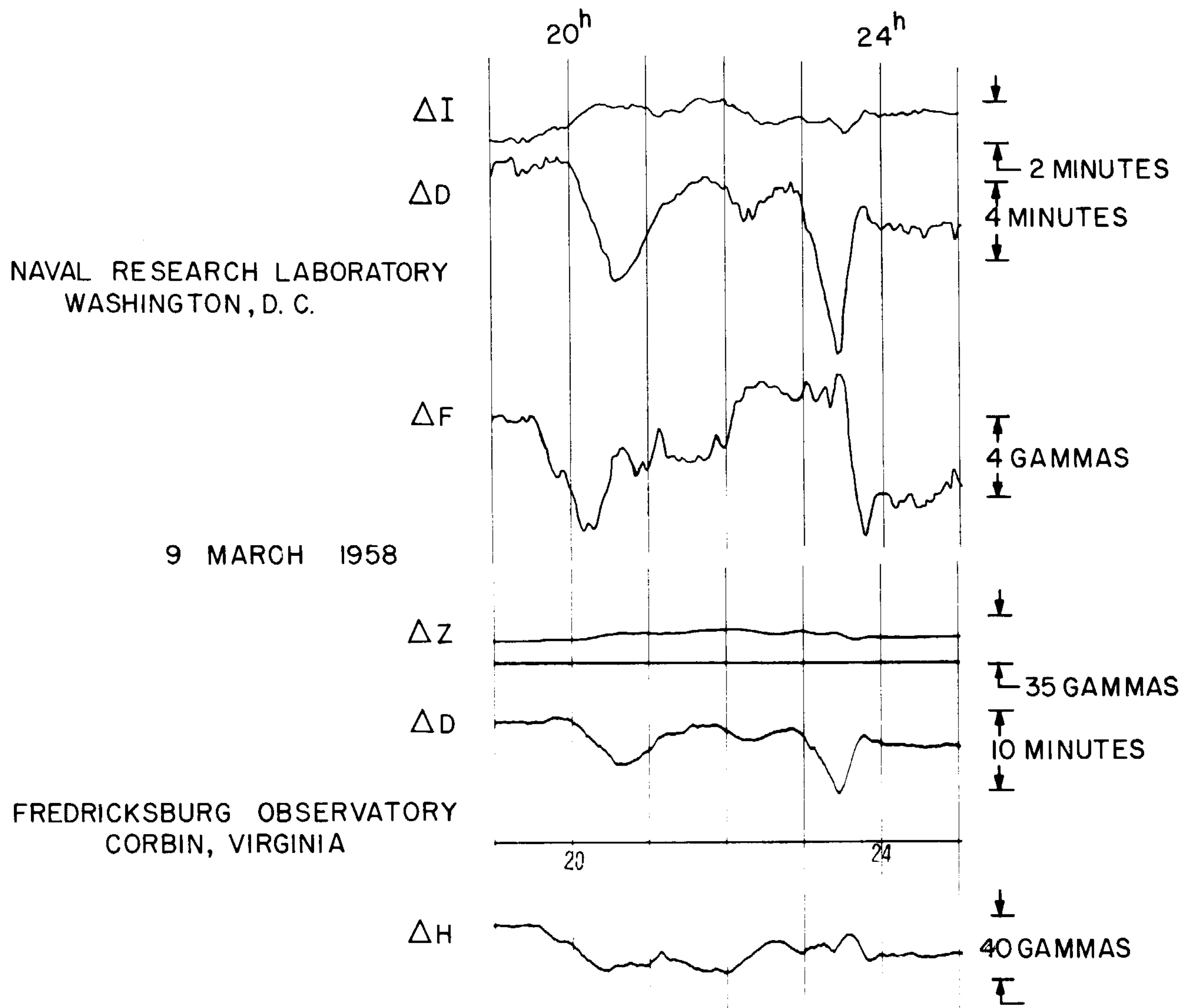

Fig. 4 - Magnetogram comparison

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