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High Precision Profiling With a Rubidium Magnetometer Pair

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W. P. HASBROUCK

BOULDER, COLO.
NOVEMBER 1970

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High Precision Profiling With a Rubidium Magnetometer Pair

W. P. HASBROUCK

EARTH SCIENCES LABORATORIES
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HIGH PRECISION PROFILING WITH A RUBIDIUM MAGNETOMETER PAIR

W. P. Hasbrouck

Reliable mapping of quasi-static total magnetic field changes to 0.1 gamma between stations separated by 1/2 km can be accomplished by use of a special paired rubidium magnetometer technique. This report discusses the limitations on profiling accuracy imposed by the intrinsic reproducibility of a rubidium horizontal gradiometer. It then describes a pier-differencing method of traversing which has been used to overcome this insufficiency and which has produced long-spaced station-to-station results of tenth gamma reliability. Nonlinear instrumental drift between the paired sensors is minimized by use of a differential drift correction. Examples show how this correction is computed and applied.

1. INTRODUCTION

A high precision magnetic traverse is one along which a 0.1 gamma accuracy in station-difference readings is obtained. A 0.001-gamma sensitivity to time variant total field changes occurring over a time span of less than a minute can be claimed with a 2 sensor, self-oscillating rubidium vapor magnetic system. But a precision equal to this sensitivity cannot be obtained in the determination of the quasi-static total magnetic field differences between two stations; attainment of a reproducibility to 0.1 gamma is more realistic. The disparity between instrumental accuracy and sensitivity exists because instrumental drift, not necessarily linear, occurs; there is no guarantee that a rubidium sensor when retuned or when shut down and restarted in the same magnetic field will give the same reading (Allen, 1968) ; and jumps of as much as 3 gammas have been observed in the difference readings from a sensor pair after the normal warm-up time. This lack of intrinsic reproducibility makes the use of a set of simple synoptic differences from a rubidium-sensor pair insufficiently reliable for high-precision magnetic profiling.

The procedure discussed in this report was designed and field experiments have shown it to be effective in mitigating the effect of nonlinear instrumental drift and in detecting the occurrence of jumps. By assessing the quality of data as they are taken, those sections of the traverse over which results are unacceptable can be rerun before sensors are moved to the next locations. The field equipment consists of a commercially available magnetic gradiometer (with printer output) supplemented with additional coaxial cables and batteries to allow difference readings to be obtained between stations separated by as much as 1/2 km.

The method has been employed in geopiezomagnetic investigations in which an accuracy of 0.1 gamma in the determination of quasi-static magnetic field difference between stations is necessary (Breiner, 1967). Although developed specifically for this application, the high-precision method also can be used in the determination of gross magnetic susceptibility of large isolated blocks of material through introduction of susceptibility as a parameter in terrain effect computations. Development of high-precision traversing reopens the possibility of remote determination of movement of concealed shallow blocks of significant magnetization contrast.

2. INTRINSIC REPRODUCIBILITY OF THE HORIZONTAL GRADIOMETER

Intrinsic reproducibility of a gradiometer is the degree to which it will duplicate a given field change without the need for special computations or the necessity for refinement of the observation technique. Data for determination of intrinsic reproducibility were obtained by electronically differencing Larmor frequency outputs of 2 closely spaced rubidium sensors and then counting and printing this difference frequency. Assessment of these gradiometer-type results indicated that a simple 2-sensor system could not, by itself, produce the quality of results required.

A time series of frequency differences (scaled in gammas) from a particular pair of closely spaced rubidium sensors, and the ambient temperature variations plotted against the same time base are displayed in figure 1. These data were taken during a magnetically quiet time. It is difficult to refute a correlation between change in gradiometer reading and change of air temperature. The lag in observed gradiometer response as ambient temperature decreases might be expected because the magnetometer system contains an active thermal element, a temperature control module designed to maintain the sensor's optical section at 50°C.

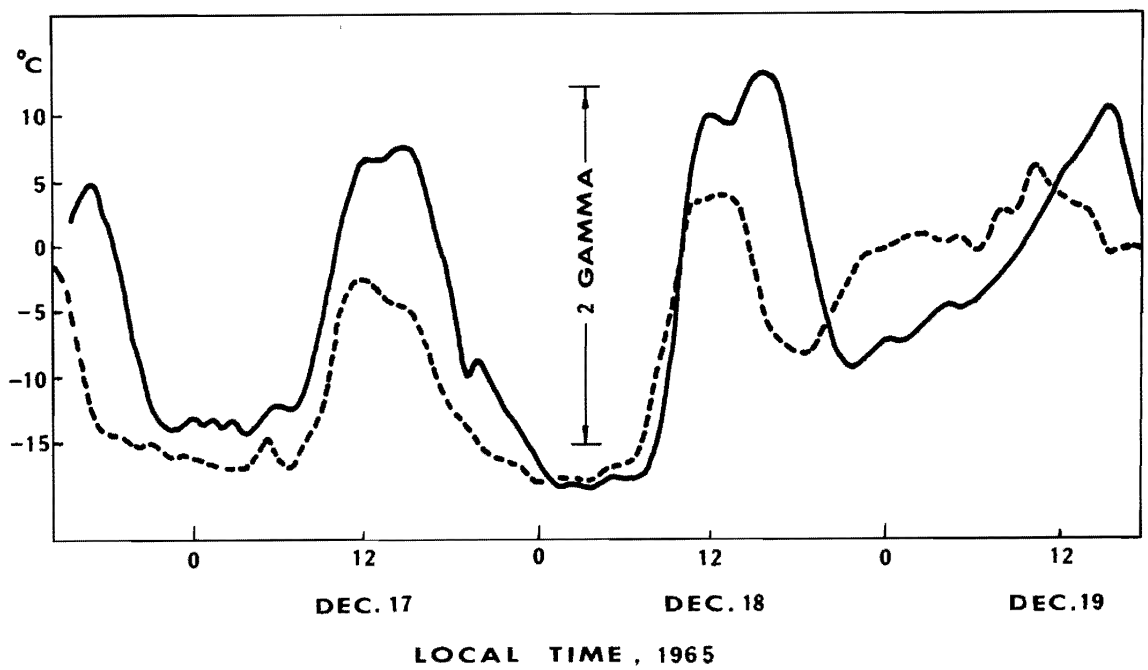

Figure 1. Difference reading from 2 rubidium magnetometers (solid line) in gammas and ambient temperature variations (dashed line, left scale) in °C against local time. Sensor separation is 3 m.

Figure 2 shows the result of comparing field variations observed with each of the two rubidium magnetometers with those of a metastable helium instrument. Both the January 4 and 5 curves exhibit an increase in apparent magnetic field difference following an increase in ambient temperature. But these increases are not at the same rate; the maximum slopes differ by about 1 gamma per hr. Because

behavior of the ambient temperature field was not the same on both days, exact comparisons cannot be drawn between the left and right sets of curves (fig. 2), but the inference is strong that the 2 rubidium sensors tested respond differently to temperature changes and that the variations in rubidium gradiometer response shown in figure 1 is primarily the result of temperature effects. Comparison of results in figures 1 and 2 indicates that either the metastable helium magnetometer is less affected by temperature variations or that partial temperature compensation occurs with a paired set of rubidium sensors. Data for these tests were taken at the Colorado School of Mines' Bergen Park Observatory (elevation about 2400 m). During the winter months, under clear sky conditions, temperature variations there can be large; 20°C in less than 2 hours on Dec. 18th, for example. Thus the observed changes in the difference between the two sensors after sunrise on Dec. 17 and 18 can be considered to be almost an extreme in the anticipated amount of variation.

On Dec. 19th (fig. 1) the sky was cloudy, the temperature did not rise as rapidly during the morning hours, and changes in magnetometer difference readings were not as pronounced.

During the course of geopiezomagnetic experiments, minimum instrumental drift is observed when the sky is overcast and air temperatures are almost constant and in the range from 10° to 20°C. When the ambient temperature exceeds 30°C under bright sky conditions the sensor signal output often drops below the voltage threshold of the frequency counter (a condition remediable by use of additional signal amplification) and instrumental drift sometimes become so great that traverse results are unacceptable.

Ambient temperature variations can only be reduced by surrounding the sensor system with a constant temperature region. The temperature of the sensor room at a magnetic observatory is held fixed and it is probably for this reason that Allen (1968) was not able to detect variations such as those shown on figures 1 and 2. When sensors are to be carried along a traverse the observatory approach is impractical. Adding more thermal insultation will not solve the problem for the heat from internal sources within the rubidium magnetometer system will not be dissipated and the temperature will rise to such a level that the unit will become inoperative, maybe even damaged. In geopiezomagnetic studies three choices for reduction of temperature effect are available: a set of observatory-like buildings can be constructed (or one can be carried along with the sensor); sensors can be lowered into holes, the earth acting as a low-pass thermal filter and large heat sink; or corrections can be made for the effect of temperature by use of data obtained with a high-precision profiling technique as described in this report.

The shape of the gradiometer response curve is representable by a polynomial of low degree. Over the time interval required to observe traverse data (usually less than 1 hr) these instrumental drift curves are sufficiently smooth to be fitted by second degree curves. This fact is used in the development of the computing scheme.

When sensor separation is small and when both sensors are far from artificial noise sources there is little reason to expect naturally caused data jumps of several gammas over a time span of less than 30 sec.

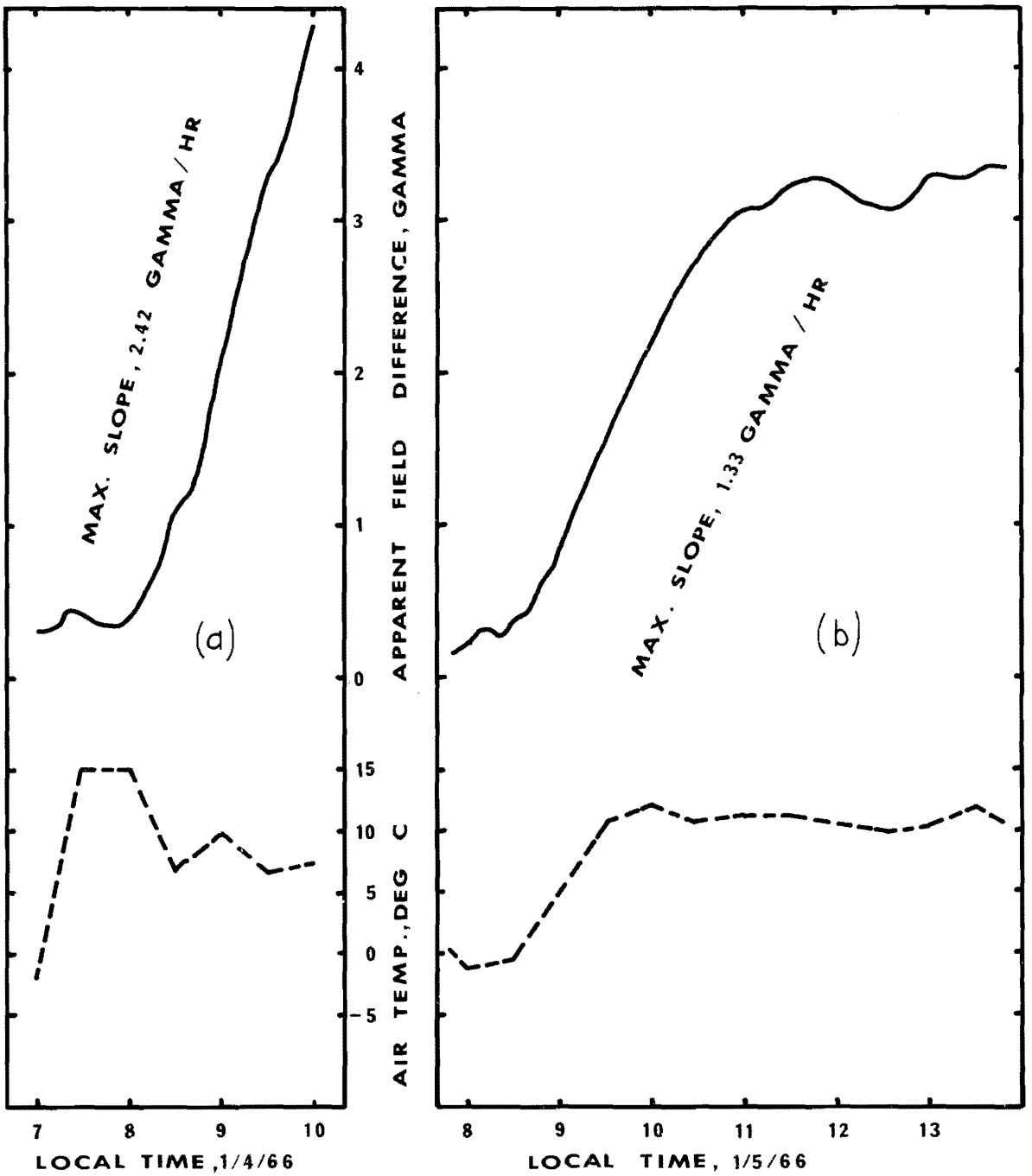

Figure 2. (a) Difference reading between one of the rubidium magnetometers and a metastable helium magnetometer in gammas, and air temperature in °C versus local time. Sensor spacing is 3 m. (b) Same as (a) except test of second rubidium magnetometer on following day.

However, as shown in figure 3, these jumps or steps do occur. These data were taken at the Boulder Magnetic Observatory site which is, of course, magnetically noise free. Neither the single nor double jump observed are reflected by a corresponding change in the total-field magnetogram shown on the lower part of figure 3. Sharp breaks in slope of the apparent field difference curve were observed at about

0300 and 1300 hours of the second day. The discontinuities are either preceded or followed by sustained large changes in the observed apparent field differences.

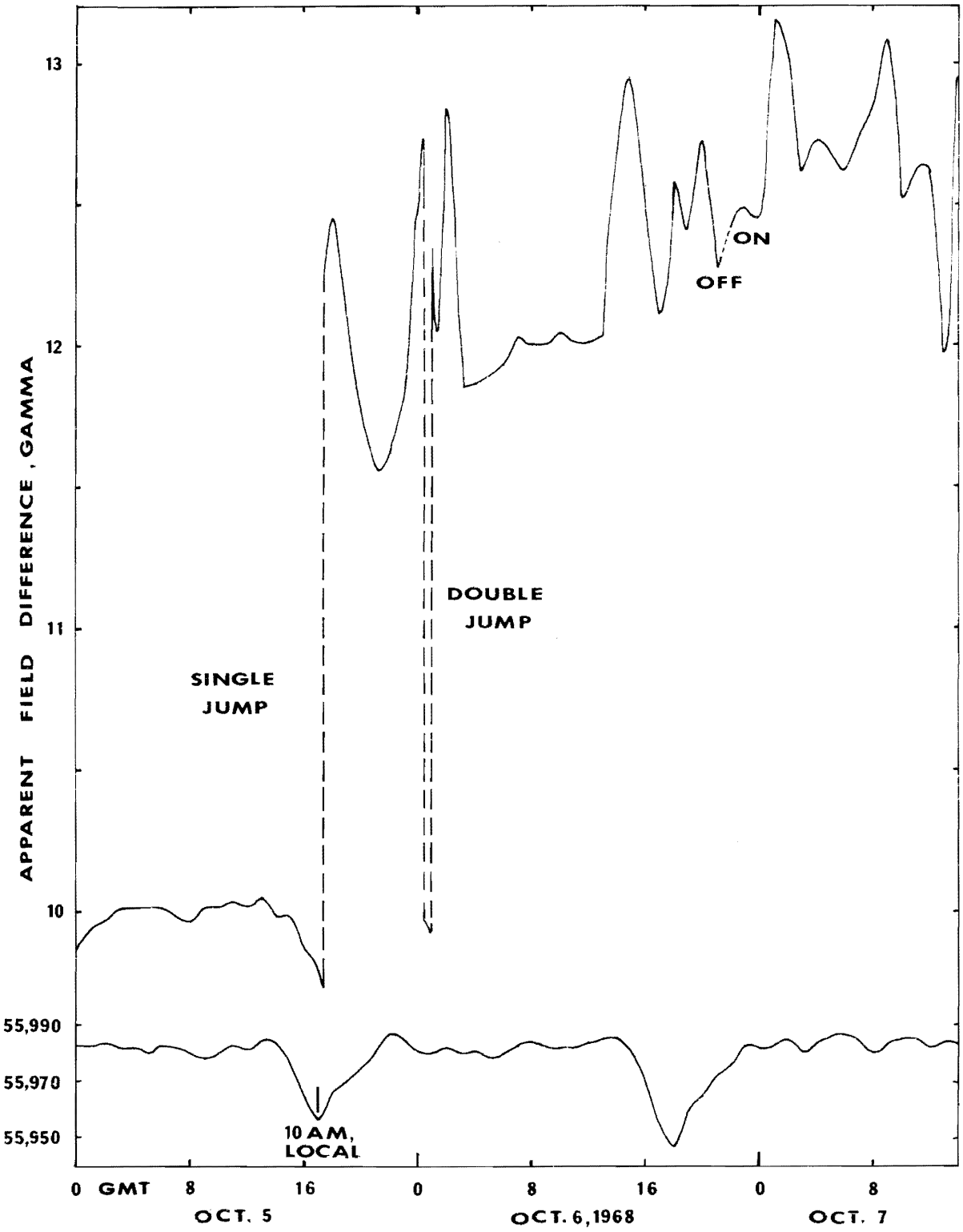

Figure 3. Apparent magnetic field difference (upper curve) in gammas between 2 rubidium magnetometers separated by 50 m and total magnetic field variations (lower curve) in gammas against time.

Jumps were also observed in a magnetic-field coherence study conducted between stations at Nordman, Idaho, and Newport, Washington. The jumps displayed on Figure 4 are certainly due to instrument malfunction at one or both of the rubidium systems because no sudden commencements were observed on the magnetograms from the Newport Geophysical Observatory. Neither the time of occurrence, the length of step, nor the direction of jump (whether an increase or decrease) can be predicted.

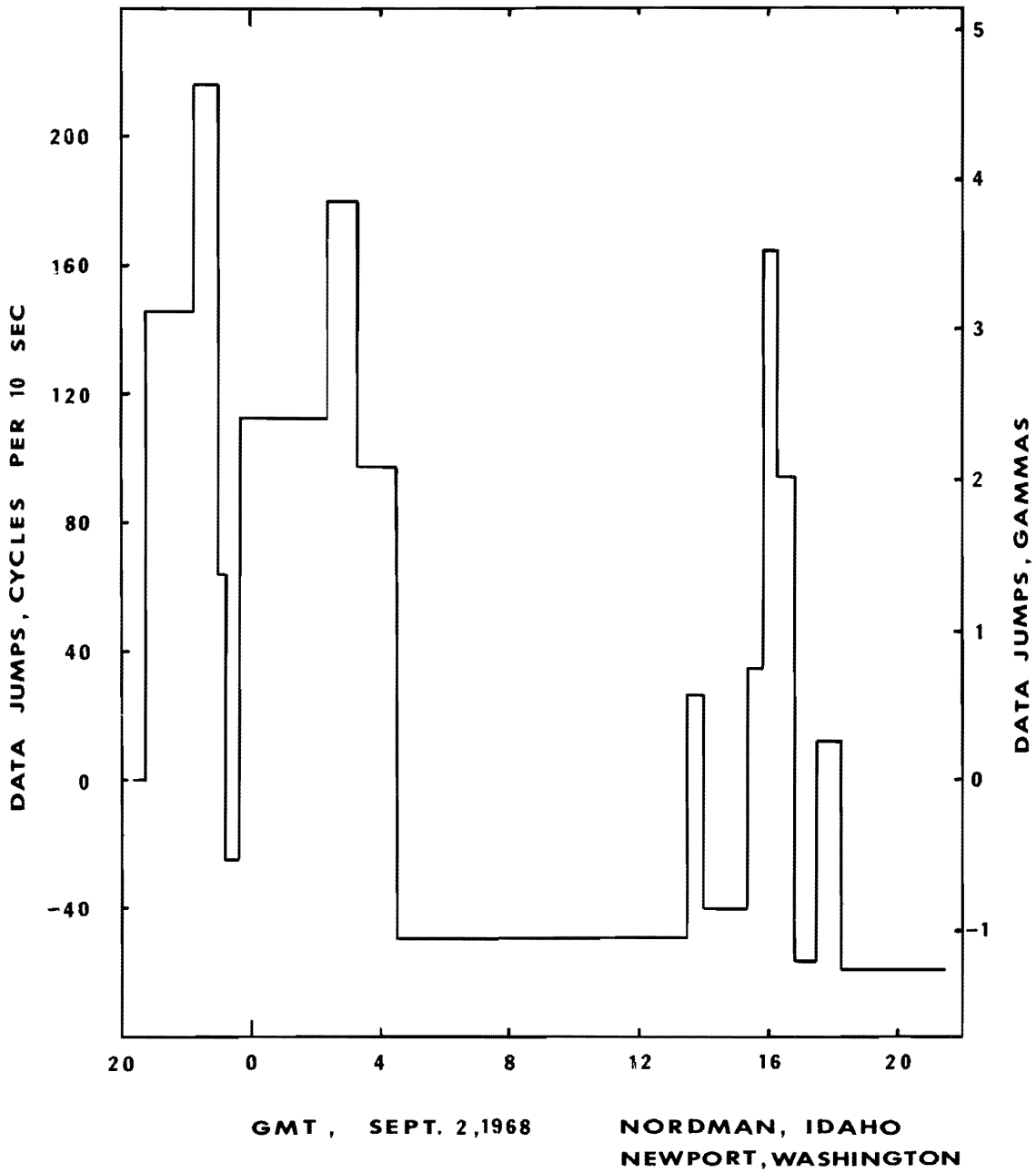

Figure 4. Data jumps observed in synoptic difference reading between rubidium sensors at Nordman, Idaho, and Newport, Washington, in cycles per 10 sec (left scale) and in gammas (right scale) against time.

The conclusion drawn from the test results displayed on figures 1 through 4 is that the inherent reproducibility of a rubidium-sensor pair is insufficient to produce station-difference data of 0.1-gammas reliability.

3. FIELD EQUIPMENT AND OPERATIONS

There are three categories of field equipment: commerically available components, specially built equipment and auxiliary convenience systems.

Commercially Available Equipment

- 2 Rubidium sensor systems and 2 sensor couplers
- 2 30-volt batteries and 2 25-m coaxial cables
- 3 Sets of coaxial cables and 2 cable reels*
- 1 Frequency counter, with 10-sec gate and power system
- 1 Battery charger

  * If cable length exceeds 300 m, additional amplification of Larmor frequency and extra cable reels are required.

Specially Built Equipment

- 1 Electronic differencing unit
- 2 Aluminum Y-shaped staffs*
- 2 Instrument boxes to house 30-volt batteries and sensor couplers

  * If locations are to be reoccupied, aluminum cylinders embedded at each location are required.

Auxiliary Convenience Systems

- 1 Digital printer and digital clock
- 1 Electronic signal-switching unit with automatic or manual scanning
- 1 Signal-monitoring oscilloscope
- 1 Generator or power source
- 1 Weather-protected instrument stand
- 1 24-volt battery for standby sensor power
- 1 Radio receiver tunable to WWV frequencies

The aluminum Y-shaped staff is designed to reflect the purpose of the magnetic traverse. If change in traverse readings over long periods of time are sought, such as would be required in geopiezomagnetic and in block-movement studies, then the base of the staff contains 2 collars of nongauling material which fit smoothly into keyed aluminum cylinders that have been embedded and cemented into the ground. If stations are to be read only once, a sturdy tripod is mounted on the staff so that sensors can be positioned above a location stake. The sensors are held tightly in plastic half cylinders attached to

the arms of the Y-shaped staff and these holders are tipped so that the axis of the sensors is at 45° to the earth's field, an orientation that produces maximum sensor output. Sensor-holder separation is approximately 1 m and the sensor height above ground level is 2 m. Provision must be made on the staff to secure the sensor electronic package at its full length from the sensor and to hold it always in exactly the same position; if this precaution is not observed, reproducible results will not be obtained.

A 1-Hz Larmor frequency change is produced by a self-oscillating rubidium-85 magnetometer when the total field varies by 0.214 gammas. Thus, for a single observation, a frequency counter operated at a 1-sec gate and with a $\pm$ 1-count ambiguity cannot be depended upon to display tenth-gamma field changes. If the gate setting is increased to 10 sec, however, a 1-count change could be representative of 0.0214 gamma variation, and thus the $\pm$ 1-count ambiguity effect is less important. When the differenced outputs of 2 side-by-side sensors were studied statistically, deviations from the trend line were skewed rather than being normally distributed as would be anticipated with $\pm$ 1-count deviations being equally likely. Experimental results were in closer agreement to the theoretically determined probability for a random access gate; the probability of recording N counts is given by

$$F_N = 2\ (1-\alpha)/(1+\alpha) \qquad (1)$$

where α is the fractional part of an incoming stationary signal not seen in the gated interval. According to this statement, even if half the signal were missed in the frequency-counting interval, the probability of recording N counts is 2/3. Although it is tempting to consider decreasing the counter ambiguity effect by further increasing the gate time, say to 100 sec, this step is not recommended for the following reasons: a) longer waiting times are needed to verify repeatability; b) a signal dropout can be detected readily when data are recorded with the 10-sec sample interval, but could be masked with the longer interval; c) the effects of a car driving by a sensor located some 10 m from a road usually last 10 to 30 sec, thus 7 to 9 of the 10 sec samples are acceptable, whereas the entire 100-sec sample would have to be discarded; and d) instrumental-drift effects are minimized if speed of operation is increased.

The deployment of equipment for high precision traversing is schematically represented in figure 5; specific directions, station numbering, and separations are shown. The narrative below describes the one-man field measurement procedure which was followed by the writer in a recent geopiezomagnetic study:

(1) The field area was entered from the station 30 side. The aluminum "Y" staff used for even-numbered stations was set into the cylinder at station 30. The truck was driven to a position midway between stations 30 and 31, the generator was unloaded, and the recording equipment was then placed on an aluminum-frame table, which was immediately covered to protect the printer, clock, oscilloscope, mixer unit, and scanner from rain or volcanic dust.

(2) Sensors were carried by truck to station 31 where the A sensor was set into the westerly cradle and the B sensor into the easterly cradle of the "Y" staff. Power packages were positioned 25 m north of station 31. Sensors were energized at least 1 hour before any readings were taken.

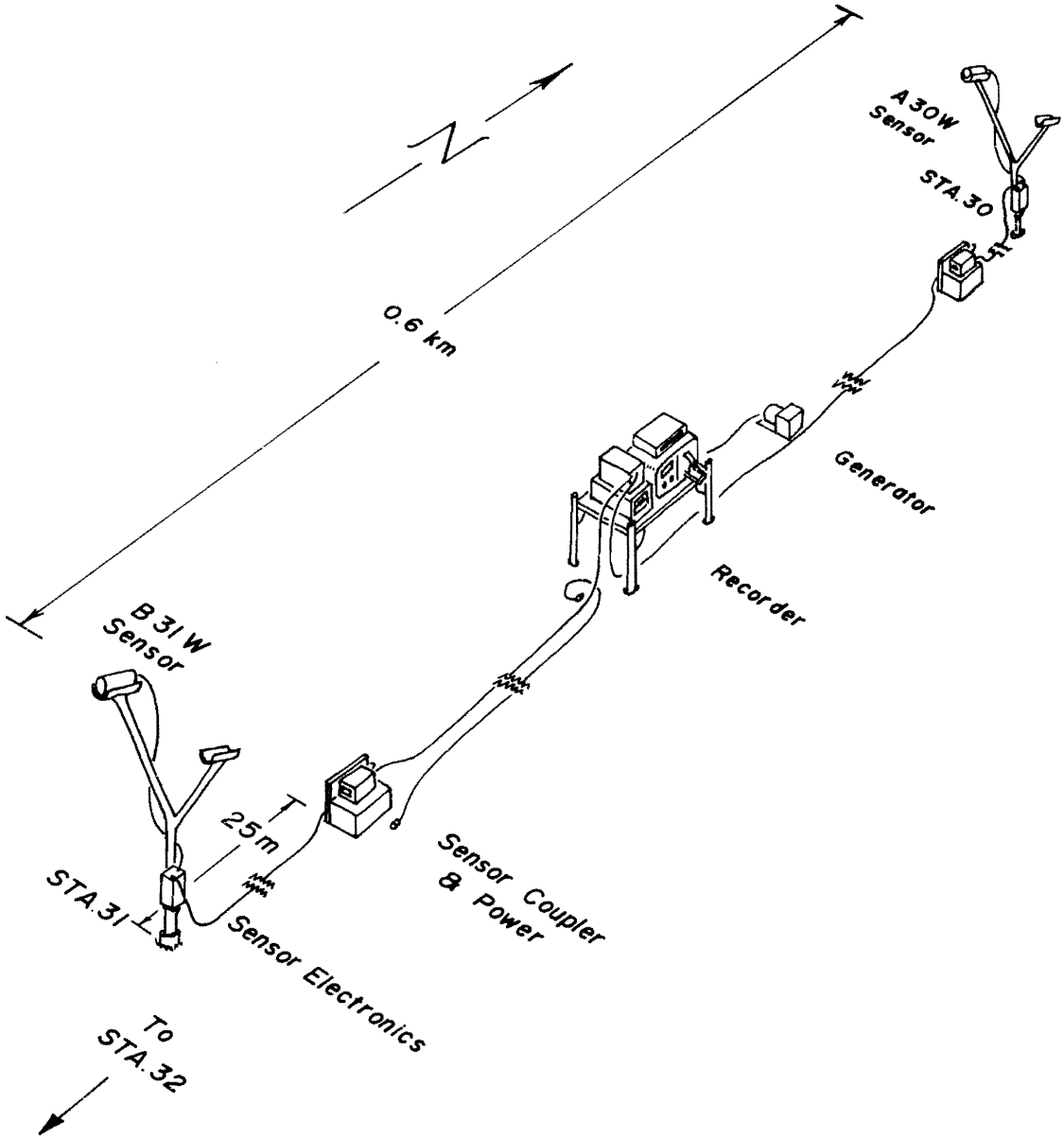

Figure 5. Deployment of high-precision-profiling equipment. Recorder need not necessarily be positioned centrally. Sensor height is 2 m.

(3) Cables were laid out (two from station 31 and one from station 30) and then connected to the sensor couplers mounted on the power-supply boxes.

(4) Recording equipment was turned on, input-signal cables were connected, and the Larmor frequency output from both magnetometers was viewed on the oscilloscope. Two sweep speeds on the oscilloscope were used; a fast sweep to examine wave form of the Larmor-frequency signals and a slow sweep to detect signal drop outs. If the signal quality from both sensors and their mixed output were acceptable, the frequency

counter was switched to normal reset time, and the constancy of frequencies were observed. If the counts held to $\pm$ 1 at a 1-sec gate setting, then the gate was set to 10 sec, and the frequencies were again observed.

(5) The digital-clock time was set approximately, the WWV receiver was turned on, the printer was readied, the counter was set to fast reset, and the reset button of the counter was held in until the WWV tone was heard.

(6) Recording sequence began with the signal from A31W (the A sensor in the west cradle at station 31) and then readings were taken from the sensor of the B31E position followed by the difference reading between A31W and B31E. Individual-sensor readings were needed to gauge the activity of the magnetic field and to determine the sign of the difference value.

(7) If the difference readings held to several counts, they were recorded for approximately 100 sec. The individual-sensor frequency outputs were then printed, after which difference readings again were recorded.

(8) If this second set agreed to within several counts with the first set, then the observer drove to station 31 (difference recording continued) and switched sensors so that now the A sensor was in the easterly cradle and the B sensor was in the westerly cradle.

(9) Upon return to the recording position, this difference frequency was observed, and then individual readings from A31E and B31W were taken.

(10) Next, with only B31W being recorded, the cable for A31E was disconnected and the cable extending to station 30 was connected to the recorder input. The observer then drove to station 31; picked up the A sensor, its power supply, and its coupler; and then carried this ensemble (always under power) to the station 30 area. Here the power supply-coupler system was set up some 25 m south of the station, the signal cable was connected, and the A sensor was set into the west cradle of the "Y" staff at the station.

(11) The quality of the signal from sensor A was scanned for acceptability and several readings from A30W were recorded. The difference frequency for A30W-B31W was recorded for some 10 data sets, the individual sensor frequencies were recorded, then another 10-set recording of the difference, and finally 2 sets of A30W and B31W. With signal from B31W being recorded, the cable to station 30 was disconnected and the cable to station A31E was connected to the recorder.

(12) After driving to station 30, the A-sensor group was picked up and transported quickly to station 31 where the A sensor was set into the east cradle and the power supply-coupler unit returned to its original position.

(13) Back at the recording position, the A31E, A31E-B31W, A31E, B31W, A31E-B31W sequence was then recorded, after which the observer went back to station 31, switched sensors in the cradles and returned to the recording position to record the sequence: A31W-B31W, A31W, B31E, A31W-B31E.

(14) Computations of initial sums and differences were made; and, if a reasonable check were obtained, the recording equipment was shut off and the generator and battery charger were carried to the station 31 area.

(15) Sensors were disconnected from 30 v-dc power and switched to 24 v-dc standby power. The 30 v-dc power systems were put on charge, and the task of hand pickup of cables was begun. After all cables were picked up and the recording equipment loaded; the observer drove to station 30, extracted the "Y" from the cylinder, recapped the cylinder, and drove to station 32 where the "Y" was placed in the cylinder at that location. Cables were then laid (see fig. 5) for running the station 31,32 differences. The 24 v-dc standby power supplies were recharged during recording. Both battery sets were checked and charged every evening.

With a one-man field crew, it took approximately 5 hours to run the full 3-station sequence. When stations had to be reached by walking, production was halved and instrumental-drift effects became so pronounced that on almost every walked out sequence of the geopiezomagnetic study the procedure had to be repeated until confirming results were achieved.

4. TRAVERSE DATA COMPUTATION

Two rubidium magnetometers in the same magnetic field will not necessarily produce the same Larmor frequency. Large horizontal magnetic field gradients (particularly in lava-covered areas) can exist. Thus, it is unlikely that observed differences in Larmor frequency between two sensors will be equal when they are exchanged in the west and east cradles of the "Y" staff. The separation of the observed frequency difference into its instrumental and positional components is the function of the initial and expanded sum and difference procedures developed in the sections which follow.

Consider two magnetometer sensors, A and B, initially positioned respectively in the west and east cradles of a "Y" staff at station 32. Assuming that the magnetic field is 25 gammas greater at the west position than at the east position (let its value there be H) and assuming that the A sensor intrinsically produces readings that are 10 gammas more than those produced by the B sensor; then the reading from sensors at A32W and B32E, converted to gammas, would be

$$A32W = 10 + (25 + H) \text{ and } B32 = H;$$

giving a difference, D1, of

$$D1 - A32W - B32E = 35.$$

After the sensors are interchanged in the cradles,

$$A32E = 10 + H, \text{ and } B32W = 25 + H,$$

and the difference, D2, would be

$$D2 = A32E - B32W = -15.$$

The sum of D1 and D2 equals twice the instrumental effect (A-B), and their difference, D1 - D2, equals twice the west-east positional effect (W-E).

In more general terms,

$$A32W - B32E + (A-B) + (W-E) = D1, \tag{2}$$

$$A32E - B32W = (A-B) - (W-E) = D2, \tag{3}$$

and

$$A-B = (D1 + D2)/2, \tag{4}$$

$$W-E = (D1 - D2)/2. \tag{5}$$

If there is no differential instrumental drift, then the simple sum and difference method will give the correct instrumental and positional differences.

The decision to move to a new station pair was based on the comparison obtained between the computed (W-E) difference from data taken at the beginning of the run to the computed (W-E) difference from data observed at the end of the run. If the checks proved unsatisfactory, this station pair was rerun while the cable and instrument setup was still intact. When the differential drift curve is almost linear, the (W-E) check procedure is sufficiently valid. Near the beginning of a data run at times T_1 and T_2,

$$D1 = (A-B) + (W-E),$$

and

$$D2 = (A-B) + (W-E);$$

thus,

$$(W-E)_{1,2} = \frac{D1-D2}{2} - \frac{(A-B)_1 - (A-B)_2}{2}, \tag{6}$$

and near the end of the run at times T_3 and T_4,

$$(W-E)_{3,4} = \frac{D3-D4}{2} \quad \frac{(A-B)_3 - (A-B)_4}{2} \tag{7}$$

If the drifts were linear and the time differences, (T_1-T_2) and $(T_3- T_4)$, were almost the same; then the second terms on the right side of the last two equations would be small, (D1-D2) would approximately equal (D3-D4), and a fairly good check should be obtained between the calculated initial and final (W-E) values.

Final computations of station differences by use of an expanded sum and difference procedure are made graphically. When applied to test cases, the expanded sum and difference procedure has produced set of results that agree to within 0.02 gamma. In the expanded sum and difference procedure, it is assumed that the magnetic field is coherent between adjacent station pairs of the traverse and that the differential-drift curve is representable by a polynomial of low degree. If the estimated sample standard deviations of difference data over a time span of several minutes exceeds 2 counts and if the magnetic field appears to be stormy (activity of the field can be judged by looking at results obtained from the B sensor whose output is continuously recorded as the A sensor is moved), field work should then be suspended temporarily. Differential drift curves after an initial warm-up time of one hour or after about 1/2 hour following a data jump appear to be sufficiently smooth to allow their representation by second and third degree polynomials.

The following example is representative of a case where results of the initial sum and difference procedure would be misleading. In the sample problem: the differential drift is such that the initial and final values are nearly the same, the drift curve is almost parabolic with its largest values occurring near the center of entire interval, and the total magnetic field has decreased approximately 10 gammas during the course of data acquisition. Simulated field data are given below.

Station Difference	Average Time	Reading in Cycles/10 Sec	*Reference Letter
A3W - B3E	9:02:50	353	a
A3W - B3E	9:06:50	356	b
A3E - B3W	9:11:50	79	c
A3E - B3W	9:15:50	81	d
A4W - B3W	9:29:50	18,892	e
A4W - B3W	9:32:20	18,892	f
A3E - B3W	9:43:50	83	g
A3E - B3W	9:47:50	81	h
A3W - B3E	9:53:20	358	i
A3W - B3E	9:57:50	354	j

* These reference letters are keyed to the upper plot on figure 6.

The graphical computation procedure begins by blocking out data from the printer record and plotting these values, upper curves in figure 6. A form contouring method is then used to extend the curve sketched between a and b to the right and to extend the curve sketched between c and d to the left. Next, values of the two extrapolated curves are read at the b,d midpoint and their difference computed; in the example, 357.7 - 77.4 gives 280.3. The same process is repeated for the g through j region; the difference value there is 281.1. The two differences (280.3 and 281.1) are added and their sum divided by 4 giving a quotient (140.4) which, rounded to the nearest integer, represents the best value of the positional difference. The rounded quotinet (140) is then subtracted from the AW-BE readings (a, b, i, j) and added to the AE-BW readings (c, d, g, h) producing a new set of 8 points that are plotted (lower curve on figure 6) and connected by a smooth curve. The value of (A-B), the instrumental difference, at the A4W-B3W mean time is read from the differential drift curve (225 in the example) and then it is subtracted from the mean of the A4W-B3W readings (e and f). In this sample problem, error by the expanded procedure is +1 count per 10 sec but with the initial sum and difference calculation the error is +6 or approximately 0.12 gammas.

Shown in figure 7 is the result of application of the expanded sum and difference procedure to one set of high-precision traverse data obtained in a geopiezomagnetic experiment. The positive slope between 18:29 and 18:32 in the A19W-B18W data (station separation 2000 ft) is reflected in the shape of

the differential drift curve. When the indicated instrumental drift corrections (-117 and -118) are applied to the individual sets of station-difference values (2420 and 2421) the corrected differences (2303) are the same.

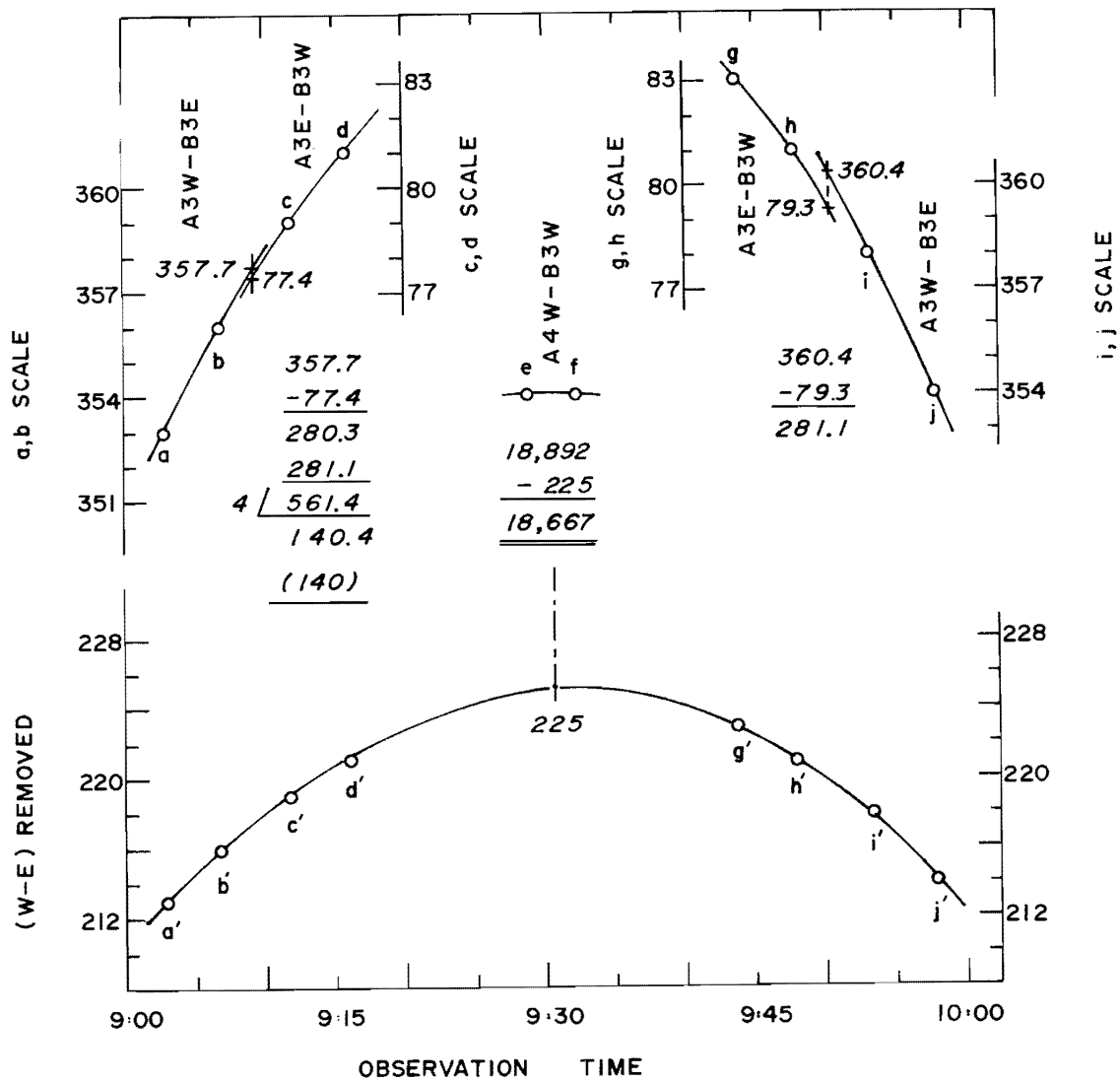

Figure 6. Plot of sample-problem data (upper curves) and resulting differential drift curve (lower plot). Vertical scales are in cycles per 10 sec. See text for explanation.

5. CONCLUSIONS

It is possible to obtain 0.1-gamma instrumental accuracy in magnetic traversing by use of a high-precision profiling method in which a sum and difference computational scheme is applied to data taken with a pier-differencing technique. The procedure has been applied in a geopiezomagnetic study requiring high precision measurement of differences in total magnetic field between stations deployed at

separations of 1/2 km along profiles that traversed across rocks of widely varying magnetization. By testing for quality of data as they are taken and repeating observations where required, it is possible to leave the field site with some assurance that the accepted data are instrumentally correct.

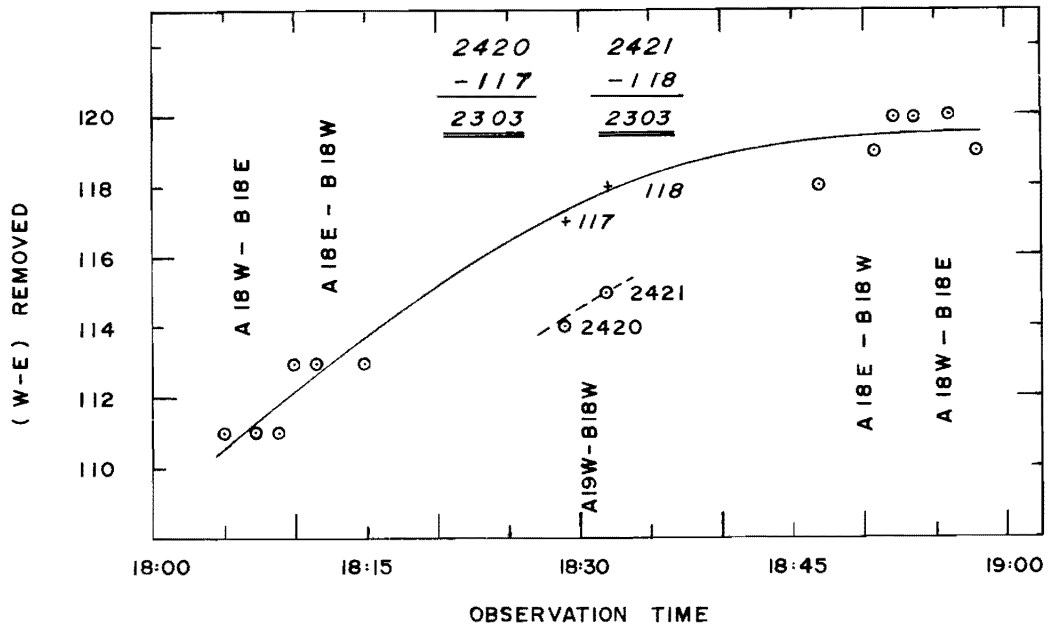

Figure 7. Differential drift curve from field results obtained at stations 18 and 19. Differential drift corrections, -117 and -118 cycles per 10 sec, when applied to observed station-differences values, 2420 and 2421, give a station difference of 2303, or 49.28 gammas.

However, measurement to high precision does not necessarily imply high accuracy has been obtained. On several replication tests, differences to a tenth-gamma accuracy have been observed between stations reoccupied on a daily or on a morning-to-evening basis, but this degree of accuracy was not obtained between sets of readings taken after several months had elapsed. Either the land surface had been altered (in the field area of the geopiezomagnetic experiments the predominant rocks are highly magnetic volcanics), or the very long period telluric current system had been changed, or the detection of a long-term geopiezomagnetic anomaly had indeed been accomplished.

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7. REFERENCES

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