A Portable Three-Component Magnetic Variometer**

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(Received April 10, 1967)

Abstract

A three-component recording magnetic variometer has been designed and constructed for field use. It can be built in a research instrument shop at low enough cost so that simultaneous recording over an array of twenty or more instruments is possible on a moderate research budget. The design is classical, the angular positions of three magnets suspended on torsion wires being recorded photographically at ten second intervals. The resolution is better than one gamma and variations of period greater than one minute are well recorded. The variometer records unattended for three weeks on power from modest batteries. A cardinal point of the design is the construction of the instrument in a long narrow tubular case of aluminum. In use it stands vertically in a hole drilled in soil so that the suspended magnets are efficiently thermostatted. In addition, first-order thermal compensation is provided. Tests of the prototype and of eight similar variometers have shown no detectable interaction between the suspended magnets, no measurable effect of temperature changes of the air above the ground, and acceptable rates of drift, and have established that the variometer is a reliable and effective instrument for field study of local conductivity anomalies.

1. Introduction

The mapping of local magnetic-variation anomalies with a dense array of fifteen or twenty portable variometers may lead to real advances, by making it possible to separate the internal from the external field without unduly restrictive assumptions. The work of Siebert and Kertz (1957) in north Germany, for example, suggests what might be done quantitatively with a close network of observing stations. In hopes of assembling such an array at a practicable cost, we have designed a portable three-component variometer that can be built in a research instrument shop at a cost of \$ 1500 or less for materials and labor. Our experience with several of these instruments built so far shows that they are practical to install and maintain in the field, and have resolution and stability that compare well with those of common observatory variometers.

2. General Description of the Variometer

In its main principles, the design of this instrument is classical: three magnets suspended on taut torsion wires rotate through small angles in response to variations in the three

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** Contribution No. 43 of the Geosciences Division, Graduate Research Center of the Southwest, Dallas, Texas.

field components Z , H , and D ; the rotations are magnified by optical levers and are recorded as displacements of images on a film strip. Much of the cost of instruments with suspended magnets is likely to come from the care that must be taken to eliminate the effects

Fig. 1 Schematic diagram of variometer, not to scale.

sense of the arrows shown, are balanced by torsion in the wires. A positive H or Z variation, representing a small increase in the northward or downward component of the earth's field, will turn the H or Z magnet in the sense of the arrow through an angle θ , to a new position where the added magnetic torque, proportional to the added field and to $\cos\theta$, is balanced by the added torsion, proportional to θ . The D magnet is aligned with the main horizontal field; in the absence of an east-west variation field D , there is no torsion in the wire and no magnetic torque about the suspension axis. A D variation representing a small added westward field, will turn the magnet through an angle θ to a position where the added torque is balanced by steady magnetic torque proportional to $\sin\theta$ and by torsion proportional to θ . The response of all three magnets is thus effectively linear for small θ , such that $\cos\theta \cong 1$ and $\sin\theta \cong \theta$.

The H and D magnets produce detectable steady torques on one another, but their deflections interact only in the second order, since a rotation of one magnet through small θ will only change the torque on the other proportionally to $(1 - \cos\theta) \approx \theta^2/2$. The distance between adjacent magnets is 0.5 m. in our variometer; at this separation the steady field at one magnet from another is about 60γ , and deflection of one by a 100γ variation produces a change of less than $10^{-2}\gamma$ in the field at the other.

Fig. 1(a) also shows a pair of fixed auxiliary magnets flanking each suspension wire,

of temperature changes on the magnets and torsion wires. The new instrument is designed to fit in a long tube, and is operated in a hole in the ground with the temperature-sensitive parts at depths of 1.5 metres or more, where the temperature will not vary more than 0.1°C during periods of weeks. First-order temperature compensation is provided in the suspension systems themselves, so that changes of 0.1°C if they do occur will not produce significant errors.

The arrangements and orientations of the suspended magnets are shown schematically by Figure 1. In Fig. 1(a), the Z and H magnets are viewed end-on, looking horizontally toward magnetic east. The steady magnetic torques about the suspension axes of these two magnets, tending to turn them in the

oriented so as to reduce the steady vertical field at the Z magnet and to reduce the steady horizontal field at the H and D magnets. The auxiliary magnets are made of the same material (Alnico V) as the suspended magnets, and will provide first-order compensation for the changes with temperature of the moments of the H and Z magnets if they are adjusted at some temperature to cancel half the relevant component of the earth's main field at the suspended magnet. The steady magnetic torque on the suspended magnet at another temperature is then proportional to $(J_0 + \Delta J) \left[H_0 - \frac{H_0}{2} \left(1 + \frac{\Delta J}{J_0} \right) \right]$, H being the main field component and J the intensity of magnetization of the material used in the magnets. This expression is equal to $\frac{J_0 H_0}{2} \left[1 - \left(\frac{\Delta J}{J_0} \right)^2 \right]$, and depends only in the second order on changes of moment with temperature. The adjustment is made by moving the auxiliary magnets along slots, so changing their distances from the suspended magnet. The suspension wires are made of Iso-Elastic alloy, whose modulus of rigidity has temperature coefficient much smaller than that of J . The zero positions of the H and Z magnets might thus be made virtually independent of temperature by very careful adjustment of the auxiliary magnets, as is done with some observatory instruments that use this scheme of compensation (Chapman & Bartels 1940, p. 87). For a portable variometer, though, it is simpler to make approximate preset adjustments and to thermostat the suspensions well in a two-meter hole, than to make the optimum adjustment for the field components at every site where the variometer is to be used.

The D magnet does not need temperature compensation for its zero position, which is determined by the direction of the main field. Here the auxiliary magnets are provided only to increase the sensitivity of the movement by reducing the magnetic restoring torque as much as may be wanted. In all three movements there remains a temperature coefficient of sensitivity proportional to $\frac{\Delta J}{J_0}$; it amounts to less than $10^{-3}/^{\circ}\text{C}$ with Alnico magnets, and will be insignificant in a thermostatted instrument.

Following Blackett (1952) and using a demagnetization curve published by the makers of the magnets, we have calculated a maximum theoretical moment of 138 gauss cm.³ for a sintered Alnico 5 magnet $18 \times 3 \times 3$ mm. (the size used). As the measured moments are about 80 gauss cm.³ it is clear that the magnets have been considerably demagnetized, in the manufacturing process, from maximum remanence following saturation. They have been assumed, therefore, to be stable and have not been demagnetized further.

The optical system that translates small rotations of the magnets into displacements of images on a film is also outlined in Figs. 1(a), (b), and (c). The suspensions are mounted on plates attached to a rigid frame and carrying mirrors ($M3$ to $M6$) which reflect vertical rays from the lens above onto polished and aluminized faces of the magnets. These rays come from a line filament lying north-south in the upper focal plane of the lens, so that all three magnets are illuminated by parallel light. Images of the filament are formed in the focal plane by light reflected back through the lens from each magnet face and from two fixed mirrors $M1$ and $M2$. The five images are adjusted to lie side-by-side across an east-west camera slit directly below the recording film in the focal plane. The reflection from a magnet or re-

ference mirror will thus produce a rectangular spot of light, bounded by the edges of the slit and the sides of the image. Rotation of a magnet through a small angle θ , positive in the sense of the arrows, will displace the corresponding image a distance $f\theta$ to the eastward (f being the focal length of the lens) regardless of the distance of the magnet from the lens, except in the case of the Z magnet, whose image is displaced by $2f\theta$ because of the second reflection from the magnet face by way of the mirror $M6$. This mirror is introduced both to double the sensitivity of the Z system and to allow adjustment of the image without moving the magnet or the suspension.

So far, no part of the instrument has been mentioned that is of more recent conception than Iso-Elastic alloy (Sayre and de Forest 1936). More modern elements are used to give good timekeeping and unattended operation for long periods with small and lightweight batteries. One is a fork-controlled electric watch (Accutron) with periodic contact closures. The other is a solid-state switching circuit, shown in Fig. 2, which carries out the following sequence of operations: At ten second intervals when the Accutron contact closes, the lamp is turned on for a predetermined exposure time and then is turned off. After a delay to allow

Fig. 2 Variometer switching circuit, actuated at 10-second intervals by contact closure in an Accutron process timer. 100k variable resistor between transistors 1 and 2 controls exposure time. Switch between transistors 3 and 4 is normally open; when closed it keeps lamp on for adjustments of torsion heads. Transistor 8 and relay operate time marking coils.

the filament to cool, a solenoid-and-ratchet mechanism is actuated to advance the film southward by a discrete step of about two slit widths. The field of the solenoid disturbs the suspended magnets appreciably when the film is advancing, but since the magnets are nearly critically damped by copper plates and have a free period of about one second, an interval of six seconds between exposures reduces the initial deflection by a factor of order 10^{12} . These unrecorded periodic deflections of the magnets probably do more good than harm to the accuracy of the whole system, since each recorded spot represents a freshly-attained equilibrium position of the magnet. With one 6 volt 80 ampere-hour car battery and one 12 volt lantern dry battery the variometer runs for about 25 days unattended, apart from visits

to place time marks on the record with a magnet. In this time 43 metres of film are exposed; the camera accepts reels which take this length of 35mm. film whose base is Estar 0.10mm. thick.

3. Some Essential Features of the Design

After the above overall view of the variometer, we may consider some details of design and construction that directly affect its accuracy, in the two senses of stability and resolution. Once temperature effects are brought under control, the most important remaining sources of error are possible changes of zero positions resulting from small tilts of the instrument or from actual shifts of grip in the wire mountings, and drift of the zeroes resulting from relaxation of stresses in the wires. The mounting of the wires and magnets is designed to make these effects harmlessly small, through careful balancing of the magnets in aluminum mounting rings and through defining the ends of the suspensions by bending the wire about a small radius. Fig. 3 shows cutaway views of a ring and of an end clamp. At its ends, the wire, whose diameter is 0.05 mm., is bent through 90° around the slightly rounded lip of a hole 1.0 mm. in diameter, offset so that the wire will lie on the centerline of the mount, and then clamped under a screwhead. The magnet is held by a nylon set-screw in its aluminum ring, through which the wire is threaded as shown, entering a 0.35 mm. hole on each side with a 45° bend. The position of each magnet in its ring, and the length of its set-screw, are adjusted in a dummy suspension to make the zero positions of H and D insensitive to small tilts in a magnetic field representative of the region where the variometer will be used. This means that the center of mass of the D movement must be somewhat south of the wire axis, and that of the H movement somewhat west of the axis (Bobrov 1962). The center of mass of the Z movement should be at the same height as the wire axis, to avoid either instability or gravitational restoring torque that would lower the sensitivity. The steady magnetic torque on the Z magnet may be partly balanced by gravity, if desired, by setting the center of mass somewhat to the west of the axis.

The Iso-Elastic wire used for the suspensions has a high elastic limit and excellent creep and hysteresis properties. To minimize creep we have avoided all needless stressing of the wire. In the first place, the sizes of the magnets and wire have been chosen to obtain a useful sensitivity without approaching the yield point of the wire. With a wire of radius r and a magnet of given mass and moment, the sensitivity will vary as r^{-4} , the limiting shear stress in

Fig. 3 Cutaway view of a ring and end-clamp of a suspension. The magnet is held by a set screw in the deleted half of the ring.

torsion as r^{-3} , and the tensile stress as r^{-2} , so the fixing of a maximum allowable stress and length of suspension sets upper limits to the size of the wire and magnet for a specified sensitivity. Iso-Elastic wire can safely be used at working shear stress 4×10^9 dyne/cm² (Sayre and de Forest 1936). Of the three suspensions in our variometer the Z component suspension is the most highly stressed in shear at high latitudes, and in tension everywhere. With suspension 13 cm. long of diameter 0.05 mm., and a magnet of mass 1.3 gm. and moment 80 gauss cm³, the limiting shear stress at the wire surface is 0.8×10^9 dyne/cm². if a vertical component of 0.5 oe. is halved by the temperature compensating magnets. The tensile stress will be 10^9 dyne/cm². if a sag of 2° is allowed in the wire. With the optical system shown in Fig. 1(c), which provides two reflections at the magnet surface, this system gives sensitivity close to 2×10^{-4} radian/gamma in all our variometers so far constructed.

The wire is installed carefully in the following way, to escape needles bends or torsion. It is loosely threaded through the ring first, and tautened to form the bends where it leaves the ring. Next it is threaded through the vertically aligned end-pieces and the upper end is clamped in the fixed end-piece with the magnet roughly in position. A weight is now hung on the lower end to form the upper bend, and the upper end-piece is turned to make the magnet lie in line with the earth's horizontal field when the weight is not spinning. The wire is then free of torsion, and the lower end is clamped in its end-piece, whose spring mounting controls the tension. The frame is next placed in its working position and the magnet is rotated to its working orientation by roughly equal turning of the two suspension ends. Last, the ends may be moved in or out to center the magnet and to set the tension. Gears and control rods are provided so that the torsion can be adjusted for changes in the ambient field by turning one end-piece from the top of the variometer; stops prevent the magnets from turning more than a few degrees. If the rods are turned only in the direction and amount needed to bring the magnets off the stops and into position at a new site, the suspensions will then have the quietest possible history of stress changes. All these measures seem to have been successful in allowing all the movements we have built to stabilize with a negligible rate of drift after one or two days in a new place. In field operation we set each instrument in place and set the reflected images on the camera slit, but do not start the camera drive. When all the variometers of the array have been set up, we return and start the cameras after resetting the torsion heads. This procedure stabilizes the suspensions and secures simultaneous recording by all instruments for a maximum length of time.

Given stable suspensions of specified angular sensitivity, the resolution with which magnetic variations may be recorded is limited by the clarity of the images produced on the film. With an angular sensitivity of 10^{-4} radians/gamma and a lens of 500 mm. focal length, the displacement of the images is about 0.05 mm./gamma, so that a variation of amplitude 250γ will range over half the 25 mm. space between sprocket holes on 35 mm. film. To resolve 1 gamma, the east-west distance between a magnet spot and a reference spot must be determined to 0.05 mm. This may be done if each spot is clear and symmetrical and not more than 0.25 mm. wide, supposing that it is practicable to locate the center of a well-defined spot within a tenth of the spot-width either by eye or with a suitable split photocell,

with the aid of optical magnification as desired. Since the filament, which is imaged at unit magnification, is less than 0.1 mm. in diameter, the optical requirements are not severe. We have obtained satisfactory images about 0.2 mm. wide using crudely-figured magnet faces, inexpensive mirrors, and a simple uncorrected lens, through several artifices. The chromatic aberrations of the lens are made harmless by admitting only filtered green light to the camera (Kodak Wratten gelatin filter number 58). The depth of field is made large enough to bring all the images to an acceptable focus in the same plane by stopping the aperture used by each magnet down to about $f/100$ with black tape masks near the magnets, so that a little curvature in the mirrors or magnet faces is made harmless. These measures all gain definition at the expense of intensity, requiring longer exposures and greater battery drain for the lamp as the light is more sharply filtered and apertures are reduced. More refined optics might be economical in the long run, but here we emphasize that very simple optics can give useful resolution.

An error of 1° in orienting or levelling the variometer will cause the record of one variation field component to include about 2 percent of another component. The contamination may be serious if, say, the instrument is 0.5° off level while recording a variation for which the horizontal field is ten times the vertical, so that ten percent of the recorded Z amplitude might be spurious. The suspension mountings must accordingly be orthogonally located in a rigid frame, and the whole instrument in its case must be held level in its hole within 0.1° . So far we have found that packing the case in the hole with soil and stones provides stable levelling for several weeks at least, but special precautions may be needed for some soils and climates.

The effectiveness of the ground in thermostating the Z and H movements will depend to some degree on how the variometer is mounted in the hole. In a half-space of diffusivity κ , subjected to a surface temperature variation $T_0 \sin \omega t$, the amplitude of the variations at depth is given by $T_0 \exp\{-z\sqrt{\omega/2\kappa}\}$, so that a weekly variation of 30°C at the surface would produce a variation smaller than 0.1°C at a depth of 1.5 meters in soil whose $\kappa = 0.01 \text{ cm}^2/\text{sec}$ (a high value), while the effects of a 30° daily variation would be scarcely detectable. The presence of a metal tube will not seriously change this result if the tube is in reasonably good thermal contact with the soil, since with an aluminum tube such as we are using (17 cm. diameter, 2 metres length, 3 mm wall) the relaxation time for 90 percent of an axial disturbance to dissipate into the soil is several times shorter than the longitudinal relaxation time of the tube (see Bullard, 1954). The goodness of thermal contact should not be taken for granted, though, and it is wise to pack the hole around the tube with fine soil and to bury the top of the case about 30 cm. below ground level under an insulating hat.

The Accutron watch that controls the exposures and the film stepping has a nominal accuracy of about one minute per month, sufficient for most, but not all, geomagnetic studies. Separate time marks may be placed on the film by displacing the images with a magnet outside the instrument case. Since the film advance makes an audible click, the time may be recorded on the film within a second or so (the duration of an exposure) whenever the instrument is visited. If made with a stabilized and calibrated bar magnet located

in a jig on the variometer lid, the time marks may also be made to serve as calibrations of the movements. If the temperature of the magnet is noted, its moment can be known to a few parts in a thousand, as can the cube of its central distance from each suspended magnet, so each movement may be repeatedly standardized in the field with an accuracy better than one percent. Small coils mounted near the movements are energized by one-hour and twenty-four-hour contacts on the Accutron to give internal time-marks and rough sensitivity checks.

When all these matters affecting accuracy are dealt with in the ways we have described, there still remain many free choices in designing the final form of the instrument. The low cost of the instruments we have built comes about because the fundamental design calls for few delicate or critical machining processes and only one bought component, the Accutron, which is necessarily expensive in itself. Many straightforward designs could achieve a similar low cost, and we need not describe more details of our instrument fully. Table 1, however, lists some design parameters and components, while Figs. 4 & 5 give a general view of the complete variometer and closer views of the Z and H suspensions and camera drive. Three other points are worth mentioning.

Table I: Design elements

Suspension wire:	.002" (0.05 mm.) diam. Iso-Elastic alloy
Suspended magnets:	$18 \times 3 \times 3$ mm., Alnico V. $M \approx 80$ gauss-cm. ³
Auxiliary magnets:	$\begin{matrix} D \\ H \end{matrix} \} 12 \times 1.5 \times 1.5$ mm., Alnico V. $M \approx 14$ gauss-cm. ³ $Z - 6 \times 1.5 \times 1.5$ mm., Alnico V. $M \approx 7$ gauss-cm. ³
Suspension Length (end to end):	D & H, 19 cm., Z, 13 cm.
Distance of magnet below lens:	D, 7 cm.; H, 57 cm.; Z, 108 cm.
Typical displacement sensitivity:	D, 0.05 mm./ γ ; H, 0.10 mm./ γ ; Z, 0.12 mm./ γ .
Lens:	plano-convex, $f = 483$ mm., diam. = 89 mm.
Lamp:	straight filament, < 0.1 mm. diam., 1.6 cm. long; operates at ~ 4.5 V, 0.6 amp.; rated 6.0 V., 0.8 amp.
Slit:	0.1 mm. wide, reduced negative photo on glass plate of black line on white card.
Film advance:	0.2 mm. step every 10 sec., equivalent to 1.7 m./day.
Exposure:	0.7–2.5 sec. every ten sec.
Power drain:	lamp: 2.2 amp.-hours per day at 6 V at 1.5 sec. exposure circuitry: 0.03 amp.-hours per day at 6 V. solenoid: 1.0 amp.-hours per day at 18 V.
Batteries:	6 V lead-acid automobile battery. ~ 100 AH 12 V lantern cell (NEDA 922).
Outside dimensions of tube:	lower section: 17×155 cm. upper section: 22×36 cm.
Accutron timer:	Bulova Watch Co. TE-11-16, contact closures, 10 sec., 1 hr., 24 hr.

Driving the camera with a solenoid and ratchet instead of a motor has three main advantages: the power consumption is much less, there is no problem of brushes wearing, and the film is advanced by precise increments at precise intervals. The ratchet wheel is geared positively to the sprocket in the camera and through a cork-disc clutch to the takeup reel, to wind the film under controlled tension. Once adjusted properly, this sort of mecha-

Fig. 4 Complete variometer and its case. At the top are the camera, lamphouse and switching circuits. Equally spaced down the frame are the D, H and Z suspensions. The case is 2 m long.

nism is usually very reliable. The camera slides on to two metal pillars and is removed for film change.

The copper damping plates around each magnet provide some protection from shock, but not enough to prevent wires breaking when the instruments are trucked over rough roads. We have introduced clamps on the damping plates to hold the magnets against their stops for transport. In order to find out which way to turn the torsion control rods at a new site, we orient each instrument outside of its tube before installing it; hence we have not provided for unclamping the magnets while the variometer is in the tube.

A more or less constant feature of the power spectrum of geomagnetic variations is a decrease of power density by two orders of magnitude as the period falls from about 30 to 12 seconds (Herron, 1967). A sampling interval of 10 seconds (available with standard Accutrons) will thus give reliable records of events whose period is greater than one or two minutes, with no important errors due to aliasing. With a slit width of 0.1 mm. and a film advance of 0.2 mm. every ten seconds, 1.7 meters per day of record are produced. A sample, printed from 35 mm. film, is shown in Fig. 6.

4. Test Runs

The first variometer built to this design was tested by operating it for nine days in a 2-meter hole in a field about 1 km. from the Dallas Magnetic Ob-

servatory. Seven variometers built later were tested for several days in the same place. All comparisons of their records with those from the observatory show that the variometers were indeed recording three properly separated components of magnetic variations with no significant contamination from temperature effects or other sources. Fig. 7 gives comparisons of records from the prototype variometer, transcribed with suitably contracted time scale, with observatory records, showing the correspondence both for a short event and for hourly values over several days. The drifts of 2 or 3γ /day shown in Fig. 7b appear to be linear, or at least smooth, and are somewhat larger than those we have observed since in well-settled instruments. Surface temperature at the variometer site during these days varied from -5°C to $+23^{\circ}\text{C}$ with snow, rain, and warm sun, without disturbing the records of the variometer. Direct tests on one instrument in a room with varying temperature have shown, in fact, that the first-order temperature compensation reduces the tem-

(a)

(b)

(c)

Fig. 5 Detail of parts of variometer (a) Z suspension (b) H suspension (c) top assembly with switching circuit swung aside to show camera (black box), camera drive solenoid (on top of lamphouse) and gears.

Variometer C ; Baker, Montana

Fig. 6 Print of 42-minute section of a variometer record, with explanatory key.

perature offsets to at most 3 or $4\gamma/^{\circ}\text{C}$, so that temperature variations of 0.1°C should be barely detectable.

Typical displacement sensitivities on the film are: $D=0.05\text{ mm}/\gamma$ in a horizontal field of 0.245 oe. ; $H=0.10\text{ mm}/\gamma$; $Z=0.12\text{ mm}/\gamma$. The definition of the images is such that it is easy to resolve less than 1γ by direct measurement of distance on a good image of the film with a magnification of 15 (see Fig. 6).

5. Development Programme

The flow of data from an array of twenty variometers, and the precision required, will

Fig. 7 (a) Comparison of time-contracted transcription of record of a bay given by the new variometer (upper trace) with record from Dallas Magnetic Observatory.

Fig. 7 (b) Smooth curves joining hourly values through four days from the new variometer (lower trace) and from the records of Dallas Magnetic Observatory.

demand a high-speed read-out machine to convert the analogue data to digital form and to record them with an incremental tape recorder in format compatible with the computer.

Such a read-out machine is being designed and a prototype will be constructed shortly. It is our intention to convert to digital form only those parts of a record, selected by scanning it, which contain variation events useful for investigating conductivity anomalies in the upper mantle and crust.

At the time of writing there are eight variometers at the Graduate Research Center, Dallas, Texas, and fourteen are under construction there. Another twenty-two are being constructed at the University of Alberta. During 1967 we hope to make experimental studies with arrays of twenty or more variometers recording simultaneously.

Acknowledgements

A great part of the success of this variometer must be attributed to the skill of Mr. John A. Keiller in the detailed design of many parts. The mechanical parts were made in the machine shop of the Geoscience Division, Graduate Research Center of the Southwest, by Mr. Keiller, Brian M. Bernhardt and Romee A. Bianchi. Mr. D. Lee Bacon designed the switching circuit. We have profited from many discussions with colleagues, especially Anton L. Hales and John W. Graham. The work was supported by U.S. National Science Foundation grant number GP-4650.

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