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THE ADJUSTMENT AND USE OF THE PROTON VECTOR MAGNETOMETER

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SUMMARY

The proton-precession magnetometer accurately measures the magnitude of the magnetic field at its sensor; that is, it measures the absolute scalar magnetic total intensity (F). If bias fields of known magnitude and direction are added vectorially to F and the resultant field is measured, vector components of F may be calculated. The 'proton vector magnetometer' (PVM) is an instrument which enables this to be done.

The Elsec proton vector magnetometer (PVM) Type 5920 provides bias fields by means of Helmholtz coils for cancelling the vertical intensity (Z) to leave the horizontal intensity (H) vector, and for cancelling H to leave the Z vector. It therefore provides an absolute geomagnetic standard for measuring H and Z.

Formulas are derived expressing the errors resulting from improper adjustment of the PVM, as functions of the magnitudes of the field components. The most critical adjustment is the horizontality of the PVM base; all other adjustments are not critical and some of the induced errors may be eliminated by appropriate observing techniques. In the extreme cases at BMR observatories the tolerances allowable are: 2 seconds of arc for the base level, 15 minutes of arc for alignment in the magnetic meridian and for the directions of the coil axes, and 1 mA for the biasing current.

It is not necessary to know with any great accuracy the direction of the magnetic meridian, the constants of the Helmholtz coils, or the magnitudes of the bias currents. It is necessary that the PVM coils maintain directional stability during rotation, that the coil base is firm and can be accurately levelled, and that levels and bias currents remain within tolerance for at least 30 minutes at a time. It is desirable that the proton magnetometer be of the direct-reading type and have a resolution of 0.1 nT.

1. INTRODUCTION

The possibility of using the proton precession magnetometer (PPM) to provide an accurate, absolute standard for the measurement of vector field components was mooted soon after the introduction of practical PPMs. In particular, Nelson (1958) proposed the construction of a 'Proton Vector Magnetometer' (PVM) designed to measure the components horizontal intensity (H) and vertical intensity (Z); subsequently several geomagnetic institutions have constructed PVMs along the lines proposed by Nelson.

A PVM was made by the Geophysical Branch of the Bureau of Mineral Resources, Geology & Geophysics (BMR) in the early 1960s, to the general design of Dr W.D. Parkinson. It proved to be a satisfactory instrument for Z measurements but was not a practical instrument for measuring H, mainly because of instability of the mechanical components. Therefore when the Littlemore Scientific and Engineering Company placed their commercially produced system (the Elsec Type 5920) on the market about 1970, BMR adopted it as the new observatory standard to replace semi-absolute quartz horizontal-force magnetometers and magnetometric zero balances. This new standard ought to eliminate the need for periodic calibration of local magnetometers against overseas ('International') standards, i.e. it ought to provide the 'Australian Magnetic Standard'.

For observatory purposes the PVM measurements need to be accurate to about 0.5 nT. Assuming that the PPM and coil system themselves are error-free, errors arise only from three mis-adjustments: non-horizontality of the base, mis-alignment of coil axes, and incorrect bias fields. In this Record error-formulas are derived for each mis-adjustment, and these are used to calculate allowable tolerances. Obviously, to keep the total error within 0.5 nT the errors at each stage should be less, and it will be shown that this can be easily achieved except in the levelling of the base.

The discussion refers specifically to the Elsec PVM Type 5920 and each source of error is examined individually and in an elementary way; second-order terms are excluded as they are negligible when the mis-adjustment is small. But, within these limitations, the results are true generally; Hurwitz & Nelson (1960) have presented comprehensive error-formulas which are completely general.

In the Appendix the discussion is extended by deriving the general solution for the resultant between a randomly directed bias-vector and the earth's field-vector, and then considering some particular cases of it; from the latter a proposal is made to simplify and improve the measurement of H and Z by a combination of the 'cancellation' and 'addition' methods.

2. PRINCIPLE OF THE PVM

Plate 1 shows the Elsec PVM type 5920, and complete details of it are given in the manufacturers' handbook. A PPM sensor is placed at the centre of two pairs of Helmholtz coils mounted on a base which can be rotated in the horizontal plane. One pair of coils has its axis vertical for cancelling Z, and the other pair has its axis horizontal, for cancelling H. The base is levelled by means of three footscrews and a sensitive spirit level, and the coils can be adjusted with respect to the base by footscrews. There are four cardinal positions on the base (0, 90, 180, 270) fixed by a dowel; a micrometer tangent screw allows for fine adjustment over a range of 10^{o} about these positions. The base is orientated initially so that the 0-180 line corresponds approximately with the magnetic meridian as indicated by a compass needle. The axis of the H-cancelling coil is placed in the magnetic meridian by adjusting the tangent screw until biased resultant fields on each side of the meridian become equal.

A constant-current source provides the bias currents in the coils. The required bias current is found by the method described below, and the resultant field is measured by the PPM. Providing the coil and current adjustments are kept within the tolerances derived in the next section, the resultants will be H or Z.

Plate 2A shows the vectors involved in the measurement of H and Z in a perfectly adjusted PVM. It is necessary to know to what accuracy the magnitude and directions of the bias fields Hc and Zc must be set in order to achieve the desired accuracy in the measured component. In deriving the error-formulas an approximation of this form is used frequently:

$$(x' - x) = (x'^2 - x^2)/2x \qquad \text{(i)}$$

as shown by the following:

Put $dx = x' - x$

Then

$$\begin{aligned} x'^2 - x^2 &= (x' - x)(x' + x) \\ &= dx\ (2x + dx) \\ &= 2x\ dx + (dx)^2 \end{aligned}$$

In all cases of interest, the ratio $2x\ dx/(dx)^2$ is greater than 4×10^5 and therefore $(dx)^2$ is negligible with respect to $2x\ dx$. Hence

$$x'^2 - x^2 = 2x\ (x' - x)$$

<u>Determination of the cancelling bias field</u>

As shown in Plate 2A, in the case of the H measurement, the resultant vector Fr is given by

$$Fr^2 = F^2 + Zc^2 - 2FZc \cos(90 - I) \qquad \text{(ii)}$$

$$= F^2 + Zc^2 - 2Zc\,(F \sin I)$$

$$= F^2 + Zc^2 - 2Zc\,.Z$$

$$= F^2 + Zc\,(Zc - 2Z) \qquad \text{(iii)}$$

Two particular cases of (iii) are of interest:

(a) Zc = 2Z: Fr has the same magnitude as F, and by inspection lies on the opposite side of H. When this condition is satisfied, or nearly so, Fr will be labelled F-.

(b) Zc = Z: then

$$Fr^2 = F^2 + Z(-Z)$$

$$= H^2$$

so this is the condition for measuring the horizontal intensity. When this condition is satisfied, or nearly so, Fr will be labelled Hr.

Condition (a) facilitates the establishment of the cancelling field: the bias current is varied until the PPM reading increases from a minimum to again equal F; then the current is halved (by a simple switch/resistor circuit) to meet condition (b).

The same reasoning applies in the measurement of Z, the corresponding equations being:

$$Fr^2 = F^2 + Hc^2 - 2FHc \cos I \qquad \text{(iv)}$$

$$= F^2 + Hc(Hc - 2H) \qquad \text{(v)}$$

3. ERRORS DUE TO MIS-ADJUSTMENTS OF THE PVM

The bias field

H measurement. In equation (ii) when Z - Zc is small, write Fr = Hr so that

$$Hr^2 = H^2 + (Z - Zc)^2$$

and by re-arranging and using (i), with dH = Hr - H,

$$Hr^2 - H^2 = 2HdH$$

i.e. $$2HdH = (Z - Zc)^2$$

or

$$(Z - Zc) = (2HdH)^{\frac{1}{2}} \qquad \text{(vi)}$$

This expresses the error in H due to an error in the bias field, but as the bias field is not determined directly, the allowable difference between the true and 'opposite' total intensities (condition (b) above) is required. In this situation we have:

$$F_-^2 = H^2 + (Z - 2Zc)^2$$

$$= H^2 + Z^2 + 4Zc(Zc - Z)$$

or

$$F^2 - F_-^2 = 4Zc(Z - Zc)$$

and from (i)

$$F - F_- = 2Z(Z - Z_c)/F$$

Inserting (vi)

$$F - F_- = 2Z(2HdH)^{\frac{1}{2}}/F \qquad \text{(vii)}$$

Although the experimental procedure obviates the need to measure the bias current at any stage, its stability and the accuracy of the halving circuit need to be known in terms of (vi). If the coil-constant is C, the current is i, and $dZc = Z - Zc$, then from (vi):

$$dZc = (2HdH)^{\frac{1}{2}}$$

hence

$$di = dZc/C$$

$$= (2HdH)^{\frac{1}{2}}/C \qquad \text{(viii)}$$

<u>Z measurement</u>. The analysis is the same as for H and the corresponding error formulas are:

$$H - Hc = (2ZdZ)^{\frac{1}{2}} \qquad \text{(ix)}$$

$$F - F_- = 2H\ (2ZdZ)^{\frac{1}{2}}/F \qquad \text{(x)}$$

$$di = (2ZdZ)^{\frac{1}{2}}/C \qquad \text{(xi)}$$

Table 1 shows the allowable errors in the bias fields and currents for errors of 0.1 nT in H and Z.

<u>The magnetic meridian setting</u>

Suppose that the H-cancelling coil is orientated so that its axis is at an angle d to the magnetic meridian. This mis-adjustment will not affect the measurement of H, but it will affect the measurement of Z. Plate 2B shows the vectors involved in the Z measurement and, clearly, rotation of the coils through 180° will not eliminate the error.

The bias field Hc (= H cos d) can be resolved into components Hcp parallel to H and Hcn normal to H.

$$Hcp = Hc \cos d$$

$$= H \cos^2 d$$

$$Hcn = Hc \sin d$$

$$= H \sin d \cos d$$

$$= (H \sin 2d)/2$$

For small angles (d less than 1°), sin 2d = 2 sin d within 2 parts in 10^4.

Hence

$$Hcn = H \sin d$$

Now the residual horizontal field in the magnetic meridian is

$$Hr = H - Hcp$$

$$= H (1 - \cos^2 d)$$

$$= H \sin^2 d$$

and combined with Z this produces a resultant 'total intensity' Fr given by

$$Fr^2 = Z^2 + H^2 \sin^4 d$$

Therefore the measured vertical intensity Zr is given by

$$Zr^2 = Fr^2 + Hcn^2$$

$$= Z^2 + H^2 \sin^4 d + H^2 \sin^2 d$$

or $$Zr^2 - Z^2 = H^2 (\sin^4 d + \sin^2 d) \qquad \text{(xii)}$$

For small angles the ratio $\sin^2 d/\sin^4 d$ is greater than 3×10^3 so the first term on the right hand side is negligible with respect to the second, and (xii) may be approximated by

$$Zr^2 - Z^2 = (H \sin d)^2$$

and after (i)

$$Zr - Z = (H \sin d)^2/2Z \qquad \text{(xiii)}$$

Table 1 shows allowable values of d for an error of 0.1 nT at the BMR observatories.

<u>The base level</u>

Assume that the axes of the H and Z-cancelling coils are parallel and perpendicular respectively to the plane of the base, and that the base, and therefore the coil axes, are tilted at an angle e. Now, if the base is rotated through 180°, the directions of the coil axes will not change so there will be constant errors (dH, dZ) in the vector measurements.

<u>H measurement</u>. Let the coil-axis be inclined southwards in the meridian plane at an angle e. We apply coil-current as before to make (F-) = F, and halve it, but in this case the vectors are as shown in Plate 3A(i), where:

$$H' = F \cos (I - e)$$

$$= (F \cos I) \cos e + (F \sin I) \sin e$$

$$= H \cos e + Z \sin e \qquad \text{(xiv)}$$

and the error in horizontal intensity is

$$dH = H' - H$$

$$= H (\cos e - 1) + Z \sin e$$

If the coil axis is inclined northwards, the vectors involved are shown in Plate 3A(ii); the vector measured is

$$H' = H \cos e - Z \sin e \qquad \text{(xv)}$$

and the error expression is

$$dH = H (\cos e - 1) - Z \sin e$$

Provided e is less than 5', the ratio of the coefficients (cos e - 1)/sin e is less than 7.3×10^{-4}; hence the first term is negligible compared with the second.

Therefore

$$dH = \pm Z \sin e \qquad \text{(xvi)}$$

Next assume that the coil axis is vertical in the meridian plane but is tilted in the prime-vertical plane (Plate

2C). The situation is analogous with that for an ex-meridian error in the Z measurement: the bias field Zc (= Z cos d) has components Zcp parallel and Zcn normal to Z, and following the same reasoning as in the discussion on the magnetic meridian setting, the error in H (dH) is given by

$$dH = (Z \sin e)^2/2H \qquad \text{(xvii)}$$

In all practical cases the ratio of (xvi) to (xvii) is greater than 3 x 10^3 and so the required accuracy for levelling the base is set by (xvi).

Z measurement. The vectors involved are shown in Plate 3B and the expressions for the resultants are

$$Z' = F \cos (90 \pm (I - e))$$

These reduce to

$$Z' = Z \cos e \mp H \sin e \qquad \text{(xviii)}$$

and the error in the measurement is

$$dZ = Z' - Z$$

$$= Z (\cos e - 1) \mp H \sin e$$

As before, the first term is negligible if e is less than 5', and can be ignored in practice. Therefore

$$dZ = \pm H \sin e \qquad \text{(xix)}$$

Table 1 gives the allowable errors for an error in H or Z of 0.5 nT.

Tilt of the coil-axis

Assume that the base is levelled accurately but that the coil axes are tilted at an angle e to the vertical and horizontal respectively. In this case, when the base is rotated the direction of the coil axis changes with orientation, so the resultant vector is not constant. The errors incurred at the standard dowel positions are examined.

H measurement. Assume that the Z-cancelling coil axis is vertical in the magnetic prime vertical plane (dowel positions 90/270), but is tilted in the meridian plane (dowel positions 0/180).

(a) Dowel position 0. The vectors are shown in Plate 3A(i) and the resultant vector (when e is southwards as shown) is given by (xiv)

$$H_0 = H \cos e + Z \sin e$$

(b) Dowel position 180. The direction of the coil axis is now reversed to be towards the north (Plate 3A(ii)), and the resultant vector is given by (xv).

$$H_{180} = H \cos e - Z \sin e$$

(c) Mean reading (0/180). The mean of the two resultants is

$$\bar{H} = (H_0 + H_{180})/2 \qquad \text{(xx)}$$

$$= H \cos e$$

Hence the mean value is always less than the true value; the allowable tilt error for an error (dH) is found as follows:

From (xx)

$$H - \bar{H} = H(1 - \cos e)$$

$$= dH$$

Hence

$$\cos e = 1 - dH/H$$

and the difference in readings is

$$H_0 - H_{180} = 2Z \sin e \qquad \text{(xxi)}$$

$$= 2Z \sin \cos^{-1} ((H - dH)/H)$$

Allowable values of this difference at the main BMR observatories for dH = 0.1 nT are included in Table 1.

(d) Dowel position 90/270. The vectors are those shown in Plate 2C and the error equation is (xx); in terms of the tilt angle it is

$$\sin e = (2HdH)^{\frac{1}{2}}/Z \qquad \text{(xxii)}$$

This formula allows computation of the allowable tilt in the magnetic prime-vertical, but as this tilt cannot be measured directly, a formula is needed in terms of magnetometer readings.

When the coils are turned through 90^o to dowel position 90 (or 270) the coil tilt is transferred from the prime-vertical plane to the meridian plane, and the preceding results apply. Thus, inserting (xxiii) into (xx):

$$H_{90} - H_{270} = 2Z.\ (2\ H\ dH)^{\frac{1}{2}}/Z$$

$$= 2.83(HdH)^{\frac{1}{2}} \qquad \text{(xxiv)}$$

Table 1 shows the allowable differences in measured H at the two pairs of dowel positions.

Z measurement. A tilt in the meridian of the H-cancelling coils will cause an error in measured Z. The analysis for a base tilt applies and the resultants are given by (xvii).

(a) Dowel position 0: the resultant is (for example);

$$Z_0 = Z \cos e - H \sin e$$

(b) Dowel position 180: the resultant is

$$Z_{180} = Z \cos e + H \sin e$$

(c) Mean reading (0/180). The mean value is

$$\bar{Z} = (Z_0 + Z_{180})/2$$

$$= Z \cos e \qquad \text{(xxv)}$$

Again it is seen that the mean value is less than the true value, and the allowable tilt is found in the same way as for H.

From (xxv)

$$Z - \bar{Z} = Z\ (1 - \cos e)$$

$$= dZ$$

Hence

$$\cos e = (Z - dZ)/Z$$

and the difference in readings is

$$Z_0 - Z_{180} = 2H \sin e$$

$$= 2H \sin \cos^{-1} ((Z - dZ)/Z)$$

4. CONCLUSIONS AND RECOMMENDATIONS

The formulas relating the errors in measured values of H and Z and the several kinds of mis-adjustment of the PVM are:

Horizontal intensity

Bias field	$(Z - Zc) = (2H\ dH)^{\frac{1}{2}}$
Bias current	$di = (2H\ dH)^{\frac{1}{2}}/C$
F difference	$(F - F-) = 2Z\ (2H\ dH)^{\frac{1}{2}}/F$
Base level	$dH = Z \sin e$
Coil axis tilt	$H_0 - H_{180} = 2Z \sin \cos^{-1}((H - dH)/H)$
	$H_{90} - H_{270} = (8H\ dH)^{\frac{1}{2}}$

Vertical intensity

Bias field	$(H - Hc) = (2Z\ dZ)^{\frac{1}{2}}$
Bias current	$di = (2Z\ dZ)^{\frac{1}{2}}/C$
F difference	$(F - F-) = 2H\ (2Z\ dZ)^{\frac{1}{2}}/F$

Meridian	dZ	$= (H \sin d)^2/2Z$
Base level	dZ	$= H \sin e$
Coil axis tilt	$Z_0 - Z_{180}$	$= 2H \sin \cos^{-1}((Z - dZ)/Z)$

These formulas have been used to calculate the tolerances shown in Table 1 for each of the main BMR observatories. The tolerances are for an error of 0.1 nT except in the levelling of the base where the assumed error is 0.5 nT. Plate 4 illustrates some of the formulas over larger ranges of error, at Kowen, A.C.T.

In practice it is difficult to level the base to better than about 0.2 divisions of the spirit level, which corresponds to 2" of arc, i.e. to about 0.5 nT.

The other tolerances are easily met. Thus the F difference in establishing the bias field can be made to be within 20 nT - much less than the values shown in the table; and reversed readings relating to coil-axis tilts can be 'equalised' within a few nanoteslas. Even the requirement to set the H-coil axis within 6' of the magnetic meridian at Port Moresby is not impracticable because of the low amplitude of the diurnal variation there (about 5' peak to peak).

Therefore it is clear that the levelling of the base, and the stability of this level, set the accuracy which can be achieved with the PVM. The 'rules' applicable to all observatories for adjusting the PVM should be:

1. Level the base to within 0.2 division, and preferably to 0.1 division.

2. Make the meridian adjustment to 0.2^{o} (Australia) or 0.1^{o} (Port Moresby).

3. Adjust the coil axes so that the reversed readings differ by less than 50 nT.

4. Adjust the (x1) bias current until the difference between total intensities is less than 50 nT.

5. Check the halved current occasionally to ensure that the bias-current supply is working within tolerance.

The critical adjustment is the first and it must be made carefully and thoroughly at the beginning of each measurement, and repeated during a prolonged set of measurements.

5. REFERENCES

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NELSON, J.H., 1958 - A new absolute instrument - the proton vector magnetometer. J. geophys. Res., 63, pp. 880-881.

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APPENDIX

The general resultant between the Earth's field vector and a randomly directed bias vector; and some particular cases

Suppose the bias field, magnitude B is tilted at an angle i to the horizontal, and lies in a vertical plane which is at an angle d to the magnetic meridian plane, as in Figure 1(i). Using the constructed figures shown, we have

$$R^2 = w^2 + x^2$$

$$= (H^2 + y^2 - 2Hy \cos d) + (Z - B \sin i)^2$$

$$= H^2 + (B \cos i)^2 - 2HB \cos i \cos d$$

$$+ Z^2 - 2BZ \sin i + (B \sin i)^2$$

$$= H^2 + Z^2 + B^2 (\sin^2 i + \cos^2 i)$$

$$- 2B (H \cos i \cos d + Z \sin i)$$

$$= F^2 + B^2 - 2BF (\cos I \cos i \cos d + \sin I \sin i)$$

Note also that

$$R^2 = F^2 + B^2 - 2BF \cos \phi$$

Hence, comparing the two equations, the angle between the two vectors is given by

$$\cos \phi = \cos I \cos i \cos d + \sin I \sin i$$

Some particular cases of the first result are used in PVM applications as will now be illustrated. The vectors involved in these cases are included in Fig. 1.

(a) The bias field is applied in the magnetic-meridian plane i.e. $d = 0^o$. The resultant is now:

$$R^2 = F^2 + B^2 - 2BF\,(\cos I \cos i + \sin I \sin i)$$

$$= F^2 + B^2 - 2BF \cos (I - i)$$

as may be seen by inspection.

(b) The bias field is horizontal and southwards ($d = 0^o$, $i = 0^o$).

$$Rs^2 = F^2 + B^2 - 2BF \cos I$$

$$= F^2 + B^2 - 2BH$$

$$= F^2 + B(B-2H)$$

which yields the conditions for measuring Z (cf. text equation (v)) viz

$Fs = F$ when $B = 0,\ 2H$

$Rs = Z$ when $B = H$

(c) The bias field is vertical and downwards ($d = 0^o$, $i = 90^o$)

$$Rd^2 = F^2 + B^2 - 2BF \cos (I - 90)$$

$$= F^2 + B^2 - 2BF \sin I$$

$$= F^2 + B^2 - 2BZ$$

$$= F^2 + B^2\,(B - 2Z)$$

which gives the conditions for measuring H (cf. equation iii) viz:

$$Rd = F \quad \text{when } B = 0,\ 2Z$$

$$Rd = H \quad \text{when } B = Z$$

The particular cases above are those applied in the cancellation method discussed in detail in the text. However, other particular cases can be applied to measure H and Z, as follows:

(d) The bias field is horizontal and northwards ($d = 0^{o}$, $i = 180^{o}$).

$$Rn^2 = F^2 + B^2 - 2FB \cos (I - 180)$$

$$= F^2 + B^2 + 2BH$$

From this and the result in (b)

$$B = \left[(Rn^2 + Rs^2 - 2F^2)/2\right]^{\frac{1}{2}}$$

$$H = (Rn^2 - Rs^2)/4B$$

(e) The bias field is vertical and upwards ($d = 0^{0}$, $i = -90^{o}$)

$$Ru^2 = F^2 + B^2 - 2FB \cos (I + 90)$$

$$= F^2 + B^2 + 2BZ$$

Combining this with the result in (c)

$$B = \left[(Ru^2 + Rd^2 - 2F^2)/2\right]^{\frac{1}{2}}$$

$$Z = (Ru^2 - Rd^2)/4B$$

The application of the results (d) and (e) is the method devised by Serson (1962) and has the advantage that all the vectors to be measured are large; hence good PPM signals can be obtained in situations where the cancellation method would provide weak signals. There are other advantages and instrumental requirements in applying the method, as indicated in the next discussion.

Some numerical results of the application of the method at Kowen, ACT will indicate the scope, limitations, and requirements of the method.

(A) <u>Magnitude of the bias field</u> (H measurement). From the result in (d):

$$dH = -H\ dB/B$$

Therefore B should be of the same order of magnitude as H, and this is also the requirement (b) to measure Z by the cancellation (Nelson's) method. This fact suggests a convenient way of determining both Z and H using one pair of coils (with horizontal axis) and one bias current. The proposed procedure is, in outline:

(i) Observe F

(ii) Apply a bias field = 2H southwards and observe F-

(iii) Halve the bias current to give Bs = H and observe Rs = Z (Nelson's method)

(iv) Reverse the bias current to give Bn = H northwards and observe Rn

(v) Calculate H from the relations given in (d)(Serson's method).

It is obvious that this scheme could be applied to measure Z (Serson) and H (Nelson) where Z is the weak component; in this case a coil with vertical axis would be needed.

(B) Bias field stability

Numerical examples for Kowen ACT will be used to demonstrate the magnitudes of bias fields and resultants, and the required stability of the bias field. The basic data and computed parameters are listed in the table, and it shows the effects on computed H due to changes in the bias current.

The method seems worthy of practical investigation. It appears to offer a neat and simple means of measuring H and Z in one operation, the only additional critical requirement, above those required by the cancellation method, is for a stable current supply; the numerical examples indicate that a stability of 0.5% should suffice and this is technically feasible.

TABLE

MEASUREMENT OF H BY SERSON'S METHOD

(adapted by the author as an adjunct to the measurement of Z by Nelson's method)

Representative parameters, Kowen Forest, ACT

$H = 23900.0$ $\quad C = 154$ nT/mA

$Z = 53800.0$ $\quad i_s = 155$ mA (constant)

$F = 58869.8$ $\quad i_n = i_s + di$

Parameter	di (mA)				
	0	1		5	10
Bs			23870		
Bn	23870	24024		24640	25410
Rs			53800		
Rn	71947.3	72049.7		72460.8	72963.2
B	(23870)	24023.9		24634.4	25365.0
H	(23900)	23900.4		23911.0	23942.0
dH	(0)	0.4		11.0	42

$$Bs,n = C \times is,n$$

$$Rs^2 = F^2 + B^2 - 2BH$$

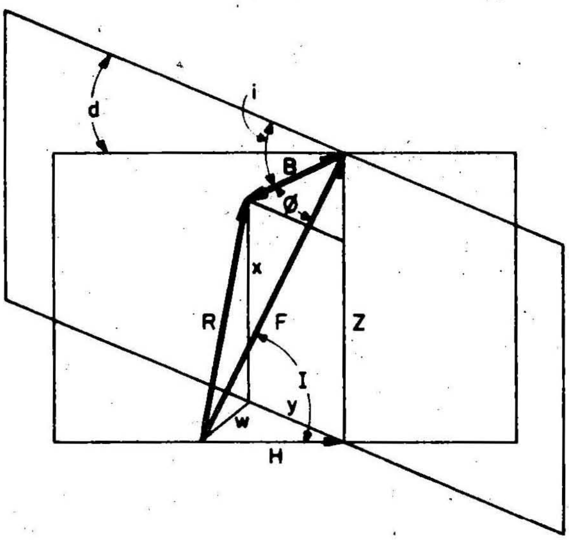
$$Rn^2 = F^2 + B^2 + 2BH$$

$$B^2 = (Rn^2 + Rs^2 - 2F^2)/2$$

$$H = (Rn^2 - Rs^2)/4B$$

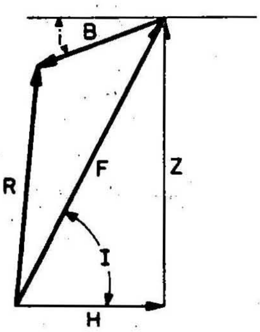
Fig. 1

(i) d = d , i = i



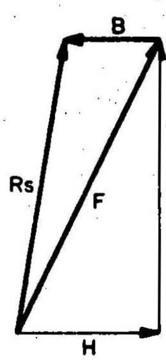
$$R^2 = F^2 + B^2 - 2FB(\cos I \cos i \cos d - \sin I \sin i)$$

(ii) d = O , i = i



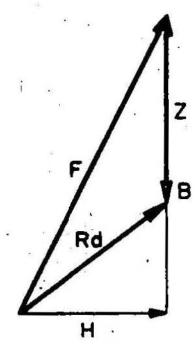
$$R^2 = F^2 + B^2 - 2FB\cos(I - i)$$

(iii) d = O , i = 0°



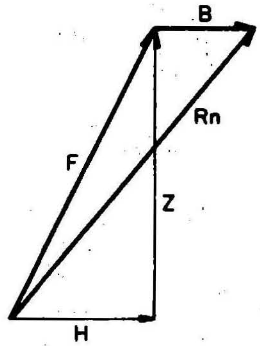
$$Rs^2 = F^2 + B^2 - 2BH$$

(iv) d = O , i = 90°



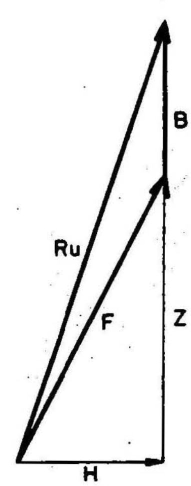
$$Rd^2 = F^2 + B^2 - 2BZ$$

(v) d = O , i = 180°



$$Rn^2 = F^2 + B^2 + 2BH$$

(vi) d = O , i = 270°



$$Ru^2 = F^2 + B^2 + 2BZ$$

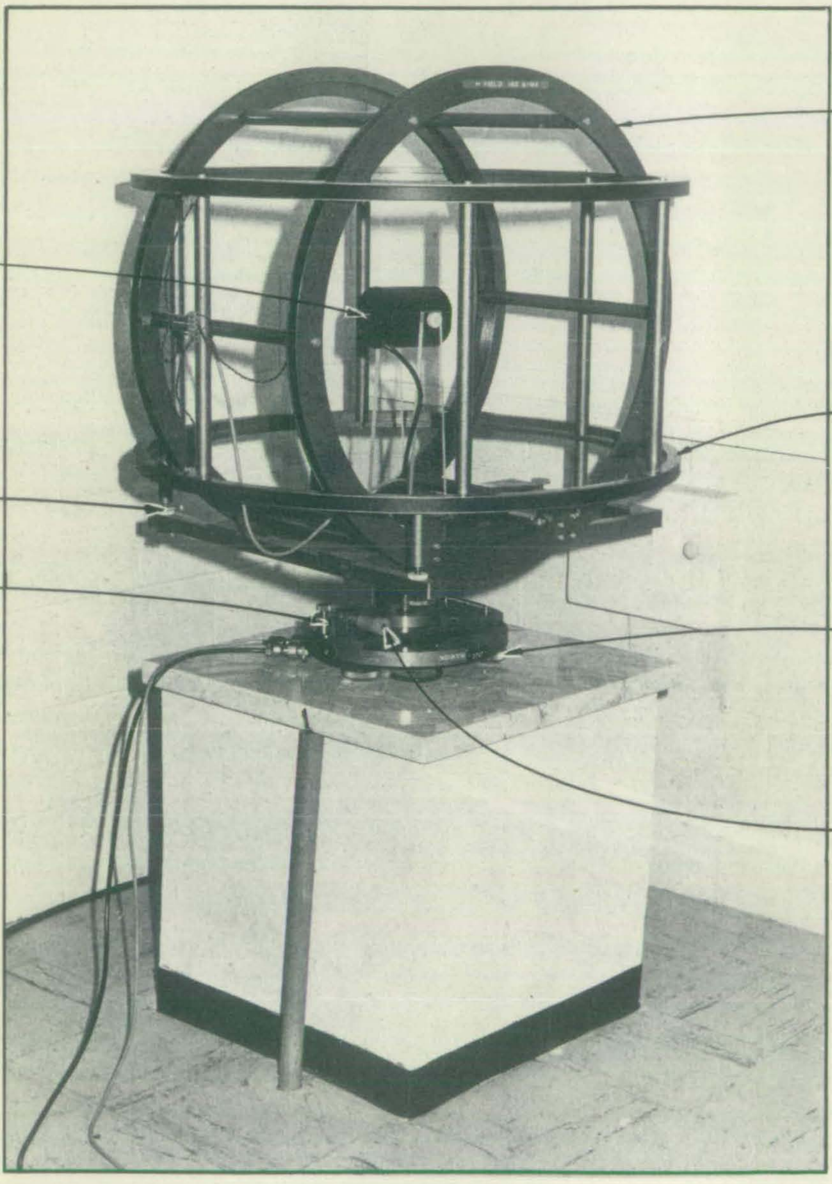
PVM VECTORS

TABLE 1

Tolerances in PVM adjustments
(for an error of 0.1 nT)

Place	Mean values H Z F nT	Base level* H (seconds of arc)	Base level* Z (seconds of arc)	Meridian (minutes of arc)	Bias H Field nT current mA dF nT	Bias Z Field nT current mA dF nT	Coil tilt H $H_0 - H_{180}$ $H_{90} - H_{270}$ nT	Coil tilt Z $Z_0 - Z_{180}$ nT
Kowen	23 900 53 800 58 900	02	04	15	69 0.4 126	104 0.7 84	311 138	92
Gnangara	23 600 53 400 58 500	02	04	15	69 0.4 125	103 0.7 84	311 137	91
Toolangi	22 200 56 300 60 500	02	05	16	67 0.4 128	106 0.7 78	338 133	84
Port Moresby	36 100 23 400 43 000	04	03	06	85 0.6 92	68 0.4 115	110 170	211

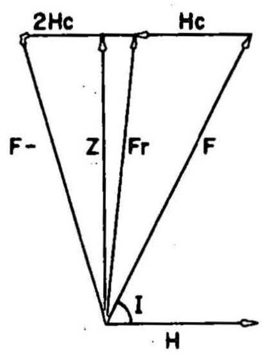
* For an error of 0.5 nT



THE ELSEC PVM TYPE 5920

A. Determination of the bias fields

Vertical intensity



$$Fr^2 = F^2 + Hc^2 - 2HcF\cos I$$
$$= F^2 + Hc(Hc - 2H)$$

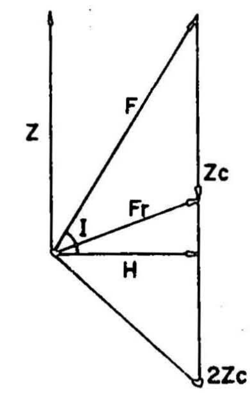
When $Hc = H$

$$Fr^2 = F^2 - H^2 = Z^2$$

When $Hc = 2H$

$$Fr = F$$

Horizontal intensity



$$Fr^2 = F^2 + Zc^2 - 2ZcF\sin I$$
$$= F^2 + Zc(Zc - 2Z)$$

When $Zc = Z$

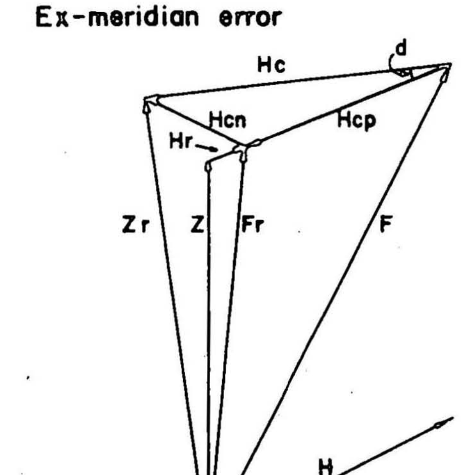
$$Fr^2 = F^2 - Z^2 = H^2$$

When $Zc = 2Z$

$$Fr = F$$

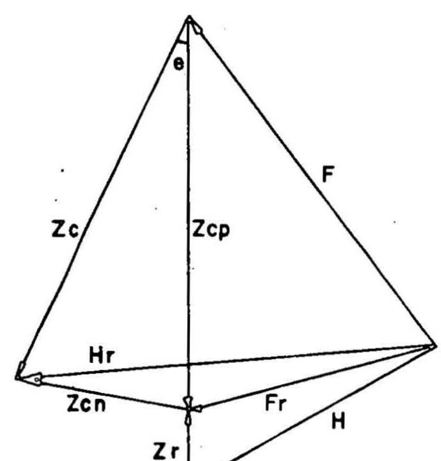
B. Z measurement

Ex-meridian error



C. H measurement

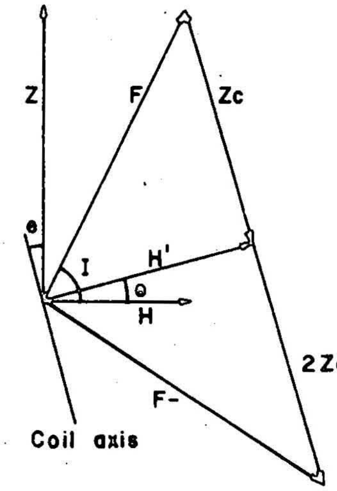
Coil tilt in prime vertical



PVM VECTORS

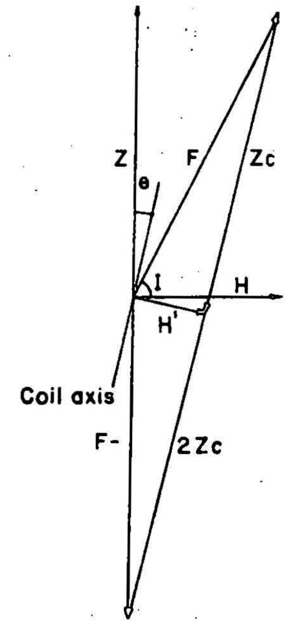
A. Horizontal intensity measurement

(i) Southwards tilt



$H' = F\cos(I - e)$
$= H\cos e + Z\sin e$

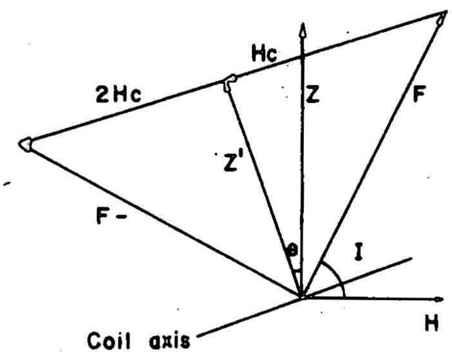
(ii) Northwards tilt



$H' = F\cos(I + e)$
$= H\cos e - Z\sin e$

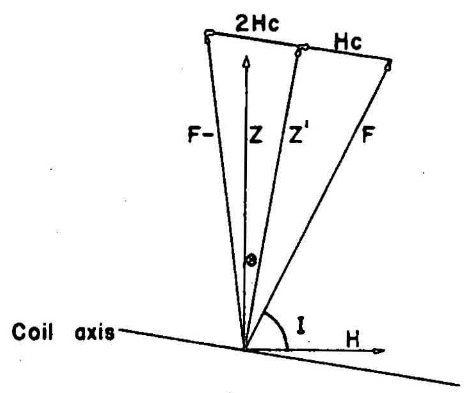
B Vertical intensity measurement

(i) Upwards tilt



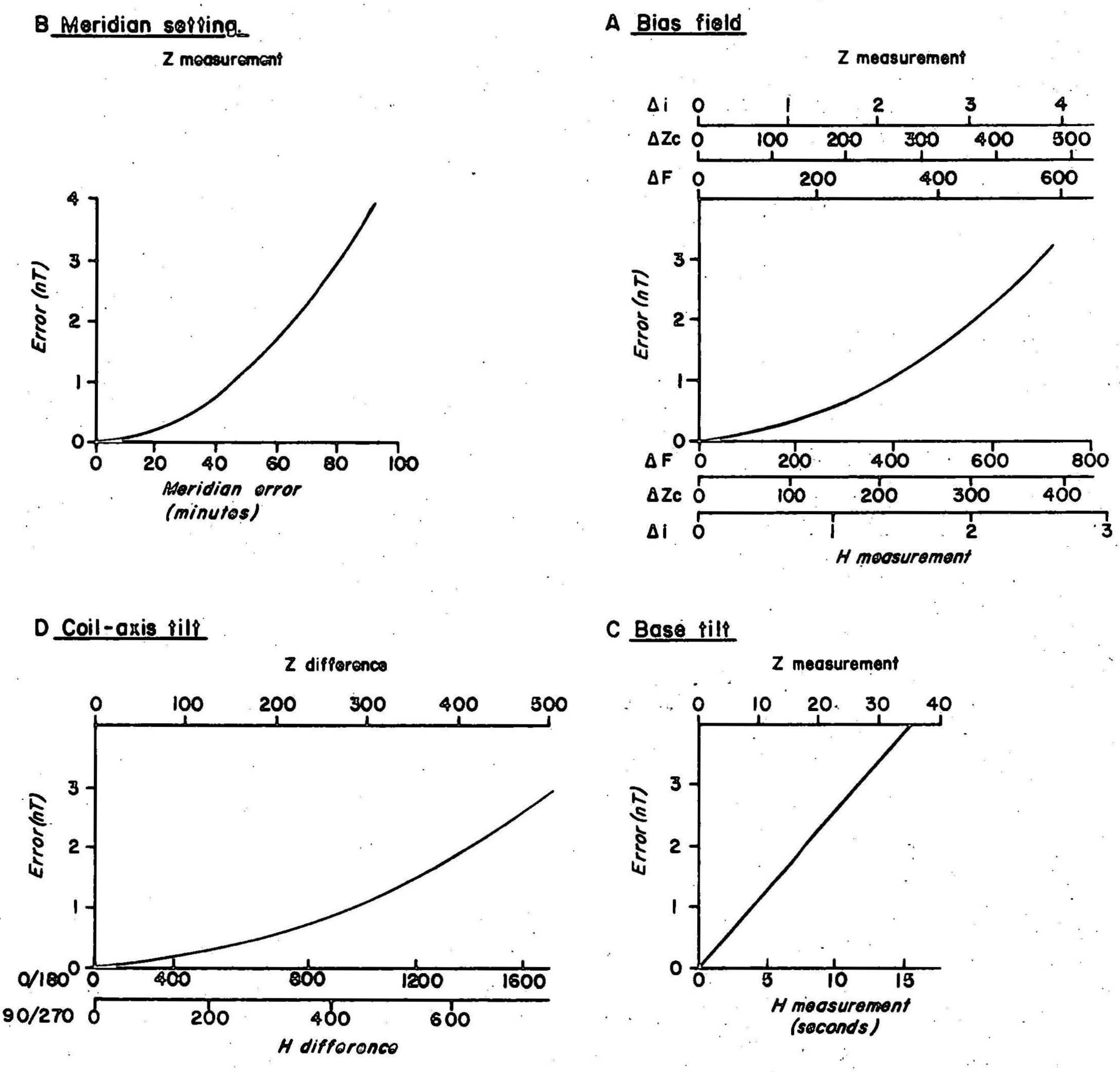
$Z' = \cos(90 - (I - e))$
$= Z\cos\theta - H\sin\theta$

(ii) Downwards tilt



$Z' = F\cos(90 - (I + e))$
$= Z\cos e + H\sin e$

PVM VECTORS - TILTED BASE OR COILS



PVM MIS-ADJUSTMENT ERRORS

(Kowen ACT: H=23900 Z=53800 F=58900)