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NOTES ON THE USE OF THE QHM MAGNETOMETER IN THE MEASUREMENT OF HORIZONTAL INTENSITY AND DECLINATION

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SUMMARY

The results of earlier investigations, combined with observations at Gnangara, show that the QHM quartz fibre suffers from an elastic after-effect (creep) and that the angle due to initial (residual) torsion is variable on a short term basis. The collimation error is essentially constant.

These effects can produce errors in horizontal intensity (H) amounting to several gammas, and in declination (D) amounting to several minutes.

Errors in H due to creep can be made constant by observing at a fixed rate. Errors in D can be made comparable to those of a declinometer by determining the value of residual torsion existing at the time of the observation.

1. INTRODUCTION

The quartz horizontal-force magnetometer (QHM) came into use in the mid-1930s (La Cour, 1936). It is a relative (semi-absolute) instrument with which a practised observer can measure horizontal intensity (H) within 1 or 2 gammas in 8 to 10 minutes. It is light and robust, and can also be used to measure declination (D). These attributes have caused it to gain favour as an observatory and field instrument and it has largely replaced the classic theodolite magnetometer for H measurements. All BMR observatories have depended on QHMs since 1961; those in Antarctica have employed them throughout their life. In the world network existing during the IGY (1957 to 1958), 57% of observatories used them.

Several investigators have examined its reliability for H or D. The purpose of this note is to collect their results, to present some others derived from observations with BMR instruments, and to draw attention to areas where care must be given if the above accuracy is required.

For completeness, the theory and methods of use of the QHM are summarised in Chapter 2. Appendix 1 gives a list of the symbols used and their meanings.

2. QHM PRINCIPLE AND PROCEDURES

The QHM is a torsion device, in which the deviation ϕ of a suspended magnet, caused by the application of torsion to the suspension, is a measure of H. The applied torsion is always exactly $n\pi$ radians. Usually $n = 2$, and the constants M and T (see Appendix 1) are arranged so that ϕ is about 60°. The measurement of H thus reduces to the measurement of an angle from readings (A1, A2, ...) of a theodolite base to which the QHM tube is secured (Plate 1A).

Declination may be determined by sighting on the magnet ($n = 0$) and on a reference mark, provided the index correction u is known (Plate 1B).

In the BMR the QHM is assembled either by using the makers' components ('QHM mode') or by fitting the suspension tube to an Askania circle ('Askania mode'). In the QHM mode a small telescope is fastened to the tube, which in turn is secured to the horizontal circle. In the Askania mode, an adaptor is screwed to the base of the QHM tube and it is clamped to an Askania declinometer circle. In this case the telescope is independent of the QHM body.

The advantages of the Askania mode are: superior optical qualities, larger circle, larger range of vertical telescope adjustment, the telescope may be adjusted during an observation without vitiating the result, and the complete absence of refracting windows in the optical system when viewing a reference mark. Its disadvantage is that stray light can enter the system, reducing the image brightness, but this may be overcome by covering the rear window of the QHM tube and inserting an opaque cylinder between the front window and the objective; a piece of one-inch plastic water pipe socket is ideal.

La Cour (1936) presents the H reduction formulas for the QHM and gives the observing schedule: n = 0, +2, -2, 0. However, the calibration sheets provided by the makers give the schedule; n = 0, +2, -2, -2, +2, 0, and this has become the universal 'standard' procedure. It is shown later that one schedule should be adopted and adhered to when accuracies of 2 gammas or better are desired.

Ignoring corrections for temperature and induction, the reduction formulas are (for n = 2):

$$H = 4\pi T/M \left[\sin (a + a_1) - \sin (a - a_2) \right] \tag{1}$$

$$\tan a = (\sin a_1 - \sin a_2)/(2 - \cos a_1 - \cos a_2) \tag{2}$$

When a is small, $(a_1 - a_2)$ is small and equation 1 is approximated by:

$$H' = 2\pi T/M \sin (a_1 + a_2)/2 \tag{3}$$

$$= 2\pi T/M \sin \phi \tag{3a}$$

Formula 3a is assumed to apply in all routine observations and leads to the operational formula:

$$\log H' = C - \log \sin \phi \tag{3b}$$

The effects of this assumption are discussed in Chapter 3.

The formula for computing D is:

$$D = Az - (B - A) + u \tag{4}$$

$$= Az - (B - A) + (c - a) \tag{4a}$$

The calibration sheets give values of c and a at Rude Skov, and state that a varies inversely with H, and may be computed when H is known. The inference is that at a given location both are constant, at least for periods of weeks. This is discussed in Chapter 3.

3. RELIABILITY AND STABILITY OF THE QHM

Horizontal intensity

The long-term stability of the QHM depends on the constancy of C (formula 3b), i.e. on the constancy of T and M. Olsen (1942) found that over a three-year period, in fourteen QHMs, c was constant within the equivalent of 5 gammas/gauss/year. In some cases C increased and in others it decreased. Van der Waal (1966) presents the corrections obtained for 26 BMR QHMs during the period 1951 to 1965. In nearly all cases drift rates are linear and range from zero (4 cases) to -18 gammas/gauss/year. The average rate is -7 gammas/gauss/year, equivalent to about -2 gammas/year. Thus recently constructed instruments are as stable as earlier models and drift rates are sufficiently constant to allow corrections to be extrapolated forward one or two years.

Frøshaug (n.d.) investigated two aspects of the QHM. Firstly, he showed that C is independent of torsion for values of $n = 2$ to $n = 10$, within the equivalent limit of 6 gammas/gauss. Secondly he showed that the thermometer gives the magnet temperature to the same accuracy provided the temperature variation does not exceed about $0.2^{\circ}C$/minute.

The operational formula (3b) neglects the effect of residual torsion, which was examined by Howe (1938). Proceeding from the exact equations 1 and 2 and the approximation, equation 3, he derives:

$$H = 2\pi T/M \sin \phi \cos (a + \theta) \tag{5}$$

$$a = \theta \cos \phi \, / \, (1 - \cos \phi) \tag{6}$$

and $$dH = (H - H') = 4.23 \times 10^{-8} \, H \, \theta^2 \, / \, (1 - \cos \phi)^2 \tag{7}$$

where θ is small and is expressed in minutes of arc in (7).

The last formula gives the error in H resulting from the use of the operational formula 3b. This can be rewritten:

$$\theta = 4.86 \times 10^3 \, (1 - \cos \phi) \, (dH/H)^{\frac{1}{2}} \tag{7a}$$

Table 1 gives values of 2θ (which can be derived readily from the observation form) corresponding to an error of 0.5 gamma at BMR observatories, assuming $\phi = 60^{\circ}$.

Table 1

Observatory	H (10^4 gammas)	2θ (minutes of arc)
Gnangara	2.39	16
Macquarie Island	1.31	21
Mawson	1.83	18
Port Moresby	3.63	12
Toolangi	2.25	16
Wilkes	0.92	26

At Gnangara, QHMs Nos. 192, 292, and 293 are each used every week for routine control of the H magnetograph. From the observations made in 1965, values of 2θ were derived, the results being summarised in Table 2.

Table 2

QHM	Median 2Θ (minutes)	Range	Upper quartile	Lower quartile
291	17.8	44.7	29.9	- 0.9
292	-16.2	56.1	- 8.7	-38.3
293	-17.8	43.1	- 5.0	-30.3

The variability of Θ is obvious, and inspection of the individual values shows that it may occur from one week to the next, by amounts of the same order as the ranges given in Table 2. The changes are random; they may be caused by (a) elastic after-effects due to the variable amount of torsion applied to the fibre when clamping the system and (b) different location of the QHM tube with respect to the telescope optic axis each time the unit is assembled in the Askania mode.

Tables 1 and 2 show that by neglecting residual torsion, errors in H of the order of 1.5 gammas can result in determinations made on different days at Gnangara.

Several investigators (van Wijk and Gotsman, 1951; Thiesen (n.d.); Wienert, 1959) have, in the course of tests on the suitability of the QHM for D measurements, mentioned an elastic after-effect (referred herein as 'creep'). Thiesen presented a graph showing the change in a_1 and a_2 with time; in the first few minutes after applying torsion, the deflection angle decreased at a rate exceeding 0.2 minute/minute, which is equivalent to 1 gamma/minute in H. All these investigators made the comment that observations should be made to a standard schedule and at a constant rate. As far as the writer knows, this has not been followed in the BMR; certainly this creep effect was not appreciated by staff at Gnangara, where the time taken for QHM observations has ranged from six to twelve minutes.

A series of eight observations made at Gnangara between August and October 1966 shows the error that may be caused by creep. The observing schedule was: n = 0, +2, +2, -2, -2, -2, +2, +2, 0. Settings were made at two-minute intervals and values of H computed from the following combinations: 'standard', A_1 and A_3, A_4 and A_6; 'delayed -2π', A_1 and A_4, A_5 and A_6; 'delayed +2π', A_2 and A_4, A_4 and A_7; 'delayed both', A_2 and A_4, A_5 and A_7. After correcting for time variations, the 'standard' values were equal to:

'Delayed -2π'	+	1.8 gammas
'Delayed +2π'	+	2.0 gammas
'Delayed both'	+	3.3 gammas

The first two correspond to a delay of 2 minutes in one setting, while the third corresponds to a delay of 2 minutes in both settings.

The creep effect may be seen in most of the weekly control observations. The second -2π circle reading, made about one minute after the first, is generally greater than it, corresponding to a decrease in a_2, or an apparent increase in H. This is due to creep because at Gnangara changes in temperature and H are nearly always such as to cause an <u>increase</u> in a_2.

These observations therefore confirm Thiesen's result and show how an observer, or observers, may produce results differing by 2 gammas or more. Likewise, changes in observing schedules may produce similar differences.

Declination

Generally, the QHM has not been favoured for D measurements. It has been used at BMR observatories when no other declinometer was available (see Appendix 2) and by regional magnetic parties. Most of the observers commented on the poor results obtained, relative to a standard declinometer, and have generally attributed the scatter to poor quality optics, variable refraction in the windows (at different elevations), etc. Some of the observers did make allowance for changes in a but assumed that it remained constant over periods of months or years (see Oldham, 1958; McGregor, 1959; Kirton, 1960).

However, other investigators, notably van Wijk and Gotsman (1951) have shown that the QHM can produce results of the same quality as those of a declinometer, when allowance is made <u>individually</u> for residual torsion.

The routine weekly observations at Gnangara in 1965 confirm this finding, at least for QHM 291. During the baseline observations, an Askania declinometer observation (D) is followed within a few minutes by a QHM 291 H observation, made to the 'standard' schedule. For the 36 observations made using the Askania mode, values of QHM declination (Dq) were derived from the first zero torsion reading; the difference (D - Dq) is, very closely, the index correction u of the QHM (no allowance was made for variation of D, which was generally very small). From the H observation, 2θ was derived, and then a, according to equation 6. This step was simplified by reference to a table of ϕ versus $\cos\phi / 2(1-\cos\phi)$ presented by Wienert, part of which is reproduced as Appendix 3. Finally, values of the collimation angle c were computed. Table 3 summarises the results.

<u>Table 3. Parameters for QHM 291</u>

	Angles in minutes			
	u	2θ	a	c
Mean	56.0	11.8	4.6	60.6
S.D.	13.33	14.02	5.46	0.61
Range	16.7	44.7	17.8	2.6

8

The range of c is not much greater than that of the declinometer base-line values, and would probably be reduced by making allowance for the time variation in D mentioned above. Therefore, the collimation angle for this QHM is effectively constant for periods at least as long as a year (see below), and the instrument will give accurate values of D when individual corrections for residual torsion are applied. As stated by Wienert, the table of Appendix 3 makes this a slide-rule affair.

The value of c at 1955 quoted in the instrument sheets was "about 63 minutes". This suggests that the collimation may be long-term variable to the extent of 1 minute in 5 years, but declinometer comparison results scatter by similar amounts (van der Waal, 1966). Extension of the above analysis over several years would give more reliable information on the stability of collimation.

<u>Summary</u>

QHM observations made by several investigators, supplemented by results at Gnangara observatory, show that, in general:

(a) the angle due to residual torsion (and therefore the index correction) is variable on a short-term basis, and can cause large errors in D;

(b) the inequality in deflection angles is, correspondingly, variable and can cause errors in H exceeding 1 gamma;

(c) the deflection angle depends on the time elapsed after applying torsion because of elastic creep, which can produce errors in H exceeding 2 gammas;

(d) the observed value of H depends on the observation schedule;

(e) the observed value of H depends on the rate of change of temperature.

4. DISCUSSION AND RECOMMENDATIONS

The QHM is an admirable instrument for H variometer control; its operation is simple, demands no special skill from the operator, and gives highly accurate results. However, experienced operators occasionally produce results outside the range expected from observer errors. Again, it is sometimes noted that a series of observations made on one day differs significantly from another made the next day (as during intercomparisons). A possible explanation for these discrepancies is the effects (b), (c), and less likely (d).

Effects (b) and (c) may have some bearing on a result demonstrated by Small (1965). He showed that fluctuations in H baseline values at Toolangi measured by 3 QHMs occur simultaneously. He eliminated three possible correlated errors in the QHMs as causes, and concluded that they resulted from variometer changes. These effects are a fourth possible source of correlated changes in QHMs.

As a declinometer the QHM has been much maligned; a glance at any series of baseline values computed on the assumption of constant residual torsion (e.g. McGregor, 1956) makes this understandable. The mean of such a series may depart considerably from the true value (depending on the value a at the time of intercomparisons) but it has been shown that properly treated individual observations can yield results with an accuracy approaching that of a standard declinometer. Values adopted from them would certainly engender more confidence in derived data.

In the light of the above findings it is recommended that, when accuracies of 1 to 2 gammas (H) or a few tenths of a minute (D) are aimed for:

1. The standard observation schedule and a uniform observing rate be adopted; a convenient rate is given in Plate 1A. The schedule produces only <u>one</u> value of H (the mean of the two).

2. An observer be considered sufficiently trained when he can adhere to this schedule.

3. An observation should not commence until the QHM is in temperature equilibrium with its surroundings, the criterion being that the rate of change does not exceed $0.2^{\circ}C$/minute.

4. Care be taken not to introduce appreciable torsion in the fibre when clamping the magnet; it must never be clamped in a 'torsion' position(n = 1 or more).

5. Declination data derived from QHM observations be examined and where appropriate be corrected for variability of residual torsion.

5. REFERENCES

FRØSHAUG, J. n.d. Two experimental investigations on the reliability of the QHM magnetometer for measuring the geomagnetic horizontal force. <u>Geophysica</u> 5, 147 - 149.

HOWE, H. E. 1938 Note on effect of torsion in QHM observations. <u>Terrestrial Magnetism and Atmospheric Electricity</u> 43, 167 - 168.

KIRKTON, M.	1960	Mawson geophysical observatory work, Antarctica 1959. Bur. Min. Resour. Aust. Rec. 1960/115.
LA COUR, D.	1936	Le quartz-magnetometre QHM (Quartz horizontal-force magnetometer). Danske Met. Inst. Comms. Mag. No. 15.
McGREGOR, P. M.	1956	Magnetic results from Macquarie Island, 1952. Bur. Min. Resour. Aust. Rep. No. 27.
McGREGOR, P. M.	1959	Magnetic results from Mawson Antarctica, 1956. Bur. Min. Resour. Aust. Rep. No. 40.
OLDHAM, W. H.	1958	Magnetic results from Mawson Antarctica, 1965. Bur. Min. Resour. Aust. Rep. No. 39.
OLSEN, J.	1942	Some investigations on the constancy of the QHM magnetometer. Danske Met. Inst. Comms. Mag. No. 20.
SMALL, G. R.	1965	Fluctuations in the H-baseline value at Toolangi observatory, Victoria. Bur. Min. Resour. Aust. Rec. 1965/235.
THIESEN, K.	n.d.	On the determination of D by means of QHM. Geophysica 5, 63 - 69.
van der WAAL, C. A.	1966	Corrections for absolute and semi-absolute magnetic instruments. Bur. Min. Resour. Aust. Rec. 1966/207.
van WIJK, A. M., and GOTSMAN, B.	1951	Note on the use of the quartz horizontal-force magnetometer for the determination of magnetic declination. South African Journal of Science 47, 316 - 318.
WIENERT, K.	1959	Declination measurements with QHMs. Helwan Observatory Bulletin No. 44.

APPENDIX 1

Explanation of symbols

A, A_1,...	Circle readings of normal to mirror
a	Angle due to residual torsion
a_1, a_2	Deflection angles when $n = +2$, $n = -2$
Az	Azimuth from true south of reference mark (RM)
B	Circle reading of reference mark
C	Main constant ($= \log 2\pi T/M$)
c	Collimation angle; angle between normal to mirror and magnetic axis of a magnet
D	Declination as measured by declinometer
Dq	Declination as measured by QHM
H	Horizontal intensity, calculated by exact formula
H'	Horizontal intensity, calculated by operational formula
M	Moment of magnet
n	An integer; $n\pi$ equals applied torsion, H determination
T	Torsion constant of quartz fibre
t	Temperature
u	Index correction of QHM as declinometer ($= D - Dq = c - a$)
θ	Half the inequality between deflection angles ($= (a_1 - a_2)/2$)
ϕ	Mean deflection angle ($= (a_1 + a_2)/2$)

APPENDIX 2

BMR Observatory declination results based on QHM observations

Observatory	Interval	QHM
Gnangara	June 1957 to June 1959	291
Macquarie Island	April 1952 to December 1955	177, 178, or 179
Mawson	September 1955 to February 1964	300, 301, or 302
Port Moresby	August 1957 to December 1959	189

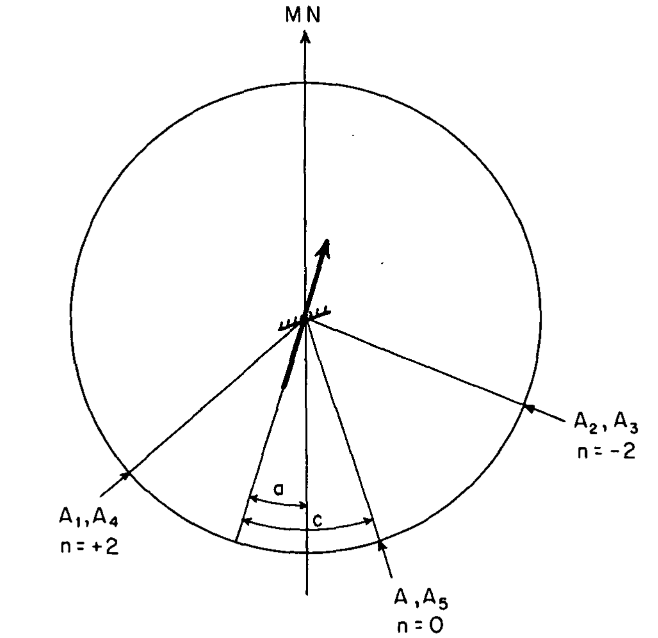
APPENDIX 3

Table of the ratio a/2Θ (after Wienert, 1959)

Angle ∅ (degrees)	cos ∅ / 2 (1 - cos ∅) = a/2Θ									
	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
45	1.208	201	194	187	180	173	166	159	152	145
46	1.138	131	125	118	112	105	098	092	085	079
47	1.072	066	060	054	048	042	035	029	023	017
48	1.011	005	000	994*	988*	982*	977*	971*	965*	960*
49	0.954	949	943	938	932	927	922	916	911	905
50	0.900	895	890	885	880	874	869	864	859	854
51	0.849	844	839	835	830	825	820	815	811	806
52	0.801	796	792	788	783	778	774	770	765	760
53	0.756	752	747	743	739	734	730	726	722	717
54	0.713	709	705	701	697	692	688	684	680	676
55	0.672	668	664	661	657	653	649	645	642	638
56	0.634	630	627	623	620	616	612	609	605	602
57	0.598	595	591	588	584	581	578	574	571	567
58	0.564	561	557	554	551	548	544	541	538	534
59	0.531	528	525	522	519	516	512	509	506	503
60	0.500	497	494	491	488	485	482	479	476	473
61	0.470	467	464	402	459	456	453	450	448	445
62	0.442	439	437	434	431	428	426	423	420	418
63	0.415	412	410	408	405	402	400	398	395	392
64	0.390	388	385	383	380	378	376	373	371	368
65	0.366	364	361	359	357	354	352	350	348	345
66	0.343	341	339	336	334	332	330	328	325	323
67	0.321	319	317	315	313	310	308	306	304	302
68	0.300	298	296	294	292	290	288	286	284	282
69	0.280	278	276	274	272	270	268	266	264	262
70	0.260	258	256	254	252	250	249	247	245	243

PLATE 1

A. DETERMINATION OF H

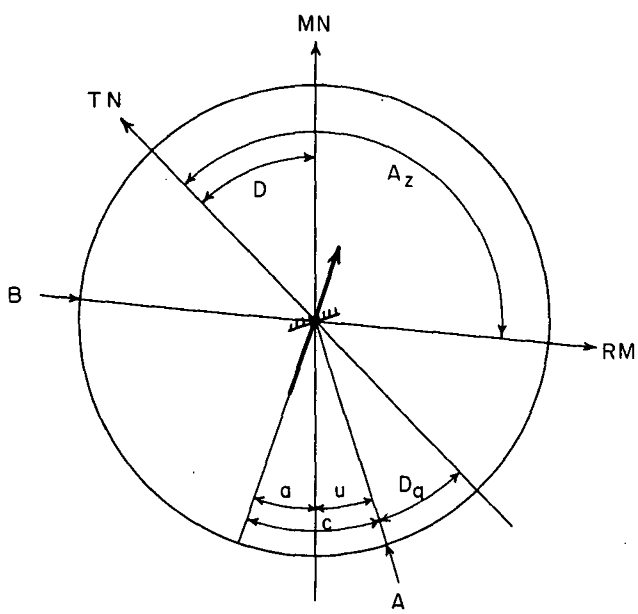


STANDARD SCHEDULE

Setting	n	Circle reading	Time (min)
1	0	A	0
2	+2	A_1	2
3	-2	A_2	4
4	-2	A_3	5
5	+2	A_4	7
6	0	A_5	9

$$a_1 = A_1 - A$$
$$a_2 = A - A_2$$
$$\phi = (a_1 + a_2)/2$$
$$\theta = (a_1 - a_2)/2$$

B. DETERMINATION OF D



$$D_q = A_z - (B - A)$$
$$D = A_z - (B - A) + u$$
$$= D_q + u$$

QHM READING POSITIONS AND ANGLES

Geophysical Branch, Bureau of Mineral Resources, Geology and Geophysics. G82/2-66

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