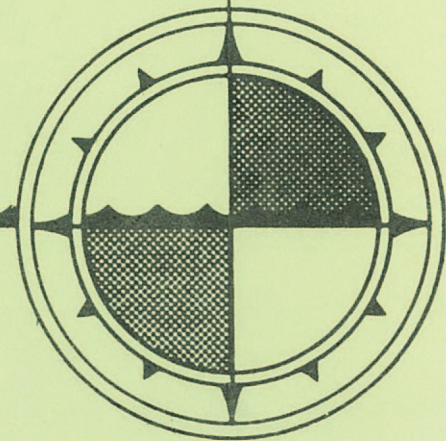


**MEASUREMENTS OF THE DIRECTION SENSITIVITY OF
THREE CURRENT METERS AS A FUNCTION
OF MAGNETIC FIELD INTENSITY**

by

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Arctic Sciences Limited



**INSTITUTE OF OCEAN SCIENCES, PATRICIA BAY
Sidney, B.C.**

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For

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Abstract

Three self-recording current meters, the Aanderaa RCM-4, the Braincon type 381 and the General Oceanics Model 6011, were tested for their directional sensitivity in low horizontal magnetic fields in a laboratory where the magnetic field intensity is controlled. In the tests, the relative direction error was measured; this is the difference between the indicated direction at low horizontal magnetic fields and the indicated direction in a horizontal magnetic field of 16,000 gamma, a field strength typical of mid-latitudes where most compass calibrations are made. The tests indicated that, of the instruments tested, the Aanderaa current meter is the most sensitive in direction measurements, with relative direction errors of five degrees at horizontal field strengths ranging from 700 to 4,400 gamma about a mean of 2,500 gamma depending on the orientation of the instruments and the applied magnetic field. The Braincon current meter indicated relative direction errors of five degrees in horizontal fields ranging from 1,700 gamma to 9,900 gamma about a mean of 3,800 gamma. While the General Oceanics current meter registered larger errors, it is suggested that improved digital resolution of this instrument and improved accuracy in the inclination sensor would substantially improve its direction sensitivity. Further tests of the direction sensitivity of Aanderaa current meters are recommended in view of differences between the results of this study and an earlier study (Barfoot, 1972).

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1. Introduction

The limitations of magnetic compasses in polar regions are well known to those involved in northern shipping and aviation. For oceanographers, the weak horizontal component of the earth's magnetic field (H) also poses a problem because conventional current meters rely on the earth's magnetic field to provide a reference for measuring the direction of water currents. One can avoid this difficulty by deploying current meters on rigid structures mounted on the bottom or suspended below the ice (Lewis, 1975) but for deep water regions or areas that are not ice covered all year, these techniques are not applicable. Gyro compasses, commonly used on ships and airplanes in polar regions, require relatively large amounts of power so that leaving the instrument 'in situ' for long time-series measurements is not possible. An acoustic positioning system, consisting of an attachment to a conventional current meter which determines its orientation from the bearing to a bottom-mounted transponder, is currently under development (E. L. Lewis, personal communication) and this system may provide a method of allowing moored current measurements that is not dependent on the earth's magnetic field.

2. Review

The requirements of current measurements for the summer of 1977 in eastern Lancaster Sound, N.W.T., an area with water depths of 650 to 800 m and a horizontal component of the earth's magnetic field of 3,000 gamma, led to a review of previous current measurements in polar regions. Since Lancaster Sound has little or no ice cover from May through November, together with its large water depths, we ruled out the possibility of rigidly mounting current meters from the surface or the bottom. In regions with similar values of H, conventional current meters have been used with apparent success. Avis and Coachman (1971) measured currents in northern Baffin Bay (H = 3,800 gamma) using Braincon meters, while in Fury and Hecla Strait (H = 3,000 gamma), Barber (1960) used an Ekman current meter to measure the water flow. Also in Fury and Hecla Strait, the Ice Research Group of Defence Research Establishment Pacific, Department of National Defence, has found Braincon current meters to give reliable estimates of direction (R. Chow, personal communication). From an ice floe, located in the Arctic Ocean north of Ellesmere Island, (H = 2,800 gamma) scientists from the University of Washington using Aanderaa current meters measured the water current direction after correcting for temporal changes in the magnetic field variation monitored with a magnetometer located on the ice floe (D. Hanzlick, personal communication).

The only laboratory study of the directional sensitivity of current meters in weak H fields of which we are aware is that of Barfoot (1972). Barfoot measured the directional sensitivity of one unit each of three different types of current meters, the Aanderaa RCM-4, the Plessey M201 and the N.B.A. (Controls) DNC-2A. His results, shown in Table 1, indicate that current direction measurements reliable to 10 degrees require a horizontal field strength of 5,000 to 6,000 gamma for those meters tested.

Since Barfoot's conclusions were based on a rather limited data set

Table 1

The horizontal magnetic field strengths required to produce direction errors of 5 degrees and 10 degrees. These results are taken from the report of Barfoot (1972).

Current Meter	Orientation	Magnetic Field Strength (gamma)	
		5 degree	10 degree
Plessey	North	3000	2000
	East	8000	6000
		7000	5000
	South-West	10000	6000
Aanderaa	North	6000	3000 ¹
	South-West	6000	4000
	East	3000	1000
N.B.A. (Controls)	North	5000	5000
	South	5000	4000
	East	5000	3000

¹ Barfoot (1972) states a value of 6000 gamma. However, based on the data presented in Appendix A-2 of Barfoot's report, the size of the dead band in the potentiometer of the compass apparently has been taken as the equivalent of 9 degrees while we use 9 bits or 3 degrees as the correct value. Therefore, we have recomputed the direction errors for this trial (see the plot of direction error as a function of field strength in Appendix 1.

(three trials for the Plessey and Aanderaa current meters, each with a different heading), we decided to extend his results by conducting further tests on the Aanderaa RCM-4 current meter and by testing two other current meters, the Braincon type 381 and the General Oceanics Model 6011. The Braincon current meter was chosen since it has been widely used in the Arctic, while the General Oceanics current meter is a recently developed instrument which utilizes three orthogonal Hall effect sensors to measure components of the magnetic field. From measured values of the components, together with the inclination of the meter from the vertical, the direction of the currents is computed. The Aanderaa and Braincon current meters both have permanent magnet viscous damped compasses to provide a magnetic north reference direction. A large vane is attached to the body of these current meters and the water current direction is determined as the orientation of the current meter with respect to magnetic north.

3. Laboratory Test Procedure

The laboratory tests were made at the Geomagnetic Laboratory, Earth Physics Branch, Department of Energy, Mines and Resources near Ottawa, from April 13th to 20th, 1977, employing the same facilities as those used by Barfoot (1972). Within a small non-magnetic building (Figure 1a), the current meters were placed inside a set of Helmholtz coils (Figure 1b). Helmholtz coils consist of three pairs of wire coils mounted on large (130 cm in length) wooden frames so that a current applied to each pair of coils results in a magnetic field directed between this pair of coils near the centre of the enclosed region. The three pairs of coils are arranged orthogonally (Figure 2a) with two horizontal fields being produced, the H field aligned in the direction of magnetic north and the D field aligned 90° clockwise from this. The Z field is parallel to the local field of gravity.

During the tests, electrical currents were applied to the D and H coils to produce magnetic fields equal and opposite to the horizontal component of the geomagnetic field. These currents were varied to compensate for temporal changes in the geomagnetic field as measured by a flux gate magnetometer at another location within the Geomagnetic Laboratory. From direct measurements of the magnetic field strength at the centre of the region enclosed by the Helmholtz coils made from time to time during the course of the tests, it is estimated that the remaining horizontal component of the magnetic field is less than 100 gamma.

While conducting tests on the current meters, the ambient vertical component of the geomagnetic field was not cancelled since the vertical magnetic field has nearly the same strength in Ottawa and the Canadian Arctic Islands.

To test the direction sensitivity of the Aanderaa and Braincon current meters, an additional electrical current was applied to the D or H coils to generate known magnetic fields. First, a reference field with a field strength of 16,000 or 20,000 gamma was created to orient the magnetic compass in a known direction. Then, the reference field was removed and a magnetic field, usually orientated at 90° to the reference field, was produced. This field



Figure 1a: The non-magnetic building within which the tests were carried out

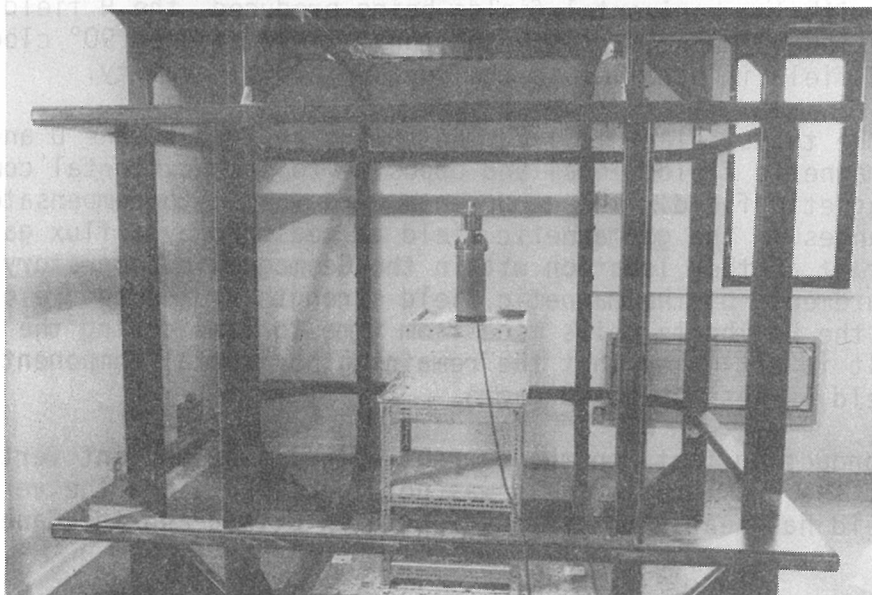


Figure 1b: An Aanderaa current meter within the Helmholtz coils.

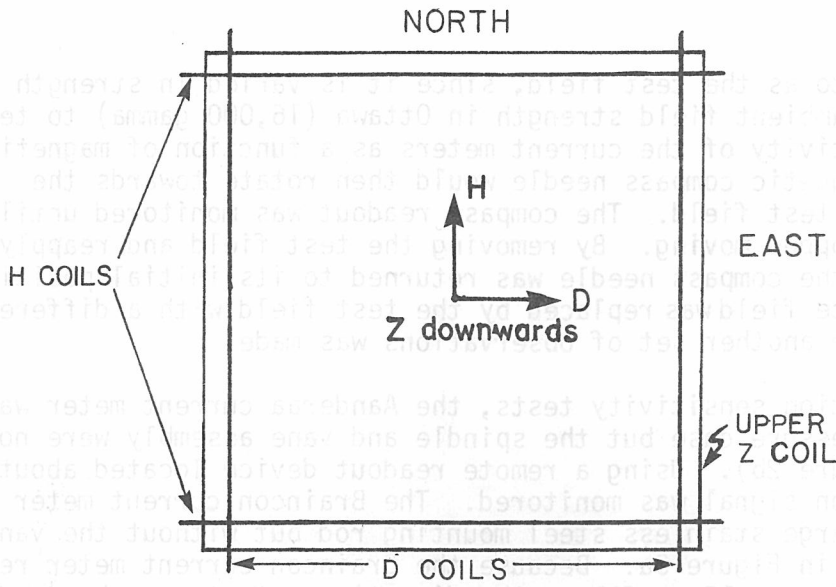


Figure 2a: Schematic diagram of the Helmholtz coils (top view)



Figure 2b: The Aanderaa RCM-4 current meter within the Helmholtz coils.

will be referred to as the test field, since it is varied in strength from near zero to the ambient field strength in Ottawa (16,000 gamma) to test the directional sensitivity of the current meters as a function of magnetic field strength. The magnetic compass needle would then rotate towards the direction of this test field. The compass readout was monitored until the compass needle stopped moving. By removing the test field and reapplying the reference field, the compass needle was returned to its initial position. Then, the reference field was replaced by the test field with a different field strength and another set of observations was made.

For the direction sensitivity tests, the Aanderaa current meter was mounted in its pressure case but the spindle and vane assembly were not attached (see Figure 2b). Using a remote readout device located about 8 m away, the direction signal was monitored. The Braincon current meter was tested with the large stainless steel mounting rod but without the vane assembly as shown in Figure 3a. Because the Braincon current meter records its data, optically, on 16 mm film, the direction output was observed visually by removing the upper cap and camera and looking down on to the compass display from above.

For the General Oceanics current meter, the test procedures were somewhat different. The current meter was placed in a field of constant field strength (2,000 gamma, 3,000 gamma, 5,000 gamma, 6,000 gamma or 16,000 gamma) and rotated in increments through 180 degrees. For each heading of the current meter, the digital output from the three orthogonal field sensors and the tilt sensor were recorded. From these data, the measured heading was computed and compared to the actual heading. The General Oceanics current meter was tested without its pressure case in order to connect the deck readout unit (see Figure 3b). While testing this meter without its pressure case may not be a fair test due to possible magnetization of the case which could produce direction errors, the test results indicate that large errors due to limited digital resolution occur. These errors, discussed in Section 4, are sufficiently large that the absence of the pressure case is unlikely to change the conclusions regarding the direction sensitivity of this instrument.

During the course of the tests, the importance of placing the compass unit of the current meter near the centre of the region enclosed by the Helmholtz coils became evident. For example, during trials with the compass of the Aanderaa current meter located 20 cm below the vertical centre of the coils (130 cm in length), the measured direction sensitivity was markedly poorer (e.g. the field strength required to reduce the direction error to 5 degrees was 1,000 to 2,000 gamma higher when the compass level was 20 cm below the centre of the field). In this report, we shall only discuss the results of those trials in which the compass level of the Aanderaa or Braincon current meters was within 10 cm of the vertical centre of the Helmholtz coils.

4. Results

In presenting the results we shall use the following terminology :

relative direction error ($\Delta\theta$) - the difference between the indicated

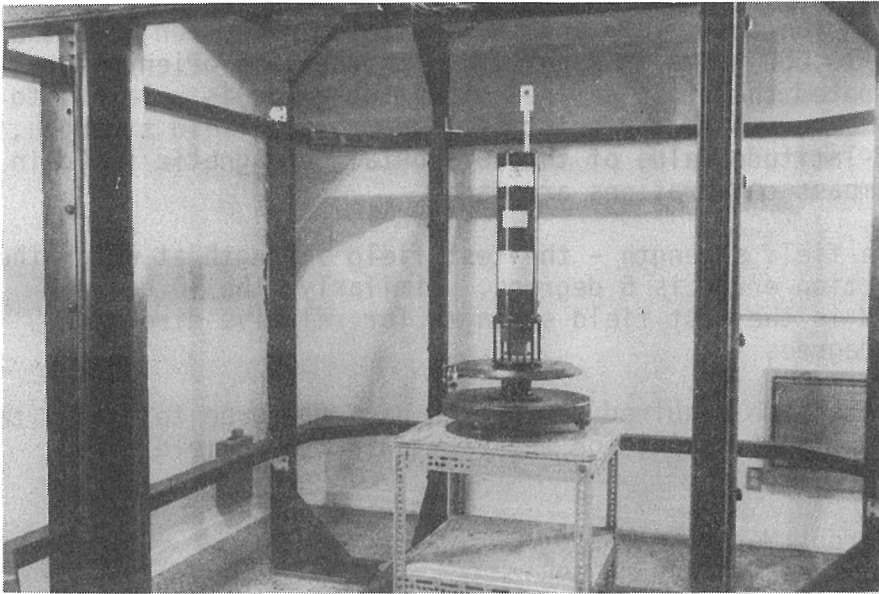


Figure 3a: The Braincon current meter under testing

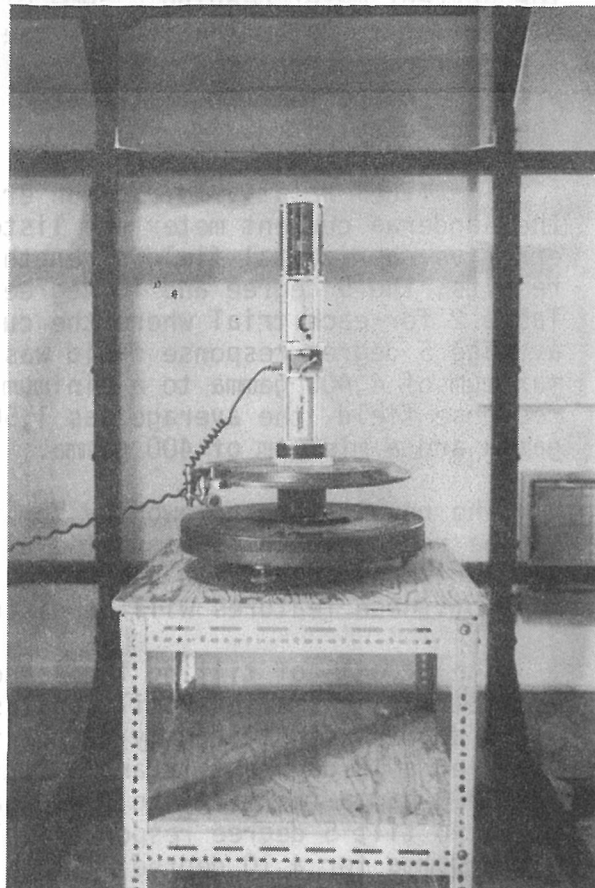


Figure 3b: The General Oceanics current meter undergoing tests.

direction using the test field and the indicated direction when the test field is 16,000 gamma in magnitude with the same orientation. It should be noted that this defined direction error is relative to any direction error which may exist at 16,000 gamma field strength, a typical mid-latitude value of the horizontal geomagnetic field in which most compass calibrations are made.

5 degree response field strength - the test field strength at which the relative direction error is 5 degrees. Similarly, the 10 degree response field is the test field strength for relative direction errors of 10 degrees.

response time - the time required for the compass to agree to within two degrees of the final reading for the particular test field being applied.

4.1 Aanderaa Current Meter

4.1.1 Direction Sensitivity

For the Aanderaa current meter, nine different trials of the direction sensitivity were made, with each trial involving a different combination of the test field direction, reference field direction and the current meter heading. Some of these trials were repeated so that a total of 13 determinations of the direction sensitivity were made. In addition, seven trials of the direction sensitivity were conducted with the current meter tilted at either 5 degrees or 10 degrees from the horizontal.

The final relative direction errors measured during each trial of the Aanderaa current meter are listed and presented as plots of direction error vs. horizontal field strength in Appendix 1. To summarize the results, the 5 degree and 10 degree response fields are listed in Table 2 for each trial where the current meter was not tilted. The average 5 degree response field was 2,540 gamma, ranging from a maximum of 4,400 gamma to a minimum of 700 gamma. For the 10 degree response field, the average was 1,500 gamma with a maximum of 2,800 gamma and a minimum of 400 gamma.

The results are noteworthy for two reasons - the large variation in the response fields among the different trials, and the generally lower response fields in comparison with Barfoot's (1972) results. Both of these features will be discussed in the following section.

The effect of tilting the Aanderaa current meter on the direction sensitivity is small for tilt angles of 5 degrees, while tilt angles of 10 degrees significantly reduce the direction sensitivity. For example, a 10 degree tilt angle increased the 5 degree response field from 900 gamma (no tilt) to 5,400 gamma for trial 2. For trial 6, the zero tilt 5 degree response field was 1,700 gamma as compared to 7,500 gamma for a 10 degree tilt.

Table 2

The 5 degree and 10 degree response fields of the Aanderaa current meter.

a. zero tilt

Trial No.	Time/Date	Variable Field	Reference Field	C.M. Heading	5° Response (γ)	10° Response (γ)
1/1	944/14	D-	H+	0	1900	900
1/2	1632/14	D-	H+	0	3000	1600
1/3	1516/16	D-	H+	0	1700	900
2/1	1404/14	H-	H+	0	3200	1600
3/1	1455/14	H+	D-	0	4400	2800
3/2	936/20	H+	D-	0	3300	1700
4/1	1700/14	D-	H+	225	3400	2200
4/2	1217/20	D-	H+	225	2100	1500
5/1	1439/16	D+	H+	0	2300	1500
6/1	1200/20	H+	D+	0	1700	<1000
7/1	1152/20	H-	D+	0	700	400
8/1	1233/20	D-	H+	135	2800	1500
9/1	1249/20	D-	H-	135	2500	1400
mean					2540	1460

b. non-zero tilt

Trial No.	Time/Date	Tilt Angle	Var. Field	Ref. Field	C.M. Heading	5° Response (γ)	10° Response (γ)
1/T5		5	D-	H+	0	<3000	-
2/T10	1601/16	10	H-	H+	0	5400	2400
5/T5	1532/16	5	D+	H+	0	2500	1600
6/T5	1122/20	5	H+	D+	0	<1000	<1000
6/T10	1020/20	10	H+	D+	0	7500	3500

4.1.2 Response Time

Using data from five of the zero-tilt Aanderaa trials, an estimate of the response time of the Aanderaa compass as a function of the test field strength was made. The response times in Figure 4 are in fact over-estimated, since taking a reading with the Aanderaa current meter locks the compass for a few seconds. During the tests, a reading was taken approximately once every 25 seconds - the time required to make a complete recording of the data. The response time appears to vary inversely with the test field strength. The time required for two degree agreement with the final value averages 150 seconds for a 500 gamma variable field and 32 seconds for a 3,000 gamma field. At 6,000 gamma, the one degree response time is less than 20 seconds.

4.2 Braincon Current Meter

4.2.1 Direction Sensitivity

A total of 14 separate tests of the direction sensitivity of the Braincon current meter was made. The results, given in Table 3, indicate that the Braincon current meter requires larger horizontal magnetic fields than the Aanderaa current meter to agree within 5° and 10° of the true magnetic field direction. The average 5° response field is 3,800 gamma ranging from 1,700 gamma to 9,900 gamma. The respective values for the 10° response field is a mean of 3,200 gamma ranging from 1,200 gamma to 7,300 gamma.

One intriguing feature of the Braincon tests was the presence of a secondary peak in the relative direction error ($\Delta\theta$) as the strength of the test magnetic field was increased. Unlike the Aanderaa current meter in which $\Delta\theta$ decreased monotonically with increasing variable magnetic field strength, the tests of the Braincon current meter showed an initial sharp decrease in $\Delta\theta$ as the test magnetic field strength was increased, but then as it was further increased, $\Delta\theta$ passed through zero and began to increase with the opposite sign of the errors found at small magnetic fields. $\Delta\theta$ would then rise to a maximum of from 1 to 7 degrees in absolute value, depending on the particular orientations used in the test. Further increases in the magnetic field strength resulted in $\Delta\theta$ decreasing (see plots in Appendix 2). In eight of the 14 tests, the maximum of this secondary $\Delta\theta$ peak was greater than five degrees. This maximum $\Delta\theta$ generally was found at test field strengths between 5,000 and 8,000 gamma.

4.2.2 Response Time

Using data from six of the trials on the Braincon current meter, the time required for the reading to agree within 2 degrees of its final reading is plotted in Figure 5. The response times are lower than those found for the Aanderaa current meter (as shown in Figure 4). In all of the trials considered, the longest time for agreement with the final reading, to within 2°, was 40 seconds. The response times show

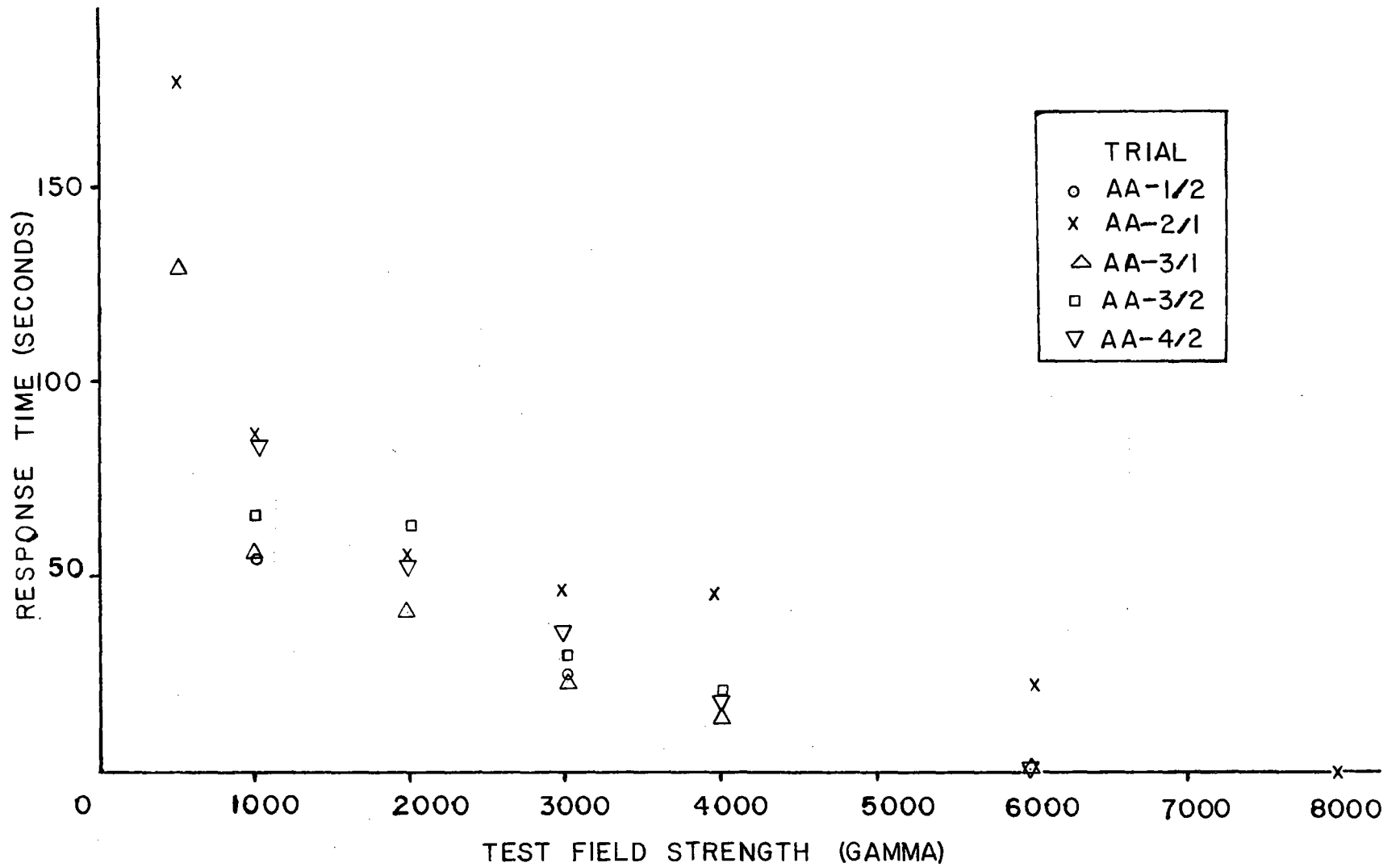


Figure 4: The measured response time of the Aanderaa current meter as a function of magnetic field strength.

Table 3

The 5 degree and 10 degree response fields of the Braincon current meter

a. zero tilt						
Trial No.	Time/Date	Variable Field	Reference Field	C.M. Heading	5 ^o Response (Kγ)	10 ^o Response(Kγ)
1/1	1228/18	D-	H+	0	4.8	4.1
1/2	1538/18	D-	H+	0	5.0	4.1
1A/2	1600/18	D+	H+	0	4.0	3.3
1/3	0909/19	D-	H+	0	3.9*	3.7
1/NW	0948/19	D-	H+	315	4.2*	3.5
1/W	1040/19	D-	H+	270	2.8*	2.2
1/NE	1055/19	D-	H+	45	4.6	4.0
1/E	1110/19	D-	H+	90	3.8*	3.4
1/S	1124/19	D-	H+	180	9.9	7.3
3/1	0916/18	H+	D-	0	2.2*	1.6
3/2	0829/19	H+	D-	0	1.7*	1.2
4/1	1323/18	D-	H+	225	2.7*	2.0
4A/1	1355/18	D-	H+	135	2.3*	1.9
4B/2	1429/18	D+	H+	135	2.0*	1.7
Mean					3.8	3.2

* indicates that a secondary maximum of 5 degrees error or more occurs at field strengths greater than the 5 degree response field. See text for details.

a slower decrease with increasing field strength; in fact, the data suggests that the response time reaches a minimum at test fields of 6,000 gamma, which corresponds to the secondary maximum in $\Delta\theta$.

4.3 General Oceanics Current Meter

4.3.1 Direction Sensitivity

Using the manufacturer's calibrations, the General Oceanics current meter indicated large direction errors even at the ambient horizontal field strength in Ottawa (approximately 16,000 gamma); the measured errors ranged from 18.0 to 49.7 degrees. As a result of these large errors, the tilt sensor and each of the three Hall effect sensors were recalibrated using the Geomagnetic Laboratory facilities. Applying these calibration values rather than those of the manufacturer, the indicated directions at the ambient horizontal field strength were re-computed. As the direction errors, over a range of headings from -90 to 90 degrees, were between -2.1 and 2.3 degrees, our own calibrations were judged to be adequate.

The indicated directions were measured at four different horizontal field strengths over a range of angles (see Figure 6). The results indicate very large errors at low field strengths; the root mean square error at 2,000 gamma was 35.1 degrees and at 3,000 gamma the error was 16.1 degrees. At 6,000 gamma, the root mean square error was 13.1 degrees, ranging from -0.4 degrees to -19.8 degrees. One contributing factor to these large errors is the low resolution of the Hall effect sensors; our calibration data indicate that a change of one bit corresponds to a change of 700 gamma in horizontal field strength. Therefore, at 2,000 gamma, the direction which is determined as $\arctan(H_y, H_x)$, where H_y and H_x are the indicated y- and x- components of the horizontal magnetic field strength, could be in error by as much as 20 degrees (e.g. take actual $H_x = 1051$, actual $H_y = 1749$; indicated $H_x = 1400$, indicated $H_y = 1400$; from these values, the indicated direction would be 45° while the actual direction is 31.0 degrees - a difference of 14 degrees). At 6,000 gamma field strength, the corresponding worst case error would be ± 5 degrees, while at 16,000 gamma, the worst case error is reduced to ± 1.8 degrees. While it seems likely that other factors contribute to these large direction errors as well, the resolution of the Hall effect sensors must be increased to provide reliable direction measurements in the Canadian Arctic Archipelago.

Another problem which could produce appreciable errors is uncertainty in the inclination of the instrument. While one of the Hall effect sensors always remains level (the so-called y-component which is perpendicular to the direction in which the instrument is free to tilt), the other two sensors tilt according to the inclination of the instrument. To find the x-component necessary for computing the instrument heading and thereby the current direction, the readings from these two sensors are combined using the relation

$$H_x = (C_1.HH + C_2) \cos \theta + (C_3.HV + C_4) \cdot \sin \theta$$

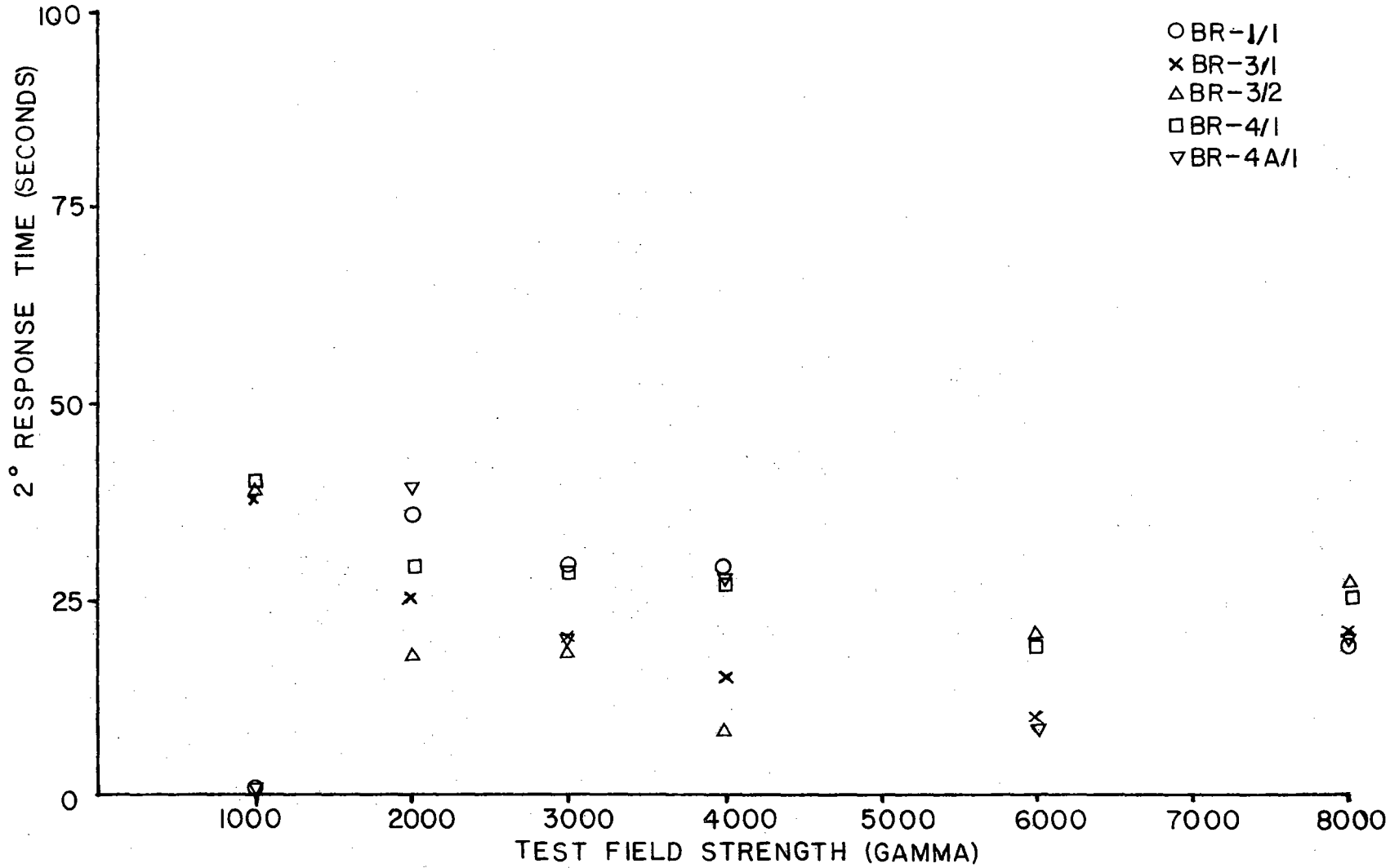


Figure 5: The measured response time of the Braincon current meter as a function of magnetic field strength.

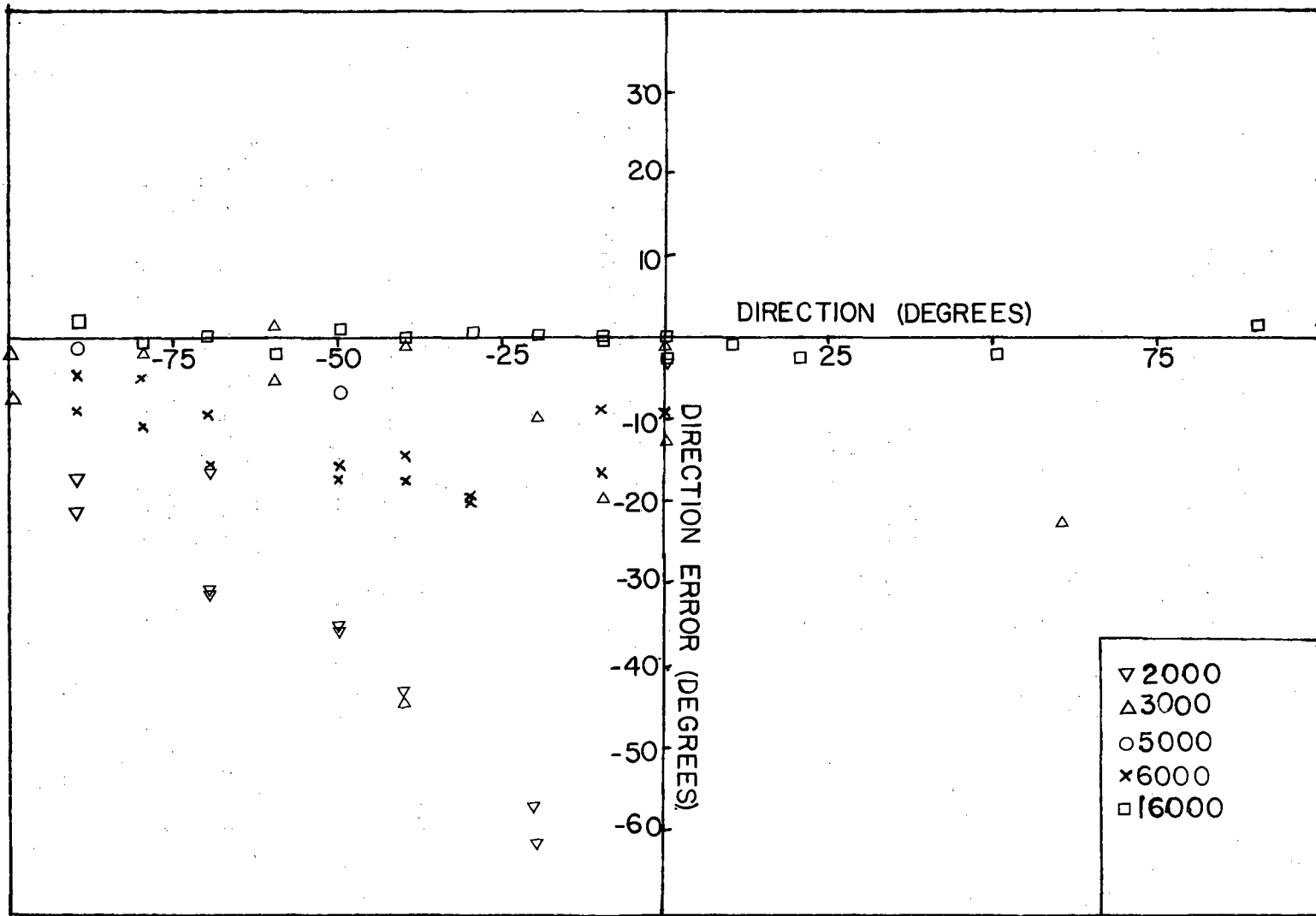


Figure 6: The direction error of the General Oceanics current meter plotted for various headings at different test field strengths.

where θ is the angle of tilt from the vertical, HH and HV are the digital outputs from two Hall effect sensors which are directed in the +x direction and -Z direction, respectively, when the instrument is level and C_1 , C_2 , C_3 and C_4 are calibration constants. The largest errors will arise when the instrument's heading is perpendicular to the earth's magnetic field, i.e. when the currents are directed towards magnetic east or magnetic west. With such a current at a horizontal field strength of 3,000 gamma, the direction error resulting from an error of ± 0.5 degree (manufacturer's specification) in tilt would be ± 9.4 degrees. The corresponding errors at 2,000 gamma, 6,000 gamma and 16,000 gamma are ± 47 , ± 14 and ± 1.8 degrees, respectively. Clearly, at low horizontal magnetic fields, the tilt accuracy of the instruments limits the reliability of direction data.

4.3.2 Response Time

The response of this current meter to abrupt changes in the applied horizontal magnetic fields or in the heading of the instrument appears to be very fast. In fact, the response is fast enough that no quantitative estimates could be made of the response time other than to say it is certainly less than 10 seconds.

5. Discussion

The direction sensitivity of the Aanderaa and Braincon current meters varies significantly both with time and with orientation of the instruments relative to the applied magnetic field direction. The causes of these variations are not clear; one possibility is that extraneous horizontal magnetic fields are present which are not allowed for in these tests.

In order to estimate the strength of such an extraneous magnetic field, consider the difference in the measured 5 degree response field of the Aanderaa current meter for two cases of trial 1 : 3,000 gamma at 16:32 EST, April 14 and 1,700 gamma at 15:16, April 16. This difference could be explained by the presence of an additional magnetic field with a component of 130 gamma directed perpendicular to the variable field direction in the earlier case. These additional magnetic fields could originate internally within the instrument being tested, or externally. We shall consider the latter possibility first.

Unaccounted-for magnetic fields of external origin could be caused by temporal changes in the geomagnetic field; however, the Helmholtz coils have circuitry which compensates for such changes. Direct measurements of the remnant magnetic field, when the Helmholtz coils were set to cancel the geomagnetic field, showed that the remaining magnetic field strength was always less than 100 gamma.

An extraneous magnetic field could arise from a slight difference between the plane in which the compass magnet rotates and the plane that is perpendicular to the ambient Z field when the horizontal geomagnetic field is exactly cancelled. Interestingly enough, both of these planes could deviate slightly from a true horizontal plane, defined with reference to a geopotential level;

a deviation of the former plane from the true horizontal would be due to slight imbalance of the compass needle, and a deviation of the latter plane could be caused by a misalignment of the Helmholtz coils with true horizontal and vertical planes. Any difference between the plane of the compass magnet movements and the plane perpendicular to the Z field would amount to an extraneous magnetic field resulting in direction errors, although this hypothesis does not explain changes in direction errors with time.

Keenan (1976) has studied the magnetic fields generated internally by the Aanderaa current meter. From tests conducted on 40 Aanderaa instruments at the Bedford Institute of Oceanography, using the ambient geomagnetic field (horizontal component of 17,400 gamma), he identified three major sources of error in the direction :

1. "The error due to the field about a magnetized pressure case range in magnitude from zero to 11.6 degrees peak-to-peak."
(Mean peak-to-peak error was 2.8 degrees).
2. "The error due to the field about the energized encoder magnet varied from 2.8 to 11.7 degrees peak-to-peak."
(Mean peak-to-peak error was 5.8 degrees).
3. "The error due to the field about the rotor and follower magnets had a magnitude of from 1.8 to 5.4 degrees peak-to-peak."
(Mean peak-to-peak error was 3.8 degrees).

Given the magnitude of these reported errors, they may be very important in explaining the direction errors reported in this report. For example, an 11 degree peak-to-peak direction error at 17,400 gamma is equivalent to an internal magnetic field strength of $\pm 1,675$ gamma. In a horizontal magnetic field of 3,000 gamma, the direction error would be increased to an amplitude of 29 degrees, or a peak-to-peak value of 58 degrees.

In our tests on the Aanderaa current meter, the effect of errors due to magnetization of the pressure case was tested in one trial only. For trial AA-1/3, with the pressure case removed and the measurements repeated, no significant change was found in the 5 degree response field strength. Keenan (1976) points out that this error can be "drastically reduced" by de-magnetizing the pressure case before use.

The second error arises when the encoder magnet is energized to set a '1' bit to a '0' bit as the mechanical encoder produces a 10-bit data word prior to recording. The largest errors from this effect are due to the most recent activations of the encoder-magnet before the compass is locked for the direction reading. In the Aanderaa current meter, the largest errors will be due to the occurrence of '0's in the pressure word (which immediately precedes the direction word) and, in particular, larger errors will arise from pressure word bits which are less significant in value. Throughout the tests on the Aanderaa current meter, the pressure reading was 54 decimal or 0000110110 binary. Thus, a moderate and constant error from the encoder-magnet is expected.

The size of the third Aanderaa direction error, listed above, due to the rotor and follower magnets, depends on the orientation of these magnets. From one trial to another, this orientation would change and, therefore, the direction errors due to this effect would vary as well. (In actual operation, this error is reduced because these magnets are in motion and the compass magnet is unable to follow these changes.)

The errors due to pressure case magnetization and encoder magnet activation should be fixed in relation to the heading of the Aanderaa current meter. For the encoder magnet error, Keenan's (1976) results indicate that the direction error varies sinusoidally over the full range (0-360 degrees) of directions, with the maximum occurring at zero degrees. To check for a similar pattern of direction errors in our results, direction errors measured at 3,000 gamma horizontal field strength were plotted as a function of true indicated direction for all of the Aanderaa tests as shown in Figure 7. The results, whilst not conclusive, do suggest that the largest positive errors occur near zero degrees direction and the largest negative direction errors near 180 degrees direction. A visual fit of these direction errors to a sinusoidal variation with direction suggests a peak-to-peak error of approximately 8 degrees. The equivalent data from Barfoot's (1972) study shows a positive direction error is found at zero degrees and a negative direction error at 215 degrees. The peak-to-peak error for this data set appears to be approximately 20 degrees.

One of the most remarkable results of Keenan's (1976) work is the differences in the direction errors among the forty-odd Aanderaa current meters tested. This makes the discrepancy between the results of Barfoot (1972) and the present study appear more reasonable. As well, the test procedures may have differed in some significant way between the present study and that of Barfoot. For example, the absence of a pressure sensor on the Aanderaa instrument used in the earlier study, would suggest that the pressure word was always 0000000000 binary, which would result in the maximum error from the encoder magnets. Another possible difference in test methods would be the degree to which instruments were centered vertically with respect to the artificial magnet fields.

Clearly, further tests are required to define the direction sensitivity of Aanderaa current meters, using additional Aanderaa meters. As well, better test procedures are required to separate the different possible internal errors. The possibility of modifying the Aanderaa current meter to reduce the effect of these errors should be considered; for example, Keenan (1976) suggests that the encoder activation error can be substantially reduced by disabling the pressure channel and wiring it to read all 'ones', or by moving "the channel-changer pin . . . to a point on the encoder cap rim 120° behind its normal position" so as to allow more time for the compass needle to return to its former position before it is clamped for the direction reading.

Other sources of direction error will be encountered during the field operation of current meters, which are not studied in this report. These include magnetic fields associated with materials used in construction of the mooring, such as steel wire rope. All of our tests have been conducted with

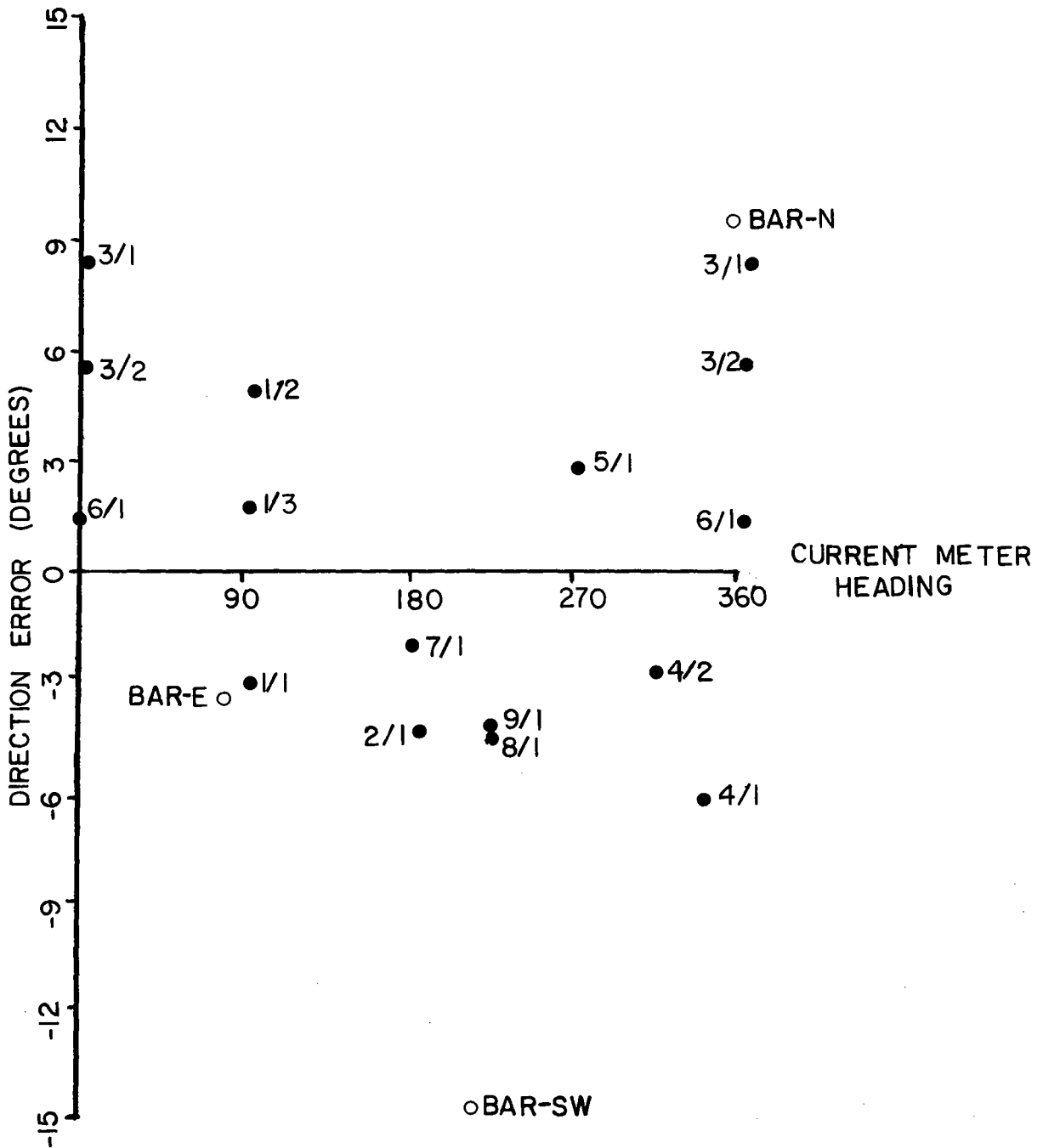


Figure 7: The relative direction errors of the Aanderaa current meters measured in a 3000 gamma horizontal field plotted as a function of the true instrument heading. The points labelled 'BAR' are taken from the study of Barfoot(1972).

a stationary current meter; additional errors can arise when the current meter is subjected to linear or angular accelerations which occur on current meters mounted on a sub-surface mooring. Another error to consider is the temporal variations in the geomagnetic field, which become relatively larger as one approaches the magnetic poles. In areas with a 3,000 gamma horizontal geomagnetic field strength, the mean daily range of magnetic variation is approximately 9 degrees while in regions of 6,000 gamma field strength, the corresponding mean daily range of magnetic variation is 4 degrees (Canadian Hydrographic Service, 1975). During magnetically-disturbed days, the daily range in magnetic variation may triple.

6. Summary and Conclusions

Laboratory tests of the directional sensitivity of three current meters, the Aanderaa RCM-4, the Braincon type 381 and the General Oceanics Model 6011 were conducted in horizontal magnetic fields ranging from 250 to 16,000 gamma. The Aanderaa current meter performed best in low magnetic fields with the average horizontal magnetic field strength necessary to produce agreement in direction to within 5 degrees being 2,500 gamma, ranging from 700 to 4,400 gamma. Measurements on the Braincon current meter showed the average 5 degree response magnetic field is 3,800 gamma, ranging from a minimum of 1,700 gamma to a maximum of 9,900 gamma. The General Oceanics current meter was less reliable in direction measurements at low magnetic field strength, with errors of typically about 16 degrees in fields of 3,000 gamma and about 13 degrees in fields of 6,000 gamma. For use in Polar regions, the least bit resolution of this instrument must be increased from its present value of 700 gamma per bit. In addition, at low magnitude fields, the accuracy of direction measurements of the General Oceanics meter depends on measurements of the instrument's inclination being accurate to within a few tenths of a degree.

The time for the current meters to agree within 2 degrees of their final direction-reading is largest for the Aanderaa meter (about 32 secs at 3,000 gamma), smallest for the General Oceanics meter (less than 10 seconds at any field strength tested), while the Braincon meter has an intermediate value of approximately 25 seconds at 3,000 gamma field strength.

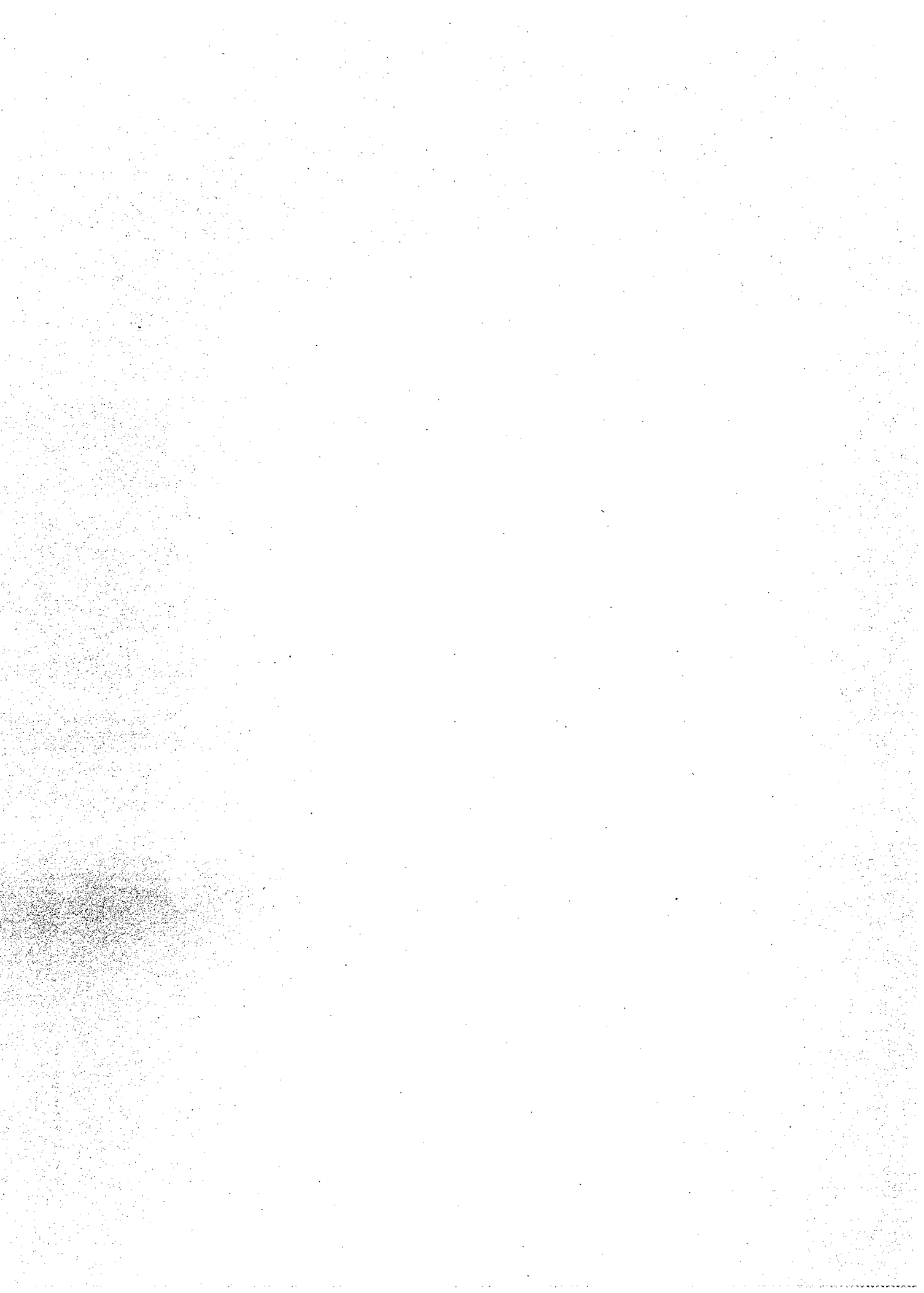
In view of the discrepancy between the results of the present study and those of Barfoot (1972) as to the directional sensitivity of the Aanderaa current meter, we suggest that further tests be made using additional Aanderaa current meters. These tests should attempt to isolate errors due to internal magnetic fields of the Aanderaa meters reported in Keenan (1976).

7. References

- Avis, R. A. and L. K. Coachman (1971). Current Measurements on Smith Sound - Northern Baffin Bay, September, 1968. Baffin Bay - Northwater Project Scientific Report No. 2. The Arctic Institute of North America, Washington, D. C. pp. 26.
- Barber, F. G. (1965). Current Observations in Fury and Hecla Strait. J. Fish. Res. Bd., Canada, 22(1), pp. 225 - 229.
- Barfoot, G. L. (1972). Current Meter Direction Detection as a Function of Magnetic Field Intensity. Canada Centre for Inland Waters, Environment Canada, Burlington, Ontario. 34 pp.
- Canadian Hydrographic Service (1975). Magnetic Chart of the Canadian Arctic 1975.0. Canada, Department of the Environment, Ottawa.
- Keenan, P. V. (1976). Sources of Compass Error within the Aanderaa Recording Current Meter. Bedford Institute of Oceanography Report Series BI-R-76-2. Environment Canada, Dartmouth, N. S. 30 pp.
- Lewis, E. L. (1975). Oceanographic Instruments for Arctic Use. Marine Science Communications, 1(3 & 4), pp. 249-268.

Appendix 1

Aanderaa Test Results



DIRECTION THRESHOLD TEST OF AANDERAA

TIME: 09:44 APR.14,1977 TRIAL NAME:AA-1/1
VAR. FIELD: D- REF. FIELD: H&
CM HEADING: 0 DEGREES TILT ANGLE: 0 DEGREES

CURRENT (MA)	MAG. FIELD (K-GAMMA)	DIR. ERROR (DEGREES)
6.2	.24	-19.4
12.6	.49	-13.7
18.8	.74	-12.3
25.3	.99	-8.8
50.6	1.98	-4.6
75.8	2.97	-3.5
75.8	2.97	-3.2
101.3	3.97	-2.5
126.7	4.96	-1.8
152.0	5.95	-1.4
177.3	6.94	-1.4
202.6	7.94	-1.1
227.9	8.93	-1.1
253.3	9.92	-.7
278.7	10.92	-.7
304.0	11.91	-.7
380.4	14.90	-.4
507.3	19.87	.0

DIRECTION THRESHOLD TEST OF AANDERAA

TIME: 16:32 APR.14,1977 TRIAL NAME:AA-1/2
VAR. FIELD: D- REF. FIELD: H&
CM HEADING: 0 DEGREES TILT ANGLE: 0 DEGREES

CURRENT (MA)	MAG. FIELD (K-GAMMA)	DIR. ERROR (DEGREES)
25.1	.98	13.7
25.3	.99	13.7
50.6	1.98	7.7
75.5	2.96	4.9
75.9	2.97	4.9
126.8	4.97	2.8

DIRECTION THRESHOLD TEST OF AANDERAA

TIME: 15:16 APR.16,1977 TRIAL NAME:AA-1/3
VAR. FIELD: D- REF. FIELD: H&
CM HEADING: 0 DEGREES TILT ANGLE: 0 DEGREES

CURRENT (MA)	MAG. FIELD (K-GAMMA)	DIR. ERROR (DEGREES)
76.1	2.98	1.8
152.0	5.95	1.1

DIRECTION THRESHOLD TEST OF AANDERAA

TIME: 14:04 APR.14,1977 TRIAL NAME:AA-2/1
VAR. FIELD: H- REF. FIELD: H&
CM HEADING: 0 DEGREES TILT ANGLE: 0 DEGREES

CURRENT (MA)	MAG. FIELD (K-GAMMA)	DIR. ERROR (DEGREES)
13.1	.50	-24.3
26.2	1.00	-13.7
52.2	1.99	-7.7
78.5	3.00	-5.3
104.7	4.00	-3.9
129.9	4.96	-3.2
157.9	6.03	-2.1
209.4	8.00	-1.8
262.7	10.04	-1.4
399.7	15.27	-.4
525.1	20.00	.0

DIRECTION THRESHOLD TEST OF AANDERAA

TIME: 14:55 APR.14,1977 TRIAL NAME:AA-3/1
VAR. FIELD: H& REF. FIELD: D-
CM HEADING: 0 DEGREES TILT ANGLE: 0 DEGREES

CURRENT (MA)	MAG. FIELD (K-GAMMA)	DIR. ERROR (DEGREES)
.0	.00	127.4
13.1	.50	67.2
25.9	.99	42.2
51.4	1.96	15.1
78.5	3.00	8.4
104.0	3.97	5.6
132.8	5.07	3.9
156.7	5.99	3.2
210.4	8.04	2.1
261.1	9.98	1.4
395.5	15.11	.4
523.1	19.99	.0

DIRECTION THRESHOLD TEST OF AANDERAA

TIME: 09:36 APR.20,1977 TRIAL NAME:AA-3/2
VAR. FIELD: H& REF. FIELD: D-
CM HEADING: 0 DEGREES TILT ANGLE: 0 DEGREES

CURRENT (MA)	MAG. FIELD (K-GAMMA)	DIR. ERROR (DEGREES)
26.7	1.02	38.4
50.7	1.94	8.8
78.9	3.01	5.6
103.0	3.96	3.5
157.5	6.02	1.8
212.2	8.11	1.1
261.1	9.98	.7
315.1	12.04	.0
367.4	14.04	.4
418.6	15.99	.0

DIRECTION THRESHOLD TEST OF AANDERAA

TIME: 17:00 APR.14,1977 TRIAL NAME:AA-4/1
VAR. FIELD: D- REF. FIELD: H&
CM HEADING: 225 DEGREES TILT ANGLE: 0 DEGREES

CURRENT (MA)	MAG. FIELD (K-GAMMA)	DIR. ERROR (DEGREES)
25.1	.96	-26.4
64.3	2.52	-8.4
75.5	2.96	-6.3
88.9	3.48	-4.9

DIRECTION THRESHOLD TEST OF AANDERAA

TIME: 12:17 APR.20,1977 TRIAL NAME:AA-4/2
VAR. FIELD: D- REF. FIELD: H&
CM HEADING: 225 DEGREES TILT ANGLE: 0 DEGREES

CURRENT (MA)	MAG. FIELD (K-GAMMA)	DIR. ERROR (DEGREES)
25.4	.99	-14.1
50.7	1.99	-5.3
76.0	2.96	-2.8
101.3	3.97	-2.1
152.0	5.95	-1.1
253.2	9.92	-.7

DIRECTION THRESHOLD TEST OF AANDERAA

TIME: 14:39 APR.16,1977 TRIAL NAME:AA-5/1
VAR. FIELD: D& REF. FIELD: H&
CM HEADING: 0 DEGREES TILT ANGLE: 0 DEGREES

CURRENT (MA)	MAG. FIELD (K-GAMMA)	DIR. ERROR (DEGREES)
25.3	.99	-19.7
50.7	1.99	-6.0
75.3	2.95	-2.8
100.4	3.93	-2.5
152.8	5.99	-1.1
511.9	20.05	.0

DIRECTION THRESHOLD TEST OF AANDERAA

TIME: 12:00 APR.20,1977 TRIAL NAME:AA-6/1
VAR. FIELD: H& REF. FIELD: D-
CM HEADING: 0 DEGREES TILT ANGLE: 0 DEGREES

CURRENT (MA)	MAG. FIELD (K-GAMMA)	DIR. ERROR (DEGREES)
26.1	1.00	8.8
52.1	1.99	3.2
77.3	2.95	1.4

DIRECTION THRESHOLD TEST OF AANDERAA

TIME: 11:52 APR.20,1977 TRIAL NAME:AA-7/1
VAR. FIELD: H- REF. FIELD: D&
CM HEADING: 0 DEGREES TILT ANGLE: 0 DEGREES

CURRENT (MA)	MAG. FIELD (K-GAMMA)	DIR. ERROR (DEGREES)
26.2	1.00	-3.2
52.3	2.00	-2.1

DIRECTION THRESHOLD TEST OF AANDERAA

TIME: 12:33 APR.20,1977 TRIAL NAME:AA-8/1
VAR. FIELD: D- - REF. FIELD: H&
CM HEADING: 135 DEGREES TILT ANGLE: 0 DEGREES

CURRENT (MA)	MAG. FIELD (K-GAMMA)	DIR. ERROR (DEGREES)
25.3	.99	-13.0
50.6	1.98	-7.0
76.1	2.98	-4.6
101.3	3.97	-3.5
152.1	5.96	-2.1
253.3	9.92	-.7

DIRECTION THRESHOLD TEST OF AANDERAA

TIME: 12:49 APR.20,1977 TRIAL NAME:AA-9/1
VAR. FIELD: D- REF. FIELD: H-
CM HEADING: 135 DEGREES TILT ANGLE: 0 DEGREES

CURRENT (MA)	MAG. FIELD (K-GAMMA)	DIR. ERROR (DEGREES)
50.3	1.97	-4.2

DIRECTION THRESHOLD TEST OF AANDERAA

TIME: 15:23 APR.16,1977 TRIAL NAME:AA-1/T5
VAR. FIELD: D- REF. FIELD: H&
CM HEADING: 0 DEGREES TILT ANGLE: 5 DEGREES

CURRENT (MA)	MAG. FIELD (K-GAMMA)	DIR. ERROR (DEGREES)
76.1	2.98	2.8
152.0	5.95	1.1

DIRECTION THRESHOLD TEST OF AANDERAA

TIME: 16:01 APR.16,1977 TRIAL NAME:AA-2/T10
VAR. FIELD: H- REF. FIELD: H&
CM HEADING: 0 DEGREES TILT ANGLE: 10 DEGREES

CURRENT (MA)	MAG. FIELD (K-GAMMA)	DIR. ERROR (DEGREES)
78.5	3.00	-9.2
156.7	5.99	-3.9

DIRECTION THRESHOLD TEST OF AANDERAA

TIME: 15:32 APR.16,1977 TRIAL NAME:AA-5/T1
VAR. FIELD: D& REF. FIELD: H&
CM HEADING: 0 DEGREES TILT ANGLE: 5 DEGREES

CURRENT (MA)	MAG. FIELD (K-GAMMA)	DIR. ERROR (DEGREES)
25.4	.99	-19.0
50.6	1.98	-6.7
75.9	2.97	-3.5
101.3	3.97	1.4
151.2	5.92	-.7

DIRECTION THRESHOLD TEST OF AANDERAA

TIME: 15:50 APR.16,1977 TRIAL NAME:AA-5/T10
VAR. FIELD: D& REF. FIELD: H&
CM HEADING: 0 DEGREES TILT ANGLE: 10 DEGREES

CURRENT (MA)	MAG. FIELD (K-GAMMA)	DIR. ERROR (DEGREES)
50.6	1.98	4.2
101.4	3.97	1.8
151.2	5.92	1.1

DIRECTION THRESHOLD TEST OF AANDERAA

TIME: 11:22 APR.20,1977 TRIAL NAME:AA-6/T5
VAR. FIELD: H& REF. FIELD: D&
CM HEADING: 0 DEGREES TILT ANGLE: 5 DEGREES

CURRENT (MA)	MAG. FIELD (K-GAMMA)	DIR. ERROR (DEGREES)
26.2	1.00	.0
52.3	2.00	1.1
78.1	2.98	1.4
130.6	4.99	1.4
261.6	10.00	.4

DIRECTION THRESHOLD TEST OF AANDERAA

TIME: 10:20 APR.20,1977 TRIAL NAME:AA-6/T10
VAR. FIELD: H& REF. FIELD: D&
CM HEADING: 0 DEGREES TILT ANGLE: 10 DEGREES

CURRENT (MA)	MAG. FIELD (K-GAMMA)	DIR. ERROR (DEGREES)
26.1	1.00	-19.0
52.6	2.01	-16.9
78.4	3.00	-11.3
104.8	4.00	-8.8
157.0	6.00	-7.7
209.3	8.00	-4.2
261.6	10.00	-1.4
315.5	12.00	-.4

DIRECTION THRESHOLD TEST OF AANDERAA

TIME: 11:42 APR.20,1977 TRIAL NAME:AA-7/T5
VAR. FIELD: H- REF. FIELD: D&
CM HEADING: 0 DEGREES TILT ANGLE: 5 DEGREES

CURRENT (MA)	MAG. FIELD (K-GAMMA)	DIR. ERROR (DEGREES)
26.1	1.00	-2.1
52.1	1.99	-1.8
78.5	3.00	-1.4

DIRECTION THRESHOLD TEST OF AANDERAA

TIME: TRIAL NAME: BAR.AA-N
VAR. FIELD: H& REF. FIELD: D&
CM HEADING: 0 DEGREES TILT ANGLE: 0 DEGREES

CURRENT (MA)	MAG. FIELD (K-GAMMA)	DIR. ERROR (DEGREES)
12.7	.49	63.7
12.7	.49	35.2
25.3	.97	31.3
25.3	.97	28.5
50.7	1.94	14.4
50.7	1.94	14.1
76.0	2.90	8.4
76.0	2.90	8.4
101.3	3.87	6.7
101.3	3.87	7.0
126.7	4.84	7.0
126.7	4.84	7.4
152.0	5.81	3.9
152.0	5.81	4.2
177.3	6.77	4.2
177.3	6.77	3.9
202.6	7.74	4.2
202.6	7.74	3.9
228.0	8.71	4.2
228.0	8.71	4.6
253.3	9.68	2.8
253.3	9.68	2.5
278.6	10.65	1.8
278.6	10.65	1.1
304.0	11.62	.7
304.0	11.62	.4

DIRECTION THRESHOLD TEST OF AANDERAA

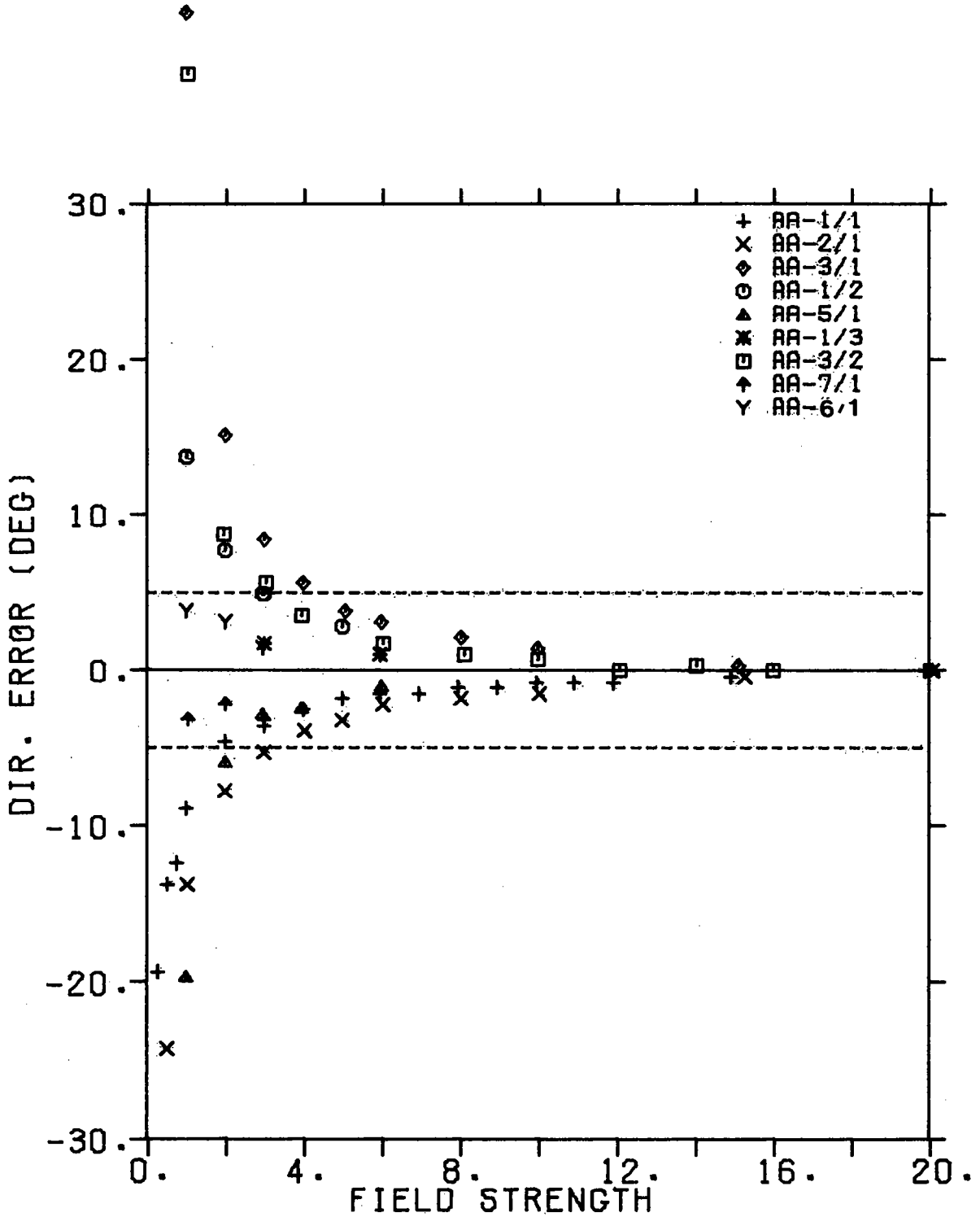
TIME: TRIAL NAME:BAR.AA-SW
VAR. FIELD: H& REF. FIELD: D&
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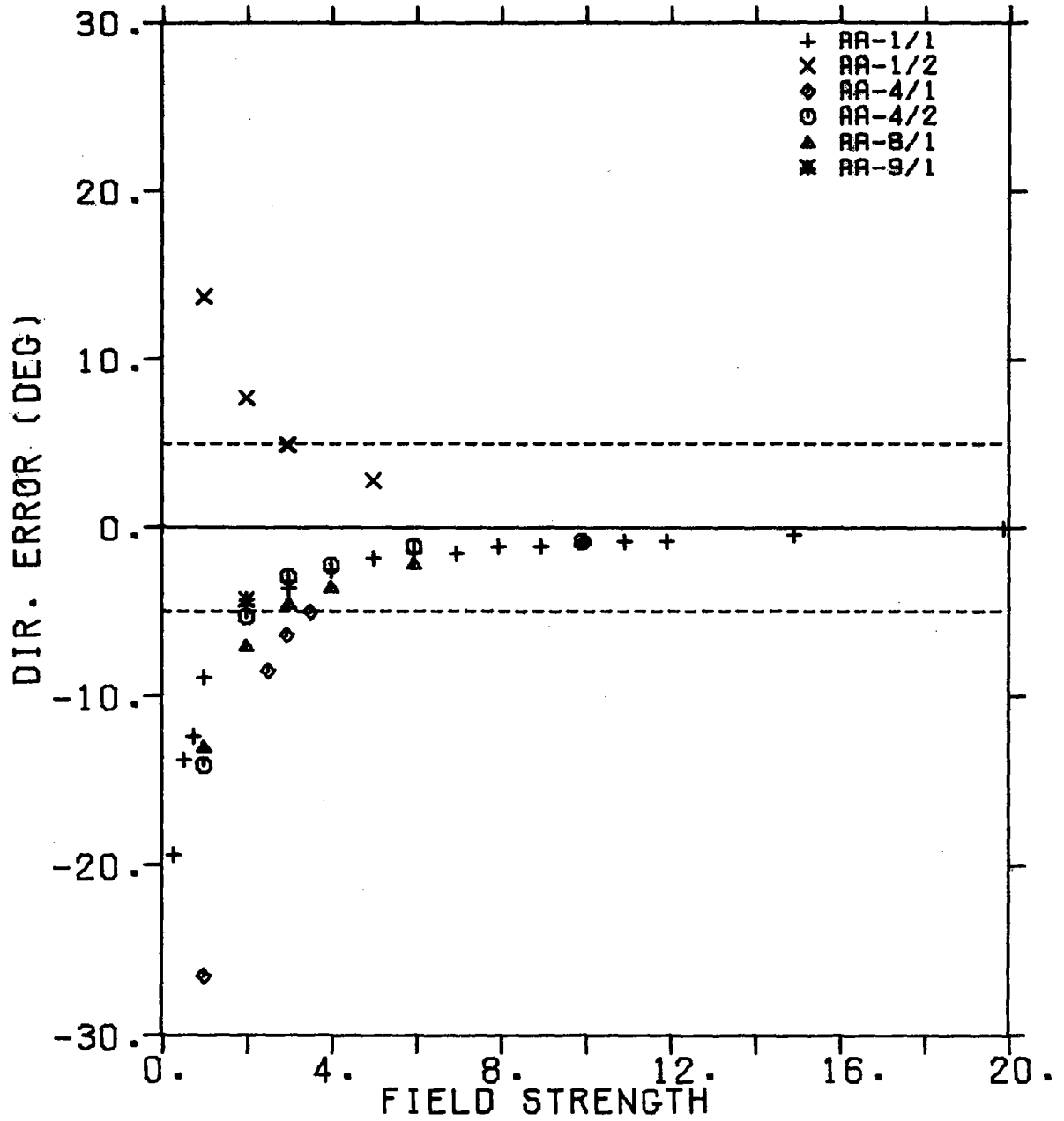
CURRENT (MA)	MAG. FIELD (K-GAMMA)	DIR. ERROR (DEGREES)
12.7	.49	-93.6
12.7	.49	-93.6
25.3	.97	-45.1
25.3	.97	-45.1
50.7	1.94	-26.0
50.7	1.94	-25.7
76.0	2.90	-15.1
76.0	2.90	-14.8
101.3	3.87	-10.6
126.7	4.84	-7.7
126.7	4.84	-8.8
152.0	5.81	-7.4
152.0	5.81	-6.3
177.3	6.77	-4.6
177.3	6.77	-6.0
202.6	7.74	-3.9
202.6	7.74	-3.9
228.0	8.71	-2.5
228.0	8.71	-2.5
253.3	9.68	-1.8
253.3	9.68	-1.4
278.6	10.65	-1.1
278.6	10.65	-1.4
304.0	11.62	-1.4
304.0	11.62	-.7

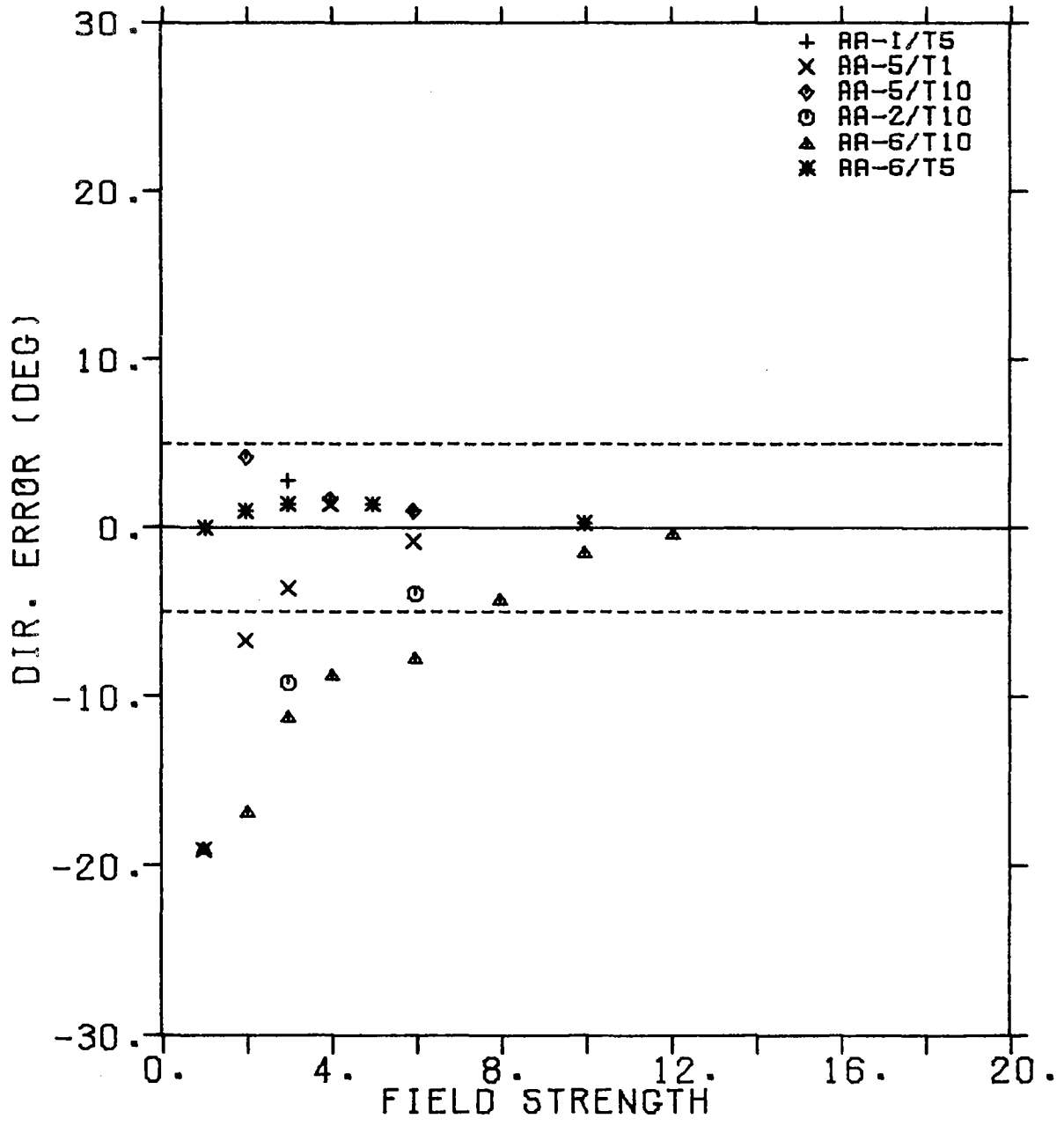
DIRECTION THRESHOLD TEST OF AANDERAA

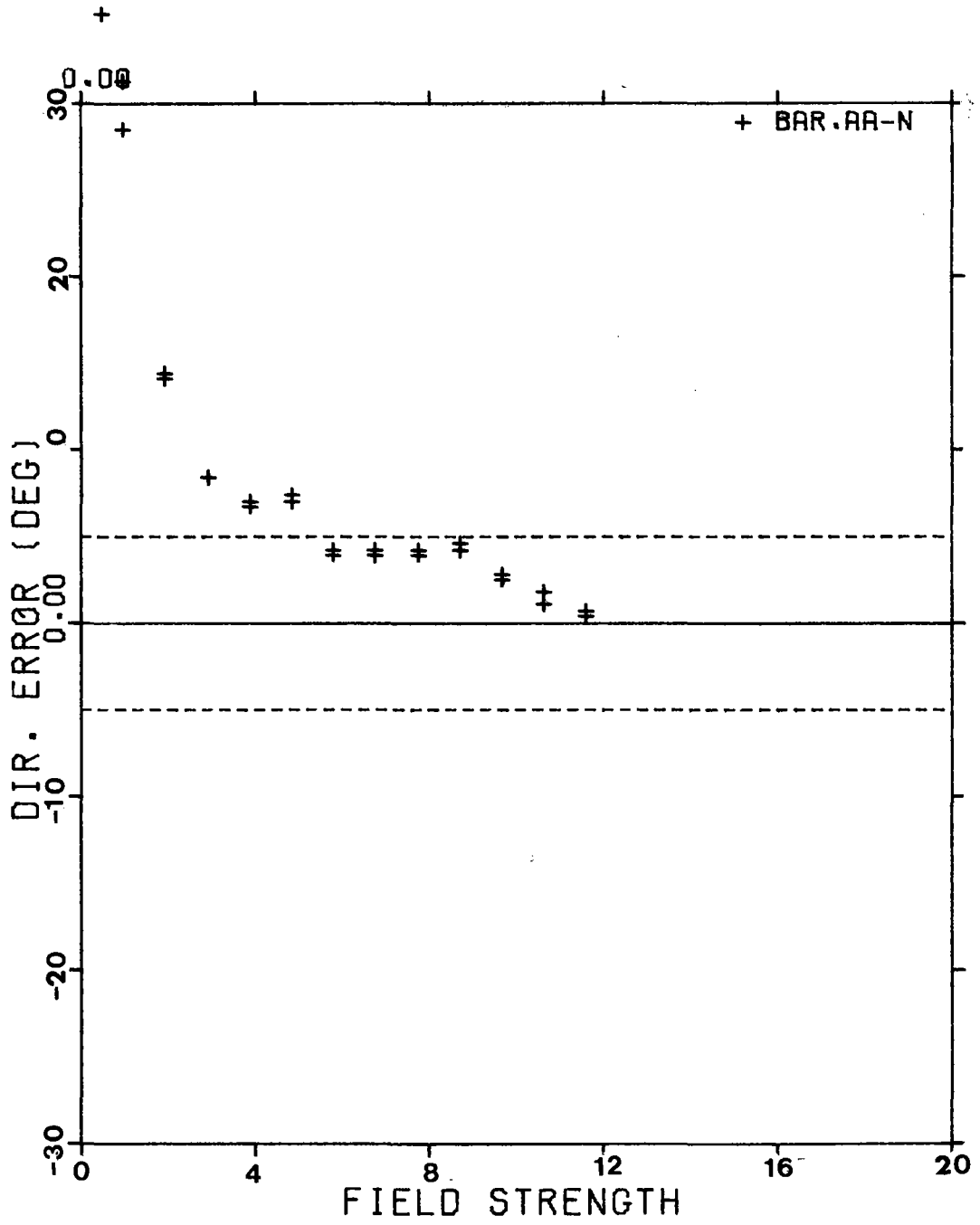
TIME: TRIAL NAME:BAR.AA-E
VAR. FIELD: H& REF. FIELD: D&
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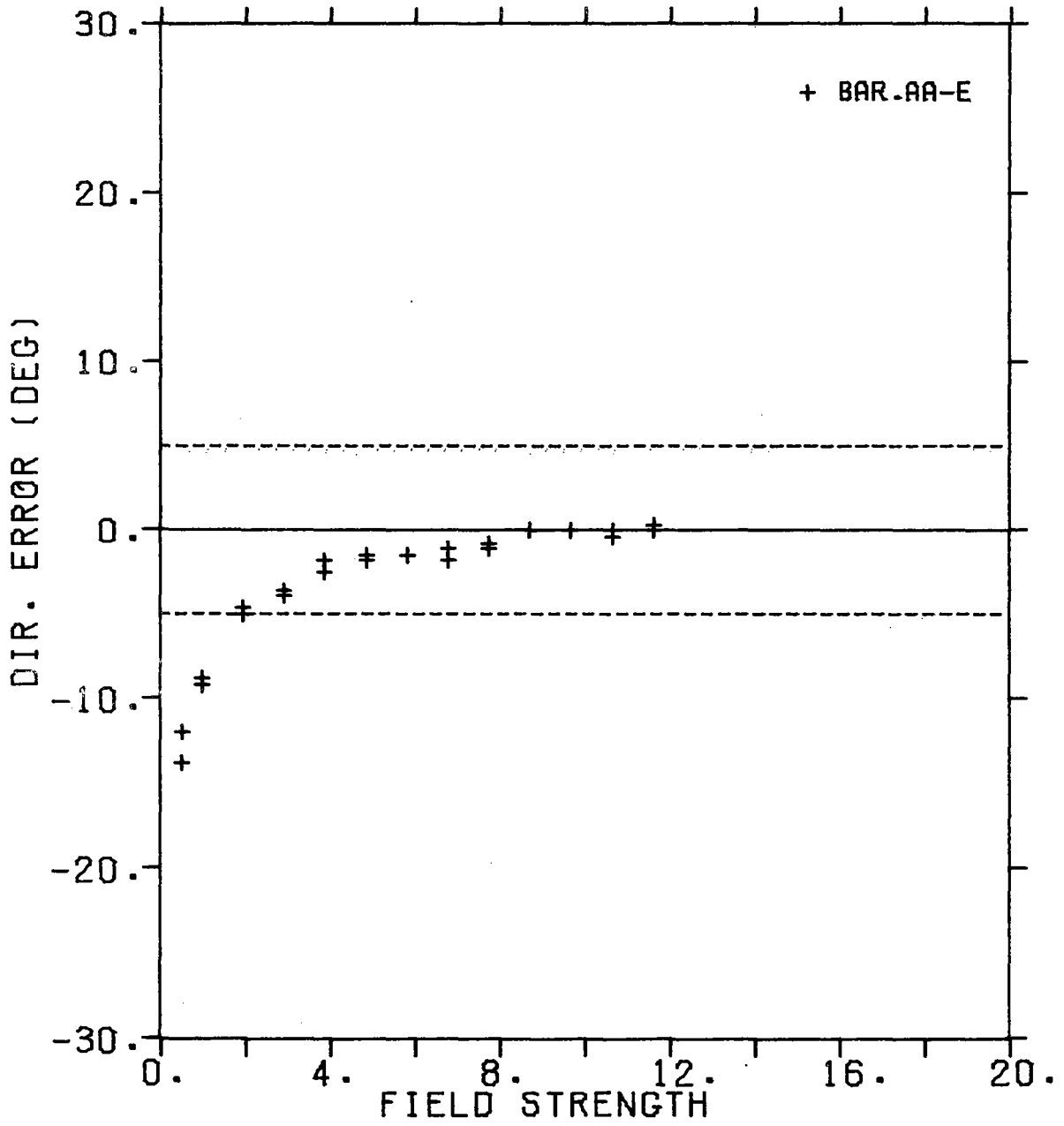
CURRENT (MA)	MAG. FIELD (K-GAMMA)	DIR. ERROR (DEGREES)
12.7	.49	-12.0
12.7	.49	-13.7
25.3	.97	-9.2
25.3	.97	-8.8
50.7	1.94	-4.9
50.7	1.94	-4.6
76.0	2.90	-3.9
76.0	2.90	-3.5
101.3	3.87	-1.8
101.3	3.87	-2.5
126.7	4.84	-1.8
126.7	4.84	-1.4
152.0	5.81	-1.4
152.0	5.81	-1.4
177.3	6.77	-1.8
177.3	6.77	-1.1
202.6	7.74	-.7
202.6	7.74	-1.1
228.0	8.71	.0
228.0	8.71	.0
253.3	9.68	.0
253.3	9.68	.0
278.6	10.65	.0
278.6	10.65	-.4
304.0	11.62	.4
304.0	11.62	.0

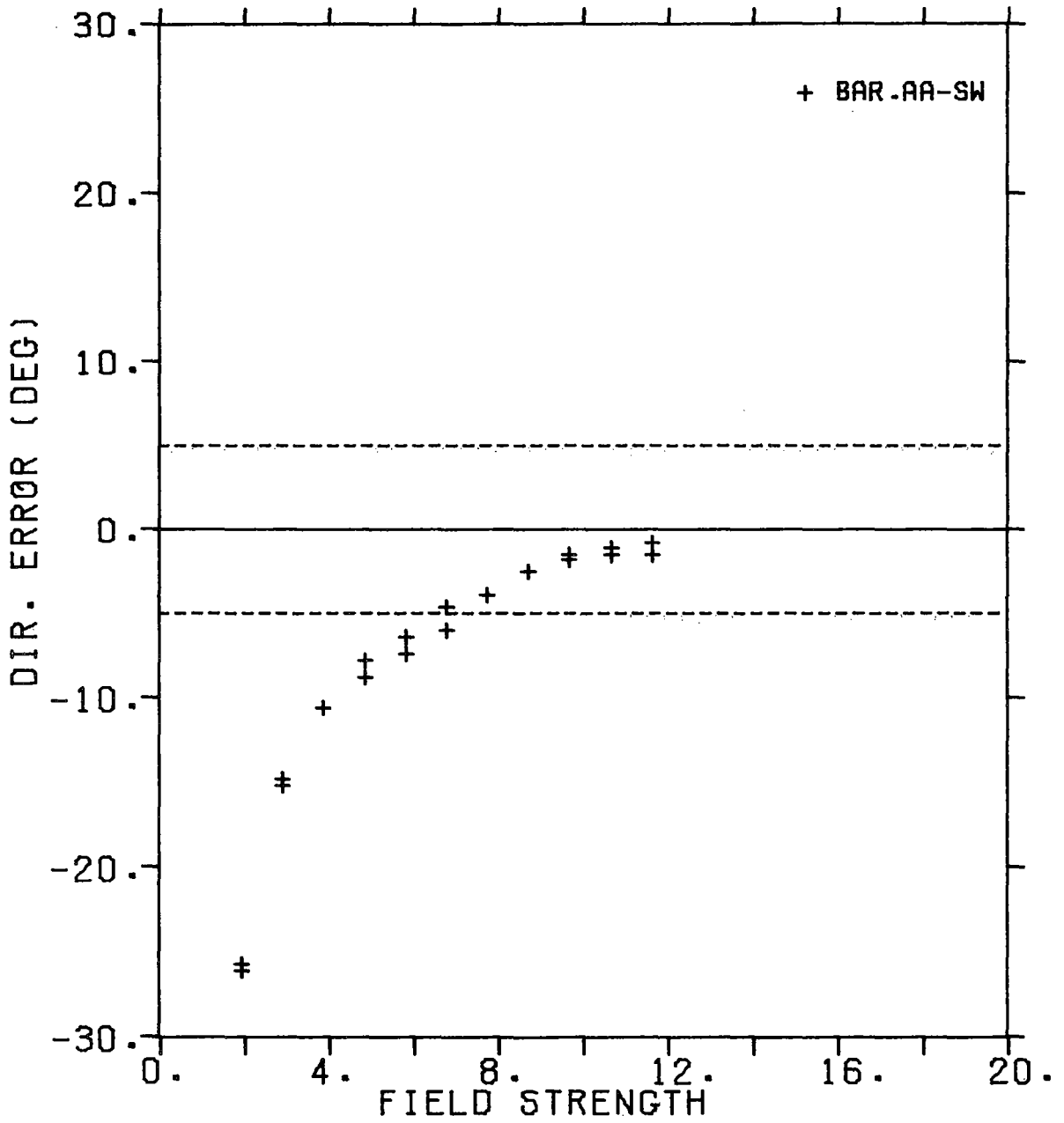










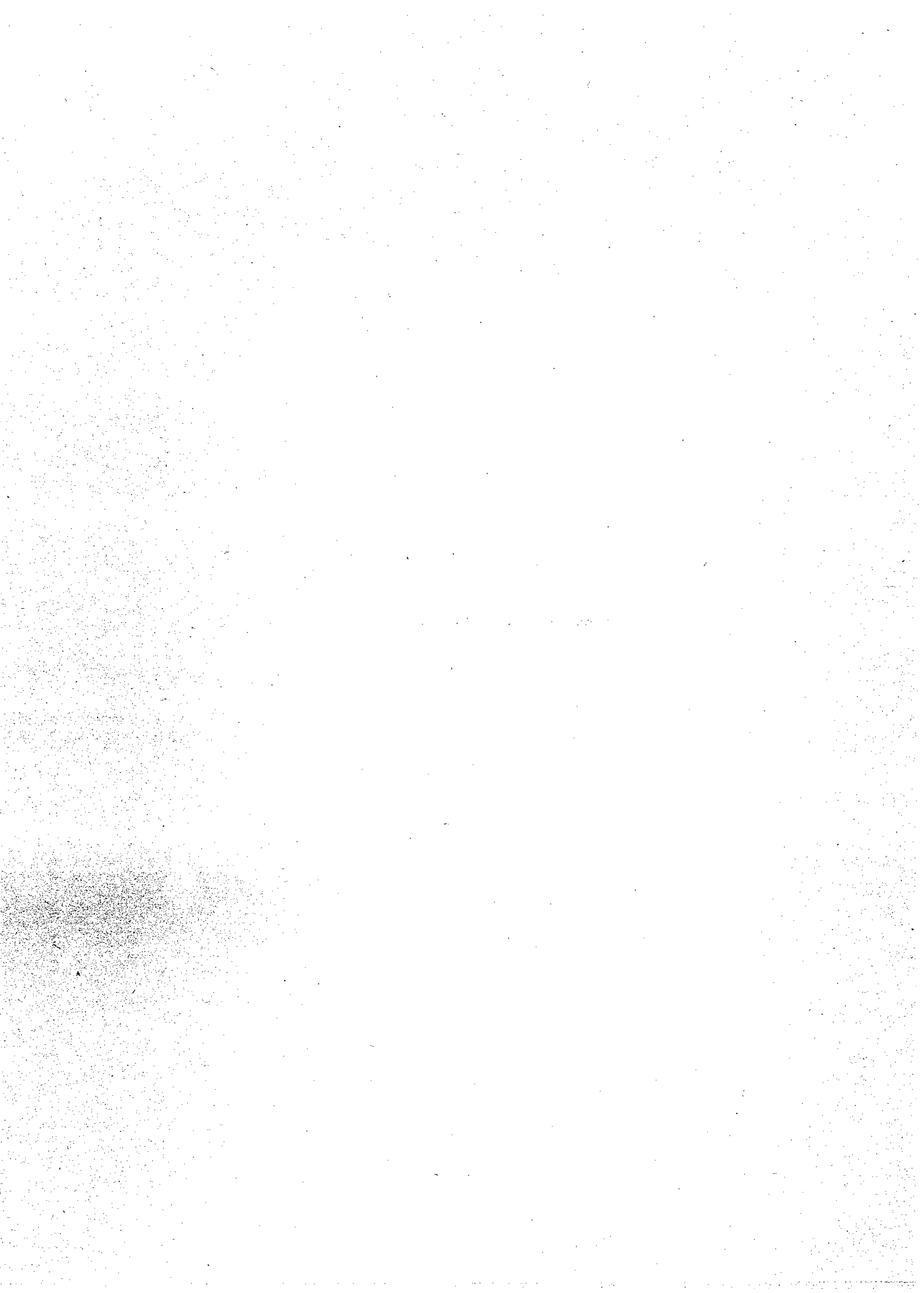


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Appendix 2

Braincon Test Results



DIRECTION THRESHOLD TEST OF BRAINCON

TIME: 09:16 APR.18,1977 TRIAL NAME:BR-3/1
VAR. FIELD: H& REF. FIELD: D-
CM HEADING: 0 DEGREES TILT ANGLE: 0 DEGREES

CURRENT (MA)	MAG. FIELD (K-GAMMA)	DIR. ERROR (DEGREES)
26.2	1.00	28.0
39.4	1.51	11.0
52.3	2.00	7.0
78.0	2.98	-1.0
78.3	2.99	.0
78.5	3.00	2.0
103.6	3.96	.0
130.8	5.00	-2.0
156.7	5.99	-5.0
157.2	6.01	-6.0
210.3	8.04	-4.0
261.7	10.00	-2.0
313.5	11.98	-3.0
420.0	16.05	.0

DIRECTION THRESHOLD TEST OF BRAINCON

TIME: 12:28 APR.18,1977 TRIAL NAME:BR-1/1
VAR. FIELD: D- REF. FIELD: H&
CM HEADING: 0 DEGREES TILT ANGLE: 0 DEGREES

CURRENT (MA)	MAG. FIELD (K-GAMMA)	DIR. ERROR (DEGREES)
25.4	.99	-93.0
40.0	1.57	-61.0
50.6	1.98	-42.0
75.9	2.97	-20.0
76.1	2.98	-20.0
101.1	3.96	-11.0
126.9	4.97	-4.0
151.4	5.93	-1.0
202.9	7.95	2.0
253.8	9.94	1.0
302.4	11.84	.0

DIRECTION THRESHOLD TEST OF BRAINCON

TIME: 13:23 APR.18,1977 TRIAL NAME:BR-4/1
VAR. FIELD: D- REF. FIELD: H&
CM HEADING: 225 DEGREES TILT ANGLE: 0 DEGREES

CURRENT (MA)	MAG. FIELD (K-GAMMA)	DIR. ERROR (DEGREES)
25.3	.99	-30.0
50.5	1.98	-10.0
75.7	2.97	-3.0
101.3	3.97	2.0
151.1	5.92	5.0
202.6	7.94	3.0
252.2	9.88	2.0
305.1	11.95	1.0

DIRECTION THRESHOLD TEST OF BRAINCON

TIME: 13:55 APR.18,1977 TRIAL NAME:BR-4A/1
VAR. FIELD: D- REF. FIELD: H&
CM HEADING: 135 DEGREES TILT ANGLE: 0 DEGREES

CURRENT (MA)	MAG. FIELD (K-GAMMA)	DIR. ERROR (DEGREES)
25.3	.99	-92.0
50.8	1.99	-8.0
76.1	2.98	1.0
101.2	3.96	4.0
152.0	5.95	8.0
202.7	7.94	6.0
253.5	9.93	4.0
304.0	11.91	2.0

DIRECTION THRESHOLD TEST OF BRAINCON

TIME: 14:29 APR.18,1977 TRIAL NAME:BR-4B/2
VAR. FIELD: D& REF. FIELD: H&
CM HEADING: 135 DEGREES TILT ANGLE: 0 DEGREES

CURRENT (MA)	MAG. FIELD (K-GAMMA)	DIR. ERROR (DEGREES)
25.3	.99	25.0
50.1	1.96	5.0
76.1	2.98	-2.0
153.5	6.01	-7.0
254.2	9.96	-2.0

DIRECTION THRESHOLD TEST OF BRAINCON

TIME: 14:54 APR.18,1977 TRIAL NAME:BR-4B/T10
VAR. FIELD: D& REF. FIELD: H&
CM HEADING: 135 DEGREES TILT ANGLE: 10 DEGREES

CURRENT (MA)	MAG. FIELD (K-GAMMA)	DIR. ERROR (DEGREES)
50.6	1.98	3.0
75.8	2.97	-3.0
101.3	3.97	-4.0
152.0	5.95	-7.0
202.7	7.94	-4.0
253.3	9.92	-1.0
303.9	11.90	.0

DIRECTION THRESHOLD TEST OF BRAINCON

TIME: 15:38 APR.18,1977 TRIAL NAME:BR-1/2
VAR. FIELD: D- REF. FIELD: H&
CM HEADING: 0 DEGREES TILT ANGLE: 0 DEGREES

CURRENT (MA)	MAG. FIELD (K-GAMMA)	DIR. ERROR (DEGREES)
50.5	1.98	-47.0
76.1	2.98	-21.0
101.3	3.97	-11.0
126.7	4.96	-5.0
152.0	5.95	-1.0
253.8	9.94	2.0

DIRECTION THRESHOLD TEST OF BRAINCON

TIME: 16:00 APR.18,1977 TRIAL NAME:BR-1A/2
VAR. FIELD: D& REF. FIELD: H&
CM HEADING: 0 DEGREES TILT ANGLE: 0 DEGREES

CURRENT (MA)	MAG. FIELD (K-GAMMA)	DIR. ERROR (DEGREES)
50.5	1.98	29.0
76.1	2.98	13.0
101.2	3.96	5.0
126.6	4.96	-1.0
152.0	5.95	-2.0
202.5	7.93	-2.0
253.5	9.93	-1.0
303.9	11.90	.0

DIRECTION THRESHOLD TEST OF BRAINCON

TIME: 08:29 APR.19,1977 TRIAL NAME:BR-3/2
VAR. FIELD: H& REF. FIELD: D-
CM HEADING: 0 DEGREES TILT ANGLE: 0 DEGREES

CURRENT (MA)	MAG. FIELD (K-GAMMA)	DIR. ERROR (DEGREES)
25.8	.99	12.0
39.3	1.50	7.0
52.2	1.99	2.0
78.7	3.01	-2.0
104.4	3.99	-5.0
130.9	5.00	-7.0
157.0	6.00	-6.0
209.4	8.00	-4.0
261.6	10.00	-2.0
313.9	11.99	-2.0

DIRECTION THRESHOLD TEST OF BRAINCON

TIME: 09:09 APR.19,1977 TRIAL NAME:BR-1/3
VAR. FIELD: D- REF. FIELD: H&
CM HEADING: 0 DEGREES TILT ANGLE: 0 DEGREES

CURRENT (MA)	MAG. FIELD (K-GAMMA)	DIR. ERROR (DEGREES)
50.6	1.98	-50.0
67.6	2.65	-33.0
76.2	2.98	-26.0
101.2	3.96	-4.0
126.7	4.96	-6.0
151.9	5.95	-2.0
202.7	7.94	1.0
253.2	9.92	1.0
305.2	11.95	1.0

DIRECTION THRESHOLD TEST OF BRAINCON

TIME: 09:48 APR.19,1977 TRIAL NAME: 08R-1/NW
VAR. FIELD: D- REF. FIELD: H&
CM HEADING: 315 DEGREES TILT ANGLE: 0 DEGREES

CURRENT (MA)	MAG. FIELD (K-GAMMA)	DIR. ERROR (DEGREES)
50.5	1.98	-28.0
76.0	2.98	-14.0
101.4	3.97	-6.0
126.0	4.94	-2.0
152.0	5.95	3.0
152.0	5.95	4.0
202.4	7.93	2.0
202.8	7.94	5.0
253.4	9.93	4.0
303.9	11.90	.0

DIRECTION THRESHOLD TEST OF BRAINCON

TIME: 10:40 APR.19,1977 TRIAL NAME:BR-1/W
VAR. FIELD: D- REF. FIELD: H&
CM HEADING: 270 DEGREES TILT ANGLE: 0 DEGREES

CURRENT (MA)	MAG. FIELD (K-GAMMA)	DIR. ERROR (DEGREES)
50.6	1.98	-12.0
76.1	2.98	-3.0
101.5	3.98	2.0
152.0	5.95	7.0

DIRECTION THRESHOLD TEST OF BRAINCON

TIME: 10:55 APR.19,1977 TRIAL NAME:BR-1/NE
VAR. FIELD: D- REF. FIELD: H&
CM HEADING: 45 DEGREES TILT ANGLE: 0 DEGREES

CURRENT (MA)	MAG. FIELD (K-GAMMA)	DIR. ERROR (DEGREES)
50.6	1.98	-50.0
76.0	2.98	-20.0
101.3	3.97	-10.0
126.7	4.96	-2.0
151.9	5.95	2.0

DIRECTION THRESHOLD TEST OF BRAINCON

TIME: 11:10 APR.19,1977 TRIAL NAME:BR-1/E
VAR. FIELD: D- REF. FIELD: H&
CM HEADING: 90 DEGREES TILT ANGLE: 0 DEGREES

CURRENT (MA)	MAG. FIELD (K-GAMMA)	DIR. ERROR (DEGREES)
50.5	1.98	-36.0
76.0	2.98	-14.0
101.3	3.97	-4.0
152.0	5.95	5.0

DIRECTION THRESHOLD TEST OF BRAINCON

TIME: 11:24 APR.19,1977 TRIAL NAME:BR-1/S
VAR. FIELD: D- REF. FIELD: H&
CM HEADING: 180 DEGREES TILT ANGLE: 0 DEGREES

CURRENT (MA)	MAG. FIELD (K-GAMMA)	DIR. ERROR (DEGREES)
25.3	.99	-1.0
50.4	1.97	10.0
75.9	2.97	11.0
101.2	3.96	13.0
152.1	5.96	14.0
201.9	7.91	8.0
253.3	9.92	5.0
405.6	15.89	1.0

