THE DEVELOPMENT OF A HIGHLY SENSITIVE MAGNETOMETER FOR SOLAR-TERRESTRIAL INVESTIGATIONS

The design, construction and calibration of a Hall device magnetometer is given. Ferromagnetic foils were used to increase the sensitivity, magnetic field changes of 150 nanotesla being measurable.

The report discusses how sensitivity depends on foil length, problems of calibration and temperature sensitivity are also included.

The magnetometer was used to determine magnetically noisy locations by Dip angle measurements of the field. Magnetic disturbances due to solar phenomena are described but non were observed due to the temperature sensitivity. However variations of the field due to the Electrical storm of 24/5/89 are included and a simple estimation of the current passing in the lightning discharges is given.

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INTRODUCTION

I became interested in the Earth's magnetic field about a year ago while working at the NPL. While there I aquired some Hall effect devices and decided in my spare time to build an instrument to measure the field. Various designs were tried and, although much was achieved, many problems still existed.

I was then allowed to continue the investigation by making it my final year project.

In the first designs it was a simple matter to obtain small signals for the field, however the literature suggested that much larger gains would be required if small changes in the field were to be observable.

The Hall effect devices have a built-in amplifier of fixed gain and so the instrument circuitry must have high gains if sensitivity is to be achieved. As a result of the high gains the Hall devices showed there intrinsic limitations.
For example, the noise was greater, variations in supply voltage effected the output, and temperature sensitivity (TS) was observed.

The aims of the project were the following, to build a highly sensitive magnetometer capable of measuring small variations of the Earth's field, to be stable to flucuations in supply voltage and temperature, and if time permits, to use the instrument to study local terrestrial and solar phenomena.

Two sets of probes were constructed to be used with the magnetometer circuitry, the first was a simple affair giving limited sensitivity, the second was for detailed investigation of the Earth's field.

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SECTION 1

HALL DEVICE MAGNETOMETER

Circuit design and practice

The Hall devices used were the RS type [1], these consisted of the Hall plates and an amplifier of set gain in a single, small package 5mm square.

These were designed to measure fairly large fields, about 1E-3 Tesla. Since the Earth's field is of the order 1E-5 Tesla amplifications of the order of 100 were required. This was simply achieved using Op-amps, Fig.1. PrintedCircuit board construction was used for all the electronics. [3]

Using gains of this order showed the limitations of the Hall devices, for example, the noise on the output increased and the devices were found to be sensitive to changes in temperature and supply voltage.

Five volt regulators were used in the design and were found to reduce the variations on the output, due to the supply, to a level too small to measure provided the supply voltage was greater than 7 volts.

The temperature sensitivity (TS) problem was tackled using a differential type circuit Fig.2. Two Hall devices were used in the probe sets, these were mounted 180° to one another Fig.13a,13c,14a,14c

It was hoped that temperature variations would be cancelled when the amplified signals, from the devices, were subtracted Fig.2. However signals due to magnetic fields would be 180° out of phase and would add producing an output with an acceptably low TS.

The noise on the output was about 50mV. This was considerably reduced by the integrator stage to about 5mV. However, there was a flicker noise level of about 30mV still present on the output. This was to be the limiting factor on the magnetometer sensitivity. The origin of this noise was thought to be from the hall devices.

Changes in the Earth's field due to Solar phenomena can occur over periods of many minutes to hours, terrestrial disturbances can be shorter in duration, and so a 1 second time constant was used as this was thought to be the best compromise between ease of measurement, responcitivity and noise on output.

the output of the system was displayed on a chart recorder because most of the measurements were to be done over long time periods. The integrator also improved the motion of the chart recorder pen, reducing high frequency vibrations.

<u>Temperature sensitivity (TS)</u>

It was found that the TS of any two devices were not identical although the response to magnetic fields were intrinsically linear and found to be very consistent from device to device. Thus, it was assumed that although they have different TS, the response would still be linear and so the gain of the amplifier with the most TS Hall device could be reduced to try and match the two.

This did not affect the linear response of the output to magnetic fields, although a slight reduction in overall sensitivity occured.

However, this procedure was to prove quite difficult in practice, it was not easy to ensure that both Hall devices were at the same temperature and also to maintain equality while varying the overall temperature.

An electronic thermometer was placed midway between the Hall devices and a bucket of ice was placed a few cm above. In this way the temperature could be varied while maintaining equality as described.

A complete cancelling of TS on the output was not found possible in the range 10-30°C. This was due to non-linear TS in the devices. However, it was possible to reduce the TS on the output from 29mV/°C to 10mV/°C by experimentation. Further, it was found that the temperature stability of the laboratory was maintained to within a few degrees (at 25°C) and thus the output was fairly stable with respect to temperature.

Over the weeks of experimentation the TS of the devices were found to vary by up to 10mV, and so the TS as given in Fig.6 is not exact.

IMPROVING SENSITIVITY

Two probe sets were constructed, the first was for simple measurements of the Earth's field and did not require any extra amplification other than that already described.
The second set was to be used for detailed measurements of the field and, as indicated, much greater gains were necessary.

The TS and flicker on the output were the main source of noise in the design and would not have improved simply by raising the gain of the amplifiers. Therefore another method was necessary in order to increase the sensitivity of the magnetometer.

Last year, while conducting experiments at home, Ferrite rod were used to increase the effective measured field, due to the high permeability of the material. What was really wanted was a more manageable material that could be cut and formed easily. A quantity of Telshield High permeability foil [2] was aquired, this seemed to be ideal.

By cutting strips of width 25mm and arranging these so that one end was in contact with the Hall devices Fig.13a,14a, considerable gains could be achieved.

Experiments for different foil lengths were carried out. By tapering the Hall device end of the foil a further increase in gain was possible Fig.3.

It was found that 50cm lengths gave optimum performance, The width was found not to affect the gain greatly, 25mm being about best.

Using this length, a gain of about 13 was obtained. Two such foils were used, one each side of the Hall device, this doubled the gain. The same was done to the other Hall device which also doubles the gain, therefore the gain due to the four foils was 2x2x13, roughly 50.

Other foil shapes and configurations may possibly improve this figure, however no time was available to carry out further investigations.

The second probe set therefore consisted of two Hall devices mounted 180° to one another, spaced about 9cm apart, a Printed circuit board was used for rigidity. This was attached to two pieces of wood 120x3x3 cm on which the foils were glued Fig. 13a,13d,14a,14d. Wooden wedges were used to raise the last 5cm of foil to the correct height and position on the Hall devices.

positioning the foils on to the Hall devices was found to be very critical, fine adjustment of the last few mm of foil was achieved by trial and error to obtain best sensitivity.
If further time was available plastic screws could have been arranged, on the foils, so that pin-point positioning of them could be achieved.

The whole assembly was mounted on a portable wooden stand about 1m high, so that the probe set was away from nearby matallic objects.

TRANSIENT BEHAVIOUR

It was found that the output drifted by about 200mV in the first hour after switch on, however no measurable drift was recorded after 2.5 hours. Thus the warm-up period for the electronics was about 2.5 hours. The magnetometer was left on continuously throughout the project so that electrical equilibrium could be maintained.

CALIBRATION

Calibration of the first Hall probe set was a simple matter, the probe set was rotated so that maximum (North) and corresponding 'antimaximum' (South) were found. The difference in voltage between these two measurements being equal to twice the Earth's field strength (52,000nT for UK). the sensitivity was found to be ;

$$dV/dB_1 = 4.9 \text{ E-6 V/nT } (+/-10\%)$$

The second probe set could not be calibrated in the same way due to its greater sensitivity. Saturation of the output occured before maximum field could be found. Calibration was achieved by using a known magnetic field. However it was difficult to achieve a uniform field over the length of the probe set, about 1 meter.

The Helmholtz system provides very uniform fields over a certain length but in this case the dimensions of the coils become too large in practice.

A ten turn coil of radius 63cm was used, as this gave a calculated field, at the centre, of 100nT for a current of 10mA. Using the Biot-Savart law, the axial field away from the centre was calculated Fig.4. It can be seen that the field had only dropped by about 50% when 50cm away from the centre.[4]

The field was integrated over +/-50cm, numerically, to find the average field over the probe set. This gave an average field of 100nT for a current of 14.6mA (+/-2%).
the error here was due to the error in constructing a circular coil, this was about 2cm of the diameter.

The probe set was placed at the centre of the coil along the axis so that the 50cm foils projected out either side.

Calibration was achieved by varying the current to the coil so that various magnetic fields could be obtained. A switch was incorporated so that the current in the coil could be reversed, in this way any hysteresis effects of the probe set could be observed. In fact no hysteresis was observed for changes in field as great as 2500nT.

The calibration is shown in Fig.5 the sensitivity being ;

$$dV/dB_2 = 2.3\ E\text{-}4\ mV/nT \quad (+/-\ 2\%)$$

The gain due to the foils is thus given by ;

$$G = dV/dB_2\ /\ dV/dB_1 = 2.3\ E\text{-}4/4.9\ E\text{-}6 \simeq 50$$

which was as expected.

A complete set of specifications for the probe set 2 magnetometer is shown in Fig.6.

A small Solenoid could have been used instead of the large coil, however this was not done because of the greater error introduced by any constructional irregularities. For example a 2cm error in the large coil results in about a 2% error in calibration, such an error in a small solenoid would produce much greater errors in calibration.

The minimum detectable signal for the magnetometer is of the order of the noise level on the output. For integration times of 1 second this is about 30mV, this is also about equal to the minimum TS in the laboratory and so the minimum detectable field is given by ;

$$B_m = (30+30)/0.23 \simeq 300nT$$

The value given in the specifications assumes no TS.

300nT is about 0.6% of the Earth's field (52,000nT)

SUMMARY OF FOIL MAGNETOMETER

It has been shown that it is feasible to construct a magnetometer, using generally available parts, which is capable of measuring small variations of the Earth's magnetic field. It has been shown that ferromagnetic foils can be used to provide considerable gain so that sensitivity was achieved. This sensitivity is crucial if magnetic disturbances due to solar phenomena are to be observed.

SECTION 2

USING THE MAGNETOMETER

Experiments with probe set 1

Fig.7 shows a simple estimation of the Earth's field for latitudes such as the UK, it assumes that the Earth is a uniformaly magnetised sphere and so can be represented as a dipole of magnetic moment M. M was determined by many measurments world-wide [6],[8], a more accurate representation of the static field can be obtained using Spherical harmonics, however this is of no use for this project.

The simple estimate shown acconts for 90% of the Earth's field and should thus agree well with experiments conducted with probe set 1.

DIP ANGLE (I) MEASUREMENT

Measurement of the angle of Dip of the field lines, relative to the horizon, (Inclination I) at a location can give an indication of how magnetically noisy the location is. This may not be apparent by measuring the magnitude only.

Fig.8 shows 14 measurements taken for two locations, the first were obtained around the University (at ground level) and the second were taken on the open land on the Hoggs back (about 2km from the University). They show that any measurements conducted at the University were subject to greater error than those done far away from buildings, power lines and other metallic objects.

Ideally it seemed that if we were to do experiments with the second probe set then the location must be as magnetically quite as possible.

EXPERIMENTS WITH PROBE SET 2

SOLAR PHENOMENA

Unlike elictrical storms, magnetic storms effect the whole planet at one time, although the extent may vary depending on latitude and intensity of the storm.

Fig.9 shows the principal variations of the magnetic field caused by solar phenomena. Very simply, plasma is continually streaming off the Sun and immersing the Earth in electrons and protons. The fast moving plasma behaves like a liquid and thus a bow shock wave forms in front of the Earth producing a wind-sock shaped hollow, called the magnetosphere, surrounding the Earth's magnetic field. Changes in the plasma flow due to solar phenomena (large groups of sun-spots and solar flares) disturb the magnetosphere causing changes in the observed magnetic field on the Earth. These changes in the field are called the magnetic storm, three main phases can be identified during a magnetic storm ;

1) Sudden commencement (sc)- sudden increase in the field due to arrival of excess plasma. Lasts for a few minutes causing changes of +10's nT.

2) Main phase (mp)- plasma enters magnetosphere and becomes trapped in the Van Allen belts. The effect is equivalent to a ring of current encircling the equator, which decreases the field. The effect lasts for hours producing -100's nT change in field.

3) Recovery (rec)- the magnetosphere and Van Allen belts recover slowly after the increase in plasma. This takes days and is a slow positive increase in field until the pre sc value is reached once more.

In general there may be several sc in close procession causing the simple graph shown in Fig.9 to become more complex At times of sun-spot maximum (1989-1992) magnetic storms producing changes of 100nT are common, great storms such as 13/3/89 when changes of 2500nT occured, are far less common.

100nT storms are to small to be detected by the magnetometer due to the TS, however the larger events are within scope of the instrument and it was hoped that these would be measured.

LONG TERM PLOTS IN THE LABORATORY-RESULTS

The plots in the laboratory, using a 1 second time constant showed the following notable characteristics ;

1) Long-term drift- changes equivalent to 300nT over 24 hours were observed, these were assumed to be real changes in field with TS superimposed.

2) Medium drift- large changes in field of 1000nT over minutes. These were found due to direct sunlight shining on the Hall devices, this was reduced to about 200nT by using polystyrene blocks around the Hall devices.

3) Erratic short term changes- very large changes of order 2000nT over periods of seconds to minutes. Were found due to the transmission from the Electronic Engineering Department to the UOS Satellite. This was a high power transmission (1k watt), a copy of the log book for future transmissions was obtained so that plots due to this could be disregarded.

4) Random fluctuations- Usually occur over seconds producing changes of about 200nT. These were due to equipment being turned on and other electrical laboratory noise.

There may have been some screening of the Earth's field due to the construction of the building, although it was not possible to determine how great this effect was.

No magnetic disturbances due to solar events were observed in the laboratory plots.

TILLINGBOURNE OBSERVATIONS

To reduce some of these effects it was decided to move the equipment to Tillingbourne house, a hall of residence at the edge of the campus site. Permission was obtained to use the loft and roof space for the experiment.

RESULTS

The first three days of recording were very satisfactory the noise being due to 2) and 3) only, with changes of less than 200nT. Temperature stability at night being very good, less than 1°C changes being common.

This suggested that the magnetic noise level of Tillingbourne was very good. Daylight variations were the main source of noise being of order 400nT. If more time was available a ready built structure could have been built to protect the probe set from direct sunlight. A typical plot is shown in Fig.10

No field changes were observed for solar type phenomena.

THE ELECTRICAL STORM OF 24/5/89

A violent storm passed over and around Guildford between 12:00 and 17:00 BST on the 24/5/89. Fig.11 shows typical storm type variations measured at Tillingbourne at about 14:10 BST changes of 5000nT being common. Positive and negative changes were observed suggesting that discharges were occuring roughly in all directions around the probe set.

A simple estimation of the current passing in these discharges is shown in Fig.12. For cloud-ground discharges the current was calculated to be about 80,000 Amps.

At about 14:30 a very near discharge caused a large change in the magnetometer output and it did not return to zero. There were still small variations ($\simeq$50nT) in the output and the flicker noise was the same level, suggesting that the electronics was functioning properly.

It seemed that the foils had become magnetised by the discharge and were not providing any gain. The apparatus was taken back to the laboratory a couple of days later to check the calibration. In this time the foils had recoverd and calibration was found to agree with Fig.5.

The changes in temperature due to rain and cold nights, after the storm, may have helped the foils to recover.

The loss of gain due to the foils behaviour, also confirmed that the changes in field around 14:10 were real and not just interference picked up by the electronics.

FURTHER LONG TERM PLOTS IN THE LABORATORY

With one week remaining the apparatus was left in the laboratory, the time constant was changed to 100 seconds as this was thought to allow any solar type disturbances to show while attenuating the flicker noise.

This reduced the flicker noise by about a factor of 3, ignoring TS this gives a minimum detectable field of about 50nT. However the noise, as described, were equivalant to at least 200nT and so no distubances were observed.

Throughout the project Ref.[10] was used to check for major magnetic disturbances, non were reported.

SUMMARY

It has been shown that Ferromagnetic foils and Hall devices can be used to build a sensitive magnetometer. The design and construction of the electronics presented no problems.

The terrestrial investigations were successful but unfortunately the temperature sensitivity of the instrument limited the observations so that solar events could not be observed. A factor of ten increase in sensitivity would allow most solar events to be observed and I feel that this could be achieved with the suggestions given below.

Possible improvements to the magnetometer could be ;

1) Better foil configurations,

2) new Hall devices, similar to the ones used here, have recently come on the market, they have superior TS, [5]

3) use of a Stevenson screen to block direct sunlight to the Hall devices, (as used by Meteorologists.).

REFERENCES

[1] RS data sheet, number 5500, 1989.

[2] Telshield, Telcon Metal Ltd., Manar Royal Crawley, Sussex.

[3] E.A.Parr, How to use op-amps, Bernard Babani Press, number 88 1987.

[4] A.Kip, Electricity and Magnetism, Mc Graw

[5] RS data sheet, number 8852, 1989.

[6] S.Chapman, Solar, Plasma, Geomagnetism and and Aurora, Gorden and Breach 1964

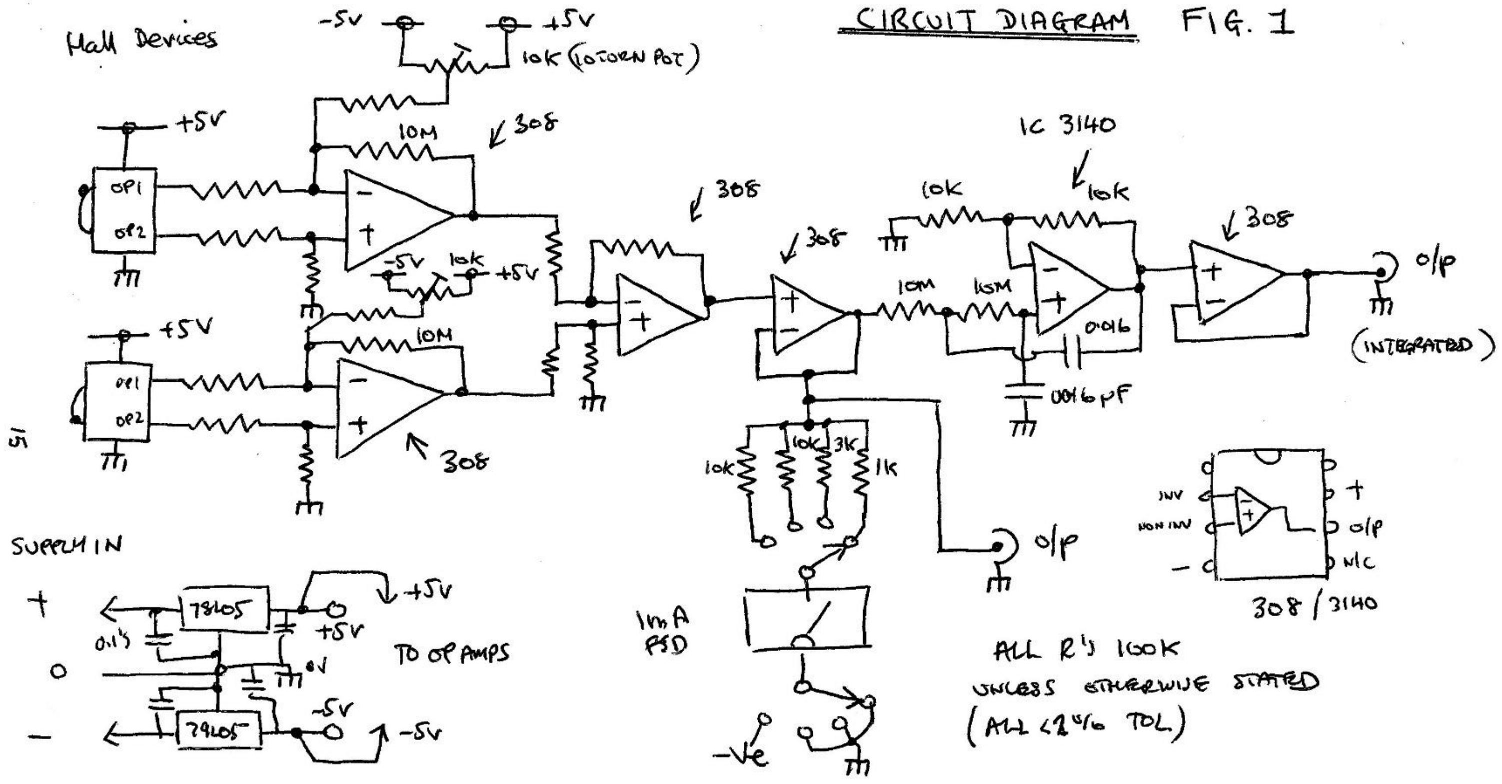
[7] Akasofu and Chapman, Solar Terrestial Physics Oxford 1972.

[8] Merrill and McElhinny, The Earth's Magnetic Field, Academic Press 1983.

[9] B.J.Mason, Physics Of Clouds, Oxford.

[10] Radio Communication, Radio Society of Great Britain (monthly journal), May, June 89

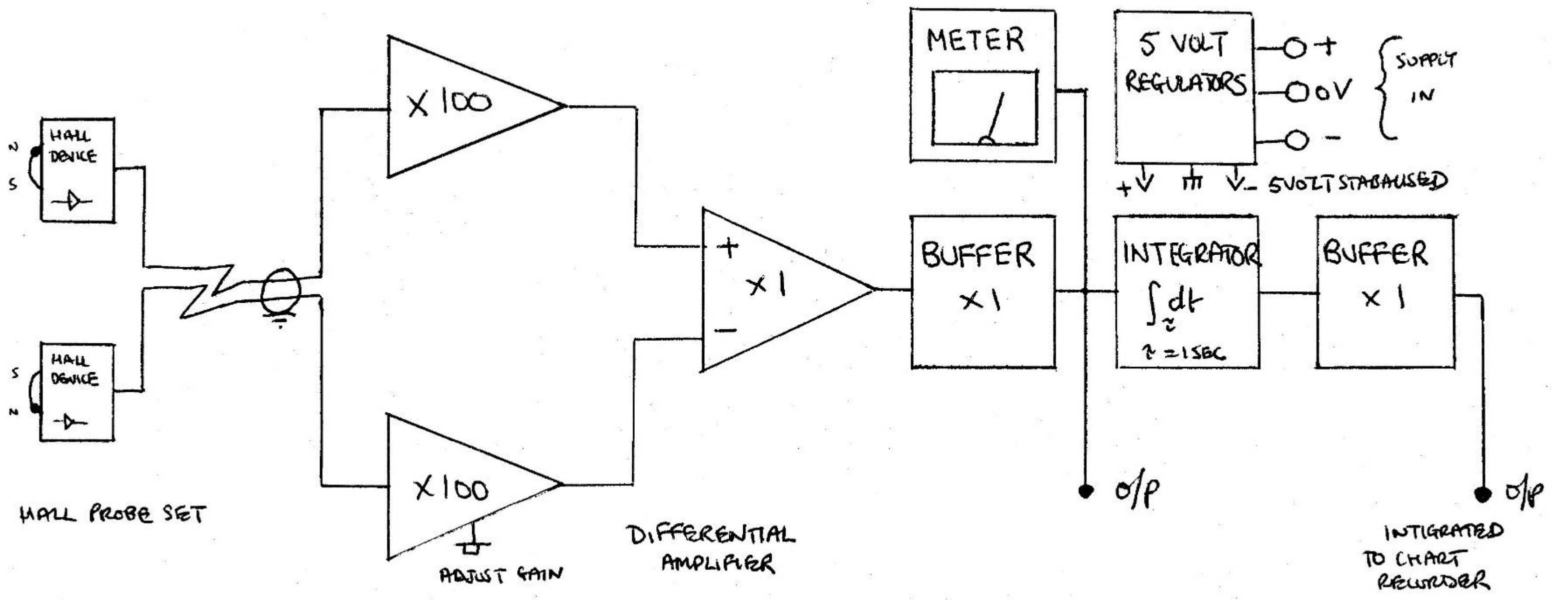
CIRCUIT DIAGRAM FIG. 1



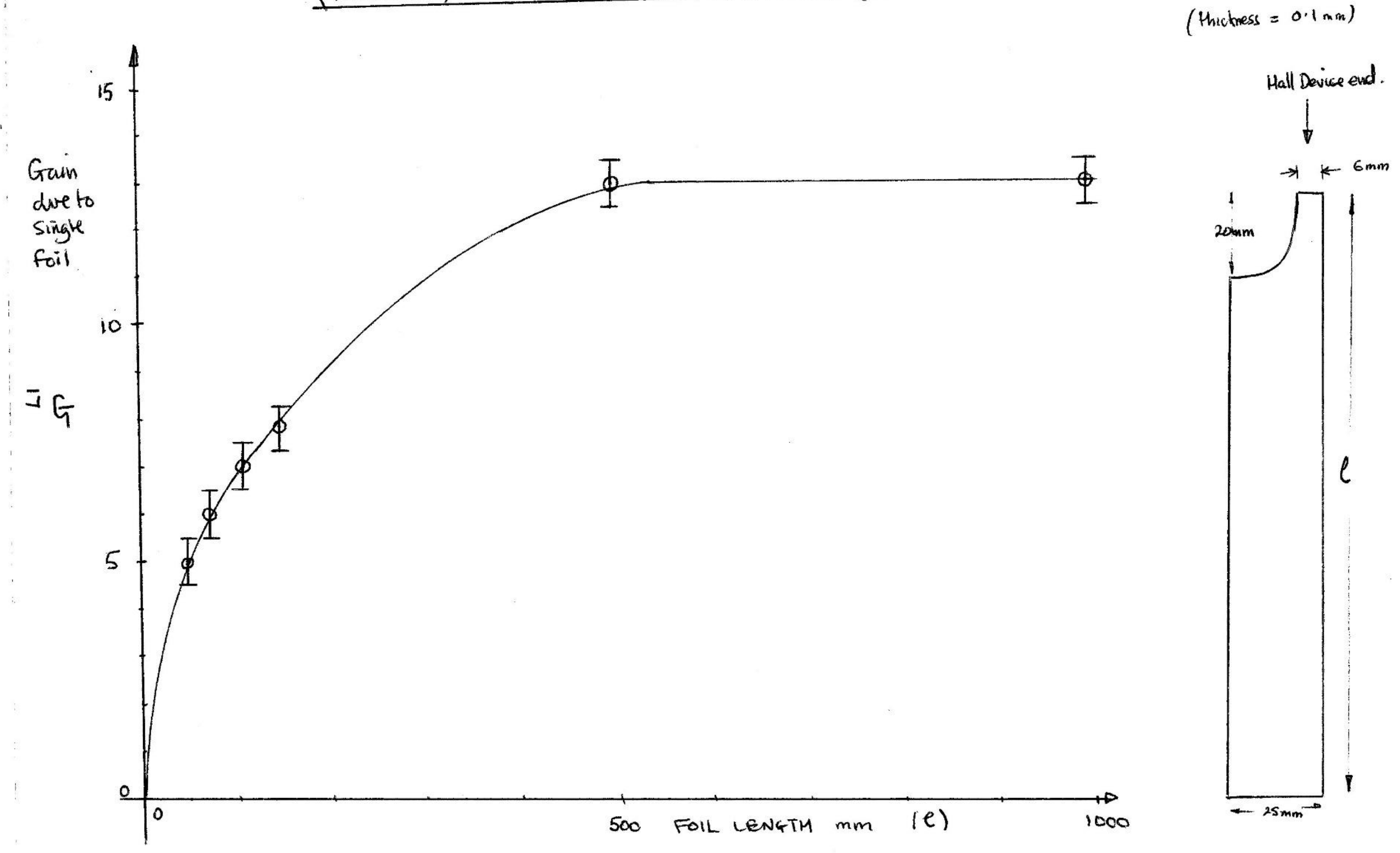
ALL R's 100K
UNLESS OTHERWISE STATED
(ALL <2% TOL)

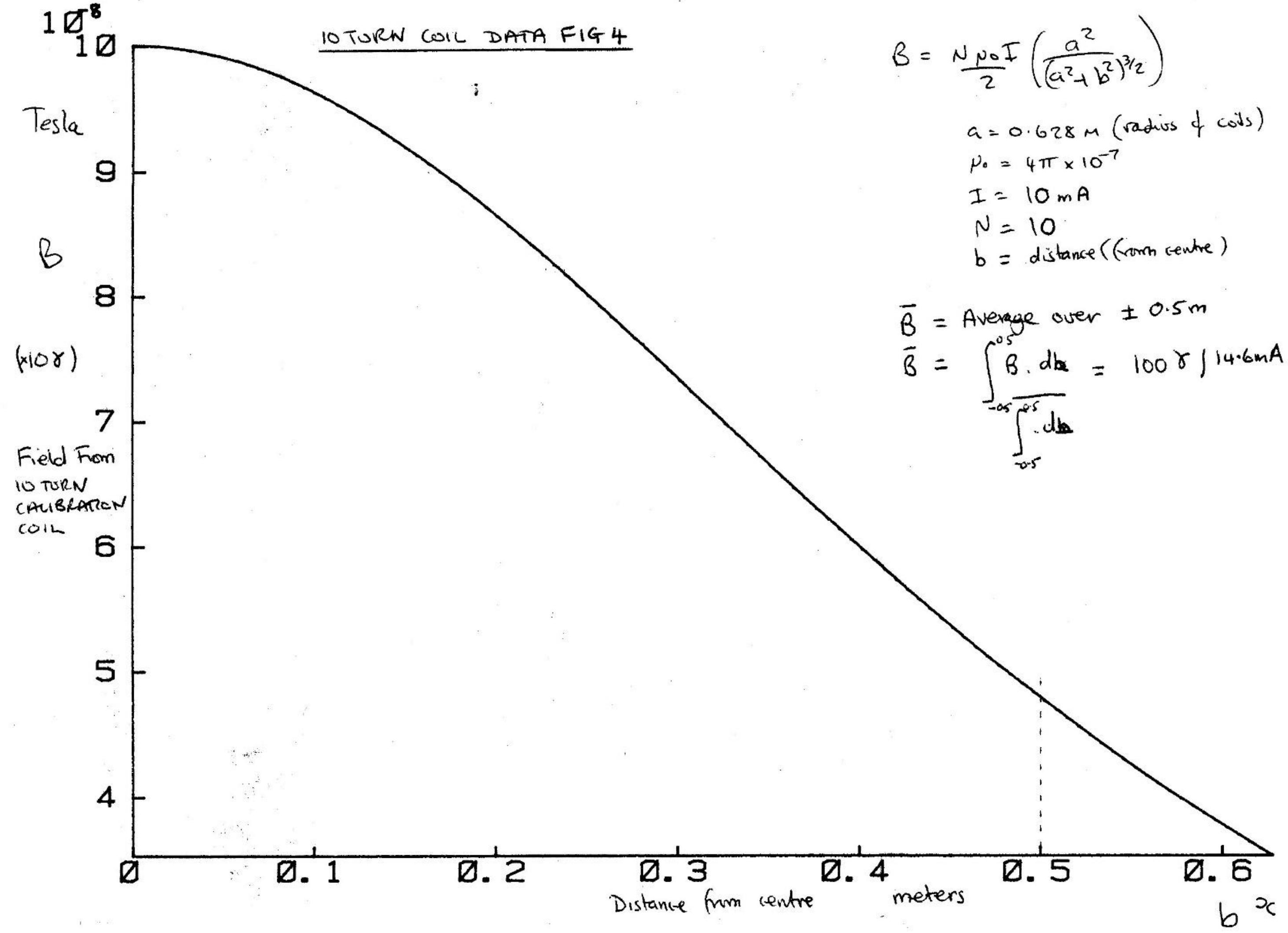
(Hall device spec as given in RS spec sheet 5500)
(IC 304-267).

BLOCK DIAGRAM FIG.2



(TELSHIELD) FERROMAGNETIC FOIL RESULTS Fig. 3




10 TURN COIL DATA FIG 4
10^8
Tesla
B
(x10 γ)
Field From 10 TURN CALIBRATION COIL
10
9
8
7
6
5
4
0
0.1
0.2
0.3
0.4
0.5
0.6
Distance from centre meters
b x
$B = \frac{N \mu_0 I}{2} \left(\frac{a^2}{(a^2 + b^2)^{3/2}} \right)$
a = 0.628 m (radius of coils)
$\mu_0 = 4\pi \times 10^{-7}$
I = 10 mA
N = 10
b = distance (from centre)
$\bar{B}$ = Average over ± 0.5 m
$\bar{B} = \frac{\int_{-0.5}^{0.5} B \, dx}{\int_{-0.5}^{0.5} dx} = 100\gamma / 14.6 mA$

CALIBRATION CURVE (FOIL MAGNETOMETER) Fig. 5

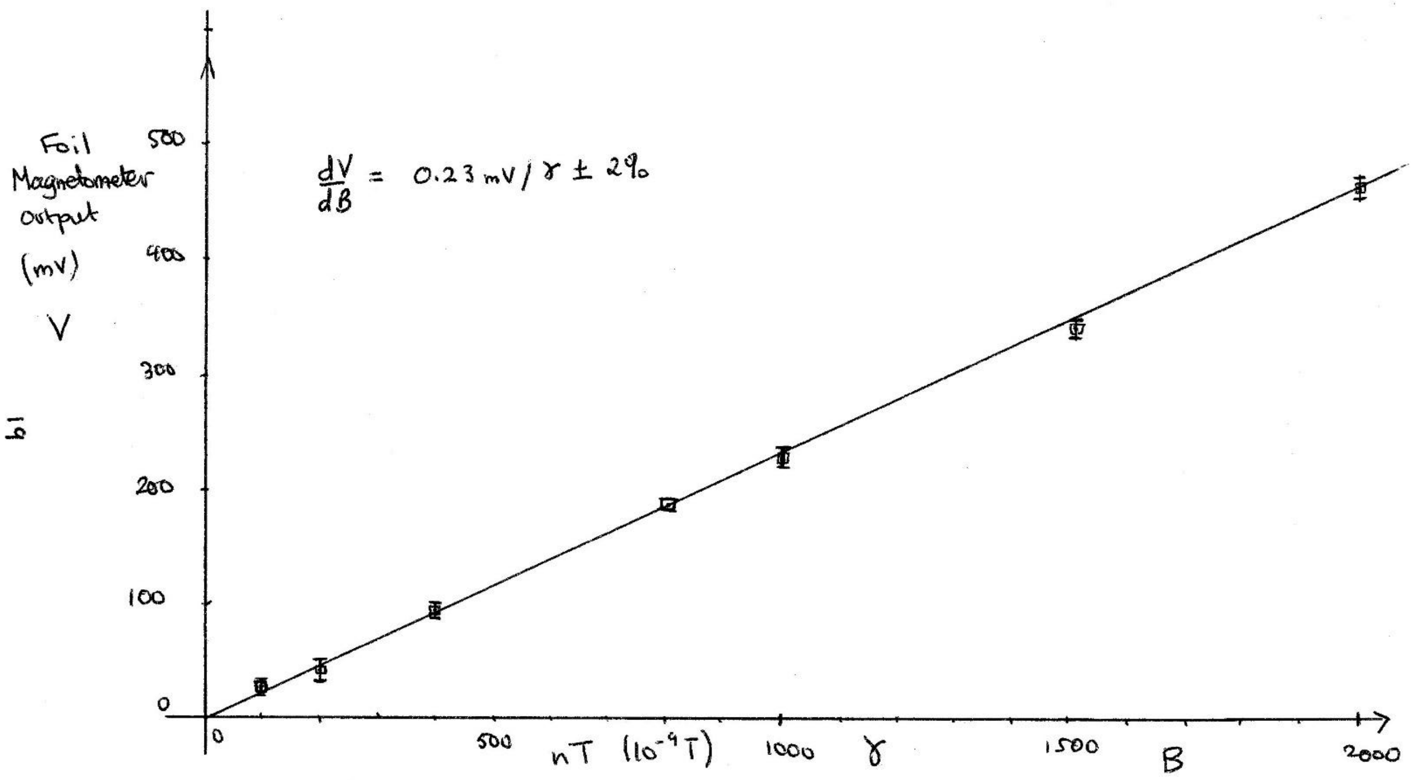


Fig. 6

FOIL MAGNETOMETER SPECIFICATIONS:

Sensitivity	0.23mV/nT
Minimum detectible field	150nT
Maximum temperature sensitivity (TS)	29mV/°C
Effect of supply variations	to small to measure
Warm up period	2.5 hours
Current consumption	40mA (8V supply)
Supply Voltage	7-20 volt (+,-)
Foil lengths	50cm
Foil gain	50 (aprox.)

OUTPUTS:

First O/P: + or - 4V max, 50 ohm

second O/P: + or - 4V max, Integrated 1sec and 100sec, 50 ohm

METER RANGES:

FSD: 1V, 3V, 10V and +-5V

DIMENSIONS:

Case (electronics)	30x25x15cm
Probe set 1	20x12x2cm
Probe set 2	100x12x5cm

FIGURE 7

A SIMPLE ESTIMATION OF THE EARTH'S MAGNETIC FIELD FOR LATITUDES SUCH AS UK

This accounts for about 90% of the field, the further 10% are due to non-dipoler terms and variations due to solar phenomena.

In this simple model we assume that the Earth is a uniformly* magnetised sphere with no currents or electric fields present. Maxwell's equation becomes equal to zero [6] ;

$$\nabla \wedge \underset{\sim}{B} = \mu \underset{\sim}{j} + \mu/\varepsilon \frac{dE}{dt} = 0$$

We can therefore construct a scalar magnetic potential such ;

$$\nabla \wedge \nabla V = 0 \quad \text{where } V = \frac{\underset{\sim}{M} \cdot \hat{r}}{r^2} \quad B = -\nabla V \quad V = -\frac{M \cos \Theta}{r^2}$$

Which in spherical polar coordinates, becomes ;

$$\underset{\sim}{B} = -\nabla V = \frac{dV}{dr} \hat{r} + \frac{1}{r} \frac{dV}{d\Theta} \hat{\Theta} \quad (\hat{\theta} \text{ comp.} = \text{zero})^*$$

If we consider an observer on the surface of the sphere (ie the Earth) then, the $\hat{r}$ component (v) will be vertically above and the $\hat{\Theta}$ component (h) will be along the horizon [6].

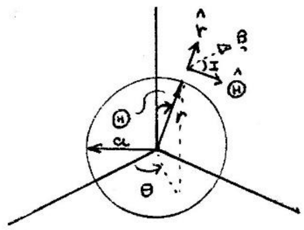
Θ is given by 90°-latitude, ie. 90-51.5 = 38.5°.

v and h are shown, we can apply Pythagoras to find the total field and Trigonometry to find the angle of Dip (I) ; where a=radius of Earth

$$V = \frac{2M}{a^3} \cos \Theta, \quad h = \frac{M}{a^3} \sin \Theta, \quad B^2 = V^2 + h^2$$
$$I = \tan^{-1}(2 \cot \Theta)$$

Merrill [8] gives M=7.9 E24 nT m^3 and a=6.4 E6 m which when applied to the above equations gives ;

B = 52,000 nT and I = 67°.



*No $\hat{\theta}$ Comp

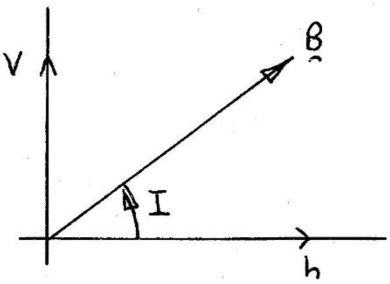
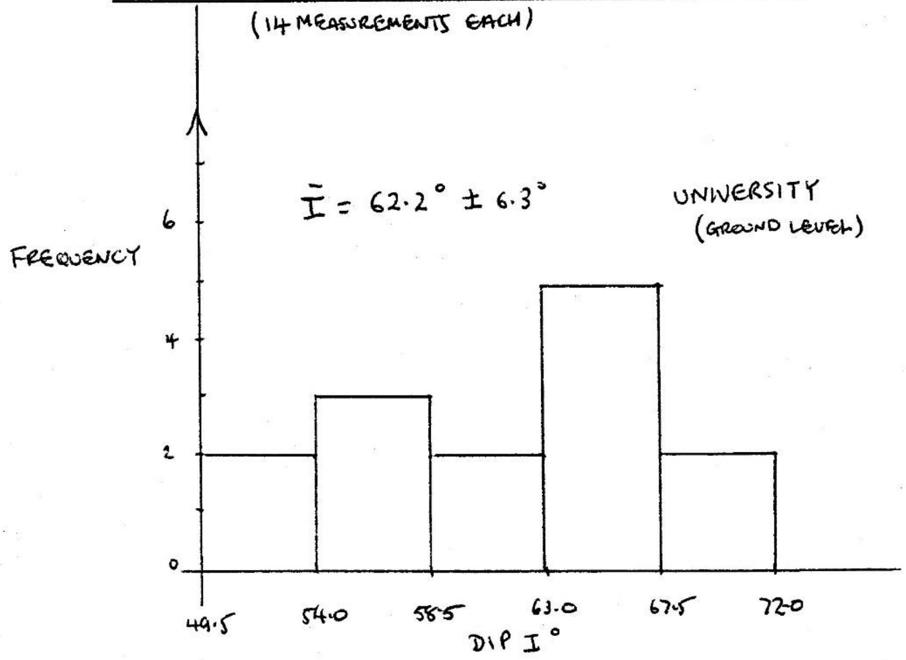
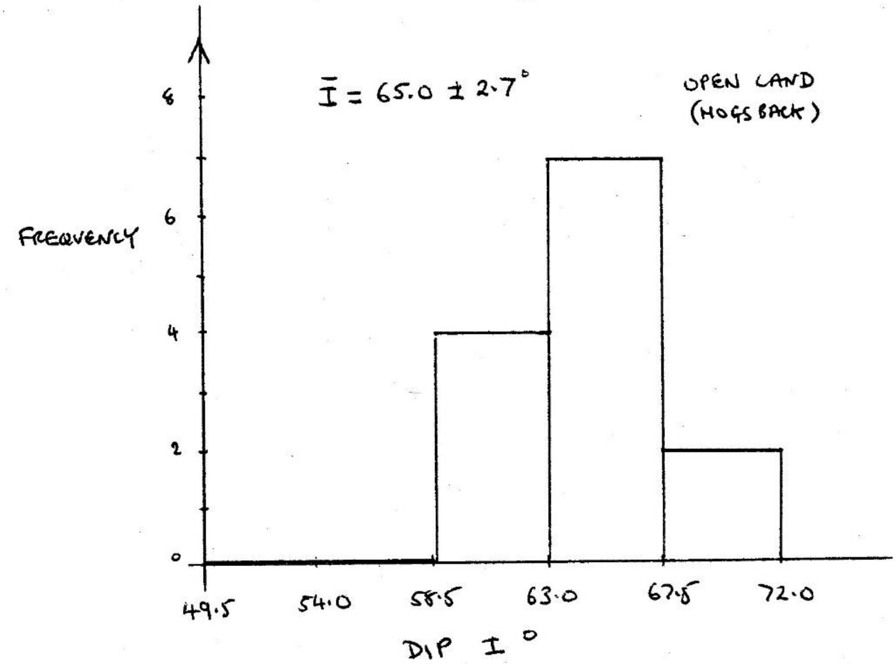


Fig. 8

INCLINATION MEASUREMENTS USING PROBE SET 1
(14 MEASUREMENTS EACH)

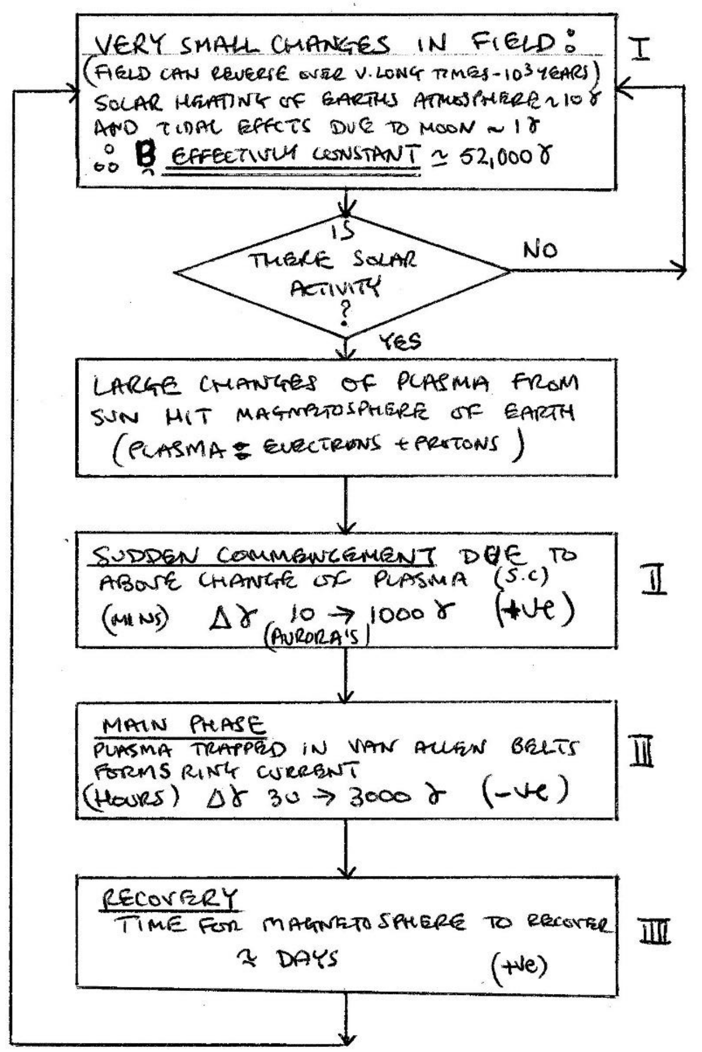


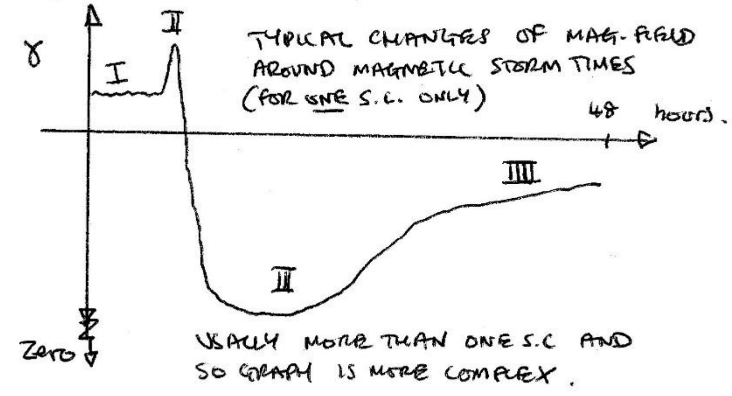


(I = Angle of dip (INCLINATION) Angle between Horizon and Earths magnetic Field)

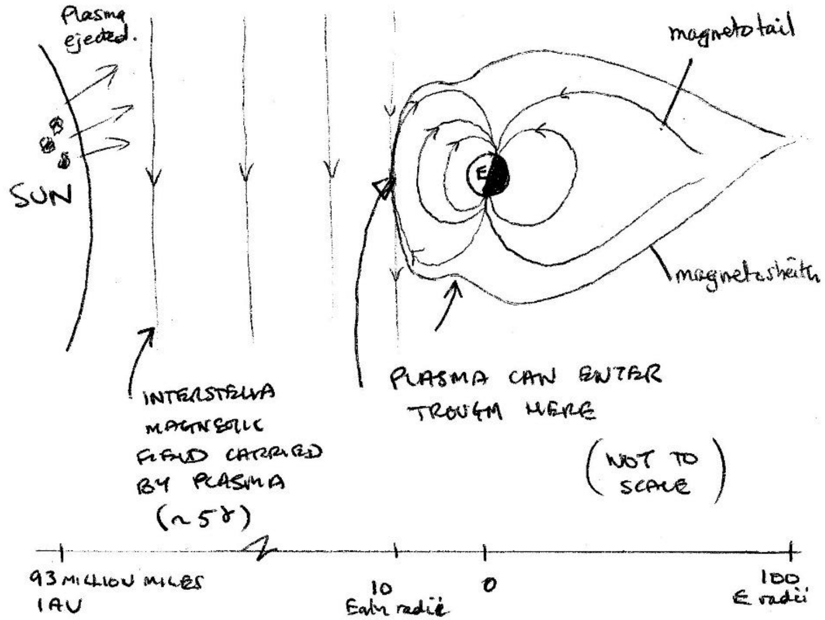
STORM CONDITIONS AND THE MAGNETOSPHERE Fig 9

[6] [7] [8] [10]





THE MAGNETOSPHERE:
(DIPOLE-LIKE FIELD OF EARTH MODIFIED BY PLASMA)



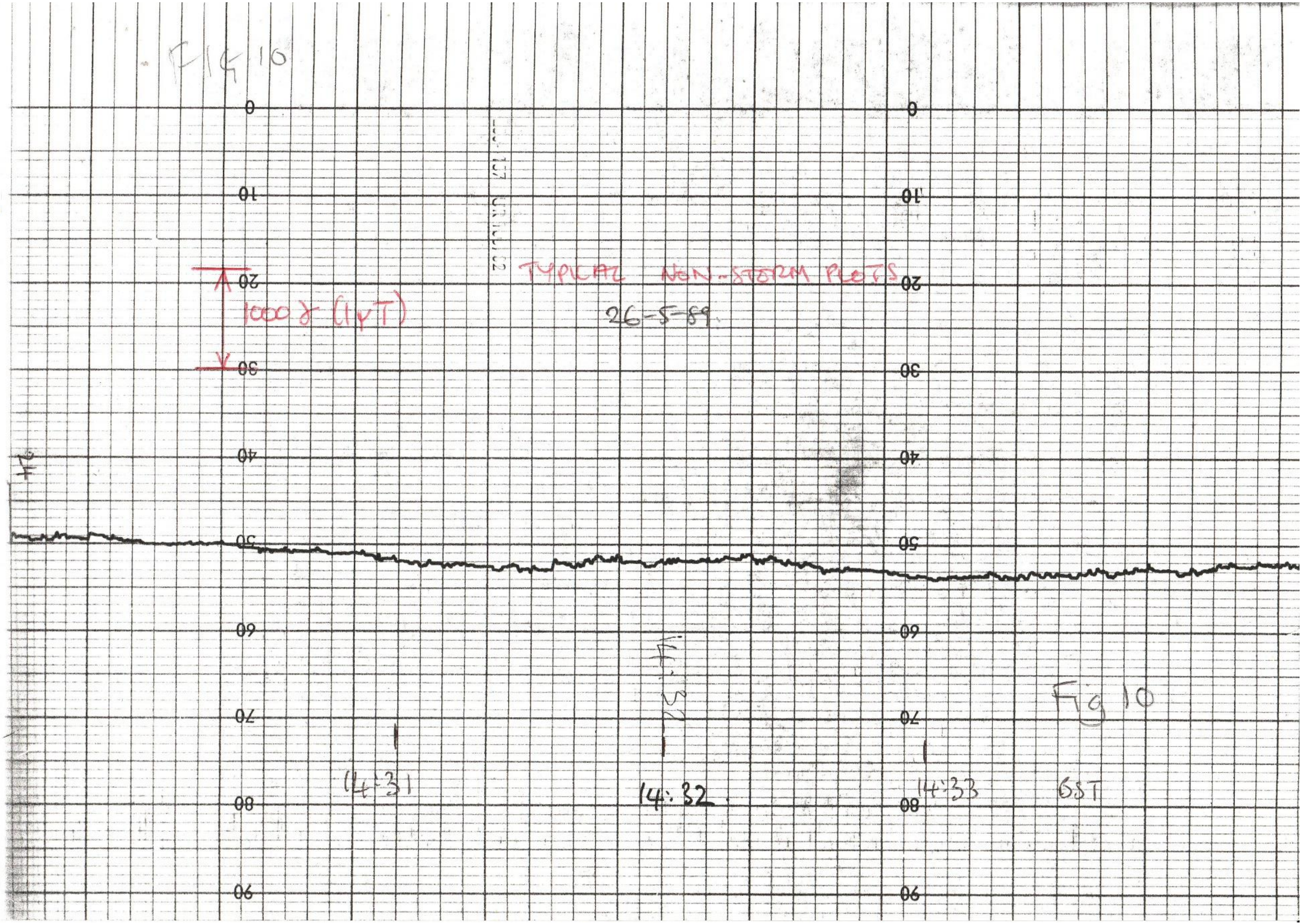


Fig 10
TYPICAL NON-STORM PLOTS
26-5-89
1000 γ (1μT)
14:31
14:32
14:33
GST
Fig 10
0
10
20
30
40
50
60
70
80
90

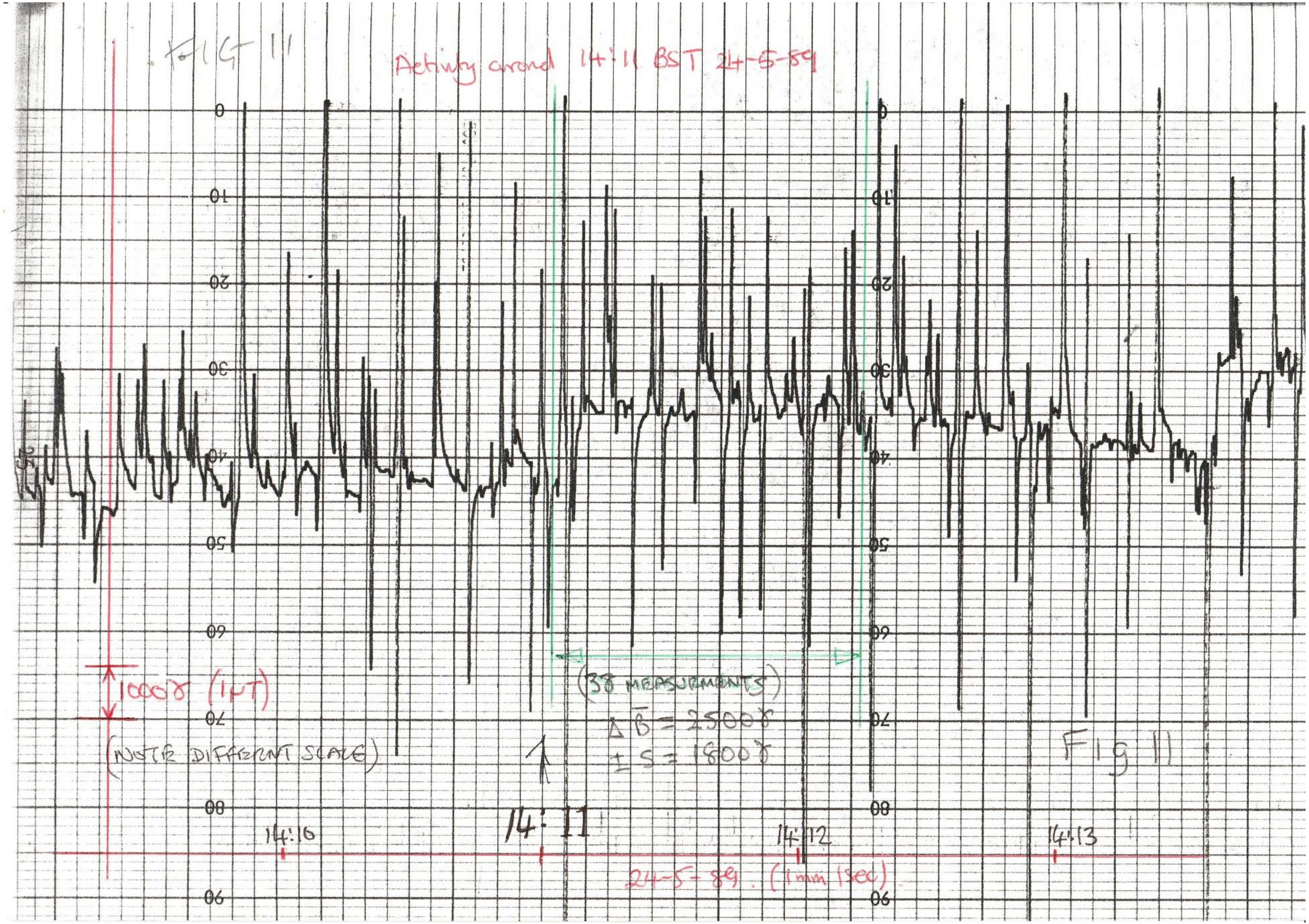
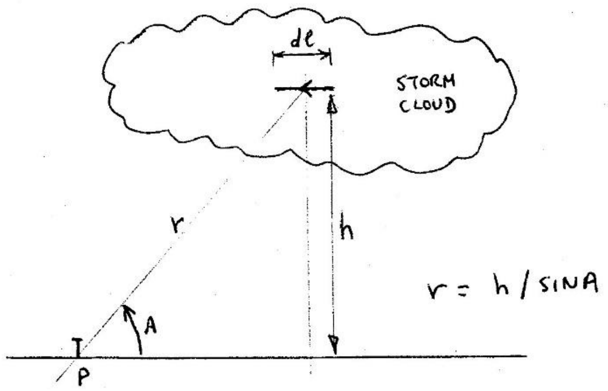


FIG 11
Activity around 14:11 BST 24-5-89
1000γ (1nT)
(NOTE DIFFERENT SCALE)
(38 MEASURMENTS)
ΔB̄ = 2500γ
± S = 1800γ
14:10
14:11
14:12
14:13
24-5-89. (1mm/sec)
Fig 11

FIGURE 12

APPROXIMATE CALCULATION FOR THE LIGHTNING DISCHARGE CURRENT FOR THE ELECTRICAL STORM OF 24/5/89

h=height of cloud
I=current in discharge
dℓ=lightning length
dB=magnetic field at P
A=average angle of lightning
r=P to cloud distance



Using the Biot-Savart law ;

$$dB = \frac{\mu_0}{4\pi} \cdot \frac{I\, d\ell \sin A}{r^2}$$

and rearranging to give ;

$$I = 4\pi h^2 dB / \mu_0 d\ell \sin^3 A$$

From Fig.11 dB = 2.5 E-6 Tesla (+/-70%) and h is given as 2km [9].

dℓ is of the order of 2km for cloud-ground (cg) discharge, but no figure was available for cloud-cloud (cc) discharge [9] As a rough estimate dℓ was taken as 200m for cc.

The lightning was assumed to be originating from a rough ring around the magnetometer (P) of approximate angle 60°, this gives values for the cg an cc by the above equations of ;

$I_{cg} = 80,000$ Amps $\qquad I_{cc} = 800,000$ Amps (all +/-70%)

[9] gives the cg and cc discharge currents to be about equal and of order 10^4 - 10^5 Amps, which agrees well with the cg value given above. The discrepancy of the cc value may be due to the poor estimate for the cc length.

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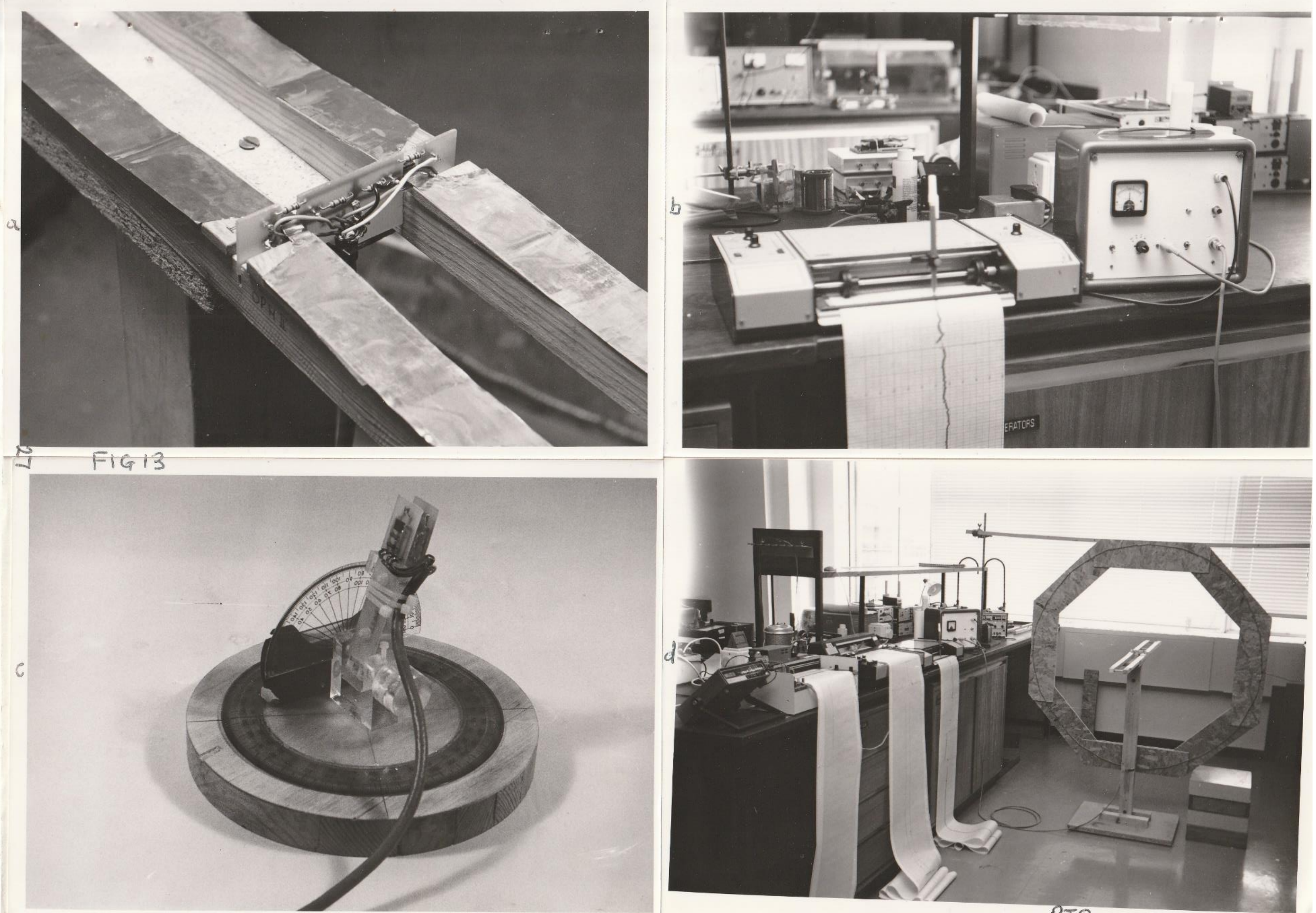

FIG 13

a b c d

PTO

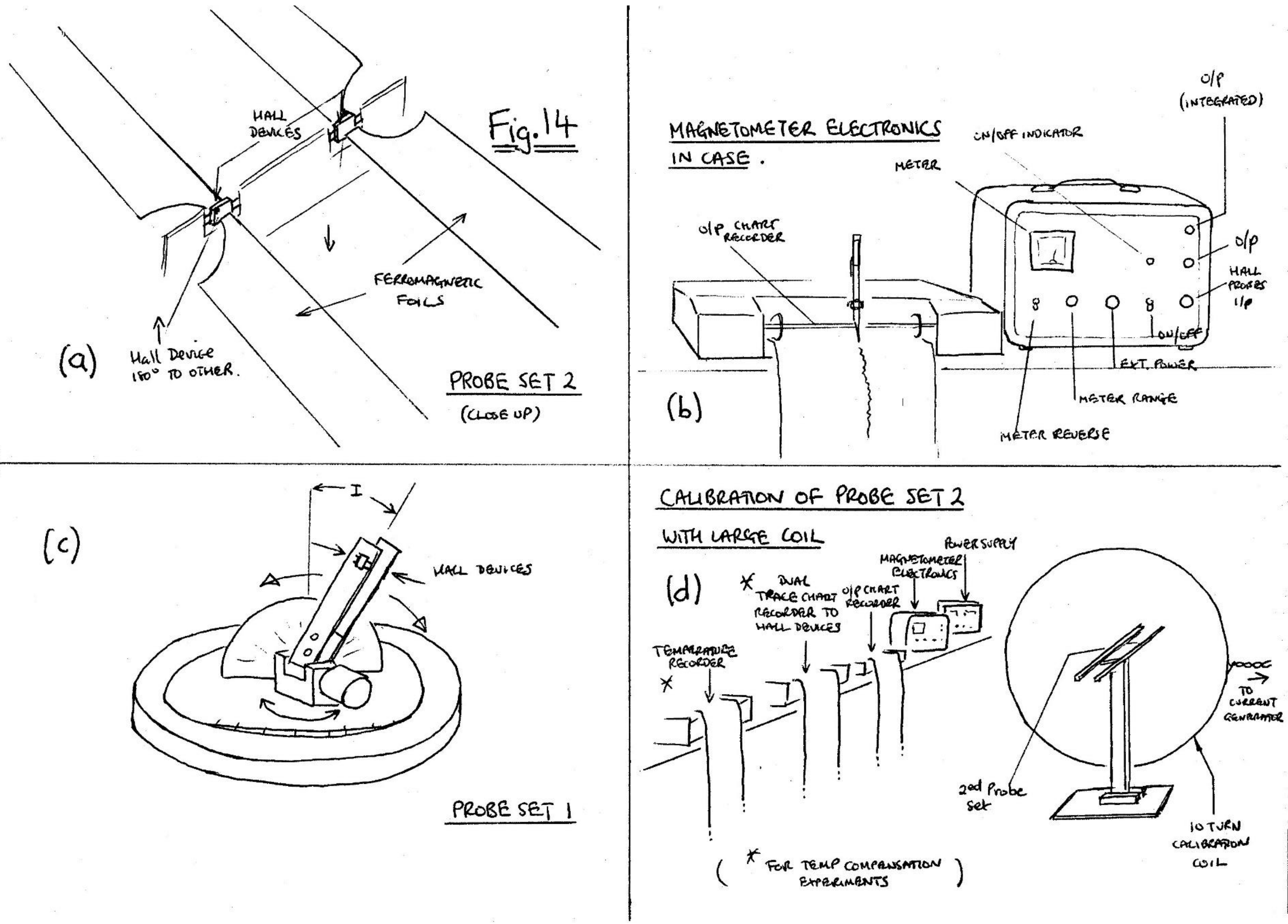
Fig.14
(a)
HALL DEVICES
Hall Device 180° TO OTHER.
FERROMAGNETIC FOILS
PROBE SET 2
(CLOSE UP)
MAGNETOMETER ELECTRONICS IN CASE.
(b)
O/P (INTEGRATED)
ON/OFF INDICATOR
METER
O/P CHART RECORDER
O/P
HALL PROBES I/P
ON/OFF
EXT. POWER
METER RANGE
METER REVERSE
(c)
I
HALL DEVICES
PROBE SET 1
CALIBRATION OF PROBE SET 2
WITH LARGE COIL
(d)
POWER SUPPLY
MAGNETOMETER ELECTRONICS
* DUAL TRACE CHART RECORDER TO HALL DEVICES
O/P CHART RECORDER
TEMPERATURE RECORDER *
TO CURRENT GENERATOR
2nd Probe set
10 TURN CALIBRATION COIL
(* FOR TEMP COMPENSATION EXPERIMENTS)