# DEPARTMENT OF NATIONAL RESOURCES

# BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

Record 1978/61



## DETECTION OF SUBSURFACE ORDNANCE BY MAGNETIC AND TRANSIENT ELECTROMAGNETIC METHODS

by

P.J. Hill

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## SUMMARY

This report deals with application of total field magnetic and transient electromagnetic (TEM) geophysical methods to the detection of subsurface unexploded military ordnance (UXO). It is a comparative study, in which the magnetic gradiometer method and the use of the TEM dual-loop coil configuration are included in the discussion. The study began as a result of BMR's involvement in UXO clearance operations at the proposed site of the ACT Police Drivers Training Centre near Queanbeyan.

The choice of optimum method depends on the nature and level of magnetic "noise" in the environment in which the UXO search is to be conducted. In most situations the TEM method is the more universally useful since it is much less affected by magnetic variations in the near-surface geology; however, in magnetically quiet areas, the magnetic method allows detection at greater depths.

The attitude of the ordnance buried in the subsurface has a strong influence on its detectability. With the TEM method, or the magnetic method at higher geomagnetic latitudes, the response obtained for a number of different ordnance samples (as well as in TEM scale modelling experienments) was approximately four times as great from a vertically orientated body as from one lying horizontal.

Under favourable (but realistic) field conditions, ordnance such as 25-pound shells and 4.2-inch mortar bombs can be detected at depths to 1.5-2 metres with the TEM method, and 2.5-3 metres with the magnetic method. However, smaller objects such as a hand-grenade cannot readily be detected.

# 1. INTRODUCTION

The Bureau of Mineral Resources, Geology & Geophysics (BMR) was approached late in 1977 by the Department of Construction, seeking assistance in detecting possible unexploded ordnance (UXO) on a site near Queanbeyan (NSW) about to be developed for the ACT Police Drivers Training Centre. The site is on Block 106, Gungahlin, adjacent to the Sutton Road and covers an area of approximately 80 hectares. It was formerly part of the Army's Majura Field Firing Range.

The incidence of UXO on the site was expected to be low because of its location near the extreme southern boundary of the Range. Indeed, a thorough visual surface search of the entire site failed to find any evidence of military ordnance. However, any buried UXO would normally be expected to be within 2 metres of the surface, and could present a particularly serious hazard on parts of the site requiring excavation.

The task of checking the feasibility of applying instrumental techniques normally used in geophysical exploration, to the detection of UXO on the site was undertaken by the Engineering Geophysics Group of the BMR.

Because most ordnance has a high ferromagnetic component (iron or steel), with possibly a certain amount of brass or aluminium, its magnetic and/or electrical conductivity characteristics are several orders of magnitude higher than that of common regolith material. Hence they can be detected by magnetic or electromagnetic methods. It was decided to concentrate on the total magnetic field and transient electromagnetic (TEM) methods because the equipment was available, and because these methods were considered suitable from both a theoretical and a practical point of view.

The Army provided eight representative unarmed ordnance samples for field testing and determination of characteristic parameters. The samples are depicted in Plate 1, and include an 18-pound shell, 4.2-inch mortar bomb, piat projectile, 17-pound shell, 2-inch mortar bomb, 3-inch mortar bomb, 25-pound shell and a hand-grenade (No. 36, Mk 1).

Although this study was carried out with the main purpose of devising the best approach to achieving optimum UXO detection on the ACT Police Drivers Training Centre site, the results of this work can be extended to other military ranges in Australia where the UXO problem exists at present (e.g. Holsworthy, Evans Head) or will occur in the future.

## 2. TOTAL FIELD MAGNETIC METHOD

### Theory

Although permanent magnetisation can produce a significant contribution to the observed magnetic anomaly associated with a magnetic body, it is a valid approximation in most cases involving roughly equi-dimensional bodies to represent the anomaly source as a magnetic dipole located in the centre of the body and oriented in the direction of the ambient field. In other words, the anomaly produced by the body is assumed to originate only from the induced magnetisation and the component of permanent magnetisation in the direction of the ambient field. Because a uniformly magnetised sphere produces a dipole field, we are in fact assuming that the body (in a particular orientation) behaves as an equivalent sphere.

Haigh (1972) derived expressions for the components of magnetic intensity in the X, Y, and Z directions at points along a horizontal traverse in the X-direction above a small inductively magnetized sphere. By normalising in terms of depth to the sphere (d), i.e. putting $X_1 = x/d$, the expressions for these become:

$$\Delta X = Md^{-3}(-3x_1 \sin I + (2x_1^{\,2} - 1) \cos I \cos \beta ).R^{-5} \qquad \ldots(1)$$

$$\Delta Y = Md^{-3} (-\cos I \cos\beta) .R^{-3} \qquad \ldots(2)$$

$$\Delta Z = Md^{-3}((2-x_1^{\,2}) \sin I -3x_1 \cos I \cos \beta ).R^{-5} \qquad \ldots(3)$$

where $R = (1 + x_1^{\,2})^{\frac{1}{2}}$

$M$ = magnetic moment

$\beta$ = azimuth angle of traverse, clockwise from magnetic north

$I$ = magnetic field inclination

Since the field of the magnetised sphere will generally be much smaller than that of the Earth, any component normal to the Earth's field will make a negligible contribution to the total field. Therefore only the component in the direction of the Earth's field needs to be considered, and so the total-field anomaly can be written as

$$\Delta F = \Delta H \cos I + \Delta Z \sin I \qquad \ldots(4)$$

where $\Delta H$ is the horizontal component in the direction of the Earths field. $\Delta H$ is given by

1 18-lb shell
2 4·2"-mortar bomb
3 Piat projectile
4 17-lb shell
5 2"-mortar bomb
6 3"-mortar bomb
7 25-lb shell
8 Handgrenade


PHOTOGRAPH OF ORDNANCE
SAMPLE TESTED

$$\Delta H = \Delta X \cos \beta + \Delta Y \sin \beta$$

Hence equation (4) becomes

$$\Delta F = \Delta X \cos I \cos \beta + \Delta Y \cos I \sin \beta + \Delta Z \sin I \qquad \ldots(5)$$

Total-field anomaly curves for three traverse azimuths ($\beta = 0^o$, $45^o$, and $90^o$) at a number of different values of inclination for the southern hemisphere ($I = 0^o$, $-30^o$, $-60^o$ and $-90^o$) have been calculated and are presented in Plate 2. $\Delta Fd^3/M$ has been plotted against x/d.

The vertical gradient of the total field is obtained by differentiating equation (5) with respect to d.

$$\frac{\partial \Delta F}{\partial d} = Md^{-4}((R^2+5x_1{}^2-10) \sin^2 I + 5(1-R^2-2x1\ 2)\cos^2 I \cos^2 \beta + 6x_1(5-R^2) \sin I \cos I \cos \beta + 3R^2).R^{-7} \qquad \ldots(6)$$

Plate 3 shows curves of total field vertical gradient for the same values of $\beta$ and I as in Plate 2. $\frac{-d^4}{M} \frac{\partial \Delta F}{\partial d}$ has been plotted against x/d.

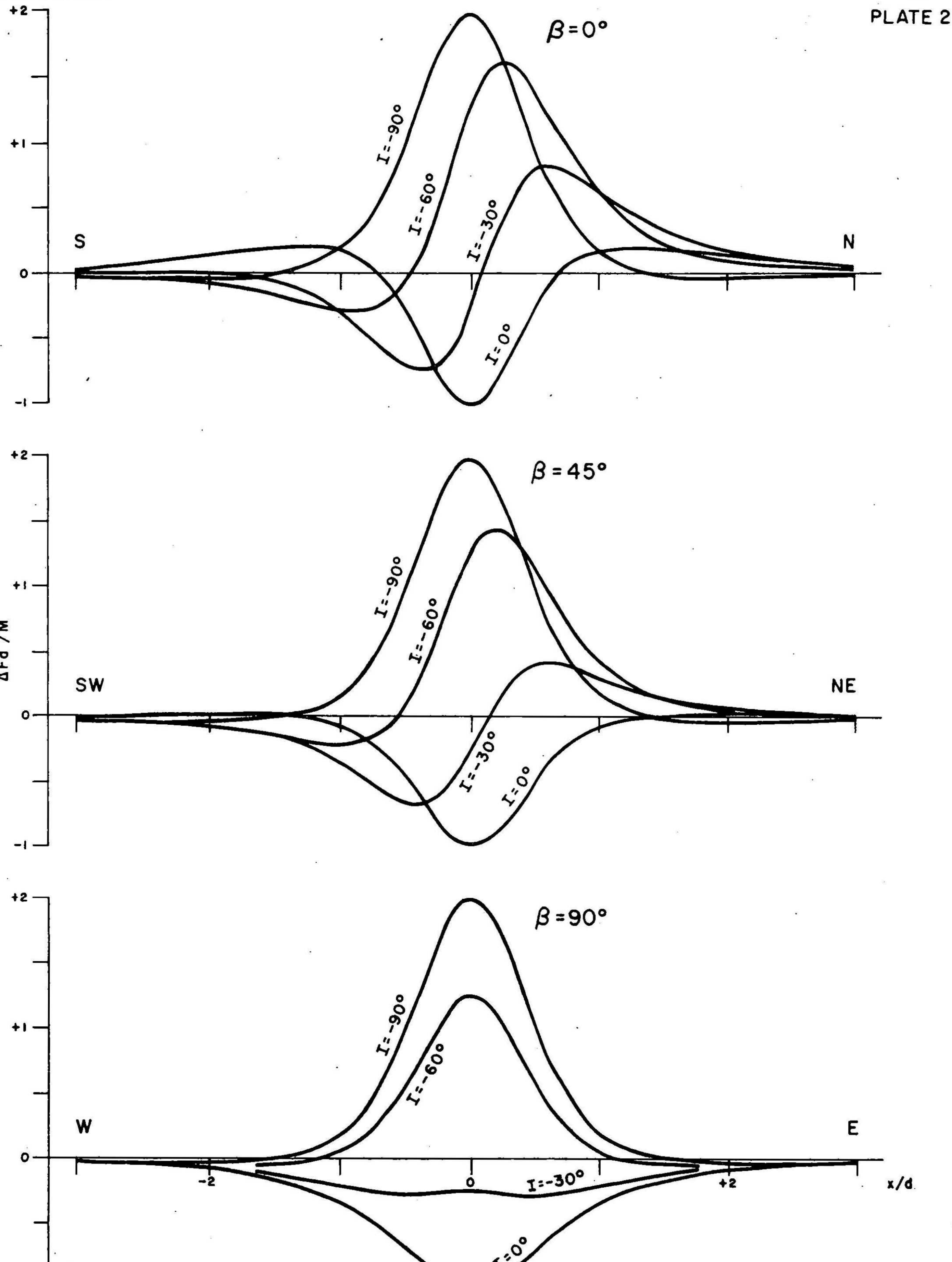
With the sphere at a depth d and in the geomagnetic latitude of Canberra ($I = -66^o$), the anomaly patterns (total field and total-field vertical gradient) on a horizontal surface would appear as depicted in the contour plots of Plate 4.

## Instrumentation

For the tests, two sets of total-field magnetometers were employed, both based on the proton free-precession principle:

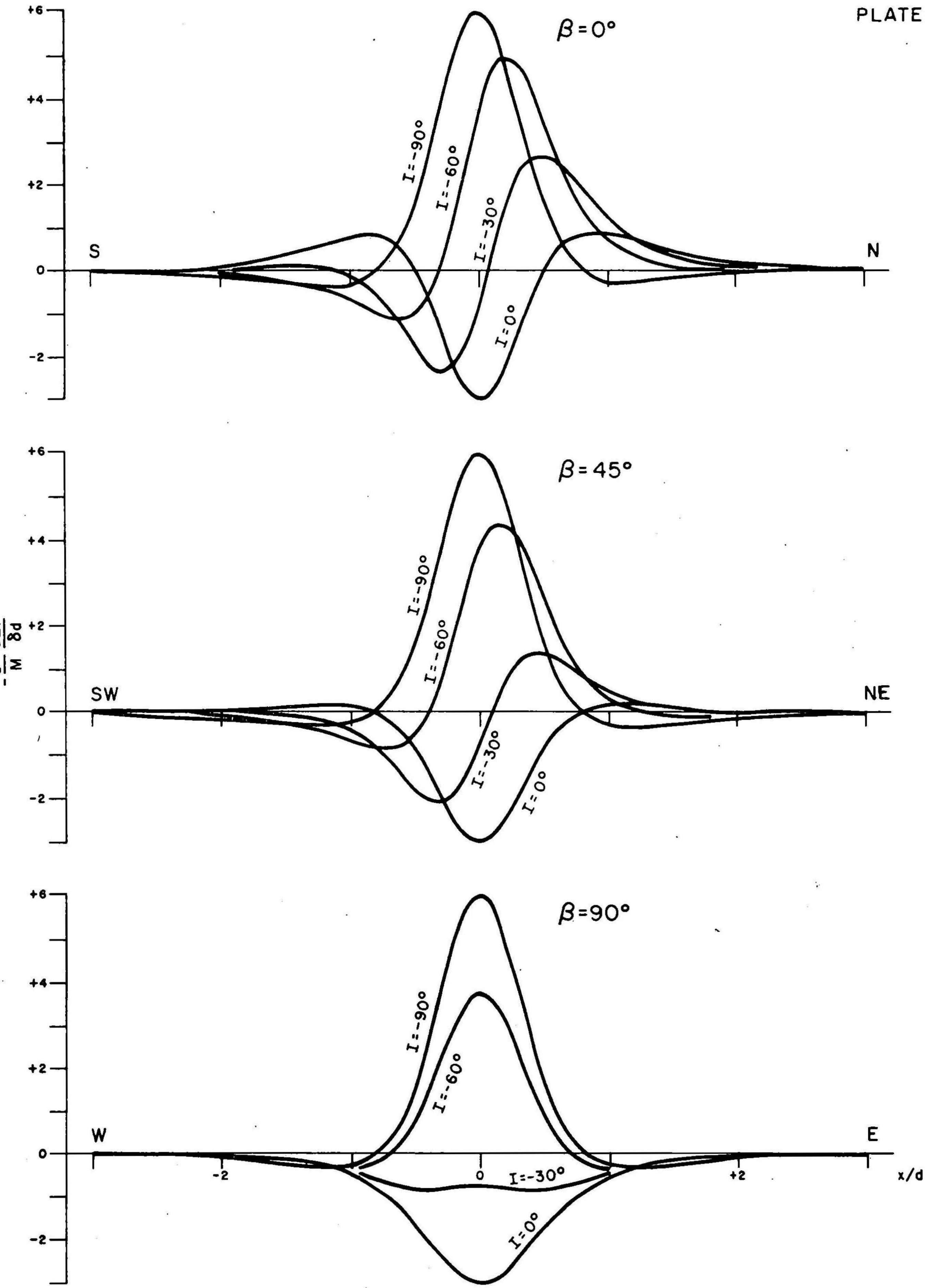
(a) Geometrics G816, which has a digital readout to the nearest nanotesla (nT), has a manually triggered minimum cycle time of about 6.5 seconds, and is designed so as to require only one operator. The sensor head is mounted on a hand-held aluminium staff which can be varied in length.

(b) Geometrics G803, a high performance airborne magnetometer, adapted for use in ground traversing by having the instrument, chart recorder (plus inverter), and 24-volt battery power supply mounted in a Landrover. The sensor, held in a cradle and harness, is carried behind the vehicle at the end of about 20 metres of cable to avoid magnetic pick-up from the vehicle (Taylor, 1975).




ΔF = Total field intensity anomaly  M = Magnetic moment induced by field F
d = Depth to centre of sphere  I = Inclination of F  x = Horizontal distance
$\beta$ = Azimuth angle of traverse, clockwise from magnetic north

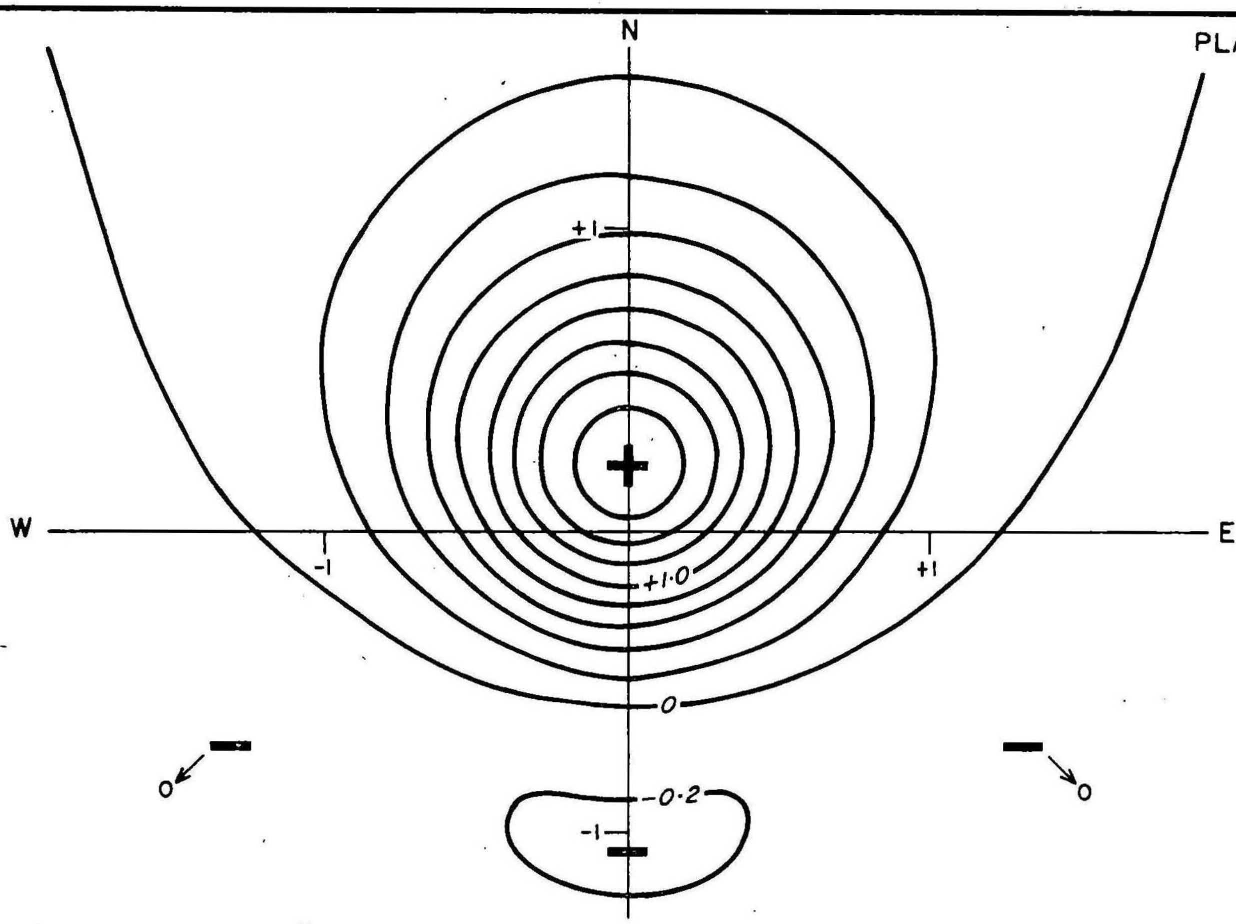
TOTAL FIELD PROFILES OVER AN INDUCTIVELY MAGNETISED SPHERE




FOR LEGEND SEE PLATE 2

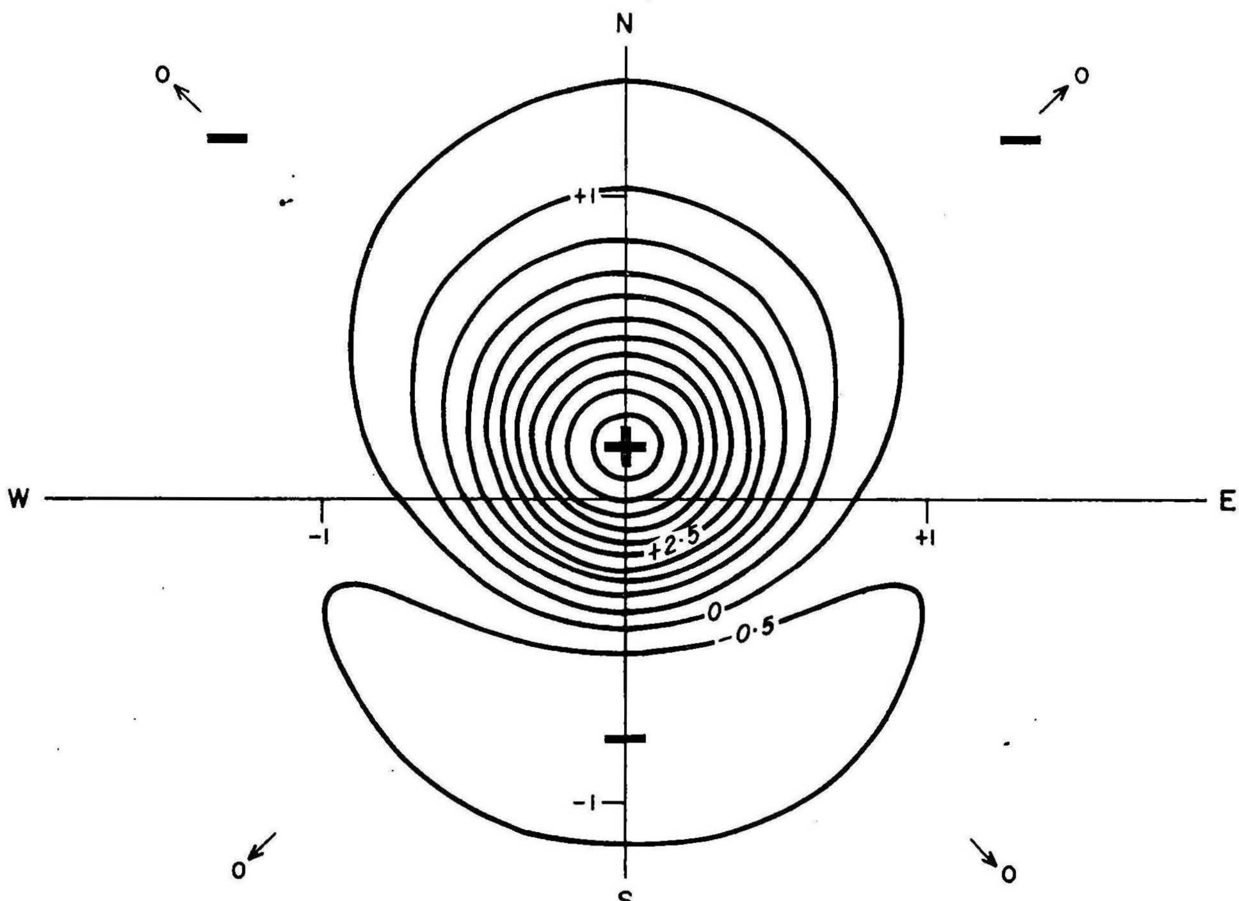
TOTAL FIELD VERTICAL GRADIENT PROFILES OVER AN INDUCTIVELY MAGNETISED SPHERE

PLATE 4




TOTAL FIELD $\Delta F d^3/M$

Contour interval $0{\cdot}2\,\Delta F d^3/M$




TOTAL FIELD VERTICAL GRADIENT

$$-\frac{d^4}{M}\,\frac{\delta \Delta F}{\delta d}$$

Contour interval $0{\cdot}5\,\frac{d^4}{M}\,\frac{\delta \Delta F}{\delta d}$

0·2 x/d

# MAGNETIC ANOMALY PATTERNS OVER AN INDUCTIVELY MAGNETISED SPHERE FOR THE CANBERRA AREA (I=-66°)

*Record No. 1978/61*

I55/B5-378A

After initial trials on the site, the G803 system developed an intermittent electronic fault. Consequently the G816 instrument was used for most of the measurements, and in fact all the magnetic results presented in this report were obtained with the G816. The G803 system has, however, been shown to be effective in the past, and achieves a sensitivity of 0.5 nT at a repetition rate of 3.5 readings per second.

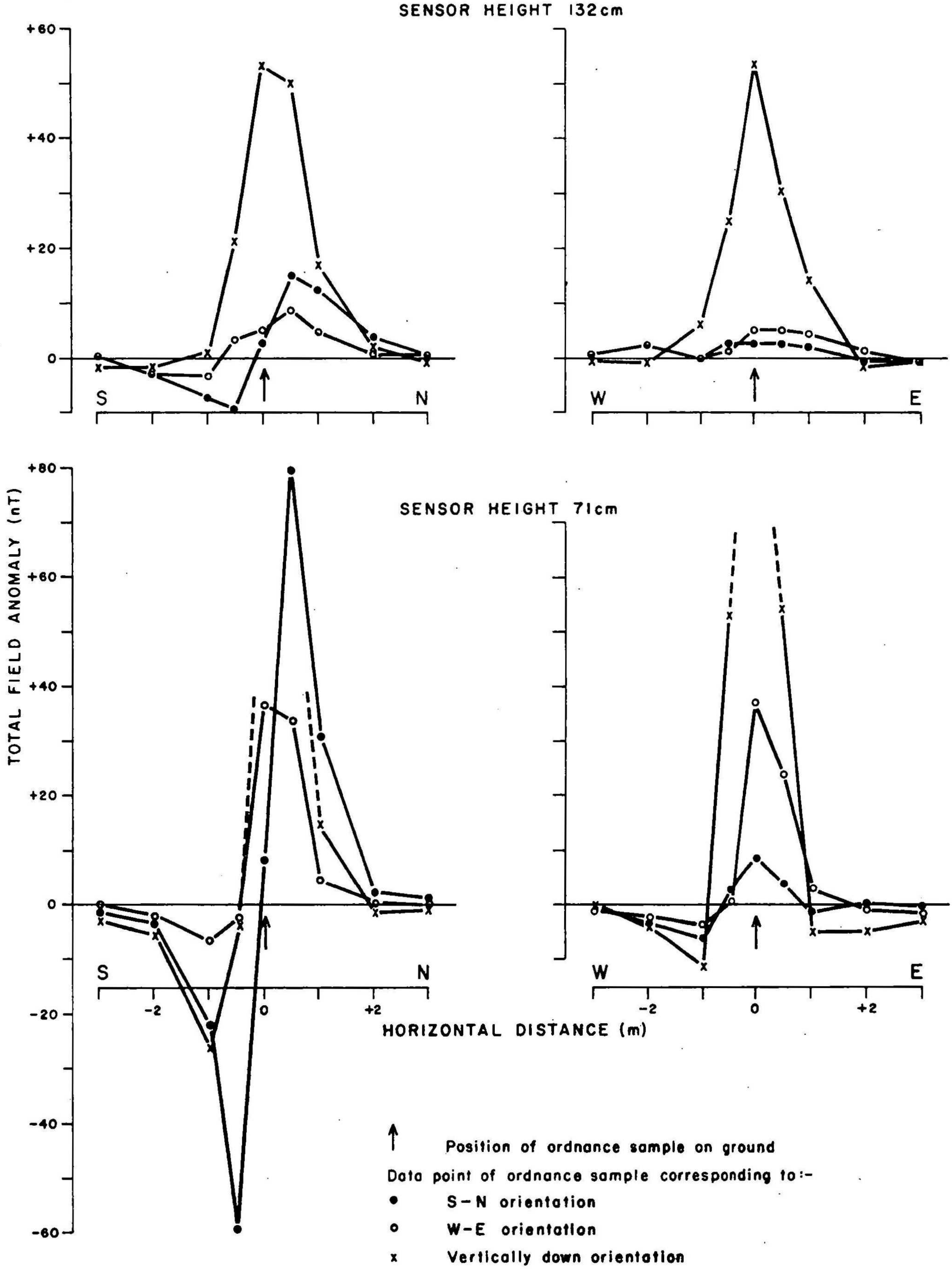
Field tests

Initially, the total-field magnetic signatures of the ordnance samples provided by the Army were determined. A magnetically quiet area was chosen and two intersecting traverses were marked out on the ground with pegs, one traverse being directed magnetic N-S and the other magnetic E-W. The PPM sensor head mounted on its staff was located above the traverse intersection point. Magnetometer readings were taken with the ordnance samples orientated in each of three orthogonal directions (vertically down, horizontal S-N and horizontal W-E) at varying distances along the traverse lines. Two sensor heights were used in the tests, and the results are shown plotted in Plates 5 to 9.

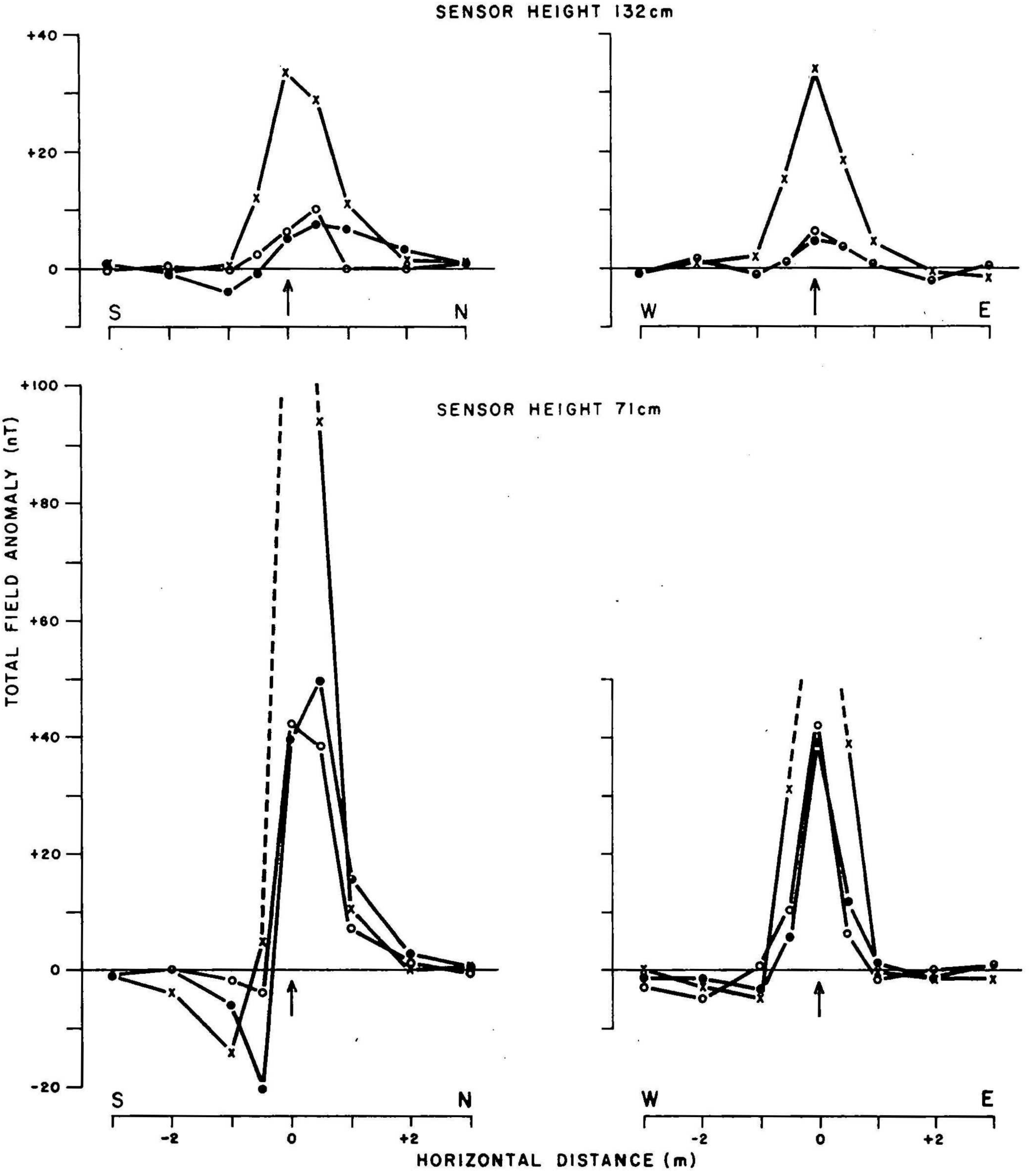
The data points have been transposed across the total-field anomaly axis so that the plots represent the normal situation, in which variations in the field are measured over the object (i.e. with the sensor head mobile and the object stationary). All distances and heights indicated were measured from the centre of the sample to the centre of the sensor head. Because of the high magnetic gradient in close proximity to some of the larger ordnance samples, meaningful magnetometer readings could not be obtained for several close positions. Some distortion of the plots (e.g. truncation of peaks on N-S traverses) has been introduced by the sampling interval.

To test the response of the ordnance samples in a simulated 'search' under actual field conditions, an 80 metre traverse line orientated magnetic N-S was arbitrarily selected on the ACT Police Drivers Training Centre site. An ordnance sample was buried just below the surface in a vertical position every 10 metres along the line. Total-field readings were then taken along the line with the sensor head held 69 cm above the ground surface; the resultant magnetic profile is illustrated in Plate 10.

The magnetic anomalies produced by the ordnance samples, with the exception of the hand-grenade, can be clearly identified. Geological "noise" along the traverse produces anomalies with a peak-to-peak amplitude of 5-10 nT, i.e as large as the anomaly produced by the hand-grenade.



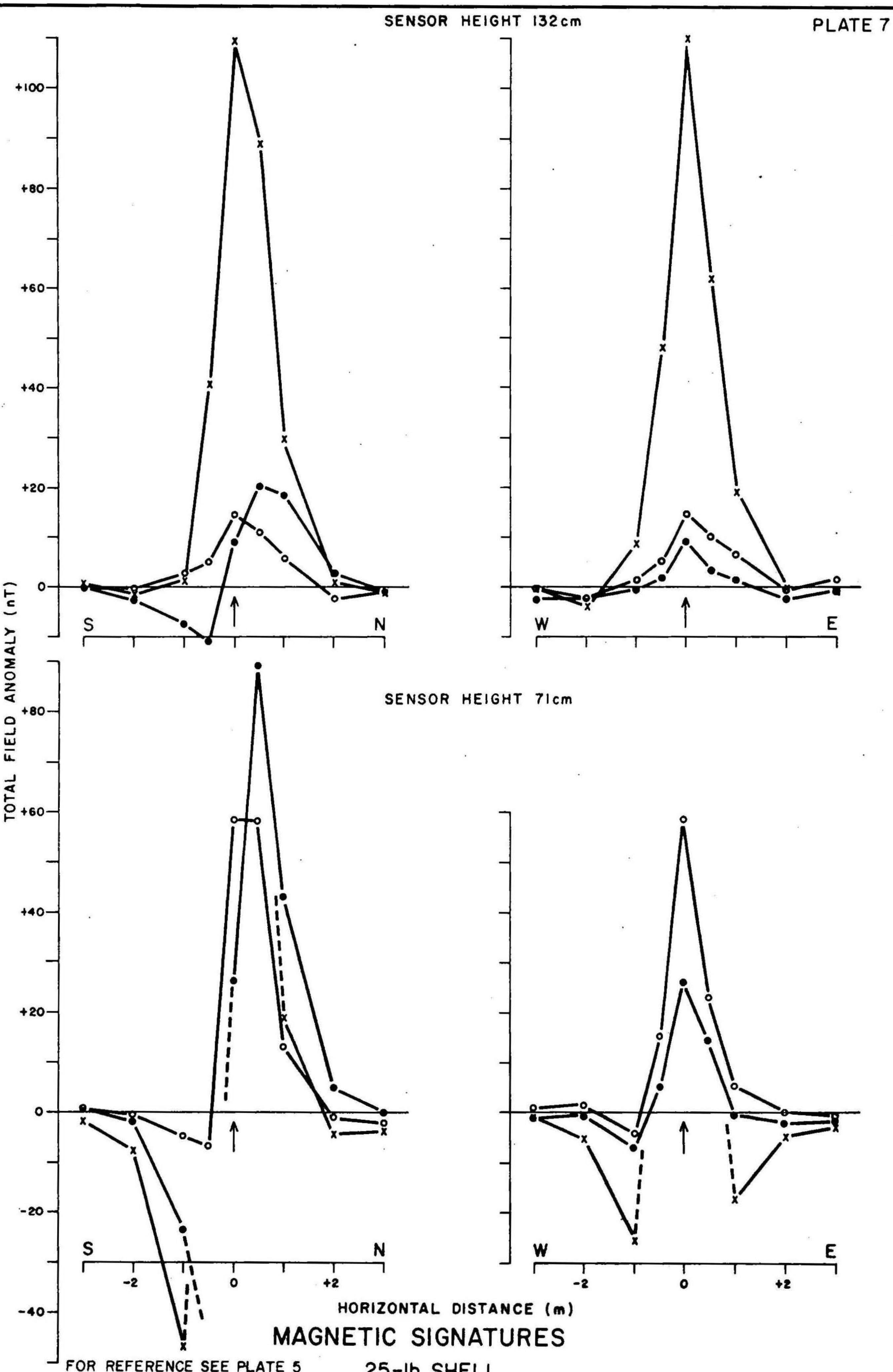

# MAGNETIC SIGNATURES
## 3"-MORTAR BOMB




FOR REFERENCE SEE PLATE 5

# MAGNETIC SIGNATURES

## 17-lb SHELL




MAGNETIC SIGNATURES

25-lb SHELL

FOR REFERENCE SEE PLATE 5

Record No. 1978/61

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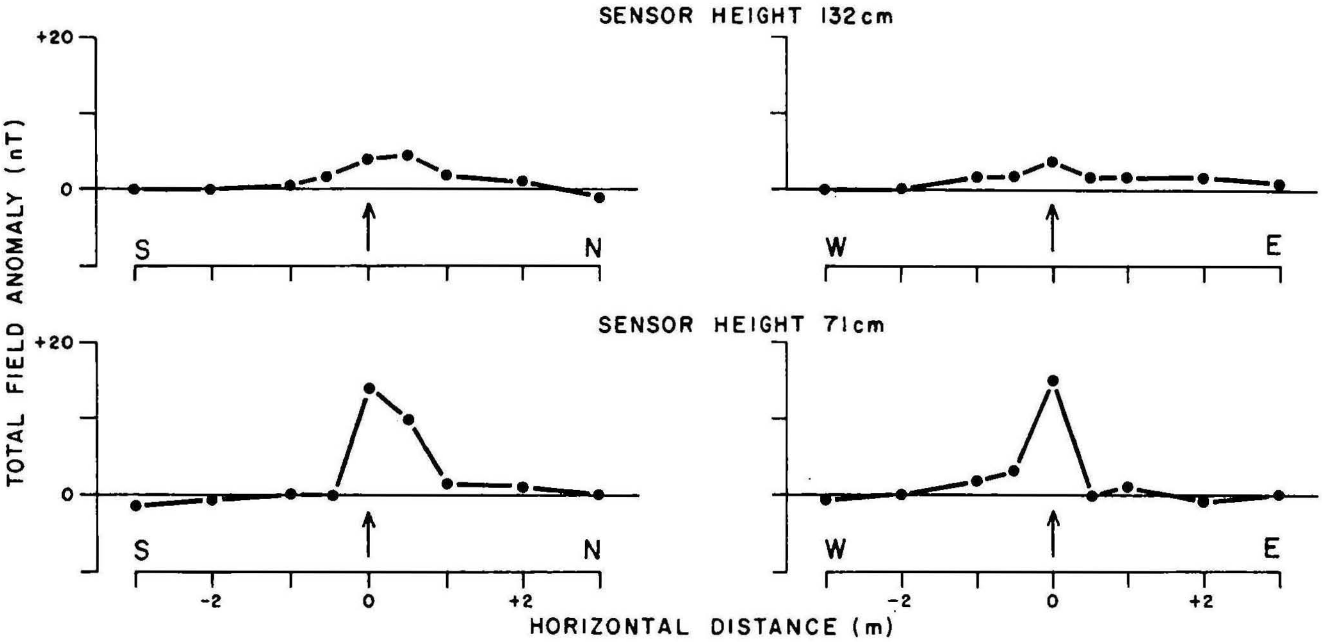
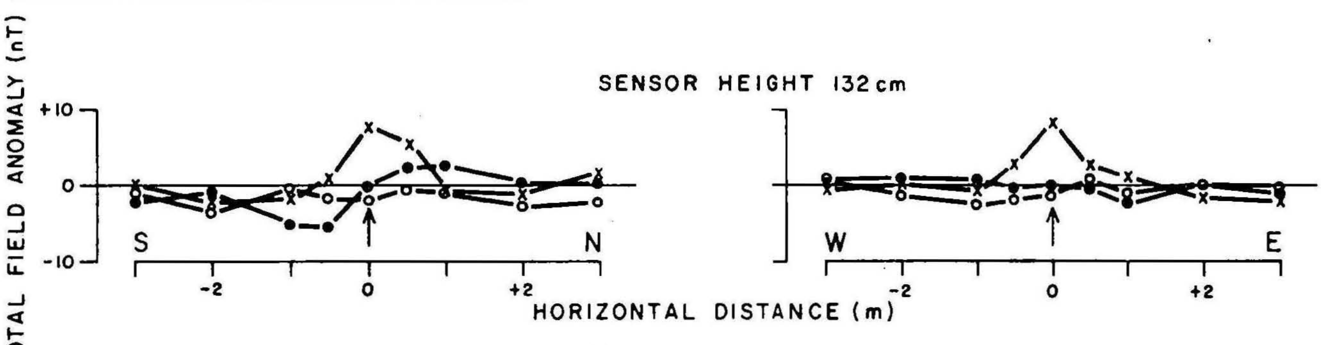
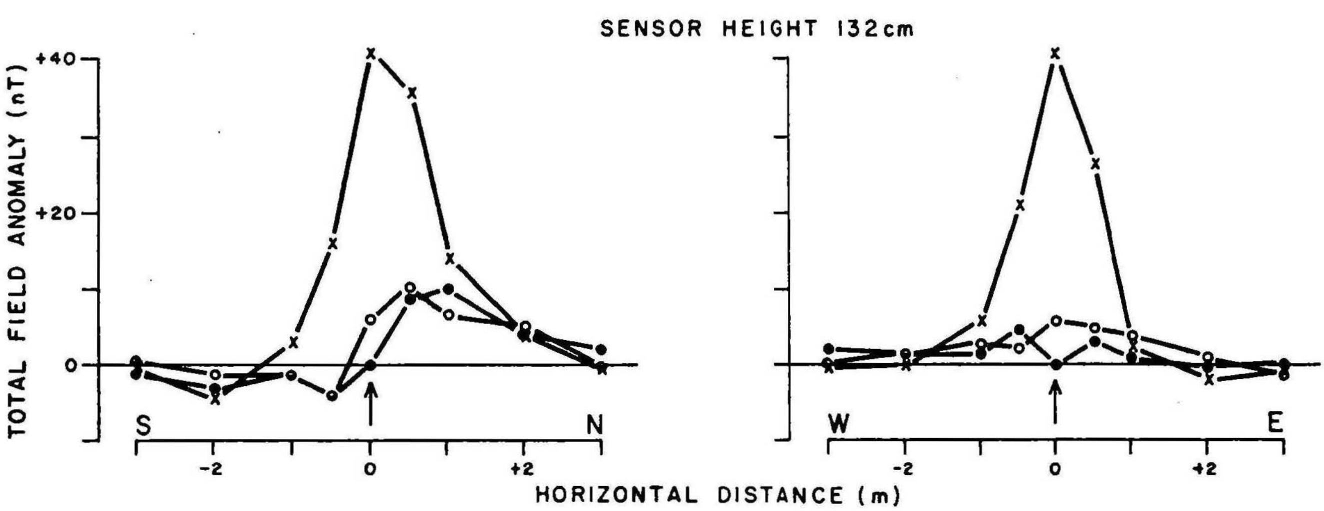



HANDGRENADE




2''- MORTAR BOMB



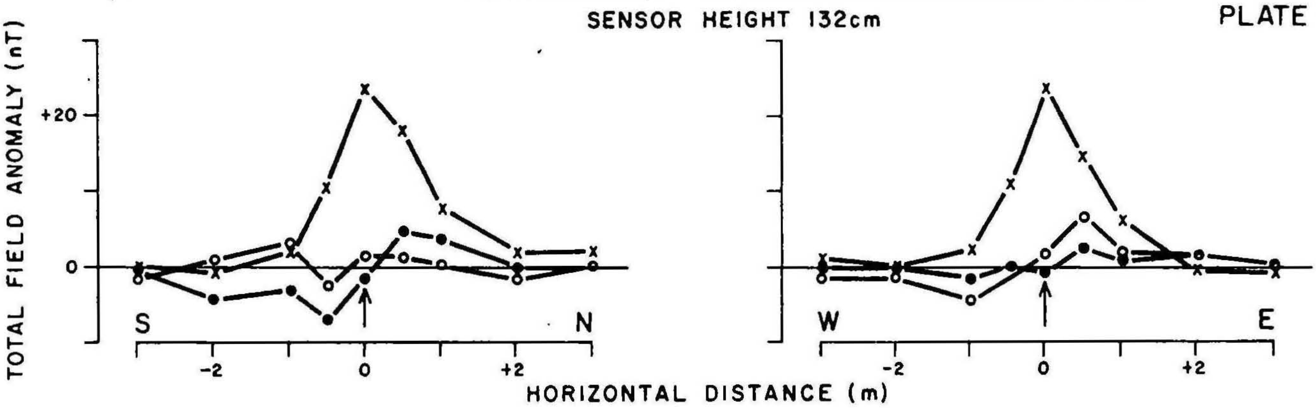

18-lb SHELL

FOR REFERENE SEE PLATE 5

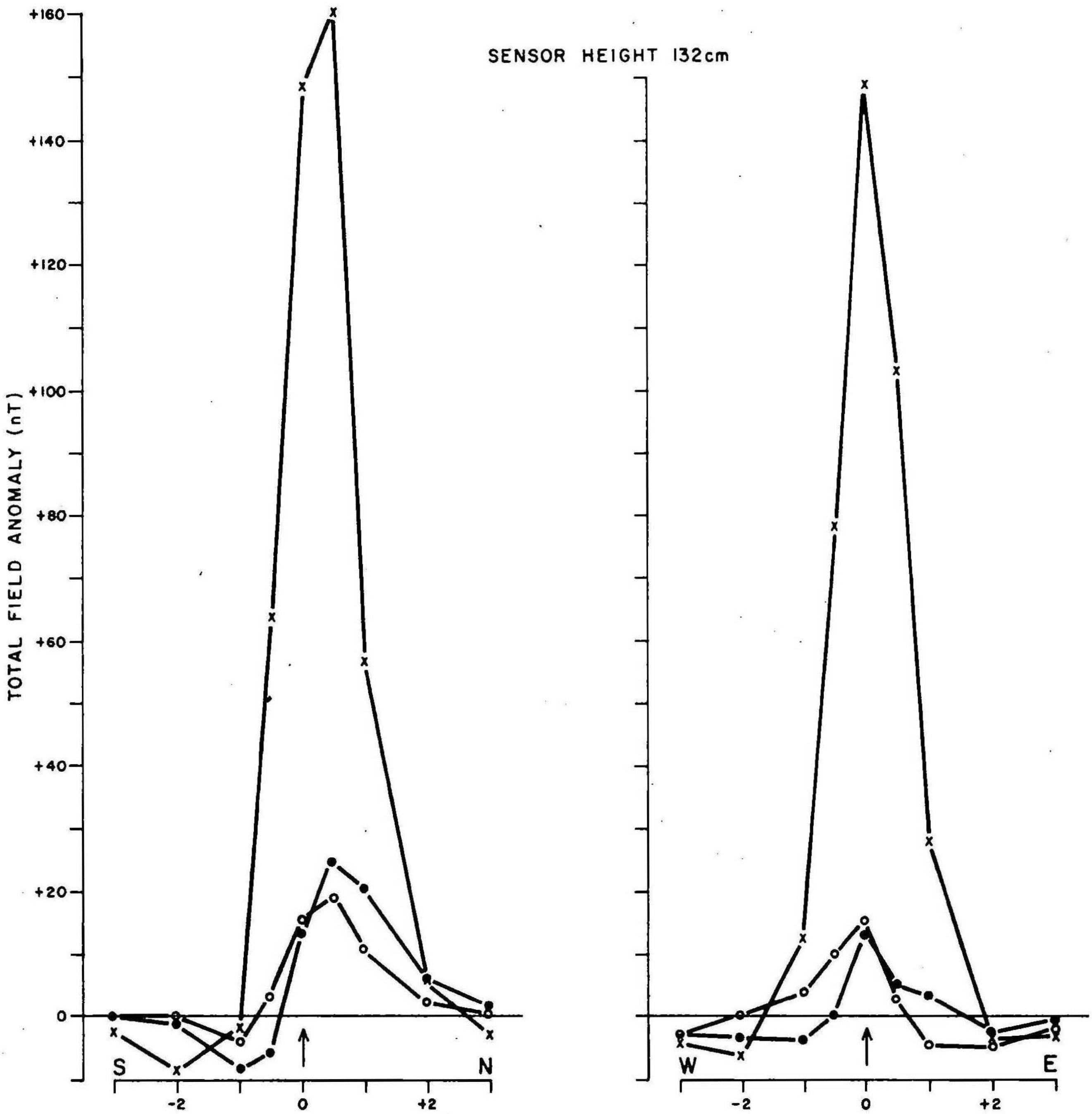
# MAGNETIC SIGNATURES

## HANDGRENADE, 2''- MORTAR BOMB AND 18-lb SHELL

PLATE 9




PIAT PROJECTILE




4·2"- MORTAR BOMB

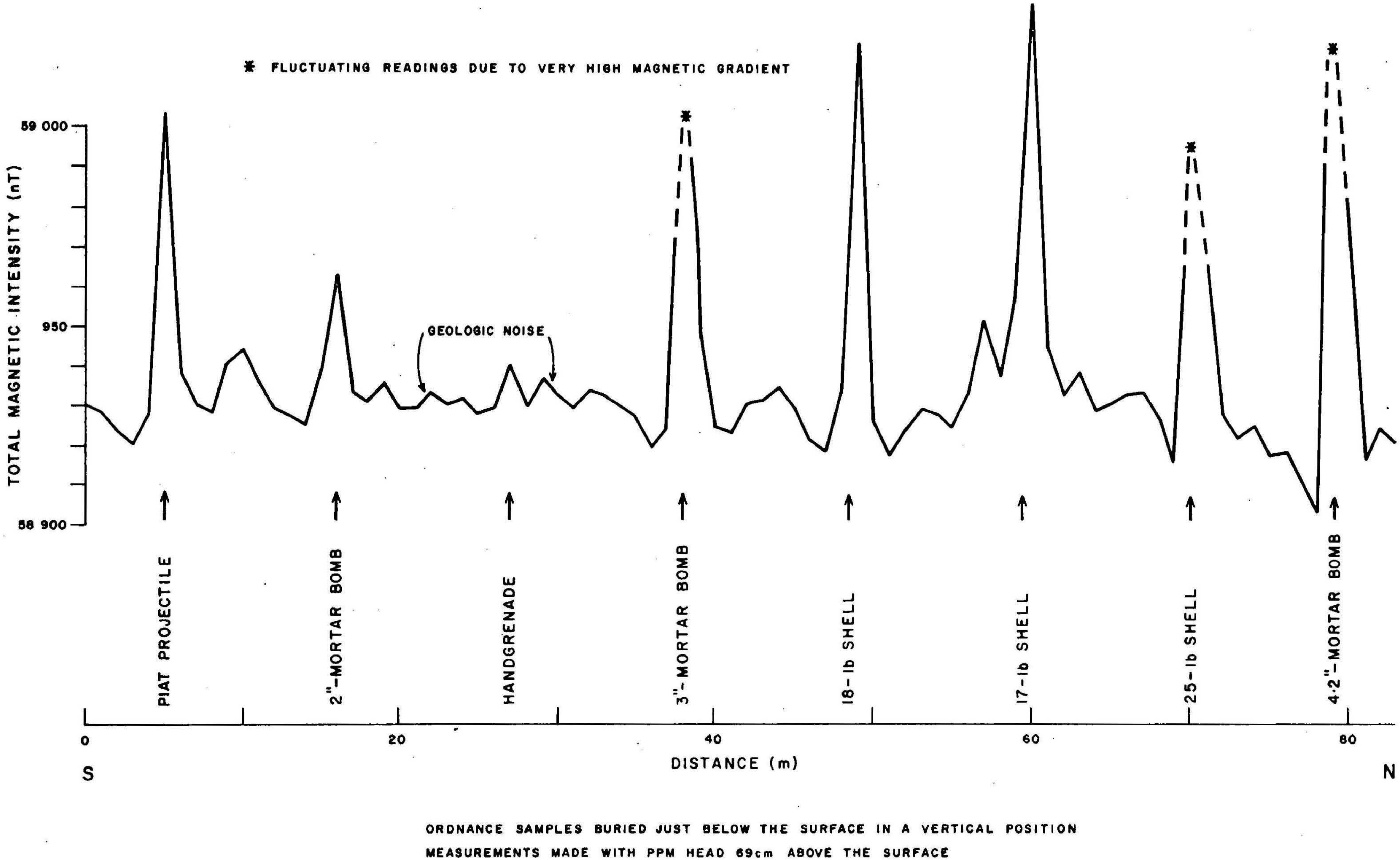
FOR REFERENCE
SEE PLATE 5

# MAGNETIC SIGNATURES

PIAT PROJECTILE AND 4·2-MORTAR BOMB

Record No. 1978/61

I55/B5-383A




MAGNETIC RESPONSE OF ORDNANCE SAMPLES ALONG ARBITRARILY SELECTED N-S TEST TRAVERSE

PLATE 10

I55/B5-384A

Maximum detection depths

By substituting $x_1 = 0$ in equations (1), (2), (3), and (4), the total-field anomaly directly above an inductively magnetised sphere is found to be

$$\Delta F = Md^{-3} \ (3 \sin^2 I - 1) \qquad \ldots(7)$$

With the assumption that the ordnance samples behave as induced dipoles (which appears to be a good approximation judging from the shapes of the magnetic signatures in Plates 5-9), it is possible to calculate the apparent dipole moments (M) of the various ordnance samples for different orientations. $\Delta F$ and d are obtained from the magnetic signature curves, while $I = -66^{\circ}$ for Canberra.

Now the anomaly maximum $\Delta F_{MAX} = 1.75 \text{ m } d^{-3}$; therefore knowing M and also the minimum $\Delta F_{MAX}$ anomaly value that can be recognised above the noise in a particular field situation, one can compute the maximum detection depth of that type of ordnance. This is what has been done in Table 1 for $\Delta F_{MAX}$ values of 10 and 20 nT. The tabulated results are slightly conservative because the small negative part of the anomaly to the magnetic south of the body will tend to increase the apparent height of the peak and so increase resolution.

Use of the gradiometer method

The detectability of an object is a function of (a) the amplitude of the anomaly produced in relation to that of extraneous sources (i.e. signal-to-noise ratio), and (b) the sharpness or width of the anomaly.

In areas which are free from spatial high-frequency noise originating from near-surface sources such as maghemite soil, it may be advantageous to measure the total-field vertical gradient rather than the total field. This can be accomplished by taking magnetometer readings with the sensor head held at two different heights (with the proviso that the height difference be small compared with the likely UXO depth). Alternatively, by using two sensor heads at a fixed separation, it is possible to polarise the heads simultaneously and get readouts of the total field at each of the heads as well as the difference (with the correct sign). At present a simpler (in the sense that less instrumental modification is needed) version is being constructed by BMR in which the two sensor heads are sequentially polarised, the two resultant readings and their difference being displayed on a chart recorder.

The advantages in employing a gradiometer system are:

1) UXO anomalies are sharper (as can be seen in comparing the curves of Plate 2 and Plate 3, and also the patterns of Plate 4), thus increasing detectability as well as enhancing discrimination in situation where two or more UXOs may be in close proximity.
2) regional variations and anomalies due to deep geological features are greatly suppressed.
3) temporal changes such as diurnal drift or magnetic storms are eliminated.

On the debit side, the greatest limitation of the gradient method is that it is restricted to areas devoid of near-surface sources of magnetic noise. In addition, greater magnetometer sensitivity is required; and as the gradient anomalies are sharper, more closely spaced sweeps are needed to adequately cover a given area.

Because most soils are magnetic to some degree, measurement of the total field rather than its gradient is the more universally useful method to adopt in locating buried UXO. However, on some sites a combination of the two methods, in which total-field scanning is carried out over the entire area followed by detailed investigation of selected anomalous zones using the gradiometer method, may be the best approach.

## Details of total-field search

As indicated by Plate 4 (and to some extent, Plate 2), the traverse direction over an anomaly produced by an inductively magnetised sphere which provides the greatest peak-to-trough amplitude is the magnetic N-S direction. Scanning of an area should therefore be done in this direction.

To record an anomaly equal to half the peak amplitude of a UXO at maximum expected depth at least once in a parallel sweep search, it is necessary to use a line spacing approximately equal to or less than that depth. This is evident from Plates 2 and 4.

Once an anomaly has been found and its areal pattern defined, an estimate of the source depth can be made from a study of the N-S anomaly shape (see Plate 2, $\beta = 0$): at high and low magnetic latitudes, the depth

TABLE 1 ORDNANCE SAMPLE DETAILS, MAGNETIC MOMENTS AND MAXIMUM DETECTION DEPTHS BY MAGNETOMETER

| ORDNANCE SAMPLE | WEIGHT (kg) | VISUAL ESTIMATED FERROUS METAL CONTENT (%) | ORIENTATION | HEIGHT OF CENTRE OF SENSOR ABOVE CENTRE OF ORDNANCE SAMPLE (cm) | TOTAL FIELD ANOMALY, IF ≥ 5nT (nT) | MAGNETIC MOMENT (cgs) IN 58900 nT (0.589 gauss) FIELD | MEAN MAGNETIC MOMENT (cgs) PER GAUSS | MAXIMUM DETECTION DEPTH (BELOW SENSOR CENTRE) FOR CANBERRA AREA (cm) | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | 10nT ANOMALY | 20nT ANOMALY |
| 3-INCH MORTAR BOMB | 4.50 | 95 | VERT. DOWN | 118 | 54 | 591 | 1000 | 217 | 173 |
| | | | " | 57 | - | - | | | |
| | | | S-N | 128 | - | - | 27 | 65 | 52 |
| | | | " | 67 | 8 | 16 | | | |
| | | | W-E | 128 | 5 | 70 | 122 | 107 | 85 |
| | | | " | 67 | 37 | 74 | | | |
| 17-POUND SHELL | 4.52 | 85 | VERT. DOWN | 118 | 34 | 372 | 630 | 185 | 147 |
| | | | " | 57 | - | - | | | |
| | | | S-N | 128 | 5 | 70 | 126 | 108 | 86 |
| | | | " | 67 | 39 | 78 | | | |
| | | | W-E | 128 | 6 | 84 | 143 | 114 | 91 |
| | | | " | 67 | 42 | 84 | | | |
| 25-POUND SHELL | 11.32 | 90 | VERT. DOWN | 114 | 110 | 1085 | 1840 | 265 | 211 |
| | | | " | 53 | - | - | | | |
| | | | S-N | 128 | 9 | 126 | 151 | 116 | 92 |
| | | | " | 67 | 26 | 52 | | | |
| | | | W-E | 128 | 14 | 195 | 266 | 139 | 111 |
| | | | " | 67 | 59 | 118 | | | |
| HAND-GRENADE | 0.58 | 100 | ON SIDE | 129 | - | - | 53 | 81 | 64 |
| | | | " | 68 | 15 | 31 | | | |
| 2-INCH MORTAR BOMB | 0,84 | 60 | VERT. DOWN | 122 | 8 | 97 | 165 | 119 | 95 |
| | | | S-N | 130 | - | - | - | - | - |
| | | | W-E | 130 | - | - | - | - | - |
| 18-POUND SHELL | 7.60 | 95 | VERT. DOWN | 117 | 41 | 438 | 740 | 196 | 156 |
| | | | S-N | 128 | - | - | - | - | - |
| | | | W-E | 128 | 5 | 70 | 119 | 106 | 84 |
| PIAT PROJECTILE | 1.10 | 90 | VERT. DOWN | 116 | 24 | 250 | 425 | 163 | 129 |
| | | | S-N | 128 | - | - | - | - | - |
| | | | W-E | 128 | - | - | - | - | - |
| 4.2-INCH MORTAR BOMB | 6.76 | 100 | VERT. DOWN | 114 | 149 | 1470 | 2500 | 294 | 233 |
| | | | S-N | 127 | 13 | 178 | 302 | 145 | 116 |
| | | | W-E | 127 | 15 | 205 | 348 | 153 | 121 |

is approximately equal to the half-width of the anomaly; at intermediate latitudes the depth approximately equals the anomaly maximum-minimum separation.

Hood (1965) shows that at the $\Delta$F anomaly peak (positive or negative) $\frac{\partial \Delta F}{\partial d} = -3\Delta F/d$. Thus an alternative method of depth determination would be to locate the $\Delta$F peak, and measure its value and also the vertical gradient at that point - substitution in the above equation then allows the depth (d) to be calculated.

## 3. TRANSIENT ELECTROMAGNETIC METHOD

### Principles of the TEM method and equipment used

The basic processes involved in the transient electromagnetic (TEM) method have been adequately described by Spies (1976). The changing current in the transmitting loop generates a magnetic field in the surrounding environment which in turn induces electric fields in any nearby conductors, producing eddy currents. These induced electric fields depend on the conductivity, shape, and size of the conductor and its position with respect to the loop. The eddy currents in the conductor tend to diffuse inwards towards the centre of the body and are gradually dissipated by resistive heat losses. With a highly conducting body, the currents tend to circulate on the boundary of the body and to decay more slowly.

The eddy currents, and accordingly the secondary magnetic field, decay within a relatively short time depending on the physical and geometrical properties of the conductor. The receiving coil produces an output voltage proportional to the time derivative (rate of decay) of the vertical component of the secondary field.

BMR has available the Russian-built MPPO-1 equipment which was designed mainly for metalliferous orebody prospecting. This equipment produces square current pulses of 20 ms length at a frequency of 18 Hz in a single ungrounded loop, which creates the primary energising field, and also receives the induced time-dependent emf, e(t), produced at time (t) after the collapse of the primary field. The amplitude of the primary current (I) depends on the loop impedance, but is limited to 3 amps. Further details on the equipment are provided by Spies (1974b).

To achieve a satisfactory degree of coupling with ordnance buried at reasonable depths (say 1 m), a coil diameter of one metre was adopted (by rule-of-thumb) for the field tests. Although it is desirable to have a large number of turns (n) on the coil because the signal strength is proportional to $n^2$, a point is eventually reached at which ringing occurs. About 50 turns was found to be an acceptable compromise between stability and signal strength. The final coil housing was constructed of 2.54 cm diameter PVC tubing (cable conduit) shaped in the form of a one metre diameter circle by the application of heat. Two cross-struts of the same tubing material helped to reinforce the housing and keep it rigid. For the conductor a multi-cored unshielded cable was used. A section of it was pushed into the circular tubing, and by soldering appropriate wire leads together a continuous single-lead conductor was produced - the resultant multi-turn coil had 54 turns and a resistance of 10 ohms. Because of its light-weight and fairly rigid construction, the coil could be pulled over the ground without effort by the twin-flex cable correcting it to the MPPO-1 instrument.

Since shielding problems, as might be caused by a highly conductive near-surface layer, were not anticipated, an early sample time could be used to achieve high signal levels. The t = 1.24 ms setting, which was the shortest delay time available on the equipment prior to BMR modifications, was chosen.

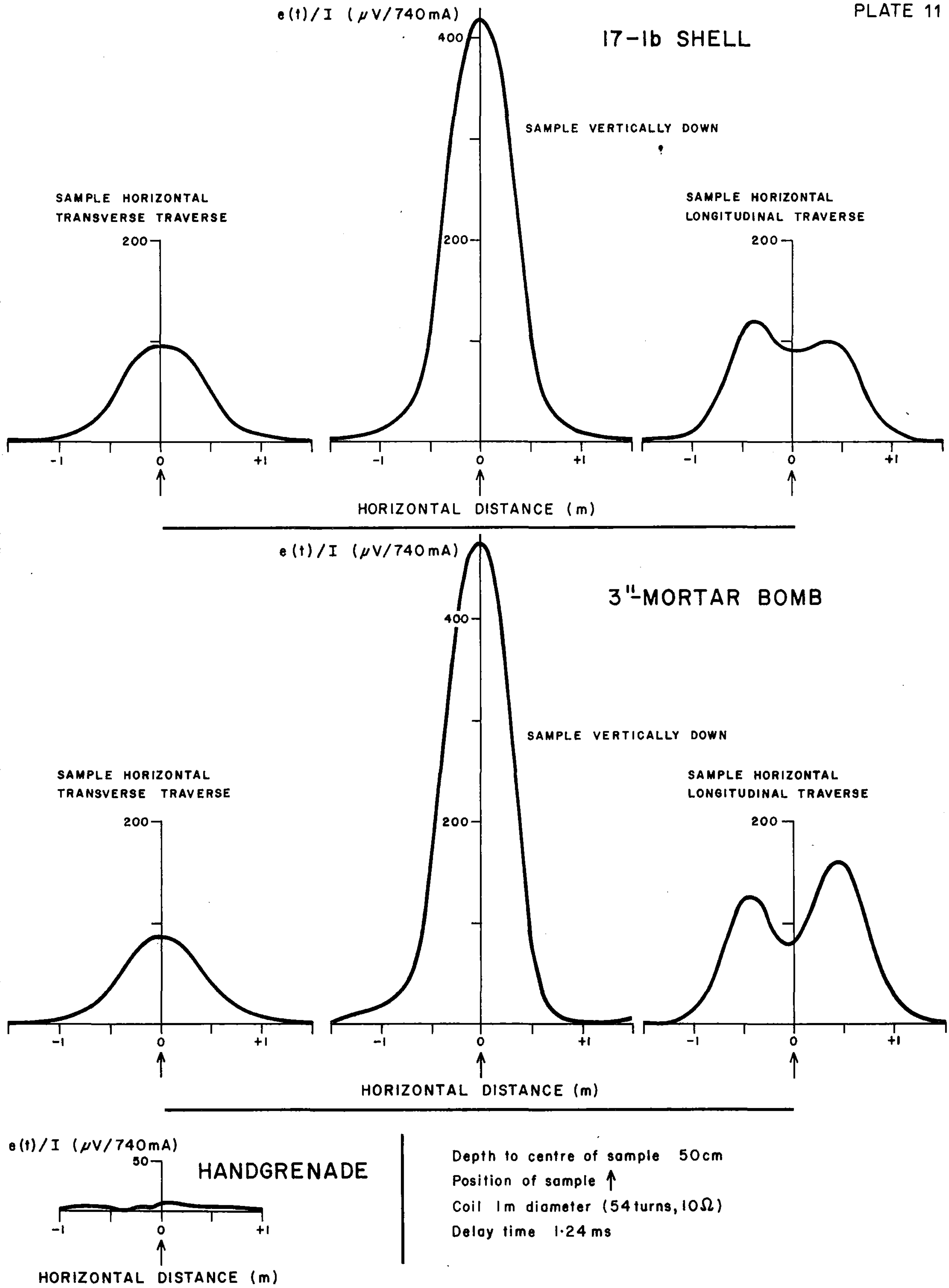
## Field tests with ordnance samples

The TEM response curves of three ordnance samples (17-pound shell, 3-inch mortar bomb, and hand-grenade), buried in soil at a depth of 50 cm, are shown plotted in Plate 11. The data were obtained by moving the coil along surface traverses which passed directly above the samples. The measurements were repeated for different orientations of the samples relative to the traverse direction (vertically down, transverse, and longitudinal).

At the 50 cm depth, the response of the hand-grenade was barely discernible. The larger ordnance samples produced strong responses, the maximum response in each case being obtained with vertical orientation of the sample. In fact, the vertical position resulted in a response about four times as great as that of the horizontal position.

Further measurements were made on all the ordnance samples to determine their response while directly below the centre of the coil and

PLATE 11




TEM RESPONSES OF BURIED ORDNANCE SAMPLES buried in a horizontal position at a depth of 25, as well as 50 cm. The results are shown plotted in the graph of Plate 16. It should be noted that the x-axis shows distance from the ordnance sample centre to the coil proper ($(d^2+R_c^2)^{\frac{1}{2}}$, where $R_c$ = coil radius), rather than the sample depth (d).

Modelling experiments (single- and dual-loop coil configurations)

Because most TEM problems are difficult to analyse mathematically, it has been necessary to resort to scale modelling in most cases in order to obtain solutions for particular coil/target situations.

A system will produce an equivalent geometric response as long as $\sigma\mu L^2/T$ ($\sigma$ = conductivity, $\mu$ = magnetic permeability, L = linear dimension, T = time) remains constant. Because the measured voltage (V) is not dimensionless, it is necessary to invoke the relation VT/L = constant, for absolute scale modelling (Spies, 1977).

Experiments simulating the behaviour of ordnance to TEM signals were conducted using BMR's scale modelling facility. The MPPO-1 instrument was used for this work, with the same delay time setting (t = 1.24 ms) as for the field tests.

Two coil configurations, the single loop and the dual loop (Spies, 1974a), were tested to measure the individual responses of a brass and steel cylinder (2.5 cm diameter and 5.0 cm length) in mutually orthogonal orientations. Each of the coils used consisted of 50 turns of transformer wire, wound in the shape of a square with side 12 cm. Tracking of the coils above the cylinder targets was done at a rate of 8cm/minute to allow for the finite response time of the MPPO-1.

Response curves for various heights of the coil system were obtained for each of the different combinations of coil configuration, model type, and model orientation (Plates 12 to 15). These curves are applicable to any linear variation of the laboratory model's geometry provided the scale modelling relation ($\sigma\mu L^2/T$ = constant) is adhered to. In such a case the shape remains unaltered, while the amplitude is controlled by VT/L = constant.

It is important to note that where $\mu > \mu_\infty$ a purely magnetic component (originating from the collapse of the induced magnetisation) is introduced into the secondary field. It is mainly for this reason that the TEM response curves for the ordnance samples and the steel cylinder model resemble each other, but are somewhat different in shape from that of the non-magnetic, entirely conductive brass cylinder model.

Comparison of single- and dual-loop coil configurations

The essential difference between the single-loop and dual-loop coil configurations is that in the dual loop the input current is concentrated in the central branch of the coil, thereby producing a strong, horizontal primary magnetic field in its vicinity. In contrast, the single-loop coil produces a vertically directed field along its axial region which is less intense at shallow depths. Coupling with the target therefore is different for the two configurations; the single-loop coil is particularly suited to detection of subhorizontal sheet-like conductive bodies, while the dual-loop coil is most effective in situations involving steeply dipping conductors (especially if shallow).

Since we are concerned with ordnance, which consists typically of approximately equi-dimensional bodies, the choice between the two configurations is not so clear-cut. From a practical point of view however, operation of the dual-loop system in the field is more awkward because of its larger size. Nevertheless, it has an advantage in its inherent ability to suppress coherent noise (emanating from sources such as radio stations and power lines). In noisy environments this can be an overriding factor in its favour.

The TEM modelling responses of Plates 12 to 15 indicate that cylindrical targets at shallow depth generally produce peaky responses as a section of the coil passes directly overhead. The central peak of the dual-loop coil response is of greatest amplitude, usually. An important exception is that of the vertical steel cylinder, for which there is in fact a decrease in response when the cylinder is directly below the centre of the coil.

This property can be used to determine the orientation of buried suspected UXO (assumed to be largely of ferromagnetic material). If no local minimum occurs in the middle of the response curve, then it is likely that the object is lying close to the horizontal. Further traverses at different azimuths across the anomaly will indicate the body's orientation in the horizontal plane -the peaks show maximum amplitude for traverses along the length of the body.

A similar but much less marked effect can be seen over the brass cylinder model for a longitudinal traverse. This case can be differentiated from the former, however, by doing another traverse at right angles. If the response curve still shows a local minimum at its centre then the source is

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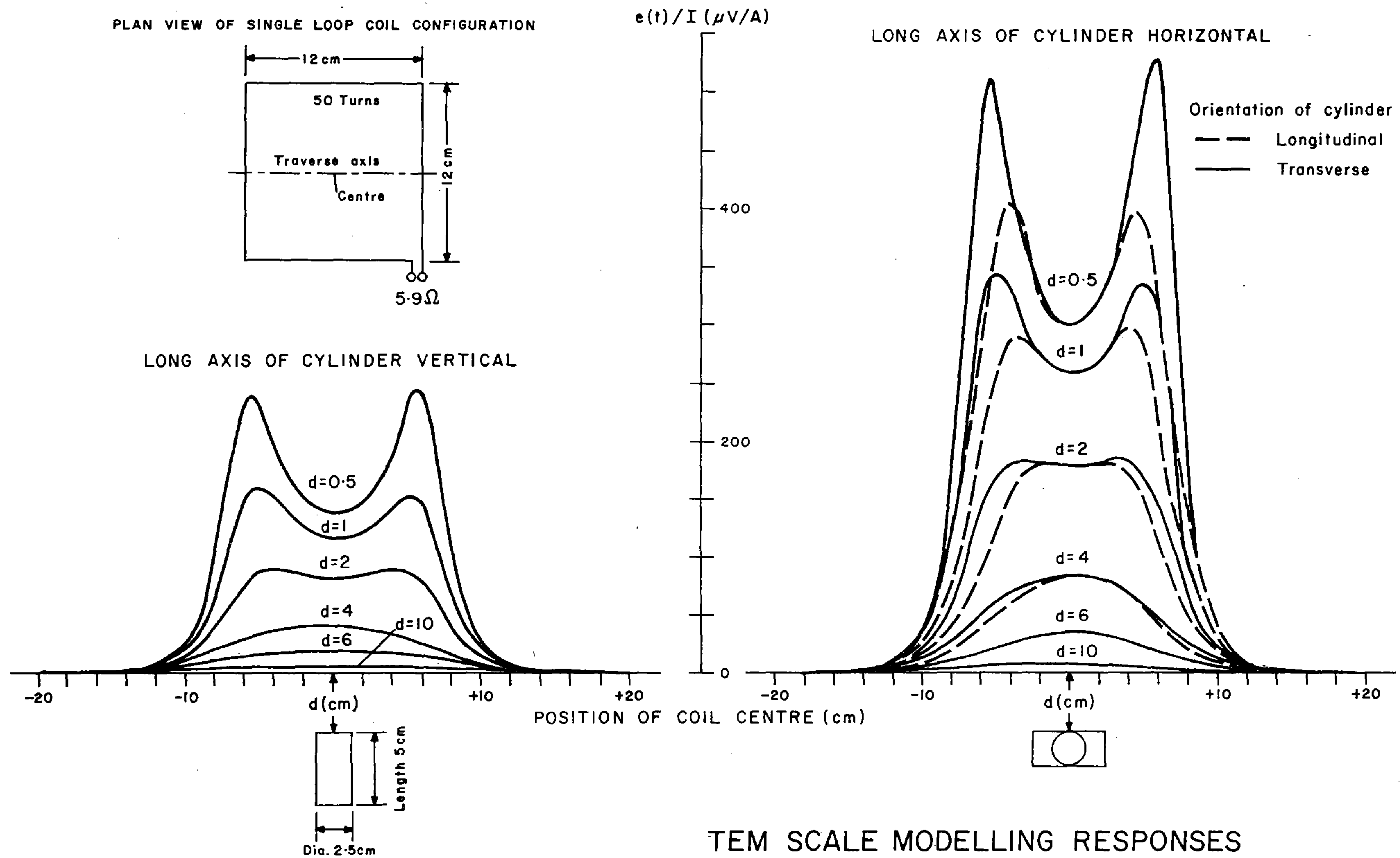
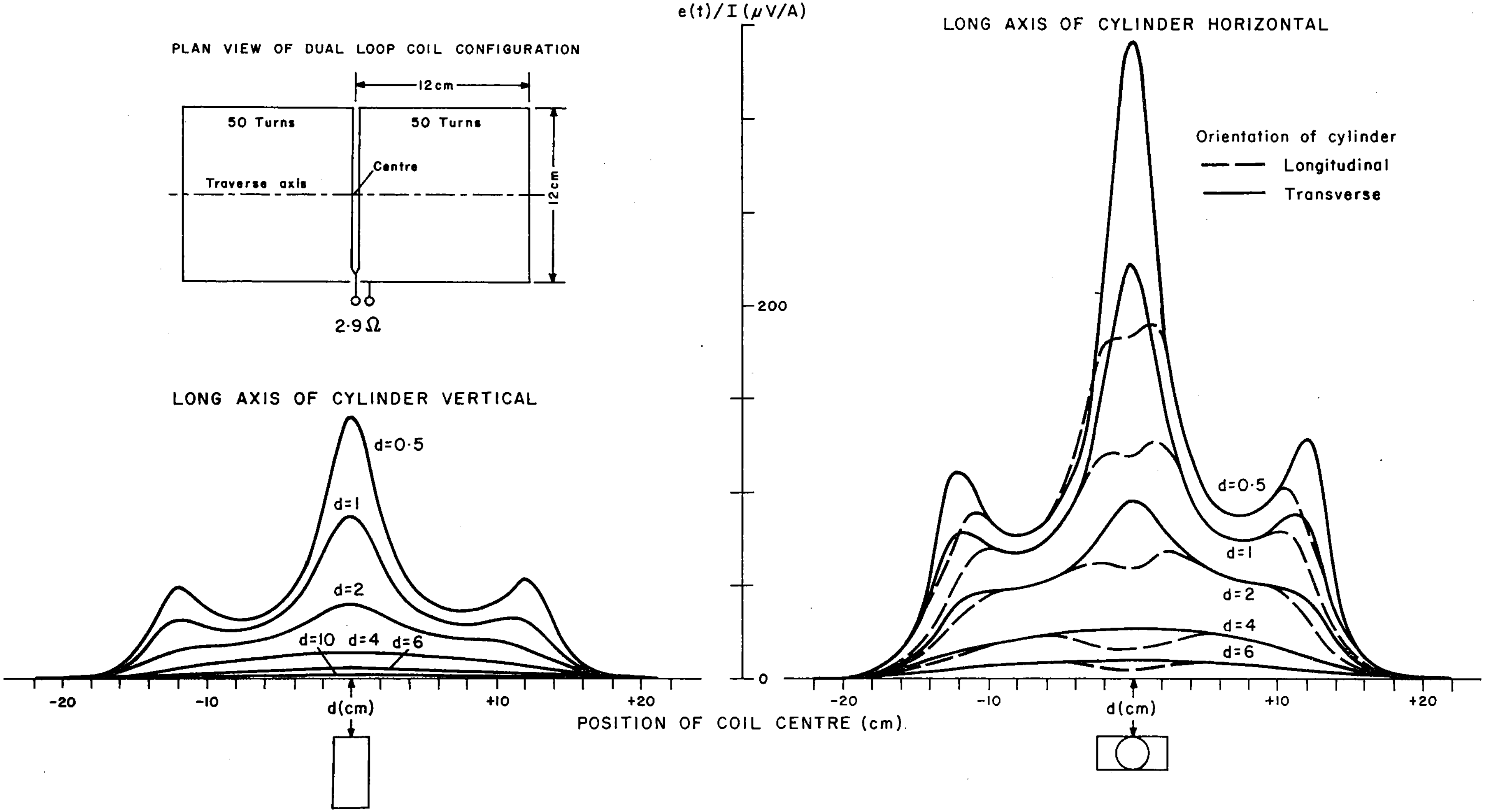



# TEM SCALE MODELLING RESPONSES
# BRASS CYLINDER MODEL

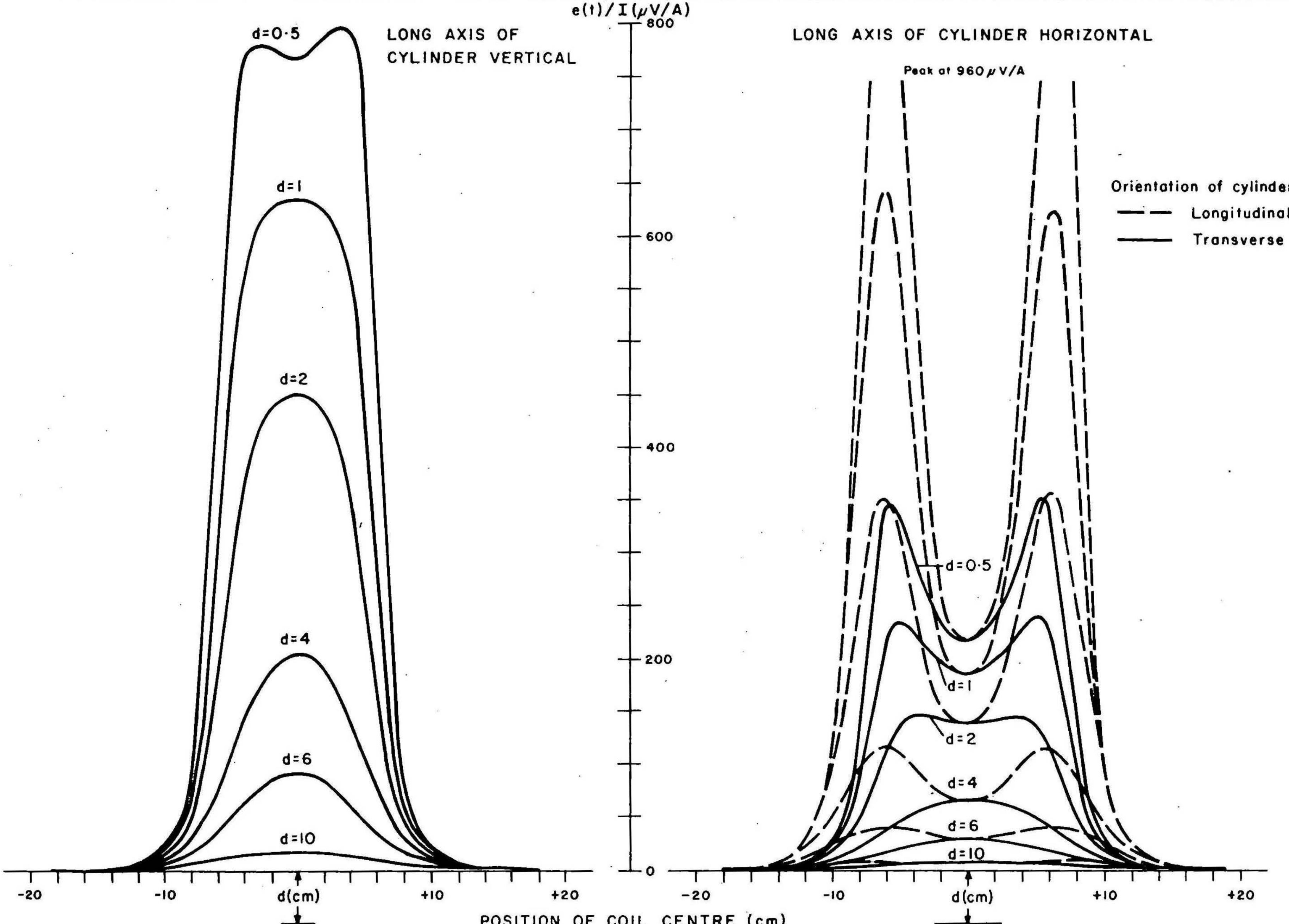
## SINGLE LOOP COIL CONFIGURATION

I55/B5-386A

PLATE 12




# TEM SCALE MODELLING RESPONSES
## BRASS CYLINDER MODEL
### DUAL LOOP COIL CONFIGURATION

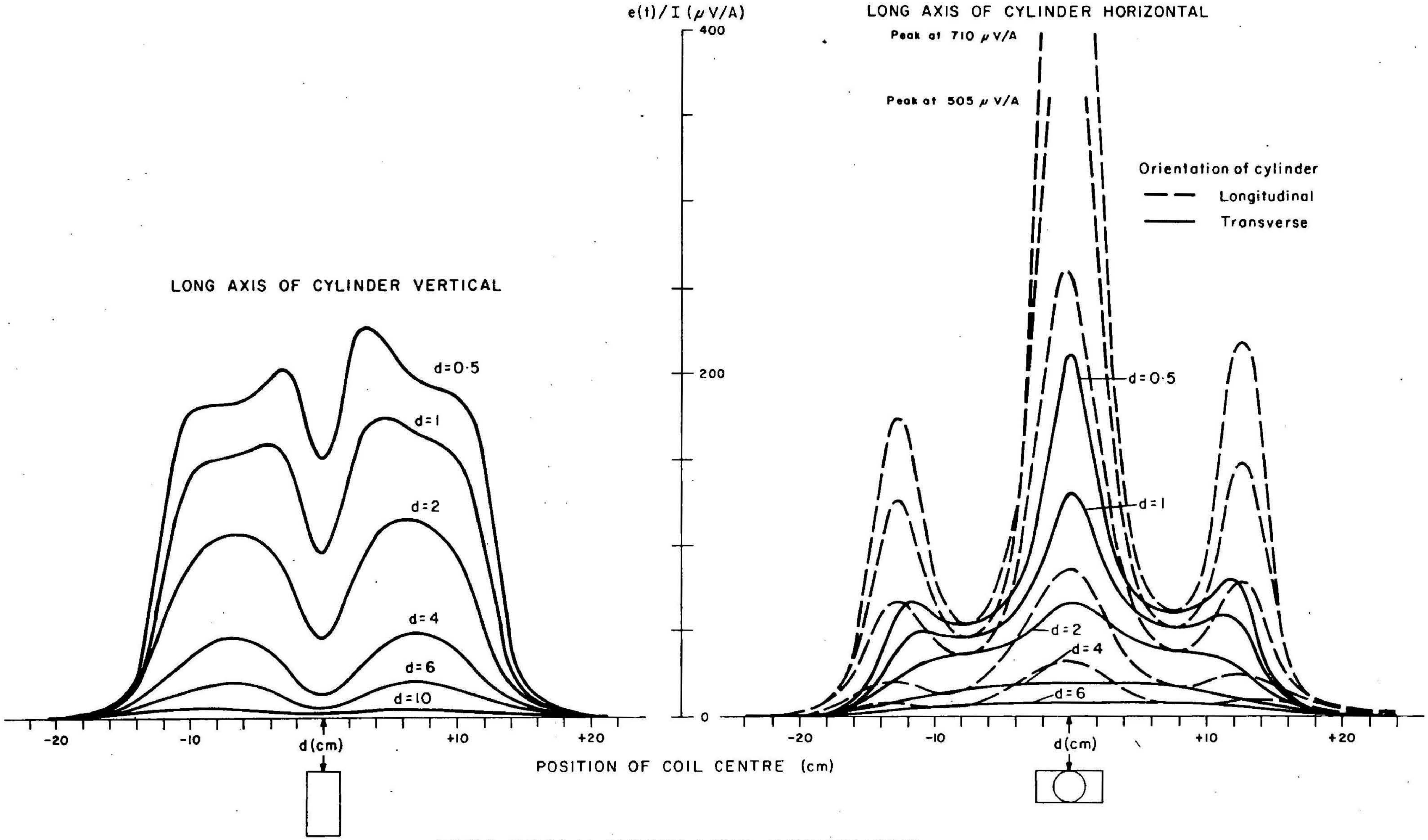



TEM SCALE MODELLING RESPONSES

STEEL ~~BRASS~~ CYLINDER MODEL

SINGLE LOOP COIL CONFIGURATION

I55/B5-388A




# TEM SCALE MODELLING RESPONSES
## STEEL CYLINDER MODEL
### DUAL LOOP COIL CONFIGURATION

I55/B5-389A

largely ferromagnetic; otherwise it is primarily conductive in its TEM reaction.

Despite its usefulness in determining source attitude and its advantages in coherent noise reduction, the dual-loop coil configuration is less efficient than the single-loop, as shown by the modelling response curves. Under equivalent conditions, the e(t)/I response is generally several times as high for the single-loop coil.

## TEM depth response

Information on the variation of TEM response with depth of the target was obtained from the modelling experiments as well as the field tests with the ordnance samples. Additional measurements were made using the one-metre-diameter coil with a cylindrical block of steel (length 15 cm, diameter 9 cm) as target. The coil was supported about 6 cm above the ground and the response measured while the block was held at a number of different heights above the coil centre.

Plate 16 shows all the sets of results plotted on a log-log scale - TEM response against distance from the centre of the body to the coil proper (r). Where more than two data points are available for a particular coil/ target combination, a linear relation is clearly indicated. The response (V) can therefore be written in the form $V = kr^{-n}$, where k and n are constants. From the plots, n is seen to lie within the range $5 \pm 1$, the ordnance samples having values of n at the lower end of the range.

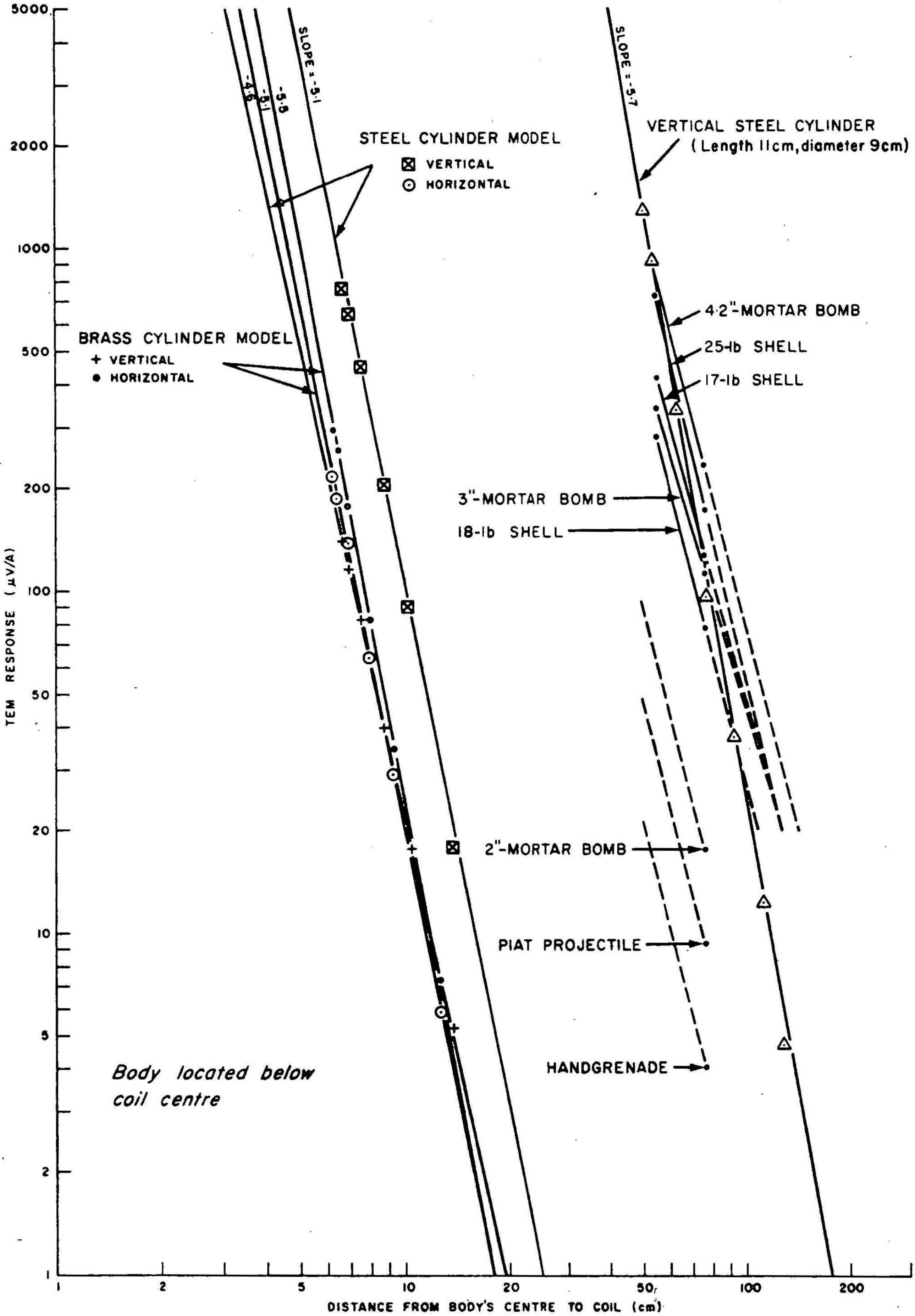
## Noise levels and maximum detection depths of ordnance

Typical peak-to-peak noise levels recorded in the field with the one-metre-diameter coil were as follows:

| | |
|---|---|
| lying on the ground, no movement | 1-2 $\mu$V |
| pulled over a relatively smooth grass surface | 10-20$\mu$V |
| pulled over tussocky grass | 50$\mu$V and over |

The higher noise levels observed when the coil is used over rough terrain are presumably due to impulsive coupling changes and possibly slight flexing of the coil.

Directly below high-voltage transmission lines the noise levels were




VARIATION OF BODY'S TEM RESPONSE WITH DISTANCE FROM COIL

TABLE 2 MAXIMUM DETECTION DEPTHS OF HORIZONTAL ORDNANCE SAMPLES, TEM METHOD (COIL DIAMETER 1 METRE)

| ORDNANCE SAMPLE | MAXIMUM DETECTION DEPTH (cm) | | |
|---|---|---|---|
| | 20 $\mu$V/A ANOMALY | 50 $\mu$V/A ANOMALY | 100 $\mu$V/A ANOMALY |
| 3-INCH MORTAR BOMB | 118 | 85 | 62 |
| 17-POUND SHELL | 118 | 87 | 65 |
| 25-POUND SHELL | 118 | 89 | 72 |
| HAND-GRENADE | - | - | - |
| 2-INCH MORTAR BOMB | 55 | 29 | - |
| 18-POUND SHELL | 100 | 71 | 52 |
| PIAT PROJECTILE | 38 | - | - |
| 4.2-INCH MORTAR BOMB | 133 | 101 | 81 |

so high that ordnance detection was virtually impossible. It was also pointless to attempt a search beside fences because of pick-up from the wire and metal posts. Of course, under these conditions, magnetic detection also fails.

By extrapolating the results of Plate 16, it is possible to predict the maximum detection depth of the various ordnance samples under field conditions which allow UXO anomalies of a certain magnitude to be recognised through the noise. Table 2 provides figures for 20, 50, and 100 nV/A anomalies. Being for horizontally orientated ordnance, these figures represent the worst case as far as response goes. At equivalent depth, ordnance in a vertical position generally produces a response several times as great.

## Depth determination

In a similar way to the magnetic case, source depth can be calculated by measuring response (V) and the vertical gradient of the response $\left(\frac{\partial V}{\partial d}\right)$ at the anomaly centre (for a particular height). From the relation $V = kr^{-n}$, it can be shown that $d = \frac{1}{2}\left(-nV/\frac{\partial V}{\partial d} \pm \left(\left(nV/\frac{\partial V}{\partial d}\right)^2 - 4R_c^2\right)^{\frac{1}{2}}\right)$. To determine the correct sign to use in this equation it is necessary to find out how $\frac{\partial W}{\partial d}$ is changing at the point of measurement. If $\frac{\partial V}{\partial d}$ decreases (or $\left|\frac{\partial V}{\partial d}\right|$ increases) with the coil at a slightly higher level i.e. $\frac{\partial^2 V}{\partial d^2}$ is negative, then the + sign applies, otherwise the - sign is the correct one to use. In practice, the best procedure to obtain the required information would be to take readings of V at three closely spaced levels.

## Possible improvements

Scanning ahead with the coil is preferable to pulling it behind the operator because of the possibility of disturbing and detonating UXO by foot pressure. An even lighter coil, fitted with a handle and counter-weight, could be constructed for advance scanning - the coil being smoothly skimmed just over the ground surface. With such a technique, the problem of noise created by uneven terrain should be significantly reduced.

The use of new instrumentation such as the SIROTEM (Buselli & O'Neill, 1977) would provide greater sensitivity and versatility as a result of higher power, greater noise rejection, and the incorporation of a micro-processor to control operations. As a result, however, the portability of this equipment is reduced because of the increased weight (16 kg for the SIROTEM, compared to 8 kg for the MPPO-1). More importantly still, because the SIROTEM has been designed specifically for geophysical exploration, it is not readily adapted for use as a metal detector. Thus, it may be desirable to build a new, less-sophisticated, portable TEM unit solely for metal detection - possibly one that samples a large portion of the decay curve, and utilises some of the more relevant refinements of the SIROTEM.

## 4. SEARCH ON SITE

Because of moderate geologic magnetic noise on some parts of the ACT Police Drivers Training Centre site, the search for subsurface UXO was carried out with the MPPO-1 TEM equipment in conjunction with the one-metre-diameter coil. In total, about 3000 $m^2$ of the site was covered, including areas where construction was proposed such as the site office, main Centre building, skid pan, fence lines, power poles, culverts, and pipelines.

Although the ambient electrical noise level was low, being in the order of a few microvolts, noise levels generated when the coil was being pulled over uneven terrain such as tussocky grass were usually about an order of magnitude higher. The coil could be used with reasonable effectiveness to within about one metre of non-radiating, metallic cultural features such as fences, but there was virtually no hope of UXO detection directly under high-voltage power-lines. In general, however, it was possible to operate on the 150 $\mu$V range of the MPPO-1.

Two people were needed to conduct the search - one to carry and operate the MPPO-1 while watching for deflections on the instrument meter, and the other to pull the coil over the area to be scanned. The optimum scan rate with the coil was a slow drag of about 15 cm/s.

No definite indication of subsurface UXO was found on the site.

## 5. CONCLUSION

In conditions of low magnetic and electromagnetic noise, detection of common types of ordnance buried in the subsurface can be achieved with approximately equal efficiency by both the total-field magnetic method and the single-loop TEM method (when using readily available instruments such as proton-precession magnetometers and the MPPO-1). Non-magnetic ordnance can, of course, be detected only by the TEM method.

Because background noise, rather than instrument sensitivity, is the limiting factor in the detection techniques considered, selection of the most effective search method depends on the nature of the dominant noise present. In many cases variations in the magnetic properties of the soil or other near-surface material are large enough to rule out any possibility of conducting an effective magnetic search. The TEM method, on the other hand, is less sensitive to changes in magnetic susceptibility commonly occurring in the subsurface, and can therefore be applied in most areas.

As discussed, the suitability of related techniques (such as the gradiometer method and dual-loop TEM) should be assessed. If considered appropriate, they could be applied to derive maximum information about possible buried UXO.

The detection depth by the magnetic method is pre-determined by the prevailing level of magnetic noise. In the case of the TEM method, scope exists for increasing the detection depth by supressing the extraneous pick-up (electronically and/or by choice of coil configuration), as well as by increasing the energising power output of the system. In areas which are almost free of magnetic noise, however, the magnetic method offers the best chance of detection at greater depths because the response of the causative body drops off in proportion to the 3rd power of depth, whereas with the TEM method it decreases much more rapidly - approximately in proportion to the 5th power of depth.

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