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USE OF A PROTON PRECESSION MAGNETOMETER TO DETECT BURIED DRUMS IN SANDY SOIL

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Summary

A commercially available proton precession magnetometer (PPM) was used to investigate the detection of containers buried in a prescribed manner at a single field site. The site consisted of relatively uniform sandy soil of low water content, this, combined with negligible magnetic interference from sources other than the containers, provided nearly ideal conditions for the study.

The results indicate that the PPM should be able to detect and delineate any typical dump site with predominantly steel (ferromagnetic) drums. In the usual surveying position (the PPM placed in a backpack or on a 6 ft shaft), single steel drums could be detected with up to six feet of soil cover and isolated groups of steel drums to significantly greater depths. Plastic containers could not be detected with this technique.

The ease of deployment combined with the reliability, sensitivity and cost-effectiveness makes the PPM surveying a very promising nondestructive testing technique for the detection of buried steel containers.

Introduction

In this paper we discuss the detection of buried drums using a commercially available proton precession magnetometer (PPM). This is the fourth paper in a series dealing with detection of buried drums in a uniform sandy soil utilizing a number of different nondestructive testing (NDT) techniques. Most of the details of the project can be found in the earlier papers published in this journal [1—3]. Here, we give only a concise description of the site and a brief description of the experimental method, followed by the results and conclusions.

Site details

An abandoned sand quarry was made available where a number of drums

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could be buried. The quarry was located in a relatively remote area where the nearest road and utilities were 1000 feet from the test site. Thus, background disturbances from man-made objects were minimal. The soil was a uniform well graded dry sand with a water table about 20 ft from the surface. This was much deeper than the maximum depth of drum burial. The lack of stratified layers in the soil proved ideal for the type of work performed. Details of the exact nature of the soil can be found in reference [2].

The containers were placed in hand-excavated and equipment-excavated holes varying from 1 to 14 ft in depth. Containers placed in the excavations varied in size from 2 gallons to 55 gallons and were made from both steel and plastic. The container burial patterns were as follows:

Pattern 1: three 30 gallon steel containers buried at 3 ft depth, but at different orientations, i.e., the drum axis 90° (vertical), 45° and 0° (horizontal).

Pattern 2: four 55 gallon steel containers buried at 4.5 ft depth in two groups, one by itself, the other three side by side.

Pattern 3: four steel containers of various sizes (2, 5, 30, 55 gal) buried at constant depths of 3.5 ft (i.e., all at 3.5 ft of soil cover).

Pattern 4: four 30 gallon steel containers buried at 1, 3, 6 and 11 ft depths.

Pattern 5: a random burial site approximately 12 × 12 × 5 ft deep, which was filled with 1 plastic drum and 10 steel drums of various sizes. (This pattern was called the "trash dump".)

Pattern 6: four 40 gallon plastic containers buried at 1, 3, 6 and 11 ft depths.

Pattern 7: three 40 gallon plastic containers buried at 2 ft depth, one filled with fresh water, the other filled with salt water.

All the data described in this paper were collected on a 2 × 2 ft grid pattern.

Experimental method

Principle of operation

When an atom or nucleus possesses a resultant angular momentum $\vec{G}$, it has an associated magnetic dipole moment, $\vec{\mu} = \gamma\vec{G}$, where γ is the magnetogyric ratio. If such a dipole is placed in an external magnetic field $\vec{H}$, it experiences a torque $\vec{\mu} \times \vec{H}$, and the equation is

$$d\vec{G}/dt = \vec{\mu} \times \vec{H} \quad (1)$$

$$= \gamma\vec{G} \times \vec{H} \quad (2)$$

or

$$d\vec{\mu}/dt = \gamma\vec{\mu} \times \vec{H} \quad (3)$$

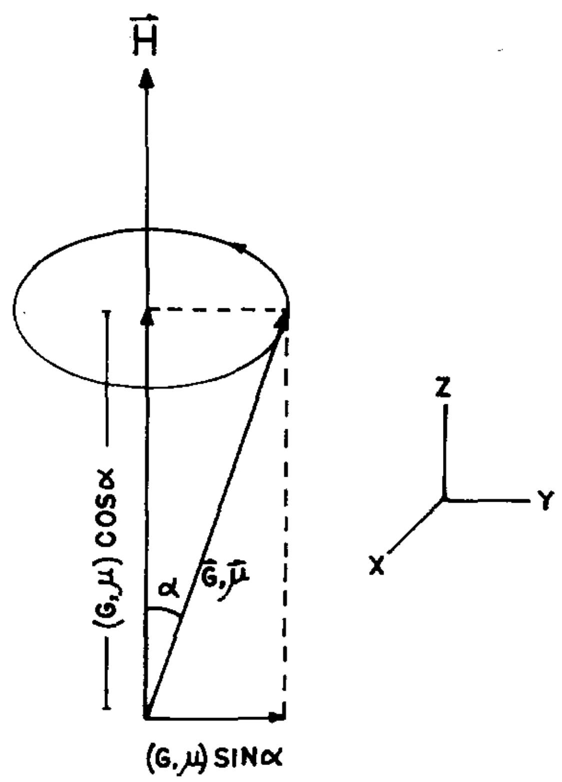


Fig. 1. Angular momentum vector, $\vec{G}$, and the associated magnetic dipole moment, $\vec{\mu}$, in an external magnetic field, $\vec{H}$.

Let $\vec{H}$ be along the Z-axis (see Fig. 1). The solution of eqn. (3) can be written as

$$\mu_x = \mu \sin\alpha \cos(\omega_L t + \epsilon) \tag{4}$$

$$\mu_y = \mu \sin\alpha \sin(\omega_L t + \epsilon) \tag{5}$$

$$\mu_z = \mu \cos\alpha \tag{6}$$

Here ϵ is the initial phase constant. Thus the motion of $\vec{\mu}$ (or $\vec{G}$) is a uniform precession about $\vec{H}$ with angular frequency

$$\omega_L = \gamma\vec{H} \tag{7}$$

The value of γ for protons in water, γ_p, uncorrected for diamagnetism, is given by [4]:

$$\gamma_p = (2.67513 \pm 0.00002) \times 10^4 \text{ G}^{-1} \text{ s}^{-1}$$

A PPM operates essentially as follows. About 300—500 cm^3 of water is subjected to a strong (~100 G) magnetic field roughly at right angles to the earth's field for a few seconds. This application partially polarizes the protonic magnetic moments in the direction of the net magnetic field. When the polarizing field is removed, the proton magnetic moment precesses about the remaining (earth's) magnetic field $\vec{F}$. Since γ_p is a constant, a measurement of the precession frequency can be used to determine $\vec{F}$.

In place of water one can also use other hydrogen-containing materials such as kerosene, hexane, or alcohol. Use of these materials may be desirable when longer coherence period (relaxation time) is an advantage, or may become necessary when the operating temperatures are below the freezing point of water. When materials other than water are used one must use the corresponding value of γ_p for the material.

The intensity of the earth's field is commonly expressed in gauss using the CGS electromagnetic system of units, whereas in the SI system the tesla (weber m^{-2}) is used, where: 1 gauss = 10^{-4} tesla. For small variations the unit called the gamma (γ) is used where: 1 gamma = 10^{-5} gauss. Most commercially available proton precession magnetometers can measure fields to within $\pm 1\ \gamma$. The photographs of the actual apparatus used in this study are shown in Fig. 2.

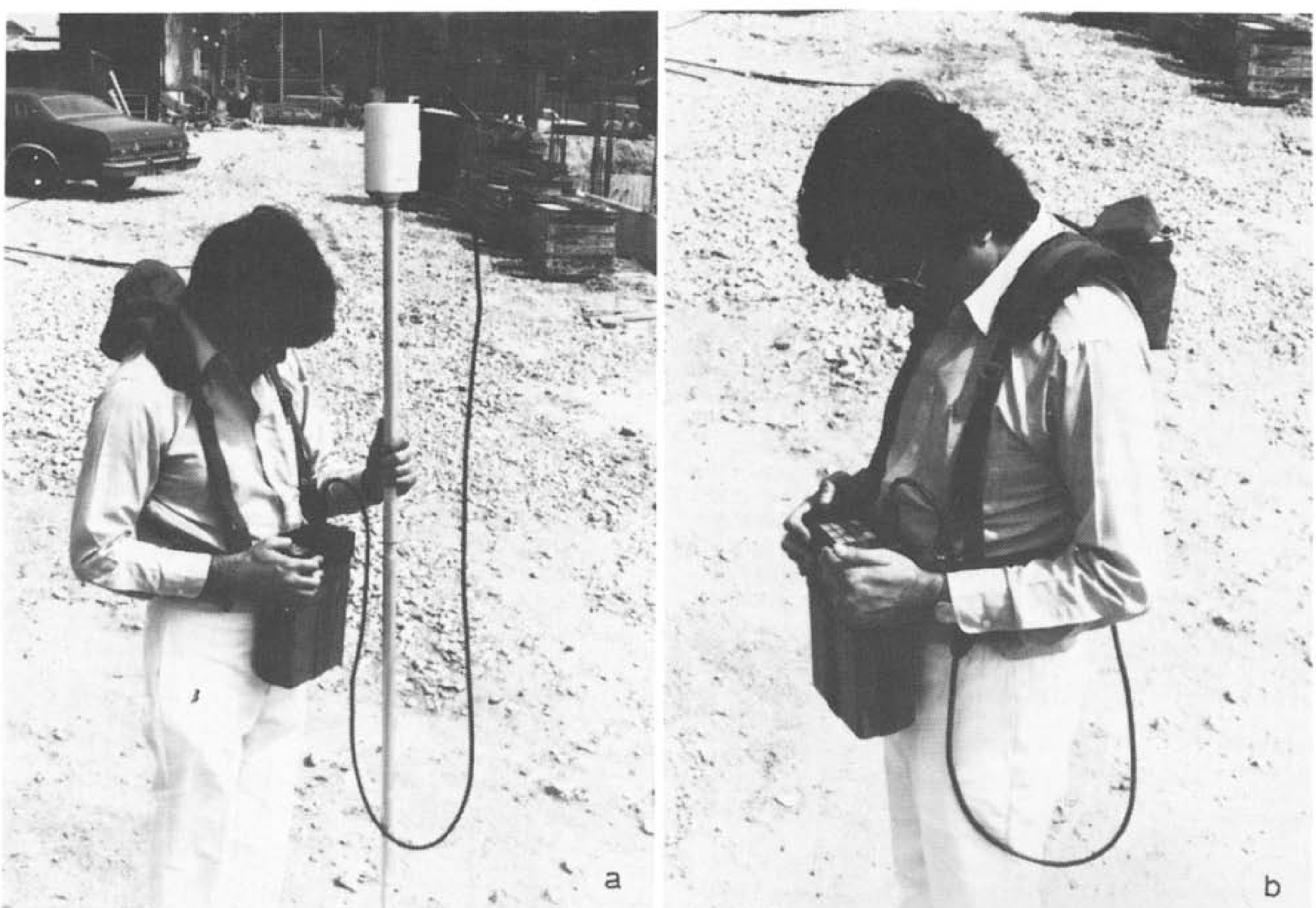


Fig. 2. Photographs of the actual apparatus used in this study; (a) on a 6 ft aluminum shaft; (b) on backpack.

Detection of anomaly

If the earth's magnetic field is given by $\vec{F}$ at a point, the precession frequency $\omega_L = \gamma_p|\vec{F}|$ of the proton will determine the magnitude of the field vector $\vec{F}$. Now suppose the PPM is moved along a traverse and encounters an anomaly of magnetic field vector $\vec{T}$ as shown in Fig. 3. For $|\vec{T}| \ll |\vec{F}|$, angle $\delta \sim 0$ and the proton magnetic moment will precess about OC with frequency

$$\begin{aligned} \omega_L' &= \gamma_p|\vec{F} + \vec{T}| \\ &= \gamma_p\,(F + T\cos\theta) \qquad (8) \end{aligned}$$

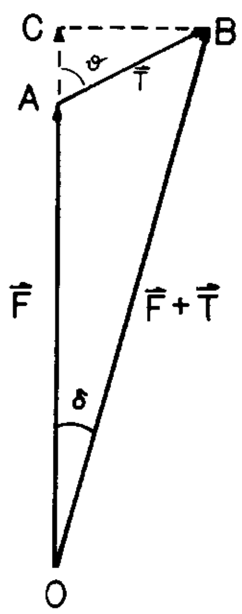


Fig. 3. Effect of an anomaly of magnetic field, $\vec{T}$, on the earth's magnetic field, $\vec{F}$.

Thus a change $\Delta\omega_L = \omega'_L - \omega_L$ in the precessional frequency will yield information on the component of the anomaly field along the earth's magnetic field vector $\vec{F}$. The approximation $|\vec{F} + \vec{T}| \simeq F + T \cos\theta$ breaks down when $|\vec{T}|$ is comparable to $|\vec{F}|$ as it is in the vicinity of iron ore deposits or other large anomalies. In such cases $|\vec{F} + \vec{T}| = (F^2 + T^2 + 2FT\cos\theta)^{1/2}$. Near anomalies that produce large field gradients ($\simeq$600 γ/m) the PPM signal is severely degraded.

The PPM is a very sensitive instrument, and magnetic cleanliness of the instrument and the investigator is very important. Magnetic materials in the wearing apparel of the observer, like keys, penknives, wrist watches, etc., must be removed. Observations in the neighborhood of magnetic mass such as iron-scrap, bridges, railroads should be avoided or should be properly compensated for, when such avoidance is not possible.

Once the area for magnetic investigation has been selected a base line for reference purpose is drawn. Measurements are then made at regular intervals along lines perpendicular to the base line. The size of the intervals is determined by the spatial extent of the anomaly. Measurements can also be made along traverses parallel to the base line for quick and approximate location of the anomaly.

After the data have been collected, several corrections must be applied. The data must be corrected for time variations of the magnetic field. Such corrections are especially important if the anomalies under investigation are broad or if the objective of the survey is a good magnetic contour map including deep seated anomaly sources, and also if the investigation is performed in the high magnetic latitudes in the auroral zone where micropulsations (rapid changes in the magnetic field) are 10 to 100 gammas. However, if anomalies are of several hundred gammas, or much smaller but the time of traversing is only a few minutes, most data do not require any time corrections. In PPM, corrections due to temperature changes are almost always negligible. Rough terrain may also give rise to anomalies. There are no general rules for applying terrain corrections. Usually the anomalies showing a strong correlation with the terrain are regarded as less significant than others.

In investigating anomalies in an area, one must also establish a zero level. This level can be located in an area of normal undisturbed geomagnetic field. Anomalies at all other points in the immediate area are then referred to this zero level. Sometimes the zero level can also be determined from the flanks of the anomaly curve. Regional anomaly gradients, terrain characteristics, or contact between rock formations of differing magnetizations, sometimes make it impossible to use the same zero level throughout the area.

The interpretation of magnetic anomalies

The magnetic field, $\vec{F}_1$, can be derived from a magnetic potential Ω

$$\vec{F}_1 = \operatorname{grad} \Omega \tag{9}$$

where Ω, in a source-free region, satisfies Laplace's equation

$$\Delta^2 \Omega = 0 \tag{10}$$

A unique general solution of this equation involving a finite number of terms does not exist. Usually, to interpret a magnetic anomaly one starts by guessing a body of suitable form, calculating its field on the earth's surface and comparing it with observations. It is then possible to adjust the depth and dimensional parameters of the body by trial and error until a satisfactory fit is obtained. Such a solution is only one of an infinity of possible solutions. However, despite the non-uniqueness of the solutions of eqn. (10), the interpretation of magnetic anomalies is not as difficult in practice as might be imagined. On the basis of available geological information and on grounds of plausibility, the number of different possible sources can be narrowed down to a few which can be used for the initial trial calculations.

The principle of anomaly source characterization can be illustrated by a simple, although a bit naive, example. Consider a dipole of magnetic moment M buried at depth z in the earth's magnetic field as shown in Fig. 4(a). $\vec{T}$ represents the anomaly field. The radial, T_r, and the tangential, T_θ, components will be given by [5]:

$$T_r = (2M \cos\theta)/r^3 \tag{11}$$

$$T_0 = -(M \sin\theta)/r^3 \tag{12}$$

The PPM will measure the component $T_z = T_F = T$, given by

$$T_z = T_r \cos\theta + T_\theta \sin\theta$$

$$= \frac{M(2z^2 - x^2)}{(x^2 + z^2)^{5/2}} \tag{13}$$

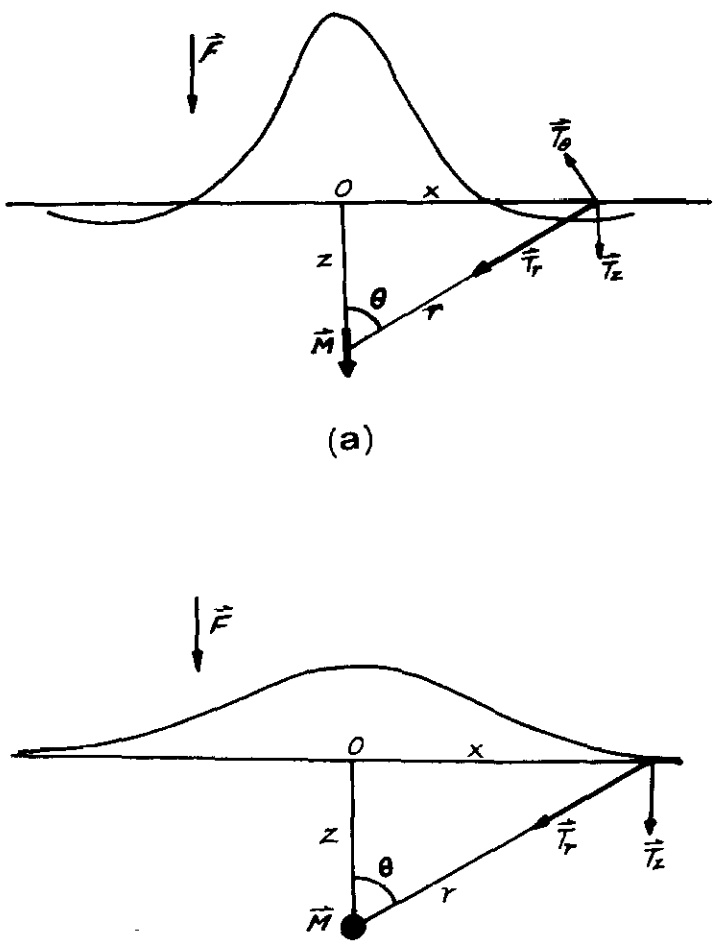


Fig. 4. (a) Magnetic anomaly due to a dipole; (b) magnetic anomaly due to a monopole.

For a monopole of moment M buried at depth z (see Fig. 4(b)) the total field at x is given by

$$T_z = T_F = T = M \frac{z}{(x^2 + z^2)^{3/2}} \tag{14}$$

From equations (13) and (14) one can make the comparison between the anomaly fields due to a dipole and a monopole given in Table 1.

TABLE 1

Anomaly fields of a dipole and a monopole as function of x

x	T_z	
	Dipole	Monopole
0	$2M/z^3$	M/z^2
$\pm z$	$0.175M/z^3$	$0.35M/z^2$
$\pm\sqrt{2}z$	0	$0.192M/z^2$
$\pm 2z$	$-0.04M/z^3$	$0.09M/z^2$

Thus, it can be seen that the rate of fall for T_z of a dipole is different from that of a monopole. Also the anomaly curve of a dipole, unlike that of a monopole, passes through zero and then assumes negative T_z values. Therefore from the shape of the anomaly curves one can distinguish between a dipole and a monopole source. Once the nature has been determined, one can adjust M and the depth parameter to obtain a good fit with the experimentally observed anomaly. A good elementary discussion on source characterization can be found in Breiner [5], Dobrin [6], Grant and West [7], Parasnis [8] and references cited therein.

Results

Pattern 1; steel drums, effect of orientation. The results of a survey of pattern 1 performed with the magnetometer placed on a 6 ft aluminum shaft are shown in Fig. 5. The signals are essentially dipolar in character as expected. The signal due to the inclined drum is stronger than that caused by the vertical drum. This is due to the higher net magnetic dipole moment of the drum in the earth's magnetic field.

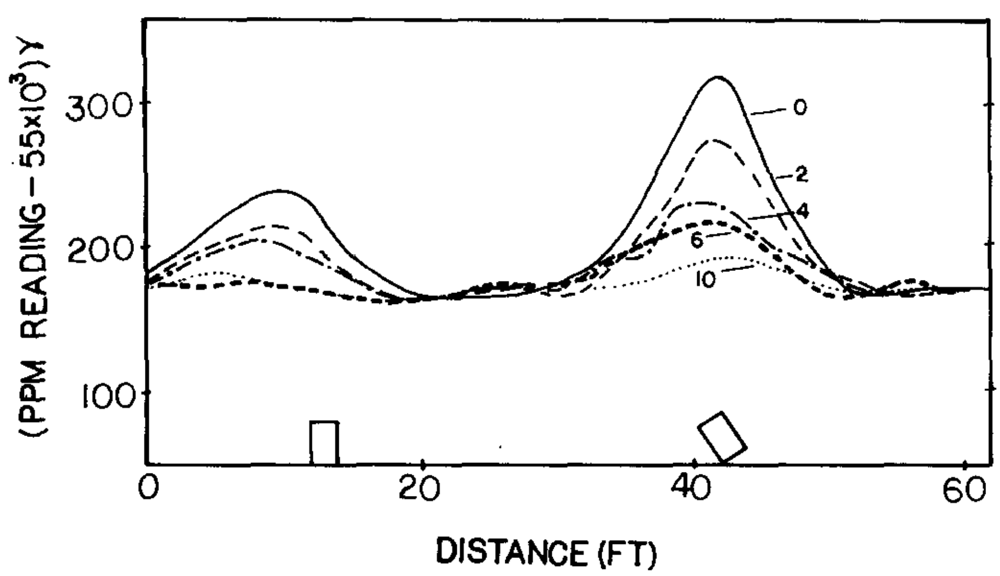


Fig. 5. Magnetometer scans over pattern 1. Labels on curves indicate traverses with offset in feet. Measurements were made on a 2 × 2 ft grid, but some of the scans have been omitted for the sake of clarity in this and subsequent figures.

Pattern 2; steel drums, effects of drum density. This burial pattern was made to test the resolution of the technique. The pattern consists of a single 55 gallon steel drum and three 55 gallon steel drums buried on their sides and 16 feet apart center to center. There was 4.5 feet of soil cover over all drums. The results are shown in Fig. 6. The maxima due the single drum and the three drums are clearly resolved although there is some interference at the lobes. For this particular pattern 16 feet is approximately the resolution separation. The resolution separation will of course be influenced by the actual distribution of drums (number and depth). Note that for the traverse with a 10 ft offset (the distance between the drum and the magnetometer probe is 11 ft) only the signal from the 3 drums can be observed.

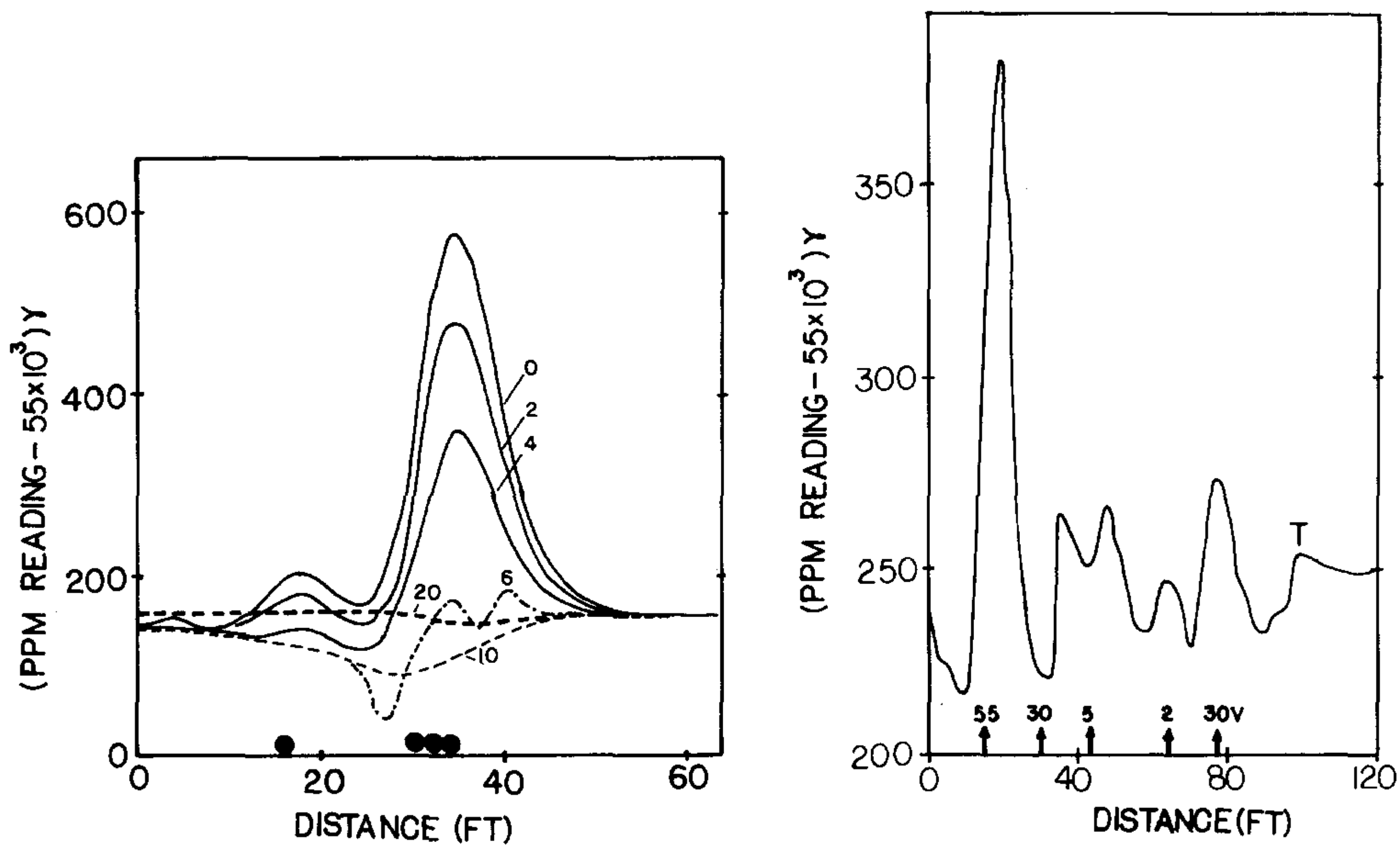


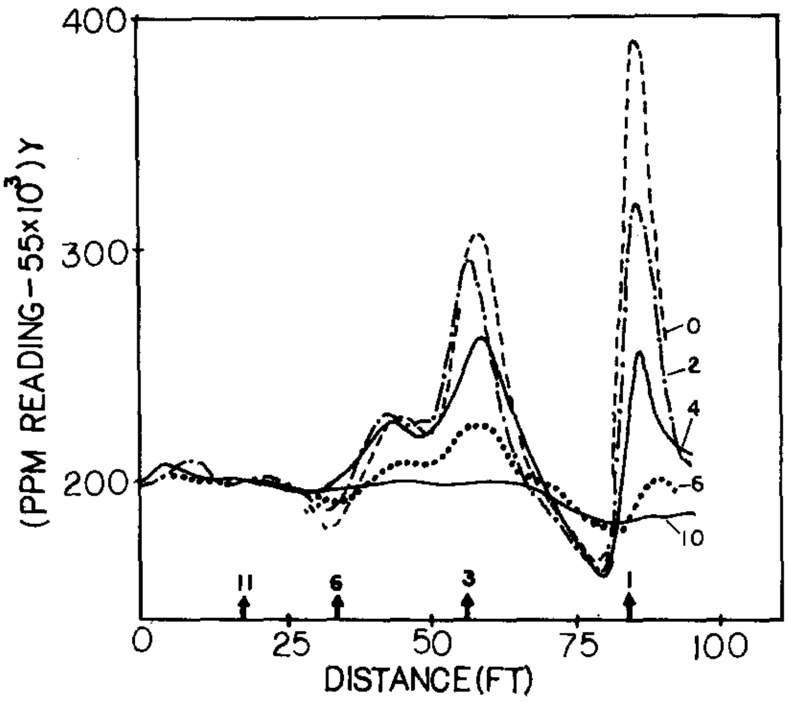
Fig. 6. Magnetometer scans over pattern 2. Actual drum positions are shown along the distance-axis. Labels on curves indicate traverses with offset in feet.

Fig. 7. Magnetometer scan over pattern 3. Actual position of drums is indicated by arrows labeled with capacity of drums in gallons. The drum marked 30v is a vertical 30 gallon drum from an adjoining pattern, and T indicates a peak due to interference from the "trash dump".

Pattern 3; steel drums, effect of size. Figure 7 shows the signals obtained on traverses made over individual steel drums of various sizes, all with 3.5 ft of soil cover. All drums including the smallest (2 gallon) could be detected. The results again indicate that for single drum distribution the resolution distance is approximately in the range of 10–15 feet.

Pattern 4; steel drums, effect of burial depth. Figure 8 shows the survey results for 30 gallon steel drums buried under various depths of soil cover. As can be seen, a 30 gallon steel drum is barely detectable under 11 ft of soil cover with the present magnetometer. A 30-gallon drum buried under 6 ft of soil cover can, however, be detected. The detection limit for a single drum therefore is somewhere between 6 to 11 feet. This, however, is not the practical limit of detection, since any known dump site contains many buried drums or other containers.

Pattern 5; "trash dump". A very small dump site was approximated by digging a 7 ft deep hole, 12 × 12 ft in area. Various steel drums and one plastic drum were "dumped" in the hole and covered with 5 ft of soil. Figure 9 shows the disposition of the drums and Fig. 10 gives a magnetic field contour map as determined by the magnetometer survey from a 2 × 2 ft grid pattern. The position of the main metal in the "dump" is quite well



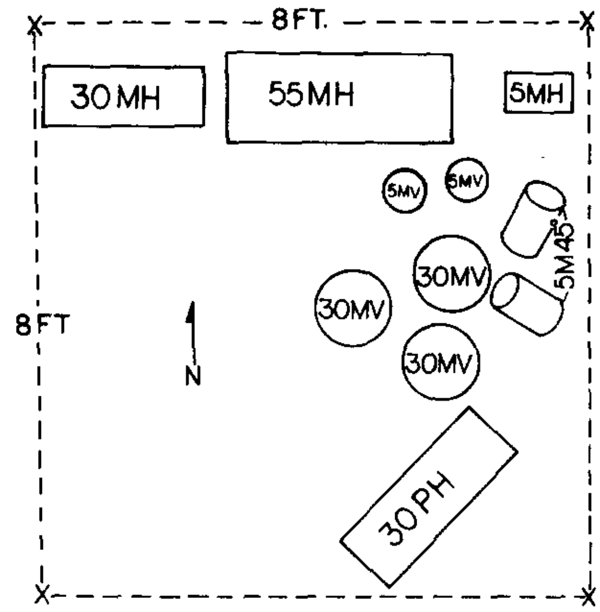


Fig. 8. Magnetometer scans over pattern 4. Actual position of drums is indicated by arrows labeled with depth of burial. Labels on curves indicate traverses with offset in feet.

Fig. 9. Distribution of objects in the "trash dump" of pattern 5. The number on the drum label indicates the capacity in gallons; H — horizontal, V — vertical, P — plastic, M — metal. The boundary of the "trash dump" is defined by the four references posts labeled X.

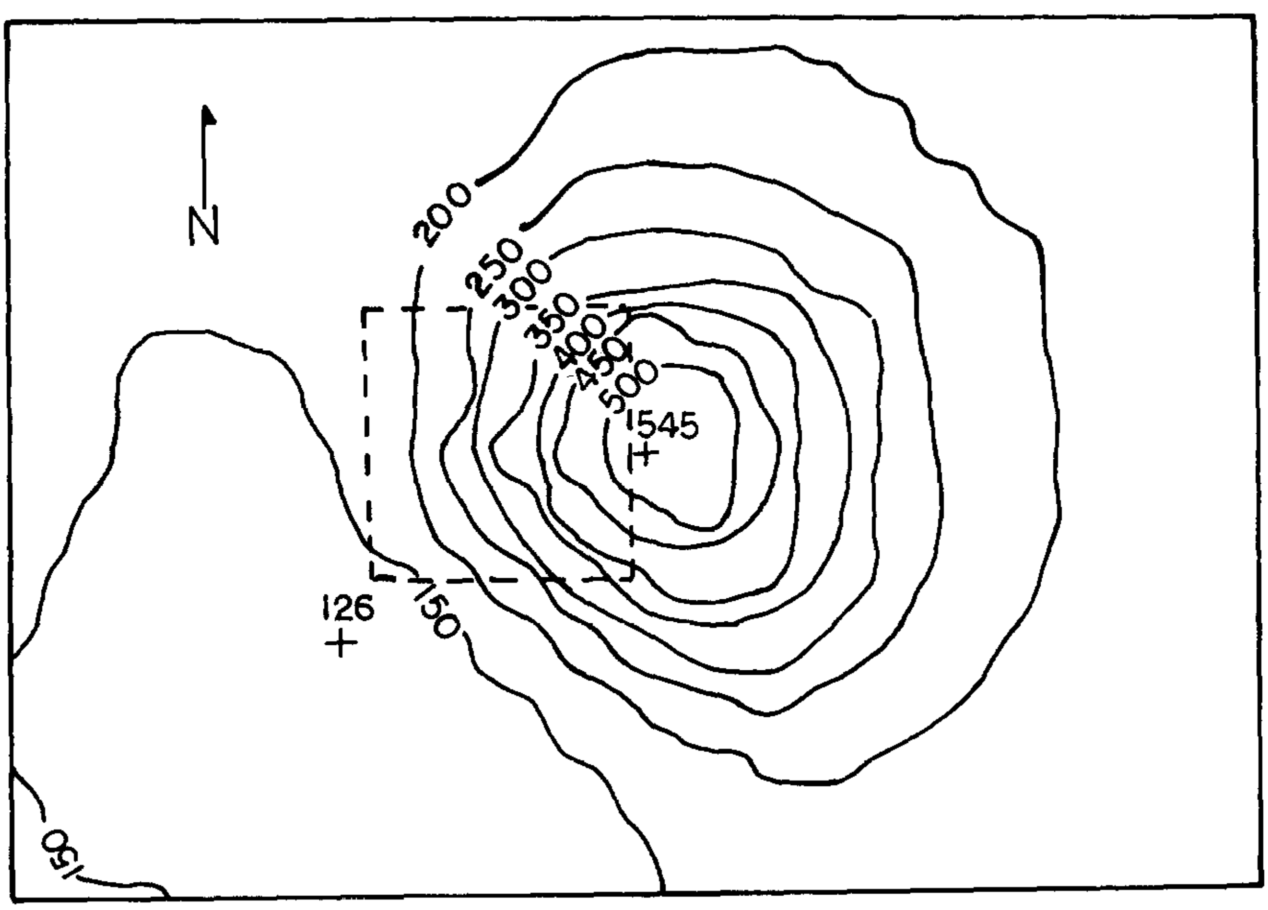


Fig. 10. Magnetic field contour map of the "trash dump" using the PPM. The actual magnetic field is 55 × 10³ γ plus the contour magnetic field label in units of γ. The "trash dump" boundary is indicated by the dashed lines.

determined from the magnetometer readings. The higher numbers indicate the higher density of steel drums.

Pattern 6 and 7; plastic drums. Empty single 40 gallon plastic drums were not detectable with the present technique. Since fresh water and salt water (0.5 molarity solution) do not appreciably change the magnetic (susceptibility) contrast, plastic drums filled with these fluids were also not detectable.

Discussion of results

Results of the PPM survey of containers in a prescribed manner have been presented. All metallic (magnetic) drums were easily detectable, with some exceptions as described previously. The single plastic drums, both empty and filled with water or salt solution, could not be detected. As an estimate, single 55 gallon drums can be detected easily under 6 ft of soil cover when separated by 12—14 ft (this estimate can change however under certain circumstances, see below). Since most dump sites contain a great many drums under few feet of soil cover, it should be possible to locate such containers without any difficulty. However, it should be mentioned that when a dump contains many drums, the resulting large magnetic mass will give rise to large magnetic field gradients making the PPM readings somewhat less reliable. This problem of large magnetic field gradient can be overcome to some extent by raising the magnetometer probe. It may still be difficult to estimate the depth of burial or to investigate the drum distribution. However, the boundaries of such a dump site can be located easily with the PPM.

The magnitude and shape of an anomaly will depend on several considerations. For example, the direction of the induced dipole moment will depend on the direction of the earth's magnetic field at the location of the buried object. This in turn will determine the shape of the magnetic field anomaly for a given traverse. The shape and magnitude of an anomaly can be further modified if the buried object has a permanent moment (i.e. magnetic moment in the absence of any applied magnetic field). For example, an anomaly will be greatly reduced if the permanent magnetic moment is of about the same magnitude but oppositely directed to the induced moment.

In light of the above discussion it is evident that one cannot give a quantitative measure of the detectability limits in terms of the number of drums (or other magnetic mass) and the position of the PPM probe alone. The other parameters that should be considered are the shape of the magnetic mass, its susceptibility, permanent magnetization, and orientation of the earth's magnetic field. Despite the large number of variables involved it is still possible to obtain a reasonable order of magnitude estimate of anomalies arising from a magnetic mass. As an example, consider magnetic anomalies produced by various masses of iron, assuming that such magnetic mass can be approximated by a magnetic dipole of moment M. A value of $M = 10^2$ to 10^3 CGS units per kilogram is a reasonable estimate for most typical iron drums. The maximum anomaly produced is given by:

$T = M/r^3$ for earth's magnetic field horizontal;

$T = 2M/r^3$ for earth's magnetic field vertical,

where r is given in centimeters. For an order of magnitude estimate we will use the first equation to construct a nomogram as shown in Fig. 11. Thus, from the nomogram one can estimate that 100 kg of iron will produce an anomaly of 9—90 γ when 16 ft from the PPM probe and will be barely detectable when about 55 ft from the PPM probe. These values as mentioned earlier are only rough guidelines.

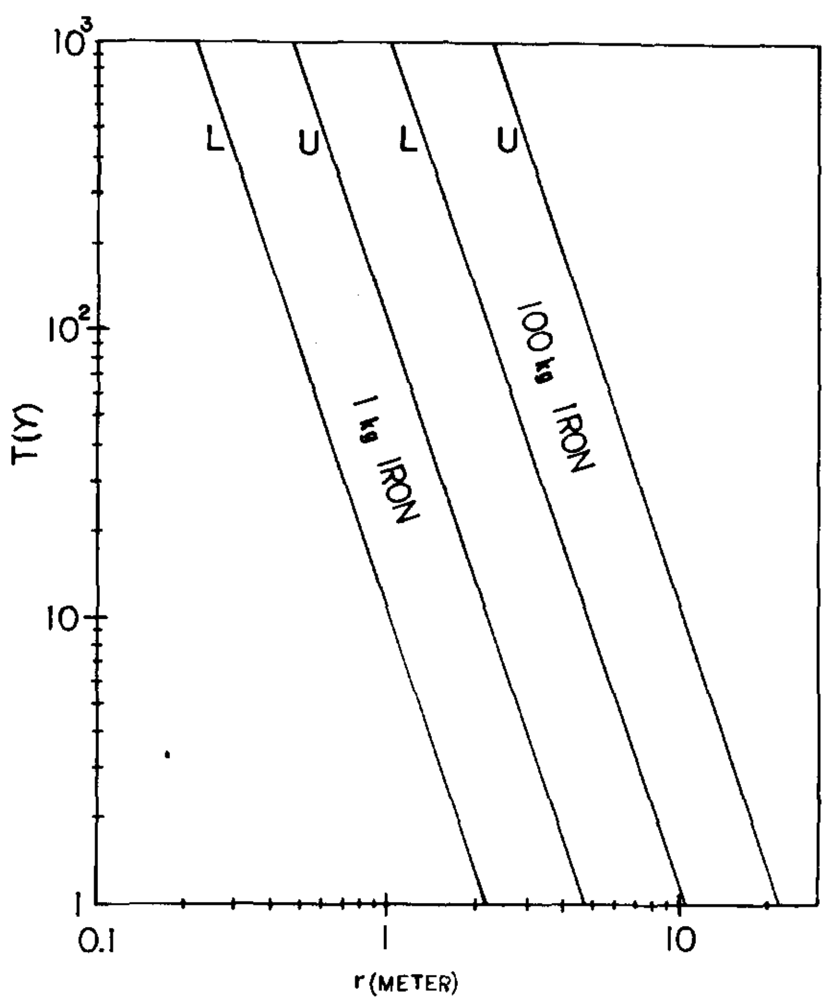


Fig. 11. A nomogram for obtaining an order of magnitude estimate of the magnetic field anomaly as a function of *r*, the distance between the magnetic dipole and the PPM probe. Curves marked L and U were obtained, respectively, using $M = 10^2$ and 10^3 CGS units per kilogram of iron.

Conclusion

The detection of buried objects by a PPM depends on the anomaly arising from the magnetic contrast created by the different magnetic properties of the buried object and the surrounding medium. The object detected need not be ferromagnetic, although the detection is easier when such is the case. From the range of problems in the hazardous material spill area, we foresee the use of PPM mostly in the detection of buried ferromagnetic containers, pipelines, etc. One cannot overemphasize, however, that when applicable, the technique is one of the most reliable, sensitive, and cost-effective techniques available for the detection of buried containers. It is obvious that in any successful systematic approach toward the solution of a hazardous materials spill problem the use of more than one technique may not only be desirable but necessary. As such, we expect an increasing employment of the PPM to be one of the basic NDT techniques in future efforts.

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