GEOMETRICS Technical Report MM-TR1

MARINE MAGNETICS SEARCH

CONTENTS

I. INTRODUCTION

Objects which are submerged, buried beneath mud or silt, or otherwise hidden from view, can be detected or mapped from surface vessels or submersibles using a variety of techniques and instrumentation. In some cases it is possible to determine some of the significant parameters of the object such as size, depth of burial and shape characteristics. This Report is intended as a guide in the search and mapping of objects which can be detected with a magnetometer in marine or fresh water areas and also on land. It is assumed that the reader of this outline has access to a booklet entitled, "Applications Manual for Portable Magnetometers" which contains a more detailed explanation of some of the aspects of magnetic search covered only in general here.

Many different techniques are employed in the search for objects beneath the water's surface. The techniques vary greatly in cost, time, complexity, effectiveness and practicality. The most obvious method for detection of the object is to try and see the object utilizing divers, viewports-on surface vessels or even airborne visual reconnaissance, all of which are attempts to overcome the factors which obscure vision into water from just above the water surface. Instruments for detection which effectively provide a 'view' of submerged objects are such devices as side-scan sonar (a device which provides an acoustically-generated picture) and underwater television monitors. A grappling hook is sometimes used to locate the object by direct physical contact. For objects which are buried or otherwise not easily viewed or detected by the above means, there are instruments which detect objects by penetration through material such as sand, silt and sometimes rock. Among these sub-bottom and remote sensing instruments are sub-bottom seismic profilers, electromagnetic detectors and magnetometers, the latter representing the principal subject of this outline.

There are various reasons for selecting one or more of these techniques or instruments. The principal advantages in using a magnetometer usually relate to the ability of the magnetometer to detect certain objects much more readily in terms of time and cost. Also, a magnetometer sensor is rugged and relatively low cost for equipment which is towed and therefore highly vulnerable to being snagged or lost. A magnetometer can be operated at high speed and efficiency, particularly for large objects or pipelines and is relatively unaffected by geologic, marine and similar operational factors. In many instances magnetics is the only tool capable of detecting an object buried deeply in bottom sediments.

This Report, together with the "Applications manual for Portable Magnetometers", presents the bas-ic information necessary to assess, plan, and perform a search. There are many operational considerations involved in any search problem which can only be assessed given the specific details. To be sure, most of the major problems encountered in any search are those related to logistics, operations and environment, and this should be kept in mind while studying this Report and the theoretical aspects of a given search problem from the comfort and convenience of one's office. In fact, it is prudent to be extremely conservative in any estimates for the amount of time the search may require, the distance at which one may detect a given object and the probability that a given object would even be detected or mapped. Even among these kinds of problems are those related to the location and navigation of the surface vessel, the approximate location of the object to be detected or mapped and the difficulties in towing a sensor near the bottom in a dynamic and hostile environment typical in marine or inland water areas. Forewarned of such difficulties, the following information should be useful in planning a search, particularly if magnetics is one of the tools under consideration.

11. MAGNETIC PROPERTIES OF OBJECTS

In assessing whether a magnetometer would be useful in a search, it must first be determined whether the object (direct or indirect) of the search is truly magnetic. Among the common items which are the objects of marine search efforts, would be pipelines, pipeline junctions, steel telephone cables, steel-hulled ships, engines, anchors, anchor chain, iron debris, steel reinforcing bars contained in concrete, guns, mines, submarines, well head and casing, sunken aircraft, ancient ships, iron cannon, relocation magnets, electric-current-carrying conductors, and other miscellaneous man-made items. In each of these cases, the objects of search would and should involve materials which are ferromagnetic which, for the purposes of search discussed here, must be iron or steel (in rare cases, other ferromagnetic metals or materials as cited in the Manual, but not stainless steel). Such metals as brass, bronze, aluminum, copper, gold, silver, most other metals, precious stones, wood and plastic are not ferromagnetic and will not in any direct way represent an object which could be detected with a magnetometer. In some cases involving ancient ship wrecks, some ballast stones and most pottery and Kiln-fired clay materials are slightly ferromagnetic and may be detected even if encrusted with coral or covered by silt or sand. Materials such as sand, silt, mud, coral, water and air are all non-magnetic and do not by themselves affect the magnetic anomaly from an object.

Induced Magnetism

Generally speaking, there are two types of magnetism which will create magnetic anomalies in ferromagnetic materials to allow them to be detectable with a magnetometer. These are induced and permanent magnetism. Induced magnetism is the combined effect of a magnetic property of the material (permeability), the earth's magnetic field, and the shape and orientation of the object in the earth's magnetic field. If the magnetic permeability (or a related property called magnetic susceptibility) is very high, the material is described as being ferromagnetic, which is true for most types of ordinary iron or steel. These factors cause the material to act as a magnet in the presence of the earth's magnetic field; the higher the permeability and/or the stronger the earth's field, the stronger the magnet. (The intensity of the earth's magnetic field is 6Ø,ØØØ gammas at the poles and 3Ø,ØØØ gammas at the magnetic equator, i.e., Ø.6 gauss and Ø.3 gauss, or oersted, respectively.) The shape and orientation of an object also tends to enhance induced magnetism; the longer the object and more nearly parallel to the earth's magnetic field, the stronger the magnet.

Permanent Magnetization

Permanent magnetism frequently referred to as 'perm' is a property of the material which is related only to the object, not directly to the earth's magnetic field nor to the orientation of the object (although detection of it by a total field magnetometer is related to its orientation). Perm is a property of the metallurgy and the thermal and mechanical history of the object. Usually, the harder the metal, as for example a file, the higher the perm. Some objects will attain a higher perm, i.e., become more magnetized if sufficiently mechanically shocked in the presence of the earth's magnetizing field. It may also attain a perm simply by remaining at a fixed orientation in the earth's field over a long period of time (months or years). Alternatively, some objects (e.g., a magnet) will lose their perm if heated and attain a different perm or no perm upon cooling. For most objects of a search, the permanent magnetism is much greater - sometimes more than ten times greater - than the induced magnetism. Thus, the perm sometimes represents the predominant magnetic property useful in searching for such an object and also the one which makes it most difficult to predict the amplitude of the magnetic disturbance. In actual practice, the magnetic disturbance or 'anomaly' which is observed with the magnetometer will be the sum of both the perm and induced magnetic effects. If the object is comprised of many small component parts, oriented in different directions, such as links of a chain, the perm will tend to cancel leaving only the induced magnetism to be detected by the magnetometer. Conversely, objects which are fabricated in large pieces, such as pipeline sections, engine blocks, or anchors, will be dominated by the permanent magnetic effects and would generally tend to exhibit very large magnetic anomalies relative to their weight and size and with a particular positive or negative 'sense'. The largest commonly encountered anomalies from marine objects are large steel-hulled ships, pipelines and oil wells (casing).

Long objects tend to be magnetized with the permanent or induced magnetism along the long direction. Therefore, a pipeline section will have its principal perm or induced magnetism oriented parallel or antiparallel along the pipe. The sense (i.e., positive versus negative) of the permanent magnetism is determined by the chance orientation of the object, whereas the sense of the induced magnetism is determined by the local direction of the earth's magnetic field. Objects which exhibit large perm also exhibit large variations in the perm. Since pipelines tend to exhibit large perm, each section would tend to have its own magnetic anomaly of different amplitude, and oftentimes different direction relative to adjacent sections. Therefore, it is possible in many cases to detect pipeline junctions by the anomaly which occurs at the end of each individual section.

Where long objects like pipelines are at nearly right angles to the earth's magnetic field, as would be the case for horizontal pipelines at magnetic polar regions or east-west pipelines at the magnetic equatorial regions (see Applications Manual for field inclination), the magnetism would only be induced and oriented across, instead of along, the pipeline. This would produce smaller magnetic anomalies and more difficult-to-detect junctions. For a long, horizontal pipe section oriented north-south at the magnetic equator, there is no detectable magnetic anomaly in the central region of the section, therefore rendering it more difficult even to detect or map with a magnetometer, although there should be detectable anomalies at each junction due to the normal variations in the perm for each section. Most undersea telephone cables have steel strands detectable by a magnetometer. A well head and its casing represent one of the largest man-made magnetic anomalies in the northern and southern magnetic polar regions because of the great length of casing and because there is a large component of the earth's magnetic field parallel to the casing. Such' a well-may be detected at distances of several hundred meters in any direction. Sunken steel-hulled ships are usually readily detected (see Table I) because of their large mass of steel usually containing a large component of perm. Sunken aircraft, on the other hand, usually have relatively little ferromagnetic material since they are often constructed of aluminum alloy materials. Ferromagnetic material is primarily in the engines, landing gear, some structural members, a small amount in the Flight Recorder, and other smaller components.

As will be discussed below, search for pipelines and telephone cables is greatly facilitated by the fact that they are extremely long objects easily traversed (with certainty) by the magnetometer in contrast to individual items, such as anchors, iron debris, ships, and other finite-sized objects. One must pass within the near vicinity of such objects (according to formula and nomogram given below) if one is to detect them with the magnetometer.

TABLE I

Magnetic Anomalies of Common Objects

Object	Typical Maximum Anomaly	
	Near Distance	Far Distance
Ship (1,000 tons)	30 m (100 feet) 300 to 2000 gammas	300 m (1,000 feet) 0.3 to 2.D gammas
Anchor (20 tons)	15 m (50 feet) 200 to 650 gammas	30 m (100 feet) 25 to 80 gammas
Light aircraft	6 m (20 feet) 10 to 30 gammas	15 m (50 feet) 0.5 to 2 gammas
Pipeline-30 cm (12 in.) dia.	8 m (25 feet) 50 to 200 gammas	15 m (50 feet) 12 to 50 gammas
Pipeline-15 cm (6 in.) dia.	3 m (10 feet) 100 to 400 gammas	15 m (50 feet) 4 to 16 gammas
DC Electric Train	150 m (500 feet) 5 to 200 gammas	300 m (1,000 feet) 1 to 50 gammas
cm dia.x 25 cm long) (2 in. dia. x 10 in. long)	6 m (20 feet) 60 to 200 gammas	30 m (100 feet) 0.5 to 1.5 gammas
Well casing and wellhead	15 m (50 feet) 200 to 500 gammas	150 m (500 feet) 2 to 5 gammas
Automobile (1 ton)	10 m (30 feet) 40 gammas	30 m (100 feet)

Although most sediments will not affect the anomaly, igneous or volcanic rock,as may exist beneath bottom sediments, particularly in continental shelf areas adjacent to such rock types on land, may introduce large magnetic anomalies much larger in amplitude than the anomalies from the objects of a search. However, such rocks are likely to be covered by a veneer of sediment and will thus be at a greater distance from the sensor than the object, so that anomalies from the rock are broader and may,only appear as a constant slope on which the anomaly of the object is superimposed. In fact, there is almost always some background slope to the observed magnetic field change due to such deep-seated or more distant geologic sources. It is also possible though that these geologic sources of magnetic anomalies may be so shallow as to obscure subtle effects of some objects of search. In rare cases near shore, placer, i.e., gravity - concentrated magnetite from such igneous rocks, will form lenses of such and will appear as shallow, discrete anomaly sources within the sediment or in the microtopography of ripples in the sand. In such eases, it is very important for the sensor to be as close to the object as possible in order to discriminate its anomaly from the background owing to its sharper features and larger amplitude.

Magnetic Markers

It is often of interest to be able to relocate oneself or an object after a long period of time. The purpose may be to locate a survey benchmark, an important junction in a pipeline, or a reference point in shallow marine waters. In lieu of a radio transmitter or other active source, it is possible to bury a large magnet at a depth sufficiently below any level that is likely to be disturbed by storms or dragging anchors. It should retain most of its magnetic moment for many years. In some cases, it may be reasonable to bury several magnets oriented to produce maxima or minima or in a pattern to assure easy relocation or to differentiate one magnetic marker from another. A magnet of convenient size and made of ALNICO V is available in such forms as a cylinder approximately 5 cm in diameter by 25 cm long, which produces an anomaly of 1 gamma at 3Ø meters. The anomaly will vary inversely as the cube of the distance and directly with the number of magnets laid end-to-end with opposing poles in contact with each other. Given a specialized requirement, a solenoidal coil or single long wire with an applied direct current may also serve such a relocation purpose. (Such a current may even be applied to a cable or pipeline to facilitate its detection or tracking.)

111. MAGNETIC ANOMALIES

Of great importance in any search is the estimation of the amplitude of the expected magnetic anomaly and its probable signature or appearance, if one would pass near it with a magnetometer. Knowledge of the possible size of the anomaly is useful in the planning of the search grid and sensor tow requirements and in determining the feasibility of conducting the search. An appreciation of the signature is important in recognizing a target, proceeding to its precise location and estimating its distance, or depth, from the sensor.

Anomaly Amplitude

It is possible to estimate the maximum amplitude of the anomaly from a mass of iron or steel given its weight, the distance between the object and the sensor, and whether it is a finite-sized object or a pipeline. This maximum estimate is only very approximate (within an order of magnitude) owing to the many uncertainties involved in calculating the anomaly such as the perm and induced magnetism, the orientation of the object, the location of the object with respect to the sensor and with respect to the total field direction, whether the sensor is in the 'near field' of the object and other factors.

A discrete object such as ship or anchor, which can be considered as a concentrated mass of iron, all of whose dimensions are shorter than its distance to the magnetometer (in contrast to pipelines, which are treated at the end of this section), would behave as a magnetic dipole according to the formula and rules given below. The magnetic anomaly for such an object would vary inversely as cube of the distance between the magnetometer and the object, and directly with the weight of the ferromagnetic object, i.e.,

$$T = \frac{M}{r^3}$$

(for magnetic latitudes greater than 60^o, use $T = \frac{2M}{r^3}$)

where T is the anomaly in gauss (1 gauss = 10^5 gammas}, M is the dipole moment in cgs units, and r is the distance in centimeters.

For such discrete objects made typically of iron or steel, the magnetic moment, M, is between 1Ø and 1Ø cgs units per ton: (either 1ØØØ kg or 2ØØØ lbs.). Thus, the maximum anomaly for Ø.1 ton or iron at a distance of 1ØØØ centimeters would be between:

$$T = \frac{10^5 \times 0.1}{(10^3)^3} = 10^{-5} \text{ gauss} = 1 \text{ gamma}$$

and $$T = \frac{10^6 \times 0.1}{(10^3)^3} = 10^{-4} \text{ gauss} = 10 \text{ gammas}$$

or $$1 \text{ gamma} < T < 10 \text{ gammas}$$

This same formula for a magnetic anomaly can be expressed directly in terms of gammas, pounds, and feet, if desired, for

$$1.75 \times 10^2 < M_{fps} < 1.75 \times 10^3$$

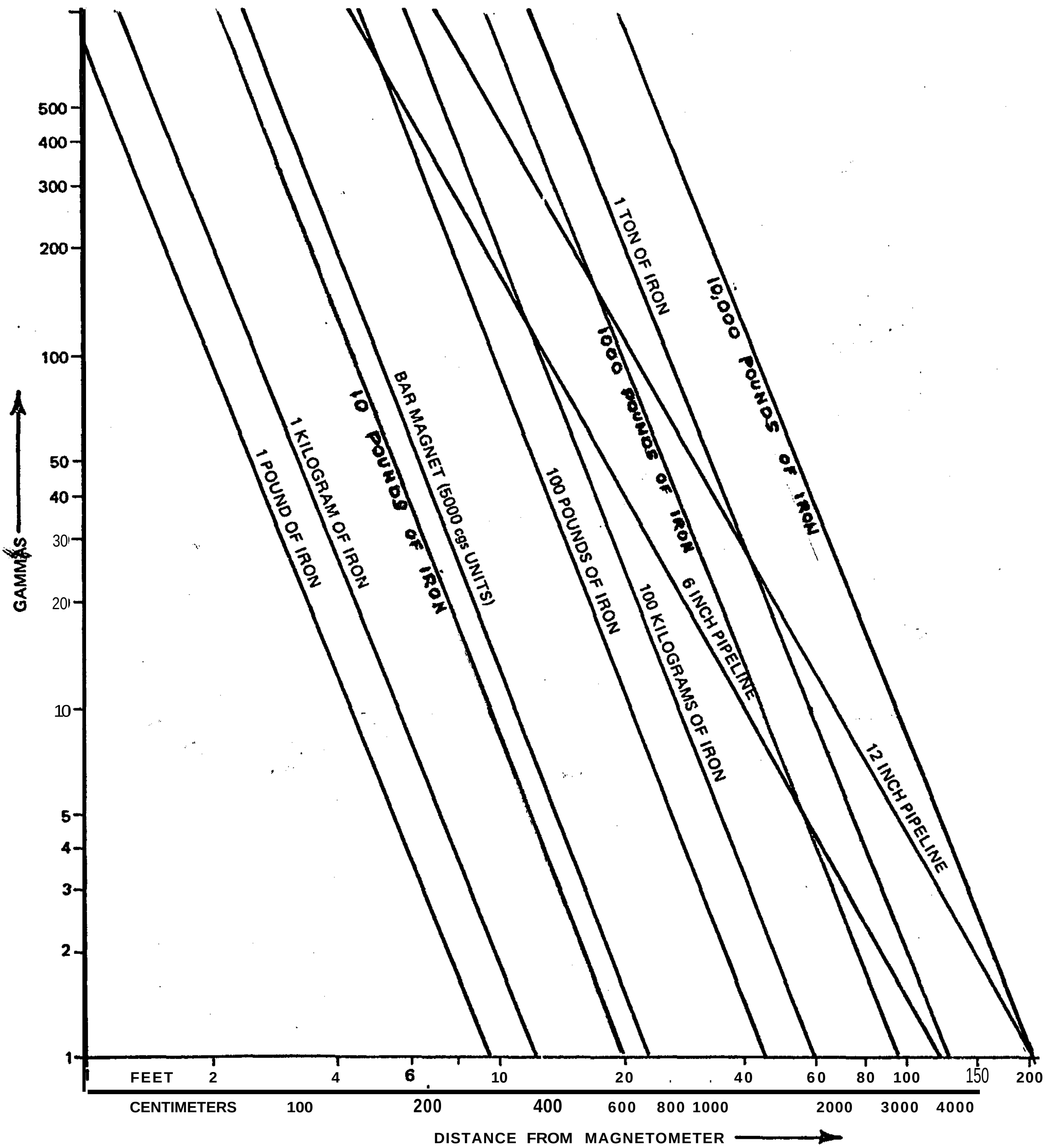
and $$T = \frac{M_{fps}}{r^3}$$

where T is the anomaly in gammas, M the magnetic moment per pound of iron, and r the distance in feet between the object and the magnetometer. A ton of iron is therefore between 0.35 and 3.5 gammas at 100 feet, or as a rule of thumb, can best be remembered as <u>1 ton of iron is 1 gamma at 100 feet,</u>

Table I lists the expected anomalies for a variety of objects of search. For any other object, Figure 1 is drawn as a nomogram or guide for graphically estimating anomaly amplitude for a given object comprised of common iron or steel. These formulae refer to finite-sized objects in contrast to pipelines which are discussed below. all rules herein assume, for simplicity, that the anomaly is produced by the induced moment only. Nevertheless, the harder the steel or the more the object is comprised of a single large piece of iron (such as an engine}, the more permanent magnetization ('perm') it will possess. In such cases, this perm may be 10 or more times greater than the induced magnetization and the estimated anomaly amplitude should use the larger value for magnetic moment, M.

Perhaps the most significant aspect of anomaly amplitude which is of concern in search projects is the large variation in anomaly amplitude for a relatively small change in distance to the object. In'other words, for a discrete object, <u>as the distance between sensor and object is doubled, the anomaly decreases by a factor of 8:</u> Therefore, it is most important for the magnetometer sensor to pass as close to the object as possible to provide more assurance of detection and/or mapping.

Figure 1 Nomogram for Estimating Anomalies from Typical Objects (assuming dipole moment $M = 5 \times 10^5$ cgs/ton, i.e., k = 8 cgs. Estimates valid only within order of magnitude)



INSTRUCTIONS FOR USE:

To use the nomogram, select a given weight or type of object from among the diagonal labeled lines. Then choose a distance along the bottom line (abscissa) of the graph and follow a vertical line upwards from that distance until it intersects the diagonal line of the selected object. At that point, move horizontally to the left to a value on the vertical axis (ordinate) of the graph and read the intensity in gammas.

At a given distance, the intensity is proportional to the weight of the object. Therefore, for an object whose weight is not precisely that of the'labeled lines, simply multiply the intensity in gammas by the ratio of the desired weight to the labeled weight on the graph. If the distance desired does not appear on the graph, remember that for a typical object the intensity is inversely proportional to the cube of the distance and for a long pipeline the intensity is inversely proportional to the square of the distance between magnetometer sensor and object. Due to the many uncertainties described herein, the estimates derived from this nomogram may be larger or smaller by a factor of 2 to 5 or perhaps more.

(reproduced in modified form, by from Applications Manual for Portable Magnetometers)

Anomaly Signature

The actual shape of the magnetic anomaly, i.e., signature, is important in order to estimate its depth and to identify an anomaly as being related to an object of interest and not simply background noise. In general, the anomaly will be smoothly varying and asyrrunetrical about the object and will have a total recognizable 'width' more-or-less 1 to 3 times the depth to the object (actually, the width of the anomaly between points which are at half maximum is approximately equal to the depth of the object). The major portion of an anomaly over an object usually has a positive 'sense' in most areas of the world and negative at the magnetic equator. However, if the object consists largely of one single fabricated unit, perm will be predominant and the anomaly may be positive or negative depending on its orientation. In most cases, this principal anomaly, positive or negative, will not necessarily be precisely over the object or even at the very closest approach to the object due to the asymmetry of most anomalies (see accompanying diagrams). As a general rule, for asymmetrical anomalies, the sensor is closest to the object at the point where there is maximum horizontal gradient, i.e., the greatest rate of change of the anomaly with respect to distance, although the shape and perm of the object may change this condition.

Typical dipole anomaly signatures (anomalies) expressed as profiles and contour maps at various orientations of the magnetic moment of the object and at various inclinations of the field appear in Figure 2. The anomaly maps expressed in these diagrams are primarily a function of the magnetic latitude and the direction of the perm. The profiles in these diagrams are, of course, simply 2-dimensional representations of what one would observe traversing across in the vicinity of the anomaly or across one of the contour maps. Therefore, the profiles are functions not only of magnetic latitude and perm, but also of where the sensor is with respect to the object. In fact, given a magnetic profile or map over any dipole and some familiarity with total field magnetics from the Manual, one should be able to recognize the inclination of the field and perhaps also the orientation of the object as a dipole.

The contour map presentation shown in Figure 2 for a magnetic field inclination of 60^{o} is the most common situation and should be studied carefully. Familiarity with this map should assist one in recognizing, in the course of a search, where one is with respect to the object after observing a single profile or, to be sure, after a second profile. An example of such a sequence of observations is shown in Figure 3. Note that the object is not always beneath a given traverse, but more than likely is at a distance to one side of the traverse as shown, requiring perhaps another traverse to be truly 'over' the object. (The distance between magnetometer and object herein referred to as depth may, in fact, only represent the 'closest approach'.)

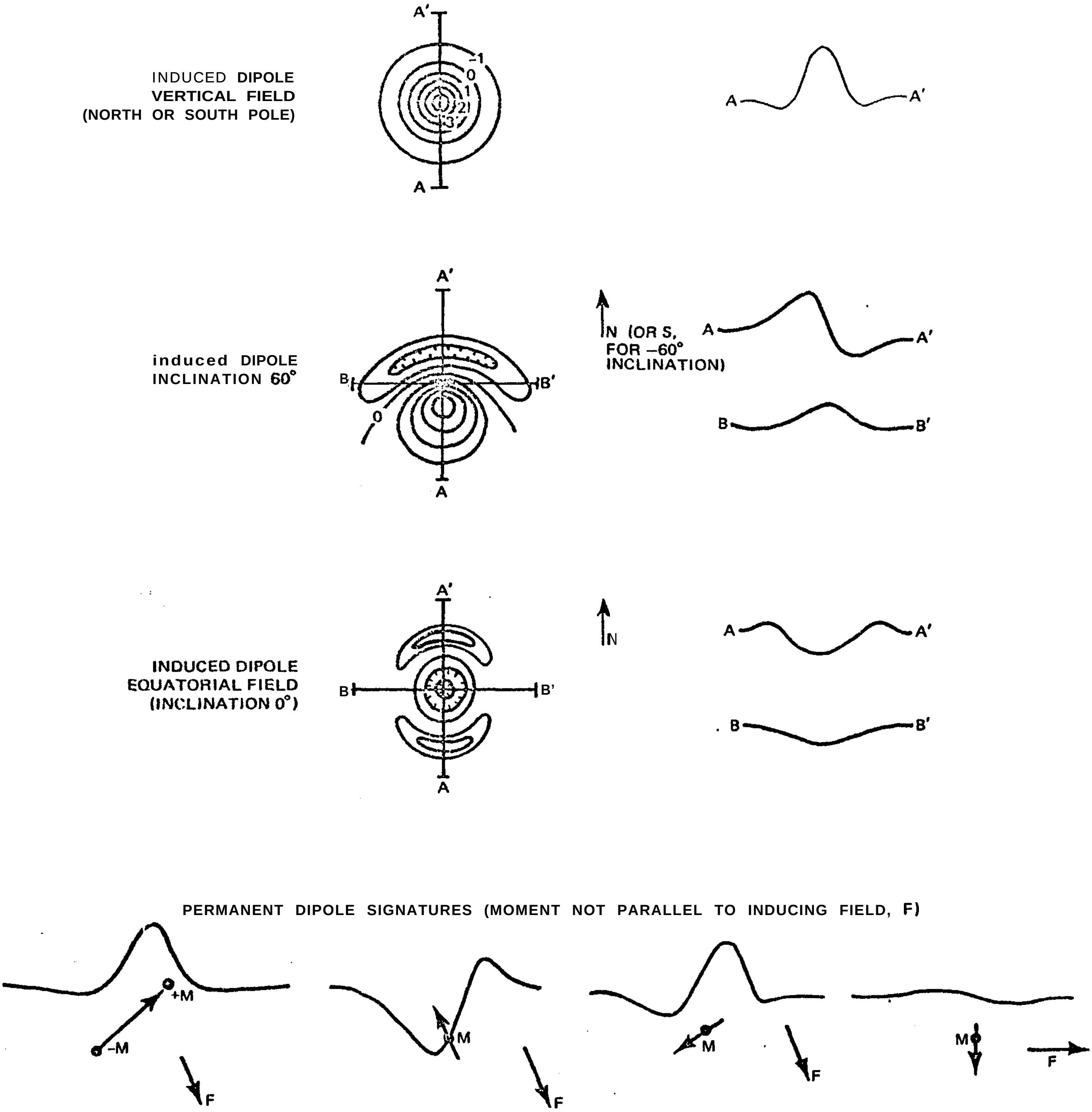


Figure 2. Contour Maps and Signature of Anomalies from Objects Assuming Induced Magnetism Only.

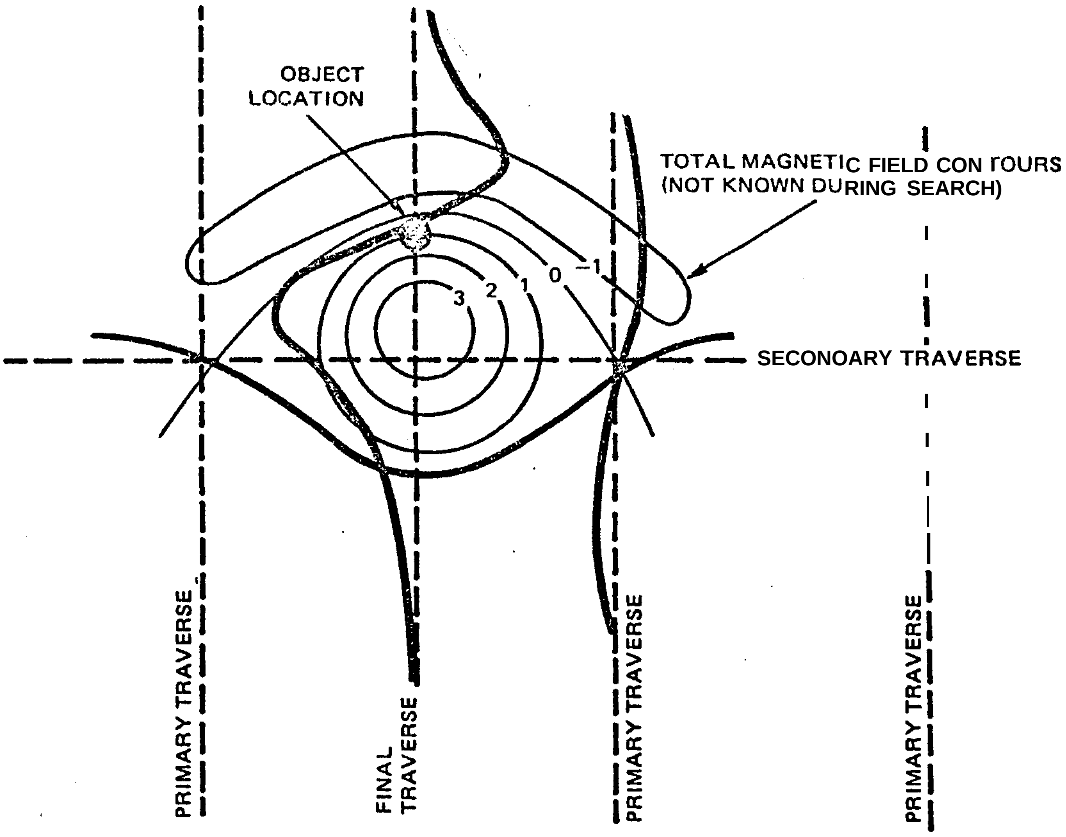


Figure 3. Typical Sequence of Traverses During Search Procedures (Profiles drawn on respective traverse lines)

Anomaly Width versus Object Depth

The anomaly for an object will appear broader proportionately as the object is deeper or more distant. This width/depth characteristic of magnetic anomaly behavior serves as a means for determining the depth to the source which can be used to one's advantage in a search. The amplitude of the anomaly will, as stated, also decrease inversely as the cube of this distance (inversely as the square for pipelines). An example of anomaly depth and amplitude behavior is shown in Figure 4 which can be extrapolated to the other signatures which appear in Figure 2.

Figure 4. Depth/Amplitude Behavior of Magnetic Anomalies from a Finite-sized Iron Object (dipole).

As a rule of thumb, the half-width for discrete objects as defined in Figure 5 will be approximately equal to the depth. (In magnetic equatorial regions, the half width is approximately equal to 0.8 x depth.) It is possible to calculate the depth of an object more precisely than the given rules of thumb, if two sensors are towed at two different elevations above an object or pipeline (see attached Manual).

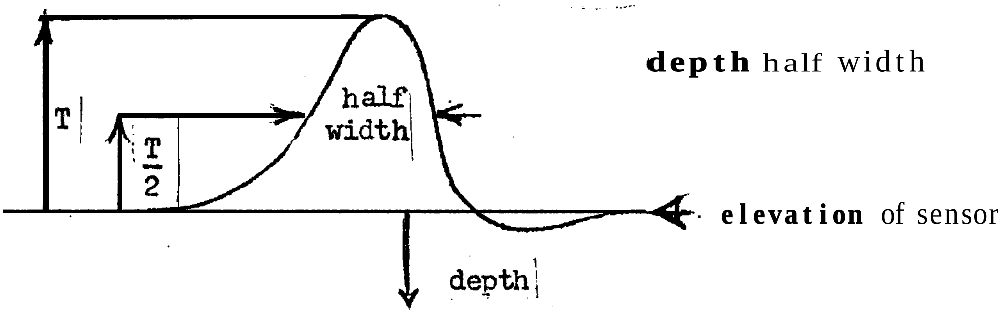


Figure 5

Familiarity with the effect of depth on anomaly width can assist in recognizing the anomaly when superimposed on the ever-present background magnetic field gradient. The background, or regional gradient, is usually the anomaly from geologic sources observed over a short distance, or over very long profiles, it is the anomaly from the main field of the earth.(e.g.,Figure15).Therefore; this regional gradient appears as a much broaden anomaly than that dueato ailocal objected examples of anomalies superimposed on the regional gradient are shown in Figure 6.

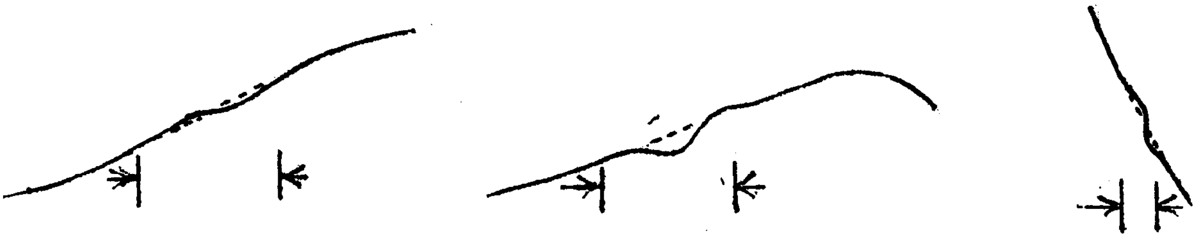


Figure 6. Anomalies $\rightarrow|$ $|\leftarrow$ from local objects as they appear 'Superimposed on Broader Background Anomaly (Regional Gradient). Dashed line would be visualized extension of background to assist in recognizing local anomaly. Assuming object at bottom, depth of water below sensor would be no greater than approximately 2 or 3 times the anomaly extent shown here.

One can assume that the object is at or near the bottom and that the anomaly extent is more or less two or three times this maximum distance from the sensor. Therefore, the only anomalies of interest in a search would be those which extend no further than approximately three times the water depth below the sensor.

Pipelines

A horizontal pipeline or steel telephone cable in steeply dipping fields or E-W at the equator varies inversely as the square of the distance between its center and the magnetometer. Thus, the maximum anomaly amplitude from a pipeline can be estimated as follows:

$$T = \frac{M}{r^2} = \frac{kFA}{r^2} \cong \frac{kF\pi Dt}{r^2}$$

where A is the approximate cross-sectional area of iron, and D and t are the pipe diameter and wall thickness respectively in the same dimensional units as the distance, r, and the other factors as used above. For most pipes, the steel is 'hard', i.e., with high perm, and k (effective) is therefore high, perhaps, 10 to 50 cgs or higher. For example, consider a horizontal pipeline diameter I5 centimeters, $k \cong 10$, wall thickness o.6 centimeters in a field of 50;000 gammas buried at a depth of 10 meters beneath the magnetometer,

$$T = \frac{10 \times 5 \times 10^4 \times \pi \times 15 \times 0.6}{(10 \times 10^2)^2} \cong 14 \text{ gammas}$$

The expression, πDt, represents the approximate cross sectional area of the thin wall of the pipe. A more precise but more complicated expression for this area might be $(\pi R_o^2 - \pi R_i^2)$ where Ro and R_i are the outside and inside diameters of the pipe respectively.

For solid rods or steel cable, a similar expression is used,

$$T = \frac{kFA}{r^2} = \frac{kF\pi R^2}{r^2}$$

where R is the radius of the rod or, say, the steel portion of a telephone cable.

The anomaly signature for pipelines in various directions and field inclinations would appear as in Figure 7. The permanent magnetic moment is often predominant in a pipeline and may commonly exhibit a signature as shown, but with the maxium and minima reversed and a very large amplitude. A pipeline is generally easy to detect because its great length often assures one of actually crossing it. Also, the signature varies inversely as the square of the distance instead of the cube of the distance as in the case of a dipole (pipelines are lines of dipoles) and the anomaly amplitude thus remains large. If one has access to

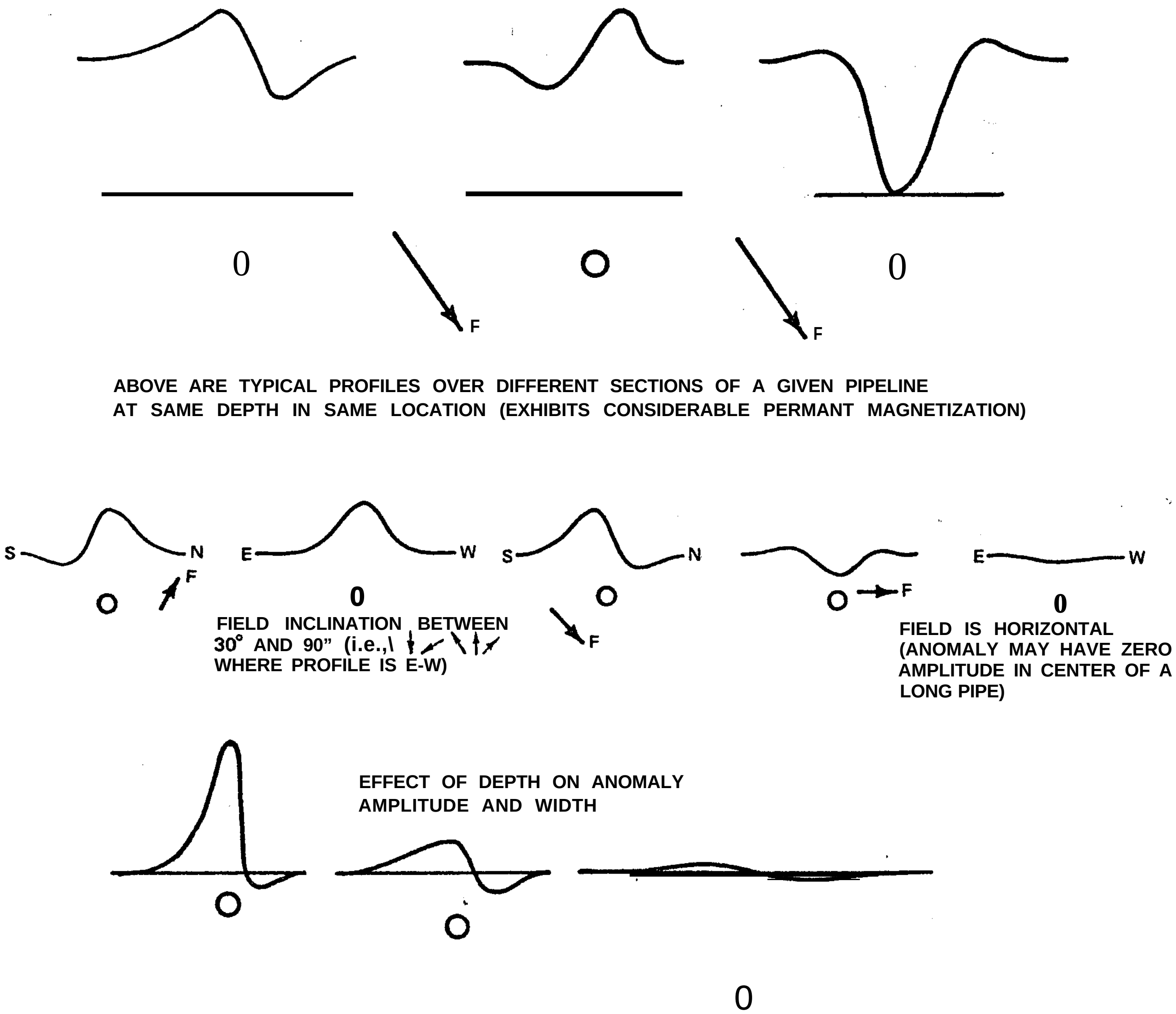


Figure 7. Pipeline Signatures

both ends of a hidden pipeline, it is also possible to pass a large DC current through it to aid in its detection by enhancing its magnetic field selectively in space or time. For example, to find one pipeline out of many possible interfering pipelines, pass a current through it for one reading and reverse the current for the next, taking two such readings at each point. The location of the one anomaly can be so mapped as the difference in these values becomes'larger as one is closer to the pipe. (1 ampere of current through an infinitely long pipe would produce 10 gammas at 60 feet and would in this case produce 20 gammas peak-to-peak and vary inversely as the distance to the pipe.)

IV. MAGNETOMETERS

Measurements of Total Magnetic Intensity

Magnetometers used for marine search and all other mobile applications always measure total magnetic field intensity, a scalar measurement, or magnitude, independent, of the orien tation of the sensor. This magnitude,'which is called total field intensity, is the only magnetic measurement possible from a sensor which is always changing in its orientation and usually in motion, whether it be towed from a ship, flown in an aircraft, or carried about on the ground.

Proton Magnetometer - Theory of Operation

The most common total field magnetometer, and for all practical purposes the only one used in the marine environment, is the proton precession magnetometer which utilizes the precession of protons in a hydrocarbon fluid for the measurement of total intensity. The fluid, typically kerosene contained within a coil of wire in the sensor, is momentarily magnetized by direct current in the wire. This current is then removed and the protons (hydrogen nuclei) then precess like a spinning top, about the direction of the earth's magnetic field at a frequency directly proportional to the total magnetic intensity and independent of the direction of the coil of wire (sensor)

The frequency of this signal' is-transmitted up a cable to the magnetometer console where it is measured accurately by electronic circuits in the magnetometer with a resolution of 1 gamma or even 0.1 gammas. Expressed in engineering terms, a signal of a few tens of microvolts at a frequency of a few thousand Hertz is passed along a 300 meter cable and then measured to an accuracy of 0.004 Hertz. This is all accomplished utilizing a sensor with no moving parts and containing only a bottle of kerosene and a coil of wire at the end of a long cable com- ponents well-suited for a towed marine environment. Measurements are made every few seconds or as utilized in search operations, at a rate of several times per second. The readings are displayed on a paper strip chart recorder and are often digitally recorded as well, should there be interest in subsequent computer proces- sing or possible preparation of a contour map.

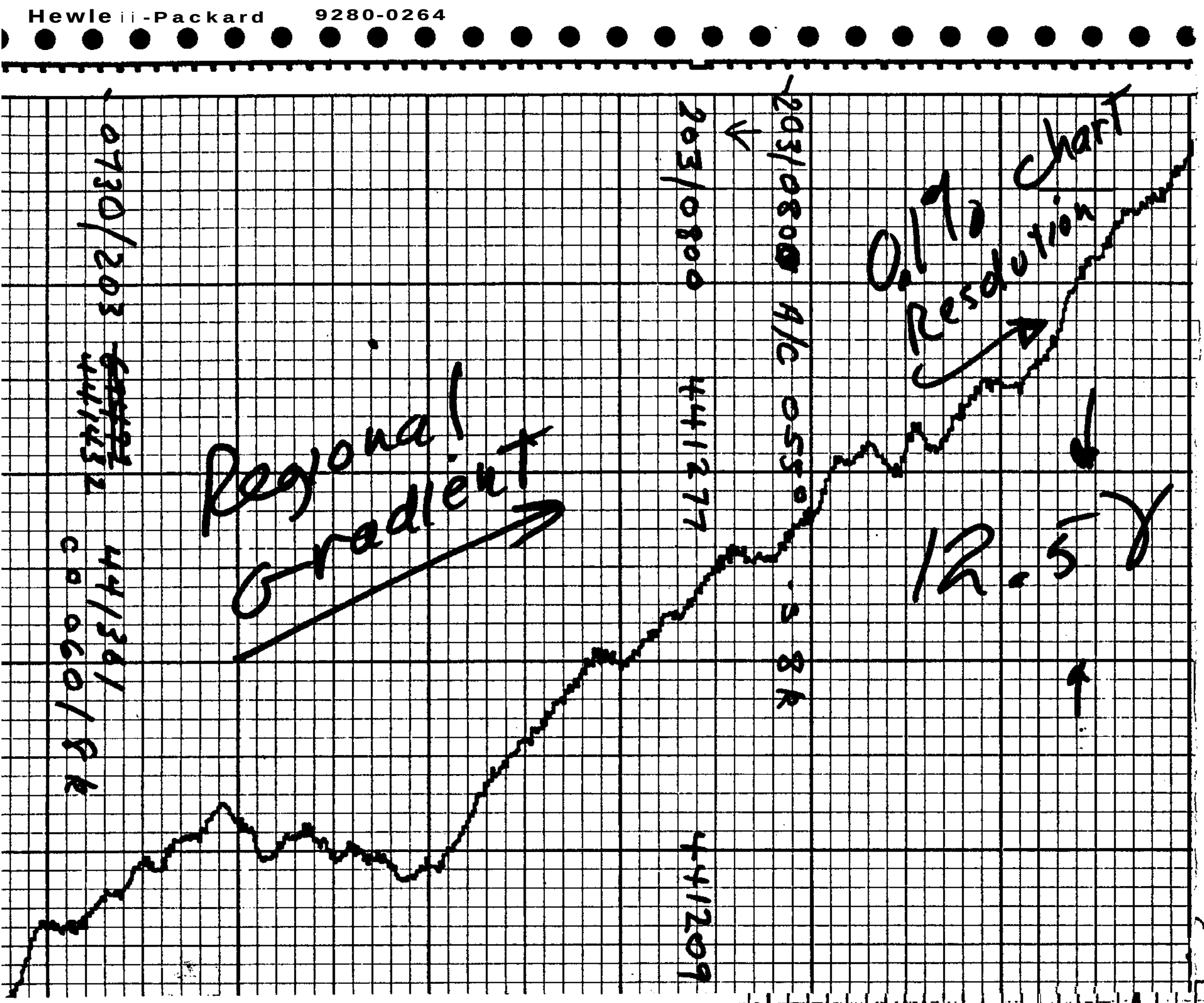
Tow System

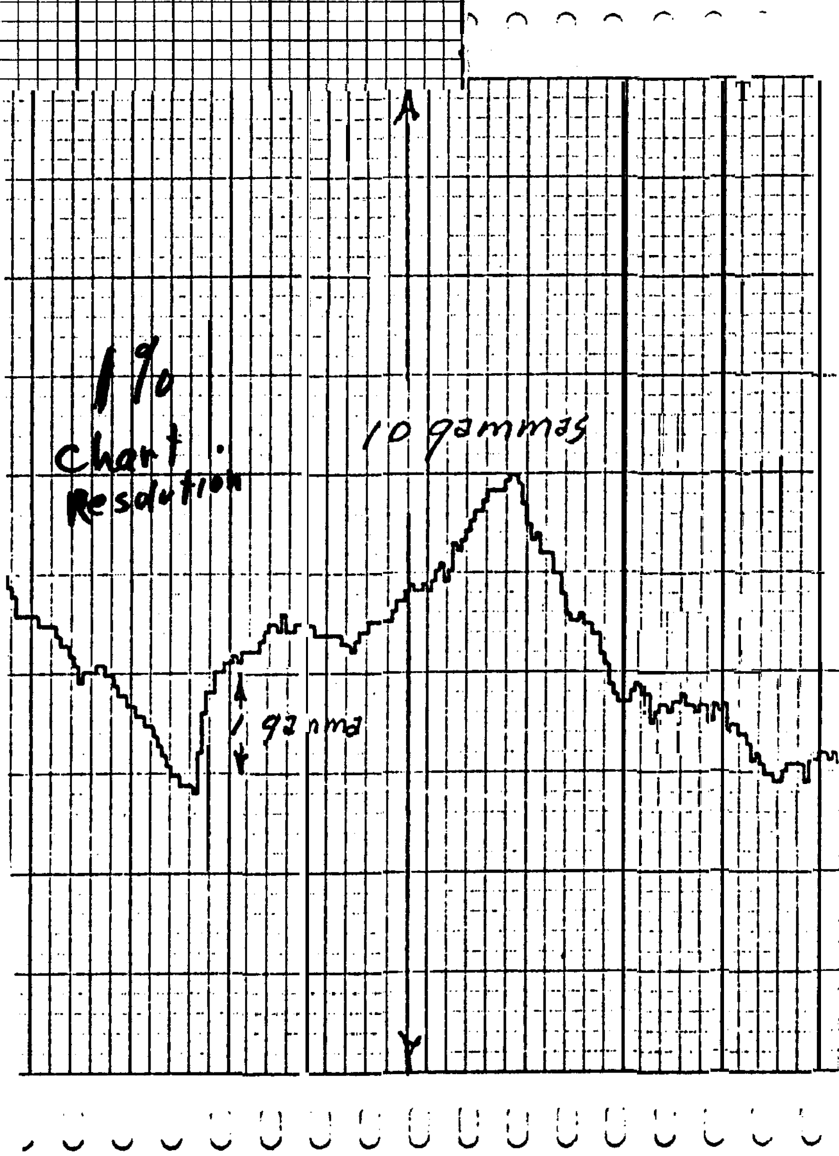
The magnetometer sensor is contained in a ruggedized housing re- ferred to as a "fish" at the end of a long, electrically suitable and mechanically durable tow cable, the entire sensor and cable referred to as the tow system. The tow system is constructed to be able to withstand the rigors of typical obstacles and condi- tions of marine tow, such as the possibility of being snagged, dragged over rough bottom conditions, towed at various speeds and subjected to pressure and able to be drawn up on a winch. More- over, the tow system must be non-magnetic, able to carry the proper electric current and be low in microphonic response. The length of the tow system is variable depending upon various oper- ating conditions encountered, but it is generally a few hundred meters long. For tow systems larger than 500 meters, it is necessary to install a preamplifier in the fish near the sensor.

Magnetometer Data Display

Conventional proton magnetometer data are presented on a dual channel analog strip chart 10 inches wide (sometimes single channel) at two different full-scale sensitivities differing by a factor of 10. One trace represents the two least significant digits of a 5 or 6 place number to an accuracy of 1% of the chart width. The other trace displays the three least significant digits to a resolution of 0.1% of the chart width (see Figure 8). The two sensitivity settings provide both resolution and dynamic range, respectively, to portray local changes due to the regional gradient or background. Typical settings are 100 and 1000 gammas full-scale or 25 and 250 gammas full-scale.

The repetition rate of a proton magnetometer is selectable from one reading every 6 seconds to a high rate of 3 times per second. For search problems involving near bottom tow or speed faster than 10 knots, the higher repetition rate is essential in order to adequately portray an-anomaly signature of short duration.





Marine Magnetometer Records

Figure 8

V. OPERATIONAL CONSIDERATIONS

Introduction

The tow system, its configuration, length, height above bottom of the sensor, actual position of the sensor, speed of tow and other operational considerations of the tow system are perhaps some of the most important considerations in a typical marine search. As will be noted in the description for magnetic search procedures, it is most important to get the sensor as close to the bottom as possible since the magnetic anomaly is typically 8 times greater when the distance between the sensor and the object is halved. Without special devices, one cannot observe either the height above bottom of the sensor or its horizontal position. Therefore, in many a search problem in either deep water or for very small objects, it is not possible to ascertain whether the sensor has passed within detection distance of the object unless certain precautions are observed, as described in the following. Among these precautions or suggestions for tow are many which are normally observed, some which have been suggested but not tried, and other aspects of tow which simply must be understood by the operator.

Magnetic Effects of Ships

In order to be sufficiently far away from the magnetic effects of the vessel, the sensor must be tens of meters or commonly hundreds of meters from the vessel, depending upon the size of the vessel and whether it is constructed of wood or steel. Most marine geophysical vessels are constructed of steel and are approximately 40 to 60 meters long. In those cases, the tow system is typically 250 meters long or up to 400 meters in the case of deeper water and near bottom search objectives (described below).

Table II expresses the magnetic effect of the ship as a function of its length or displacement and as a function of the distance from the ship, i.e., length of the tow system.

TABLE II

Approximate Magnetic Effects of Ships
Measured by a Magnetometer Tow System

Ship Size	Length of Tow System			
	30 m (100 ft)	100 m (330 ft)	150 m (500 ft)	250 m (830 ft)
25 m (84 ft) 200 tons	200 gammas	6 gammas	1.6 gammas	0.4 gamma
50 m (165 ft) 700 tons	700 gammas	20 gammas	6 gammas	1.4 gammas
70 m (230 ft) 1700 tons	1700 gammas	50 gammas	13 gamnas	3.0 gammas
90 m (300 ft) 3300 tons	3300 gammas	80 gammas	25 gammas	6.0 gammas

There are rare instances in the case of fiberglass or wooden-hulled boats where the sensor can even be rigidly mounted on the prow to 'be the maximum distance from the engine and other ferromagnetic parts of the ship. It is possible to partially compensate for the magnetic effects of such a ship through proper placement of small magnets several meters from the sensor and thus the magnetometer does not require the trailing tow system.: However, this method is only useful for search for large objects in relatively shallow water since the sensor will not pass close to the object of search.

Factors Affecting Sensor Depth

The depth below the surface (which would determine the height above bottom is a function of tow speed, cable length, type and diameter (drag) of cable, drag (shape) of sensor and weight of sensor, the slower the speed, the longer and thinner the cable, the heavier and more streamlined the sensor, the deeper the sensor. The configuration of the tow cable is not a straight line between the ship and the sensor, but rather an arcuate path caused primarily by the 'drag' on the cable through the sea water. The thinner the cable the more the sensor will tend to be towed near the bottom. The diameter of the tow cable in many cases is fixed as required by mechanical, electrical, flotation and other considerations of the tow cable. The tow cable itself can also be designed with a hydrodynamically streamlined fairing to minimize its drag, therefore allowing a steeper angle of tow cable and consequently deeper position of the sensor. It is possible to tow with a longer cable or at a slower speed, although the tow speed must be consistent with the economics of the entire search operation. In the accompanying Figure 9, it is possible to determine the approximate depths of the sensor as a function of tow cable length and tow speed using a normally-weighted sensor and the stated type of tow cable.

There are other means of bringing the sensor near the bottom such as active systems or by weighting the sensor to be extremely heavy, but still hydrodynamically towable It is possible, for example, to affix a lead-filled hose or other such weight at a distance in front of the sensor so as to weight it down, but not interfere with the sensor magnetically should the high density material or its fastenings be magnetic. A nearly neutrally buoyant sensor with its drag would then be towable at a constant height above bottom, which is an ideal tow configuration if this system is achievable. The dragging weight should, of course, be designed perhaps so as not to become snagged or cause the loss of the entire tow system, although such a loss does not represent a serious loss in monies with respect to most search objectives. It is not recommended to tow the sensor in a manner so as to drag the sensor itself on the bottom since there is a likelihood of it being snagged on bottom rocks or debris, of wearing away the sensor due to abrasion and other potentially damaging encounters.

Active Depth Control

There are active means for controlling the depth of the sensor in contrast to the more or less passive method described above. Depth controllers, as used on seismic streamers and similar towed lines, consist of a streamlined housing with horizontal vanes controlled by a pressure-actuated (and therefore depth-determined) mechanism to control the depth as long as sufficient forward speed is available for the vanes to control and as long as the weight and drag of the sensor behind (or in front) the controller is within controllable limits. In the more sophisticated search operations, a sensor can also be incorporated in a submersible or surface-controlled and powered towed housing, such as those which are equipped with self-contained TV cameras, side-scan sonars, bottom profilers, pingers and other such search devices.

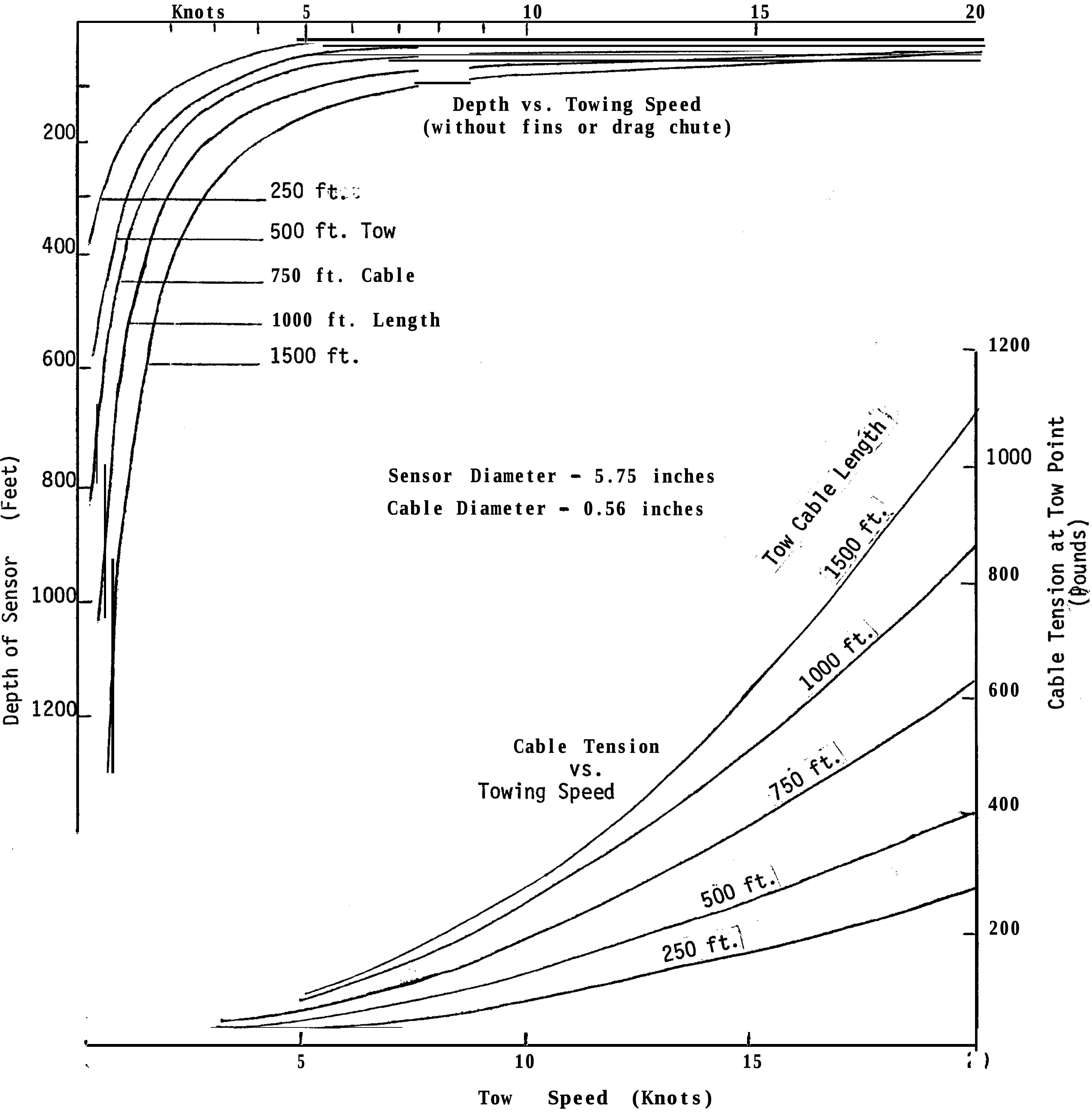

Knots
5
10
15
20
Depth vs. Towing Speed
(without fins or drag chute)
200
400
600
800
1000
1200
Depth of Sensor (Feet)
250 ft.
500 ft. Tow
750 ft. Cable
1000 ft. Length
1500 ft.
Sensor Diameter - 5.75 inches
Cable Diameter - 0.56 inches
Tow Cable Length
1500 ft.
1000 ft.
750 ft.
500 ft.
250 ft.
Cable Tension
vs.
Towing Speed
1200
1000
800
600
400
200
Cable Tension at Tow Point (Pounds)
5
10
15
Tow Speed (Knots)

Figure 9

Tow System Flotation Cable

In search operations which are in shallow water, or at very slow speed in rough bottom conditions, or those involving multiple-towed cables, it may be desirable to keep the magnetometer tow cable from becoming entangled or snarled with one of the other tow systems, thus preventing them from either being towed properly or becoming reeled in. In such cases, the magnetometer tow system might require the use of a special flotation cable which is usually a specially constructed cable consisting of a normal tow cable around which is extruded (at the factory) a very low density, but tough flotation material with a bending radius adequate for the winch drum. The tow cable would then have a net positive buoyancy. The end of the cable would be either free of flotation material, or the sensor would be weighted-properly so as to bring the-sensor to the proper depth or, as the situation requires, to tow the sensor near the water surface.

In many tow operations therefore, it is not uncommon to tow a cable which is 300-400 meters long, sometimes at a speed of less than 2-3 knots, and to have a special cable and towed body or various active or passive devices on the tow system to insure proper position of the other sensor above bottom and therefore above or near the object of search. See Figure 10 for various diagrammatic representations of tow systems. (The tow system is almost never towed at speeds greater than lO-15 knots due to excessive noise introduced on the magnetometer sensor due to vibration and due to oscillations of the sensor coil relative to the precessing protons in the sensor.) If the object of search is sufficiently large or the water depth sufficiently shallow so as to make detection relatively easy (according to estimates of anomaly amplitude described herein), it is possible to tow a sensor on shorter cables even up to 100 meters from a vessel 40 meters long, to tow at speeds of lo-12 knots, or, as mentioned above, to affix the sensor to the prow of a ship constructed of non-magnetic materials. However, these suggestions are only made where economics requires that the search be made quickly and that there is relatively high insurance that the anomaly would be detectable under these tow speed and tow system configuration conditions.

Ship Location

In conducting a magnetic search for either isolated objects or pipelines, it is first of all important to know the location of the vessel itself, if one is to make note of the location of the object for subsequent return and recovery or for simply mapping the location of the targets. It is not as important if there

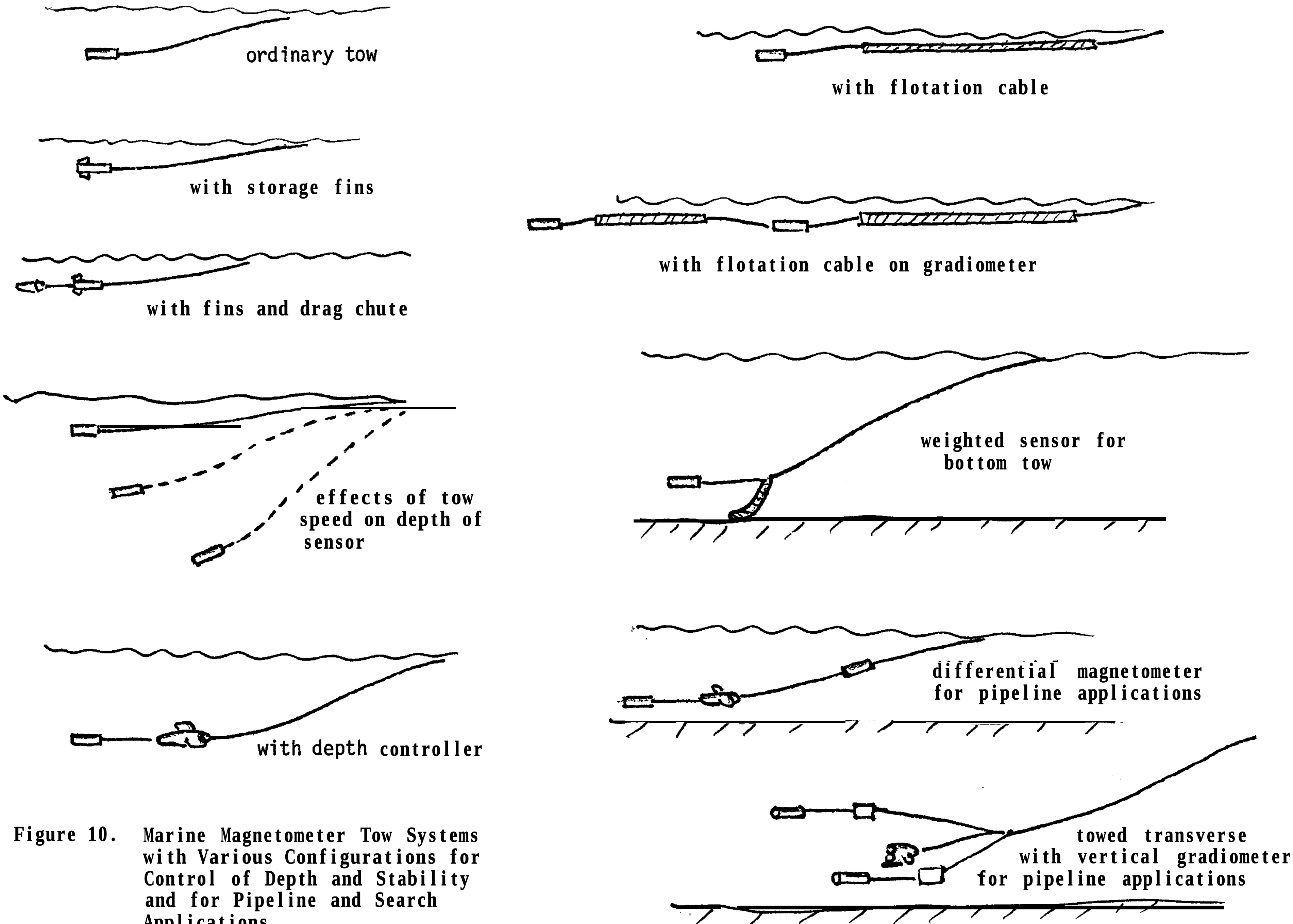


Figure 10. Marine Magnetometer Tow Systems with Various Configurations for Control of Depth and Stability and for Pipeline and Search Applications.

is a plan for immediate recovery or if one is assured that a buoy affixed to that spot will remain in that location and can be relocated easily. Location (navigation), i.e., knowing precisely where the vessel and sensor are and have been during the search, or placing them where one thinks they should be, often represents the greatest difficulties in any search effort.

Sensor Location

It is important to know as well, the location of the sensor with respect to the vessel and to know the height above bottom of the sensor if there is a possibility of missing the anomaly owing to a greater-than-desirable height above bottom of the sensor. It is relatively easy to imagine a sensor several hundred meters behind the vessel being towed over a line or weaving over an arcuate path whose location is not known even to within several tens of meters or even hundreds of meters where the sensor itself is not in visual or in navigational contact with the vessel.

The limitations in not knowing or easily controlling the location of the sensor are manyfold. For example, a cross-current at a large angle to the heading of the vessel would cause both the vessel and the sensor to track on parallel lines which are not themselves parallel to the heading of the vessel. In other words, as in any navigation problem, one must consider the vector sum of the heading and the direction of the currents with the added complication that the sensor is not precisely at the location of the ship. Also, when a vessel makes a broad turn, the tow cable may require quite a long distance and time in order to be towing directly behind the vessel instead of along the arcuate turning path. Still another possibility is that the entire tow system may be going from one side to another due to heaving of the ship, slight course changes or asymmetrical hydrodynamic effects of the tow system such that the sensor makes a path which is uncertain and unknown with respect to the vessel itself.

If the object of search requires that the sensor, to use an extreme example, be only several meters from the object, then such motion of the sensor over several tens of meters might cause the sensor to pass at undetectable distances from the object, although the operator may think that the track had traversed the ideal straight line grid. In addition to considerations of where the sensor is horizontally, one must also be concerned with the height above bottom for the same reasons, and particularly if the height above bottom varies considerably due to varying ship's speed, varying bottom topography, etc.

These considerations for location of the sensor are cited not to discourage one from undertaking a search using a magnetometer, but rather to make one aware of what is normally encountered, particularly in deep water and under vast open ocean areas where precise location is a difficulty, where strong currents exist and where operators are involved who may be inexperienced in requirements for extreme precision of location of either the vessel and/or a towed object. Some technical solutions are presented here and to be sure there are many more to solve.

The vessel's location can be determined using various radio-positioning devices to locate the vessel to an accuracy of a few meters within the search area. The sensor's position can perhaps be insured using a combination of the operational tow system considerations enumerated above such as extremely slow speed, weighted sensor, etc., or, in some special cases, even a diver-controlled sensor. Alternatively, the sensor location can be determined by attaching to it a pinger(s) for location of the sensor with respect to the vessel. Pingers are acoustic devices which emit detectable signals measured by arrays of devices affixed to the vessel.

Pipeline Search and Tracking

Pipeline search procedures are in many cases different than those which would be followed for the search for isolated objects. Information is often desired regarding pipelines that is not of interest in other types of searches. Among the kinds of information desired for pipelines that can be obtained from a towed magnetometer(s), it is possible to detect the pipeline, map the pipeline, profile the depth of overburden in the case of a buried pipeline, and with some difficulty detect the pipeline sections or joints. With tens of thousands of kilometers of pipelines in the Gulf of Mexico, soon in the North Sea and in many other offshore oil producing areas and for pipelines across navigable waterways, it is important to be aware of the capabilities and limitations of magnetometers for various aspects of pipeline mapping. Pipelines and most submarine communication cables contain or are made of steel and are effectively infinitely long objects, properties which allow a magnetometer to be used for various location and mapping projects for submarine pipelines and cables.

Detection and Tracking

Very special tow system configurations are often required to obtain some of the above pipeline information such as tracking, depth of burial or section locations. In order to simply detect a pipeline (or cable), it is possible to tow a single sensor at a distance sufficiently close to the bottom to insure easy detection of a given-size pipeline (see formula for pipeline anomalies). Each traverse should begin a long distance away from the pipeline to insure that the pipeline is indeed crossed. In order to crudely track a pipeline, one may follow a path which weaves or 'snakes' back and forth across the pipeline about its approximate location each time verifying that a crossing has indeed occurred and noting the precise location of each crossing. Buoys could be emplaced if the search requires it. Of course, it is possible to miss a single appearance of the anomaly and therefore temporarily lose contact with the pipeline. The pipeline may even change direction should it have reached a junction or wellhead.

It is possible to tow two or more sensors on a single cable for detection and tracking so that the leading sensor, which would normally be higher above the bottom than the trailing sensor (except! under special tow configurations), would first detect a broad, low-amplitude anomaly from the pipeline. This would alert the operator to note the confirming anomaly from the trailing sensor which would be much more distinct, higher in amplitude and would provide more assurance of detection and location of the pipeline. With a sufficiently long cable, this second sensor may also obviate the "lost contact" problem above. Moreover, the depth of the pipeline can be estimated using the anomaly observed from each of the two sensors, the estimated depth of each sensor and the 1 formula given herein.

r^2

Due to the complex and variable nature of magnetic anomalies that one would experience from each section, it is not practical to assume that one could follow directly along the pipeline with a single or dual (tandem) magnetometer sensor and maintain a course monitoring only the magnetic anomaly; for the magnetic anomaly is often asymmetrical, it may change its sense and it would vary along the pipeline, especially at junctions, leading one to believe falsely that the sensor is at one side or another of the pipeline. This event may then cause a course change which would lead the ship away from the pipeline, and later require another course change to come back across the line itself. Worse still, if the sensor were immediately off of an asymmetrical anomaly peak, a course correction may cause the sensor and ship to deviate away from the pipe without knowledge of which direction to turn to re-establish proper position. Other problems would ensue, but suffice it to say that a single magnetometer sensor and a straight course will not satisfy the requirements for tracking.

Transverse Sensor Array for Tracking

A more ideal configuration for tracking than the configurations suggested above would be to tow two lateral magnetometer sensors 'straddling' the pipeline so that each sensor is effectively away from the principal magnetic anomaly and well out of the linear field' of the anomaly. By monitoring each of the individual traces of the two magnetometers and perhaps a third, centrally located to confirm the existence of the anomaly, one could more or less keep the array centered over the pipeline. Each lateral sensor would have to be approximately 1 to 2 times as far away from the pipeline as it would be if it were directly over the pipeline in order to insure the relative 'absence' of the anomaly during normal tracking. The sensors may be towed by paravanes (as used in mine clearance) or self-powered vehicles operating from the mother ship with a taut cable between them to maintain the array configuration. Alternatively, it may be more practical to tow the array nearer to the bottom and therefore closer to the pipeline in order to decrease the dimensions of such a lateral sensor array. A multiple lateral array in this general configuration allows several parallel traverses over a wide swath and is therefore useful for small object search as well.

Measurement and Computation of Pipeline Depth of Burial

The magnetometer can be used to measure depth of cover of buried pipelines and cables using a two-sensor vertical array to provide information to calculate the distance between sensor and pipeline. The calculation from two sensors is considerably more accurate than from one sensor due to the fact that the equations or anomaly from the two levels above a pipeline obviates the need for information regarding the magnetic properties of the pipeline (see Manual, pg. 53). Simultaneous measurements from two sensors attached rigidly, or by cable one or two meters apart, can be used for such measurements. Alternatively, the towed tandem (in-line) array cited earlier, where the leading sensor would traverse a path somewhat higher than the trailing one, would marginally qualify as a two-sensor 'vertical' array. The computed depth of the pipeline beneath the sensor(s) together with either the water depth and depth of sensor or height above bottom of the sensor, can be used to calculate the depth of cover over the pipeline. A combination of the transverse tracking array and this vertical array would allow continuous profiling of the depth of cover (depth of burial) of the pipeline.

Pinpointing the Location of a Buried Pipeline

In many problems relating to buried pipelines (or other objects), it is necessary to know as precisely as possible the location of the pipeline, say, to fractions of a meter. Unfortunately, when a proton magnetometer is very close to a large-ferromagnetic object sufficient to cause a magnetic field gradient greater than perhaps 1000 gammas per meter, the signal of the magnetometer is seriously affected. However, even though the recorded trace of the magnetometer may appear to have degraded the raw precession signal from the magnetometer as seen on an oscilloscope would probably still be present. As the sensor is closer to the pipeline, the gradient becomes larger and the signal 'decays' more quickly. Therefore, if a marine sensor is towed extremely slowly by a ship or manually by a diver in the very close proximity of the pipeline, the precise location can be determined by monitoring the location&s) where there is maximum signal decay'or where the signal decays completely on either side-of this closest approach to the pipeline.

Data Analysis

The recognition of an anomaly due to an object may be relatively straight forward if the sensor passes close to-the object and the background gradients due to the geology are small. Figures 11 through 15 portray several anomalies actually observed over pipelines and other objects to give an indication of easily discernible anomalies. Those cases where there is a high background gradient as shown in Figure 6, one must try to visualize the regional gradient and the anomaly superimposed on it. Recall the rules given in Chapter III relating to anomaly width-versus-depth to the object, and therefore, depth to the sea bottom in order to ascertain the maximum width of the expected anomaly. Anomalies of much broader appearance would thus be due to the regional gradients or other more distant sources. In order to better discriminate the anomaly due to the object, it sometimes helps to pencil through the "assumed regional gradient", and, if one has the time and opportunity,to even subtract the regional gradient of the anomalous feature on a point-by-point basis (see Manual, pg. 14).

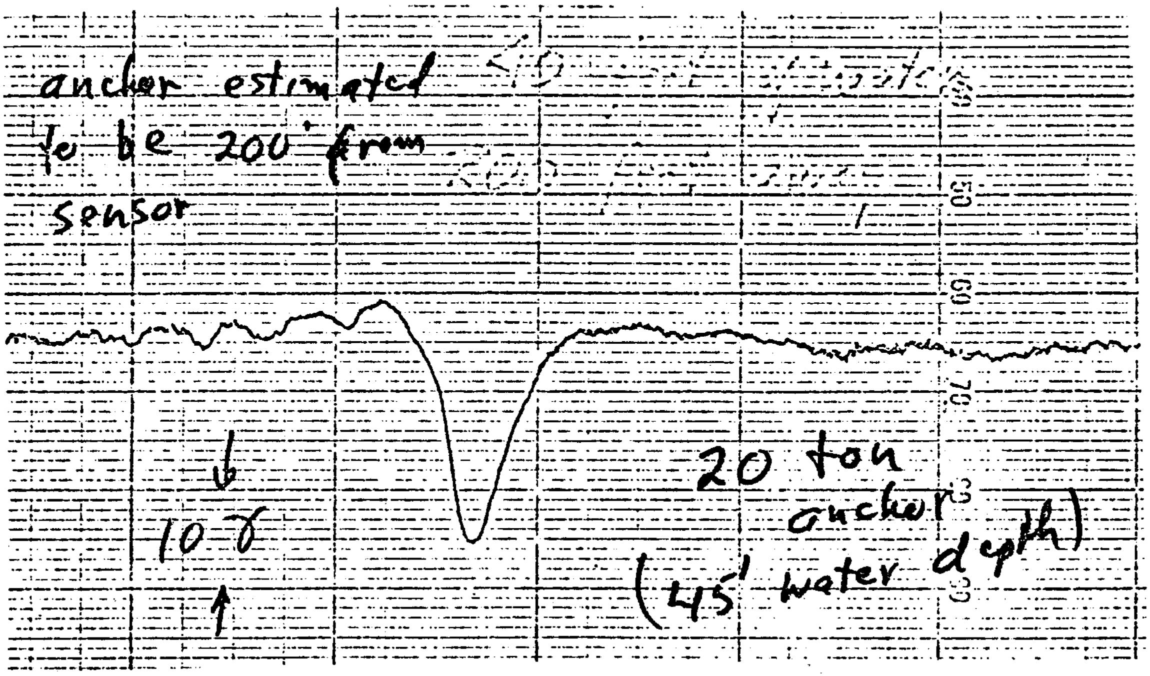
Instrumentation is available that will assist in real time in the removal of the regional gradient and other background effects from the analog or digital output of the magnetometer. From a single magnetometer, for example, it is possible to filter out the regional background by computing the horizontal gradient along the profile of the total field, otherwise called the time differential or slope. This gradient can be computed by measuring the difference between readings, say 2, 5 or 10 meters apart, then plotting this difference for every reading of the magnetometer. This would remove the broad regional gradient (operating as a "high-pass" filter) leaving only the local anomaly which is the desired objective. The closer together these readings are spaced, the more the local anomaly will be enhanced at the expense of the background gradient. However, as the spacing between readings becomes shorter, the resolution for individual readings must be better in order to utilize the method. The speed of the vessel must be constant as well to prevent virtual anomalies caused only by changes in the ship's speed. Alternatively, one can use a two-sensor gradiometer or closely-spaced differential magnetometer as described in relation to its use in pipeline tracking. A gradiometer automatically removes the regional gradient and enhances local anomalies and is free of the sometimes disturbing effects of solar-induced magnetic storms.

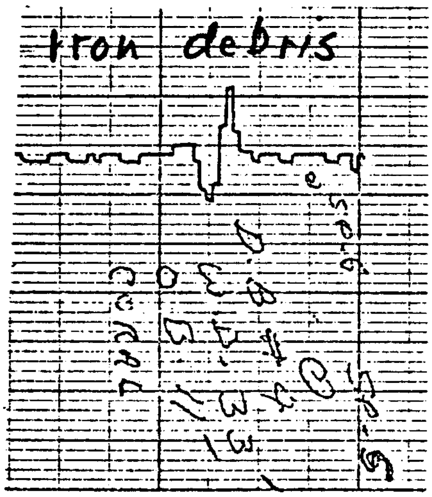
Operational Magnetometer Sensitivity

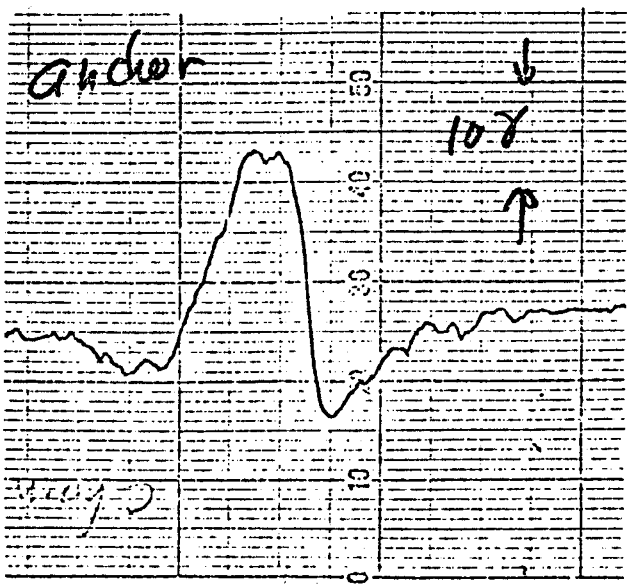
The effective sensitivity or resolution of the magnetometer under actual marine search conditions may be only several gammas or perhaps one gamma or, under ideal conditions, 0.1 gamma, the latter being an effective limit on the resolution for a variety of reasons described in the following.

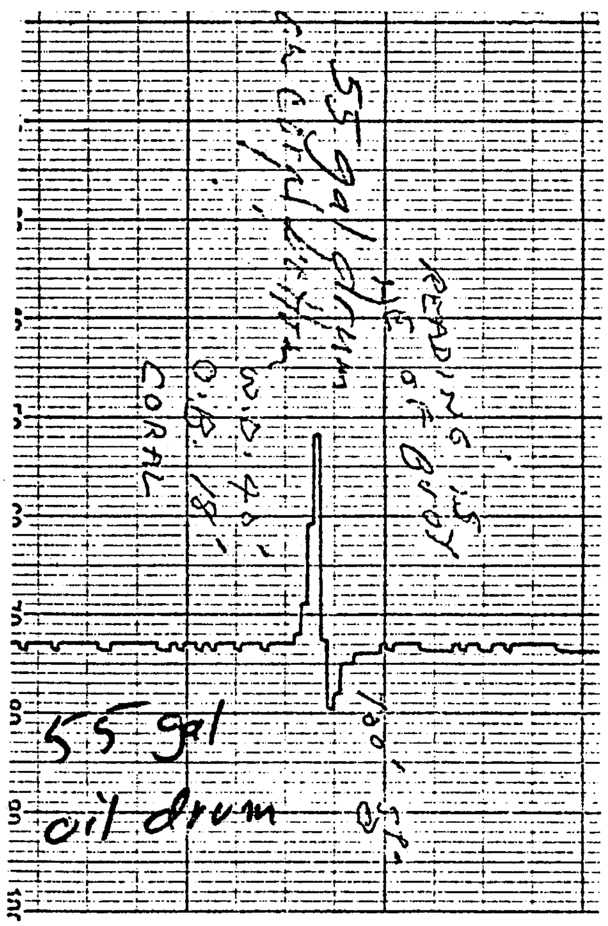
An ocean swell produces an induced magnetic field anomaly because it represents a mass of conducting sea water moving through the earth's magnetic field. The effect of the swell is to produce'electrical currents which in turn have associated magnetic field perturbations observed by the magnetometer as sinusoidal variations with the period (frequency) of the swell and with amplitudes between a few tenths of a gamma and several gammas for swells of a meter to seven meters in amplitude. The maximum effect of the swell as seen by the magnetometer is proportional to the velocity of the swell, the amplitude of the swell, the direction of the swell with respect to the earth's magnetic field, and the depth of the magnetometer beneath the swell (this effect varies approximately inversely with the depth).

The instrument noise of the magnetometer will depend partly upon the specifications of the instrument and partly upon the mechanical stability of the fish. The rotation of the sensor, for example, produces an error proportional to the rate of rotation and the cosine of the angle between the rotational axis and direction of the earth's magnetic field. This effect, sometimes called Doppler precession error, will be very noticeable if there are violent motions of the sensor and for this reason it is always desirable to tow the sensor out of the effect of the turbulence and wake of the ship and to utilize devices on the fish that will minimize its rotation and swing from side-to-side. For higher resolution search applications, fins will greatly reduce this rotational error; a drag chute on the fish or larger diameter housing to increase drag will similarly reduce the rotation as well as swings of the entire tow system due to imparted motions from the ship, Alternate stretching of the cable due to variable loads imparted by swinging of the tow system or by lurching of the ship causes microphonics (especially if the cable has ever suffered severe strain just short of failure) which can affect the magnetometer signal which is only a few tens of microvolts in amplitude.



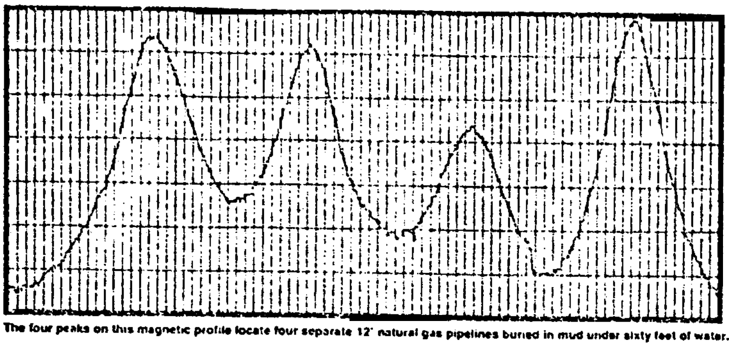






Marine Magnetometer Anomalies from Iron objects.

Figure 11



The four peaks on this magnetic profile locate four separate 12" natural gas pipelines buried in mud under sixty feet of water.

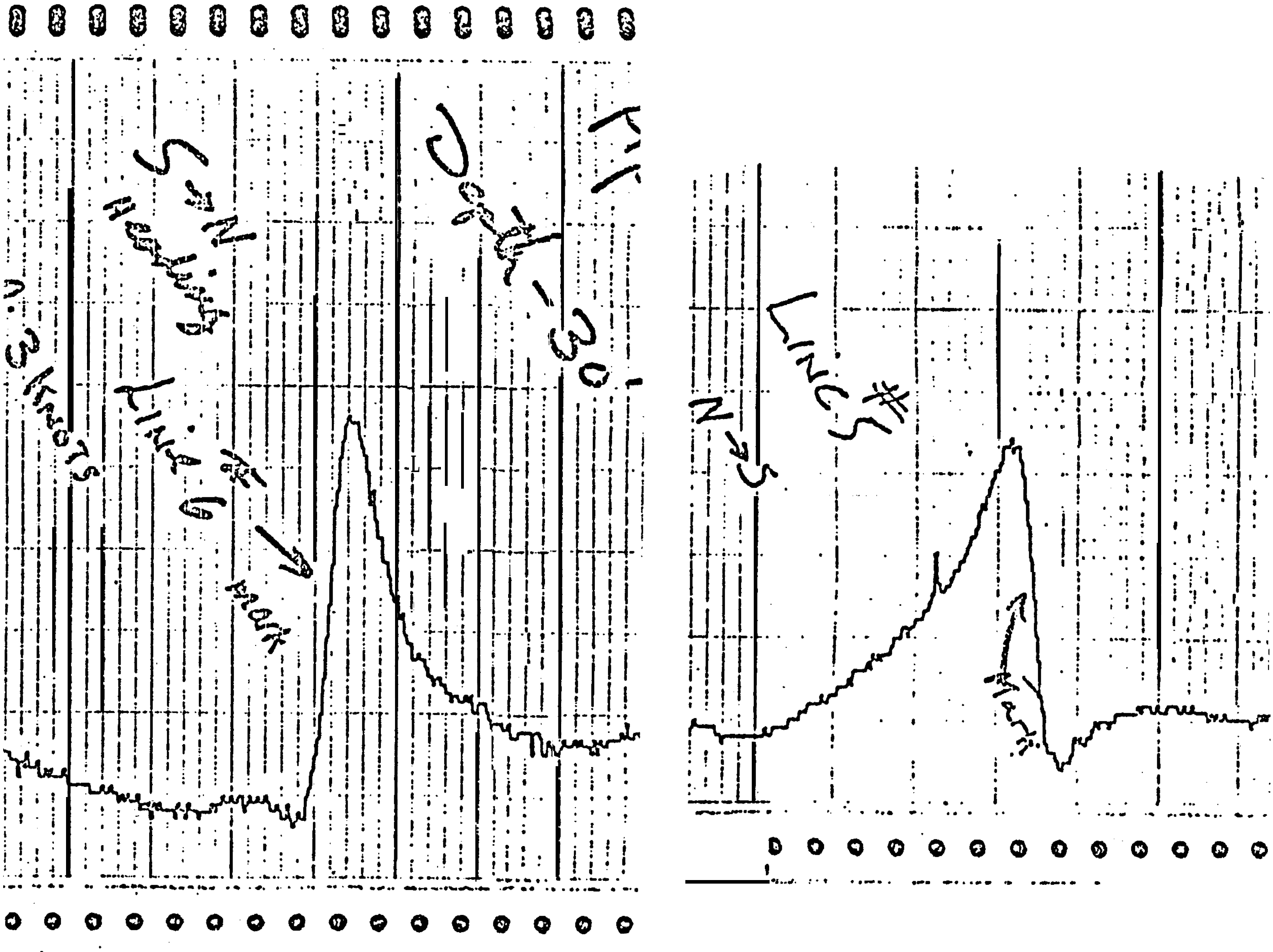
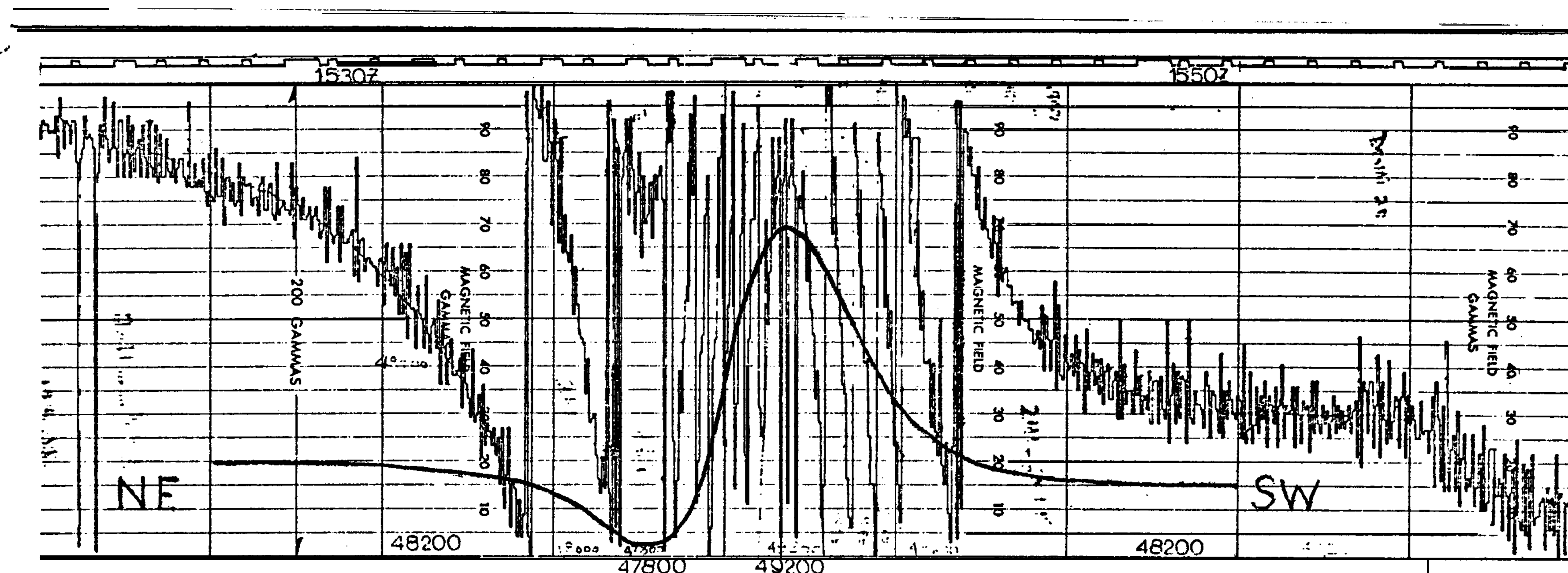
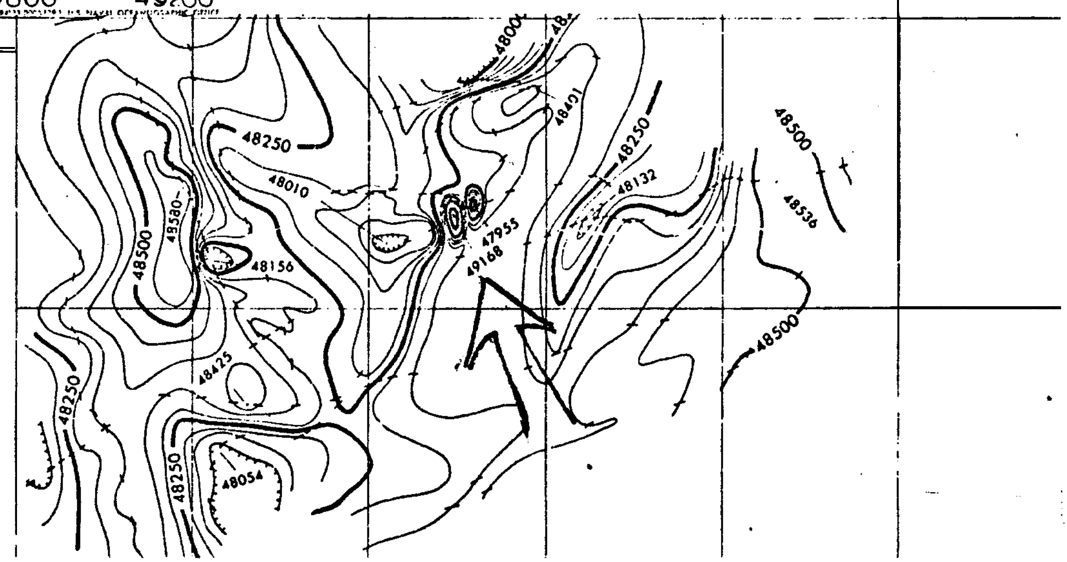


Figure Anomalies from Miscellaneous Pipelines,





Magnetic Profile and Contour Map over Large Sunken Ship

(from U.S. Naval Oceanographic Office Special Publication, Chase VI Search Operations, February 1968)

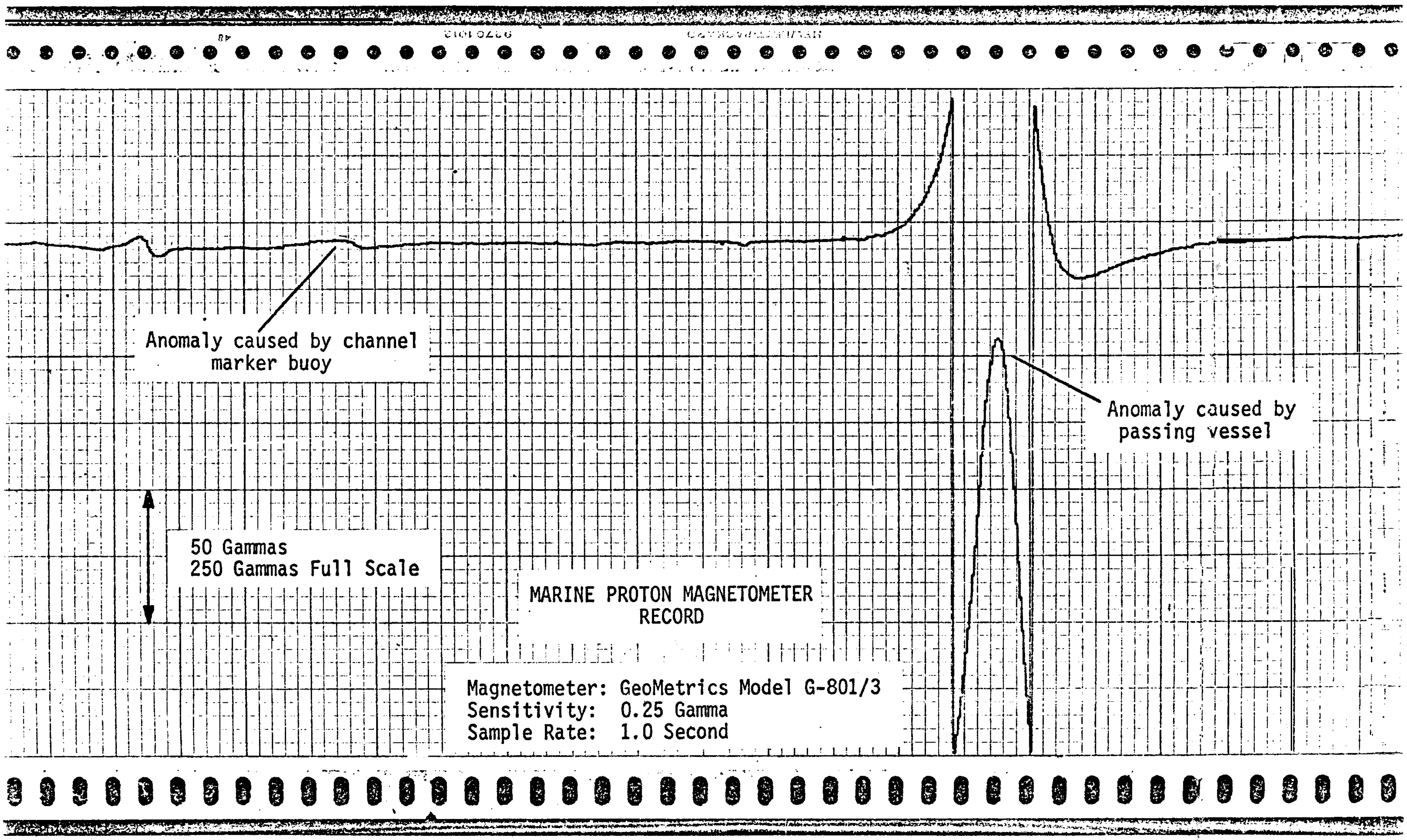

Anomaly caused by channel marker buoy
Anomaly caused by passing vessel
50 Gammas
250 Gammas Full Scale
MARINE PROTON MAGNETOMETER RECORD
Magnetometer: GeoMetrics Model G-801/3
Sensitivity: 0.25 Gamma
Sample Rate: 1.0 Second

Figure 14

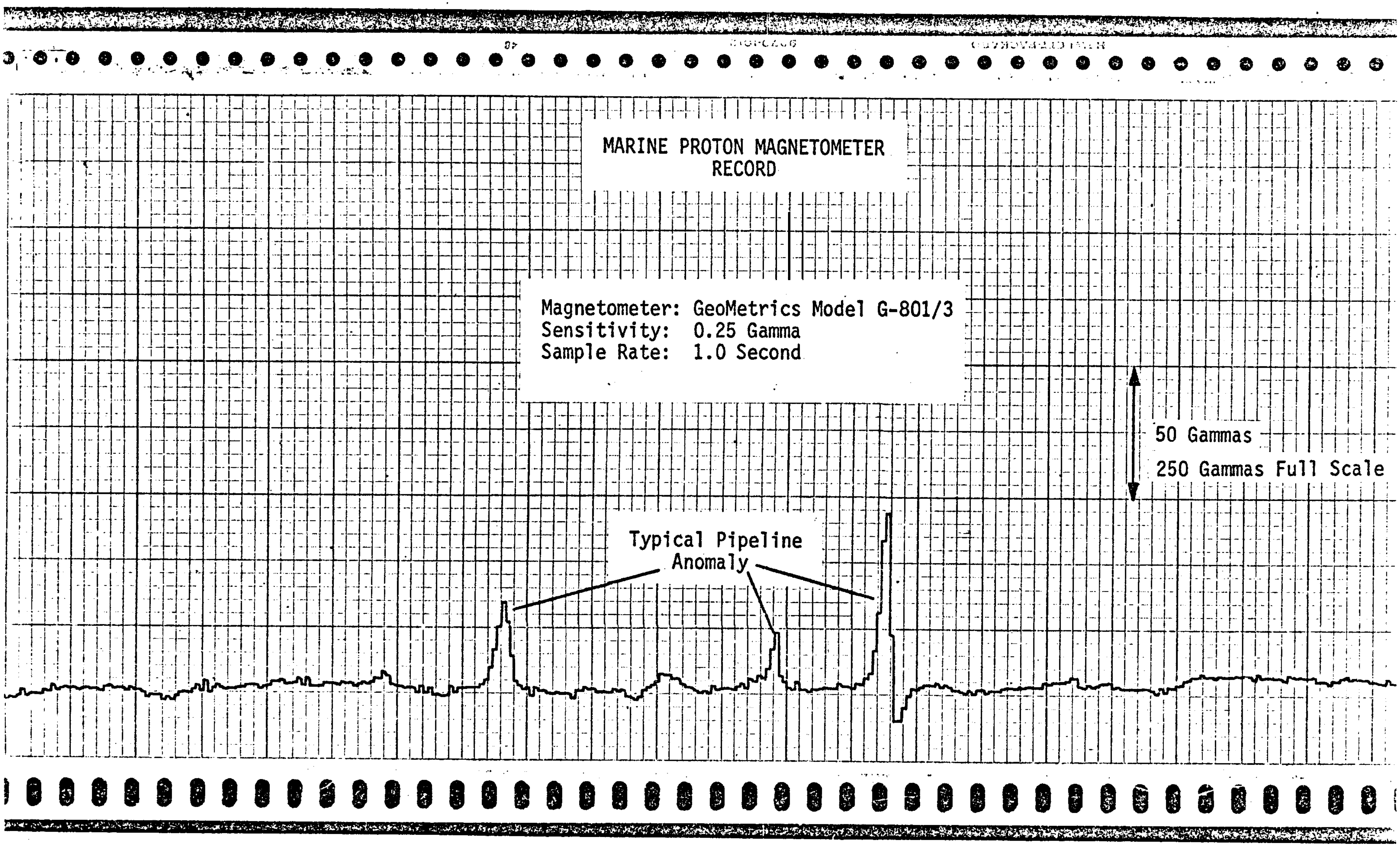

MARINE PROTON MAGNETOMETER
RECORD
Magnetometer: GeoMetrics Model G-801/3
Sensitivity: 0.25 Gamma
Sample Rate: 1.0 Second
50 Gammas
250 Gammas Full Scale
Typical Pipeline
Anomaly

Figure 15

The magnetic heading effects of a ship were described previously If the ship has a maximum peak-to-peak offset about a 360 turn around the sensor of, say, ten gammas, the heaving of the ship in swells and small course correction changes may cause effects equal to approximately l/3 to l/2 of this maximum effect or three to five gammas. Depending upon the search requirement and the frequency of these effects, such heading effects may be acceptable. For search applications requiring very high resolutions, however, say, 0.25 gamma, it would be desirable to have no'greater than one or two gammas heading effect from the ship and therefore one should tow the sensor at the appropriate distance as given in Table II earlier in this Chapter.

The effective resolution of the magnetometerrfor search applications must also include the disturbing effects of background gradients from geology and the difficulty in observing a small change over a long distance through the water or a long time interval on the chart. Even if the noise level from most of the above sources were only one gamma, it may not be possible at times to resolve a change smaller than a few gammas over a distance of several tens of meters or longer. In other words, one must be conservative with regard to the ability to resolve changes over a long distance because of the more subtle, long-period effects which may be present due to geology, time variations and other sources cited above.

Search Procedures

Search considerations involving pipelines were described above and are usually dictated by very specific job descriptions. For a search of individual or discrete objects, however, there are many more choices in the procedures and parameters of the search. The first consideration in conducting a search is to determine as much as possible what is magnetic, if anything, in the object or related to the object. Frequently, a similar object can be obtained and measured in the presence of a magnetometer at varying distances and orientations according to the methods outlined in Chapters 2 and 3. Remember that it is only the mass of ferromagnetic material and not the mass of the entire object that is of importance in magnetic search. Once the magnetic mass is estimated, it is possible to determine the maximum probable- anomaly at various distances. Estimation of this maximum anomaly is important to determine whether the object can practically be detected, how close the grid must be spaced, how close the sensor must be to the bottom and, lastly, whether or not the entire search problem is feasible considering economics, time, etc. Ideally, one should lay out a regular grid covering the area such that the anomaly is readily detectable on any two adjacent traverses, particularly if the water depth is great and control of sensor position minimal.

If no other constraints dictate the direction of principal traverses, they should be made in a north-south direction, for in any latitude there will be a greater peak-to-peak magnetic anomaly in this direction, as may be observed on the contour maps of anomalies in Chapter III. Also, the maximum and minimum of an anomaly will be adjacent on such a line thereby creating a larger effective peak anomaly and a maximum rate of change or slope, both of which enhance its detectability. In the case of long horizontal pipelines, traverses should be made perpendicular to the probable direction of the pipeline (except for north-south pipelines at-the magnetic equator where there is no anomaly over the mid-portions of the pipeline except for perhaps small perm anomalies at pipe-section junctions).

It is important to cover the area objectively and to know where one has already mapped and has yet to map. For this reason, precise radio navigation systems and dependable buoy emplacements are important as are other local and stable markers such as visible features on nearby land, emplaced pingers on the sea bottom or other such means of location.

If location is an extremely difficult problem, if the water depth varies greatly and the object is relatively small and difficult to detect, it may be very advantageous to utilize a multiple transverse sensor array such as described previously in connection with pipeline tracking. Such a multiple array of sensors utilizing, say, two, three or four sensors deployed in a line perpendicular to the line of the ship's track might give much greater assurance of the actual detection of an object, decrease the number of traverses, time and money, and greatly decrease the requirements for precise navigation of the ship as well as knowledge and control of the position of the sensor.

Detailed Mapping of Anomaly Location

After noting an anomaly on a given traverse, its location on that traverse should, of course, be noted either on the data or by proper buoy emplacements (remember that when an anomaly is located and confirmed, not only is the sensor well past the anomaly location, but so is the ship even further away from the anomaly, yet the ship is the only point whose location is noted by navigation techniques. This may seem to be an obvious fact, but is frequently overlooked in the early phase of a search program). In any event, when the anomaly is located, it is likely that the object is not precisely under the original traverse, but rather to one side and subsequent traverses as noted may have to be conducted to confirm the position and actual peak anomaly amplitude.

VI. SUMMARY

Throughout this paper on marine magnetic search, various practical hints and consideration are brought out to facilitate planning and the actual conduct of a search, particular emphasis is placed on involvement with the tow system in trying to get the sensor near the object or pipeline to provi'de better assurance of detection and/or any calculations of depth. Some of the tow configurations have never been attempted, but all have been discussed at one time or another by people experienced in marine operations. Navigation and positioning of both sensor and ship remains a problem. Even the estimated location of an object at the onset of a search problem may limit the success of a search remembering "if it ain't in the search area, it won't be found". Compared to the problems related to proper towing of the sensor, the electronics and magnetometer console operation or their dependability is certainly no problem today.

Should there be additional questions regarding any aspect of a search problem, please contact GeoMetrics Conversely, we would all gain from the collective experiences of others involved with search from the standpoint of methods that work as well as methods that do not work.

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