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MAGNETIC SIGNATURE CHARACTERISTICS INVESTIGATION

Erwin Myrick

Army Mobility Equipment Research and Development Center
Fort Belvoir, Virginia

July 1973

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER 2070	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) MAGNETIC SIGNATURE CHARACTERISTICS INVESTIGATION		5. TYPE OF REPORT & PERIOD COVERED Interim May 1972 to June 1973
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Erwin Myrick		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Mine Neutralization Division, Countermine/Counter Intrusion Dept, U. S. Army Mobility Equipment Research and Development Center, Fort Belvoir, Virginia 22060		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 1J76271275J23-03
11. CONTROLLING OFFICE NAME AND ADDRESS U. S. Army Mobility Equipment Research and Development Center Fort Belvoir, Virginia 22060		12. REPORT DATE July 1973
		13. NUMBER OF PAGES ~~40~~ 35
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Magnetic Signature
Magnetic Sensors
Dipole Model
Magnetic Countermeasures

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report addresses four Magnetic Signature Characteristics of interest to the Counter-mine problem: the magnetic signatures of vehicles, sensors employed by magnetic fuzes, a theoretical model of vehicles, and development of fundamental aspects of countermeasure theory to defeat magnetic fuzes.

The physical phenomena of the inherent and induced magnetic dipole moments of

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ferromagnetic objects are discussed in relation to the origin of magnetic signature features. The sensors employed to detect these objects are classified into two categories: those measuring absolute flux and those sensitive to flux-rate changes. To develop a basis for dealing with the gross features of ferromagnetic objects or vehicles and relate them to signatures, a theoretical model based on the dipole moment characteristics of magnetic material is developed. Experimental data obtained as part of this investigation shows general agreement with the basic features of the model. Intrinsic magnetic signature parameters are identified within the model and experimental data base. Each of the parameters is bracketed by calculations and field measurements to determine a range of values available for fuze design and consequently to CM techniques. The relative merits of using large ferromagnetic masses, permanent magnets, and electromagnetic coils are discussed as potential countermeasure tools.

SUMMARY

This study has demonstrated that the concept of magnetic signature duplication appears feasible and that it offers an effective step toward countering the threat of target-activated munitions. Through careful design of magnetic field parameters for a device or method to be used, a valid target signature can be artificially created and controlled in order to neutralize a mine sensor.

It has been shown that magnetic sensors can be classified into two basic groups: (a) those sensitive to flux-rate changes, and (b) those measuring total flux change. From these, a multitude of configurations and sensing methods have been developed which offer direct applicability to target sensing requirements. Despite the availability of many sensor and attendant signal-processing techniques, effective signature duplication countermeasuring of these techniques appears possible.

A primary aspect of this study concerned the magnetic signatures generated by combat vehicles. It was found that the use of ferromagnetic materials in vehicles contributes toward producing a dipolar magnetic field around a vehicle. This permanent field plus the field induced by vehicular motion through the geomagnetic field comprise the total magnetic signature of a vehicle. The actual spatial and time distribution of a signature is a complex phenomenon due to the many variables, such as vehicular mass, size, and geomagnetic field inhomogeneity, which produce the signature.

To facilitate data comprehension, a simple magnetic-dipole model for a vehicle was proposed. The model assumed that at some distance away from a ferromagnetic mass the signature resembled that of a dipole. The dipole axis generally coincided with that of the vehicle. Subsequent test data was in general agreement with the approximation and gave further support to the concept that magnetic signature duplication could be achieved by using methods which generated dipoles.

A countermeasures analysis demonstrated that magnetic sensors are constrained by technical practicalities to operational envelopes making them vulnerable to countermeasures. This situation arises due to upper and lower signal-threshold requirements, sensor bandwidth, mine size limitations, and available electric power for the sensor; and other considerations which serve to limit the operating options available in sensors. These limitations help to quantify and define a number of possible solutions toward countermeasures. It was finally concluded that methods using electromagnetic coils appear to provide the necessary requirements and versatility needed to generate an acceptable signal for magnetic countermeasures.

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I. INTRODUCTION

1. **Scope.** Mine neutralization by attack of the target-sensing element of emplaced mines may be achieved by projection of a false target signature (signature duplication) to effect premature mine actuation, target-signature suppression to inhibit mine actuation, or physical attack of the sensor components to make the device inoperative. The effort reported herein was directed toward the achievement of mine neutralization by target-signature duplication. Specifically, significant aspects associated with the definition of effective countermeasures for combat vehicles against magnetically activated land mines are addressed.

2. **Principle of Operation.** Sensible target signatures available for practical land mine sensors are limited. The greater number of land mines comprising the current and projected threat employ contact or overpressure/duration mine sensors. Magnetically-activated sensors have been developed to provide effective influence fuzing for land mines designed to attack combat vehicles. The operational principle of these sensors rests on the fact that a vehicle containing considerable ferromagnetic material will produce a localized perturbation in the geomagnetic field near the target. This magnetic anomaly is a complex phenomenon and is a function of such quantities as the target vehicle's size, mass, orientation in the geomagnetic field, and geographic location.

3. **Signature Duplication.** The general amplitude and shape of a target signature can be predicted, within limits, to provide a basis for mine-sensor design. Mines employing these sensors could be effectively neutralized by a device or technique which projects a false target signature in the vicinity of the mine.

A magnetic signature duplication device could be mounted on a combat vehicle and operated in such a manner as to project a false target signature in front of the vehicle to provide continuous neutralization of encountered mines employing magnetic sensors. Such a device could also be incorporated into other countermine equipment to provide such devices with an increased capability. Still another potential application of the magnetic-signature-duplication techniques includes aerial sweeping of suspected mined routes.

Successful magnetic signature duplication requires thorough understanding of the physical processes producing magnetic signatures in vehicles and the operation of mine magnetic sensors. The investigation described by this report addresses these requirements and also includes an analysis of the methods and design of potential countermeasures.

II. SENSORS

4. **Sensor Types.** A magnetic sensor is a device which detects or senses the presence of a magnetic field at some location. The sensor may be designed to be actuated by the amplitude of the field or its time rate of change. The most widely used and most versatile sensors are magnetometers using search coils, fluxgate, Hall effects, and resonance effects. Thin film, magneto-resistance, and superconducting magnetometers are usually either specially built or adapted by the user to meet a particular magnetic-field measuring problem.

It is possible to divide the above groups of sensors into two basic categories according to their detection methods. The first category includes sensors that detect either the time rate of flux change or the total flux or some magnetic field component of the total. An induction coil magnetometer (search coil) is in the first category. This is a fluxmeter whose output is a function of flux-rate changes occurring through the windings of the coil. The second category includes magnetic-field-component sensors which sense flux changes also but which do not require sensor movement or flux change of the field for measurement or detection. Using this categorization, a brief summary of how the two basic sensor types operate, their potential use, and currently available sensitivities is provided in the following discussion.

5. **Search-Coil Magnetometer.** The search-coil magnetometer (Fig. 1) operates on an induction principle. The output voltage of the search coil is given by Faraday's law,

$$\vec{E} = 10^{-8} N [(d/dt) (\vec{B}) (A)],$$

where $\vec{E}$ is the voltage induced in a coil of wire by a changing magnetic flux ($\vec{B}$). The sensitivity can be controlled by varying N, the number of turns in the coil, and A, the area of the coil. For periodic magnetic fields, i.e., those varying in some repetitive manner, the coil sensitivity increases with the field frequency until coil resonance effects limit further increases. Various search coils (both air and iron core) have been built to cover wide frequency and sensitivity ranges. Utilization of an iron core tends to concentrate the magnetic flux and thereby increase sensitivity. Sensitivity here means the ability of a coil to sense small variations in the magnetic field, thereby either sensing a small vehicle at close range or a large vehicle at a great range. The coil sensitivity range is from 10^{-9} to 10^{-7} oersted.

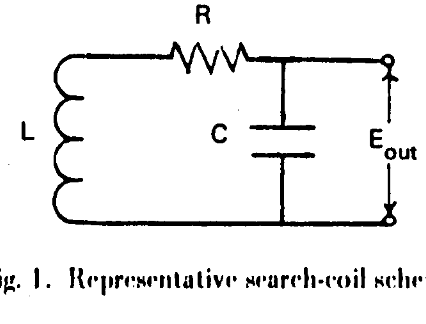

Fig. 1. Representative search-coil schematic.

A fundamental problem with sensors employing these methods is that their usefulness is limited to a.c. field measurements in the low frequency range, such as that generated by moving vehicles. This means that the sensor output is a direct function of vehicle velocity unless additional signal integrating and processing electronics is added to a particular sensing system. As an example, the sensor would have zero output, thus indicating no vehicle present, were it to stop within sensor range. Alternatively, a time-varying magnetic field due to natural sources such as lightning or man-made sources such as powerlines could cause a sensor output.

The other basic type of sensor measures the magnetic field itself. From the many variations available, three appear to be of significant countermine interest because of their use in existing systems and their future potential in sensor applications. They are the fluxgate, Hall-effect, and thin-film magnetometers.

6. **Fluxgate Magnetometer.** A fluxgate magnetometer is a device for measuring magnetic fields by utilizing the nonlinear magnetic characteristics of ferromagnetic core material in its sensing element. Figure 2 shows a typical representation and schematic of a fluxgate magnetometer. The device shown is known as a parallel-gated fluxgate sensor because the signal field $\vec{H}_s$ is parallel to the driving or excitation field. It is a directional device, measuring the component of the field parallel to the axis of the sensing coil. This magnetometer is and has been attractive to many civilian and military applications because of its reliability, relative simplicity, low power, and ruggedness.

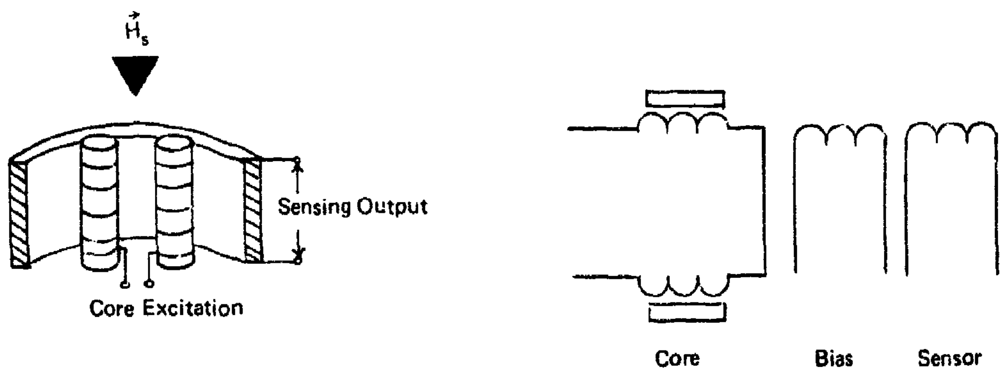

Fig. 2. Fluxgate magnetometer schematic.

There are several modes of operation for fluxgate sensors based on variations in sensor configuration, driving source, and detection method. In a general sense, the ferromagnetic core of the sensor is driven cyclically to saturation by means of a periodic current in the drive windings. In the absence of a signal field (usually d.c. or very low frequency a.c. from a vehicle), the voltage induced in the sense winding is symmetrical with the driving current. In the presence of a signal field, the sense-winding voltage becomes asymmetrical. For example, in the schematic shown in Fig. 2, in the absence of a signal, flux changes in the two cores are identical, and the induced voltage is zero because of the opposed orientation of the excitation. When this balanced condition is altered by the vehicle's signal, flux changes in the cores are not identical and a voltage is induced in the output windings. This change is very sensitive to the signal field and is detected for signal processing. Typical sensitivities are in the gamma to oersted range (1 gamma is 10^{-5} oersted) with a frequency bandpass of 0 to 10 Hz.

For applications such as vehicle sensing at relatively close range, high sensitivity and absolute accuracy are not required. Construction simplicity, low cost, low power consumption, and small size requirements are met at the price of degradation in performance. Often the signature signal is processed with simple circuitry variously called "peak" or "peak difference" detectors. In the specific case of magnetometers for use in land mines, low cost, low power consumption, and small size are critical design factors. An example of a sensor having many of these necessary capabilities is a simple ring-core fluxgate magnetometer Such a unit uses a toroidally-wound core. A transistor oscillator usually supplies the necessary excitation current.

7. **Hall-Effect Devices.** One of the most versatile genre of available magnetometers is based on the Hall effect. The basic effect occurs when an electrical current flows through a conductor placed in a transverse magnetic field. An emf is generated in a direction normal to both the current and field directions. This emf is proportional to the transverse magnetic field, the control current, and the cosine of the angle between them as follows:

$$E_H = K\,IB \cos\theta,$$

where E_H is the Hall-effect emf, K is a constant dependent on conductor material, I is the current, B is the vehicle's magnetic field, and θ is the angle between I and B.

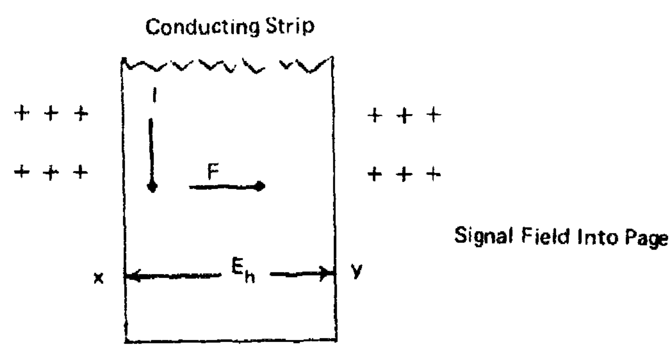

Fig. 3. General schematic of Hall-effect sensor.

Figure 3 shows a schematic presentation of a copper strip in which a current I is set up in the direction of the arrow. The magnetic signal field is considered to be at right angles to the plane of the strip, in this case perpendicular to the plane of the paper. This field exerts a deflecting force F on the strip (given by Lenz's Law) pointing to the right in the figure. Since this sideways force on the strip is due to the sideways forces on the charge carriers, it follows that the carriers will tend to drift toward the right as they drift along the strip, producing a transverse Hall potential difference E_H, such as between points x and y. This voltage is directly proportional to the signal field in frequency and magnitude. The sensors based on the Hall effect are mainly limited by two factors: deviations from linearity, and temperature dependence.

8. **Plated-Wire Magnetometer.** The most promising sensor using thin films is the plated-wire magnetometer. The device utilizes the anisotropic characteristics of thin magnetic films to detect magnetic fields. The basic configuration of this magnetometer is shown in Fig. 4. The signal field is being applied along the "hard" axis of magnetization, while the excitation field is varied across the "easy" axis. A representative voltage output is shown at the bottom of the figure.

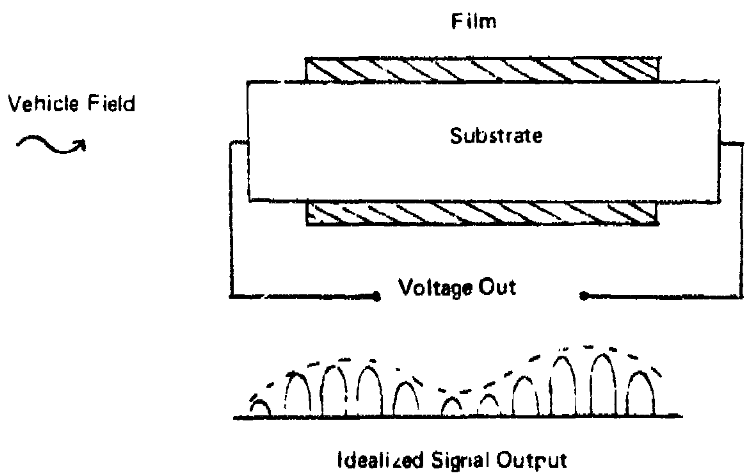

Fig. 4. Plated-wire magnetometer: operation/principle.

The plated-wire magnetometer is fabricated by depositing a magnetic film on a wire substrate while direct current is passing through the wire. The film thereby is magnetized circumferentially around the wire. This direction of magnetization is called the easy axis, while the axis perpendicular to the magnetization (wire axis) is called the hard axis. A locally produced a.c. magnetic field across the deposited film produces an emf in the wire due to the rate of change in magnetization circumferentially around the wire. In the presence of a vehicular signal field which is applied along the hard axis, a voltage, which varies in magnitude with the signature rate (Fig. 4), is developed in the magnetometer. This modulated signal is then processed for further use. These film magnetometers are most useful in the .10- to 20-oersted range.

The choice of a particular magnetometer appears to depend almost exclusively on a particular requirement or system application. Constraints arising from mine hardware requirements may dictate low power and small size. Also, as previously mentioned in discussing the fluxgate magnetometer, performance degradation with respect to sensitivity may be acceptable or even desirable for certain applications. In this sense then, all of the sensor types discussed could be considered as having real and valid utility in a system requiring the sensing of vehicular signatures.

The next section will address how and why these magnetic signatures originate in ferromagnetic objects such as combat vehicles.

III. SIGNATURES

9. **Signature Types.** The signature of a vehicle is any combination of physical disturbances caused by the presence or motion of a vehicle. These disturbances can be magnetic, electric, seismic, acoustic, or mechanical in nature. Different types of transducers can be used to detect and record the various types of disturbances. These recordings can be analyzed to evaluate differences and similarities among numerous types of vehicles producing their own unique signature.

One primary concern of this study is the magnetic signature peculiar to different vehicles. The use of ferromagnetic materials in vehicles gives rise to a dipolar magnetic field at points in space outside the vehicle. The distribution and density of ferromagnetic materials throughout a vehicle determine the spatial distribution of the magnetic flux as well as its time rate of change as the vehicle moves. The latter effect determines the vehicle's dynamic magnetic signature.

10. **Geomagnetic Field.** One of the major external influences on the intrinsic magnetic signature of a vehicle is the Earth's magnetic field. It is the interaction of a vehicle's own field with the geomagnetic field which actually produces the external magnetic signature of a vehicle.

The permanent, or main, field is that portion of the geomagnetic field originating inside the Earth. This field is roughly equivalent to a center dipole which is inclined slightly to the Earth's axis of rotation. The magnitude of the field strength at the surface is approximately 0.6 oersted in the northern regions and decreases to about 0.3 oersted in the equatorial areas. There are other natural and manmade magnetic sources. However, due to their small magnitude and high frequency, they can be safely ignored here. Power lines are a good example of a small-magnitude, high-frequency type of disturbance. Figure 5 presents the different components of the Earth's field and their associated angles. The magnetic induction at a point in space is the vector $\vec{F}$; the scalar F describes the intensity of the total field. The Cartesian components of the field are x, y, and z. The vertical field intensity is Z and is positive in the downward direction. The scalar intensity of the horizontal component of the field is designated H. The deviation D is the angle between north (x) and H. It is measured clockwise from north. The inclination (or dip) I is the angle between H and F and is positive when directed downward from H to F. As an example, the vertical intensity of the Earth's magnetic field varies from about 0.4 to 0.6 oersted in moving from south to north in the Northern Hemisphere.

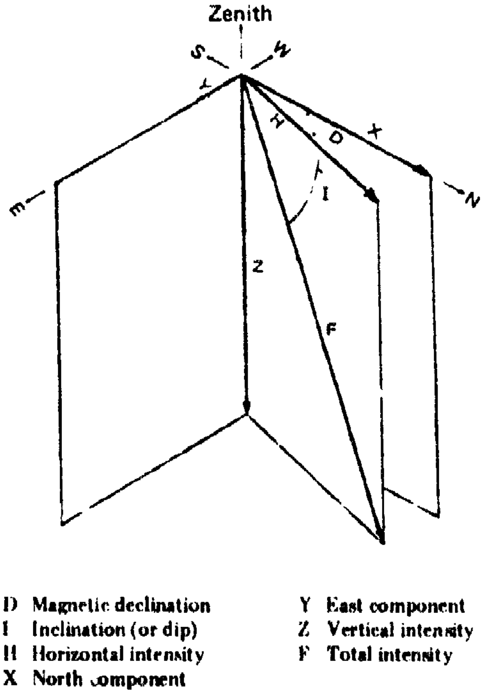

Fig. 5. Geomagnetic field vectors.

A portion of a vehicle's signature is the interaction between its own magnetic dipole moment and the geomagnetic field. The resultant field is simply the distortion, or vector sum, of the geomagnetic and vehicle field intensities. Therefore, the resultant vertical and horizontal components are both a function of the vehicle's geographic location and the orientation of its magnetic-moment axis with the geomagnetic field.

11. Local Disturbance of Field. The actual amplitude of the magnetic signature is a function of the quantity of ferromagnetic material present in the object. Different-sized objects at different ranges may present similar magnetic signatures to a sensor. Vehicular signatures may vary by an order of magnitude at the same range when compared to each other. For example, an armored vehicle, due to its large ferromagnetic mass, would present a larger magnitude signature than a Jeep. Generally, the total magnetic field measures four times that of the local undisturbed geomagnetic field. The magnitude of the signature decreases as the cube of the distance from the object, the exact expression being given by the equation,

$$\vec{B} = \frac{\mu_0}{2} \frac{\vec{m}}{r^3},$$

where μ_0 is the magnetic permeability of the space surrounding the magnetic dipole $\vec{m}$ and r is the distance from the center of the dipole. In this particular expression, the field is given along the axis of the dipole.

Figure 6 is a typical contour map of the vertical, magnetic components of an armored vehicle. The particular measurements were taken with the vehicle heading due magnetic north. The vertical-field component is the most informative of the three directional components for target sensor parameters and is most frequently utilized in magnetic sensors for mines.

An examination of Fig. 6 reveals several interesting features regarding the signature of this vehicle in particular and signatures in general. The vehicle contains several areas of high, magnetic intensity arising from local, magnetic anomalies. These areas are not directly related to a particular physical feature; rather, they appear to be a function of construction methods. It will be noted that the contour distribution is asymmetric with respect to both the lateral and longitudinal axes of the vehicle. It can be shown that this total line distribution appears to shift over the general area of a vehicle (in the figure, the flux lines are slightly forward) as the orientation of the vehicle is changed from a north to south heading.

Figure 6 shows the overall magnetic intensity of a vehicle at a relatively close range. Since this amplitude decreases by the cube of the distance from the vehicle, the signature magnitude is rapidly reduced and loses its detailed aspect quickly. At some distance from the vehicle, the magnetic disturbance resembles that of a simple magnetic dipole or sinusoidal shape.

12. Vertical Field Component. Another significant aspect in analyzing a magnetic signature is the vertical amplitude versus the longitudinal (long-axis) distance at, or near, a vehicle. As previously stated, the vertical-signature component is most often

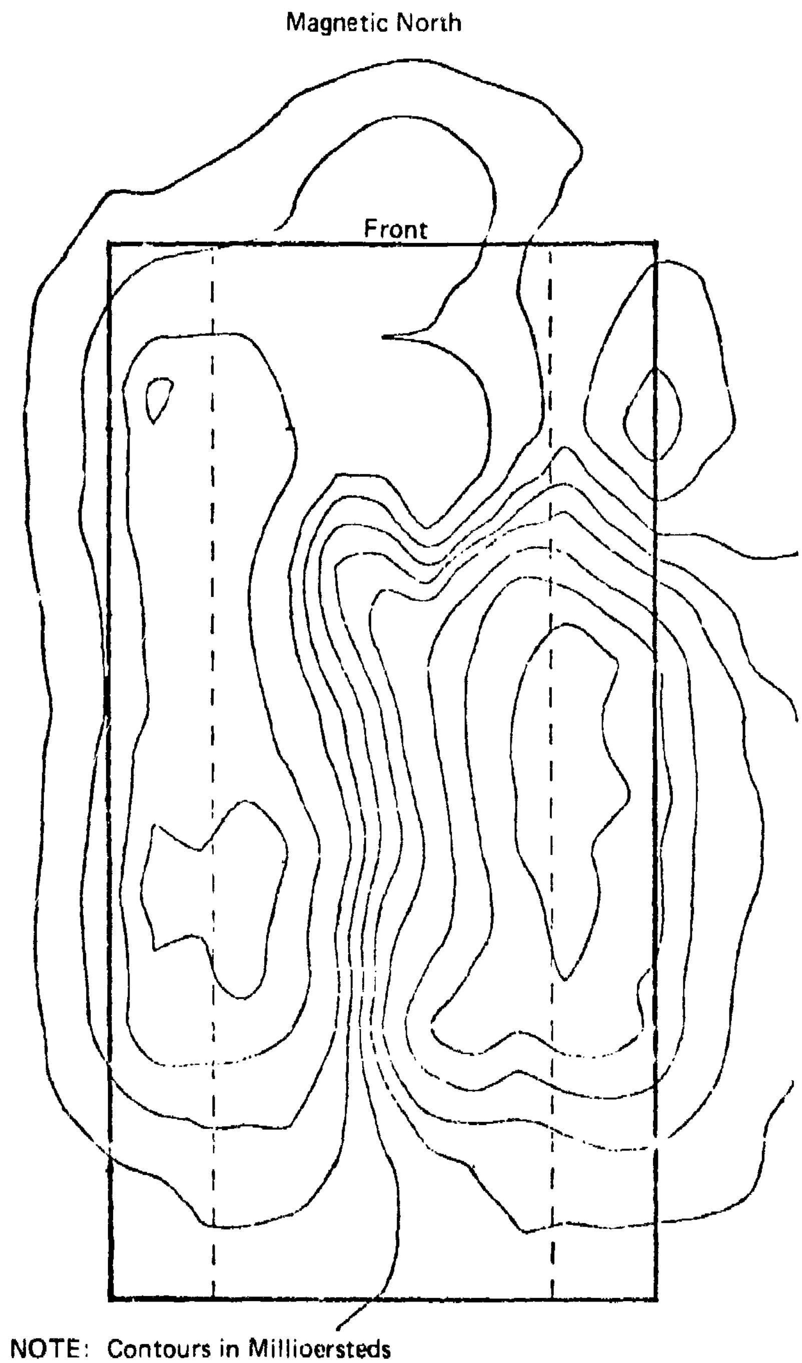

Fig. 6. Magnetic contour map of vehicle.

utilized and is easily measured by a sensor. A sample signature appears in Fig. 7. It shows the vertical amplitude variation along the centerline of a vehicle. Of interest here is variation of amplitude as the vehicle passes over a sensor. There is a pronounced rise in amplitude above the local ambient field, a reversal of the field, and then another peak followed by a return to approximately the previous ambient conditions. This signature was taken in the d.c. mode. If the amplitude were measured farther out on a vehicle, low-frequency effects from road wheels and other slow moving parts would also be observed. In addition there are high-frequency, or a.c., components due to rapidly moving mechanical components such as engine parts. Electrical and electronic equipment provide an additional contribution. The high-frequency components, while significant in vehicle detection and classification work, provide little additional information to conventional signature studies and are therefore not considered further.

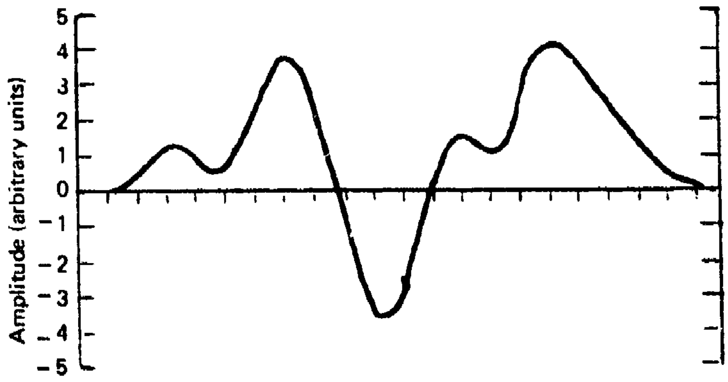

Fig. 7. Typical vehicular-magnetic-signature vertical component.

Another feature of interest is that the slope of the amplitude variation is altered by vehicle velocity. While velocity is not specified in Fig. 7, the slope would increase or decrease as the vehicle velocity changed in either direction.

IV. MAGNETIC MODEL ANALYSIS

13. Dipole Moment. Magnetic effects in materials have their origin in the atomic structure of the atoms constituting the material. The circulation of charge and electron spin within the atom gives rise to magnetic dipoles. Their strength and direction are measured in terms of the magnetic dipole moment m. Ferromagnetic materials such as iron and nickel are composed of atoms having large moments. The moment of a sample of material is determined by the alignment of atomic dipoles within the sample. The atomic and crystal structure of the material determines the net dipole moment in the absence of an external magnetizing field.

The magnetization $\vec{M}$ of a material is defined as the vector sum of all atomic dipole moments per unit volume. Consequently, the total dipole moment results from multiplying the magnetization by the volume V of an object and thus,

$$\vec{m} = \vec{M}\, V \, .$$

The moment is also equal to

$$\vec{m} = \vec{M}\, A L = \vec{m}_p L \, ,$$

where the quantity $\vec{M}A$ is defined as the pole strength $\vec{m}_p$ of a bar of the material having a cross-sectional area A, and L is the bar length.

A dipole produces a magnetic field which depends upon the distance and orientation with respect to the dipole. The magnetic field is difficult to define close to the dipole, but for distances greater than about three times the dipole length, the equations for the field reduce to a simple form. The important feature of these equations is that the flux density $\vec{B}$ due to the dipole is inversely proportional to the cube of the distance r from the dipole. The equation for this can be expressed as

$$\vec{B} = \frac{K \vec{m}}{r^3}$$

where K depends on the orientation of the dipole and the units used.

14. Vehicle Model. A theoretical and idealized model can be composed to describe the magnetic signature of a vehicle. Assume that the sum of the dipole moments for the vehicle can be represented by a large, single dipole for the entire vehicle and that this dipole follows the above equation for distances greater than three times its length. Other sources of dipole moments exist in vehicles and include the induced moments due to the geomagnetic field and current loops in electrical equipment. These sources contribute to the vehicle signature but serve only to modulate the predominant features peculiar to a single, large dipole.

The model is represented pictorially in Fig. 8. The vehicle is represented as a single, large dipole with an effective length ℓ_{eff} when viewed from a distance greater than 3ℓ. This effective length and the model's total magnetization $\vec{M}$ are determined by the vector sum of the distributed dipole strengths in the vehicle. There is no simple relation between the effective dipole length and the vehicle dimensions, nor can the net

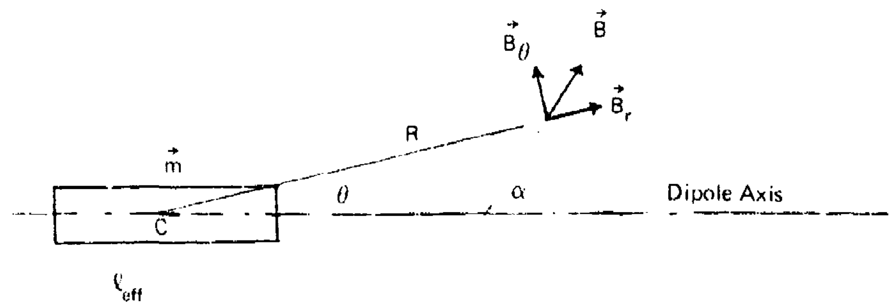

Fig. 8. Dipole field.

magnetization be predicted along any preferred spatial axis within the vehicle. It will be assumed for simplicity that the dipole center C (Fig. 8) coincides with the center of mass of the vehicle. The dipole axis subtends an angle θ relative to the position of an arbitrarily placed sensor at a distance $r \geq 3\ell_{eff}$. Additionally, the sensor is higher by a vertical distance z above a surface-implanted sensor. The total flux density and its component strengths (using cylindrical coordinates) may be represented by

$$\vec{B} = \frac{\vec{M}}{r^3}(1 + 3\cos^2\theta)^{1/2},$$

$$\vec{B}_\theta = \frac{\vec{M}}{r^3} \sin\theta, \text{ and}$$

$$\vec{B}_r = \frac{2\vec{M}}{r^3} \cos\theta,$$

where B, B_θ, and B_r are defined by Fig. 8. The equations are each an approximation to an infinite series but are reasonably valid for $r \geq 3\ell$.

Using these expressions, it is possible to predict the signature of a vehicle at large distances. The maximum magnitude occurs along the dipole axis when $\theta = 0°$. An interesting feature of all the magnetic field components is their trigonometric dependence, with that of $\vec{B}_r$ and $\vec{B}_\theta$ being most obvious. For example, let the sensor be located at some arbitrary angle θ off to either side of a vehicle as the dipole moves past it at some velocity. Considering the B_θ component, the sensor would experience a sinusoidal increase in total flux amplitude with the maximum occurring at $\theta = 90°$ and then a subsequent decrease until at $\theta \approx 180°$ it would decrease to a very small value.

The second factor will be the r-dependence. Again, considering the sensor to be stationary and the vehicle in motion, we have a situation where r will have some initial large value when θ is small and then decrease to a minimum at the point or closest approach: then r will increase again as the vehicle moves past the sensor. If the distance factor is considered to give some absolute flux amplitude, the sinusoidal aspect could be interpreted as a modulating component. The vehicle signature for a side pass could be represented by Fig. 9 where at some time T_0 the amplitude B_θ rises above the detector threshold, reaches a peak at r_{min} $(\frac{m}{r^3})$, and then decreases below threshold at time T.

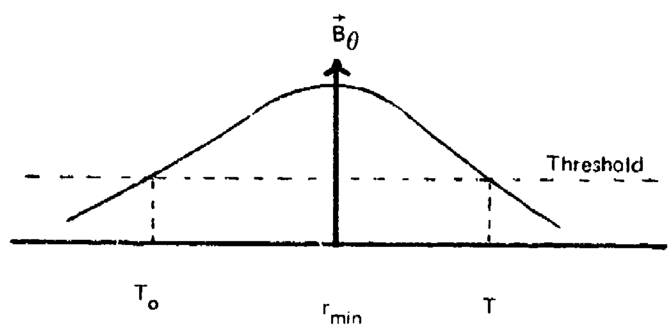

Fig. 9. Flux-component waveform.

Inspection of the equation for $\vec{B}$ shows that it will be at some maximum value for small values of θ and then decrease to zero at $\theta = 90°$; then it will be increasing again toward another maximum as the vehicle moves past the sensor. If this were plotted versus time, an identical picture as the one for the previous argument results, the only difference being that the curve is now inverted. This would not make any difference to a sensor because it would not distinguish between the polarity of a signal—just amplitude variations.

The total flux density $\vec{B}$ shows basically the same variation as its components. Inspection of the expression as θ goes from 0° to 180° reveals that $\vec{B}$ has two relative maximums at $\theta = 0°$ and $\theta = 180°$ where the B-values are approximately $\frac{2(\vec{m})}{r^3}$. The minimum occurs when the vehicle is directly abreast of the sensor and has an amplitude of $\frac{\vec{m}}{r^3}$. This shows then that the maximum is twice the minimum for the total flux density. Any sensor measuring total flux would thus also experience a sinusoidal variation in detector output with a 2 to 1 amplitude difference between the minimum and maximum.

Another useful aspect of the analysis is to consider the gradient of the components and the total flux density. If again one considers $\vec{B}$ (angular component), $\vec{B}_r$ (radial component), and $\vec{B}$ (total flux density), partial differentiation with respect to r and θ yields the following expressions for the components:

$$\frac{\partial \vec{B}_\theta}{\partial r} = \frac{-3\vec{m}\sin\theta}{r^4} = \frac{-3\vec{B}_\theta}{r} ,$$

$$\frac{\partial \vec{B}_r}{\partial r} = \frac{-6\vec{m}\cos\theta}{r^4} = \frac{-3\vec{B}_r}{r} .$$

The dipole-field gradient for the total flux density is given by:

$$\frac{\partial \vec{B}}{\partial r} = \frac{-3\vec{m}}{r^4}(1 + 3\cos^2\theta) ,$$

and

$$\frac{\partial \vec{B}}{\partial \theta} = \frac{-6\vec{m}\sin\theta\cos\theta}{r^3} .$$

The interesting aspect of these expressions is that they clearly show how the previously analyzed features originate. The components, as well as the expression $\frac{\partial \vec{B}}{\partial r}$, have a basic inverse-r dependence in addition to their regular dipole expressions when the extreme right term in each equation is considered. The expression for $\frac{\partial \vec{B}}{\partial \theta}$ demonstrates that the flux-density gradient is zero from three θ-values of 0°, 90°, 180°, and some maximum value(s) in between. This corresponds to what was shown previously, namely, that the signature follows a sinusoidal pattern with a maximum (zero gradient) at one point during the side passage.

15. On-Axis Detection. Previous sections have dealt with the off-axis, or side-pass, situations. This section will consider the on-axis case. This is interpreted as considering the flux density when the vehicle moves directly toward and over the sensor. The vehicle and dipole axes (Fig. 8) are considered lying along the same line. The dipole equations introduced previously are still valid; however, the situation must now be considered in the three-dimensional sense. This means that the model and vehicle have three dimensions, and the vehicle is actually at some distance off the ground plane—the dipole also being situated at some corresponding distance above the surface. The situation can be interpreted as corresponding to Fig. 10.

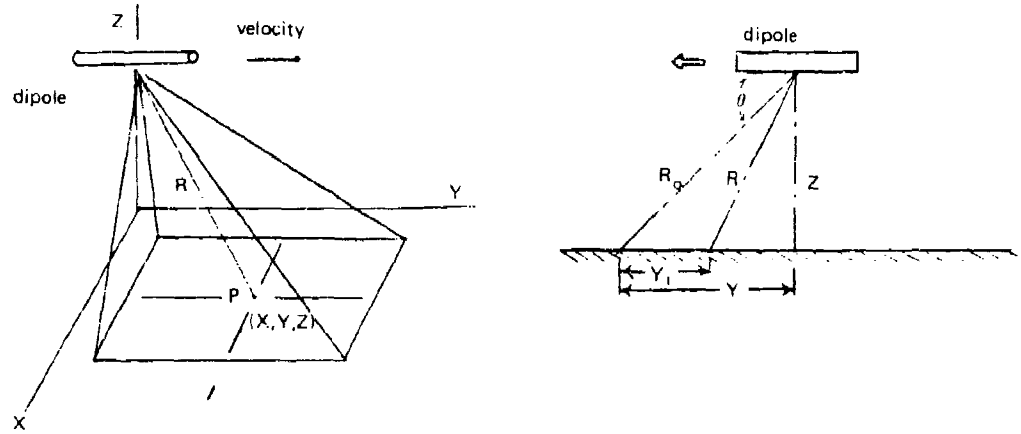

Fig. 10. Theoretical dipole orientation.

The dipole is situated (diagram (a)) at a distance Z above the surface and is moving forward with velocity $\vec{v}$. Point P is at a distance r from the center of the dipole. As the vehicle now moves toward P, the geometrical situation is shown in diagram (b) for one distance interval, and it can be seen that:

$$\frac{\partial r}{\partial y} = \frac{Y - Y_1}{r} = \frac{vt}{r} .$$

Utilizing the foregoing equations for the dipole, it is obvious that, for $r \gg 1$, $\vec{B}$ will initially have a $\frac{2\vec{m}}{r^3}$ expression which then changes according to the gradient term for $\vec{B}$. The interesting and important feature here is that while the cosine term tends to decrease field strength B, the r term increases B since the distance to the sensor is decreasing constantly as the vehicle moves toward it. However, the slope of the amplitude (starting at zero) will increase to some maximum value as the dipole moves closer and then (as $y \to o$) reach zero at the point of closest approach ($Z = r$). Also, according to the expression for $\frac{\partial r}{\partial v}$, the slope will be a function of the velocity of the vehicle. According to the above, the dipole curve should give an appearance as depicted in Fig. 11.

The maximum amplitude occurs at the point of closest approach, and the vector nature of $\vec{B}$ and m serves to force the curve negative since, after the dipole center is passed, the vectors will be oppositely directed. An implicit assumption for the dipole analysis has been that, at the point of closest approach to P, $z \geq 3\ell$. For distances closer than 3ℓ, the cube relationship is no longer totally valid.

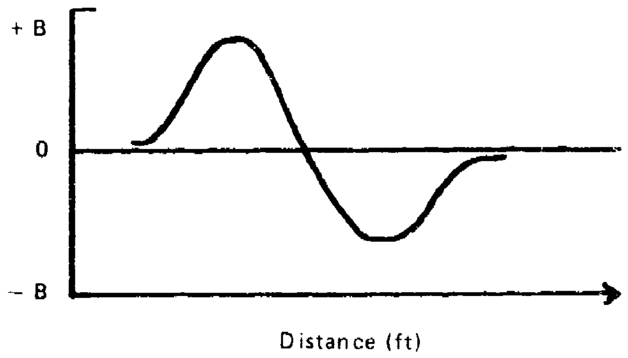

Fig. 11. Dipole signature characteristic ($\vec{B}$ vs R).

16. Practical Example. As previously stated, one of the problems in relating the model concept to actual vehicles arises due to the inhomogeneity of the vehicle's mass and the existence of several dipoles in one vehicle (turret, engine, etc.). However, one should look for the dipole equations to be generally valid and for the other terms to take over at close distances. Figure 12 is a representative signature of a ferromagnetic vehicle and shows the basic features discussed in the above model analysis.

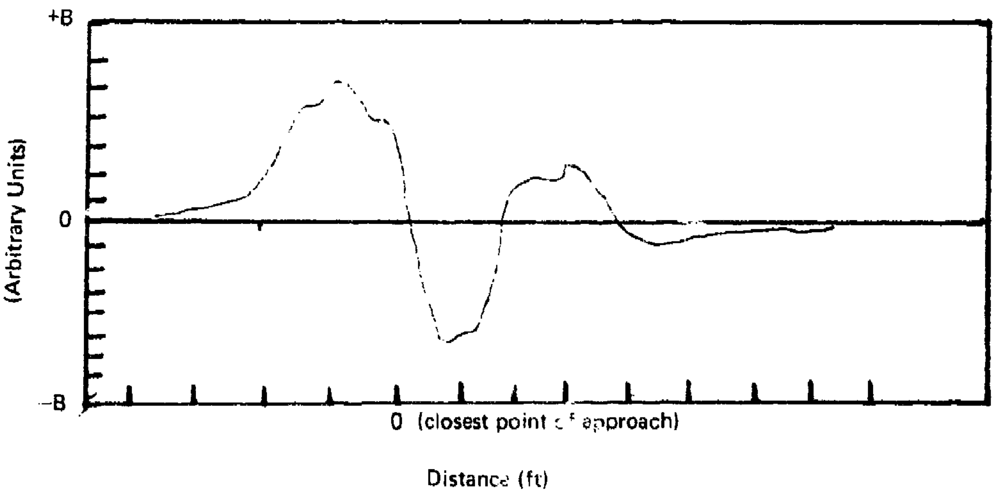

Fig. 12. Vertical component of vehicular signature.

The horizontal scale of the figure has been divided into arbitrary distance units to facilitate discussion. The amplitude shown represents the vertical component of the total flux density ($\vec{B}$). Data analysis was done on this and other signatures and resulted in several interesting findings. As the signature develops from left to right in Fig. 12, the amplitude follows essentially an r^{-3} dependence from 40 to about 20 on the distance scale. Sections of the curve from 20 to 0 appear to have an r^{-2} dependence with small sections representative of r^{-1} laws. Figure 13 is a graph showing a plot of vertical signal amplitude versus distance. In order to arrive at the values indicated by the points, the vehicle's center was considered to be at about 14 on the distance scale.

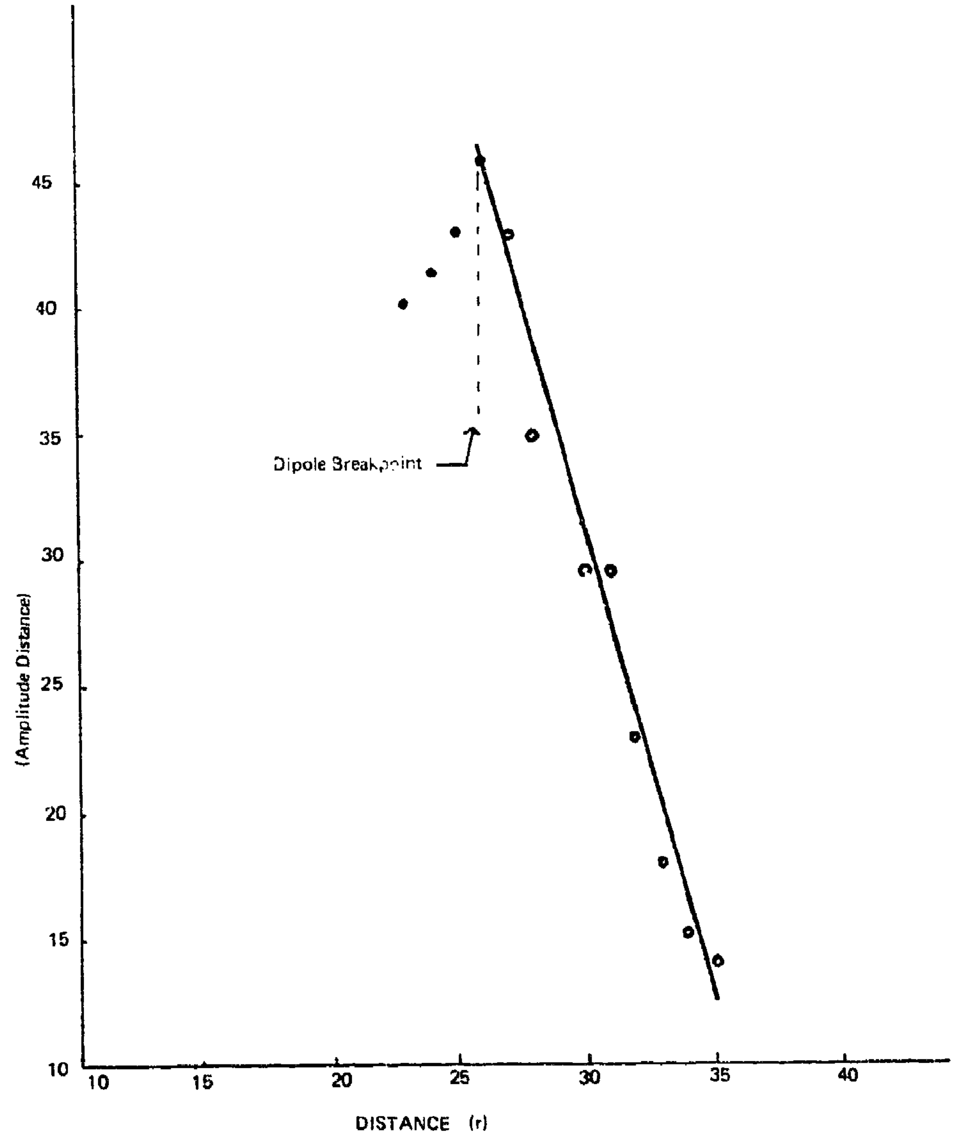

Fig. 13. Vertical amplitude of signature.

It should be pointed out that the vehicular and magnetic centers do not necessarily coincide, nor is there always a direct correlation between the magnetic field from the vehicle and a structural feature. This results from the complex interaction of all the dipole sources on a ferromagnetic object. The graph actually shows Ar^3 versus r, thereby giving a straight line if the law is applicable. This line provides a means by which the slope can be measured. The scatter of data indicates that other than r^{-3} influences are present and are serving to modulate the signature. The breakpoint appears to be where the first major deviation occurs and other dipole influences serve to make the slope positive.

One of the real difficulties encountered in all the analyses is the placement of dipole centers or deciding from which point on the curve the magnitude of the flux dependence on distance should be calculated. In the case of one simple dipole, the field would have the general form shown in Fig. 11. Actual data appear to indicate that multiple dipoles exist within vehicles and that these dipoles interact in a complex and vectorial manner to produce the resultant field. One interpretation of the large flux buildup with its attendant "bumps" is that the various dipoles in the vehicle first give an overall additive effect; then, as the sensor finally passes under one or several dipoles, the field drops slightly and then increases again as other dipoles begin to interact. When a large number of the dipoles have been passed, the field then shows a general and final return to an ambient level.

The departure from the model can thus be interpreted as arising from other than r^{-3} influences and the fact that various unspecified vehicle components are assumed to contain their own effective dipoles. The total signature of the vehicle, then, appears to be a function of the composite vector field of all dipoles present (some being time-dependent in orientation and magnitude) and of the r^{-x} functions, some of which have been identified as having r^{-1} and r^{-2} dependence according to existing data.

V. COUNTERMEASURES ANALYSIS

17. General Considerations. Most magnetic signatures, especially vehicular magnetic signatures, are complex phenomena arising from the induced and inherent dipole of an object. It is difficult, if not impossible, to exactly and totally duplicate the signature of a particular vehicle. Within a specific class of vehicles, e.g., armored vehicles, there exists a large variance in signature from one vehicle to another. The sensor that activates a munition must accept a range of possible signatures. Additionally, current fuze design uses only one spatial component of a signature—the vertical. The attractiveness of using the vertical component lies in its ability to provide information regarding a vehicle's location relative to the sensor. Also, a single, spatial-component sensor requires minimum processing electronics for firing a warhead. It is realistic to assume, however, that future sensors may use two- or three-dimensional sensing techniques.

Any countermeasures using magnetic signature duplication, irrespective of method or form, must produce a magnetic field comparable to a particular vehicle or series of vehicle types being defensed. This requires that countermeasures produce the general equivalent dipole of vehicles upon which the sensors are targeted. Consideration of countermeasures necessarily involves simultaneous discussions of sensors and signal-processing techniques.

Despite the multitude of detection methods available, one can consider that the following features of a magnetic signature will be common to all signatures. These are signal amplitude, threshold, slope, and the bandpass of the system.

The amplitude is the absolute value of the magnetic field or flux density produced by the vehicle itself plus that induced by virtue of the geomagnetic field.

The threshold is the signal amplitude below or above which a sensor should reject information. This is required so that magnetic noise from sources other than valid targets does not actuate a firing sequence.

The bandpass of a system is the total time given for obtaining information from the signal. The reason for considering only certain-sized or -shaped pulses is to improve target discrimination. Electronic filters accomplish this function. These bandpass filters also improve the signal-to-noise ratio. However, the sensor design must incorporate a rather broad filter, since the signature frequency is a function of vehicle velocity.

The slope of the signal is the change of its amplitude with time. It has been experimentally shown that the value of the slope at a particular point in space and time is related to vehicle location. Changes in the sign and value of the slope can be used to relate the position of the vehicle relative to the sensor. The absolute value of the slope is a function of vehicle velocity and consequently can be confined to values corresponding to realizable vehicular velocities.

18. Range of Parameters. Each of the previous quantities is a variable and can have a range of expected values for a particular target. Sensor detection probabilities are functions of a vehicle's range, velocity, size, orientation of the vehicle dipole relative to a sensor, and the Earth-field component at the sensor site. Another aspect of sensor performance must consider environmental magnetic noise (man-made, atmospheric, and geomagnetic) as it affects the sensor's noise threshold, bandpass, and sensitivity.

A primary requirement of any sensing system is a minimum threshold capability which is immune to environmental noise. Of the three environmental magnetic noise sources identified above, the geomagnetic is the largest, with the Earth's field being on the order of 0.5 oersted. Also, a vehicle sensor should be insensitive to men or vehicles smaller than those for which it is targeted. If the dipole moment of a rifle is given as 400 cgs units, the field will be about 0.1 oersted at a distance of 1 meter for an orientation giving maximum coupling, assuming no other dipole sources on a person. Another threshold factor is that the detection radius of the sensor relates to the ferromagnetic content of the vehicle. This means that a ferromagnetic object smaller than the vehicle (mass concept) can produce the same amplitude of signature at a smaller range.

It is possible to perform the same type of analysis for the upper, or maximum, threshold of sensor operation. If, for example, one assumes a ferromagnetic object with a density and mass representative of typical armored vehicle material, a 60-ton vehicle (idealized as a sphere) would have a dipole moment of about 4×10^6 pole-cm. This would produce a field of about 1.0 oersted at 2 meters from the vehicle for the best-case situation. Therefore, the amplitude of any duplication signature should operate within the upper and lower limits of the magnetic flux produced by the dipoles at distances dictated by operational considerations. This situation is shown in Fig. 14 where a hypothetical vertical signature of a duplication device or vehicle is shown.

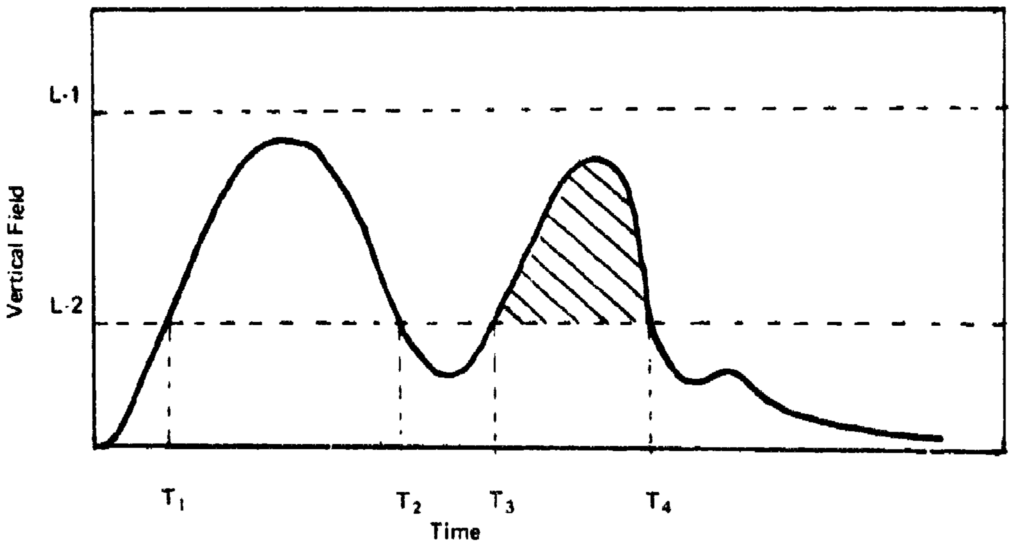

Fig. 14. Hypothetical signature of a vehicle.

Returning to the prior analysis for two amplitude extremes of a man and a tank, at 1 meter the tank model would result in an approximately 8.0-oersted field while the man's field would be 0.1 oersted. A sensor thus could be designed to reject any flux amplitude below 0.6 and above 8.0 oersted as represented by L-2 and L-1 respectively in Fig. 14.

Consider a rudimentary type of sensor which responds only to a change of total flux level. A good example of this would be a fuze employing a magnetic dip needle or any other mechanism which depends solely on a certain level of signal amplitude for actuation. Such a sensor would be countermeasure to any susceptible technique capable of providing a sufficient magnetic field to exceed the pre-set threshold of the transducer (L-2 in Fig. 14 for example). Additionally, if an upper-threshold capability were present, a duplication technique would have to exercise caution so as not to exceed a certain amplitude level and be rejected as a false target by the sensor. Such a transducer would be vulnerable not only to duplication devices passing over it but also to side-pass situations. This arises because the latter also generates a sinusoidal signal.

An exception would be the case where a magnetic sensor is used in conjunction with other methods of target acquisition such as seismic and acoustic detection. In these situations, the magnetic sensor usually functions as a range-gating device—being part of the decision circuitry which only fires a warhead when the target is within munition range. Even then, however, a magnetic duplication device would cause erroneous target range values and hopefully lead to a premature mine detonation.

19. Optimum Thresholds. It is apparent that upper and lower threshold requirements limit the total range of flux amplitudes to which a sensor can respond adequately. A limit that is set too low can result in a multitude of premature or random firings due to magnetic noise. Amplitude values set too high could cause a sensor to never recognize a valid target. A nonmagnetic constraint on any munition would be the range of its warhead. With the continuing and increasing employment of Miznay-Schardin-type warheads in present and probably future mines, a definite range limitation arises. Therefore, threshold and range constraints dictate vehicle tread and belly restrictions for munitions and sensors.

For close-in signatures, the sensor can assume added degrees of sophistication. A device could contain both an upper and lower threshold condition where activation occurs after a time T_{min}, and if a preset time T_{max} were exceeded would reject a signature as false. In addition, one must now consider certain signal features such as the slope of the signal with respect to distance and/or time, the bandwidth of the amplitude versus the bandpass of the sensor, and any unique signal features a sensor could key on for a vehicle or class of vehicles.

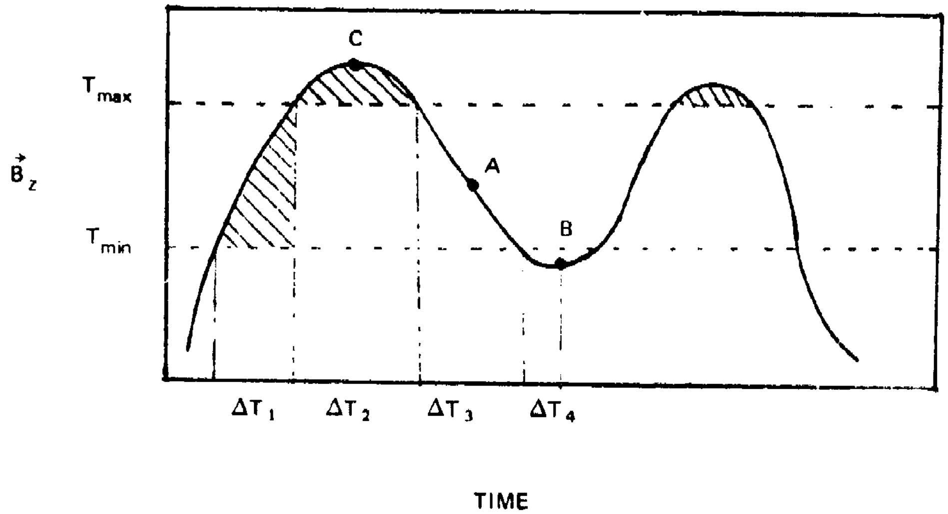

Fig. 15. Signal amplitude vs time.

A hypothetical situation is shown in Fig. 15 where a signal amplitude (vertical or horizontal) is plotted versus time. One of many potential methods to process this kind of signal would be a simple amplitude-histogram method. Here the signal is divided into a series of time and amplitude cells into which target features fall, and by examining their content a firing decision is made. Another facet is that the slope of the signal curve is dependent on the vehicle's velocity (flux-rate sensors). The velocity has a finite limit; usually the velocity of a typical armored vehicle in a combat environment ranges from 0 to 40 mph. Another limiting assumption can be made in that minefield clearing operations would probably restrict a vehicle to a velocity in the 2 to 5 m/sec range (10 mph maximum). The slope is additionally influenced by the r^{-x} influences coming into dominance at very close ranges. For the $r \geq 3\ell$ condition, $B = \frac{A}{r^3}$, where the dipole terms have been incorporated in the constant A. Taking the time derivative and setting up a ratio gives:

$$\frac{\dot{B}}{B} = \frac{-3v}{r}$$

where $\dot{B} = \frac{dB}{dt}$, and v is the velocity.

If one assumes r^{-2} and r^{-1} dependences, the same procedure gives ratios of $\frac{-2v}{r}$ and $\frac{-v}{r}$ for these respectively. This again shows that the slope of the signature is constantly changing and is also a function of vehicle velocity. In reality, the slope is more complex than this because actual data show the existence of a multiplicity of dipole sources within vehicles.

The duplication effort must consider all of the features discussed above. The velocity restriction of the vehicle would definitely characterize a general slope, while the slope changes from the dipole effects would also occur in a duplicating device whether mechanical or electrical. The exact slope change could not be duplicated since the dipole distributions could not be matched exactly.

Referring to Fig. 15, it is apparent that a sensor could be configured to trigger at any point along the curve. If an amplitude-histogram method is used, then any duplication device must follow the general slope of an actual object, because the amplitude/time cells ΔT_1, ΔT_2, ΔT_3 . . . must add up to certain preset values. If a slope method is used, a decision must be made by the fuze designer whether to trigger on negative, positive, or zero slope and after which peak on the curve. It seems logical that a firing point on the downward side of the curve or a zero-slope point would be chosen. Existing data indicate that the first peak roughly represents the leading edge of the vehicle, so that for belly targeting, the downward slope or any subsequent valley or peak would place the explosive charge somewhere under the vehicle. From the countermeasure viewpoint it is, therefore, important to assure that any device attached to a vehicle is situated so that the downward or zero slopes (A, B, C of Fig. 15) of the signal occur at a location on the vehicle or device which could survive a mine detonation. In the case of mechanical systems, this would require a device at a distance in front of the vehicle which takes the vehicle speed and mine actuation delay into account.

20. Signature Simulation Methods. A variety of methods are available to produce and control magnetic fields in order to simulate signatures. Of these, three concepts appear to be basic:

a. Bulk Ferromagnetic Mass
b. Permanent Magnetic Material
c. Electromagnetic Coils

Prior discussion has already considered the production of magnetic dipoles by ferromagnetic and pure magnetic materials. The difference between the two is that the amount of mass or volume required for the bulk concept is considerably greater than that for permanent magnets. The magnetic moment of ferromagnetic material is given by $\vec{M} = \kappa \vec{H} V$, where κ is the magnetic susceptibility, $\vec{H}$ is the ambient field, and V is the volume of the material. The expression shows that large amounts of material are needed to produce a large magnetic moment, because κ and $\vec{H}$ are fixed quantities. The magnetic susceptibility κ is dependent on the geometry of the material because it contains the de-magnetizing factor, while $\vec{H}$ is the geomagnetic field strength. A general guideline that has been experimentally developed gives a value for $\vec{M}$ of approximately 4×10^6 units per ton of ferromagnetic material. For an ideal situation where the field is measured on the dipole axis, the field at an arbitrary distance of 2 meters would be 0.5 oersted. This points out that a relatively large amount of material is needed to produce a field roughly equivalent to the geomagnetic field.

Permanent magnets produce a magnetic dipole field which depends on the distance and orientation with respect to the dipole. The flux density of the magnet on its axis can be expressed by the equation:

$$\vec{B} = \frac{2(\vec{m})r}{\left[r^2 - \left(\frac{L}{4}\right)^2\right]^2}$$

where $\vec{m}$ is the dipole moment, r is the distance to the point of measurement, and L is the magnet length. Field strength $\vec{B}$ is given in units of gauss or oersted, since they are equivalent in a nonmagnetic medium such as air. The magnitude of the dipole moment $\vec{m}$ is a function of the magnetization and volume of the material used. It can be shown that the volume of material required to produce a specified flux density is proportional to the flux density squared. The quality of a magnet is judged by the amount of volume required to produce a certain flux density and is smallest for those materials having the greatest $(BH)_{max}$ value. The product is a measure of a magnet's quality and is called its energy product. This expression reduces to the regular dipole equation for $r \geq 3\ell$ and for any off-axis situations.

As an illustration, relatively high flux densities can be obtained by using such materials as Alnico 5, which has a residual induction of slightly less than 1.2×10^4 gauss for a rod having a length-to-diameter ratio of 8.0. The L/D ratio merely serves to reduce the effective field available, i.e., the ratio is inversely proportional to the demagnetizing field for a certain material configuration. The rod would produce a magnetic field of about 250 oersteds at the pole faces of the magnet which of course would decrease cubically away from it.

Electromagnetic coils are not limited by any material consideration as are permanent magnets but can operate at any flux density within the limits of parameters such as space, weight, and available power. Any current-carrying wire has circulating charge and therefore can be classed as a magnetic dipole. Its dipole moment may be calculated; the field equations for distances greater than three times the largest dimensions of the coil become identical to those for a magnetized bar. The magnetic field due to any current-carrying wire may be calculated by the Biot-Savart Law. Such calculations are straightforward for simple arrangements such as long, straight conductors.

For example, the flux density $\vec{B}$ of a flat circular coil for an on-axis situation is given by:

$$B = \frac{.1\, nIA}{(r^2 + d^2)^{3/2}} ,$$

where n is the number of turns on a coil, I is the coil current in amperes, A is its effective area (equal to $\frac{\pi}{3} [r_1^2 + r_2^2 + r_1 r_2]$ where r_1 and r_2 are the inner and outer coil radii), r is its effective squared radius ($r^2 = 1/\pi\, A_{eff}$) and d is the distance from the coil along the axis. Note that the equation reduces to a regular dipole expression for $d \gg r$ and that the dipole moment of the coil is equivalent to the numerator of the fraction.

21. **Comparison of Methods.** Each of the three general categories of magnetic countermeasures has certain advantages and disadvantages. The ferromagnetic mass, or bulk, concept distorts the geomagnetic field and will generally produce a vertical component similar to that produced by a vehicle. The amplitude of the signal will of course depend on the density and amount of ferromagnetic material present. A distinct advantage of this method is that such a device would be passive and have no electrical power requirements. The total mass required to produce a given B amplitude would be a high percentage of a vehicle's mass. The bandpass requirements of any potential sensor must also be considered here because, although a bulk device may meet the amplitude specification, any significant deviation in amplitude-curve structure (wrong bandwidth) would probably cause a moderately sophisticated sensor to reject the device as a false target. Also, the large amount of mass requred to fully duplicate a vehicle would make the device vulnerable to blast damage.

Permanent magnets offer essentially the same advantages of bulk devices. There would be no electrical power requirements. Again, a magnet or series of magnets would have to meet basic vehicle requirements for amplitude and bandwidth. The big advantage of this concept over the previous one is that much less mass would be required to generate a given magnetic field. The field orientation, amplitude, and shape could be carefully controlled and specified by judicious design. Current magnetic materials are essentially immune to temperature, shock, and vibration effects and thus appear to have an indefinite operating life in a field environment. It must be considered, however, that since the dipole field has a negative-cubic dependence, the strength (dipole moment) or size of any magnet must be large to duplicate the vehicle over the area required.

The electromagnetic coil is not a passive device and requires electrical power. This is not wholly disadvantageous, since it provides a precise means for controlling the field—an option not available with other methods. Coils can be mounted in a manner similar to permanent magnets. One approach could be to place the coil or combination of coils in front of the vehicle. The design must be such as to produce the desired field over the areas being defensed. In any practical approach, the combined effects of vehicle and coil must be considered.

The use of pulsed electromagnetic coils can result in a reduction of power required to produce a given field. The magnetic pulses can be controlled to generate the variety of pulse amplitudes and shapes required for signature duplication. For example, pulse rates cannot be too rapid, since a sensor will have a certain bandpass. Conversely, the rate must not be too slow or mine actuation may occur too late.

Another advantage of a pulsed-coil system would be to neutralize sensors with a "count" feature, where certain pre-determined waveforms would simulate the passage of a number of vehicles. Once the maximum count of a particular fuze is determined, this method could simulate the required number of vehicle passes to cause detonation of mines.

VI. CONCLUSIONS

22. Conclusions. Depending upon the degree of sensor complexity and countermeasures selected, magnetic signature duplication appears possible and offers a viable means to defeat magnetic sensor mines. It has been found that these sensors are constrained by certain physical limitations imposed by signal threshold, bandpass requirements, target range, and mass. These constraints serve to bracket the variables and define duplication efforts by providing for a means to produce a magnetic signal falling within these limits. Another factor is that the basic magnetic similarity of ferromagnetic vehicles further limits sensor targeting and may permit the duplication method to be the same for most vehicles. However, added degrees of sensor sophistication, such as possible future use of multiple-axis transducers, will require additional responses from countermeasures to meet those problems.

The investigation has considered three fundamental methods for signature duplication: bulk ferromagnetic material, permanent magnets, and electromagnetic coils. Each has merit when considered in a particular situation and application. The bulk method could provide the required signal; but, due to its large size, would adversely affect the mobility of any vehicle transporting it. The use of permanent magnets offers a good solution in that a large number of desired amplitude and spatial configurations of magnetic flux could be achieved by proper design. The method has a disadvantage because material and mechanical attachments required on the front of the vehicle could pose a mobility problem. Vulnerability to shock and warhead blast would also require study. Additionally, once a particular magnet configuration were adopted and mass-produced, it would not be easy to alter if found to be marginally effective against new or modified munitions.

Electromagnetic coils seem to offer the most versatile method for duplication. The magnetic signal amplitudes required can be achieved by coils of reasonable dimension and weight relative to an armored vehicle. The coils can produce virtually unlimited types of waveforms and signal shapes. This is possible because modulation of the magnetic flux would only involve altering the current and voltage to the device. Thus, this method can be designed to meet the problems posed by present and future magnetic sensors as well as to offer good versatility and moderate size constraints.

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