Electromagnetic Induction Spectroscopy for Clearing Landmines

I. J. Won, Dean A. Keiswetter, and Thomas H. Bell

***Abstract*—An estimated 110 million landmines, mostly antipersonnel mines laid in over 60 countries, kill or maim over 26 000 people a year. One of the dilemmas for removing landmines is the amount of false alarms in a typical minefield. Broadband electromagnetic induction spectroscopy (EMIS) is a promising technology that can both detect and identify buried objects as landmines. By reducing the number of false alarms, this approach significantly reduces costs associated with landmine removal. Combining the EMIS technology and a broadband EMI sensor, the scientific phenomenology that has potential applications for identifying landmines, unexploded ordnance, and hidden weapons at security checkpoints can now be explored.**

***Index Terms*—Automatic target recognition (ATR), broadband EMI sensor, clutter reduction, detection, discrimination, electromagnetic induction (EMI), electromagnetic induction spectroscopy (EMIS), GEM-3, identification, landmine.**

I. INTRODUCTION

ACCORDING to United Nations statistics, an estimated 110 million landmines, mostly antipersonnel (AP) mines laid in over 60 countries, kill or maim over 26 000 people a year. While an international treaty banning the AP mines, thus removing the source, is getting popular support, many organizations, including the U.S. government, have invested in the "humanitarian de-mining" effort to remove existing landmines from the earth.

Clearing a landmine requires two-steps: detection and removal. The most common tools used to find landmines are metal detectors and, less commonly, magnetometers. These sensors are relatively simple to use, light, and affordable, a factor particularly important in developing countries where these mines are buried. Other potential sensors, e.g., ground-penetrating radar, are still in the research or prototype stages, and their ultimate utility for landmine detection is not certain at this time.

Landmines are cheap to make, commonly costing less than a few dollars a piece. Yet, it costs several hundred dollars to remove each landmine. Some so-called "plastic mines" contain only a small amount of metal and thus, are often hard to find with metal detectors. The overriding reason for the high removal cost, however, is not the difficulty in detecting landmines but the amount of clutter in typical minefields. The clutter may be natural (e.g., magnetic rocks) or manmade objects (e.g., nails, pull-tabs, and metal cans) that trigger the sensor in a way similar to a real mine. When its identity is unknown, each clutter item must be treated as a landmine during the removal, which is the most painstaking, time consuming, and costly phase of the job. Often, as many as 95% of suspected anomalies are nonordnance items [1]. At this clutter rate, the cost of landmine removal becomes so high that no society can afford it. The most desirable solution is to come up with smart sensors that can reduce the clutter by identifying it as such and thus eliminate the need of excavation except for real mines. We present in this article such an approach, one that uses a broadband electromagnetic induction spectrum.

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II. ELECTROMAGNETIC INDUCTION SPECTROSCOPY

An object made partly or wholly of metals has a distinct combination of electrical conductivity, magnetic permeability, and geometrical shape and size. When the object is exposed to a low-frequency electromagnetic field, it produces a secondary magnetic field. By measuring the broadband spectrum of the secondary field, we obtain a distinct spectral signature that may uniquely identify the object. Based on the response spectrum, we can "fingerprint" the object. This is the basic concept of electromagnetic induction spectroscopy (EMIS) [2].

When an electrically conductive and/or magnetically permeable object is placed in a time-varying electromagnetic field, a system of induced current flows through the object. By observing the small secondary magnetic field emanating from the induced current, we attempt to detect the object. This is the foundation of the well known electromagnetic induction (EMI) method. Although EMI physics is completely described by Maxwell's four equations, analytical solutions beyond the simplest geometry are rare due to mathematical complexity.

The EMI principle is the basis of common metal detectors used for airport security checks as well as for treasure hunting on the beach. They are popular, inexpensive, and common. They cannot, however, distinguish one metallic object from another, so that the number of false targets generally far exceeds that of real targets. In other words, they detect metal objects indiscriminately and thus produce much wasted effort in excavating false targets.

EMIS technology explores the frequency dependence of the EMI response. By measuring an object's EMI response in a broad frequency band, we attempt to detect and characterize the object's geometry and material composition. Electromagnetic theory shows that an object must exhibit different responses at different frequencies. This fact has not been exploited because there have been no practical broadband EMI instruments

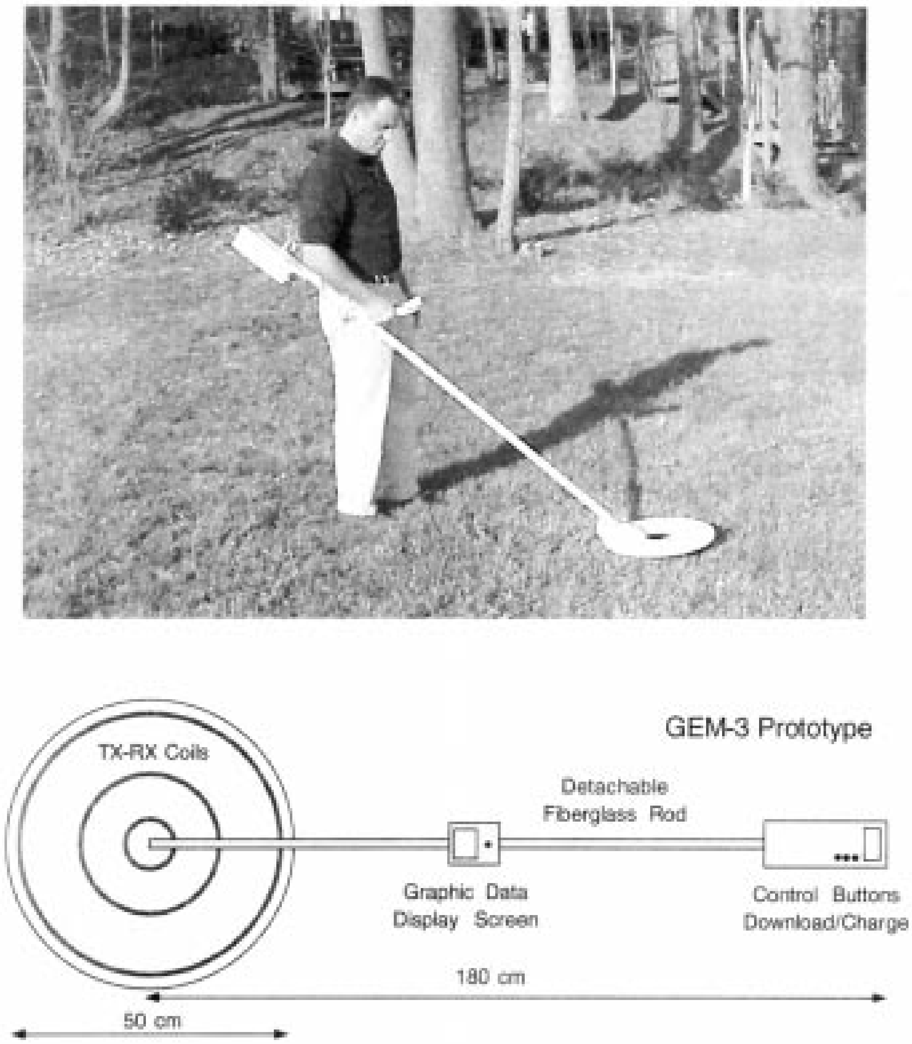

Fig. 1. Top: photograph of the GEM-3 monostatic broadband EMI sensor. Bottom: schematic diagram showing its internal construction.

to study the phenomenon. Most commercial EMI sensors (including common metal detectors) operate at single frequency or, rarely, at a few discrete frequencies. However, with the recent development of broadband EMI sensors, it is now possible to exploit broadband EMI spectra in order to detect and identify the targets.

III. Broadband EMIS Sensor

To explore EMIS-based landmine identification, we have employed the GEM-3 (Fig. 1), a monostatic, broadband, electromagnetic sensor designed for subsurface geophysical investigation. Because the GEM-3 sensor details have been discussed in detail, including an analytic description of the transmitted and received fields [3], [8], only a summary of the sensors salient features are presented here.

The GEM-3 operates in a bandwidth from 30 Hz to 24 kHz. The sensing head consists of a pair of concentric, circular coils that transmit a continuous broadband digitally controlled electromagnetic waveform. The two transmitter coils connected in an opposing polarity, with precise dimensions and placement, create a zone of magnetic cavity (*viz*., an area with a vanishing

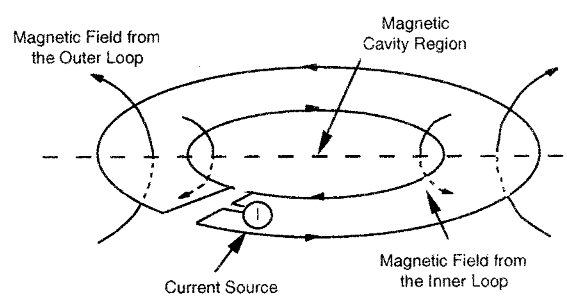

Fig. 2. Conceptual representation of creating a central magnetic cavity region using two concentric, circular loops that are electrically connected in an opposing polarity.

primary magnetic flux) at the center of the two coils. A magnetic cavity is defined as a region where a directional sensor, placed in a specified orientation, produces zero signal induced from the magnetic field. It has been shown [3], [8] that a magnetic cavity can be created at the center of two concentric circular current loops that are electrically connected in series into one circuit. The GEM-3s receiving coil is placed within this magnetic cavity so that it senses only the weak, secondary field returned from the earth and buried targets (Fig. 2) [3].

The GEM-3 is a transmitter-bucked sensor, and its concentric geometry is called a "monostatic" configuration because all coils are co-located [3]. The coils are molded into a single light circular disk in a fixed geometry, rendering a very portable package. The disk, along with a handle boom, is made of a Kevlar-skinned foam board. Attached to the other end of the boom is a removable electronic console (Fig. 1). The entire unit weighs about 4 kg.

For a frequency-domain operation, the GEM-3 prompts for a set of desired transmitter frequencies. Built-in software converts these frequencies into a digital "bit-stream," which is used to construct the desired transmitter waveform for a particular survey. This bit-stream represents the instruction on how to control a set of digital switches (called the H-bridge) connected across the transmitter coil, and it generates a complex waveform that contains all frequencies specified by the operator. This method of constructing an arbitrary waveform from a digital bit-stream is known as the pulse-width modulation (PWM) technique.

The base period of the bit-stream for GEM-3 is set to 1/30th of a second for areas having a 60-Hz power supply, as the U.S. does. The period is 1/25th of a second at 50-Hz areas, as in Europe and Japan. This sampling period minimizes the effect of ubiquitous powerline noise. The GEM-3 transmitter switches at a rate of 96 kHz and, therefore, the bit-stream contains 3200 steps within the 1/30-second base period. Any integral number of the base period may be used for a consecutive transmission in order to enhance the SNR [4].

IV. Theoretical and Experimental EMIS Data

To establish the validity of the GEM-3 frequency response, we measured the spectral response of many metal spheres and calibration targets such as circular coils with known electrical properties. Spheres are one of the few geometrical shapes for which rigorous analytic solutions are available [5], [10]–[15]. An EMI response is a complex quantity; its real part is called the "inphase" component while the imaginary part is called the "quadrature" component.

Fig. 3 shows a comparison between the computed (solid line) and observed (symbols) EMIS spectra consisting of the inphase and quadrature components, for a three-inch chrome sphere measured in air. The computed curve is derived as follows. The dipole moment m of a sphere of radius a placed in a uniform magnetic field H_0 is given by [5], [10]–[15]

$$m = -2\pi a^3 (X + iY) H_0 e^{i\omega t} \tag{1}$$

where $X + iY$, called "response function," can be shown as (2), shown at the bottom of the page, and

μ_0 permeability of free space ($4\pi \cdot 10^{-7}$ henry/m);
μ relative permeability of the sphere $= \mu_{\text{object}}/\mu_0$;
k^2 $i\omega\mu\sigma$;
σ sphere conductivity (S/m);
ω angular frequency.

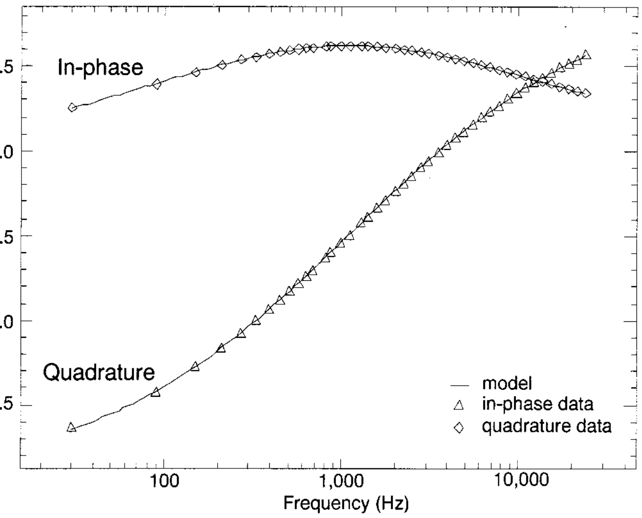

Fig. 3. GEM-3 data from a three-inch diameter chrome steel sphere compared to the sphere model (measured in air at a height of 37.3 cm).

This approximation is valid when the sphere is small so that the illuminating field may be considered uniform across the sphere. Equations (1) and (2) are used to compute the secondary magnetic field at the GEM-3 receiver coil, which is then normalized against the primary field to produce a dimensionless "ppm" unit defined as

$$\text{ppm} = 10^6 \cdot \frac{\textit{secondary magnetic field at receiver coil}}{\textit{primary magnetic field at receiver coil}}. \tag{3}$$

The ppm value is a complex number that obviously depends on the distance between the sensor and the sphere. However, the curve shape of Fig. 3 is independent of the distance and is determined by $X + iY$ of (2), where X generates the inphase (real) component, and Y generates the quadrature (imaginary) component. Therefore, the shapes of EMIS spectra of spheres are independent of the target-sensor distance. The comparison in Fig. 3 is mainly for the curve shapes because the conductivity and permeability of the sphere are those that produced the best fit ($\sigma = 510^5$ S/m, and $\mu = 210$ for this chrome sphere).

Because EMIS exploits an object's conductivity and permeability, we here briefly review such properties for common metals. The metals used in large quantities for equipment (tools, weapons, etc.), structural strength (beams, rebar, etc.), or packaging (cans, cases, etc.) typically contain some iron, aluminum, copper, nickel, or other elements. These metals mix in many ways to produce a plethora of metal alloys widely used for products from pots and pans to bomb casings. Table I shows the electrical conductivity of common metals, which ranges from about 1×10^6 S/m (nickel) to about 60×10^6 S/m (copper) [6]. Table I also shows the magnetic susceptibility for common nonferrous metals. The values are very small. Those with small positive values (e.g., aluminum) are called paramagnetic, while those with small negative values (e.g., copper) are called diamagnetic metals.

$$X + iY = \left\{ \frac{[\mu_0(1 + k^2a^2) + 2\mu\mu_0]\sinh(ka) - (2\mu\mu_0 + \mu_0)ka\cosh(ka)}{[\mu_0(1 + k^2a^2) - \mu\mu_0]\sinh(ka) + (\mu\mu_0 - \mu_0)ka\cosh(ka)} \right\} \tag{2}$$

TABLE I
ELECTRICAL CONDUCTIVITY AND MAGNETIC SUSCEPTIBILITY OF COMMON NONFERROUS METALS

	Electrical Conductivity ×10⁶ Siemen/m	*Magnetic Susceptibility ×10⁻⁶ (mks)*
Copper	58.82	-9.4
Brass	14.29	-
Aluminum	35.71	21.0
Monel	2.38	-
Lead	4.55	-17.0
Tin	8.70	31.0
Zinc	17.24	-11.4
Nickel	1.28	ferrous
Silver	62.50	-26.0
Gold	40.98	-34.0

TABLE II
ELECTRICAL CONDUCTIVITY AND MAGNETIC PERMEABILITY OF COMMON FERROUS METALS

	Electrical Conductivity $\times 10^6$ S/m	*Relative Magnetic Permeability @ B=20 Gauss*
Cold rolled steel	10.0	100
Iron	10.0	200
Purified iron	10.0	5,000
4% Silicon iron	1.7	500
45 Permalloy	2.2	2,500
78 Permalloy	6.3	8,000
4-79 Permalloy	1.8	20,000
2-81 Permalloy	0.0001	125
Supermalloy	1.7	100,000
Mu Metal	1.6	20,000
Hiperco	4.0	650
Hypernik	2.0	4,500
Monimax	1.3	2,000
Sinimax	1.1	3,000
Permendur	14.3	800
2V Permendur	3.8	800

Table II shows commonly used ferromagnetic metals along with their ranges in relative permeability and conductivity. In comparison to nonferrous metals (Table I), the metals in Table II show very high permeability ranging from 100s to 100 000s.

It can be shown that the inphase response of conductive-only metals (e.g., copper and aluminum) is always positive [X from (2) by letting $\mu = 1$], while ferrous metals ($\mu > 1$) exhibit negative inphase at low frequencies. This fact alone is a significant attribute for an object identification process.

The quantity ka in (2) is called "response parameter," which governs the response of a target under EMI excitation. From the ranges shown in Tables I and II along with the operating bandwidth of the GEM-3, we note that the response parameter spans several decades, which, in turn, provides potentially an ample breadth for target identification.

As noted in (1), conductivity and permeability values are required to calculate the theoretical response for a sphere. Although the conductivity and permeability values for the calibration chrome sphere are not available, we can estimate these explanatory variables (by minimizing the residual during the sphere fitting algorithm) and then compare the model parameters with published values. A comparison of the model parameters (conductivity and permeability) with published values for similar metals are shown in Fig. 4.

Conductivity:

Estimate for three-inch Sphere	1.82E6 S/m
Plain carbon steel (AISI-SAE 1020)	1.E7 S/m
Stainless steel type 304	1.39E6 S/m

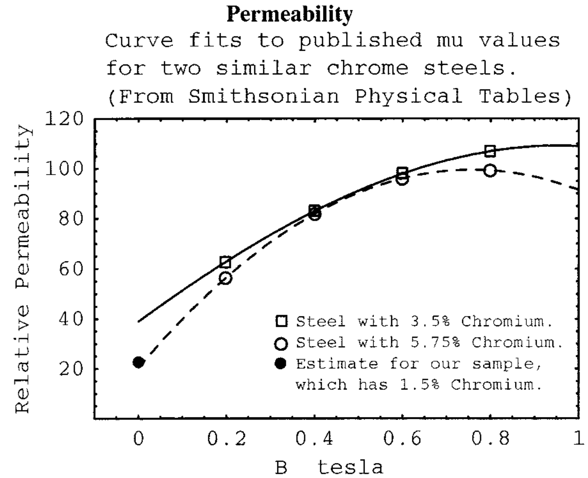

Fig. 4. Comparison between model fits of conductivity and permeability to published values for similar metals.

V. SPECTRAL RESPONSE OF LANDMINES

Fig. 5 shows the EMIS spectra (measured in air) for seven common landmines, along with their photographs. The amplitude unit in Fig. 5 is ppm defined by (3). Shown on the right is the commentary on the construction and detectability of each mine [7]. The EMIS spectra depend on the mine-sensor distance to a certain extent, but as stated before, their shapes remain relatively unchanged particularly for small sphere-like targets. Two mines in Fig. 5, M-14 and PMA-3, are common plastic mines that have very small metallic parts in their pressure activation mechanisms. As expected, the two plastic mines show the smallest amplitudes, less than 0.1 ppm. Yet Fig. 5 indicates that the metal parts are not only clearly detectable by the GEM-3 but also render specific EMIS spectra.

We note from Fig. 5 that the EMIS spectrum of each landmine is unique and clearly distinguishable from other landmines. At the same time, these spectra may be considered bland in the sense that they lack the sharp peaks in, say, a molecular absorption spectrum. To make up its blandness, the EMIS spectra contain 1) inphase and quadrature components, and 2) positive and negative polarities. Thus, the EMIS spectrum contains as many distinguishing attributes as do spectra with sharp peaks.

In addition to their general spectral shapes, some obvious EMIS attributes include 1) response amplitude, 2) peak frequency in quadrature, 3) zero-crossing frequency in inphase, 4) phase angle, i.e., the ratio between the two components, and 5) negative inphase at low frequencies for ferrous metals. We note from Fig. 5 that two mines, TS-50 and PMA-3, contain mostly nonferrous metals because of only positive inphase (the small negative inphase for TS-50 indicates a negligible amount of ferrous metals, if any), while others are made of mostly ferrous

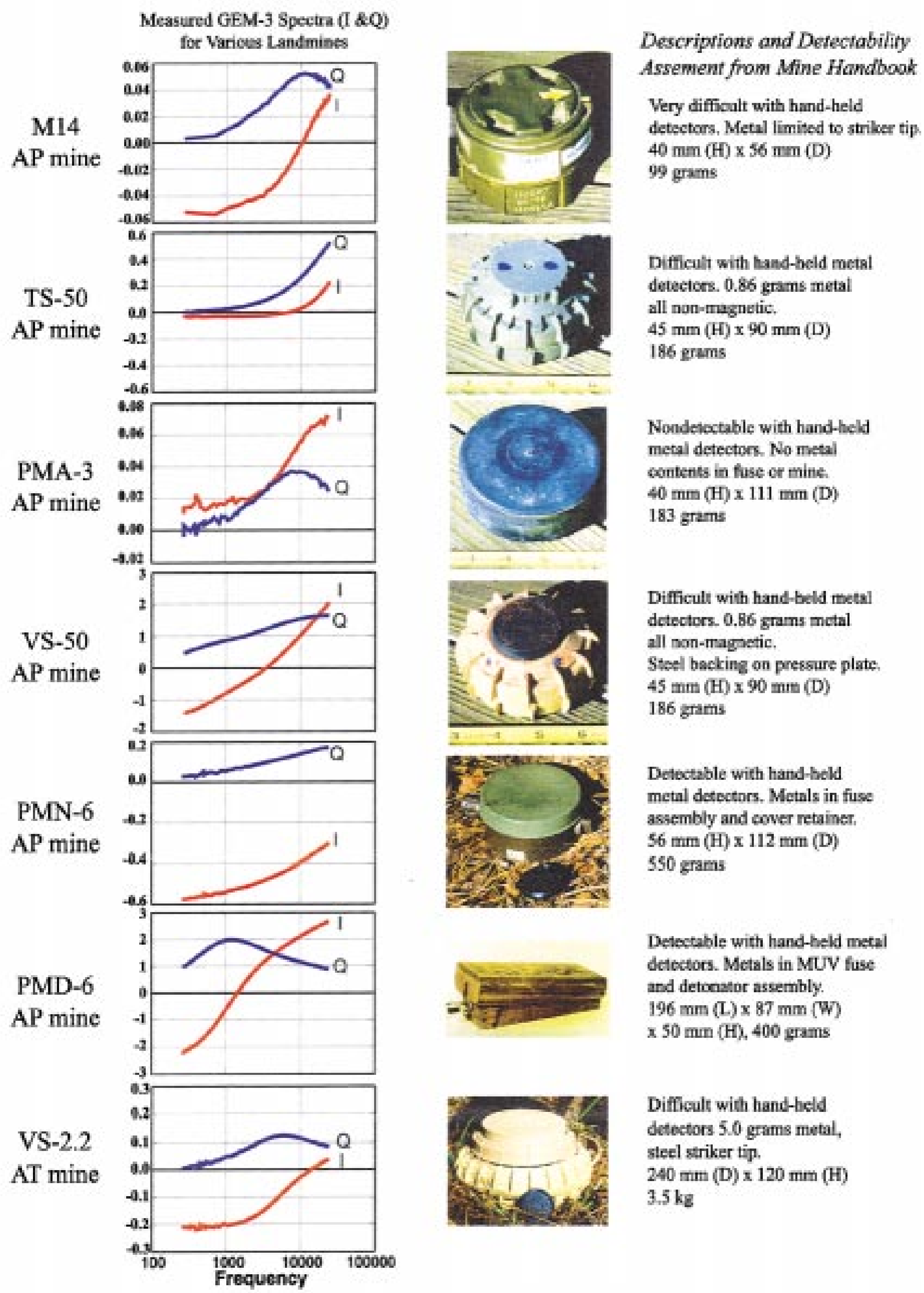

Fig. 5. EMIS spectra measured by the GEM-3 for various landmines, along with their photographs. Shown on the right is the commentary on the construction and detectability of each mine. The vertical axis has a ppm unit as defined in the text. M-14 and PMA-3 are common plastic mines that have very small metal parts, showing amplitudes less than 0.1 ppm. We note that each mine has a clearly detectable and distinct EMIS spectrum.

metals in various proportions. Also note that for three mines, TS-50, VS-50, and PMN-6, the spectra lack peaks in the quadrature, indicating that the GEM-3 bandwidth should be further broadened.

In order to show the method's target identification (or clutter elimination) potential, we compare in Fig. 6 the EMIS spectra of an M-14 landmine and several common clutter items. Again we note that each EMIS spectrum is unique, implying that we

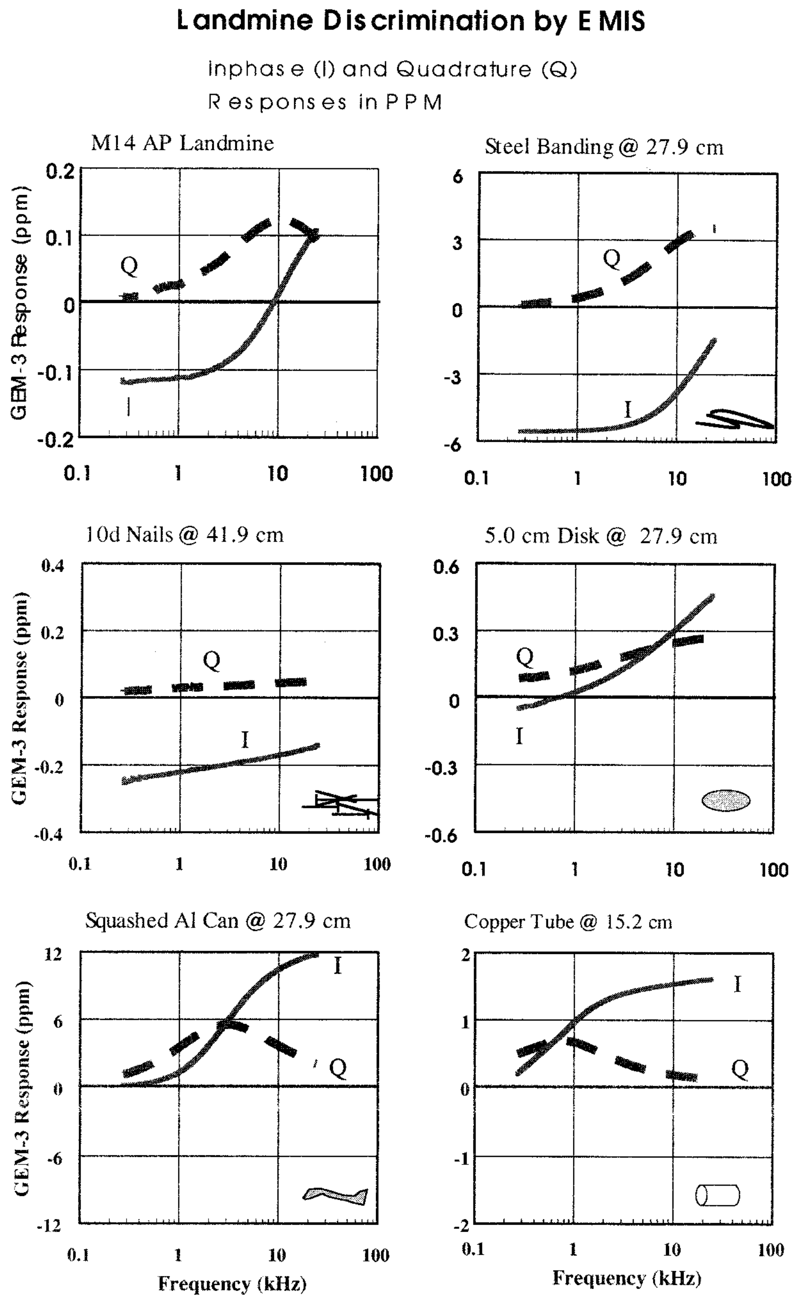

Fig. 6. EMIS spectra measured by the GEM-3 for an M-14 plastic landmine compared with various ordinary clutter items. We note that the EMIS spectrum of the M-14 is clearly distinguishable from the clutter and thus can greatly reduce the false alarm rate, which, in turn, would reduce the cost of clearing a minefield.

should be able to identify an individual object based on the EMIS response.

VI. Discussion

As shown in Figs. 3 and 4, the GEM-3 sensor is capable of accurately and reliably measuring the broadband EMI spectral response of small targets, including landmines. All data presented herein were acquired in air and therefore neglected the response of soil materials. Because certain soil types (such as magnetic rocks of laterite soils) may complicate the analysis of EMIS data for low-metal content mines, we chose to conduct controlled experiments in air to demonstrate the techniques potential. The effects of competing factors, including soil type and proximity to ancillary clutter, are an area of active research. These spectral data indicate that the landmines included in this analysis possess distinct spectral signatures when the competing factors are ignored.

As described above, a general approach for identifying specific landmines, as well as for discriminating between landmines and clutter, is to compare the sensor response to a library of signatures. This often includes a preprocessing step that fits the data to a model, from which estimates of the target orientation and depth can be derived. Once this is done, the target can be effectively rotated into a principal axis coordinate system and the spectral response in this system can be compared to the library responses. Another way to state this is that the eigenvalues of the magnetic polarizability tensor that models the target are derived from the data. These eigenvalues are orientation invariant and can be used as intrinsic target signatures [9]. In this paper, however, we examined the inphase and quadrature components for a fixed orientation. Future work will combine both the orientation and range invariant aspects of the problem into a single procedure.

VII. Future Deployment

In a simple scenario, consider an EMIS-based mine detector that has in its memory the spectral signatures of all known landmines. The detection phase can be accomplished using a few discrete frequencies that are chosen to be optimal for a given geologic and cultural environment. Once a target is suspected, we start the identification phase that involves recording the target's spectral response. The measured spectrum may be scanned through the signature memory in order to identify a particular landmine or, if no match is found, to reject the target as clutter. A given minefield would likely contain only one or, at most, a few types of mines, which would considerably simplify the identification process.

Experiments have shown that the EMIS spectrum of a spherical target (or one that, owing to its aspect ratio, can be approximated as such) in the far field is independent of the sensor view angle (the far field of a circular coil is at a distance further than five times the coil radius, where the coil can be approximated as a dipole to better than 99%). Under this condition, the dependence on distance is quite predictable: the spectral amplitudes change, but their shapes do not. Commonly, landmines are cylindrically symmetric and laid flat for vertical pressure activation. Since the GEM-3 also has a cylindrical symmetry, the mutual view is fixed when the sensor is directly above the mine.

In general, however, the EMIS spectrum is dependent on the target's view from the sensor, just as a person may look different from different angles. This view-dependency of the EMIS spectrum is a serious drawback since it requires storing an infinite number of views of a target in order to match an observed EMIS spectrum of a hidden target with an unknown view.

Theoretically speaking, however, if we have at least three orthogonal views of an object, we then have a "complete" view. Thus, the object can be identified. For instance, if an object's EMIS spectra are recorded from three principal views (e.g., one top view and two side views), it can be identified from any angle through a coordinate rotation. For a buried object, however, we do not know how much to rotate to match the stored views. This is one of the subjects that need a concentrated effort to advance EMIS technology to its full potential.

Theoretical and experimental work to date suggests that these potentials are well worth pursuing. For the past years, we have conducted field tests of EMIS-based sensors under a variety of conditions with extremely promising results. We hope that increased knowledge of EMIS will lead to development of second and third generation EMIS-based sensors that can address current and future landmine detection challenges throughout the world.

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