Resolving Power of Some Geophysical Methods as Applied to Detecting Buried Unexploded Ordnance

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ABSTRACT

Various geophysical sensors are employed for the purpose of detecting and clearing unexploded ordnance (UXO) items buried in the battlefield including inland, beachhead, surf-zone, and the ocean. Similar sensors are also used for environmental investigation of ordnance and explosive waste (OEW) sites including bombing ranges, target practice areas, and explosive manufacturing facilities, as well as nuclear, biological, and chemical (NBC) waste sites. One of the most important issues is the concept of "standoff" detection so that the survey crew and their equipment are reasonably safe from accidentally setting off buried explosives or contacting hazardous materials.

Despite the long history of geophysical sensors used at UXO sites, there exists a knowledge gap between geophysicists and the end-users in understanding the applicability and limitations of the geophysical tools. I attempt in this article a heuristic review of classical geophysical methods from a perspective of their usefulness for standoff, non-intrusive target detection.

The most routinely used UXO sensors are magnetometers and metal detectors. A magnetometer is a passive sensor that measures the geomagnetic distortion caused by a nearby ferrous target. A metal detector actively broadcasts an electromagnetic field and receives the secondary field induced by conductive targets. Barring unforeseen developments, I advocate in this article that magnetic and electromagnetic methods are, and will be, perhaps the only acceptable and effective tools in the near future for detecting buried UXOs.

A discussion follows on the resolving power of the magnetic and electromagnetic methods in terms of UXO sizes and standoff distances. This quantitative discussion provides a theoretical basis for determining whether a given survey platform and a specified modus operandi would detect and resolve a specific, buried UXO at a stipulated standoff distance. The relationship between the standoff distance and the required resolution also governs whether survey platforms may be ground-based or airborne.

Overview of Various Geophysical Methods for the UXO Survey

Established geophysical techniques having potential applications to the UXO detection include magnetic, electromagnetic, electrical, seismic, and ground-penetrating radar (GPR) methods. General advantages of geophysical methods for the UXO problem, if applicable, are obvious:

- Minimal intrusion: thus, inherently safe for the survey personnel during the initial phases of a site characterization process;
- Synoptic description of a site: owing to rapid coverage over a large area, the method can pinpoint, by eliminating portions of the site, locations for further studies (e.g., boring and trenching); geophysical methods can be used for both reconnaissance and delineation phases;
- Large search radius: because most geophysical sensors have finite "footprints" or search swaths, they have less chance of "missing" the target by a short distance, which is common to boring and trenching; and
- Cost effectiveness: the methods provide relatively high returns on the amount of information versus cost incurred; nor do they require costly decontamination process common to drilling and trenching.

For the UXO problem, selection of geophysical methods must be based on (1) acceptable degree of intrusiveness of the survey methodology (some methods are more intrusive than others); (2) likely degree of success for detecting specific targets (some methods are not applicable for certain targets); and (3) desired spatial resolution of the survey results. I will first discuss why some geophysical methods, in my opinion, would not be suitable for the UXO problem.

Seismic and electrical methods require intrusive surveys that involve planting geophones or electrodes as well as inducing mechanical impacts or electrical currents into the earth, which may be considered dangerous for certain UXOs. From theoretical viewpoints, these methods are not capable of detecting a small object; "small" in the sense that its dimension is much shorter than the wavelength of the imping-

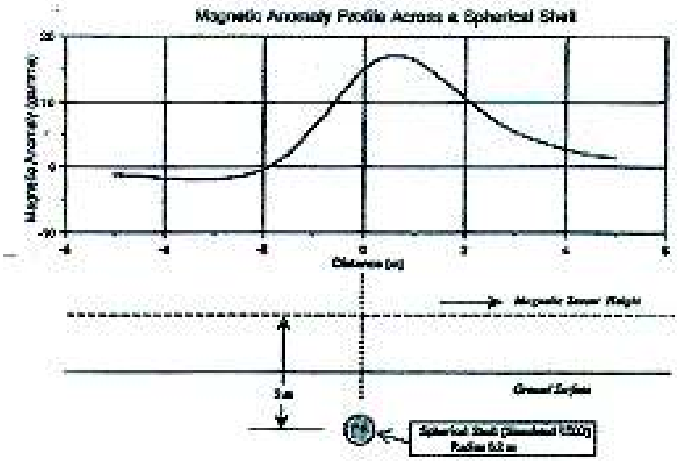

Figure 1. Theoretical magnetic anomaly profile across a small spherical shell.

ing field. If multiple (preferably uncased) boreholes are available at a site (i.e., serious intrusive activities have already occurred), seismic and electrical methods may be used as single-hole logging or cross-hole tomographic tools.

GPR is often promoted as a "panacea" geophysical tool. Based on years of field surveys under a variety of cultural and geologic conditions, however, I consider that the ability of GPR to detect buried objects is rather overrated. This is partially due to the unfortunate fact that most GPR profiles shown in published articles present only the successful ones, leaving many failed ones untold and unseen. Those successful ones render the uninformed an overexpectation toward the method, as well as the illusion that such resolutions can be routinely achieved.

There are some fundamental drawbacks in GPR: (1) the ability of an electromagnetic pulse emitted by a GPR to penetrate into a geologic medium is severely limited by the medium's electrical conductivity (causing rapid attenuation with depth); (2) typical shallow earth hosting a target object is invariably heterogeneous (boulders, irregular soil texture and moisture content, etc.) and, thus, generates numerous false images and misinterpreted targets; and (3) GPR has a very narrow vision, particularly for shallow targets, and requires dense survey coverage. These drawbacks, which are highly site-dependent and thus often unpredictable, make GPR one of the most finicky geophysical sensors. GPR is also "mildly intrusive" for the UXO search since the sensor must be in contact with the earth (an airborne GPR is yet to be demonstrated for UXOs). It also requires preparing smooth survey paths (ground bumps cause false targets) of a few feet in width, often involving clearing vegetation and leveling the ground.

GPR can be, however, an excellent tool during the final stage of a UXO survey when the search area has been reduced to an absolute minimum. In practice, GPR works in favorable geologic conditions only when a target is well understood in advance in terms of its physical properties and approximate geometry.

There are other methods that conceivably can be used for detecting UXOs, such as a chemical analyzer for vapors that may emanate from buried munition residues. Examples also include infrared (IR) or other near-optical band sensors that can be applicable to freshly buried UXOs over an arid or unvegetated area; however, these are traditionally referred to as "remote-sensing" methods (in contrast to geophysical methods) and not considered in this report.

Having reviewed various geophysical methods in terms of their theoretical and practical applicabilities to the UXO detection, I now explain why the remaining two geophysical methods, viz., magnetic and electromagnetic methods, could be the most promising techniques. I advocate the use of these methods particularly during the early site characterization stage. Some of the prominent advantages of the two methods include:

- Nonintrusiveness: no hardware contact with ground thus minimal safety concerns and no decontamination requirement;
- Convenient survey modes: either initial airborne survey (to avoid explosion hazard to survey personnel) or high resolution ground survey;
- Light logistics and simple survey operation; and
- Data integrity: high quality data can be obtained by technician-level survey personnel.

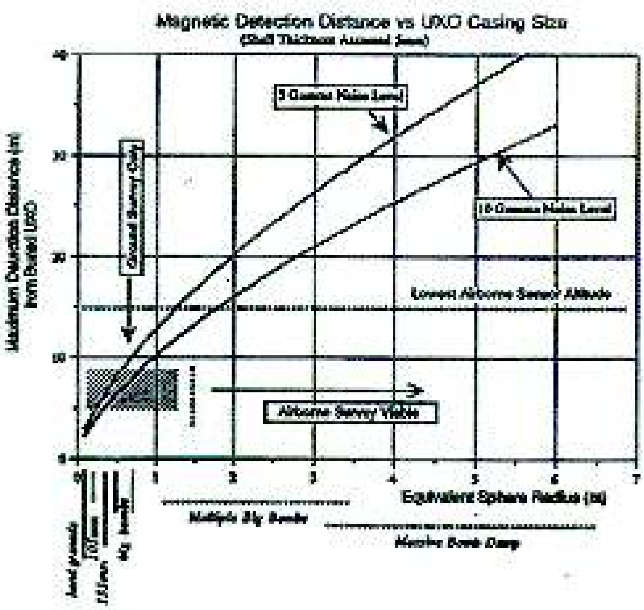

Figure 2. Theoretically computed, magnetic detection distance as a function of the UXO size.

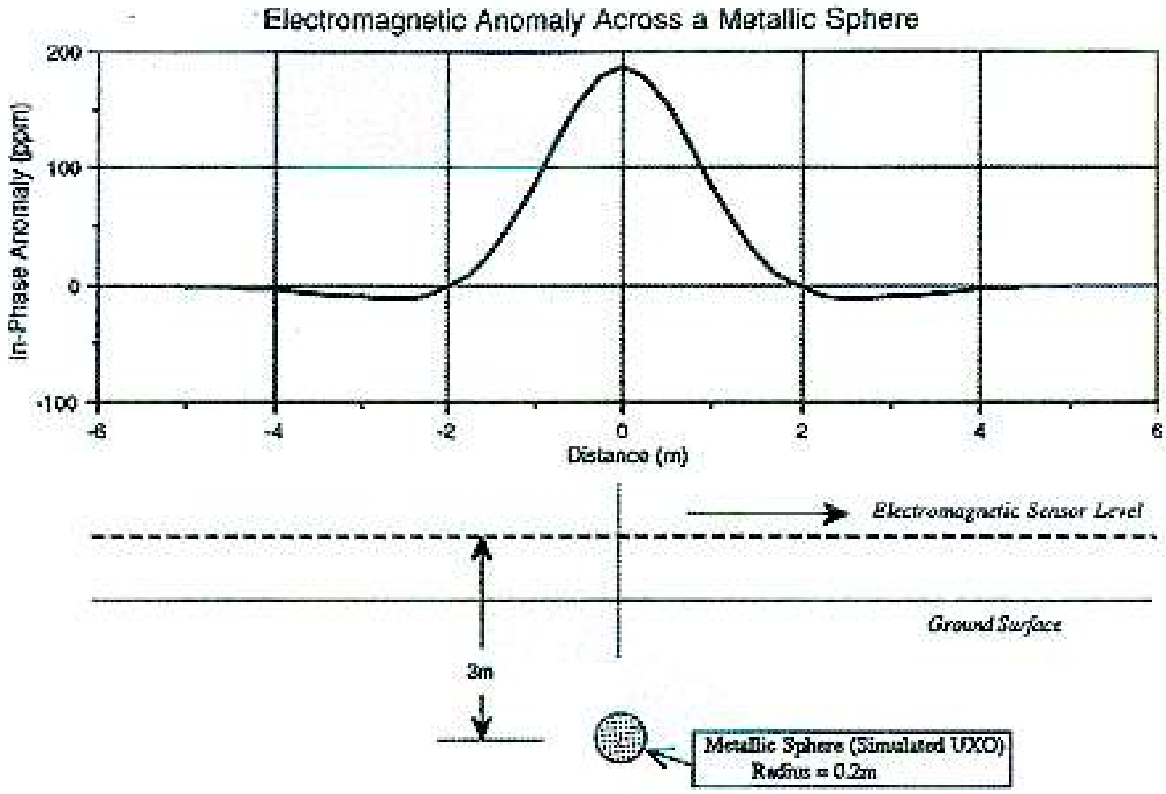

Figure 3. Theoretical electromagnetic anomaly profile across a small sphere.

The last item refers to the fact that, owing to the well-founded physical principles and hardware, magnetic and electromagnetic measurements are relatively simple to obtain and their data are "honest" and not finicky as some other data (e.g., seismic and GPR require highly skilled surveyors to adjust numerous knobs on the instrument panel.). By the same token, processing and interpretation of magnetic and electromagnetic data tend to be intuitive and less operator-dependent compared with some other methods.

Resolution of Magnetic and Electromagnetic Methods for UXO Survey

Having advocated the magnetic and electromagnetic methods as the most applicable geophysical tools, I now consider the theoretically achievable resolution of the methods, specifically for UXOs. Such theoretical sensitivity analyses are indeed possible and very necessary in order to (1) set theoretical operating parameters and thus prevent false hopes and (2) focus efforts on the most likely successful approaches instead of the common "let-us-try-and-see-if-it-works" attitude of some project managers who may not have a rigorous geophysics background and experience.

The physics of magnetic and electromagnetic methods is one of the best understood sciences and, therefore, the mathematical reasoning alone can predict and thus determine their resolving power for a particular UXO of a given size and geometry buried at a given depth. Specific questions to be answered through such an analysis may include:

- Given instrument resolution and typical background noise (cultural or geologic), what is the maximum distance at which the sensor can detect the presence of a specific UXO?
- What is the minimum survey line density to assure the detection of a specific UXO of given size and burial depth? and,
- Under what conditions does an airborne survey become a viable option?

We cannot answer these questions in generalized terms since UXOs come in various sizes and shapes and in different materials. Not having specified any particular UXO, I adopt in this discussion a simple UXO model that is represented by a spherical shell of a specified radius and a shell (casing) thickness. A typical oblong UXO can be modeled as an "equivalent" spherical shell whose diameter is somewhere between the short and long dimensions of the UXO. The approximation is particularly good when the aspect ratio between the two dimensions is small. [I emphasize that a rigorous theoretical modeling is possible for many simple

UXO shapes (e.g., a circular cylindrical shell) for specified geometry and burial attitudes.] I also assume that the content within the shell is neither magnetic nor electrically conductive. In other words, the shell is considered empty in this presentation, although the shell contents, whether chemical compounds or detonators, would likely enhance detection.

Resolution of Magnetic Method for UXO Survey

As an example, fig. 1 shows a theoretically computed magnetic anomaly profile across a spherical shell having a radius of 20 cm and a shell thickness of 1 cm. Magnetic properties of soil or geologic overburden can be ignored in most UXO burial sites and are not considered in the computation: soils, overburden, and most sedimentary rocks are known to be nonmagnetic.

This example shows the total field anomaly profile along a north-south survey line (thick-dashed line in the lower half of the fig.) that is placed at 3 m directly above the single UXO. For this computation, I assumed an ambient earth field of 53,000 gamma with a geomagnetic inclination of 67 degrees, typical in the North Carolina region. The earth magnetic field ranges from about 30,000 gamma at the equator (with a zero-degree inclination) to about 60,000 gamma at the poles (with a 90-degree inclination).

Notice that the anomaly is about 20 gamma in amplitude and spreads over a distance of about 6 m, twice the depth of the UXO. This spread, or "footprint," helps reduce the survey line density, by enabling the surveyor to see a large area centered along the survey line. The footprint, at the same time, can be considered to reduce the spatial resolution since the anomaly covers an area much larger than the target. In practice, the line density problem is more important in the survey design since the spatial resolution can be enhanced by proper data interpretation and possibly other follow-up surveys (e.g., GPR).

Typical resolution of a portable ground survey magnetometer is 1 gamma, while that of airborne magnetometers can be higher by an order of magnitude or two. Compared with the ambient earth field, the instrument resolution is, therefore, in the range of 0.1 to 10 parts-per-million (ppm). Unfortunately, however, it is the cultural noise (nearby buildings, powerlines, etc.), rather than the hardware resolution, that would limit the achievable survey resolution in typical UXO environments.

In fig. 2, I attempt to show the theoretical detection limit of the magnetic method for various UXO targets. The graph shows the maximum detection distance as a function of the radii of the "equivalent" sphere representing UXOs. In all cases, the UXO is assumed to have a casing thickness of 1 cm. Since the detection limit depends obviously on the ambient magnetic noise level, I present two arbitrarily assumed (yet realistic, based on our survey experience) noise levels of 5 gamma and 10 gamma.

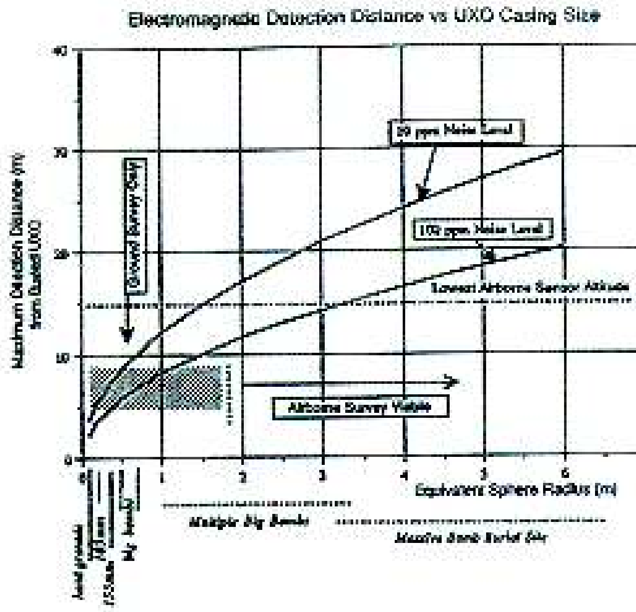

Figure 4. Theoretically computed, electromagnetic detection distance as a function of the UXO size.

Notice in fig. 2 that no individually isolated UXOs, even the biggest ones, can be detected unless the magnetic sensor is within a distance of 10 m or less from the target. For a helicopter-towed magnetometer, our experience suggests that the lowest safe and stable sensor altitude, even over flat terrain, cannot be less than about 15 m (about 50 feet) above ground level (AGL). This minimum AGL sensor altitude is shown in fig. 2 as a thick dotted line. At this survey altitude fig. 2 shows the smallest detectable target is about 1.5 m in radius or about 10 feet in diameter. It is obvious, therefore, that even the largest of UXOs, if buried in an isolation, cannot be detected by an airborne sensor.

On the other hand, fig. 2 demonstrates that all isolated UXOs can be detected if the sensor is sufficiently close to the target. Most single UXOs produce enough magnetic anomaly to be detected within a distance of 2 to 10 m, depending on their size. Since the footprint of these anomalies is approximately twice the distance between the sensor and target, the ground survey lines may be 4 to 20 m apart, depending on the size of UXOs under search. Simply speaking, a typical square grid of 10 feet (or preferably 5 feet over anomalous areas) should be sufficient to locate most UXOs. As fig. 2 indicates, only massive and multiple UXO burial sites can be detected by an airborne survey.

Resolution of Electromagnetic Method for UXO Survey

Figure 3 shows a theoretically computed, electromagnetic anomaly profile across the same sphere discussed in the previous section. The anomaly is likewise computed at a distance of 3 m directly above the target. Unlike the magnetic method where the anomaly is caused by the ambient earth field, the electromagnetic method (applicable to the UXO problem) actively transmits its own field, induces a secondary current flow in a conductive target, and measures the secondary electromagnetic field seen at the receiver location. The received field, consisting of inphase and quadrature components, is then compared with the transmitted field. The ratio between the transmitted field and the anomalous portion of the received field is commonly expressed in parts per million (ppm) or, for some commercially available units, is converted into an "equivalent half-space conductivity" in the unit of Siemen/m. The ppm unit is commonly used in airborne survey, and is not absolute, but hardware-dependent.

Achievable electromagnetic resolution is similar to that of a magnetometer, i.e., a range of 0.1 ppm to 10 ppm. For instance, Geophex's Airborne Electromagnetic System (Geophex AEM-1) has a resolution of about 0.1 ppm within a frequency range of about 300 Hz to 20 kHz. A handheld version (Geophex GEM-2) currently has a resolution of about 10 ppm.

Figure 4 shows the theoretical detection limit of the electromagnetic method for various UXO targets. The ppm anomaly shown in this graph is based on the transmitter-receiver geometry adopted for Geophex's GEM-1. The graph shows the maximum detection distance as a function of the radii of the "equivalent" sphere representing UXOs. As is the case for the magnetic method, the detection limit depends on the ambient electromagnetic noise level. We present two arbitrarily assumed (yet realistic, based on our survey experience) noise levels of 10 ppm and 100 ppm (the upper end possibly being overly conservative).

Conclusions derived from fig. 4 are similar to those from fig. 2 for the magnetic method. No individually isolated UXOs, even for the biggest ones, can be detected unless the electromagnetic sensor is within a distance of 10 m or less from the target. Similarly, all isolated UXOs can be detected if the sensor is sufficiently close to the target, while only massive and multiple UXO burial sites can be viable targets for an airborne survey.

Conclusions

Summarizing this short discourse, I present the following conclusions:

- Magnetic and electromagnetic methods are the most acceptable geophysical tools for an initial UXO survey;
- The methods are theoretically well-understood, predictable, and modelable; produce dependable data quality with technician-level field personnel; are least-intrusive; and are logistically convenient;
- The methods are applicable to either ground or airborne surveys;
- Single UXOs can be detected only by ground survey at a line spacing of 10 feet or less; and
- Only massive and multiple UXO burial sites can be detected by the airborne survey.

There is no single panacea geophysical method that can solve the problem of detecting buried UXOs. It is fundamentally difficult to detect a small, buried object. Some combination of different geophysical methods would work if the survey is well designed and correctly implemented. I advocate in this report a combination of magnetic and electromagnetic methods. Although they are not perfect, these are the best diagnostic tools we have, and a far more intelligent approach than mindless and dangerous drilling and trenching.