

2.4 The Environment

2.4.1 Response from the natural environment

This book's consideration of magnetic responses is generally cast in terms of magnetic permeability and *magnetic susceptibility* χ . Those quantities are related by the expressions

$$\mu = \mu_r \mu_0 = (1 + \chi) \mu_0. \quad (2.45)$$

Both μ_r and χ indicate the extent to which the magnetic permeability of a medium differs from that of free space. Both quantities are dimensionless. Hereafter, the terms “permeability” and “susceptibility” refer implicitly to *magnetic* permeability and susceptibility.

Previous sections discussed the kinds of magnetic responses that may be produced by permeable bodies, e.g., spheres. Because targets of interest often exhibit such high μ_r values relative to materials in the environment, their responses tend to be treated as if they resided in a magnetically inert background. However, soil and rock may have non-zero susceptibilities, as well. Although their susceptibilities may be rather small compared to ferrous steel, a much greater volume of ground is perceived by a sensor than is occupied by the target. The sensor may also be much closer to the responsive ground; thus the ground response may still be significant. In some locales (particularly volcanic settings), the ground response may be relatively strong and can complicate EMI surveying. While important, the most difficult such sites only comprise a small minority of UXO cleanup terrains. That said, significant magnetic ground responses have appeared erratically at sites where it was not expected.¹²

Natural magnetic material in the ground may produce magnetic responses in a number of modes: permanent, remanent magnetism is locked in during the formation of mineral deposits and primarily affects DC magnetometer surveying. The ground also produces signals associated with induced magnetism when ground materials are present with $\mu_r > 1$ and a primary field is applied. This response can be further subdivided into

- cases in which a constant valued response is effectively instantaneous relative to the applied field, and
- those exhibiting viscous permeability, not responding instantly to magnetic stimulus but showing a reaction that evolves according to relaxation mechanisms.

For TD or FD MQS surveying, static permanent remanent magnetism is excluded from consideration because its DC presence is effectively filtered out. Beyond this, the simplest case is that of semi-infinite uniform ground with constant (non-viscous) permeability. From a mathematical physics standpoint in the FD, with the instrument's co-located Tx and Rx units residing in the air above, this is a classical, static halfspace potential problem. Imaging

techniques¹³ show that the secondary field from the ground will be like that from an image of the sensor in the lower halfspace; the image is located at a depth below the surface that is equal to the sensor elevation above the surface. The image and its effects are *not* to be confused with a reflection, in the wave sense. Similarly, although the fundamental boundary conditions [Eq. (1.25)] imply some discontinuity in the slope of field lines across the ground surface, this is not refraction in the wave sense. Investigations have shown that, for reasonable magnetic ground parameters, it should not be necessary to compensate for this bending effect when computing the target response. That is, the bending of excitation and response field lines and changes in magnitude are of such a magnitude that one may compute the secondary field as per usual, as if both the sensor and buried object reside in the same free space. One may simply superpose ground and target responses.

From a practical standpoint, if one only needed to deal with agreeable halfspaces that were uniform more or less on the scale of the signal anomalies, then things would be relatively easy. It should be possible to record the ground response nearby and subtract it from readings at the location of interest, perhaps using the mathematical (image) formulation mentioned above to compensate for changes in sensor elevation and tilt. However, knowing the precise sensor elevation and tilt and performing this compensation is often difficult. Furthermore, the greatest difficulty may result from non-uniformities in the ground, both in elevation, local slope, and in spatial distribution of permeable material. There may be isolated permeable lumps, rocks, or soil deposits, as well as rough ground surface features that pass much closer to the sensor than the larger background surface. This may make it difficult to obtain a uniform or reliable background for subtraction. Very local distortions can be smoothed somewhat at the cost of some loss in either signal strength or resolution by maintaining the sensor at a greater elevation or by smoothing the record along the survey. In principle, upward continuation of relatively strong signals from a lower elevation can project what would be obtained at a higher elevation. The lower-elevation data and resolution requirements for doing so may be daunting, however.

Ground variability aside, the physically simplest case occurs when the ground permeability may be regarded as a constant, invariant with frequency and instantly responsive in time. In the FD, this scenario contributes a constant offset to the real, in-phase component of the signal, as illustrated in Fig. 2.20. In this case, measurements were made on a target in air and then in the soil in a particular outdoor test plot. While other test plots with alternative soils showed no notable magnetic soil response, the one chosen for the figure did. Like the others, this plot contained only native NH soil that was not expected to exhibit any peculiarly enhanced magnetic effects.

For the case in Fig. 2.20, the impinging primary field elicits a soil response, as if in a magnetostatic problem, in proportion to the magnitude of

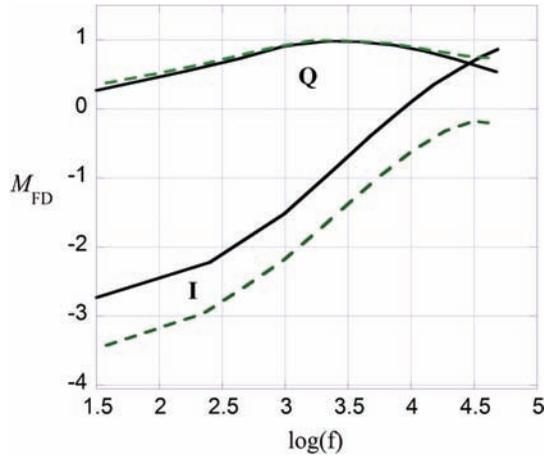


Figure 2.20 Comparison of normalized, measured FD response $M_{FD} = I + iQ$ of a steel sphere. The solid lines indicate a sphere in air, and the dashed lines indicate a sphere buried in soil.

the primary field and following it instantaneously. That is, the soil response simply contributes an approximately constant shift in the real part of the total response. One can either attempt to estimate this offset or ignore the in-phase component altogether and focus analysis entirely on the quadrature component, which depends only on induced electric currents in the target.

EMI surveying of this kind of ground permeability becomes simpler in the TD, where signals are typically only recorded after the Tx has been shut off to register the trailing response of a metallic target. If the ground responds instantaneously, then no response should be evident during the Tx off time. However, the ground may also respond via a viscous magnetic relaxation, which would be evident in the FD as an additional relaxation mixed with that from a target. Thus, one would assume that any relaxation effects in the FD case shown in Fig. 2.20 are simply overshadowed by the magnitude of the instantaneous response, together with obscuration due to measurement imprecision (background distortion). This need not be the case, however. Absent the instantaneous response, TD measurements from a field site (Fig. 2.21) isolate the ground relaxation response distinctly, if noisily.

Modeling the ground response may allow one to estimate its magnitude and shape, thereby better account for it as a signal component. Rigorous formulations and parameter values specifically for the relaxation effect in environmental materials are lacking. Investigators have suggested classical relaxation function forms, containing relaxation time parameters that must somehow be estimated. As established earlier, functions in the FD of the form

$$\chi(\omega) \frac{\tilde{I}}{1 + i\omega\tau} \quad (2.46)$$

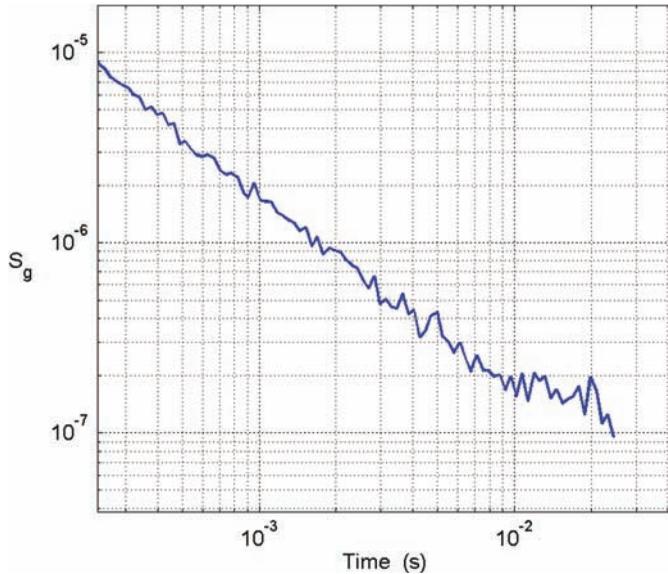


Figure 2.21 TD ground response S_g (arbitrary units) versus time, from a field site at the former Camp Beale, showing $1/t$ behavior (courtesy of F. Shubitidze).

correspond to a simple relaxation, that is, to exponential decay through time (here with time constant τ). In a complex material such as soil, with mixtures of materials and grain sizes, some distribution $F(\tau)$ of relaxation times should be expected. Thus, speculatively,

$$\chi(\omega) = \int_0^{\infty} d\tau \frac{F(\tau)}{1 + i\omega\tau}. \quad (2.47)$$

A number of distribution forms recommend themselves, such as log-uniform, log-normal, or Cole-Cole. In practice, it may not matter very much which form is chosen. In practical applications over data for some sizeable expanse of terrain, it is highly unlikely that one will possess *a priori* the values of specific parameters that define or specialize these distributions. Rather, one must assume that some broad range of possible relaxation times is possible and then adjust parameters as indicated by the data. The alternative distributions can usually be made to yield similar results in shape and value, if not in mathematical form. Even a modest smattering of chosen relaxation times can spread the relaxation effect rather widely and smoothly over the response spectrum.

Investigators have assumed log-uniform distributions between very widely spaced lower and upper relaxation times τ_1 and τ_2 limits, and have then adjusted parameters in response to data. When calibrated, this method has produced quite good matches against measured values of χ at UXO cleanup sites with strongly magnetic ground. Applying the model and

introducing various simplifying approximations suggests a signal of the form $S \sim 1/t$ for a loop sensor over a halfspace. This relation has held up under observations at a number of sites (e.g., Fig. 2.21), contrasting with the $t^{-5/2}$ dependency that would be expected if the decay were due to induced ground currents (see Part B of Kaufman¹). It has been suggested that FD inversions for target properties can benefit if viscous soil susceptibility models are enlisted for background estimation, relative to ad hoc estimation of background from peripheral measurements.^{14,15} Also, in principle, instruments may be calibrated to enable direct estimation of μ_r from signals,¹⁶ but this may not always be practical or helpful.

This is an area in which work remains to be done. Although very strong magnetic ground effects are relatively rare at known UXO sites, they are hardly unknown. A very notable case is that of Kaho'olave, a smaller island off the coast of Maui in Hawai'i, where UXO has been and continues to be a challenge.¹⁷

2.4.2 Metallic clutter

Metallic clutter presents an enormous problem in the sensing of subsurface UXO. Experience indicates that at many sites there may only be a few TOIs relative to perhaps thousands of signal anomalies, whether from scraps of practice targets or fragments of exploded munitions (see Fig. 1.1). Miscellaneous anthropogenic clutter may contribute as well—horseshoes, wrenches, bailing wire, etc. It is probably fair to say that, overall, UXO discrimination capabilities are clutter-limited. The careful digging of false alarms, usually due to such clutter, causes by far the greatest field expense in UXO cleanup projects.

There is little that can be done to eliminate clutter signals from consideration *a priori*. To some extent, common sense and site-specific knowledge are useful. For example, during early screening of data, a relatively strong signal might be observed that is confined to a very small ground area, i.e., within a very narrow spatial peak. This scenario likely indicates the presence of a small, shallow item. If reliable records indicate that only sizeable ordnance were employed at the site, then such an anomaly might be eliminated at the outset. On the whole, however, deeper analysis is needed to eliminate clutter items from the dig list. From a discrimination point of view, it is fortunate when distinctive types of clutter produce recurrent, identifiable signal forms. For example, tail fins that have broken off a particular type of ordnance that was commonly used at a site may have a distinctive signature; however, the sheer variety of clutter and its associated signals make specific classification problematical. This issue has spawned a substantial array of strategies, as outlined in Chapter 8, that attempt to identify distinctive UXO signatures while relegating most clutter signals to the category of “other.”

Some characteristics of clutter may make it particularly troublesome but simultaneously recommend particular maneuvers to ameliorate its difficulty.