Development and applications of geometric-sounding electromagnetic (EM) systems

Richard S. Taylor, Dualem Inc.

Introduction

The earliest practitioners of geophysical EM varied the transmitter-receiver geometry to change the portion of the earth sampled by their systems. The first practitioner to define the sampling volume of a system was Doll (1949), with the introduction of the induction logger.

Geometric-sounding EM (G-SEM) systems, such as the induction logger, remain unique among geophysical EM systems for the constancy of their sampling volumes and the ease of interpretation of their measurements.

Following theoretical development by Wait (1962), Howell (1966) constructed a G-SEM instrument for use at the surface. Further development by McNeill (1980) facilitated the adoption of G-SEM systems for a variety of near-surface applications.

An enhanced G-SEM system, which simultaneously samples two volumes-of-earth, is presented herein, along with a classification of G-SEM applications.

Surface G-SEM Instruments

In contrast to systems for which the sampling volume is related to operating frequency or time-interval of measurement, the separation and orientation of the transmitter and receiver determine the sampling volume of G-SEM systems.

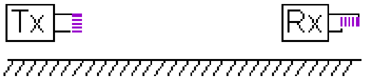
For efficiency of operation, G-SEM instruments transmit a time-varying sinusoidal magnetic field. The sampling volume remains solely dependent on geometry as long as the frequency of the field is consistent with the low-frequency-approximation, as defined by Wait (ibid.):

$$\left|(i\sigma_0\mu\omega)^{1/2}\rho\right| \leq 1/2$$

where i is the square-root of –1, s_0 is the conductivity and m is the permeability, respectively, of the material in the volume-of-exploration, w is the angular frequency of the transmitted field, and r is the spacing between the transmitter and receiver.

Wait (ibid.) analyzed the response of a perpendicular system, i.e. where the windings of a transmitting coil are horizontal, and the windings of a receiving coil are vertical and perpendicular to the location of the transmitter. Figure 1 is a schematic profile of a perpendicular system over the earth.

Figure 1: Perpendicular system.



For instruments used above the surface, the cumulative response of the earth to a given depth is convenient both as a measure of the sampling volume and as a guide to interpretation. After Wait (ibid., 1982), the cumulative response of the perpendicular system, in relative terms, is:

$$r_{cp} = 2h/\left(4h^2+1\right)^{1/2}$$

where h is the depth in the earth, in units of the separation between the transmitter and receiver.

Howell's (ibid.) instrument incorporated a perpendicular system but, due in part to design tolerances, this system became much less popular than the horizontal co-planar system, in which the windings of the transmitter and receiver are horizontal and co-planar.

Figure 2: Horizontal co-planar system.

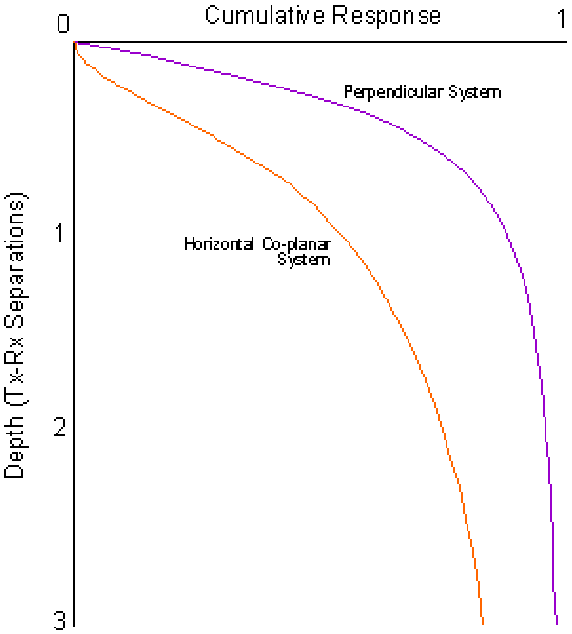
Figure 2 is a schematic profile of the horizontal co-planar system; its cumulative response (after McNeill (ibid.)), in the terms used previously, is:

$$r_{ch} = 1 - 1/\left(4h^2+1\right)^{1/2}$$

The cumulative responses for the perpendicular system and horizontal co-planar system are plotted in Figure 3.

A depth-of-exploration (DOE), beyond which a system has little sensitivity, may be inferred from its cumulative response. McNeill (ibid.) has proposed 1.5 transmitter-receiver separations as the DOE for the horizontal co-planar system, and this value has become widely accepted. A corresponding DOE for the perpendicular system is 0.6 separations.

Figure 3: Accumulation of response with depth.



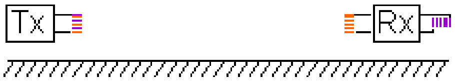
Enhanced G-SEM System

Users of G-SEM frequently need more than a single DOE to assess the subsurface feature-of-interest. A common technique to address this need is to rotate a horizontal co-planar system about its axis-of-separation to orient its coils vertically. After McNeill (ibid.), the DOE of this vertical configuration is 0.75 separations.

G-SEM instruments require no contact with the ground. This enables G-SEM surveys to be conducted continuously at walking speed. To obtain dual depths-of-exploration with a horizontal co-planar system, however, requires halting the survey, taking a measurement, rotating the coils and taking a second measurement. This makes the survey slow and laborious, and discourages full use of the technique. The need for efficient dual-depth surveys motivated the development of an enhanced G-SEM system.

In recent years, much greater progress has occurred in electronic-signal processing than with portable power-supplies. As a result, EM receivers have advanced much further than EM transmitters, and the addition of a receiver adds little to the weight or power-requirement of a system.
Figure 4 shows a system with one transmitter and two receivers that is equivalent to a perpendicular system combined with a horizontal co-planar system. This dual system can sound two volumes-of-earth simultaneously.

Figure 4: Dual-geometry EM system.



The independence of the simultaneous soundings given by the dual system, as indicated by DOE, is greater that of horizontal/vertical co-planar soundings. Thus, in addition to surveying convenience, dual-system soundings yield slightly better resolution of the geo-electric section.

Single-receiver G-SEM instruments have encountered increasing competition from frequency- and transient-EM devices that incorporate advances in electronic design. The dual system incorporates such advances as well, and may encourage users to take renewed advantage of the simplicity of both operation and interpretation inherent in G-SEM.

G-SEM Applications

The number and range of G-SEM applications increased rapidly after 1980 with public interest in environmental monitoring and groundwater assessment. The categorization and examples of applications presented herein are drawn from an annotated bibliography of more than 250 entries maintained by Taylor (1999).

The basis of the applications is contrast in geological EM properties, especially conductivity, for which Keller (1988) and Palacky (1988) provide excellent summaries.

A useful distinction may be made between two groups of applications. The first group deals with geological exploration, and the second group deals with the detection (and monitoring) of anthropogenic features. Although the characteristics of some features may be identical across group definitions, the preparation and techniques for surveying are influenced by group considerations, such as the physical surrounding and social significance of the feature.

The most common feature for geological exploration is the freshwater aquifer; other features are mineral resources, cavities, faults and soils.

Freshwater aquifers that are more conductive than their hosts tend to be on-or-near the surface of buried igneous- or carbonate-bedrock. The largest conductivity-contrasts occur where igneous bedrock is deeply weathered, and the aquifer matrix consists of weathered material confined in a trough or fracture zone. Due to lower contrast with bedrock, aquifers of coarse glacial-or-other sediments present a greater challenge for EM, but one that many times has been successfully met.

Freshwater aquifers are less conductive than their hosts when they are confined by conductive materials, such as shales, clays and saline groundwater. In these situations, surveyors seek depressions in the conductive material that may be filled with pools of freshwater.

Clay-caps on kimberlite pipes and bitumen-saturated sands have been mineral-resource targets of G-SEM surveys, but exploration for aggregates is a more frequent application. Aggregates, which are relatively free of clay, present a resistive zone if they are enclosed laterally and at depth by finer, more conductive material.

In general, soils are amenable to surveying with G-SEM, due to their layered structure and the link between clay-content and conductivity. Geotechnical investigation is the principal application for mapping soils and frozen ground. Other applications deal with soil salinity, with regard to agricultural productivity or the corrosion of buried utilities.

Faults and cavities become more easily mapped as the conductivity increases of the material they contain. Air-filled structures are undetectable if they are hosted by resistive material, and difficult to interpret if they are hosted by conductive material.

The second group of applications deals with man-made features. Some of these, such as buried metal and disturbed ground, are unchanging and one-time surveys are designed for their detection. Others, resulting from the chemical contamination of soil and groundwater, may be repeated as part of a monitoring process.

Although the confined shape and conductivity of buried metal-objects cause G-SEM systems to respond beyond the low-frequency-approximation, metal detection is an important application as it is intimately related to conductivity sounding for archaeology, environmental assessment and forensic investigation.

Disturbance can alter the conductivity of the ground, by changing its physical or its electrical structure. Through careful use, G-SEM systems have detected varied features, such as ancient burial-excavations and clandestine tunnels. G-SEM systems have also located sites of ancient fires, through the altered magnetic susceptibility of the heated ground.

The most frequent G-SEM application is the delineation of conductive contamination in soils and groundwater. Fertilization, irrigation and other practices change the conductivity of agricultural soil. The decomposition of domestic waste produces salts and acids that give landfill-leachate its conductivity.

Many industrial and commercial activities generate conductive wastes, such as the processing of agricultural products, chemicals, coal, forest products, metals, minerals and ores, as well as petroleum production, power generation and road maintenance.

Applications that require special expertise in selected situations are the monitoring of hazardous wastes and contamination from organics.

Summary

G-SEM is unique among EM techniques for the simplicity with which its sampling volume is defined and its results are interpreted.

The first G-SEM instrument developed for use at surface incorporated a perpendicular arrangement of transmitter and receiver. Almost all instruments in current use incorporate a horizontal co-planar arrangement.

A G-SEM system that incorporates a horizontal transmitter, a perpendicular receiver and a horizontal co-planar receiver sounds two sampling-volumes simultaneously, yielding additional information about the geo-electric section. This dual system represents a practical implementation of advances in electronic-signal processing.

The dual system is suitable for the wide range of G-SEM applications, which include the monitoring of contamination in soil and groundwater, the detection of disturbed ground and buried metal for archaeology, environmental assessment and forensic investigation, and exploration for groundwater, minerals, soils and geological structures.

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Addendum

The preceding document discusses the cumulative sensitivities with depth of the perpendicular (PRP) and horizontal co-planar (HCP) geometries. Cumulative sensitivities are useful for the quantitative interpretation of conductivity layering within the DOE of a G-SEM instrument.

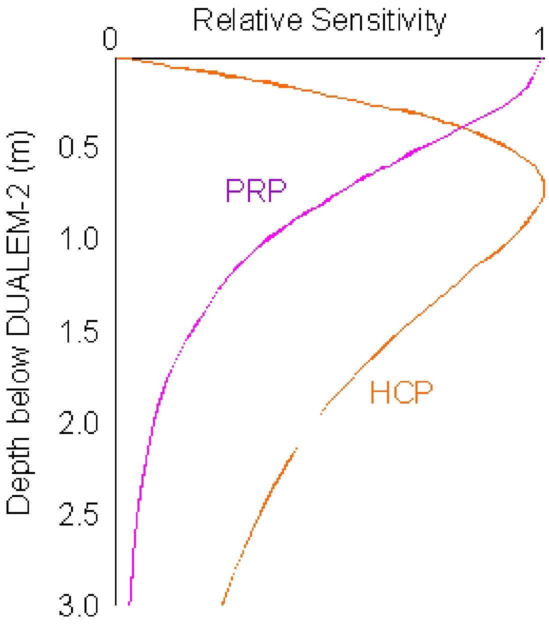
To supplement the description of the volumes sampled by G-SEM, this addendum discusses the incremental sensitivities with depth of the HCP and PRP geometries, and illustrates them (see Figure 5) for a popular G-SEM instrument, the DUALEM-2. The Tx-Rx separation of the DUALEM-2 is 2 m for the HCP geometry, and 2.1 m for the PRP geometry.

The formulae for the incremental sensitivities are taken from Wait (1962) and McNeill (ibid.).

Figure 5 shows that the PRP geometry of the DUALEM-2 is most sensitive to the earth at the instrument (i.e. zero depth). Sensitivity decreases gradually to a depth of about 0.2 m, and then more rapidly. Sensitivity at the nominal PRP DOE of 1.2 m is about one-fourth of the maximum at the instrument.

In contrast, the figure shows the HCP geometry is insensitive to the earth at the instrument, but the sensitivity rises rapidly to peak at a depth of about 0.7 m. Sensitivity at the nominal HCP DOE of 3 m is, again, about one-fourth of the maximum.

Figure 5: Incremental sensitivity with depth.



Without consideration of incremental sensitivity, users of G-SEM might assume that the instrument samples somewhat uniformly to the DOE. A better guide might be the depths between which the sensitivity exceeds, say, half of its maximum value. Using this guide for the DUALEM-2, we would conclude that the PRP geometry samples from the instrument to a depth of about 0.8 m, and the HCP geometry samples between depths of about 0.2 m and 2 m.

Since G-SEM sensitivity is linearly proportional to Tx-Rx separation, the curves of Figure 5 are valid for other instruments with different separation, provided that the depth scale is adjusted accordingly. For example, the depth scale for the DUALEM-4 would range from 0 to 6 m.

Thus we can generalize the half-sensitivity guide for all G-SEM instruments, e.g. the PRP geometry samples to a depth of about four-tenths the Tx-Rx separation, and that the HCP geometry samples between depths of about one-tenth and one Tx-Rx separation.