Identification of mineral deposits using airborne electromagnetic spectra

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Summary

Broadband frequency-domain electromagnetic sensors can be used not only to detect but also to characterize and identify a particular mineral deposit based on its spectral response. The concept is similar to identifying a particular landmine based on its unique spectral response, which is known as Electromagnetic Induction Spectroscopy (EMIS). Recent advances in single-coil, broadband sensors have brought a potential application of EMIS to airborne mineral prospecting. This paper describes a method of identifying an ore deposit using the EMIS spectrum and shows examples from a helicopter-towed digital broadband EM system.

Airborne multi-frequency EM sensors

Most commercial frequency-domain airborne EM sensors employ a set of transmitter and receiver coils in an L-C tuned circuit, requiring such a set for each frequency of operation. For a five-frequency system, for instance, typical helicopter-towed EM sensor (HEM) carries 15 coils (one transmitter and two receivers for each frequency). Housing so many coils obviously renders a towed HEM bird heavy, bulky, and nightmarish wiring problems. Minimizing cross talk among coils is another issue. Above all, because each frequency operates its own independent electronics, it is very difficult to calibrate the sensor over a broad bandwidth.

A tuned coil derives its main signal strength from its Q (called the figure of merit; the sharper the resonance, the higher the Q) that provides an amplification factor at a particular frequency set by the coil inductance and an external tuning capacitor. Q of coils used in typical HEM systems is about 20-30. While a high Q easily provides usable signal strength, weaknesses are also abound: (1) poor thermal stability, (2) difficulty in independently calibrating each coil set, (3) different drift characteristics for each coil, requiring arbitrary "leveling" of each trace during post processing (Huang and Fraser, 1999), and (4) cross talks among coils. Most importantly, due to the independent behavior of each coil, it is difficult to calibrate the entire bandwidth to as to obtain a continuous and consistent EM spectrum.

GEM–2A broadband EM sensor

The GEM-2A is a digital broadband HEM system, presently employing a single set of three coplanar coils. Adding a coaxial coil set is planned for the future. Geophex built and flown the first prototype in 1988 as a part of the U.S. Navy airborne bathymetry program. The system works, in principle, in time domain as well using time-series analysis technique in each operational base period. For production surveys, however, the system has mainly been operated in a multi-frequency mode. Subsequently, Geophex produced and commercialized handheld broadband EM sensors, GEM-2 and GEM-3 (Won et al., 1996 and 1997) in particular, for ground surveys for environmental and geotechnical projects.

In 1998, the new generation GEM-2A went into service for airborne survey. The sensor package (bird), about 6-m long, is towed by a helicopter. The bird also contains a cesium-vapor magnetometer that operates in toggle with the EM sensor. The EM bandwidth, somewhat dependent on environmental noise, is generally between 270 Hz to 48 kHz. The GEM-2A weighs about 150 kg, about a half of traditional HEM birds, with minimal cockpit support instruments. A computer in the bird performs all raw signal processing; the tow cable supplies DC power and only digital data to and from the bird.

The GEM-2A is based on a single set of three coils: one transmitter and two receiver coils. All coils are designed to have a flat response (i.e., Q=1) over the design bandwidth. The lack of high Q is compensated by high driving voltage for transmitter and low-noise signal amplifications for receivers. The system operation is programmable in either frequency domain, or in time domain, or both. Typical data rate is 30Hz, regardless of the number of frequencies or time gates. Further details may be found in Won et al. (1996).

In a frequency-domain operation, the operator specifies a set of frequencies and the system builds a high-speed digital switching command sequence that produces a multi-frequency current waveform in the transmitter. The received signal is amplified and digitized into a time-series whose length is determined by the duration of transmission (called "base period") and the digitization (A/D) rate. The GEM-2A has a typical base period of $1/30^{th}$ of a second and a 24-bit A/D at 96 kHz and, therefore, it produces a 3,200-long time-series per base period. The series then undergo a sine and a cosine convolution at each frequency to extract the inphase and quadrature responses in parts per million (ppm), the raw data outputs of the sensor. The time-series is also convolved with powerline frequencies (not transmitted by the system), an added feature for passively monitoring the powerline noise. The overall throughput rate is 30 Hz, regardless of the number of frequencies, typically 5 to 10.

If desired, each base period can be digitally controlled to accommodate multiple functions. For instance, the system may be turned off for certain base periods, during which other sensors (e.g., magnetometer) can operate without being interfered by the EM transmission. This feature allows colocating multiple sensors that cannot be activated at the same time. Similar operation may also apply to toggling between coplanar and coaxial coil configurations. Such operational versatilities open many new possibilities in configuring active and passive sensors in a single package.

The fact that the GEM-2A uses a single set of coils to share all frequencies makes this system much more predictable than the conventional HEM sensors. One of the outstanding features is that it produces a continuous and consistent broadband spectrum, owing to a single set of coils for all frequencies. This is because all frequencies share the same coil parameters (inductance, resistance, decay-time constant, etc.), geometric stations, and front-end analog electronics. Therefore, once digitally calibrated using a known target, such as a Q-coil or a ferrite rod, the system can accurately measure spectral responses of any other targets, including that of ore deposits. This ability to collect continuously calibrated EM induction (EMI) spectrum renders a potential means of detecting, characterizing, and identifying a particular mineral deposit, all in a single survey, by it spectral EM response.

Electromagnetic induction spectroscopy (EMIS)

Electromagnetic Induction Spectroscopy (EMIS) is a nascent method of identifying a buried metallic object such as a landmine, based on its spectral response (Won et al., 1998, 2001; U.S. Patent No. 5,963,035; granted in 1999). Most metal detectors can detect small metal pieces such as landmines, but cannot effectively discriminate a landmine amid ubiquitous false alarms in cluttered environment. In this paper, we explore a potential application of EMIS to identifying mineral deposits using a broadband HEM system.

When an electrically conductive and/or magnetically permeable object (e.g., landmine, ore body) is placed in a time-varying EM field, a system of induced current flows through the object. By observing a small secondary magnetic field emanating from the induced current, we attempt to detect the object; this is the foundation of the EMI method. If, in addition, we can measure a broadband spectrum of the secondary field, we may obtain a distinct spectral signature that may identify the object. Based on the response spectrum, we can "fingerprint" the object. This is the basic concept of EMIS.

A major issue in mineral prospecting is to distinguish anomalies caused by desirable mineral deposits from others, such as conductive overburden. Broadband EM sensors have been promoted to this end (e.g., Won, 1983); however, traditional sensors have not had a sufficient bandwidth or spectral stability to meet the requirements. Others (e.g., Palacky, 1976) advocated multi-channel time-domain EM sensors to measure decay patterns. Time-domain sensors require a large dynamic range to measure a rapidly decaying secondary field and have difficulties in overcoming environmental noise for late time channels. Although it has been repetitively argued that the frequency-domain and time-domain measurements are equivalent, practical hardware limitations have separately sustained the two systems with pros and cons on each side.

EMIS is based on frequency-domain data to detect and identify a mineral deposit in a given geologic setting. By using the EMIS responses from known or producing deposits as fingerprints, we look for locations having similar spectra within a local mineral province.

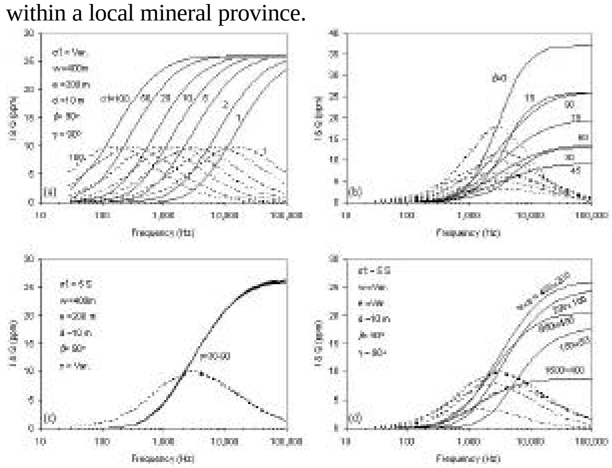

Figure 1. The EM spectra of thin sheet with various model parameters for coplanar coil-pairs.

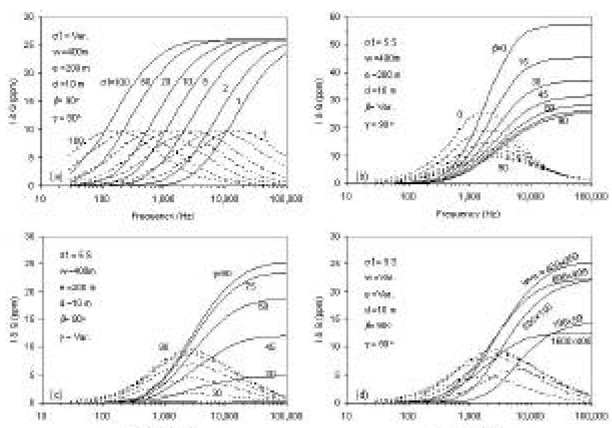

Figure 2. The EM spectra of thin sheet with various model parameters for coaxial coil-pairs.

Theoretical EMIS examples of simple geologic models

We show theoretical EMIS examples for three simple geologic models -- thin sheet (Weidelt, 1983), sphere (Grant and West, 1965), and layered earth (Ward, and Hohmann, 1988). Using a coil separation of 5.1m (that of the GEM-2A) and a nominal bird height of 30m, we compute the model response in a bandwidth of 30Hz to 100 kHz.

Thin sheets

A thin sheet model may be appropriate for mineralized veins, elongated graphite sheet, or shear zone. Variable parameters for the model may include conductance (st: conductivity-thickness product), width (w), length (e), depth (d), dip angle (b), and the angle between the flight line and strike (g). Spectral responses of various thin sheets are shown in Figure 1 for a horizontal coplanar coil configuration and in Figure 2 for a coaxial coil configuration. As st increases from 1 S to 100 S, the spectra move toward lower frequencies, while the shape of the spectra remains the same. This reflects the common knowledge that higher frequencies are needed for a poor conductor, and vice versa (Figures 1a and 2a). Figures 1b and 2b show the dependence on dip angles, varying from 0° to 90° at an increment of 15°, where the horizontal sheet produces largest amplitude. The spectra are strike-independent for the horizontal coplanar coil-pairs (Figure 1c), while the perpendicular crossing (90°) gives a maximum response for coaxial coil-pairs but their relative (i.e., amplitude-normalized) shapes remain unchanged. Figures 1d and 2d show the dependence on the sheet size. Self-inductance of a conducting sheet is proportional to its size and, therefore, a small sheet ($100 \times 50 m^2$) responds best at high frequency, while a large one ($1600 \times 800 m^2$) at low frequency. It may appear strange in these examples that the mid size ($400 \times 200 m^2$) sheet gives a highest amplitude: the reason for a larger conductor yielding lower amplitude is because the induced currents spread out through the entire sheet thereby reducing the overall current density, particularly at the top where the sensor is closest.

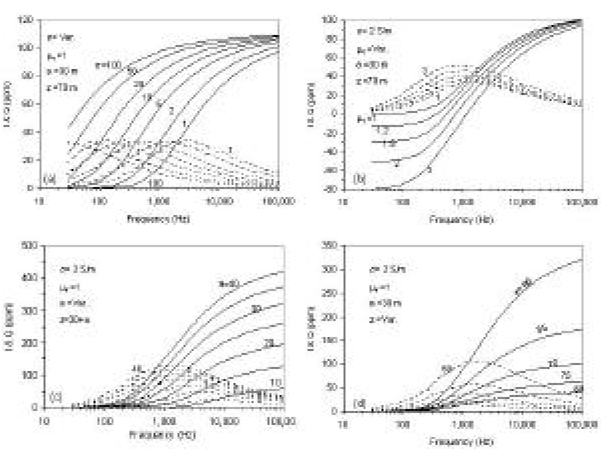

Figure 3. The spectra of sphere with various model parameters.

Spheres

An isolated conductor is often modeled as a sphere whose spectra depends on the response parameter $(smw)^{1/2}a$, which is consisted of relative magnetic permeability m, conductivity s, angular frequency w, and the sphere radius a. Within the bandwidth shown, its conductivity does not change the amplitudes but only causes a shift along the frequency axis. When m is greater than 1 (i.e., ferrous), the inphase becomes negative at the lower frequency and the quadrature response increases (Figure 3b). As the sphere gets bigger, the amplitude increases accompanied with a shift to lower frequencies (Figure 3c). As the sphere gets deeper, its amplitude decreases but with negligible changes in the spectral shape (Figure 3d).

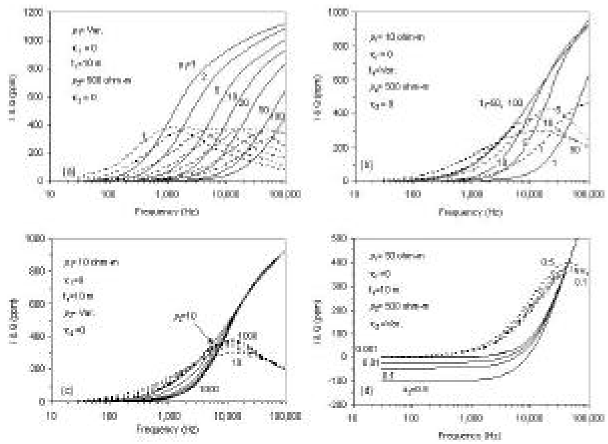

Figure 4. The spectra of two-layer earth model with various model parameters.

Layered half-space

Layered half-space models are useful to study responses of a conductive overburden. Varying overburden thickness often produces false anomalies that are hard to distinguish from anomalies from bedrock conductors. Figure 4 shows spectra of a two-layer model consisted of a conductive overburden covering a resistive and magnetic basement. Changes in the layer thickness and resistivity impact the spectra. When the overburden is thick and resistive, the equivalent inductance of the earth increases, resulting in spectral shifts towards low frequency. Basement resistivity has little impact on the spectra and ferrous bedrocks produce negative inphase at low frequency.

EMIS Field Data Example

In the simulated examples shown above, we notice that the EMIS response is invariant to many parameters (e.g., sphere size or depth, flight-line vs. strike). This parametric invariance offers a potential for discriminating a mineral deposit based on a broadband spectrum. Since the concept of spectral identification of a mineral deposit is new, and mainly because the traditional multi-coil HEM system cannot easily produce coherently calibrated multi-frequency spectra, there are not many useful data examples to apply the EMIS concept to mineral exploration. Even for the GEM-2A, we have just begun to look into this possibility.

Figure 5 shows the GEM-2A data collected over a kimberlite deposit in Australia using three frequencies: 1,325 Hz, 4,925 Hz, and 11,025 Hz. The figure shows an apparent conductivity map at each of the three frequencies and an apparent magnetic susceptibility map derived from the lowest frequency (Huang and Fraser, 2000). The region of high conductivity in the center of the maps, indicated by letters A and B, is associated with a known kimberlite pipe. The spectral features of locations A and B are indeed very similar. While high conductivity may indicate a possible kimberlite target, it alone does not provide enough clues for discrimination. For instance, locations C and D that exhibit similar conductivity highs but not kimberlite, show spectra that are quite dissimilar to those from A and B.

The apparent magnetic susceptibility data indicates a local high over the kimberlite, which may offer additional discrimination. Samples taken from the kimberlite showed to have susceptibility about 14 times greater than that of samples taken from the neighborhood.

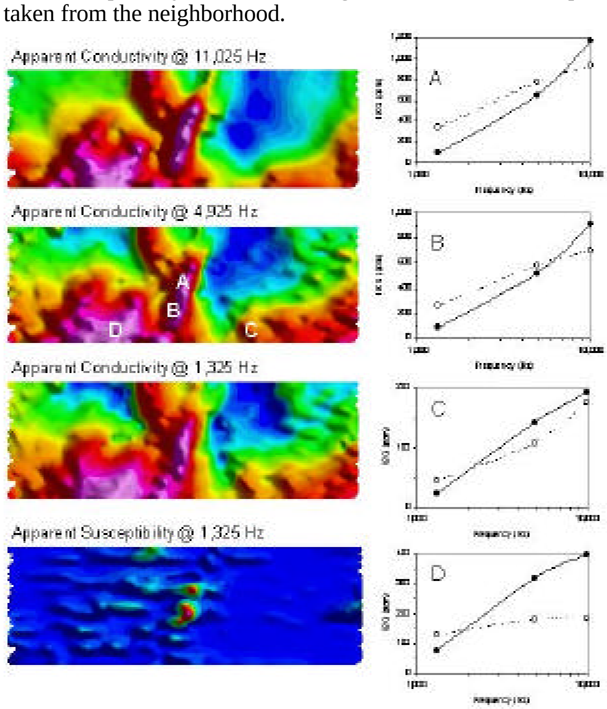

Figure 5. Conductivity and magnetic susceptibility maps derived from GEM-2A data obtained in Australia, and the spectra extracted at points A, B C and D.

Conclusions

We have shown in this article a potentially powerful means of identifying a mineral deposit based on its broadband spectral response. The idea is using EMIS spectra from known deposits or outcrops as a fingerprint to look for similar bodies in a local geologic province. The method may not be universally applicable to a particular mineral type because different geologic processes may produce different EMIS response. We have shown that certain features of an EMIS fingerprint is invariant to many parameters, such as the size and depth for a spherical body and the survey direction across a sheet-like body. Such parametric invariance is the basis for potential EMIS identification. An example of kimberlite deposit supports such a potential. In practice, an EMIS signature may not be unique for a deposit due to a combination of many factors yet to be studied.

The EMIS identification requires multi-frequency data that are rigorously calibrated in a broad bandwidth. The sensor must be rigorously calibrated with well-understood frequency dependence in amplitude, phase, long-term drift, etc. It has been difficult to obtain such calibrated broadband data from the traditional multi-coil HEM systems. A promising approach shown here is a system that broadcasts and receives all frequencies using a single set of coils, which can be calibrated with a relative ease and rigor. The GEM-2A is the first of such a system.

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