Small frequency-domain electromagnetic induction sensors

How in the world does a small broadband EMI sensor with little or no source-receiver separation work?

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Over the past several decades, we have witnessed the emergence of portable electromagnetic induction (EMI) sensors: to name a few, Geonics pioneered portable sensors such as EM-31, EM-34, and EM-61; Zonge Engineering successfully developed and marketed variations of controlled-source EMI sensors. These portable and popular EMI sensors have been used successfully for many geophysical investigations, particularly for shallow engineering and environmental surveys.

The most recent entry in this field is a new generation of one-man portable, digital, broadband EMI sensors developed by Geophex: the GEM-2 has a separation of 1.67 m between the transmitter (TX) and receiver (RX), while the GEM-3 has no practical separation because all coils are collocated in a concentric circular disk (Figure 1). Both sensors have a 30-Hz data rate at typical 3-10 simultaneous frequencies and, currently, a bandwidth of 30 Hz to 48 kHz, a span of about three decades. Each weighs about 4 kg (8 pounds) and comes in a single handheld package. The primary incentive for such small sensors is obvious: portability and speed.

Most traditional EMI sensors have separate TX and RX coils connected by cables. This is due to the notion that the TX-RX separation ultimately governs the depth of exploration: the farther they are separated, the deeper we can see. If that notion is indisputably true, one may ask: How in the world do handheld broadband EMI sensors with small or no TX-RX separations see any depth at all? A short answer: They work because the RX is designed not to see the TX. To qualify this answer, let us briefly review where the state of the art stands.

Geometrical sounding versus frequency sounding. By technical necessity, most old frequency-domain (FD) EMI sensors have employed the principle of "geometrical sounding" where the coil separation is the only variable, because all coils operate at a factory-set frequency. Because these coils are tuned to a particular frequency by their inductance and external capacitance, one cannot change the operating frequency without replacing all coils or associated electronics. A tuned coil derives its signal strength from its Q (called the figure of merit—the sharper the resonance, the higher the Q), a voltage amplification factor at the tuned frequency. Therefore, the only means left to the user of such a system is changing the coil separation, which often requires multiple operators tending separate coils connected by cables to a measuring console. Furthermore, the system must maintain a considerable coil separation to avoid RX saturation from the primary TX field. It is obvious that such a sensor cannot be made into a small, handheld package.

Editor's note: The Meter Reader is a regular column in TLE, originated by the Gravity and Magnetics Committee and currently coordinated by John Peirce, that seeks to highlight new ideas in geophysical fields besides seismic—particularly gravity, magnetics, and electromagnetics. If you have a short contribution on these topics that is written in the relatively informal but informative style of TLE, please submit it to Dean Clark, editor of TLE in Tulsa, or to John Peirce, at GEDCO in Calgary. This article describes a new class of small EM sensors that have successfully overcome one of the inherent limitations that many of us were brought up to accept as gospel. The examples in this paper represent the solutions developed by one company. They are used as examples, and this usage does not imply they are the only solutions or that these products are endorsed by SEG. The author and I thank Ted Glenn for a very helpful review.

Figure 1. Portable, digital, broadband EMI sensors. The instrument in the left photo has three linearly spaced coils with a maximum separation of 1.67 m. The concentric instrument in the right photo comes in three disk sizes up to 96 cm in diameter. The largest one is typically cart-mounted.

In contrast, depth sounding by changing frequency (or "frequency sounding") measures the earth response at multiple frequencies at a fixed TX-RX geometry. In frequency sounding, there is no exclusive relationship between the coil separation and the depth of exploration. In principle, the TX-RX separation can be arbitrarily small and, therefore, we can produce an arbitrarily small sensor package. This alternative, however, has faced many technical hurdles, particularly in terms of dynamic range and resolution, which could not be solved until recently when we witnessed explosive advancements in analog and digital electronics along with mechanical miniaturization. This lack of enabling technologies explains why there has been a dearth of multifrequency EMI sensors for general usage in the geophysical community until very recently.

It must be noted, however, that there have been several commercial multifrequency FD EMI systems, albeit not handheld or very portable. Well-known examples include the ground "Slingram" system and the large, helicopter-towed, rigid-boom sensor, commonly known as HEM, both of which have been successfully used for mineral exploration for several decades. The coil separation of a HEM system is so small compared to the sensor height that all coils are practically collocated. In other words, the GEM-2 and GEM-3 are not the first FD EMI sensors that have small or no coil separations. There is a significant difference, though: The traditional HEM sensor has a set of coils for each frequency, while the GEM sensors use only one set of coils for all frequencies. The range of frequencies used by the HEM sensors is similar to that of the GEM sensors.

Requirements for broadband EMI sensors. To operate a coil at multiple frequencies in a broad bandwidth, one must abandon the tuned-circuit concept and come up with new

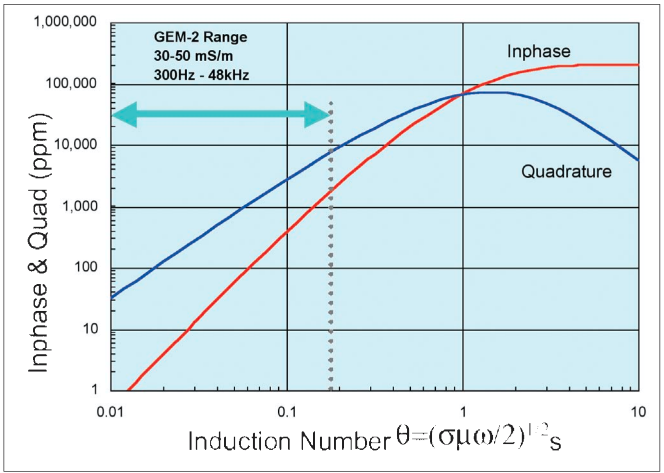

Figure 2. The inphase (I) and quadrature (Q) responses as a function of induction number over a half-space. The arrow indicates the range of the induction number for an instrument having a coil separation s=1.67 m over an earth having a conductivity range of 30-50 mS/m and operating in a bandwidth of 300 Hz to 48 kHz. Note that both I and Q are quite strong and frequency-dependent.

modus operandi in real-time signal processing. Some major technical hurdles that must be addressed for a small FD EMI sensor include:

- The receiver must employ a "source cancellation" or a "bucking" scheme so that it is not saturated, or "blinded," by a nearby transmitter.
- Both analog and digital electronics must have a large dynamic range and a high resolution.
- The coils' self-resonance frequency must be considerably higher than the high end of the desired bandwidth. This calls for reducing the number of turns, resulting in reduced signal level and, thus, necessitates very low-noise front-end signal amplification.
- All coils and electronics must work in a broad bandwidth to accommodate composite waveforms containing multi-frequency components.

In short, a small FD EMI sensor is possible only if the sensor employs an ideally bucked receiver having sufficient dynamic range and resolution, not trivial requirements by any means. Every condition listed above carried with it a technical problem to overcome. These stringent technical requirements have impeded development of small broadband sensors until now.

Different source-cancellation schemes have been developed and used by all HEM systems in the past. The GEM-2 employs a "receiver-bucking" scheme that is common to HEM sensors. GEM-3 uses a patented "transmitter-bucking" scheme. These source-cancellation schemes, through physical layout of the coils, typically reduce the primary field as seen by the receiver by a factor of 100-1000 s, corresponding to a gain of 40-60 dB in dynamic range. The source cancellation, or bucking, is a must for a small FD sensor so as not to saturate a nearby receiver coil. An ideally bucked receiver, as discussed above, does not see the primary field at all and, thus, the old concept of the coil separation does not apply.

An EMI sensor designed to buck out the primary field must be exceptionally stable in calibration with minimal temporal drift, requiring many special design considerations in coils geometry, front-end electronics, and packaging. The sensor is commonly calibrated using a known target, often called "Q-coil" having known radius, turns, resistance, and inductance and, thus, a known spectral response. A small-unbucked portion of the primary field (often called the "free-air response") is usually measured as a function of frequency by raising the sensor high above the ground (for instance, by hanging it to a tall tree). The free-air response is stored in the sensor and subtracted from the measurements in real-time during a survey.

Additional dynamic range comes from high-resolution analog-to-digital converter (ADC). By combining the dynamic ranges of the bucking scheme and the ADC, we can achieve a dynamic range close to 200 dB, an impressive feat by any means. The high A/D resolution and the large dynamic range are two important enablers for small FD sensors that may be used for depth sounding using multiple frequencies. Such resolution and dynamic range have not been achievable until very recently.

Special consideration for depth sounding in resistive environments. A low-frequency EMI sensor needs a large TX-RX separation for sounding in resistive environments so as to raise the induction number. A small coil separation coupled with a limited bandwidth can result in low induction number responses on a resistive earth where a given bandwidth may not produce sufficient frequency dependence for depth sounding. An argument solely based on the induction number, however, is misleading. As stated before, a small sensor can be used for depth sounding if it has (1) a sufficient sensitivity to resolve the small frequency dependence in a resistive area, (2) a large dynamic range to accommodate near surface conductive effects, and (3) an ability to avoid certain frequencies with high noise levels caused by local environments such as power lines. A sensor that can meet these requirements can be used for depth sounding at many venues.

The low induction number for a half-space is often defined as $\theta=(i\omega\mu\sigma/2)^{1/2}s$ where ω is the angular frequency, μ magnetic permeability, σ conductivity, and s the coil separation. Spies and Frischknecht (1991) define the low induction number or resistive limit for a half-space as $\theta \leq 0.02$. In this range, multifrequency data may not provide additional information. However, if the sensor has a large dynamic range capable of measuring the small ratio between the secondary and primary field to three significant figures over the range of induction numbers 0.01 to 1.5, then a sufficient resolution can be achieved by using the horizontal coplanar coil configuration.

Figure 2 shows the response of one sensor over a half-space, as a function of the induction number. The EM response in a low induction number range ($\theta < 0.02$) is low and becomes virtually frequency-independent, which renders no additional information. When $\theta >> 1$, inphase (I) reaches its highest value and quadrature (Q) goes to zero, which also provides no additional information. A successful EM sensor, therefore, should operate in the middle induction number zone. The arrow in Figure 2 indicates the range of the induction number for this sensor over an earth having a conductivity range of 30-50 mS/m and operating in a bandwidth of 300 Hz to 48 kHz. Note that both I and Q have healthy signal strength and strong frequency dependence, testifying that such a small sensor is quite suitable for soundings in such environments.

There are ample case histories that have used broadband EM data for characterizing landfills, pits and trenches, contaminant plumes, underground facilities, depth-sounding, bathymetric charting, and many others. Figure 3 shows depth sections inverted from a two-frequency profile (1050 Hz and 12 270 Hz) over a buried trench containing a large

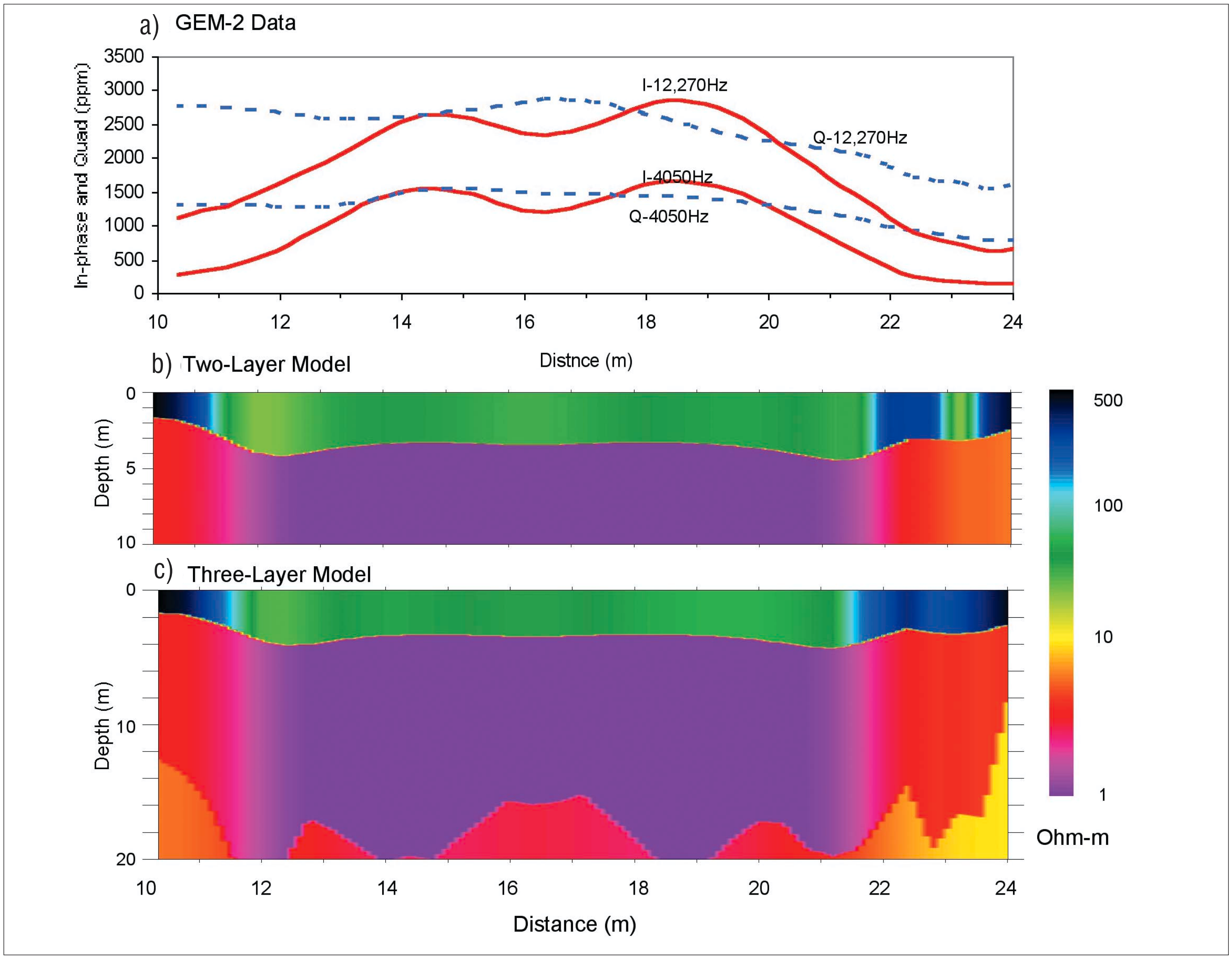

Figure 3. The top graph shows a two-frequency profile over a buried trench containing a large volume of broken mirror pieces (called cullet) in the middle section with high metal contents particularly lead and silver that have contaminated groundwater. By stitching 1D inversion results, the profile generates a two-layer (middle) and a three-layer (low) depth section. Note that the first layer remains similar for either case. The inversion results indicate an approximate vertical and horizontal trench extent for potential cleanup.

volume of broken mirror pieces (called cullet) in the middle section of the profile. The trench has high metal content, particularly lead and silver, that has contaminated groundwater. By stitching 1D inversion results, the profile generates two-layer and three-layer depth sections. Note that the first layer remains similar for either case. Although no uniqueness is implied, the inversion results indicate an approximate vertical and horizontal trench extent for potential cleanup.

Summary and conclusions. Small frequency-domain EMI sensors can be used for depth sounding for environmental and engineering applications. Despite their small or virtually nonexistent TX-RX separation, these compact sensors can be made to perform by employing a good source-cancellation scheme for the receiver along with large dynamic range and high digital resolution. For a well-bucked sensor, the RX-TX separation exerts little influence upon depth sounding. Such sensors have become technically feasible with recent advancements in digital electronics along with real-time signal processing.

Suggested reading. "Electromagnetic sounding" by Spies and Frischknecht (in *Electromagnetic Methods in Applied Geophysics*, SEG, 1991). "A new method of subsurface imaging—the LASI high frequency ellipticity system: part 3: system tests and field surveys" by Sternberg and Birken (*Journal of Environmental and Engineering Geophysics*, 1999). "Characterizing the distribution of near-surface solution channels using electromagnetic induction and ground penetrating radar" by Witten and Calvert (*Journal of Environmental and Engineering Geophysics*, 1999). "GEM-2: A new multifrequency electromagnetic sensor" by Won et al. (*Journal of Environmental and Engineering Geophysics*, 1996). "GEM-3: A monostatic broadband electromagnetic induction sensor" by Won et al. (*Journal of Environmental and Engineering Geophysics*, 1997). "Electromagnetic induction spectroscopy" by Won et al. (*Journal of Environmental and Engineering Geophysics*, 1998). TLE

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