GEM-2: A New Multifrequency Electromagnetic Sensor

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ABSTRACT

A new broadband electromagnetic sensor, GEM-2, has been tested at several environmental sites for subsurface investigation. A hand-held, digital, multi-frequency sensor based on an earlier, similar helicopter-towed sensor, GEM-2 operates in a frequency range of 90 Hz to 22 kHz, and can transmit an arbitrary waveform containing multiple frequencies. The unit is capable of transmitting and receiving any digitally-synthesized waveform by means of the pulse-width modulation technique. Owing to the arbitrary nature of its broadcast waveform and high-speed digitization, the sensor can operate either in a frequency-domain mode or in a time-domain mode.

Depth of exploration for a given earth medium is determined by the operating frequency. Therefore, measuring the earth response at multiple frequencies is equivalent to measuring the earth response from multiple depths. Hence, such data can be used to image a 3-D distribution of subsurface objects. Results from several environmental sites indicate that the multifrequency data from GEM-2 is far superior in characterizing buried, metallic and non-metallic targets to data from conventional single-frequency sensors.

Introduction

Of many geophysical exploration techniques, the electromagnetic (EM) method provides significant advantages for shallow geophysical exploration. During the past several years, Geophex has developed and field-tested a new generation of EM sensors. The first sensor, Model AEM-1, a helicopter-towed unit weighing about 250 pounds, was built for the U.S. Navy and successfully flown in 1988 for airborne bathymetric surveys over the shallow ocean. The first hand-held version, GEM-1 completed in 1992, weighed about 12 pounds and was used for many environmental site characterization surveys to detect landfills, unexploded ordnance, and buried drums containing hazardous waste.

GEM-2, the most recent portable version, completed in early 1995, is shown in fig. 1. The sensor, weighing about 9 pounds, operates in a frequency band between 90 Hz to about 22 kHz. Its built-in operating software allows a surveyor to cover about one acre per hour at a line spacing of five feet. Along a survey line, the data rate is about one per foot, resulting in about 10,000 data points per acre per hour. Such portability, survey speed, and high data density are important requirements for geophysical surveys at environmental sites.

Advantages of a broadband, multifrequency, EM sensor are obvious. The idea of using multiple frequencies stems from the so-called "skin-depth," also known as the depth of exploration, which is inversely proportional to frequency: a low-frequency signal travels far through a conductive earth and, thus, "sees" deep structures, while a high-frequency signal can travel only a short distance and thus, "sees" only shallow structures. Therefore, scanning through a frequency window is equivalent to depth sounding. Figure 2 shows a nomogram from which one may determine the penetration depth for a given frequency (Won, 1980).

Depth sounding by changing the transmitter frequency is called "frequency sounding," which measures the target response at many frequencies in order to image the subsurface structure. Because the method involves a fixed transmitter-receiver geometry, the sensor can be built into a single piece of hardware, such as GEM-2; as a result, it produces extremely precise, sensitive, and thermally stable measurements. In contrast, depth sounding by changing the separation between the transmitter and receiver is called "geometrical sounding," which usually requires multiple operators tending separate coils connected by wires and measuring consoles. Maintaining a precise coil separation is difficult and, therefore, some measurements (e.g., in-phase components) are often abandoned. For shallow survey, the frequency sounding method offers high spatial resolution, survey speed, light logistics, and data precision.

GEM-2 Operating Principles

Figure 3 shows the electronic block diagram of GEM-2. The sensor contains a transmitter coil and a receiver coil separated by about 5.5 feet. Such geometry is called "bistatic" configuration. It also contains a third "bucking coil" that removes (or bucks) the primary field from the receiver coil. All coils are molded into a single board (dubbed "ski") in a fixed geometry, rendering a light and portable package. Attached to the ski is a removable signal-processing console.

For a frequency-domain operation, GEM-2 prompts for a set of desired transmitter frequencies. Built-in software converts these frequencies into a digital "bit-stream," which is

Figure 1. GEM-2, a multifrequency electromagnetic sensor, in operation.

used to construct the desired transmitter waveform for a particular survey. This bit-stream represents an instruction on how to control a set of digital switches (called H-bridge) connected across the transmitter coil, and generates a complex waveform that contains all frequencies specified by the operator. This method of constructing an arbitrary waveform from a digital bit-stream is known as the pulse-width modulation technique.

The base period of the bit-stream for GEM-2 is set to 1/30th of a second for areas having a 60-Hz power supply as does the U.S. The period is 1/25th of a second at 50-Hz areas, as in Europe and Japan. For an H-bridge switching rate at 72,900 Hz, for instance, the bit-stream contains 2,430 steps within the base period. Any integral number of the base period may be used for a consecutive transmission in order to enhance the signal-to-noise ratio. For a typical environmental survey in urban areas, we employ six base periods, resulting in a transmission period of 0.2 seconds (6 times 1/30) per data location, totaling 14,580 switching events to construct the transmitter waveform.

In fig. 4a, we show an example transmitter current waveform, generated by a bit-stream designed to transmit eight frequencies from 150 Hz to 15,000 Hz. The software that generates the bit-stream for a given set of operator-specified frequencies, takes into account the built-in electronic parameters, such as the resistance and inductance of the transmitter coil. The graph shows the current waveform for the bit sequence from 1 to 1,215, the first half of the based period. Figure 4b depicts the waveform details between Bit 30 and Bit 90, showing the current flow in the transmitter coil. Each bit in this case lasts for 1/72,900 seconds. Figure 4c shows the amplitude spectrum of the transmitter current waveform of fig. 4a. Note that the transmitter current decreases logarithmically with frequency. The maximum current for the present transmitter is close to 10 amperes, corresponding to a dipole moment of about 3 A-m^2.

GEM-2 has two recording channels: one from the bucking coil (called the reference channel) and the other from the bucked receiver coil (called the signal channel). Both channels are digitized at a rate of 36,450 Hz (half the transmitter rate) and at an 18-bit resolution. This produces a 7,290-long time-series per channel during 0.2 seconds. In order to extract the in-phase and quadrature components, we then convolve (i.e., multiply and add) the time-series with a set of sine series (for in-phase) and cosine series (for quadrature) for each transmitted frequency. This convolution renders an extremely narrow-band, match-filter-type, signal detection technique. An 8-frequency operation, shown in fig. 4a, with a transmitter duration of 0.2 seconds, typically requires a total of about one second to complete the entire measurement cycle per data location. Reducing the number of frequencies would reduce

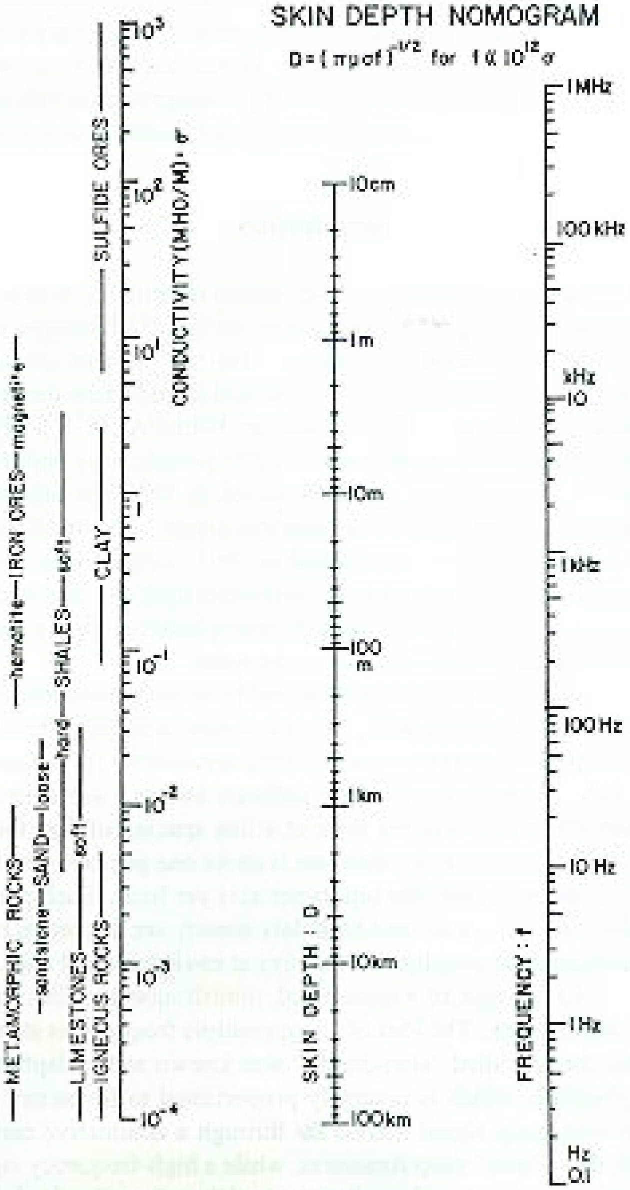

Figure 2. Relationship among source frequency, ground conductivity, and skin depth (from Won, 1980).

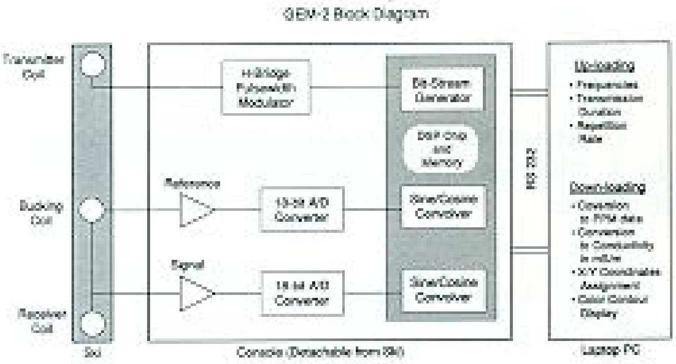

Figure 3. GEM-2 electronic block diagram.

the measurement to a shorter period. A single computer in a DSP chip coordinates all controls and computations for both transmitter and receiver circuits.

GEM-2 also allows the operator to measure and display the background environmental noise spectrum in real-time, in the bandwidth of 0 to 22 kHz. This is obtained from the signal-channel time-series at a typical location within a specified survey area, then computing its entire Fourier spectrum at an interval of the base frequency (30 Hz). Using the environmental noise spectrum, the operator can safely avoid locally-noisy frequency bands.

Basic Measurement Unit

The in-phase and quadrature data derived through the convolution are converted into a part-per-million, or ppm, unit defined as:

$$\text{ppm} = 10^6 \times \frac{\text{secondary magnetic field at receiver coil}}{\text{primary magnetic field at receiver coil}} \qquad (1)$$

These ppm values are the raw data logged by GEM-2. It is obvious that the ppm unit defined by Eq. (1) is sensor-specific and has little physical meaning. GEM-2 allows up to 50,000 data points before down-loading to a PC through an RS-232 protocol. All parameters required for the ppm computation, such as the sensor output in free-space (simulated by hanging GEM-2 from the top of a tall tree), amplifier characteristics of the two receiving channels, and the coil geometry, are stored in GEM-2 for real-time use.

In most shallow geophysical surveys, the ppm data generated by GEM-2, often plotted into a contour map for each frequency, is sufficient to locate buried objects without going through elaborate processing or interpretation. One can also estimate the target depth from the data obtained at multiple frequencies.

This *modus operandi* is the most common "bump finder" survey, which is appropriate and productive where there are numerous shallow, small, nondescript targets and the survey objective is to find as many targets as possible. The goal is

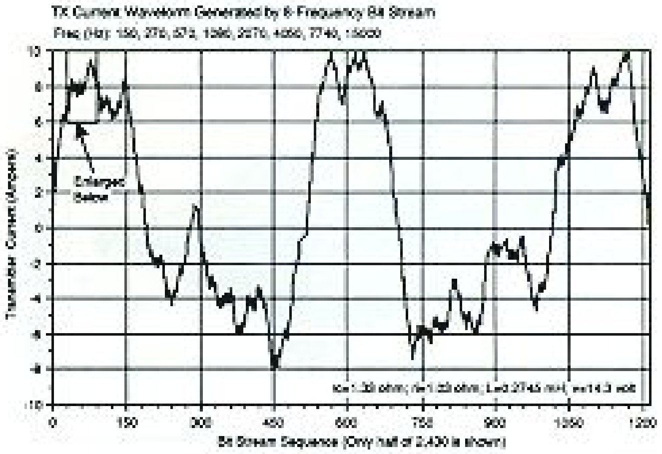

Figure 4a. An example transmitter current waveform (shown only one-half of 2,430 points) generated by an 8-frequency bit stream. Figure 4b shows an enlarged portion.

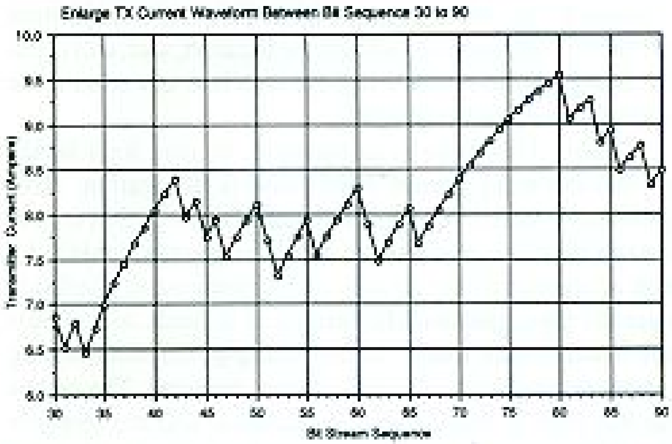

Figure 4b. Enlarged section of Figure 4a between the bit sequence 30 to 90.

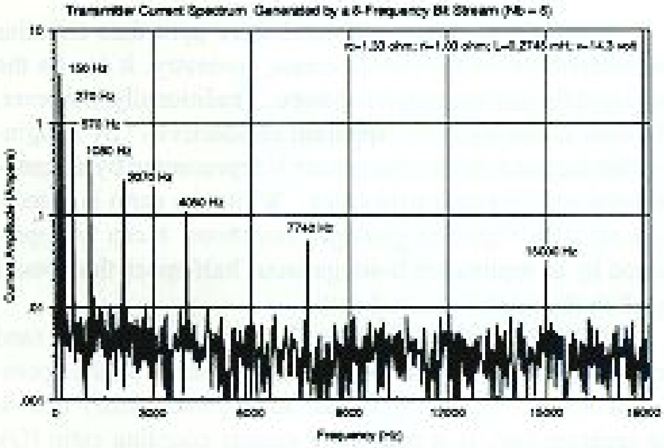

Figure 4c. Amplitude spectrum of the transmitter current waveform shown in Figure 4a.

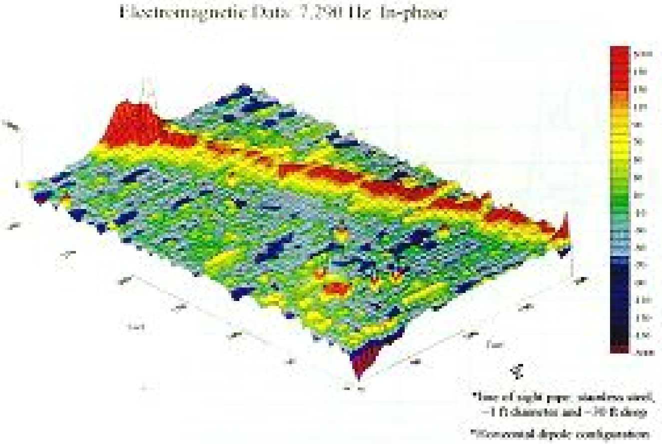

Figure 5. GEM-2 7,290 Hz in-phase data over an 18-inch diameter stainless steel pipe buried at 30 feet below surface.

not to determine a detailed geometry for each object, given typical time constraints and the large quantities of objects to be detected. In such a survey, the in-phase and quadrature ppm data are sufficient to indicate the location, size, and depth of a "bump" without converting the data into any other more physically meaningful quantities.

Figure 5 is shown as an example; we look for a buried pipe and our main interest in this case is its location. This figure shows the GEM-2 in-phase response at 7,290 Hz over a known stainless-steel pipe of 18-inch diameter, buried at a depth of approximately 30 feet. A magnetic survey failed to detect the pipe, presumably because it is made of stainless steel, a non-ferrous metal. In this example, the plot showing the ppm response is sufficient to locate the pipe. The survey over this pipe included seven frequencies, and the response was highly dependent on frequency. For example, the pipe was not recognizable at around 2 kHz or 12 kHz.

Conversion to Apparent Conductivity

Since the in-phase and quadrature ppm data contains all information on the measurement geometry, it can be the raw input for any inversion software. Traditionally, however, EM data is displayed in "apparent conductivity" by imagining that the earth below the sensor is represented by a homogeneous and isotropic half-space. While the earth is heterogeneous with regard to geologic variations, it can be represented by an equivalent homogeneous half-space that would result in the same observed data.

GEM-2 measures the secondary field from the earth (and buried objects therein) at frequencies specified by the operator. When the field is normalized against the primary field at the receiver coil, it is called the mutual coupling ratio (Q), which, for horizontal coplanar mode (or vertical dipole mode), can be written as:

$$Q = \frac{H_s}{H_p} - 1 = -r^3 \int_0^{\infty} \lambda^2 R(\lambda) J_0(\lambda r) e^{-2\lambda} \qquad (2)$$

The sensor geometry with respect to the earth is shown in fig. 6. The kernel function R corresponding to a uniform half-space is:

$$R(\lambda) = \frac{\lambda - \sqrt{\lambda^2 + \iota 2\pi f \mu \sigma}}{\lambda + \sqrt{\lambda^2 + \iota 2\pi f \mu \sigma}}, \qquad (3)$$

where

H_s: secondary field at receiver coil,
H_p: primary field at receiver coil,
r: coil separation,
h: sensor height,
J_0: zeroth-order Bessel function,
f: transmitter frequency (Hz),
μ: magnetic susceptibility, and
σ: earth conductivity.

We note that the ppm unit defined by Eq. (1) is the same as Q multiplied by one million. GEM-2 can be configured to

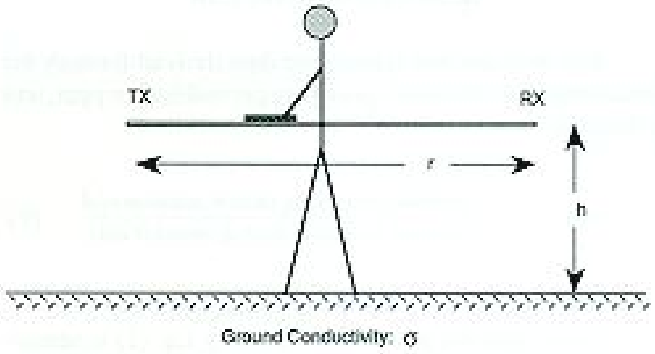

Figure 6. GEM-2 in a horizontal coplanar coils configuration.

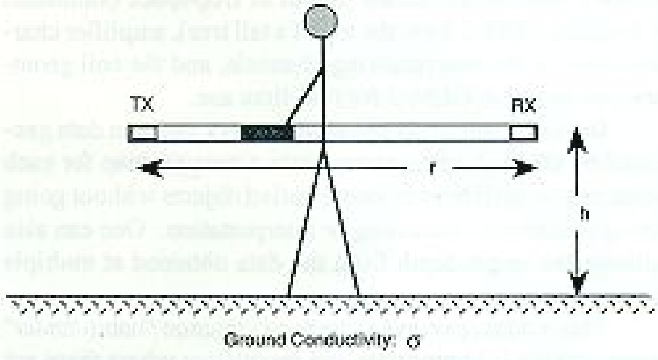

Figure 7. GEM-2 in a vertical coplanar coils configuration.

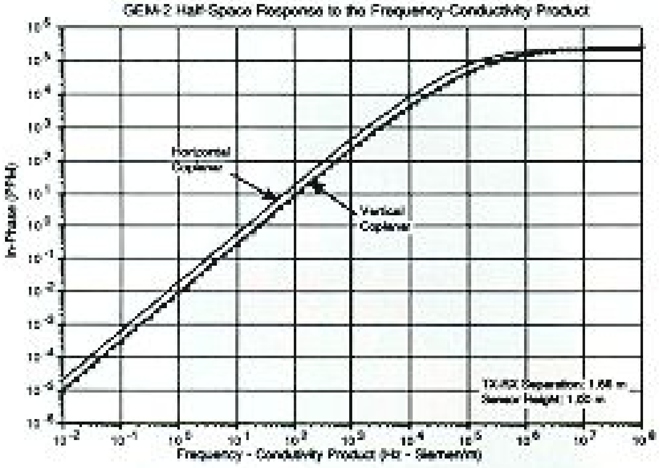

Figure 8. GEM-2 interpretation chart (in-phase) for converting ppm data to earth conductivity.

a vertical coplanar mode (or horizontal dipole mode) by simply turning it 90 degrees about the ski axis (fig. 7). The mutual coupling ratio for this is:

$$Q=\frac{H_s}{H_p}-1=-r^2\int_0^\infty \lambda R(\lambda)J_1(\lambda r)e^{-2\lambda h}d\lambda \qquad (4)$$

where J_1 is the first-order Bessel function. The integrals in Eqs. (2) and (4), known as the Hankel transform integrals, can be computed by the linear digital filter method with known filter coefficients for a fast digital convolution (Kozulin, 1963; Frischknecht, 1967). We notice from the above equations that conductivity and frequency appear as a single product. For multifrequency data, therefore, Eqs. (2) and (4) provide the relationship between the ppm unit and the conductivity-frequency product.

Figures 8 and 9 illustrate the computed in-phase and quadrature responses over half-space for the GEM-2 horizontal and vertical coplanar coils. We assume for this example the sensor height at 1 meter, typically waist level for a surveyor. In essence, the observed ppm value (y-axis) determines the conductivity-frequency product (x-axis), which is then divided by the transmitter frequency to obtain the half-space conductivity.

As an example, figs. 10a through 10d show the GEM-2 apparent conductivity data, in units of millisiemen/m (mS/m), over a 6-acre trench complex in the southeastern U.S. Materials, including radioactive waste, were "systematically" buried in many parallel trenches. For comparison, fig. 10e shows, for the same area, the total-field, magnetic anomaly map, while fig. 10f shows the total-field, vertical magnetic gradient. For the magnetic data, we employed a cesium-vapor magnetometer (Geometrics G-858G) with two sensing heads vertically separated by 30 inches. Magnetic anomalies are inherently dipolar in nature and, thus, a target is commonly located at the slope, rather than the peak, of an anomaly. This problem of target location renders the magnetic anomaly hard to interpret, particularly for a target made of many individual items such as drums and cans buried in these trenches. In contrast, it can be shown theoretically by a forward modeling that a GEM-2 anomaly is almost monopolar centered directly above the target and, consequently, is easier to interpret than dipolar magnetic anomalies.

Figure 10g is from an old facility engineering drawing that supposedly shows the trench locations. We do not know whether this old drawing was intended to show the design plan before, or the "as-built" map after, the trench construction. Regardless, it is obvious that the trenches implied by the GEM-2 data are significantly dissimilar from those indicated by the old map. In the end, we concluded that the GEM-2 data best depicts the current trench distribution; therefore, the geometrical boundaries determined from the GEM-2 data were used to compute the waste volume within the trenches. Each map, depicting the apparent conductivity derived from the in-phase and quadrature data at 1,350 Hz and 7,290 Hz, shows a slightly different picture of the trenches. Presumably, the low-frequency data indicates the deep trench structures, while the high-frequency data indicates the shallow trench structures. For plotting convenience, each conductivity map, Figures 10a through 10d, has an average conductivity value (noted on the top of the color scale bar) removed in order to balance the color distribution. The conductivity values may contain a constant offset resulting from imprecise calibration of the GEM-2 free-space response; the problem is being corrected.

Other Developments

Until now, the GEM-2 multifrequency data have been useful for: (1) scanning a broad EM band to insure target detectability, since a target may be better detected in a certain

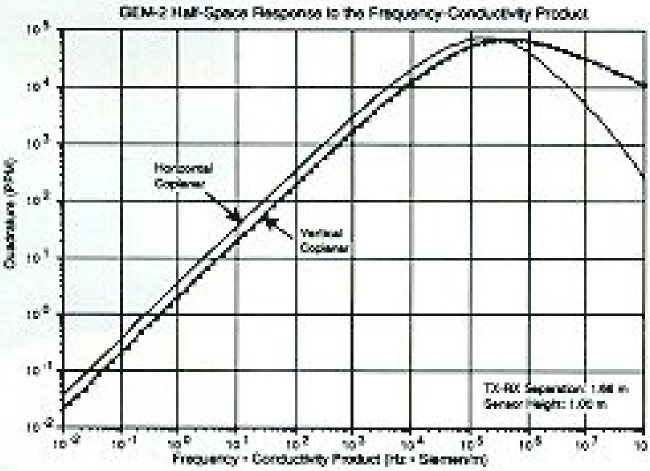

Figure 9. GEM-2 interpretation chart (quadrature) for converting ppm data to earth conductivity.

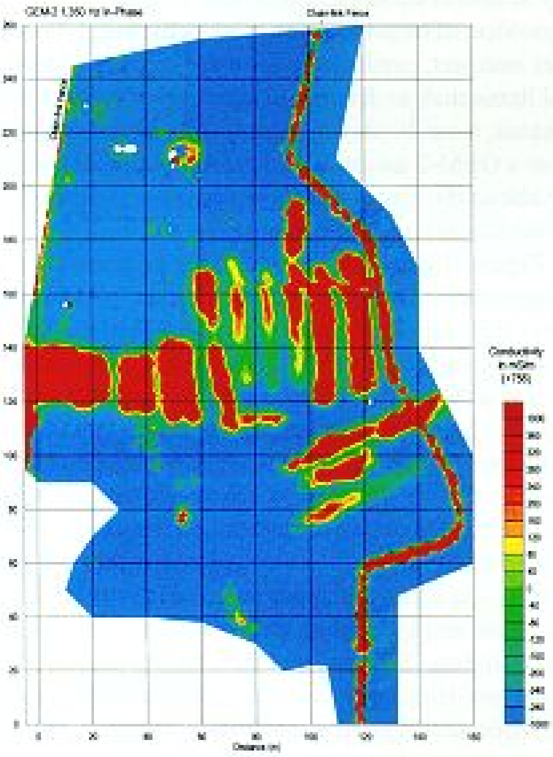

Figure 10a. GEM-2 in-phase data at 1,350 Hz over a 6-acre landfill.

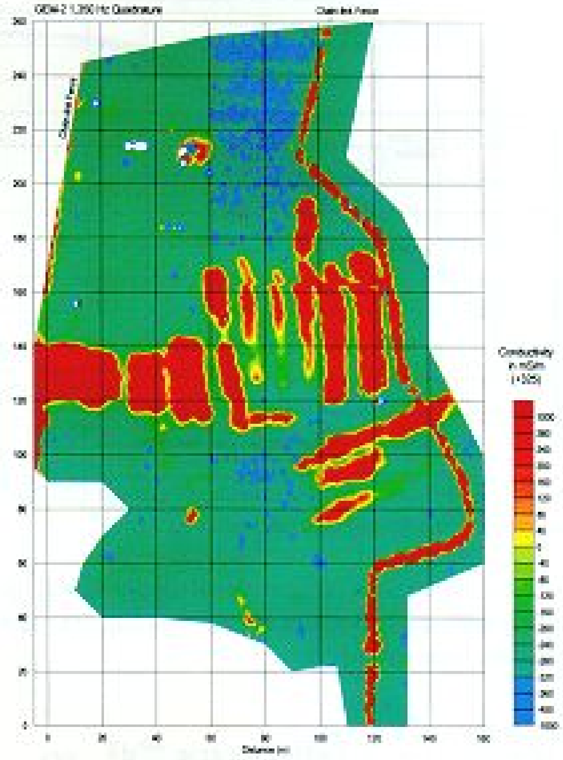

Figure 10b. GEM-2 quadrature data at 1,350 Hz over a 6-acre landfill.

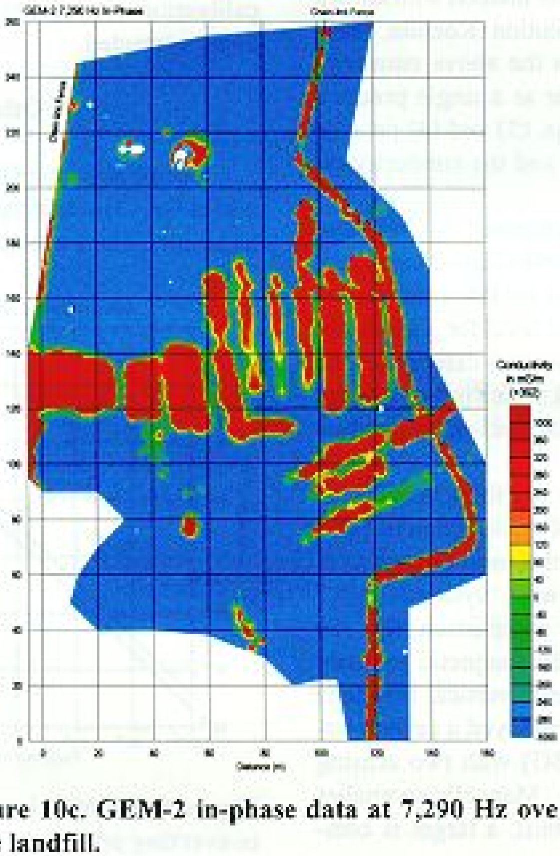

Figure 10c. GEM-2 in-phase data at 7,290 Hz over a 6-acre landfill.

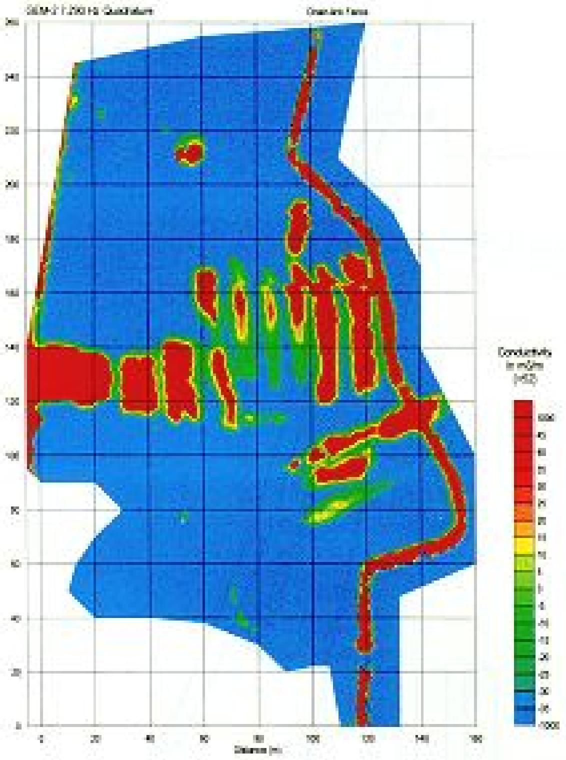

Figure 10d. GEM-2 quadrature data at 7,290 Hz over a 6-acre landfill.

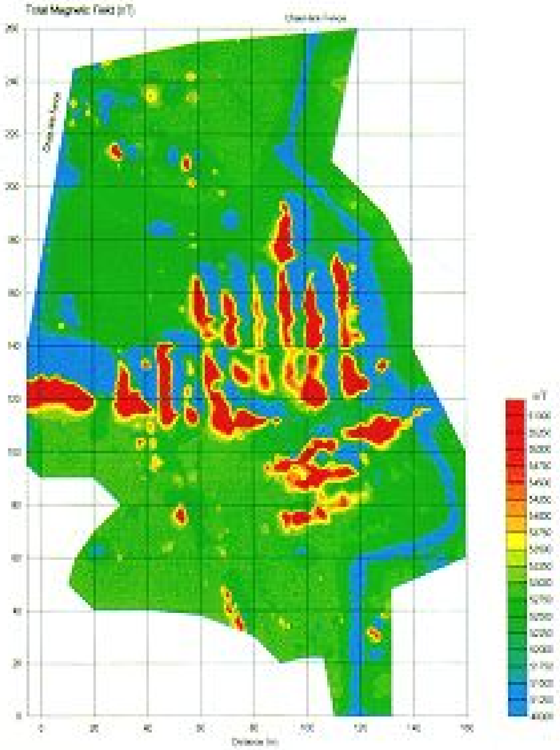

Figure 10e. Total-field magnetic anomaly map over a 6-acre landfill.

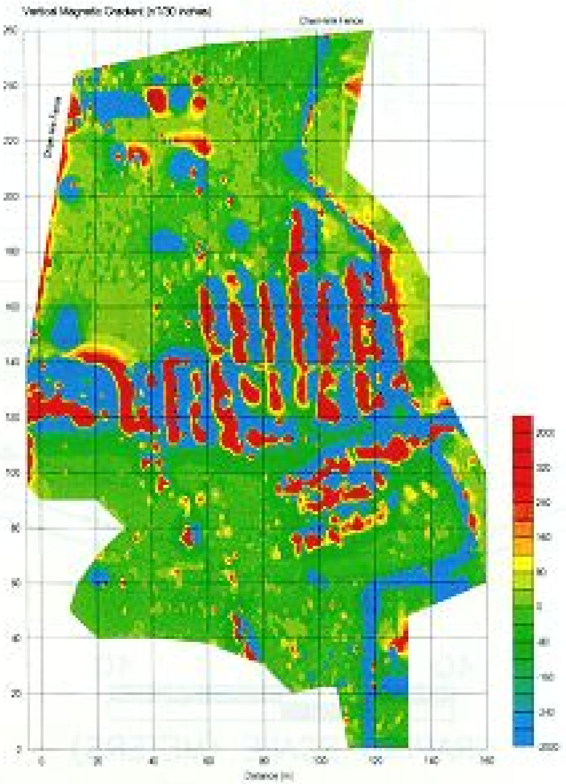

Figure 10f. Total-field, vertical, magnetic gradient anomaly map over a 6-acre landfill.

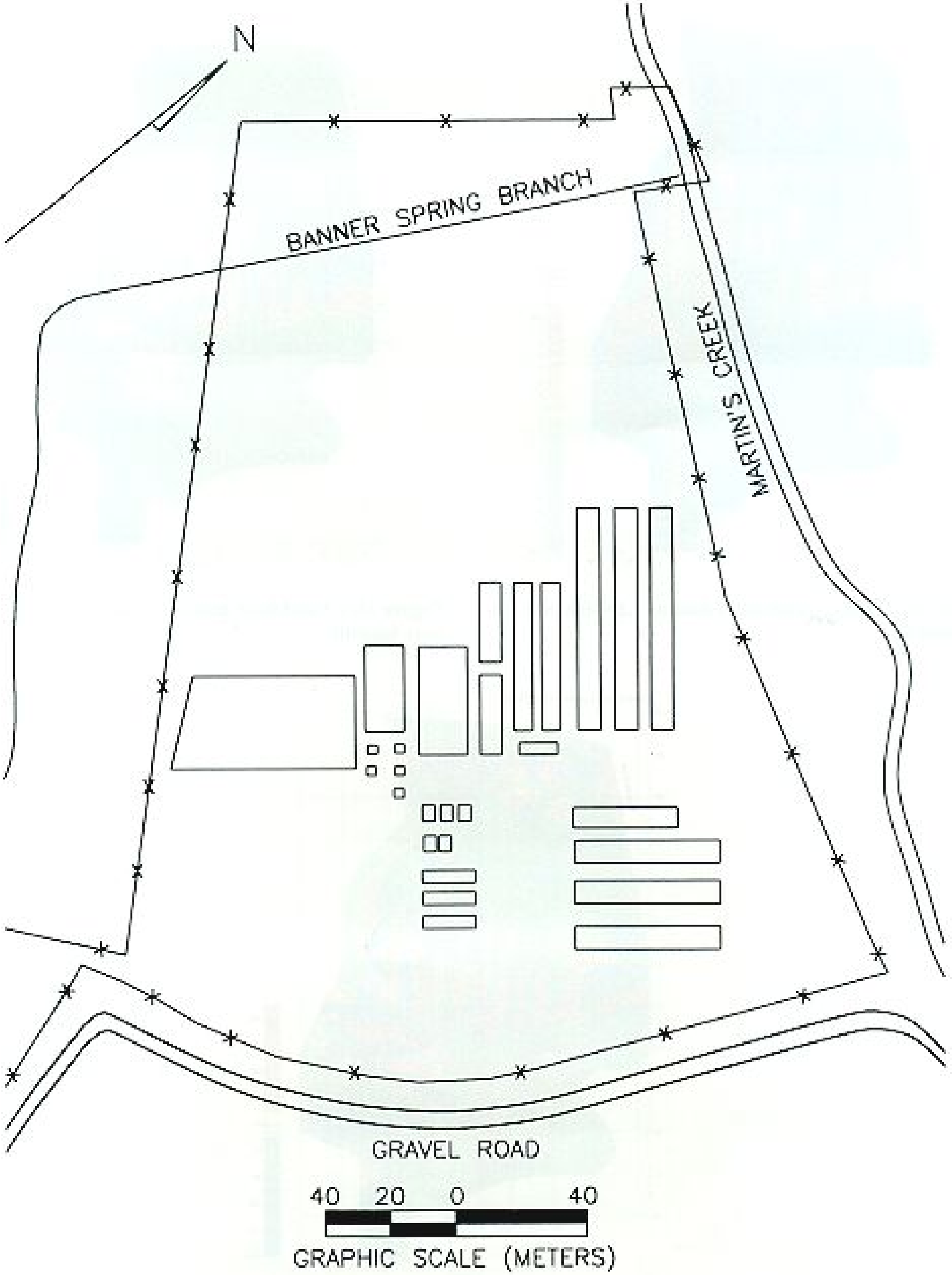

Figure 10g. 'As-built' trench map from old records for the 6-acre landfill.

frequency band than elsewhere; and (2) characterizing the 3-D geometry of a target from the broadband data. In most environmental surveys, the detectability issue addressed by the broadband (the main feature of GEM-2) is more important than resolving minute details of an individual target. A parallel effort, however, is given to the inversion of multifrequency data to produce the subsurface image of the earth. We take a two-prong approach: the multifrequency data can be principally used for: (1) imaging, preferably in 3-D, isolated targets such as buried drums, unexploded bombs, and tunnels; and (2) producing shallow geologic stratigraphic sections similar to those from reflection seismics. The two approaches are being pursued using different mathematical models. In co-operation with several scientists in the U.S. government and universities, we hope to advance this ambitious theoretical front in the near future.

The design principle of GEM-2 is now being extended to a monostatic (i.e., co-located transmitter and receiver coils) configuration, tentatively called GEM-3. All coils for GEM-3 are contained in a circular disk, a pancake-shaped package. Owing to the geometry, the transmitter dipole moment can be much larger than that of GEM-2 for a given sensor dimension. GEM-3, currently under a prototyping process at Geophex, would have improved thermal stability, a small data footprint, a high transmitter moment, and the mathematical beauty of its circular symmetry. Another effort is underway to raise the operating frequency for GEM-2 and GEM-3 to several hundred kHz, while still allowing the broadband operation, similar to an earlier sweep-frequency system by Won (1983).

Geophex has licensed Geophysical Survey Systems, Inc. (GSSI) in North Salem, New Hampshire, to produce a commercial version of GEM-2. GSSI, widely known for its commercial ground-penetrating radars, is planning to market GEM-2 worldwide in late 1996.

Conclusions

Of the many geophysical sensors, the EM method provides significant advantages for shallow environmental characterization. Unlike seismic or ground-penetrating radar methods that involve heavy logistics and labor-intensive field work, GEM-2 requires only a single operator, does not touch the earth (thus, is less intrusive), and can operate at stand-off distance. An instrument like GEM-2 is ideal for many environmental and geotechnical applications including mapping underground storage tanks, landfill and trench boundaries, certain contaminant plumes, and buried ordnance. In addition, GEM-2 has applications for finding shallow orebodies for the mineral exploration industry.

Despite many compelling advantages, the broadband EM method has not received sufficient attention from the geophysical community. With the advent of digital, multifrequency data, we have opened a new dimension in data quality and quantity for imaging and characterizing buried subsurface features. GEM-2 is only the beginning of a new generation of many broadband EM sensors.

Acknowledgments

The original funding for GEM-1 was provided to Geophex in 1991 by the U.S. Army Construction Engineering Research Laboratory in Champaign, IL. Prior to that, the Office of Naval Research funded the development of Geophex's helicopter-towed, multifrequency sensor, AEM-1, for shallow ocean bathymetric application. AEM-1 is still operational at the Naval Research Laboratory in Bay St. Louis, Mississippi.

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