GEOPHYSICS, VOL. 68, NO. 6 (NOVEMBER-DECEMBER 2003); P. 1888–1895, 7 FIGS.
10.1190/1.1635041

GEM-2A: A programmable broadband helicopter-towed electromagnetic sensor

I. J. Won*, Alex Oren*, and Frank Funak*

ABSTRACT

We present a new helicopter-towed broadband electromagnetic sensor, GEM-2A, for mineral prospecting and geologic mapping. The sensor uses one set of transmitter and receiver coils for a multifrequency operation. For a given survey, the user initially specifies a set of operational frequencies in the current bandwidth of 90 Hz to 48 kHz. The transmitter coil then emanates a current waveform that contains all specified frequencies. The duration of this current waveform, called the base period, is typically 1/30 s (a submultiple of local powerline frequency) resulting in an overall data rate at 30 Hz. Receiver channels digitize the secondary field into a time series over a base period, which is then subjected to discrete sine and cosine transforms or convolutions at each transmitted frequency to produce the raw in-phase and quadrature data. Additional convolutions may be included for passively monitoring environmental noise, including powerline emissions. The entire operation, including the system upload/download and realtime monitoring and communication, is done in Microsoft Windows.

The fact that the sensor contains only a single set of coils for the broadband operation provides several unique advantages, some of which include (1) corelatable and coherent drift characteristics among frequencies, (2) spectral integrity among frequencies that may be useful for anomaly classification and, possibly, mineral discrimination, (3) tolerance to sferics, (4) tolerance to powerline noise, and (5) light tow body with minimal cockpit hardware suitable for a small helicopter. This paper presents the sensor construction, operation, and data examples.

INTRODUCTION

The GEM-2A (Figure 1) is a rigid-beam, helicopter-towed electromagnetic (HEM) system. AMAX in Canada first flew such a system in 1955 followed by several systems, including the Barringer HEM system in 1967. Dighem, in the 1970s, introduced the first multifrequency and multiaxis HEM system (Fraser, 1978, 1979) that eventually established the modern HEM standards. Palacky and West (1991) and Fountain (1998) give excellent reviews on the history of HEM systems, as well as other airborne electromagnet (AEM) systems. In fact, a prototype of the GEM-2A was first built and flown in 1987 by the principal author (Won) and Geophex for the US Navy for an airborne bathymetric application. The GEM-2A described here is the most recent version that for the first time went into commercial production surveys in North America by Geophex in early 2002.

It may be appropriate here to justify the introduction of yet another HEM system in this seemingly saturated AEM market. All existing frequency-domain AEM sensors employ a set of transmitter and receiver coils in an inductor-capacitor (LC) tuned circuit, requiring such a set for each frequency of operation. For a five-frequency system, for instance, a typical HEM tow body (bird) carries 15 coils (one transmitter and two receivers for each frequency). Housing so many coils obviously makes the bird heavy and bulky, as well as rendering nightmarish wiring problems. Minimizing crosstalk among coils is another difficulty. Above all, because each frequency is operated by its own independent electronics, it is very difficult to calibrate the sensors 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), which is a voltage amplification factor at a particular frequency set by an inductor-capacitor tuning circuit. The Q of coils used in typical tuned HEM systems is 10–30. While a high Q conveniently provides the necessary signal strength, weaknesses abound: poor thermal stability; difficulty in independently calibrating each coil set; different drift characteristics for each coil, requiring arbitrary "leveling" and "microleveling" of each trace during post processing; and crosstalk among coils. Most

Manuscript received by the Editor October 24, 2002; revised manuscript received July 2, 2003.

*Geophex, Ltd., 605 Mercury Street, Raleigh, North Carolina E-mail: ijwon@geophex.com; oren@geophex.com; funak@geophex.com.

importantly, due to the independent behavior of each coil, it is difficult to calibrate the entire bandwidth so as to obtain a continuous and consistent broadband, electromagnetic (EM) spectrum.

The GEM-2A has been developed to address some of these weaknesses in the existing HEM systems. The goal is to produce a digital HEM system that can collect continuous broadband data that can be used to detect, characterize, and possibly identify a particular mineral deposit based on its spectral response. Specifically, the GEM-2A has been developed to address the following technical and operational improvements: (1) broadband multifrequency operation using a single set of

FIG. 1. GEM-2A sensor on the ground (bottom) and towed by a Bell Jet Ranger (top).

coils, (2) interfrequency spectral integrity, (3) predictable drift characteristics among all frequencies, and (4) light tow body and minimal cockpit instruments.

PRINCIPLE OF OPERATION

The GEM-2A employs a single set of three coplanar coils. The system works, in principle, in the time domain using a time-series analysis technique in each operational base period. For production surveys, the system has mainly been operated in a multifrequency mode.

Figure 1 shows the sensor on the ground and towed by a helicopter. Figure 2 shows the internal sensor layout. The tube, made of filament-wound Kevlar fibers, is about 6-m long and 50 cm in diameter. As indicated, the bird also contains a cesium-vapor magnetometer as well as auxiliary sensors such as a radar altimeter and global position system (GPS) navigation antennas. The GEM-2A in its operational principle is similar to the GEM-2 (Won et al., 1996), a handheld sensor developed and marketed by Geophex.

The sensor bandwidth, somewhat dependent on the environmental noise level, is generally between 90 and 48 kHz. The bird weighs about 120 kg, half that of traditional HEM birds. The cockpit contains a dc power supply, a GPS navigation screen for the pilot, and a laptop computer for two way digital communication with the bird. A computer in the bird performs all raw realtime signal processing; the tow cable carries the dc power and digital communication to and from the bird.

Figure 3 shows a functional block diagram of the GEM-2A. It has 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 the transmitter and low-noise signal amplifications for the receivers.

The coil, labeled Receiver 2 in Figure 2, serves two purposes. First, located near the transmitter, its output provides a transmitter reference in terms of its amplitude and phase. For this reason, its output is called the reference channel. Second, it is used to cancel the source field at the receiver coil and, for this reason, it is often called the bucking coil. The output of two coils, labeled Receiver 1 and Receiver 2, that are connected in series, but in an opposite polarity, constitutes the signal channel, which is designed to produce a vanishing output in free space by obeying the following bucking relation between the two coils:

$$\frac{A_1 n_1}{X_1^3} = \frac{A_2 n_2}{X_2^3}, \tag{1}$$

where A is the coil area, n is the number of turns, and X is the distance to the transmitter coil for Receiver 1 or 2 as indicated in Figure 2. The source-field bucking is necessary to reduce a strong primary field from the signal channel. The signal channel output, the response of the earth during a survey, is later normalized against the reference channel output through a complex division at each frequency, which constitutes the raw EM data stream. This bucking method typically reduces the primary field in the signal channel to less than 1%, or by about 40 dB. This, along with the 24-bit analog-to-digital conversion (ADC) resolution (144 dB), provides an overall system dynamic range of about 180 dB.

FREQUENCY-DOMAIN OPERATION

The system operation is programmable in the frequency domain (FD), the time domain (TD), or both. In FD operation, the operator initially configures the system using a laptop computer in a Microsoft Windows setup. The operator specifies a set of parameters for a particular survey such as a set of desired frequencies and the powerline frequency in the survey area. A processor in the bird stores these parameters for the survey duration. Based on the specified set of frequencies, the processor also builds a high-speed digital switching sequence—the *bit stream*—that produces a multifrequency current waveform in the transmitter. In a multifrequency FD operation, the transmitter current waveform $I(t)$ may be represented as

$$I(t) = \Sigma A_n \sin 2\pi f_n t, \tag{2}$$

which is a sum of sinusoids, each having an amplitude A_n at frequency f_n. The waveform lasts precisely over a *base period* that is selected to minimize the powerline noise. A typical base period is 1/30 s in a 60-Hz powerline area (e.g., the United States) and 1/25th of a second in a 50-Hz area (e.g., Australia). The base period may be lengthened or shortened by integral multiples. This selectable base period defines the basic data rate for a survey. Since the current waveform starts and ends at 0, each frequency selected must be a multiple of the base frequency. The current waveform specified by equation (2) is produced by

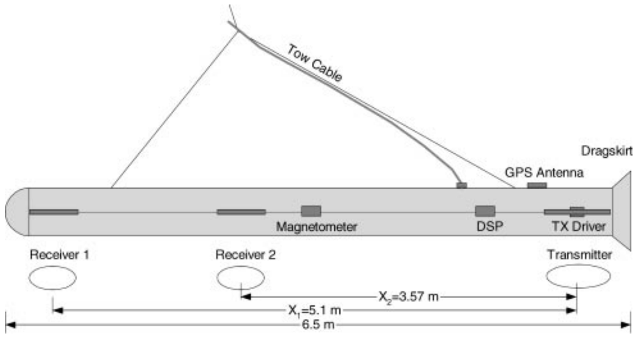

FIG. 2. GEM-2A internal construction. It has one set of three coils: a transmitter and two receiver coils. Note that the tow body also includes a magnetometer, an altimeter, and GPS antennas.

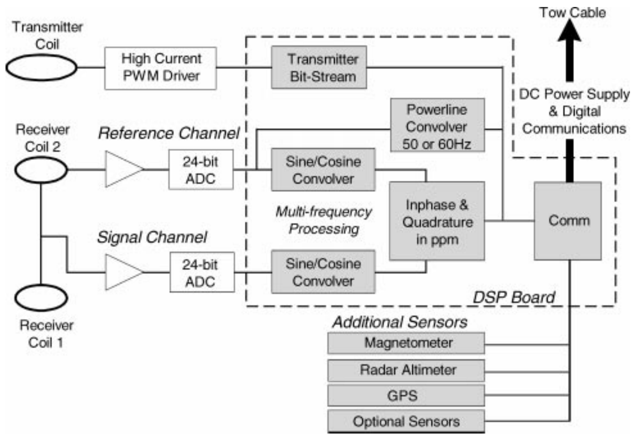

FIG. 3. GEM-2A electrical block diagram.

the bit stream that controls a bank of digital switches connected across the transmitter coil to produce the desired waveform.

Assume a base period of 1/30 s for the following discussion. The transmitter-switching rate is currently 384 kHz and, therefore, the bit stream has 12800 steps over a base period (i.e., 384 000/30) to make a desired current waveform. The transmitter coil radiates a vertical dipole field to the earth below. Figure 4a shows an example current waveform composed of seven frequencies, from 270 to 47 970Hz, over a base period. Clearly visible in the graph is the 270-Hz component that has nine (270/30) cycles in the base period. Higher frequencies are less noticeable. Figure 4b shows the first 40 points in a magnified detail; the "computed" curve is based on equation (2), while the "actual" curve is generated by the switching actions specified by the bit stream.

Figure 4c shows the amplitude spectrum of the current waveform, which indicates all seven frequencies included in the waveform. The noise floor in Figure 4c comes from the transmitter switching. Notice that the current is inversely proportional to frequency, as would be the resulting magnetic field generated by the coil. A reverse process occurs, however, in the receiver coil, where the induced voltage is proportional to the time derivative of the magnetic field and, thus, is proportional to frequency. Therefore, the spectrum of the signal channel in free space is more or less flat over the entire bandwidth.

Each channel in Figure 3, signal or reference, receives, amplifies, and digitizes its output into a time series lasting over the base period. The length of the time series is determined by the base period and the digitization (ADC) rate. The GEM-2A has an ADC rate of 96 kHz and, therefore, each time-series has 3200 points per base period of 1/30 s (i.e., 96 000/30). Both the signal and reference channels produce such a time series at every base period. The two times series constitute the first line of raw data from the system. The raw time series are available only on demand, simply because storing them continuously would require a large memory. If desired, the sensor can run passively as well (i.e., with the transmitter off), in which case a complete Fourier transform of the raw time series represents the environmental noise spectrum of a survey area within the system bandwidth. This feature can be useful for identifying and avoiding certain noisy frequencies in a given survey area.

In FD operation, each time series is subjected to a sine and a cosine convolution at each frequency. For a seven-frequency operation, for instance, the process would require 44 800 multiplications and additions (i.e., $3200 \times 7 \times 2$) per based period. A digital signal processor (DSP) in the bird performs the convolutions. The results from the signal channel are then normalized against those from the reference channel (complex divisions) to produce the real or in-phase (I) response and the imaginary or quadrature (Q) response in a dimensionless unit of parts-per-million (ppm), as defined by

$$\text{ppm} = 10^6 \frac{\text{secondary magnetic field at receiver coil}}{\text{primary magnetic field at receiver coil}}. \tag{3}$$

The system stores a set of I- and Q-data at all frequencies as the raw ppm data. Afterwards, the two time series are discarded. While the time-series processing goes on, the sensor now works for the next base period without interruption. The process repeats at every base period. Thus, the overall data rate

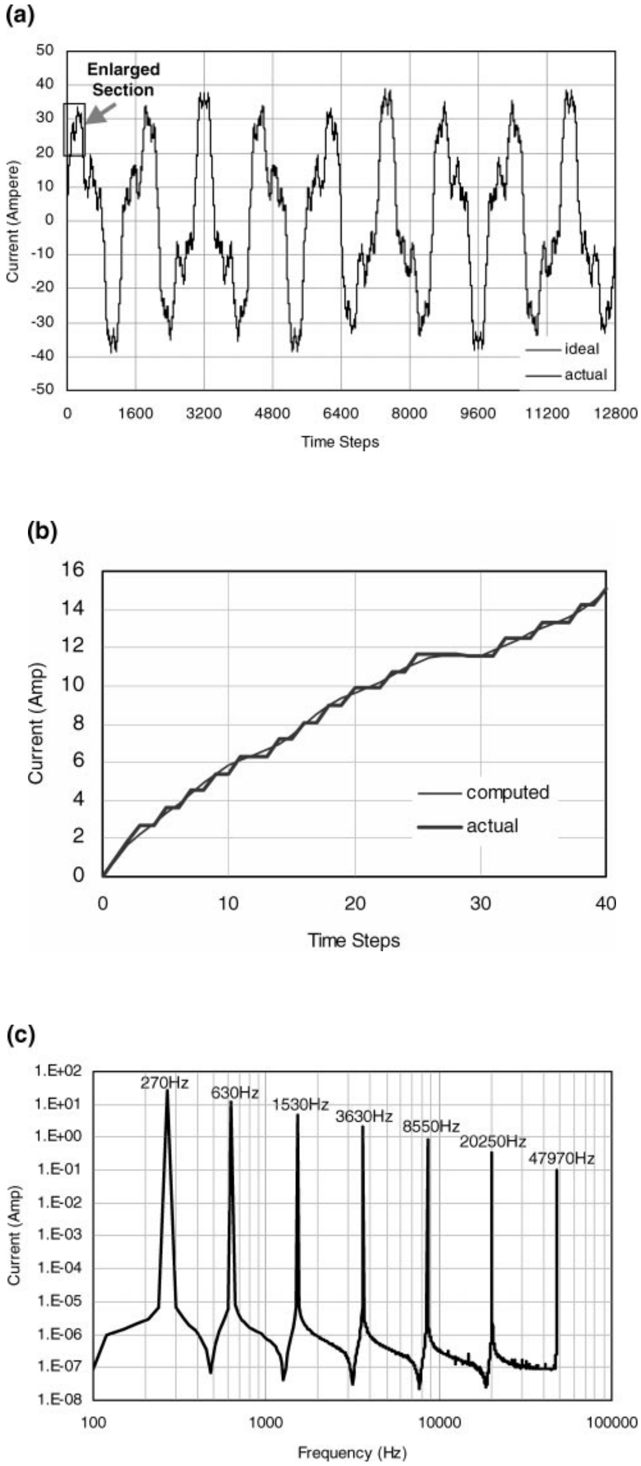

FIG. 4. (a) An example transmitter current waveform containing seven frequencies: 270, 630, 1530, 3630, 8550, 20 250 and 47 970 Hz. The waveform lasts for 1/30 second and contains 12 800 time steps over the duration. Note that 270 Hz is most prominent with nine cycles (270/30). Two graphs, labeled ideal (computed) and actual (PWM output), are practically identical and, thus, indistinguishable in this figure. (b) Enlarged section of (a) for the first 40 time steps. Two graphs, labeled computed and actual (PWM output), are now distinguishable in this figure. Each time step represents duration of 1/384,000 s. (c) Amplitude spectrum of the transmitter current waveform shown in (a).

is 30 Hz in this case, regardless of the number of frequencies used for the survey.

If desired, each base period may be programmed to accommodate multiple functions. For instance, the system may be turned off for a certain period, while other sensors may operate without interference. This feature allows colocating multiple sensors that cannot be activated at the same time. Similar operation may also apply to alternating between coplanar and coaxial coil configurations. Such operational versatilities may open up new possibilities in configuring active and passive sensors in a single package.

It is obvious from the time-series processing that the sensor can work equally well in the TD by using a transient waveform in the transmitter. The sensor can record two time series, one each from the signal and the reference channel, at a rate of 96 kHz or a time interval of about 10 μs. The transmitter dipole strength is an issue for a small source used by HEM sensors. There is a significant difference from the conventional TD system, which may compensate for a small transmitter moment: the GEM-2A bucks out the primary field, which enables the receiver coils to operate whether the transmitter is on or off. All existing TD sensors have difficulties in recording early time data due to a large decaying primary field. An obvious solution is to move the receiver coil far away from the source, or use a towed receiver, which results in uncertainties in the system geometry as well as added hardware logistics. Complete evaluation of the performance of a bucked TD system is yet to be made.

FIELD DATA EXAMPLES

The GEM-2A flew two regional surveys in 2002 for the U.S. Geological Survey (USGS) in Louisiana and Michigan. The surveys also included magnetics and, for Louisiana, radiometrics as well. Data examples from the Michigan survey, shown here, are not intended to describe the end products that are available in detail from Abraham and Duval (2003), but merely to present the general nature of the EM data. The Michigan survey was carried out as part of the Central Great Lakes Geologic Mapping Coalition, is a collaboration between the USGS and the state geological surveys of Illinois, Indiana, Michigan, and Ohio. The four states have a similar geology and need to address common societal issues by pooling their expertise and resources about land and water resources, the environment, and geologic hazards. The goal is to produce 3D geologic maps that can be used to study groundwater, mineral resources, contaminant flow paths, and potential hazards.

The GEM-2A data here are from a southern part of Berrien County in southwestern Michigan, a rural, but heavily populated, area. A specific goal here is to determine the depth of the conductive basement to understand the juxtaposition of the complex glacial deposits. Coupled with surface geophysics, drill data, and detailed surface mapping, the airborne data are used to produce a regional 3D geological map of the area.

The survey was flown east-west over an area of approximately 12 km × 18 km at an north-south line spacing of 320 m. Commensurate with population, the survey area has dense powerline grids along with at least two major north-south transmission lines at a height of about 50 m. Many smaller powerlines are 10–30 m high in this area. The survey helicopter, flying at a nominal altitude of 60 m (~200 ft), towed the bird at 30 m above the ground using a 30-m tow cable. Every time the aircraft encountered a powerline, therefore, it had to increase its altitude in advance to avoid the powerline. This caused degradation in data quality, particularly at high frequencies. Also inevitable were many flightline deviations over several towns with tall buildings, water tanks, and radio towers scattered throughout the survey area.

The operating software includes a built-in converter from the ppm data to apparent half-space resistivity at each frequency. Figure 5 shows a set of apparent resistivity maps at five frequencies: 390, 1290, 4470, 15 540, and 46 470 Hz. Two strong north-south linear anomalies in the middle section, particularly at high frequencies, are attributed to the powerlines. The maps have varying contour levels and color bars for display purposes; notice that the apparent resistivity appears to generally decrease with frequency and, thus, with depth in this example. Preliminary results showed good agreements between the basement depths that are independently computed from the airborne GEM-2A data shown here and ground time-domain EM data and drill hole data at selected locations (Jared Abraham, USGS, personal communication, 2002).

From the discussion on the time-series processing, it is obvious that this system can be used as a passive sensor. In other words, the system may operate without the transmitter. Through a Fourier transform of the time series over a base period, the system can obtain continuous spectral profiles of the ambient EM field. In fact, the sensor has been used passively for many different applications, particularly for studying EM interference sources in a given locality.

An obvious application in an HEM survey is to monitor the powerline noise in a survey area, so as to distinguish natural anomalies from man-made disturbances. The time series from the receiver coils are simply convolved with the powerline frequency of the survey area. The GEM-2A contains in its raw data stream the amplitude of the powerline noise in a magnetic field unit of gauss. The data may be used to produce a map of powerline contamination of the survey area. Figure 6 shows the 60 Hz powerline strength obtained from the same survey area in Figure 5. All linear highs represent powerlines in the survey area. We notice strong correlations between Figures 5 and 6, particularly at high frequencies.

In an area where the powerline noise may seriously affect the data quality, particularly in an urban setting, the sensor may be initially operated in a passive mode to obtain complete environmental noise spectra of the area. Often, the noise spectra manifest quiet frequency bands that may be selected for the actual survey, thus avoiding those noisy frequency bands in the area.

EM INDUCTION SPECTROSCOPY

The fact that the GEM-2A uses a single set of coils for multiple frequencies makes the system somewhat more predictable in its operational characteristics than the conventional HEM sensors in which each frequency is generated by a different set of tuned coils. One of the important outcomes is that the system can produce consistent broadband spectral profiles. This is because all frequencies share common coil parameters (inductance, resistance, and decay-time constant), geometric stations, and front-end analog electronics.

Therefore, once digitally calibrated using a known target (such as a coil with known electrical properties or a ferrite rod), the system can measure spectral responses of any other targets, including that of orebodies. This ability to collect calibrated EM induction (EMI) spectra renders a possible means of detecting, characterizing, and identifying a particular mineral deposit, all in a single survey, by its spectral EM response. The basic idea is somewhat similar to a variation of the induced polarization method, called spectral IP, using electrodes planted in the ground, which, of course, cannot be done from the air.

EMI spectroscopy (EMIS) is a method of identifying a buried metallic object such as a landmine, based on its spectral response (Won et al., 1998, 2001). Most metal detectors can detect small metal pieces such as landmines, but cannot effectively discriminate a landmine amid ubiquitous false alarms in a cluttered environment. The same idea may apply to identifying mineral deposits using a broadband HEM system.

When an electrically conductive and/or magnetically permeable object (e.g., landmine, orebody) 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, which is the concept of EMIS. By using the EMIS responses from known or producing deposits as fingerprints, we look for locations having similar spectra within a local mineral province.

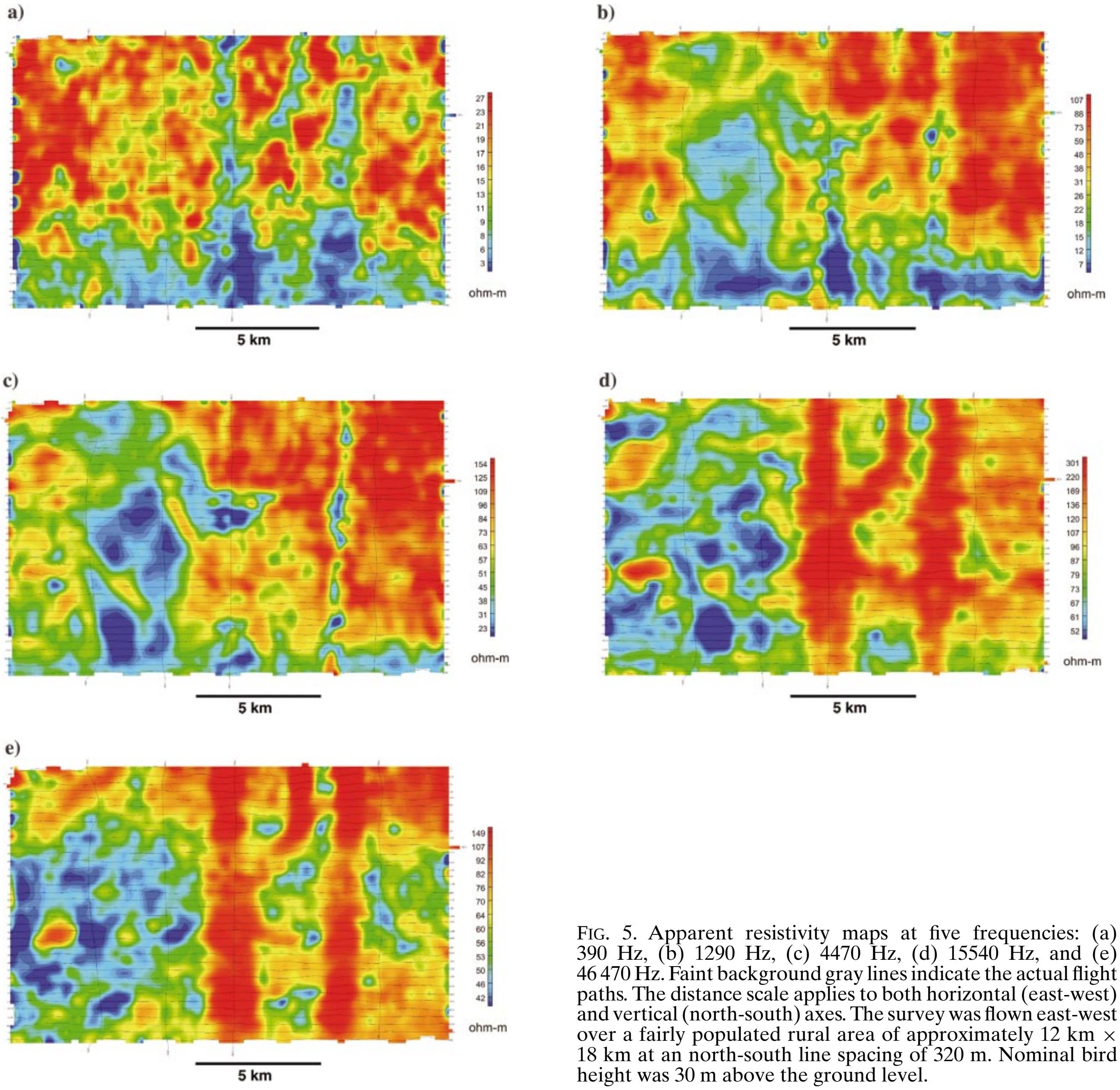

FIG. 5. Apparent resistivity maps at five frequencies: (a) 390 Hz, (b) 1290 Hz, (c) 4470 Hz, (d) 15540 Hz, and (e) 46 470 Hz. Faint background gray lines indicate the actual flight paths. The distance scale applies to both horizontal (east-west) and vertical (north-south) axes. The survey was flown east-west over a fairly populated rural area of approximately 12 km × 18 km at an north-south line spacing of 320 m. Nominal bird height was 30 m above the ground level.

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 multichannel TDEM sensors to measure decay patterns. TD 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 repeatedly argued that the FD and TD measurements are equivalent, practical hardware limitations have separately sustained the two systems, with pros and cons on each side.

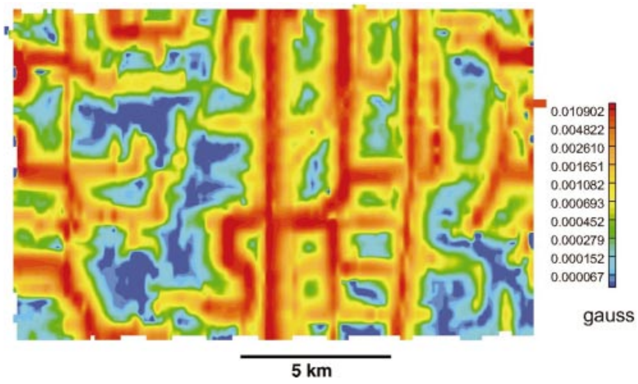

FIG. 6. The 60-Hz magnetic field amplitudes (in gauss) in the survey area. All linear highs are related to powerlines.

Figure 7 shows the GEM-2A data collected over a kimberlite deposit in Australia using three frequencies: 1325, 4925 and 11 025 Hz. The map shows the apparent conductivity at 4925 Hz. 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 similar. While high conductivity may indicate a possible kimberlite target, it alone does not provide enough clues. For instance, locations C and D that exhibit similar conductivity highs but are not kimberlite, show spectra that are dissimilar to those from A and B.

EMIS may provide a means of identifying a mineral deposit. The idea is to use 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 responses. We can show that certain features of an EMIS fingerprint are invariant to

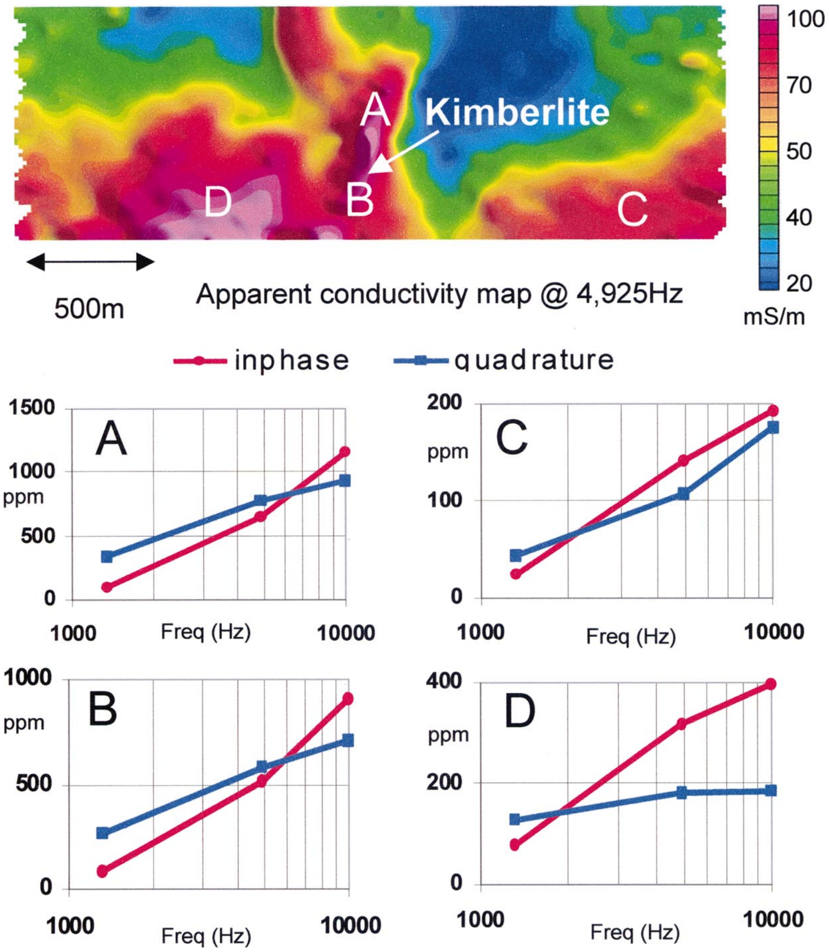

FIG. 7. Conductivity map at 4925 Hz derived from GEM-2A data obtained in Australia, and three-frequency spectra (1325, 4925, and 11 025 Hz) extracted from points A, B, C, and D. The feature over A and B (notice their spectral similarity) is a known kimberlite pipe, whereas C and D are not.

many parameters, such as the size and depth for a spherical body and the survey direction across a sheetlike body. Such parametric invariance is the basis for potential EMIS identification. An example of a 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.

CONCLUSIONS

The GEM-2A HEM system represents a new generation of programmable, broadband, AEM sensors. It uses a single set of coils to generate and receive all frequencies based on a real-time time-series analysis technique. It is specifically designed to minimize powerline-induced noise. The system is software driven and can be reconfigured to different operational modes in a Windows environment. One such example may be a dual-mode operation, alternating between FD and TD modes. It can also be used as a passive sensor to obtain environmental noise spectra. Because of the light bird weight and minimal cockpit equipment, the system should perform well for high-altitude surveys or with small helicopters.

The fact that this system uses a single set of coils for transmitting and receiving all frequencies makes it somewhat more predictable in its operational characteristics (e.g., drift) than the conventional HEM sensors in which each frequency is generated by a different set of tuned coils. One of the important outcomes is that the system can produce consistent broadband spectral profiles. This spectral integrity renders a potential means of detecting, characterizing, and identifying a particular mineral deposit, all in a single survey, by its spectral EM response—known as EMIS. The idea is to use the EMIS spectra from known deposits as fingerprints to look for similar bodies in a local geologic province. Such spectral identification can be a powerful tool for future mineral prospecting; the GEM-2A provides a means to explore such possibilities.

ACKNOWLEDGMENTS

We acknowledge the USGS in Denver, Colorado, for allowing the use of the GEM-2A data in this paper. In particular, Jared Abraham, the USGS project manager provided paragraphs explaining the purpose and rationale of the survey in the “Field Data Examples” section. We thank Victor Labson, Bruce Smith, and David Fitterman of the USGS for their comments and encouragement.

REFERENCES

Abraham, J. D., and Duval, J. S., 2003, Helicopter electromagnetic, magnetic, and gamma-ray survey in southwestern Berrien County, Michigan: U.S. Geological Survey Open File Report, in press.

Fountain, D., 1998, Airborne electromagnetic systems—50 years of development: Expl. Geophys., **29**, 1–11.

Fraser, D. C., 1978, Resistivity mapping with an airborne multicoil electromagnetic system: Geophysics, **43**, 144–172.

———1979, The multicoil II airborne electromagnetic system: Geophysics, **44**, 1367–1394.

Palacky, G. J., 1976, Use of decay patterns for the classification of anomalies in time-domain AEM measurements: Geophysics, **41**, 1031–1041.

Palacky, G. J., and West, G. F., 1991, Airborne electromagnetic methods, *in* Nabighian, M. N., Ed. Electromagnetic methods in applied geophysics: Soc. Expl. Geophys., **2**, 811–877.

Won, I. J., 1983, A sweep-frequency electromagnetic exploration method, *in* Fitch, A. A., Development of geophysical exploration methods-4: Elsevier Applied Science Publishers, 39–64.

Won, I. J., Keiswetter, D. A., and Bell, T. H., 2001, Electromagnetic induction spectroscopy for clearing landmines: IEEE Trans. Geoscience and Remote Sensing, **39**, 703–709.

Won, I. J., Keiswetter, D. A., Fields, G., and Sutton, L., 1996, GEM-2: A new multi-frequency electromagnetic sensor: J. Environ. Engin. Geophys., **1**, 129–137.

Won, I. J., Keiswetter, D. A., and Novikova, E., 1998, Electromagnetic induction spectroscopy, J. Environ. Engin. Geophys., **3**, 27–40.