Sub-Audio Magnetics. Miniature Sensor Technology for Simultaneous Magnetic and Electromagnetic Detection of UXO

John M Stanley and Stephen M Griffin
Geophysical Technology Limited
P O Box U9 Armidale NSW 2351 Australia
E-mail: jstanley@geotec.com.au

ABSTRACT

Sub-Audio Magnetics (SAM) is a technology with which time domain electromagnetic response and total field magnetic intensity may be simultaneously acquired using an optically pumped type magnetometer sensor (or array of such sensors). Data acquisition effort and false alarm rate are recognized as the two major cost drivers in the remediation of buried military and industrial waste. Magnetic detector systems generally involve least data acquisition effort, are suitable for use in all terrain conditions but they detect only ferrous items and their false alarm rate is severely affected by adverse geological conditions. Electromagnetic detectors are usually slower and more cumbersome to use, have reduced detection depth and are applicable only to even, unvegetated ground conditions. However electromagnetic detectors have the advantages that they are relatively immune to geology, they respond to all metal types and they can provide data that is more diagnostic of target shape and type. By acquiring coincidently registered magnetic and electromagnetic data in a single operation that delivers the same spatial resolution and that is nearly as efficient as acquiring magnetometer-only data, SAM delivers the best attributes of both detector systems.

Key to the SAM detector is a magnetometer processor that can acquire total field magnetic intensity measurements from an optically pumped cesium sensor at programmable rates of up to 8 kHz at nominally 1nT resolution and up to 10Hz at 1pT resolution.

A SAM survey requires first laying out a wire loop surrounding a search area that may extend over many acres. Current from a time-varying square wave source at typically 8Hz frequency ("sub-audio") is transmitted through this loop providing an excitation field of around 1A/m. This field is constant throughout the penetration depth of UXO resulting in deep targets becoming energized as much as shallow ones, an attribute that greatly improves detection depth. For HERO safety purposes, 1A/m compares very favorably with the 500A/m field of an EM-61 and unlike when using an EM-61, over-current may be applied for a period of time before personnel enter the survey area.

Hand-held, vehicle towed or even low elevation airborne survey data are then acquired along typically parallel transects as for a conventional magnetic or electromagnetic investigation. However, the signal received is separated into low-pass and high-pass streams. The low-pass signal provides the conventional magnetic response and may be recorded at appropriate distance or time intervals consistent with established sampling requirements. The high-pass data contains the transient electromagnetic response resulting from every energizing cycle. This may be measured in variable time-window samples commencing 125µS after each cycle enabling items as small as a 20mm projectile to be detected.

GTL has now trialed a "concept demonstrator" SAM receiver on a UXO test site and this has confirmed that the detection performance predicted from theory is achievable in practice.

INTRODUCTION

After extensive trials of UXO detection technologies hosted by the US Army Environmental Center during the 1990's (Robitaille et al, 1999) two technology types stood out as most generally applicable. These were electromagnetic induction (EMI) and total field magnetometer detector systems. EMI detectors are usually slower and more cumbersome to use, have reduced detection depth and are generally applicable only to relatively even, un-vegetated ground conditions. However EMI detectors have the advantages that they are relatively immune to geology, they respond to all metal types and they can provide data that is more diagnostic of target shape and type. Magnetic detector systems generally involve least data acquisition effort, are suitable for use in all terrain conditions but they detect only ferrous items and their false alarm rate is severely affected by adverse geological conditions.

Having established which technologies were capable of meeting the acceptable standards of detection, the next challenge was to deliver remediation at an affordable cost. Data acquisition effort and the detection false alarm rate are recognized as two major cost drivers in the remediation of buried military and industrial waste. Sub-Audio Magnetics (SAM) is now being developed for the purpose of reducing both data acquisition effort and the occurrence of false alarms. There are indications that it will also improve detection performance

Sub-Audio Magnetics is a technology with which time domain total field electromagnetic response (TFEM) and total field magnetic intensity (TMI) may be simultaneously acquired using an optically pumped type magnetometer sensor or array of such sensors (Cattach et al, 1993, Cattach and Stanley, 1993). The spatial resolution and survey efficiency of SAM rival that of a magnetometer-only survey. In simultaneously acquiring and jointly inverting the two most diagnostic detection data types the false alarm rate may be significantly reduced.

SAM has been very successfully used in mineral exploration applications since 1994 using GTL's TM-4 magnetometer technology. In a feasibility investigatio n n of the application of SAM to UXO detection, Boggs (2000) proved that the concept worked. Specifications for a SAM receiver capable of detecting a 20mm diameter electromagnetic source were then developed and a prototype has now been built.

THE SAM FIELD SURVEY METHOD

A SAM survey requires first laying out a wire loop surrounding the search area as shown in Figure 1. This loop may extend over many acres. Current from a time-varying square-wave source, typically 20Amp, 50% duty cycle at 8Hz frequency ("sub-audio") is transmitted through this loop. This transmitted current is synchronized to GPS time. Survey data, also synchronized to GPS time, are then acquired within the loop in the same manner as for a conventional, total field magnetic survey using hand-held or vehicle towed, single-sensor or multi-sensor array configurations. Usually the survey will extend to within 10m of the energizing coil.

THE SAM RECEIVER

Key to the SAM detector is a magnetometer processor that can acquire total magnetic field intensity measurements from an optically pumped cesium sensor at programmable rates of up to 8 kHz at nominally 1nT resolution and up to 10Hz at 1pT resolution. With this capability and synchronization to the energizing source, the entire electromagnetic decay may be recorded with optimal signal-to-noise ratio. TFEM data are positioned using DGPS or alternate system, and recorded at intervals appropriate to the survey objectives (typically 8 measurements per second).

In a second processing stream the measured magnetic signal is low-pass filtered to remove the influence of the time-varying source. The conventional TMI measurements precisely positioned with the TFEM data are then also recorded.

PERFORMANCE ADVANTAGES OF SAM

Electromagnetic Detection Depth

Beyond 10m from the transmitting coil the excitation field strength is very uniform and typically around 1A/m in strength. Of major importance is the fact that this energizing field is constant throughout the expected depth of penetration of UXO, resulting in deep targets becoming energized as much as shallow ones. This attribute greatly improves the electromagnetic detection depth when compared to roaming coil type detectors such as the Geonics EM-61 and EM-63 and the Geophex GEM-3 where the energizing field at 2m depth is up to 8 times weaker than at 1m depth. In a feasibility study using SAM, Boggs (2000) showed an inverse 1.5 power signal decay with depth for Mk82 bombs buried at depths between 0.5 and 4 meters. This compares most favorably with an inverse 4th to 6th power for conventional moving coil type detectors and the improvement obtained in detection depth is substantial. (Doubling the depth of the target reduces the conventional EMI signal by between 16 and 64 times while the SAM signal is only reduced by between 2.8 and 4 times.)

Electromagnetic Immunity to Geology

Unlike moving coil type EMI detectors, SAM measures the step-response amplitude of the electromagnetic field vector (the TFEM or “B” field) rather than its time derivative. The advantages of measuring the TFEM field in terms of signal strength and frequency response are well documented in the literature (Gupta Sarma, D. et al, 1976, Smith and Wolfgram, 1998). For example, because there is greater attenuation of the early time response (dominated by the ground) and amplification of the late time response (dominated by strong, metallic conductors) the TFEM field measurement results in a signal that has a greater signal-to-noise ratio and which is independent of the magnetic properties of the ground. In contrast, because moving coils respond inductively to passing through a spatially changing magnetic field, coil type detectors are relatively sensitive to magnetic “hot” rocks and soils.

Higher Resolution

The SAM receiver measures the anomalous TFEM field at a discrete point. In contrast, coil based receivers measure a flux density that is averaged over the area of the detector (1 square meter in the case of an EM-61). This averaging adversely affects the spatial resolution of objects that are closer together than the dimension of the coil. In measuring the precise TFEM field at each closely sampled point the SAM receiver is both better able to resolve close objects and better able to characterize each target response when spatial variation is considered in the data analysis.

Better Discrimination

The SAM system is able to utilize all of the available data processing techniques currently being used to provide discrimination using magnetic and EMI data. However, the application of these methods to SAM data can be more successful because of the advantageous data quality features such as the TFEM step response measurement, large energizing loop and the joint inversion of coincidently registered TFEM and TMI data.

The high spatial resolution, high signal-to-noise ratio and the use of a large loop (constant field) provide the opportunity to apply Fourier Domain methods to accurately extract the three components (x, y and z) from the total field measurement. Some other EMI systems provide this type of data through the use of three orthogonal receiving coils. However this type of apparatus is relatively cumbersome. Moreover, the coils must be very rigidly constructed to remain perfectly aligned during field operation otherwise the data will become noisy. Most 3-component systems must also be precisely leveled before every measurement.

SAFETY CONSIDERATIONS

Occupational Health and Safety is a concern whenever active detector systems are used where UXO containing electronic fuse systems may be encountered. Under typical conditions the electromagnetic field 0.1m from a SAM energizing coil is about 300 A/m and throughout most of the area within being investigated it is about 1A/m. For safety purposes, both these values compare very favorably with the 500A/m field of an EM-61. However, unlike when using an EM-61, before personnel enter the survey area an over-current may be applied for a period of time.

FEASIBILITY STUDY RESULTS

The results of a feasibility study conducted using a TM-4 magnetometer sampling at 400 measurements per second to 0.08nT resolution are presented in Figures 2 and 3. In this study, a Zonge GGT-10 current transmitter delivering a 50% duty cycle, 8Hz square wave of 15Amp peak current energized a two-turn current loop measuring 110m x 110m.

In this feasibility study the survey area contained an assortment of UXO types and various depths. As can be seen from the TMI data in Figure 2 the location also contains relatively high levels of magnetic disturbance from laterite minerals in the soil. The disturbance within the circled areas marked “L” is due only to laterite. Figure 3 shows the SAM TFEM data over the same area. The immunity to interference from the laterite is evident.

Due to the sampling limitations of the TM-4, only targets larger than the fin of a Mk82 bomb were detectable from this TFEM data. However, the TFEM response from a Mk 82 bomb buried at 4.2m (anomaly number 12) is clearly detected. This is detection performance significantly exceeds that of an EM-61 which can only be expected to detect a Mk 82 bomb to a depth of 2.5m.

As a consequence of this feasibility study, the sampling specifications required to detect an object as small as 20mm were defined and a prototype of a counter able to achieve this has now been built.

REFERENCES

Boggs, D. B, (2000)
“The theory and application of Sub-Audio Magnetics data acquisition and numerical modeling”
PhD Thesis, University of New England, Armidale, Australia

Cattach, M. K. and Stanley, J.M., (1993)
“Method and apparatus for simultaneously collecting spatially and temporally varying magnetic survey data”
US Patent No: 5,444,374

Cattach, M.K., Stanley, J.M., Lee, S.J. and Boyd, G.W. (1993)
“Sub-Audio Magnetics(SAM) – A High Resolution Technique for Simultaneously Mapping Electrical and Magnetic Properties”
Exploration Geophysics, **24**, 387-400

Gupta Sarma, D., Maru, V. M. and Varadarajan, G., (1976)
“An improved pulse transient electromagnetic system for locating good conductors”.
Geophysics, 40, 287-299

Robitaille, G., Adams, J., O’Donnell, C and Pope, B. (1999)
“Jefferson Proving Ground Technology Demonstration Program Summary”

Army Environmental Center Report Number: SFIM-AEC-ET-TR-99030

Smith, R. and Wolfgram, P., (1998)
"The use of B-field in conductive regime."
Proc. Airborne Electromagnetics, Sydney, February 23-25.

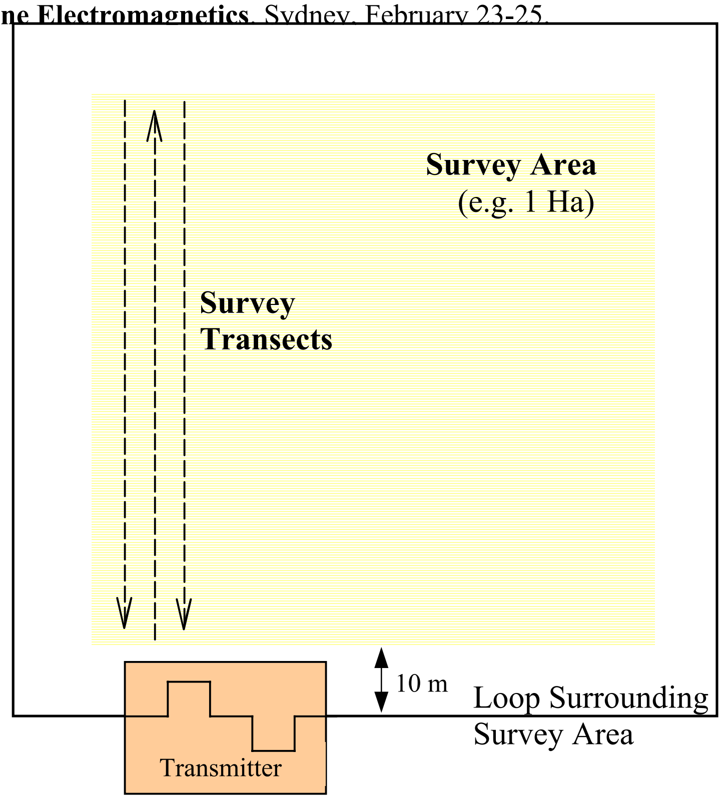

Figure 1. The field layout for conducting a Sub-Audio Magnetics survey for detecting buried unexploded ordnance. The survey area may be up to many acres in area and need not be rectangular in shape.

ID Number	Target Source	Depth Below Sensor
1	Mk 82 Bomb	2.2m (86")
2	Mk 84 Bomb	4.3m (168")
3	Mk 82 Bomb	3.2m (125")
4	Mk 82 Bomb	1.0m (39")
5	Mk 82 Fin	1.2m (47")
6	Mk 84 Bomb	3.7m (144")
7	Mk 82 Bomb	2.8m (109")
8	5" Rocket Motor	0.8m (31")
9	2 x Mk 82 Bombs	2.0m (78")
10	Mk 82 Bomb	3.6m (140")
11	Mk 82 Bomb	3.6m (140")
12	Mk 82 Bomb	4.7m (183")
13	Mk 82 Bomb	2.0m (78")

Table 1. The list of UXO items detected by the TFEM component of the Sub-Audio Magnetic data at the test site where the SAM feasibility study was performed. The number identifying each item was labeled on the SAM TMI and TFEM data images in Figures 2 and 3. The depths shown are the depth below the sensor which in this case was operated 0.5m above ground.

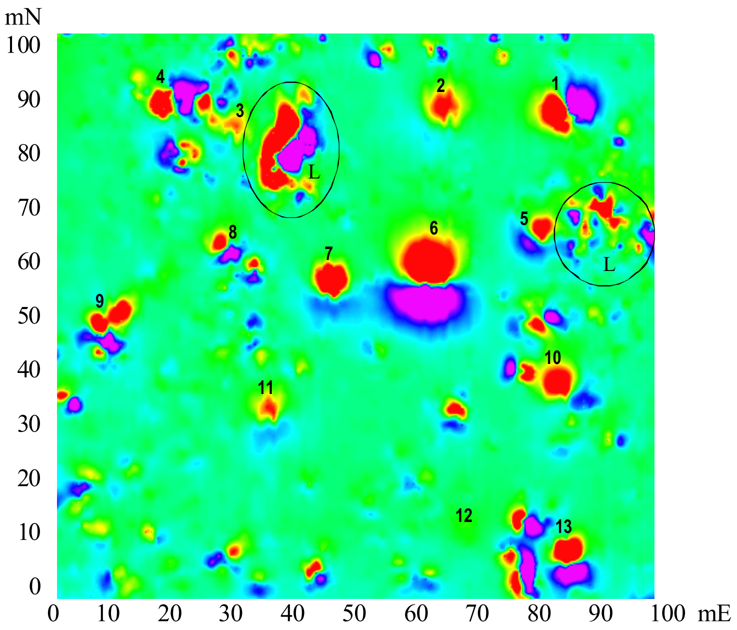

Figure 2. Color image of the total field magnetic intensity (TMI) acquired during the feasibility trial of the Sub-Audio Magnetics method. Numbered are the buried UXO items listed in Table 1. The areas circled and labeled “L” contain examples of magnetic interference from near surface laterite (“hot rocks”) occurring at this site.

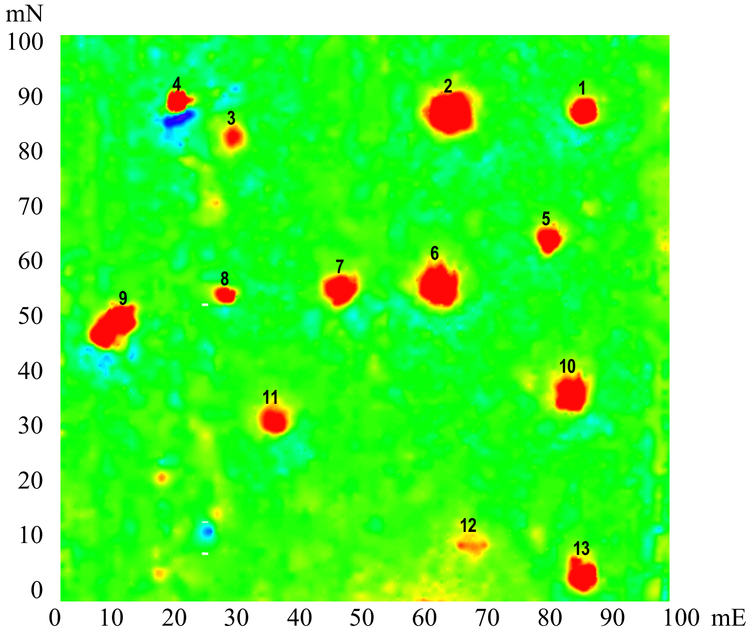

Figure 3. Color image of the total field electromagnetic (TFEM) response acquired during the feasibility trial of the Sub-Audio Magnetics method. Numbered are the buried UXO items listed in Table 1. Relative immunity to interference from laterite is evident in this data. Note that anomaly 12 is due to a Mk 82 bomb buried 4.2m below ground (4.7m below the sensor). This detection depth is nearly twice that expected from an EM-61 detector.