

A NEW VERY HIGH SENSITIVITY POTASSIUM MAGNETOMETER FOR NEAR SURFACE GEOPHYSICAL MAPPING

Dr. Ivan Hrvoic, Greg M. Hollyer and Mike Wilson (GEM Advanced Magnetometers., Richmond Hill, Ontario), and Dr. Anthony Szeto (York University, Toronto, Ontario)

Abstract

Trends in Archaeology; Environmental and Engineering; and Unexploded Ordnance Detection fields indicate the role of near surface geophysical methods is migrating from “anomaly detection” to “high detail” mapping. Accordingly, there is a parallel requirement for instrument manufacturers to develop equipment capable of resolving targets more effectively.

In the 90’s, GEM developed an Overhauser magnetometer system that met many of the requirements for “high detail mapping”, including high sensitivity, absolute accuracy and minimal orientation errors in walking surveys. Now, this work has been extended with the development of a new Potassium magnetometer / gradiometer for very high sensitivity and vehicular work.

This paper reviews two key types of quantum magnetometers (Overhauser and Optically Pumped) – focusing on the development and field testing of GEM’s new Optically Pumped Potassium system. The new technology provides high sensitivity; rapid sampling and high bandwidth; “clean” geophysical signal (i.e. low heading error); and high absolute accuracy. Gradient tolerance is also enhanced.

Case history data are also provided from a test site at York University, Canada with ferrous and non-ferrous objects. Processing methods include corrections, filtering, and gridding. Quick modeling was applied for additional detail. Results are compared to the targets shown in site design records.

Introduction

Quantum magnetometers are scalar devices that are based on the spin of subatomic particles:

- Nuclei – usually protons (or the Helium 3 isotope)
- Unpaired valence electrons

The spin of nuclei and unpaired valence electrons is associated with the magnetic moment and is characteristic for each particular particle. Coupling of each particle’s magnetic moment with the applied field is limited to a discrete set of values as determined by quantum mechanical rules. The following equations relate the magnetic moment to the gyromagnetic constant and quantum number:

$$\boldsymbol{\mu} = \gamma_n \mathbf{p} \quad \mu = \gamma_n \hbar/2\pi \quad (1)$$

where $\boldsymbol{\mu}$ and \mathbf{p} are magnetic and mechanical moment vectors, respectively, and γ_n is a gyromagnetic constant (characteristic for each particle), h is Planck's constant and I is a quantum number (a "semi-integer").

In the ambient magnetic field, there are $2I + 1$ orientations. For electrons and for protons, $I = \frac{1}{2}$. There are therefore only 2 orientations allowed (parallel and anti-parallel to magnetic field). Since the populations of each of the orientations are different, an assembly of magnetic moments will produce a tiny net macroscopic magnetization that is aligned with the magnetic field.

Macroscopic nuclear or electron spin magnetization is static. If elementary magnetic moments are forced out of alignment with the direction of the ambient magnetic field, the corresponding particles precess around the field in a plane of precession perpendicular to the field direction. The angular precession frequency is called the Larmor frequency, $\boldsymbol{\omega}_0$, and is defined as:

$$\boldsymbol{\omega}_0 = \gamma_n \mathbf{B} \quad (2)$$

where \mathbf{B} is the ambient magnetic flux density.

However, in weak magnetic fields, such as the Earth's, the signals of all scalar magnetometers are just too weak for simple measurement of Larmor frequency. They must be boosted in intensity or "polarized" to ensure sufficient sensitivity for measurement.

Polarization Theory

Due to the distribution of local magnetic fields, all particles in magnetometer sensors precess with naturally different frequencies and lose synchronism over time. The signal associated with the precession decays exponentially and the characteristic time of decay is called "transversal" relaxation time T_2 .

Similarly, if we apply a magnetic field to an assembly of spins, it takes time to establish macroscopic magnetization. The increase is again exponential with the time constant, T_1 , called "longitudinal" relaxation time. The intensity of magnetization is proportional to the strength of the applied magnetic field.

The strength of the magnetization and therefore, of the detectable precession signal, depends on the difference in populations of the two orientations of magnetic moments. Increasing that difference is called *polarization* and can be achieved in three ways:

- Application of strong auxiliary magnetic field (proton precession).
- Transfer of natural polarization of auxiliary electrons to protons (Overhauser effect).
- Optical manipulation of electrons by elevating them to a higher state selectively (Optically Pumped).

Overhauser Magnetometers

The Overhauser quantum magnetometer / gradiometer was developed by GEM to supercede lower sensitivity and less functional Proton Precession magnetometers. It also provides a light-weight, low power, sensitive and highly portable alternative to Optically Pumped magnetometers.



Figure 1: Overhauser quantum gradiometer with VLF attachment.

Other design objectives included developing a ground system with high sensitivity and absolute accuracy; rapid speed of operation (up to 5 readings per second); no dead zones or heading errors; omnidirectional sensors; virtually no maintenance; no warm-up time prior to surveys; and wide temperature range of operation.

Overhauser magnetometers achieve 0.14 nT sensitivity at 5 samples per second (per sensor) depending on particulars of design, and they can operate in either pulsed or continuous mode.

Optically Pumped Magnetometers

This group consists of 1 nuclear magnetometer (Helium 3) and four electron resonance magnetometers (Helium 4, Rubidium, Cesium and Potassium). Development of a Potassium optically pumped system was conceptualized but was known to be technically challenging. GEM is the only group with an operating and proven version with ongoing enhancements as the system matures.

Development of an Optically Pumped Potassium System

GEM's goals in developing a Potassium system included:

- Very high sensitivity. Due to its physics of operation, Potassium offers the highest sensitivity available in a ground magnetometer.
- High sampling rates (i.e. for speed of operation). This is desirable for mobile type operations where automated, high efficiency data acquisition is a pre-requisite.
- “Clean” measurement of geophysical signal (i.e. geophysical responses are not mixed with heading error effects).
- High absolute accuracy.

Principles of Operation

Alkali vapor optically pumped magnetometers use alkali metals including Cesium, Potassium or Rubidium. The cell containing the metal must be continuously heated to approximately 45 to 55 degrees Celsius to render the metal in gaseous form. These magnetometers operate on virtually the same principle as illustrated, in part, below.

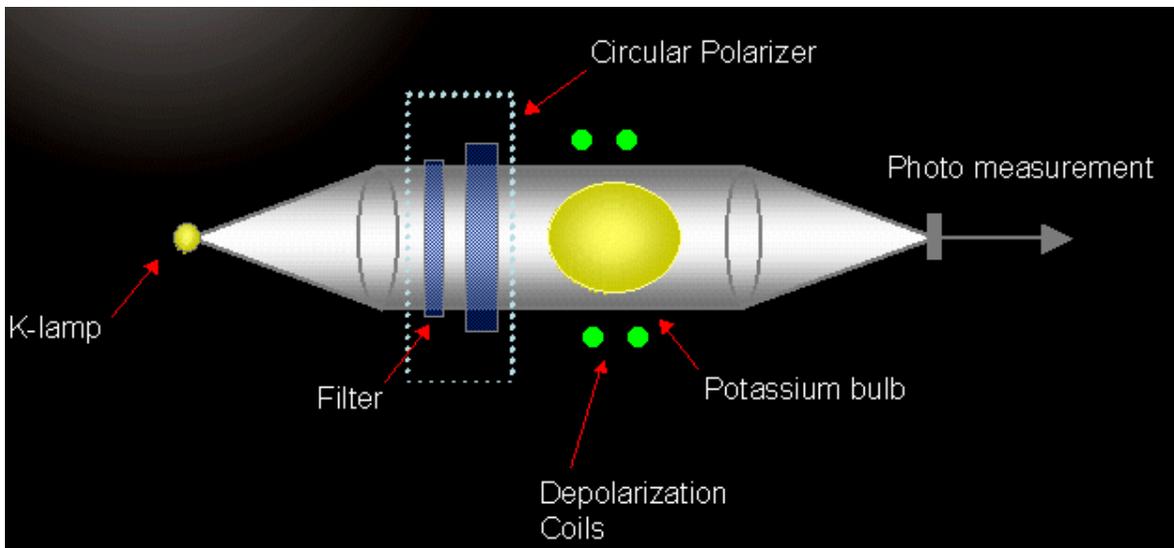


Figure 2: Potassium alkali-vapour magnetometer.

First, a glass vapour cell containing gaseous metal is exposed (or pumped) by light of very specific wavelength – an effect called light polarization. The frequency of light is specifically selected and circularly polarized for each element (i.e. the D₁ spectral line) to shift electrons from the ground level 2 to the excited metastable state 3 (Figure 3).

Electrons at level 3 are not stable, and they spontaneously decay to both energy levels 1 and 2. Eventually, the level 1 is fully populated (i.e. level 2 is depleted). When this happens, the absorption of polarizing light stops and the vapour cell becomes more transparent.

This is when RF depolarization comes into play. RF power corresponding to the energy difference between levels 1 and 2 is applied to the cell to move electrons from level 1 back to level 2 (and the cell becomes opaque again). The frequency of the RF field required to repopulate level 2 varies with the ambient magnetic field and is called Larmor frequency.

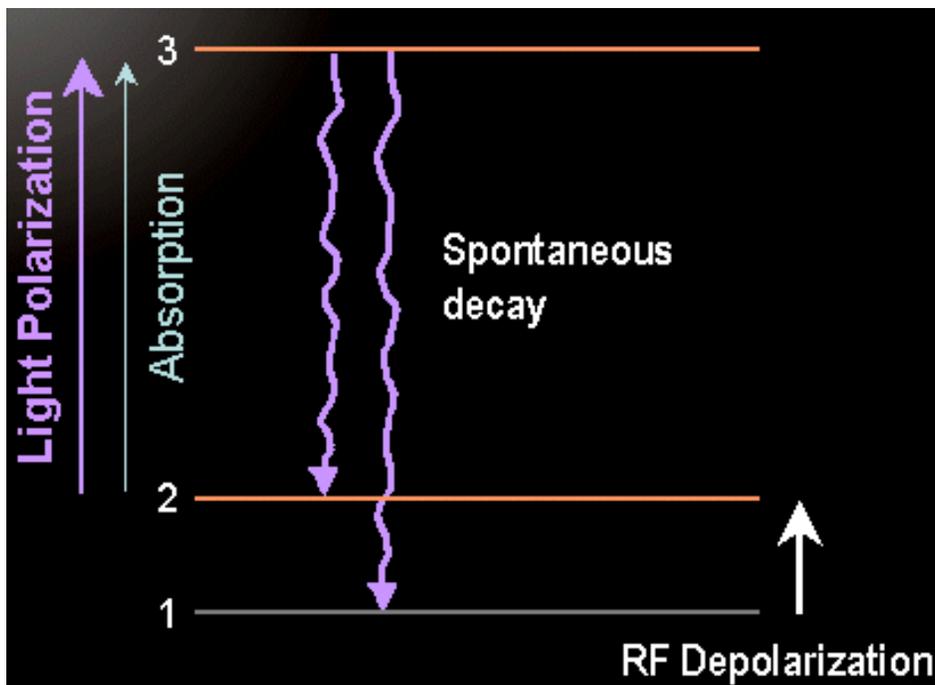


Figure 3: Quantum mechanics of alkali vapor system.

Depolarization by a circular magnetic field at the Larmor frequency will rebalance populations of the two ground levels and the vapour cell will start absorbing more of the polarizing light. The effect of polarization and depolarization is that light intensity becomes modulated by the RF frequency. By detecting light modulation and measuring the frequency, we can obtain a value of the magnetic field.

Design Objectives for Optically Pumped Potassium Magnetometers

Four objectives were previously identified. This section elaborates on these objectives.

High Sensitivity, Gradient Tolerance and Bandwidth

Sensitivity is a statistical value indicating relative uncertainty of repetitive readings of the same magnetic field intensity. It is defined as r.m.s. (root - mean - square) value per square root of a unit of bandwidth ($\text{Hz}^{1/2}$). For example, a sensitivity of $1 \text{ pT} / \text{Hz}^{1/2}$ means 1 pT r.m.s. (about 3 - 4 pT peak-to-peak depending on the character of the noise) will be a scatter of readings about any "etalon" (fixed value) of the applied magnetic field per 1 Hz of measurement bandwidth.

The sensitivity of quantum magnetometers is determined by the signal-to-noise ratio obtainable from its sensor, the spectral line width on which it operates and on the gyromagnetic constant, in accordance with the following equation:

$$\Delta B = k \Gamma / \gamma_n S_n \quad (4)$$

where k is a constant of proportionality, Γ is the spectral line width, γ_n is the gyromagnetic constant and S_n is the signal-to-noise ratio. The key factors in (4) are spectral line width and gyromagnetic constant; S_n is the responsibility of the manufacturer to control.

We assume a high and standard level of quality so that this factor is essentially normalized for all manufacturers. Sensor thermal noise is typically the limiting factor in the case of Proton and Overhauser magnetometers. In optically pumped magnetometers, the limiting factors are light shot noise and/or heading error.

Therefore, we are left with gyromagnetic constant and line width as the key factors in determining sensitivity. Based on the equation above, Overhauser magnetometers with $\gamma_n = 0.042 \text{ Hz/nT}$ can be as sensitive as, say Cesium with $\gamma_n = 3.5 \text{ Hz/nT}$, depending on parameters stated in (4). The gyromagnetic constant for Potassium is 7 Hz/nT .

The approximate spectral line widths of quantum magnetometers are as follows:

Cesium	20 nT
Overhauser	4 nT for preferred solvents and free electrons (free radicals) added
Potassium	0.1 to 1.0 nT depending on sensor size and quality
Proton	15 nT for kerosene, depends on sensor liquid

From the table, we can see that Potassium represents the highest sensitivity approach. In effect, the system is over-designed for many ground applications. However, one implication of the “over-design” is that Potassium systems can be customized to achieve the sensitivity and gradient tolerance required by individual users and in specific applications such as archaeology. This is accomplished, for instance, by reducing sensor size.

The most recent design has a 40mm sensor has a minimum gradient tolerance of 13,500 nT/m. This gradient tolerance is more than adequate for most ground applications. Cesium systems have a higher stated tolerance due to their configuration of spectral lumping; as indicated above this type of trade-off is achieved through reduced sensitivity.

Speed of Operation

Speed of operation (i.e. reading intervals or number of readings per second) is becoming increasingly important in ground applications as more and more applications, such as UXO detection, are becoming automated through the use of moving vehicles configured with one or more sensors.

For some time, standard sampling rates in optically pumped instruments were defined as 10 x per second. However, Potassium also offers sampling rates of 20 x per second or higher (i.e. 50 x per second).

Sensitivities decrease (i.e. noise increases) as a natural function of speed of operation; however, Potassium still delivers the highest sensitivities as evidenced below. Note that these values are for a single sensor value (standard deviations derived for gradiometer and divided by the square root of 2).

- 1 x per second → 0.002 nT
- 10 x per second → 0.009 nT
- 20 x per second → 0.014 nT

The Nyquist bandwidth equals one half of the reading’s frequency (i.e. 2.5 Hz for 5 Hz sampling rate). For practical purposes, the numbers of readings per second limit the bandwidth of each magnetometer. Bandwidth translates into the fastest appearing feature that can be observed with an instrument.

The Larmor frequency of any magnetometer follows variations of magnetic flux density instantly, with no delay. Natural bandwidths then depend on the magnetometer’s electronics and how quickly they can follow the changes without losing the precession signal.

With the Potassium system, Nyquist bandwidth ranges from 5 Hz at sample rates of 10 times per second to 10 Hz at sample rates of 20 times per second. Ultimately, Potassium provides a large bandwidth and the ability to resolve high frequency geophysical anomalies.

When looking at bandwidth, it is also to consider whether the manufacturer has added filtering. Some systems, for instance, apply a five point filter to smooth results; however, the result is a reduction

in bandwidth from, say, 10 Hz to 2 Hz. Therefore, comparative results at “real” bandwidths are an important parameter to consider with different systems.

“Clean” Geophysical Signal and Heading Errors

In referring to “clean” geophysical signal with respect to optically pumped magnetometers, we are referring to the relationship between system response and heading errors. Specifically, Potassium has minimal heading error therefore the resulting signal is due to “geophysical” sources rather than a combination of geophysical sources and heading errors.

To understand heading errors, one needs to consider the magnetic states of nuclei and the energy transitions between electrons and the corresponding generation of spectral lines. Spectral lines are the key measurement parameter used in obtaining magnetic measurements using optically pumped devices.

Nuclei have a number of allowed magnetic states corresponding to their quantum numbers. Alkali metals, for example, have magnetic moments with $I = 3/2$ (^{87}Rb , K) and $I = 7/2$ (Cs). The number of lines in the spectra for each type of nucleus is governed by the Breit-Rabi formulas (see reference 2).

Cs , for example, has 14 spectral lines all within 20 nT separation. With Cs , spectral lines are densely spaced and cannot be resolved in a practical magnetometer. Therefore, for the purposes of instrumentation systems, they are made very wide and overlapping. In static conditions (i.e. when the orientation of the magnetic field is stationary), a wide peak becomes apparent and the system self-oscillates at this peak. This enables frequency detection and subsequent magnetic measurements to be made.

However, a problem arises when the magnetic field direction changes because the position of this peak changes. Spectral line amplitude changes are as follows:

- For shallow angles (10 to 45 degrees), the lowest frequency line (in a constant field) is the strongest and the highest frequency line is the weakest. The differences in strength are substantial.
- For angles larger than 45 degrees, the situation is the opposite. Here, the peak of spectral lines travels from the lowest frequency at small angles to the highest frequency at large angles. The “path” of the peak can be as high as 20 nT for the same magnetic field.

Since the magnetometer usually operates at the peak of the spectral line, there are data shifts or “heading errors” that reflect the sensor-field geometry. These are corrected to a degree with split-beam methods that symmetrize the spectral lines into a lumped line and reduce heading error to some 1-2 nT.

However, since these magnetometers have an overall sensitivity in tens of 0.05 nT at 10 samples per second, heading error can completely obscure the real magnetic response. In less severe cases, readings are effectively a combination of geophysical response and heading errors (i.e. a mix of effects).

In contrast, Potassium has 6 energy transitions with mutual separations of some 100 nT at 50,000 nT field strength. Potassium’s spectral lines are found at well-defined locations for each field strength

value. Through careful sensor design, each line can be made very narrow (i.e. between 0.15 -1.0 nT). This permits the system to locate and lock very precisely on a designated line for measurement.

The result is very high sensitivity and very small heading errors (typically less than +/- 0.025nT). These heading errors are related to parasitic phase shifts in electronics or possible inclusions in the sensor's mechanics rather than actual migration of the peak of lumped spectral lines. Each manufacturer attempts to minimize these minor errors through careful sensor design.

High Absolute Accuracy

Absolute accuracy defines maximum deviation from the true value of the measured magnetic field. One of the key implications of poor absolute accuracy from a ground geophysical perspective is that results may exhibit systematic baseline shifts or offsets, particularly for systems with heading errors. In additions, replacement of sensors with poor absolute accuracy with others with the same characteristics will result in discrepancies between results.

These effects are particularly significant for surveys, such as archeological surveys, that require very high sensitivity measurements or for multiple sensor arrays where it is highly desirable to have the entire configuration operating within the same tolerances. Absolute accuracy is also important for gradiometer configurations where offsets in one sensor will affect the determination of an absolute gradiometric measurement.

Absolute accuracy cannot be derived directly since the true value is not known. Therefore, it is determined by considering the factors involved in determining the field value and their accuracy. These include consideration of the uncertainties in the gyromagnetic constant, maximum offset of the time base frequency, and zero crossing algorithms, etc. Heading errors also play a role. GEM has calculated an absolute accuracy of +/- 0.1 nT for its Potassium system. Field results have also shown that the system does not introduce any substantial biases related to time, sensor orientation or sensor changes.

Case History – York Environmental Site (YES)

The optically pumped Potassium magnetometer is now in use for archeological and other very high sensitivity work. Future applications may include Unexploded Ordnance detection where high operating speeds and sensitivity are required.

For purposes of this paper, it was decided to implement a test survey at the York Environmental Site (YES) operated by York University, Toronto, Canada.

The site comprises a grid of 6x7 cells, each measuring 15.2 m (50 ft) squared. This covers an area comparable to that of a football field. Six rows are oriented nominally east-west, and labeled from A to F. Actual bearing of grid-east is 72 degrees in relation to Geographic North. Seven columns are nominally aligned north-south (actual bearing 344 degrees), and labeled 1 to 7.

	1	2	3	4	5	6	7
A	Chalcopyrite Ore 	EMPTY	Oil 	EMPTY	EMPTY	Metallic Mine 	Plastic Mines
B	EMPTY	Paint Cans 	Steel 	Steel 	Al 	Artillery Shell 	Artillery Shell
C	Brass Steel 	Paint Cans 	Steel 	Steel 	Steel 	EMPTY	EMPTY
D	Al 	Paint Cans 	Steel 	Plastic 	Plastic 	Al 	Fe
E	Al 	Clay 	EMPTY	EMPTY	Plastic 	Al 	Fe
F	EMPTY	Clay 	Concrete 	EMPTY	Plastic 	Al 	Fe

Figure 4: YES Site. The figure shows detailed specifications for targets in terms of material and lateral location. Target dimensions are not drawn to scale.

Data were acquired using a vertical gradiometer configuration with coordinates obtained every 1 m along lines separated by 1 m. The operating mode was 10 samples per second. This method enabled efficient acquisition of data at approximately 6000 stations (i.e. a very high volume of data in less than eight hours of operation).

Data were then downloaded using the GEMLinkW proprietary software algorithm and entered into Geosoft data processing software. Data were initially viewed in profile form for purposes of quality control before other processing was applied. Other processing routines included gridding of total field and gradiometer results, and calculation of analytic signal results.

The analytic signal is the square root of the sum of the squares of the derivatives in the x, y, and z directions:

$$\text{Analytic Signal} = \text{sqrt} \left(\left(\frac{dH}{dx} \right)^2 + \left(\frac{dH}{dy} \right)^2 + \left(\frac{dH}{dz} \right)^2 \right) \quad (5)$$

The analytic signal is useful in locating the edges of magnetic source bodies and centering anomalies over their sources.

Sample Data from YES

Data that were plotted from the YES survey included total field, gradient, total field analytic signal, and gradient analytic signal. In the total field image below, several basic features are visible:

- Numerous monopolar and dipolar targets (corresponding to metallic objects at various depths).
- Large magnetic low at the top of the grid reflecting a baseball screen added after the initial development of the YES.

- Elevation of magnetic values to the right of the cursor marked in the image corresponding to in-fill surveying on a second day of operation. Data were acquired without a base station due to system unavailability. Gradient configuration was used to acquire high quality results in lieu of base station.

Data were lightly leveled using airborne micro-leveling techniques and resulting corrected gradient data was obtained. Analytic signals were then calculated for total field and vertical gradient.

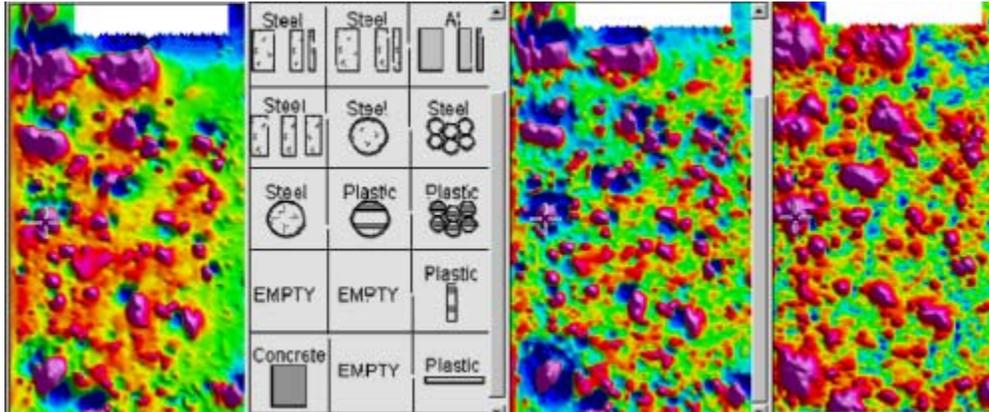


Figure 5: Optically pumped Total Field, Gradient and Analytic Signal (Gradient) are shown with a corresponding target map for the YES site.

Total field data show geologic variability at depth as well as near surface targets. Gradient data isolate near surface targets but still show complex dipolar features. Analytic Signal (Gradient) data centre anomalies over their sources and enhance interpretation of individual targets.

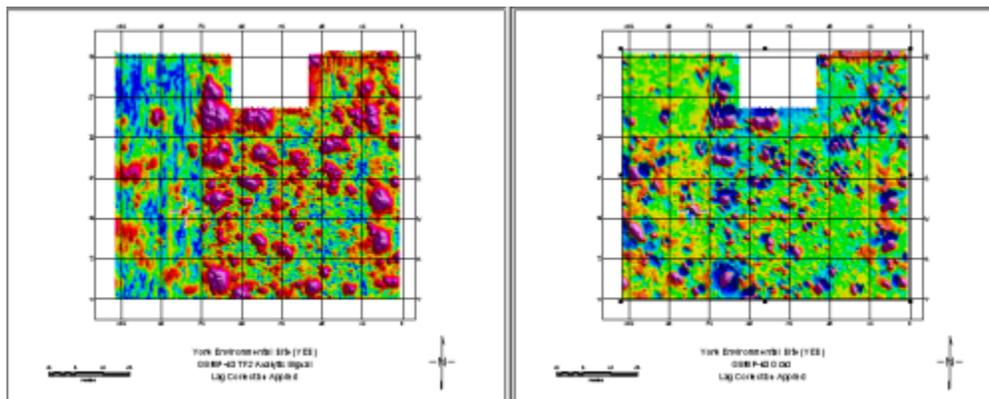


Figure 6: Optically pumped Potassium Analytic Signal (Total Field) and Vertical Gradient Results from YES. Vertical Gradient removes diurnal effects visible in the Analytic Signal data (i.e. to left).

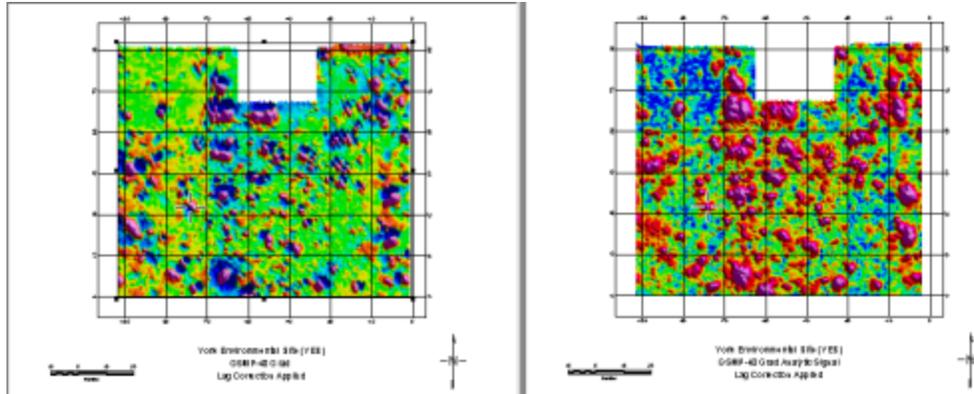


Figure 7: Optically pumped Potassium Vertical Gradient and Analytic Signal (Vertical Gradient) results. Analytic Signal results enhance target delineation through simplification of complex signatures.

As one of the final steps to interpretation, the YES target grid was geo-referenced to enable cell-by-cell comparison with Potassium results. Analysis consisted of visual interpretation of a cell containing three steel plates at 2.0m depth followed by modeling of results for a concrete “bunker” at 0.5m depth.



Figure 8. Steel plates (horizontal, dipping at 45 degrees and vertical – not shown) in Cell B4 at 2.0m depth.

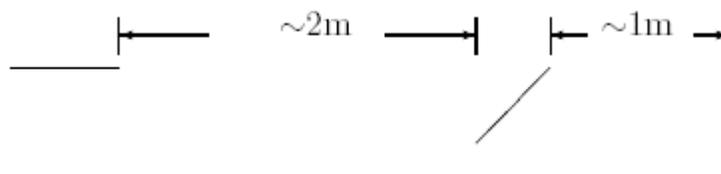


Figure 9. Cross section of steel plates.

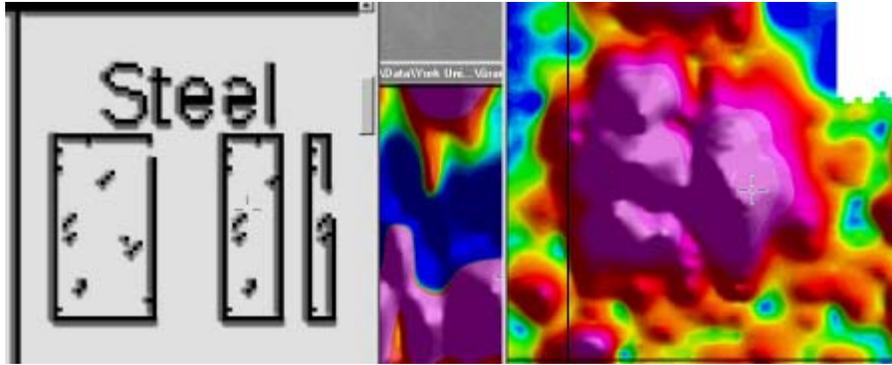


Figure 10. Steel plates with corresponding Vertical Gradient and Analytic Signal (Vertical Gradient) results.

The signatures in Figure 10 show a reasonable correspondence with the two left-most (i.e. horizontal and dipping) plates. The vertical plate is not visible in the Analytic Signal results and is assumed to be “hidden” within the signature for the dipping plate which is located at a short distance (1m) from the vertical plate.



Figure 11: Concrete vault buried at 0.5m in Cell F3.

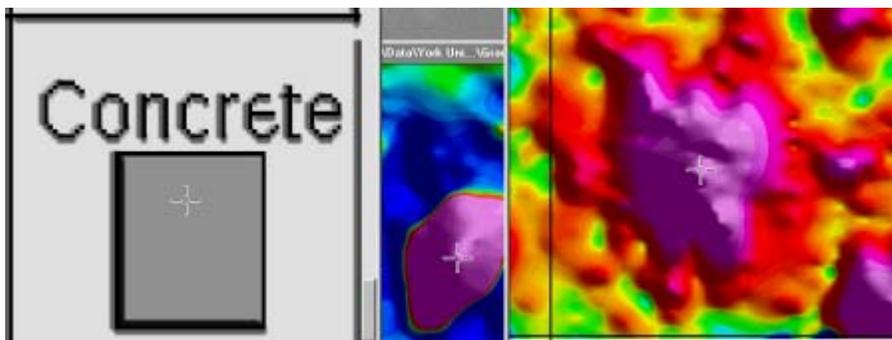


Figure 12. Concrete vault with corresponding Vertical Gradient and Analytic Signal (Vertical Gradient) results.

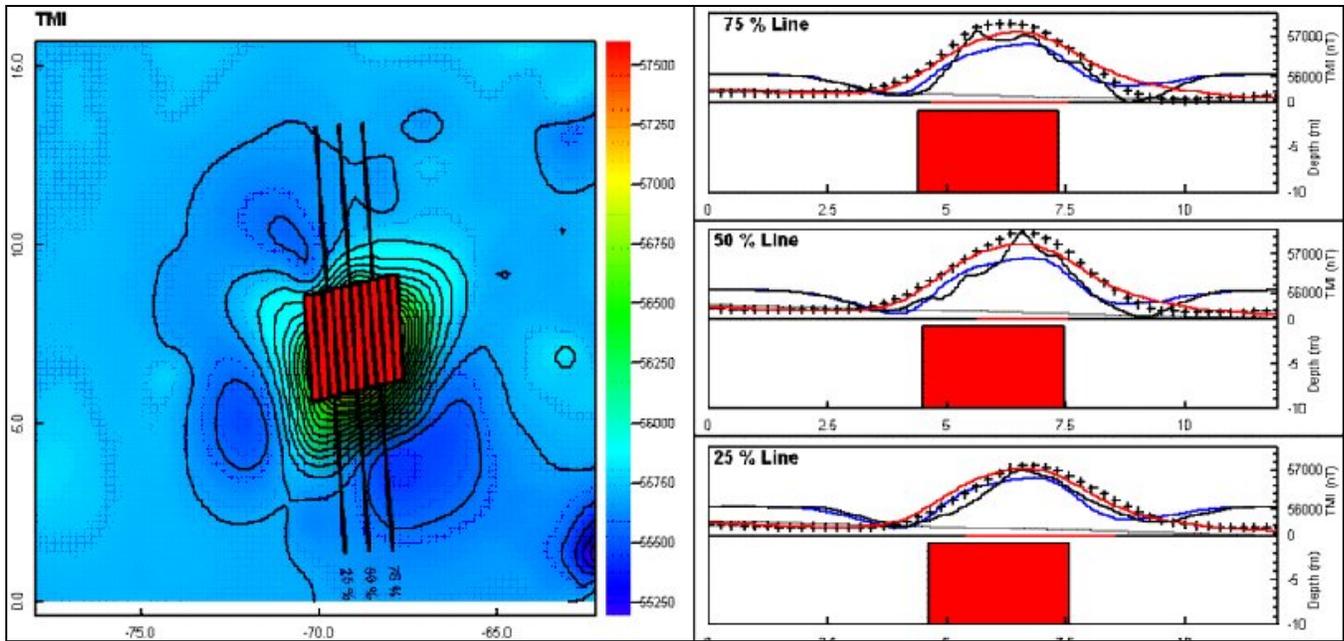


Figure 13. Modeling results obtained using Encom QuickPro for concrete vault. Total field data are in red, modeled total field results are in black (circles), vertical derivative data are in blue and modeled vertical derivative results are in black (solid).

Figure 12 shows that both the Vertical Gradient and Analytic Signal results provide a good visual outline of the “bunker” based on the positive and negative anomalies occurring in the data. The model results in Figure 13 show a depth unlimited, flat-topped structure buried approximately 0.2m deeper than the known structure.

Summary

In conclusion, one can summarize the overall characteristics of quantum magnetometers as follows:

1. **Overhauser** magnetometers have sensitivity of 0.035 nT per sensor at a bandwidth of 2 Hz. This is comparable to a Cesium magnetometer with sensitivity of 0.05 nT at 10 samples per second (i.e. with an internal 5-point filter that reduces the bandwidth to an equivalent 2 Hz). Overhauser has no dead zones and virtually no heading errors. Simplicity and moderate costs make these magnetometers effective for most ground “walking” surveys.
2. **Cesium** magnetometers have sensitivity of 0.05 nT at 10 samples per second (see remarks above for notes on over-sampling). Heading errors and dead zones are the limitations. Sampling is up to 10 times a second.
3. **Potassium** offers sensitivity of 0.009 nT at 10 samples per second due to its resolved spectral lines. It is effective for most demanding applications (i.e. archaeology and mobile surveys for UXO detection, etc)). Dead zones are a limitation. Gradient tolerance is enhanced 5 times over previous versions using a

40mm sensor. Sampling is 20 times a second maximum with enhancement to 50 or 100 samples feasible depending on application needs.

The YES tests indicated that GEM's new Potassium system provides very high sensitivity data that are effective for visual characterization of targets. Data were well behaved in modeling applications – generating results that are an almost exact match in terms of depth for the concrete vault. Systematic data acquisition with base station corrections are recommended for practical surveys.

In summary, walking applications can be addressed effectively with Overhauser technologies that are specially designed to provide high sensitivity, low power instruments on a cost-effective basis. The new Potassium technology is best suited for vehicular applications requiring high sampling as well as the most demanding applications calling for very high sensitivity and good gradient tolerance.

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