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Development of a Tri-Directional Helicopter Gradiometer for Mineral Exploration Applications

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The Tri-Directional Helicopter Gradiometer was the first three-axis gradiometer developed globally. Since its inception in the mid 1980s, the system has been outfitted with optically pumped Potassium sensors and has evolved into a reliable platform for different applications, including mineral exploration.

This special gradiometer consists of a three-armed towed bird configured with 4 sensors for calculation of magnetic gradients, including vertical and horizontal across and along track gradients. Additional components include GPS for accurate positioning of the bird during flight. Data capture is either to the GSMP-30A acquisition console or a 3rd party unit.

This paper reviews the principles of optically pumped Potassium magnetometers and the Tri-Directional Gradiometer, continuing with a discussion of Tri-Directional Design considerations, and concluding with a discussion of the role of magnetic gradients in mineral exploration.

Optically Pumped Potassium Magnetometers

Optically pumped magnetometers consist of 1 nuclear (Helium 3) and four electron resonance magnetometers (Helium 4, Rubidium, Cesium and Potassium). Although technically challenging, GEM has succeeded in developing a system that meets the following design goals:

- High sampling rates (i.e. 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 as in other optically pumped systems).
- Very high sensitivity. Due to its physics of operation, Potassium offers the highest sensitivity available.
- High absolute accuracy.

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Principles of Operation

Alkali vapor optically pumped magnetometers use alkali metals (i.e. from the first column of the periodic table) in gaseous form. These magnetometers operate on virtually the same principle as illustrated, in part, in Figure 1.

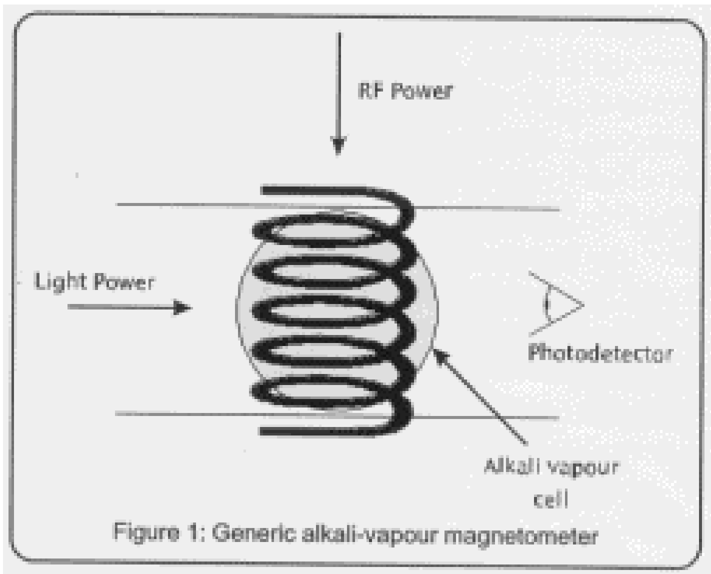

Figure 1: Generic alkali-vapour magnetometer.

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 (called the D_1 spectral line) to shift electrons from the ground level 2 to the excited metastable state 3 (Figure 2).

Electrons at level 3 are not stable, and these electrons 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.

Depolarization by a circular magnetic field at the Larmor frequency rebalances populations of the two ground levels and the vapour cell absorbs more of the polarizing light.

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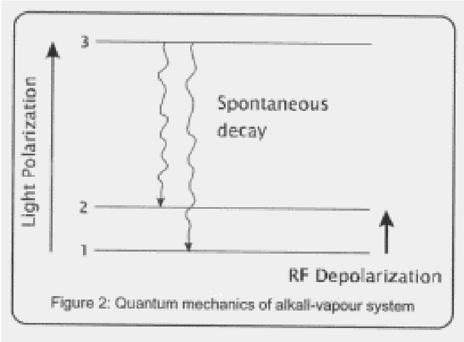

Figure 2: Quantum mechanics of alkali vapor system.

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 obtain a value of the magnetic field.

Design of the Optically Pumped Potassium Magnetometer

A number of key objectives were observed in developing a Potassium magnetometer.

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 ($Hz^{1/2}$). For example, a sensitivity of 1 pT / $Hz^{1/2}$ 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 it operates on and on the gyromagnetic constant as defined in the following equation:

$$\Delta B = k\,\Gamma / \gamma_n S_n \qquad (1)$$

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. Sensitivity does not depend only on Larmor frequency. For example, Overhauser magnetometers with 0.042Hz/nT can be as sensitive as, say Cesium with 3.5 Hz/nT depending on spectral line width.

GEM's original Potassium airborne version has a 70mm diameter sensor which achieves sensitivity at 1 sample per second of <0.001 nT (un-filtered) with a corresponding gradient tolerance of 2,500 nT/m. This is an adequate gradient specification for most airborne applications.

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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 it can follow the changes without losing the precession signal.

With the Potassium system, 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.

"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.

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 references).

Cs, for example, has 14 spectral lines all within 20 nT separation. With Cs, spectral lines 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. This effect occurs because the spectral line amplitudes change 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.
- 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. Cs systems correct these effects through the use of split-beam techniques 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 pT/ √Hz, 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. When a magnetic field of a certain strength is present, Potassium’s spectral lines are found at well-defined locations. 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 0.1nT). Here, heading errors are related to parasitic phase shifts in electronics or possible inclusions in the sensor’s mechanics rather than migration of spectral lines as in Cs systems. Careful design of the sensor and electronics, however, can reduce Potassium heading errors to some tens of pT.

Speed of Operation

Speed of operation (i.e. reading intervals or number of readings per second) is important in airborne applications as it determines the resolution (in combination with the flying speed).

Sensitivity / accuracy should be defined at each interval as there is an increase in noise that is not easy to predict mathematically (i.e. does not follow the general rule that noise is proportional to the square root of the speed of readings).

Sensitivities decrease (i.e. noise increases) as a natural function of speed of operation; however, Potassium still delivers the highest sensitivities:

- 1 x per second – 0.001 nT
- 10 x per second – 0.007 nT
- 20 x per second – 0.018 nT

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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 is that results may exhibit systematic baseline shifts or offsets, particularly for systems with heading errors. In addition, replacement of sensors with poor absolute accuracy results in discrepancies between results. Absolute accuracy is also important for gradiometer configurations where offsets in one sensor affect determination of an absolute gradiometric reading.

Absolute accuracy cannot be derived directly since nobody really knows the true value of the field. Therefore, it is determined by considering the factors involved in determining the field value and their accuracy. These include consideration of the uncertainties inherent 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.

Design of the Tri-Directional Gradient Array

For the Tri-Directional array, four Potassium sensors are used in a special configuration, shown in Figure 4. The sensors are placed in the back end of the bird shell and in the tips of three fins, 3 to 4m apart from each other. Average periods of the four precession frequencies are measured by a special computerized frequency meter, similar to the one shown in Figure 3, and converted into magnetic field units.

Figure 3: Potassium Magnetometer Console is similar to above.

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The differences in readings are taken and divided by the sensor spacings. Horizontal across track gradient is measured directly from the readings of the two lower (horizontal) sensors; the vertical is determined from the average field measured by horizontal sensor and the sensor in the vertical fin. Horizontal along the track gradient is based on the average field from the three sensors placed in the fins and the bird-end sensor. Fourth differences are calculated for all three gradients as well as four absolute values of magnetic field.

The Bird

Traditional design criteria for electromagnetic (EM) birds were observed when the bird was designed. The bird is shown in Figure 4.

Figure 4: Airborne bird shown in fully assembled state, ready for surveying.

Requirements for rigidity are very much relaxed in comparison with EM birds. It is sufficient to measure gradients with 0.1% accuracy (up to 25 nT/m and beyond) as compared with EM measurements of some parts per million. The bird's shell, therefore, was designed of sufficient diameter and wall thickness to accept the magnetometer sensor and support weight of sensors, fins, skirt, and its own weight with <0.1% change of relative sensor positions due to shell flexing.

The fins are spaced at 120 degrees to allow for simple calculation of gradients in all three directions; the average magnetic field of the two lower fins fall beneath the upper fin sensor to allow for vertical gradient determination; the average field of all three sensors falls in the centre of the bird shell to allow for simple determination of along-track gradient.

All three fins are 2.0m long to achieve a spacing for the vertical gradiometer equal to 3.0m. Horizontal across and along the track gradients are based on a sensor spacing of 3.45 and 3.76m, respectively, although the sensor in the bird shell can be moved along the shell to suit any potential requirements for along-track configurations.

The bird skirt is designed to allow for variable drag in order to experimentally optimize the bird stability and flight characteristics.

To improve the distribution of weight along the bird shell, the fins are placed in front to overweight the skirt and to make the front end heavier in a stationary state. Pick-up points are selected closed to Euler minimum flexing points, although rigidity is not critical.

Why Use Gradients for Mineral Exploration Applications

Measured gradients have come into vogue in the last few years for a variety of reasons. These include:

- Freedom from diurnal effects and noise
- Altitude correction of total field magnetics
- Improved magnetic mapping
- Enhanced interpretation

Diurnal Effects

Diurnal effects are a normal result of the interaction of the solar wind with the earth's atmosphere. Depending on the amplitude, these effects can be quite significant and require removal from the data. The standard approach is to measure the difference between simultaneous magnetic sensors. This measurement records the gradient and cancels diurnal variation since diurnal effects are the same at both sensors.

Altitude Correction

As described by Scott Hogg et al, 2004, measured vertical gradients can help correct the errors introduced by altitude variations. This process removes false changes in anomaly shape and amplitude from line-to-line changes in aircraft height rather than geological or diurnal sources. Hogg also notes that, the method is "relatively simple and can prove very effective, especially in surveys that contain strong magnetic gradients and high vertical gradients."

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Improved Magnetic Mapping

Improved magnetic mapping is one of the main attractions of gradient measurements. This capability takes advantage of the resolving power of the vertical gradient, interpolation of data using horizontal gradients, and feature placement using horizontal gradients.

The natural appeal of the vertical gradient is its tight focus. As shown in the figure 5, the vertical gradient has a smaller "footprint" than its total field counterpart, making it a higher resolution product for detecting small anomalies – particularly on the flanks of larger anomalies.

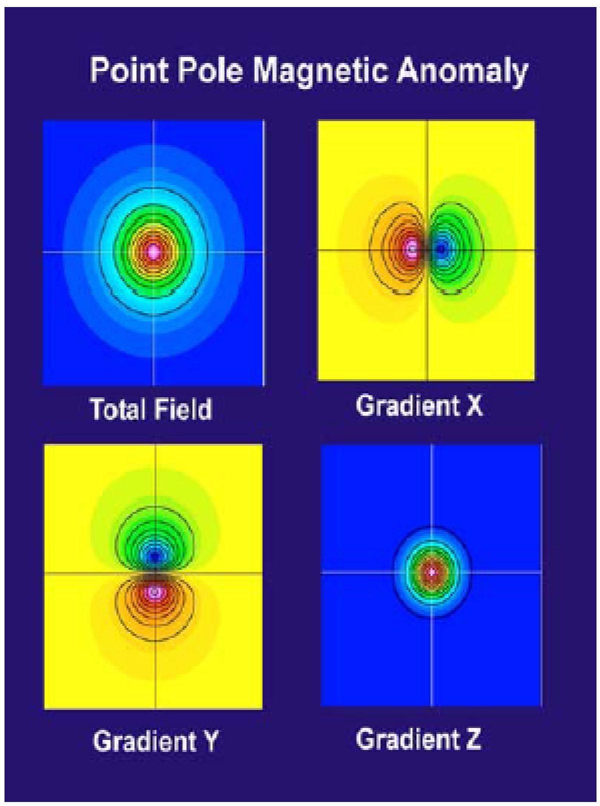

Figure 5. Comparison of total field and gradient results for the same target.
From Hogg et al., 2004

Horizontal gradients also can assist in mapping – acting as a useful counterpart to the vertical gradient. As shown in Figure 5, the point where horizontal gradients pass through zero is the location of the total field peak. If the flight lines straddle the anomaly and one line records a high and the adjacent line a low, the peak falls between the lines.

Accordingly, measured horizontal gradients can improve the interpolation of data between flight lines, and thus increase map accuracy and resolution without increasing cost.

Another attractive quality of the horizontal gradient is its ability to help place magnetic features more accurately on maps. The method requires calculation of a pseudo total field (through integration of the gradients). This works to correctly position small anomalies on maps; ensure that narrow trends at shallow angle to the flight line direction are more correctly positioned; and remove diurnal variation. Special computer methods can also render anomalies parallel to the flight direction, correctly present long wavelength information, and ensure that all calculated total field anomalies are in agreement with measured total field.

Enhanced Interpretation

Gradient surveys deliver products that in themselves can assist in the interpretation of project geology, particularly when used in conjunction with total field results. Standard interpretation products, including vertical gradient maps, analytic signal maps and Euler-based methods all depend on gradient information. Analytic signal and Euler methods based on gradients assist particularly in helping to locate objects precisely (horizontally and vertically).

Gradient surveys also enable the actual computation of “real” analytic signal values – these results are used for positioning and also for inversion (i.e. development of a pseudo geologic model based on geophysical results). The total gradient (analytic signal) is independent of sensor orientation errors, magnetic latitude variables and the effect of remanent magnetization. Omni-directional measurement of the magnetic field minimizes the directional aliases present in standard magnetic surveys.

And lastly, the horizontal gradient has interpretive value of its own. Specifically, for faults, the horizontal gradient has been found to be a more sensitive indicator of fault anomalies than gradient alone (see reference from W. C. Pearson).

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Advantages of the Tri-Directional System

The Tri-Directional system is unique in that it uses the highest resolution commercial (Potassium) magnetometer – resulting in a new level of detection of subtle anomalies. Other benefits include:

- 4 sensor system accurately computes "real" gradients using unique implementation of sensors in a triangular configuration plus one sensor housed within bird
- Provides very stable and noise-free platform for acquiring high resolution data in all types of terrain
- Delivers accurate information for reduction of positioning errors using onboard GPS
- No magnetic compensation required; distance from helicopter is sufficient to escape the noise from rotor blades and other moving parts on helicopter
- Bird skirt is adjustable to allow for flight optimization and further noise reduction

Comparison with Fixed Wing Systems

Fixed-wing surveys are an important component of many earth science programs. However, there are also certain circumstances in which the Tri-Directional Gradiometer can outperform these surveys.

For example, the Tri-Directional Gradiometer maintains the same or lower height than fixed wing surveys – generating higher resolution data. Additionally, the system does not require compensation (real-time or post-survey) and flies at reduced speeds for higher volumes of data along survey lines. Surveys can also be flown at uniform survey heights for minimization of noise-effects arising from variable ground clearances.

Comparison with Fixed Helicopter Surveys

Fixed Helicopter surveys are performed using a boom or series of booms mounted around the helicopter. Typically, a Tri-Directional survey can outperform these types of surveys in a number of areas.

- No compensation required
- Same ground clearance possible
- Simplicity of installation and operation

Conclusions

In this paper, we introduced an enhanced system for measuring tri-directional gradients (vertical, horizontal across and horizontal along track) using state-of-the-art Potassium sensors for higher sensitivity, reduced noise, high absolute accuracy, and high speed surveys. The Tri-Directional Gradiometer is an advanced magnetic system with many advantages characteristic to multi-sensor surveys, including freedom from diurnal effects and noise, altitude correction of total field magnetics, improved magnetic mapping and enhanced interpretation. Future directions will be to assist companies and organizations in adopting this new technology and to help enhance current exploration approaches. Additional information on airborne magnetics applications can be found at www.gemsys.ca/apps_airborne.htm.

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