Celebrating 35 Years
Leading the World of Magnetics

GEM Systems, Inc.
135 Spy Court
Markham, ON CANADA L3R 5H6
Ph. 905 752-2202 Fax 905 752-2205
info@gemsystems.ca www.gemsystems.ca

Brief Review of Quantum Magnetometers

By Dr. Ivan Hrvoic & Greg M. Hollyer, M.Sc. (Eng), P.Eng.

Quantum magnetometers are widely used in geophysical mineral and oil exploration, archeology, environmental surveys, ordnance and weapons detection (UXO) and other earth science applications. The purpose of this document is to give a brief technical overview of the types of quantum magnetometers available, their operating principles and some of the guidelines for using these systems in real-world geophysical environments.

Figure 1: Overhauser quantum gradiometer with VLF attachment and Gps.

GEM Systems, Inc.
135 Spy Court
Markham, ON CANADA L3R 5H6
Ph. 905 752-2202 Fax 905 752-2205
info@gemsystems.ca www.gemsystems.ca

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Topics are organized as shown below:

Magnetometers - A Brief Description

A magnetometer is an instrument with a single sensor that measures *magnetic flux density B* (in units of Tesla or As/m^2). The Earth generates a weak magnetic field that produces flux densities (in air) of about 18 micro Tesla in some parts of South America to a high of over 60 microTesla in the Arctic Circle and Antarctica.

GEM Systems, Inc.
135 Spy Court
Markham, ON CANADA L3R 5H6
Ph. 905 752-2202 Fax 905 752-2205
info@gemsystems.ca www.gemsystems.ca

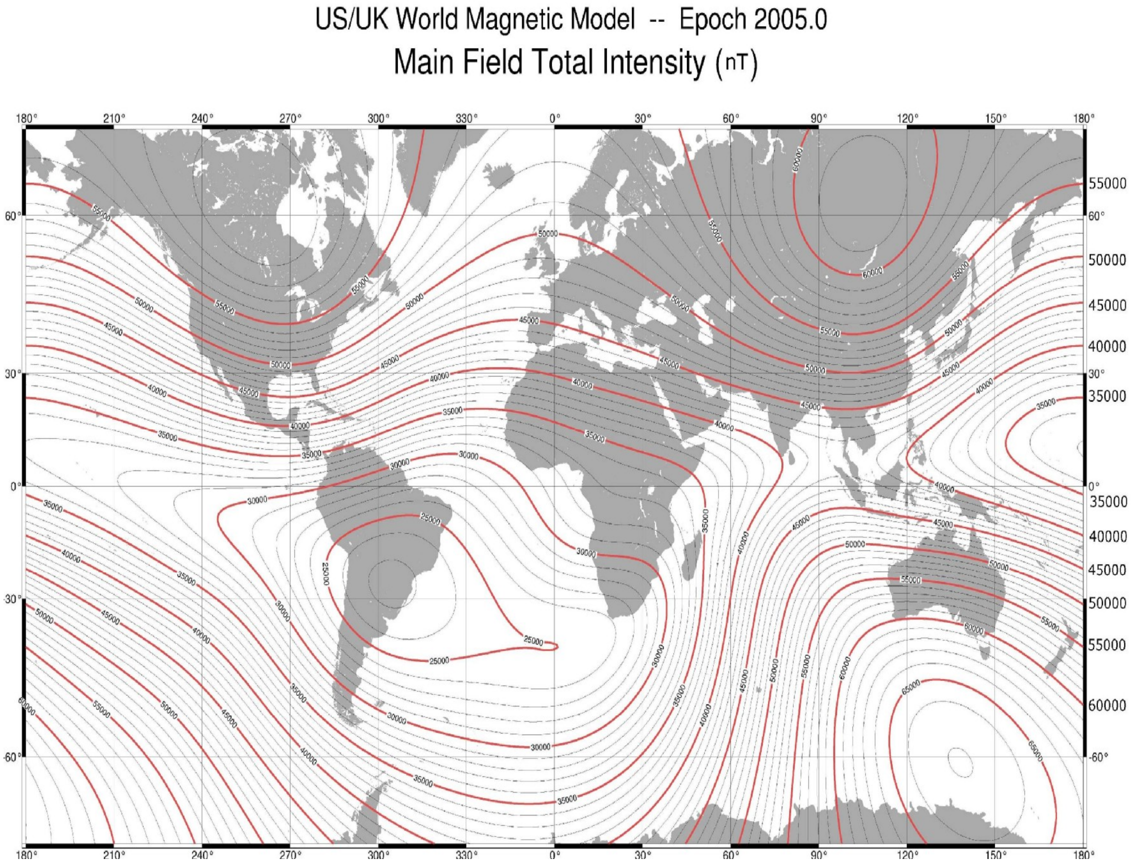

Figure 2: Earth's magnetic total field intensity in nT.

Since magnetic flux density in air is directly proportional to magnetic field strength H [A/m], a magnetometer is capable of detecting fluctuations in the Earth's magnetic field.

Recorded values can be due to either dynamic or static effects. *Dynamic anomalies* are related to activity within the molten core of the Earth, by solar activity, or by ionic jet streams and storms from space. *Static anomalies* are related to different materials present in the Earth's crust and man made anomalies.

Materials that distort magnetic flux lines are known as *magnetic*, and include materials such as magnetite that possess magnetic fields of their own, as well as very high magnetic conductivity. Materials like this create distortions in the Earth's magnetic flux that is flowing around them. Magnetometers detect these distortions.

A magnetometer measures magnetic flux density at the point in space where the sensor is located. A distortion generated by a magnetic object (magnetic dipole) usually drops in intensity with the cube of the distance from the object. Therefore,

GEM Systems, Inc.
135 Spy Court
Markham, ON CANADA L3R 5H6
Ph. 905 752-2202 Fax 905 752-2205
info@gemsystems.ca www.gemsystems.ca

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the maximum distance that a given magnetometer can detect the object is directly proportional to the cube root of the magnetometer's sensitivity.

The sensitivity is commonly measured in nanoTesla, [10^{-9} T] or *gamma* (the non-SI unit that many geophysicists commonly use), or in pico Tesla [10^{-12} T] or femto Tesla [10^{-15} T].

Generally, magnetometers are divided into two categories that vary dramatically in both functionality and principle of operation:

- *Vector magnetometers* that measure the flux density value in a specific direction in 3 dimensional space (magnetic flux density is a vector --meaning it has a direction as well as a magnitude). An example is a fluxgate magnetometer that can measure the strength of any component of the Earth's field by orienting the sensor in the direction of the desired component.

- *Scalar magnetometers* that measure only the magnitude of the vector passing through the sensor regardless of the direction. Quantum magnetometers (except for SQUIDS –- super-conducting quantum interference devices) are an example of this type of magnetometer.

We shall limit this article to scalar magnetometers, all of them being quantum magnetometers.

Quantum Magnetometers

Quantum magnetometers 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 quantized or 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:

$$m = \gamma_n \, p \qquad m = \gamma_n I h / 2\pi \qquad (1)$$

where m and p are magnetic and mechanical moment vectors, respectively, and γ_n is a gyromagnetic constant (characteristic for each particle), h is Plank's constant and I is a quantum number (a "semi-integer").

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135 Spy Court
Markham, ON CANADA L3R 5H6
Ph. 905 752-2202 Fax 905 752-2205
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In the ambient magnetic field, there are 2I + 1 orientations for electrons and for nuclei (i.e. protons and Helium 3). For each of these, I = ½. 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 (i.e. rotate) around the field in a plane of precession perpendicular to the field direction. They precess with an associated angular frequency, called the Larmor frequency, w_0, as defined according to the following expression:

$$w_0 = g_n B \qquad (2)$$

where B is the ambient magnetic flux density. B is in general proportional to the magnetic field value.

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 of measurement.

About Polarization

Due to the distribution of local magnetic fields, all particles in the sensor 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 in quantum magnetometers:

- **Application of strong auxiliary magnetic field (actually flux density) to polarize nuclear, usually protons.**

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135 Spy Court
Markham, ON CANADA L3R 5H6
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info@gemsystems.ca www.gemsystems.ca

- **Transfer of natural polarization of auxiliary electrons to protons (Overhauser effect).**
- **Optical manipulation or "pumping" of electrons by elevating them to a higher state selectively.**

Note: In practice, T_2 is very short in solid samples. All quantum magnetometers therefore use liquid or gaseous sensors. In liquids and gases T_1 and T_2 assume values between a fraction of a second to several seconds. An exception is Helium 3, which has a T_2 value of several hours or even days.

Proton Magnetometers

Proton precession magnetometers have long had a niche as inexpensive portable magnetometers, despite limitations such as relatively large power consumption and relatively low sensitivity. Typical applications include environmental and engineering surveys where targets are relatively near surface and do not require high sensitivities to detect and map, or production-oriented reconnaissance surveys for resource exploration.

Operating Principles

A proton precession magnetometer uses hydrogen atoms to generate precession signals. Liquids, such as kerosene, are used because they offer very high densities of hydrogen and are not dangerous to handle.

A polarizing DC current is passed through a coil wound around a liquid sample (water, kerosene, or similar). This creates an auxiliary magnetic flux density of the order of 100 Gauss.

Protons in this field are polarized to a stronger net magnetization corresponding to the thermal equilibrium of the stronger magnetic flux density. When the auxiliary flux is terminated quickly, the "polarized" protons precess to re-align them to the normal flux density. The frequency of the precession, f_o, relates directly to the magnetic flux density, B, (units of which are Teslas, T), according to the following equation:

$$f_o = (\gamma_p / 2\pi) B \qquad \gamma_p / 2\pi = 42.5763751 \text{ MHz/T} \qquad (3)$$

The precession signal is present from a fraction of a second to up to 2 seconds, and can be measured using a special counter. Signal quality can also be derived from the signal amplitude and its decay characteristics, which are averaged over the recording period.

Proton precession measurements are necessarily *sequential*. This means that there is an initial polarization, followed by a frequency measurement – after which, the cycle is repeated. This differs from *continuous* measurements where the nuclei are

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135 Spy Court
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info@gemsystems.ca www.gemsystems.ca

polarized and frequency measurements are made simultaneously. More information on continuous measurements is provided in the discussions of Overhauser and Optically Pumped magnetometers.

In summary, proton precession uses a simple method of polarization, but it allows measurement of sensitivities to a fraction of an nT and up to 2-3 readings per second.

Overhauser Magnetometers

The Overhauser magnetometer, with its unique set of features, represents a pillar of modern magnetometry of the Earth's magnetic field. Its sensitivity matches costlier and less convenient cesium magnetometers, for example. The Overhauser magnetometer also offers superior omnidirectional sensors; no dead zones; no heading errors; or warm-up time prior to surveys; wide temperature range of operation (from –40 to 55 degrees Celsius standard and –55 to 60 degrees Celsius optional); rugged and reliable design; and virtually no maintenance during its lifetime. Other advantages include high absolute accuracy, rapid speed of operation (up to 5 readings per second), and exceptionally low power consumption.

Overhauser magnetometers use proton precession signals to measure the magnetic field – but that's where the similarity with the proton precession magnetometer ends.

Overhauser magnetometers were introduced by GEM Systems, Inc. following R&D in the 80's and 90's, and are the standard for magnetic observatories, long term magnetic field monitoring in volcanology, geophysical ground and vehicle borne exploration, and marine exploration.

Operating Principles

The Overhauser effect takes advantage of a quantum physics effect that applies to the hydrogen atom. This effect occurs when a special liquid (containing free, unpaired electrons) is combined with hydrogen atoms and then exposed to secondary polarization from a *radio frequency* (RF) magnetic field (i.e. generated from a RF source).

RF magnetic fields are ideal for use in magnetic devices because they are "transparent" to the Earth's "DC" magnetic field and the RF frequency is well out of the bandwidth of the precession signal (i.e. they do not contribute noise to the measuring system).

The unbound electrons in the special liquid transfer their excited state (i.e. energy) to the hydrogen nuclei (i.e. protons). This transfer of energy alters the spin state populations of the protons and polarizes the liquid – just like a proton precession magnetometer – but with much less power and to much greater extent.

GEM Systems, Inc.
135 Spy Court
Markham, ON CANADA L3R 5H6
Ph. 905 752-2202 Fax 905 752-2205
info@gemsystems.ca www.gemsystems.ca

The proportionality of the precession frequency and magnetic flux density is perfectly linear, independent of temperature and only slightly affected by shielding effects of hydrogen orbital electrons. The constant of proportionality, γ_p, is known to a high degree of accuracy and is identical to the proton precession gyromagnetic constant (equation 3).

Overhauser magnetometers achieve some 0.01nT/ √Hz noise levels, depending on particulars of design, and they can operate in either pulsed or continuous mode.

Advantages Over Proton Precession & Other Quantum Magnetometers

To summarize, some of the main differences between Overhauser and proton precession magnetometers are:

- **More than an order of magnitude greater sensitivity even in the lowest of Earth's fields. This reflects the fact that Overhauser systems offset a basic weakness of proton magnetometers (i.e. deterioration of signal quality in low magnetic flux density (20µT range)) by creating a small auxiliary magnetic flux density while polarizing.**
- **Sensitivity that virtually matches cesium sensitivity.**
- **This is the only quantum magnetometer that offers continuous or sequential operation. With Overhauser magnetometers, it is possible to measure continuously or sequentially due to the use of an RF polarization field. The RF field is transparent to the measurement of magnetic field and can therefore, be enabled at all times.**
- **Cycling speed. Since the liquid can be polarized while the signal is being measured, the sampling rate is higher (as high as 10 Hz possible).**
- **Energy efficiency. Overhauser magnetometers are significantly more efficient than any other quantum magnetometer due to the low power required for RF signal generation. Power consumption can be optimized to as low as 1W for continuous operation.**
- **Omnidirectional sensors. No dead zones, virtually no heading errors and no warm up time.**

There are also other advantages related to the manufacturing process (which are of less interest to users), such as relative simplicity, reliability of design, relatively low manufacturing cost relative to sensitivity, weight and power consumption benefits.

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info@gemsystems.ca www.gemsystems.ca

Optically Pumped Magnetometers

This group consists of 1 nuclear magnetometer (Helium 3) and four electron resonance magnetometers (Helium 4, Rubidium, Cesium and Potassium). This paper focuses on Cesium and Potassium optically pumped magnetometers – the most common systems in use.

Applications are similar to Overhauser magnetometers with the exception that Cesium offers somewhat higher sampling rates than its Overhauser counterparts. Potassium exhibits superior sensitivity and higher reading speed than Cesium based on the physics of each method.

Principles of Operation

Alkali vapor optically pumped magnetometers use gaseous alkali metals from the first column of the periodic table, such as Cesium, Potassium or Rubidium. That means that the cell containing the metal must be continuously heated to approximately 45 to 55 degrees Celsius.

These magnetometers operate on virtually the same principle as illustrated, in part, in the next figure.

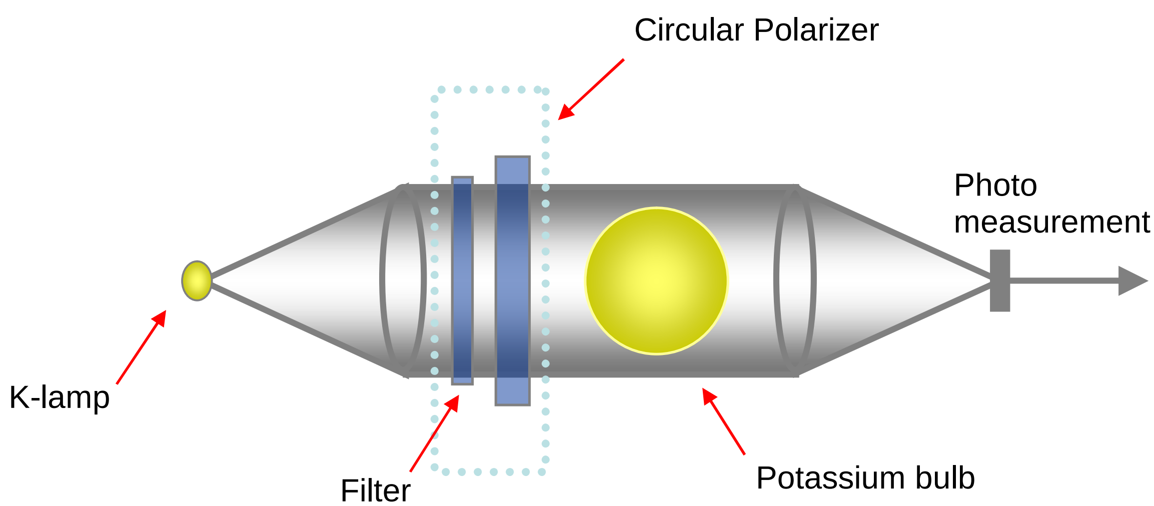

Figure 3: Generic alkali-vapour magnetometer.

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 state 3 (Figure 4).

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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.

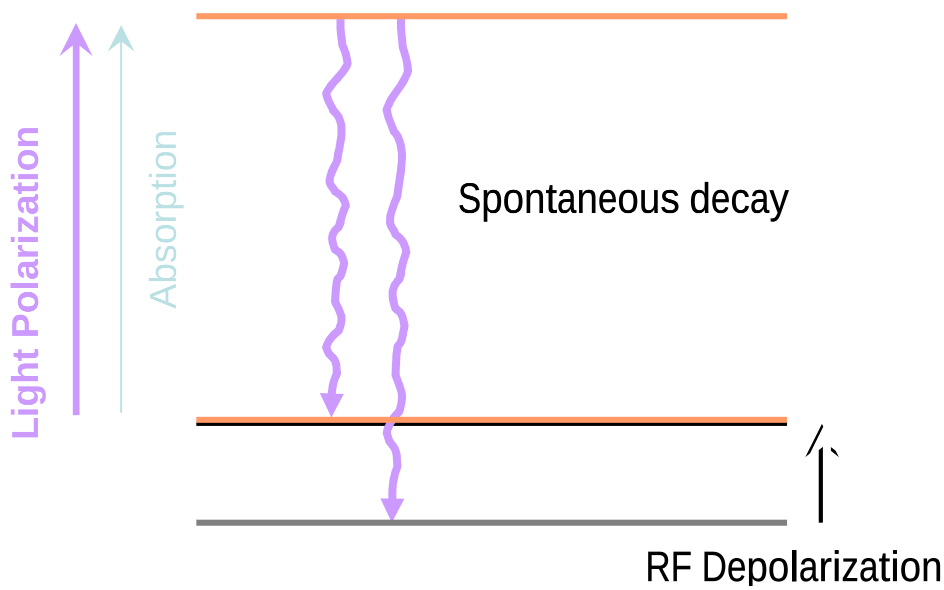

Figure 4: Quantum mechanics of alkali vapor system.

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 the 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.

Helium magnetometers (called Mz magnetometers) are slightly different in that their RF depolarization must be frequency modulated. The modulation allows operation at the centre of the spectral line but the speed of operation (bandwidth) of the magnetometer is limited to about one half of the modulation frequency. Alkali metal magnetometers are all Mx type (i.e. simple depolarizing frequency is sufficient).

Spectral Lines and the Influence of the Nucleus

GEM Systems, Inc.
135 Spy Court
Markham, ON CANADA L3R 5H6
Ph. 905 752-2202 Fax 905 752-2205
info@gemsystems.ca www.gemsystems.ca

Due to the influence of their nuclei, all alkali metal valence electrons possess several energy levels, called Zeeman-effect energy levels, that are each proportional to the magnetic field. Transitions between adjacent energy levels are called spectral lines. To understand spectral lines, one needs to consider both the nuclei and the electrons that are generating the signal.

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 exception is the Helium 4 nucleus that has no spin and magnetic moment. However, it has a single, broad spectral line (some 70nT wide).

The number of lines in the spectra is governed by the Breit-Rabi formulas (see reference 2). Potassium, for example, has 6 energy transitions with mutual separations of some 100 nT at 50 mT field and Cs has 14 spectral lines all within 20 nT separation.

The key characteristics of spectra are line widths and amplitudes. With potassium, the lines are very narrow and do not overlap. With Cs, spectral lines are strong, but also densely spaced, very wide and overlapping. Therefore, Cesium lines are typically lumped together (i.e. measurement occurs over the complete range of all spectral lines).

One implication is that Cesium and Rubidium can operate in a simple, self-oscillating mode, while Potassium needs an auxiliary voltage controlled oscillator (VCO) that is then locked to one spectral line. The VCO provides depolarization for only one line, and the other spectral lines, stay passive (i.e. do not produce precession signals). Other implications of lumped spectral lines will be reviewed elsewhere in this paper.

Cesium Magnetometer

The Cesium alkali vapor magnetometer offers good sensitivity and bandwidth (about 10 pT √ Hz) but has a few disadvantages, including heading errors.

As described previously, Cesium's spectral lines are wide, meaning that the electron energy levels associated with the Zeeman effect vary widely in magnitude over a population of Cesium atoms. In static conditions (i.e. the orientation of the magnetic field is stationary), a peak becomes apparent, and the system will self-oscillate at this peak.

When the magnetic field direction changes, however, the position of this peak will change because the spectral line amplitudes change. As a result, the self-oscillating frequency will shift, producing a heading error. Since Cesium's spectral lines are spread over some 20 nT, the heading error could be that severe.

Split-beam techniques attempt to symmetrize the lump of spectral lines over different magnetic field directions. With split-beam techniques, a polarizer is

GEM Systems, Inc.
135 Spy Court
Markham, ON CANADA L3R 5H6
Ph. 905 752-2202 Fax 905 752-2205
info@gemsystems.ca www.gemsystems.ca

constructed that attempts to polarize one-half of the electrons in one direction, and the other half in the other direction – producing two spectra that together sum to give one broad, but more symmetrical, spectrum for measurement. A consequence of split-beam techniques is considerable reduction in sensitivity of Cesium magnetometers. And, even with split-beam techniques, Cesium magnetometers cannot achieve better than about +/- 1 nT heading error.

Because of this characteristic, the performance of a Cesium magnetometer depends heavily on the orientation of the applied light power with respect to the applied RF power. Small, mechanical shifts within the sensor can cause large numerical shifts in the instrument's output. For this reason, a Cesium magnetometer must be returned to the factory periodically, for re-alignment of the sensor to avoid operation with higher heading errors. The cost of this re-alignment can be significant.

Potassium Magnetometer

The Potassium atom's spectral lines are extremely narrow and they do not overlap. As a result, the design of a potassium magnetometer is somewhat more complex than that of a Cesium magnetometer, and is probably one of the reasons that GEM Systems is the world's only commercial supplier of Potassium Magnetometers.

The fact that Potassium's spectral lines do not overlap means that utilizing Potassium will result in a magnetometer with very low heading error. It also means that a potassium system never requires calibration. The only component that wears out is the light source (the lamp), which has a lifetime of thousands of hours and is economical to replace.

Another benefit of narrow spectral lines is potassium's large bandwidth and sensitivity. In the laboratory, special Potassium magnetometers have shown noise levels of less than 0.05 pT, and have tracked varying magnetic fields as high as 10,000 nT / sec.

Less Common Versions

Helium 3 is a rarely produced magnetometer, and is probably not produced for the commercial market at all. The helium nucleus precesses for a very long time – often hours or even days – after polarization. This creates a nice, continuous low frequency signal that can be sampled easily by inexpensive electronics. The drawback is that polarization requires large amounts of energy that must be supplied quickly to the sensor. The Gyromagnetic constant is only 3.2435 kHz/G causing a large rotational Doppler error in measurement.

While alkali metal (Rb, Cs, and K) vapors readily exhibit electron spin resonance (ESR) because they have a single, unpaired valence electron, Helium 4 needs preparation (it needs to be in a metastable state). This is achieved by a weak electrical discharge of a helium sensor. The average time for an atom to be in a

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135 Spy Court
Markham, ON CANADA L3R 5H6
Ph. 905 752-2202 Fax 905 752-2205
info@gemsystems.ca www.gemsystems.ca

metastable state is only a few microseconds. After that, the atom returns to the stable state and is depolarized. This is the reason for a wide spectral line of Helium 4 (some 70 nT).

Heading Errors in Lumped Spectral Magnetometers

Heading errors reflect the physics of spectral lines in that their relative strength depends on the direction of the sensor axis relative to the direction of magnetic field:

- **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 lumped 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 serious shifts in its readout due only to the sensor-field geometry.

This is called heading error and it is the weakest point of lumped spectrum magnetometers (Rb and Cs). In the past, significant efforts were made to reduce the heading error to more normal values. The split beam technique symmetrizes the lumped line and reduces heading error to some 1-2 nT or even somewhat better then that. However, since these magnetometers have an overall sensitivity in tens of pT/ √Hz, heading error can completely obscure the real magnetic response.

Potassium spectral lines are spaced widely, they are as narrow as 0,15 -1.0 nT and resolution of individual spectral lines is a routine. The lines also vary in strength relative to sensor- magnetic field geometry and a small heading error of less than 0,1nT may exist. This will be due to parasitic phase shifts in electronics or possible inclusions in the sensor's mechanics. Careful design of the sensor and electronics, however, can reduce this to some tens of pT.

Dead Zones and Angular Doppler Effects

The intensity of Zeeman effect is dependent on the direction of the ambient magnetic field with respect to the direction of applied light and RF power. This creates "dead-zones" around the magnetometer sensor, and a loss of signal when sensor is improperly oriented in the ambient field. The tolerance of the orientation variation is high, however – usually between 10 to 80 degrees.

Dead zones (polar and equatorial) are present in all optically pumped magnetometers except for Helium 4 which has only an equatorial dead zone, while Proton and Overhauser magnetometers (due to the simplicity of their sensors) can

GEM Systems, Inc.
135 Spy Court
Markham, ON CANADA L3R 5H6
Ph. 905 752-2202 Fax 905 752-2205
info@gemsystems.ca www.gemsystems.ca

avoid dead zones completely. In addition, it is possible to obtain fully omni-directional sensors by properly engineering the shape of pick-up coils and surrounding sensor liquid.

As discussed previously, the Larmor frequency is the frequency of quantum magnetic moment precession around applied field in a plane of precession perpendicular to the field direction. Rotation of the sensor in the same plane may add to, or subtract from that frequency.

For low Larmor frequency magnetometers, this may be significant (for Overhauser and Proton Precession magnetometers it is about 23.7nT for 1 rotation of the sensor per second in the worst geometry). However, omni-directional sensor design allows for suppression or even elimination of the effect in the appropriate geometry.

Sensitivity

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:

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

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. 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 or Helium 4 with 28 Hz/nT depending on parameters stated in (4).

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

Cesium	20 nT
Helium 3	0.276 pT for 10 hour decay time. Practical spectral line width will be affected by local gradients over the sensor volume.
Helium 4	70 nT
Overhauser	4 nT for methanol solvent 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

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135 Spy Court
Markham, ON CANADA L3R 5H6
Ph. 905 752-2202 Fax 905 752-2205
info@gemsystems.ca www.gemsystems.ca

Any well-designed magnetometer's readings will eventually be limited by a noise level that can't practically be suppressed any further: 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.

Bandwidth

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 you can observe 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.

Pulsed magnetometers (Proton, Overhauser) do not have closed loops, precession signals will freely change the frequency momentarily following changes in magnetic flux density. Since they operate with tuned sensors, tracking speed limit is determined by the speed in changing tuning parameters to follow field changes – which, in turn, will be limited by the number of readings per second (each reading requires constant tuning).

Continuous reading magnetometers have closed electronic feedback loops. Helium 4 will have limits to tracking speed set by modulation frequency, which depends on the spectral line width. Modulation frequencies of few hundred Hz are customary limiting tracking speed to few tens of nT per second.

Self-oscillating Cesium and Rubidium do not seem to have obvious tracking limitations, while Potassium feedback loops allow for up to 1kHz/sec tracking speeds.

Recommended Applications

In conclusion one can summarize features of quantum magnetometers as follows

1. <u>Potassium</u> offers superior sensitivity to any other method due to its resolved spectral lines and it should be used for most demanding applications (i.e. the most sensitive static observations, high sensitivity airborne surveys, and ground surveys (UXO, mines detection, etc)). Dead zones are potassium's weak points. For larger sensors have the best sensitivity but modest gradient tolerance. Smaller sensors have excellent gradient tolerance but somewhat reduced sensitivity.

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135 Spy Court
Markham, ON CANADA L3R 5H6
Ph. 905 752-2202 Fax 905 752-2205
info@gemsystems.ca www.gemsystems.ca

2. Latest Helium 4 laser pumped magnetometers have broken 1 pT/$\sqrt{Hz}$ barrier (0.4pT/$\sqrt{Hz}$ has been reported). Helium 4 is excellent for airborne surveys and other applications where high tracking speed is not required.

3. Cesium commands good sensitivity of about 10 pT/$\sqrt{Hz}$ and it is appropriate in airborne surveys (with active compensator to correct for heading error). Also in other applications for high resolution and gradient tolerance where control of the sensor orientation is possible. Heading errors and dead zones are the limitations.

4. Overhauser magnetometers offer virtually the same sensitivity as Cesium at moderate speeds of operation, very high accuracy and no dead zones and virtually no heading errors. Simplicity of design and moderate costs make Overhauser magnetometers almost ideal for marine surveys, ground mineral and oil exploration, archeological surveys, long term monitoring of magnetic field.

5. Proton magnetometers are at the tail of the lineup as for lower sensitivity and speed of operation but with omnidirectional sensors and the lowest cost of production. Ground surveys for mineral exploration, reconnaissance surveys are the recommended fields of applications for this kind of magnetometers.

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