Technical Report TR-120

Total Field Magnetometers
Theory and Application

ABSTRACT:

This document was written to aid magnetometer users to better understand published specifications of magnetometers and in selection of the best system for their intended application. This document is divided into two main sections. The first section discusses each typical specification in turn, explaining its exact meaning and what its importance is in practical applications. The second section describes the different types of total field magnetometers and in simple terms how they work.

DEFINITIONS OF SPECIFICATIONS:

Sample rate and Cycle time:

Sample rate is normally defined as the number of readings per second reported by the magnetometer. Cycle time is one divided by sample rate and is the number of seconds per reading.

Importance:

Most magnetometers are used in survey applications where they are moved over the ground with measurements taken in many locations over the survey area. In such cases the cycle time of the magnetometer and the speed over the ground determine the distance between measurements. If this distance is even a modest fraction of the depth of the survey targets, the data will not contain the information needed for calculation of the correct target location. In other words, the data needs to be sufficiently sampled (sampled often enough to properly represent the detailed shape of the anomaly) to track even small wave form variations. In hand carried applications, the user can walk slower and compensate for this although this increases the cost of performing the survey. In airborne and marine applications this option is often not feasible.

Bandwidth:

The bandwidth of a magnetometer is an often misunderstood specification. It is becoming increasingly important in determining the usefulness of a given system in producing good data. In the recent past, magnetometers did not contain sophisticated hardware capable of significant real-time data processing (i.e., filtering) and the bandwidth of the system was a simple function of sample rate. Some modern magnetometers contain acquisition and processing hardware or firmware that can act as a low pass filter prior to sampling, simultaneously lowering perceived noise and bandwidth.

All digital magnetometers report a value based on an average of the magnetic field sampled during a "read" period. It is simply the average over a period less than or equal to the cycle time. In such cases it is the sample rate and not the averaging that limits the frequency content of the data. In other cases where there are filters that average over longer times, these filters can become the limiting factor of frequency content.

Importance:

If any significant processing of the data has been done inside the magnetometer, it is very important to know what the resulting bandwidth of the system is because this will determine the utility of the system. It is possible, for example, to make very smooth, low variability magnetic data by simply applying a filter that removes all of the high frequencies. Such a system can appear to have a sample rate many times higher than the actual frequency content of the data justifies. In such cases it is the filter and not sample rate that will determine the fastest speed at which a survey should be done. Such filters also degrade the performance of software that calculates the depth of targets and can completely mask the anomalies caused by small objects. Bandwidth, resolution, noise and sensitivity are considered during the export licensing review process.

Resolution:

The resolution of a magnetometer is the smallest change in magnetic field that its output can indicate. For example, assume a magnetometer is in a field that is smoothly increasing. The magnetometer may report data such as this:

50123.456
50123.456
50123.567
50123.567
50123.567
50123.678

In this case, the magnetometer was able to produce the values 50123.456, 50123.567 and 50123.678 , but none of the numbers in between. In this case the resolution would be 0.111 even though the least significant digit reported was 0.001.

Importance:

It is important that a magnetometer have a resolution much smaller than the smallest change in magnetic field that must be detected in the intended application. Because the resolution of a magnetometer usually varies with sample rate, it is important to make sure that the resolution specification applies to the intended sample rate in your application. If the data sheet does not make clear what sample rate was used for the determination of resolution, it is best to ask the manufacturer what the resolution will be at your desired sample rate.

Absolute error and drift:

The absolute error in a magnetometer is the difference between the average of the readings of the magnetometer and the average of the field it was actually measuring. The drift is the change in the absolute error with time. All magnetometers will have some absolute error and drift in the measurements. In most cases the drift will be much less than the absolute error.

Importance:

The drift is usually more important than the absolute error but or most systems a drift of less than 0.1nT per day is acceptable. Values greater than this can cause artifacts in surveys. Because other survey errors usually dominate (positional inaccuracies, heading errors due to instrument and mobile platform effects, diurnal) and are cumulative, absolute accuracies in the range of 2 to 4 nT are quite acceptable. When a magnetometer is being used as a primary standard or in a observatory situation, then absolute accuracy and drift specifications are primary.

Peak-to-Peak:

Peak-to-peak values are simply the difference between the highest and lowest numbers. They are the usual method for specifying heading error values. In the past they were commonly used to specify noise values. Peak-to-peak noise values are becoming less popular largely because there is no standard for the amount of data that must be scanned looking for the most largest and smallest values. Historically some makers used a relatively small amount of data while others used a large amount and discarded 10% of the readings.

Importance:

If a peak-to-peak specification with no further explanation appears on the data sheet, it will usually be the noise or heading error specification. If there is an doubt, it is best to contact the maker to determine what is actually being specified.

RMS:

The letters RMS stand for Root Mean Square. To calculate the RMS value of a list of numbers, you square all of the numbers, total up the squares, divide by the number of readings to arrive at the mean and then take the square root of the mean. RMS values are usually used for noise specifications and in some cases the word "noise" may be missing from the data sheet specification.

Importance:

RMS values have properties that are useful when dealing with things of a statistical nature, such as noise.

Noise:

Noise by our definition is quite simply any variation in the measurement not caused by actual variations in the external magnetic field. (In other venues, noise may refer to diurnal variations for example which are part of the external field, but tend to occlude the signal of interest.) In the noise specification of a magnetometer it is normally assumed that the sensor is not moving, so that the heading error is not included in the noise.

Importance:

The system noise specification of the magnetometer sets the lower limit of the noise in the data. A typical survey situation will add additional noise to the survey data. Noise is normally specified as the number of NanoTeslas (10^{-9}T) per square root Hertz (nT/%Hz) or in some cases PicoTeslas (10^{-12}T) per square root Hertz (pT/Hz). Hertz (Hz) refers to the rate at which the data is collected, i.e., faster sampling means higher Hz numbers (10 samples per second = 10 Hz). There may or may not be the letters “RMS” after these specifications, but in all cases it is assumed that the values reported are RMS specifications. Because of the nature of statistics, increasing the sample rate (Hz) by a factor of four will increase the noise in the data by a factor of two. If a noise is given only as a number of NanoTeslas, it is important to know to which sample rate this applies. In most cases it will be the noise at the slowest cycle rate of the system, i.e. several seconds or more. One can see that expressing noise only in NanoTeslas without sample frequency information is misleading in that in general noise levels at one sample every 2 seconds are far better than that experienced at 10 samples per second yet the specifications to not tell the user this information, alluding only to the best spec at the slowest and generally unusable sample rate.

Sensitivity:

The term "sensitivity" is gradually becoming obsolete in the industry. This is partly because various companies define the term differently. Since one can never be sure when comparing sensitivity specifications that one is judging the two products on an equal footing, it us usually best to ignore the sensitivity specification and refer to the resolution and noise specifications. The fairest definition of sensitivity seems to be that the sensitivity is the resolution or the noise, which ever is the larger.

Importance:

The sensitivity specification provides a single number that can be used for performance comparison between magnetometers that are limited by their resolution and those that are limited by their noise.

Heading error:

Heading error is the change in the measured value of the magnetic field caused by changing the orientation of the sensor in a constant magnetic field.

The causes of heading errors can be grouped into two basic types: heading errors inherent in the physics used to make the measurements (these will be covered in the individual sections below) and heading errors caused by the permeability of materials of which the sensor is constructed.

All materials have a permeability different from that of free space. This fact combined with the fundamental principle that no practical sensor design can assure completely uniform distribution of the materials means that no matter what technology is used to make the measurement, some heading error will always exist in the system.

Most manufacturers will specify the heading error for a sensor as a peak-to-peak value. The sensor is rotated in all directions in a constant magnetic field. The lowest value obtained is subtracted from the highest value obtained to get a peak-to-peak value. Many makers will also provide plots of the heading error curves with orientation.

Importance:

In any application where the sensor may change its orientation relative to the ambient field, heading error is important. It is most important in airborne and marine systems and less so in hand carried systems. This is because in airborne systems the aircraft must constantly change it's orientation angle to maintain the correct path over the ground and in marine systems, the sensor undergoes some change in orientation as it is towed. A person tends to hold a sensor at a more or less constant angle. In airborne systems the fixture that holds the sensor is adjustable for local earth's field angle so that during maneuvers the sensor will not enter a dead zone.

A few low end or non-professional marine and land magnetometers now on the market do not specify a heading error value or claim to have none at all. We maintain this is unscientific and in error as all systems by definition have these inherent errors. These systems should only be considered for demonstration and educational purposes, where cost is the overriding concern.

Dead-zones:

If the angle between the magnetic field and the major axis of the sensor is such that the sensor does not produce any measurement the sensor is said to be in a dead-zone. In fact the edge of the dead-zone is seldom a sharp line. The quality of the data degrades as the dead-zone is approached. The edge of the dead-zone is that point at which the manufacturer will no longer guarantee that the instrument will meet all of its other specifications. All optically pumped and proton precession and Overhauser magnetometer experience some dead zone effects to a greater or lesser degree.

Importance:

In some rare situations the orientation of the sensor cannot be controlled, a sensor with dead-zones is then not the best option. In most real situations the orientation of the sensor can be controlled and dead-zones avoided. In these situations it can become a trade off between a sensor that requires some effort to keep it out of its dead-zone and one that has no dead-zone but does not have as good performance.

TYPES OF MAGNETOMETERS:

Proton Magnetometers:

There are two types of proton magnetometers in common use, the free precession and the Overhauser magnetometers. Both rely on the fact that the proton has a mass, a charge and a spin which are all atomic constants and as a result the gyromagnetic ratio is known to within ten parts per billion. The nucleus of a hydrogen atom is a single proton and hence both magnetometers can use a hydrogen containing fluid such as water or mineral spirits as the working sample.

In proton magnetometers the signal is developed in a coil that surrounds the sample. The simplest version of this causes a dead-zone to appear when the coil's axis is aligned with the magnetic field. This dead-zone can be eliminated by using more than a single coil and arranging them so that their axis are at angles to each other.

The proton's gyromagnetic ratio is quite accurately known. According to the US NIST Reference on Constants, Units and Uncertainty as of September 1999 the shielded proton gyromagnetic ratio is:

$$2.67515341x10^8 \text{ Radians/sec/Tesla}$$

with a standard error of:

$$0.00000011x10^8 \text{ Radians/sec/Tesla}$$

It is from these numbers that we derive the constant 23.48719622nT/Hz used to convert frequencies to field values. From the standard error we know that the calculated field can be said to be within 0.004nT over the normal range of field values.

Proton Free Precession Magnetometers:

This magnetometer polarizes the sample using a large magnetic field. This field is usually produced by passing a current through coils around the sample for as long as several seconds. This applied field is switched off and then the precession signal is detected, usually using the same coils.

The sensor of the free precession magnetometer is simple and relatively inexpensive. The heading error is caused only by the materials used in its construction. The physics of free precession do not create any inherent heading error. The sampling frequency is at the most a few Hertz.

Preferred applications:
The free precession magnetometer is a good choice in those applications where the absolute accuracy of the magnetometer is important and the low cycling rate will not be a problem. They are well suited for use as a secondary standard. Their low cost also make them a good choice when the costs make other magnetometers impractical.

The sensor usually contains a modest quantity of a hydrocarbon such as mineral spirits. These need to be handled and disposed of correctly if the sensor needs to be repaired or replaced.

Overhauser Magnetometers:

The Overhauser magnetometer can be likened to a laser or maser. A high frequency RF signal provides the pumping energy to keep the protons constantly processing. A tuned circuit built around the sensing coil functions much like the cavity in a maser.

As in the maser the output frequency is a function of the tuning of the cavity and not just a function of the value of the external field as would be desired. Because of the physical nature of the proton this error in field strength measurement will be less than approximately 25nT. Smaller values can be obtained through careful design of the electronics. In Overhauser magnetometers using multiple coils to eliminate dead-zones, an additional heading error can be caused by slight differences in the coil parameters acting as the cavity.

The Overhauser magnetometer produces a continuous signal which allows a faster sampling rate than the free precession magnetometer (no polarize time required). The bandwidth and noise performance will be slightly better than that of the free precession magnetometer, but about a factor of 100 times poorer than the Cesium magnetometer. The frequency of the signal produced in the Cesium magnetometer is over 80 times higher than that produced by the Overhauser effect (between 900Hz to 4000Hz). This low frequency is in a large part responsible for the relatively poorer performance of the Overhauser. In addition, both free precession and Overhauser magnetometers are subject to noise caused by Doppler shift of the pickup coils with respect to the precessing protons in the operating fluid, as the sensor is rotated during survey procedures. Optically pumped systems are orders of magnitude *less sensitive* to these rotational effects generating substantially less noise due to rotational effects.

In general, manufacturer specifications refer to operation under laboratory conditions. Clearly, as Doppler shift noise exhibits, performance under actual field conditions is the variable most important to the customer. Optically pumped systems will always perform orders of magnitude better than proton systems due to the inherent limitations of the basic output frequency as described fully in information theory.

Preferred applications:

The Overhauser magnetometer is a good choice in those applications where the faster sampling rate is important, the absolute accuracy of the free precession magnetometer is not needed, the optically pumped magnetometers are deemed impractical and the much higher noise and lower bandwidth of the Overhauser can be tolerated.

The Overhauser sensor contains a very toxic chemical that can be absorbed through the skin. Damaged sensors should be returned to the manufacturer for repair or disposal.

Optically Pumped Magnetometers:

There are two classes of optically pumped magnetometers, the swept and the self-oscillating magnetometer. Each of these classes may use one of four materials, Cesium, Rubidium, Potassium and Helium. This amounts to eight different magnetometers. To reduce the amount of repetition in this document, matters common to all optically pumped magnetometers will be described first, followed by discussion of the two classes of magnetometer and then issues unique to the four materials will be discussed.

All Optically Pumped Magnetometers:

All of the optically pumped magnetometers use the properties of the electron to make their measurements. Light at a particular wave length is radiated through a gas cell containing the working gas of the magnetometer and from there onto a photocell. A small coil, called the H1 coil, applies a small RF field to this gas cell.

All of these magnetometers exhibit heading errors due to the physics of the measurement process. Work done at Varian Associates in the 1960's proved that, in the case of Cesium, these errors could be reduced to about 0.1nT with proper optics. Either very accurate machining or a one time adjustment can be used to obtain the correct alignment of the optics. Most makers have opted for the one time adjustment method as it generally produces better sensors. Each maker has its own method for making the adjustment. Once adjusted the setting is glued in place and never needs readjustment.

Classes of Magnetometers:

Swept Magnetometers:

As the frequency of the RF applied to the H1 coil is varied a point will be found where the light passing through the cell is dimmed due to absorption in the cell. This is called the Larmor frequency. By modulating the RF frequency slightly above and below the point of maximum dimming electronics can be contrived to follow the Larmor frequency as it changes in response to the ambient magnetic field.

Swept magnetometer do not exhibit a polar dead-zone. They do exhibit an equatorial dead-zone which causes a signal loss if the earth's field vector is at right angles to the sensor's major axis. Typically the equatorial dead-zone of a swept magnetometer is wider than that of the self-oscillating design. Because both the rate of and the width of the frequency modulation are limited to a few hundred Hertz this type magnetometer can not track rapidly changing fields. The bandwidth of a swept magnetometer will always be much less than the line width and hence much less than that of the self-oscillating magnetometers described below.

When the field is changing rapidly the output of the magnetometer lags behind this change and should it fall too far behind it will lose its lock and begin producing values that are unrelated to the external field. This is referred to as exceeding the slew rate limit. There is also a problem of the frequency modulation beating with external magnetic fields causing aliasing in the resulting data.

The noise performance of a swept magnetometer is not as good as that of the self-oscillating magnetometers. In many electronic components, such as the lamp used in the magnetometer, this is noise that varies with intensity as the inverse of frequency. Since the swept magnetometer must by its nature have its low level signals at low frequencies, this noise has more effect on the resulting measurement.

Preferred applications:

Swept magnetometers are a good choice when the polar dead-zone will be a serious problem, no rapidly changing external fields are present and the lower performance compared to the self-oscillating design can be tolerated.

Self-Oscillating Magnetometers:

When the frequency applied to the H1 coil is equal to the Larmor frequency, not only a dimming of the light will be seen, but there will also be a small signal at the Larmor frequency seen on the photocell. This signal can be amplified, limited and applied to the H1 coil creating the self-oscillating magnetometer.

This magnetometer is electronically simpler than the swept magnetometer. It does well in situations where there are rapid changes in the magnetic field because it lacks the aliasing and slewing problems that plague the swept design. There is an additional dead-zone. The polar dead-zone causes the magnetometer to stop operating when the magnetic field is aligned with the major axis of the sensor. The best signal is when the field passes through the sensor at a 45 degree angle.

Because of the physics used in a self-oscillation magnetometer the bandwidth of the measurement will always be approximately one half of the line width.

Preferred applications:

Self-oscillating magnetometers are a good choice when high performance is needed, particularly in the presence of rapidly changing magnetic fields and when the sensor's orientation can be controlled.

Optically Pumped Magnetometers Characterized by Operating Gas:

Cesium magnetometers:

Both self-oscillating and swept designs can be made based on Cesium. The line in Cesium is actually a grouping of several lines that are wide enough and close enough together that they merge to produce what appears as a single line. This makes it possible to obtain high performance from a Cesium magnetometer with relatively simple electronics.

The Cesium vapor in the cell is created by heating the cell to obtain the correct vapor pressure.

Because this apparent line is relatively narrow the modulation frequency needed for a swept magnetometer is low enough that such magnetometers suffer badly from slew and aliasing problems common to swept magnetometers. For this reason self-oscillating magnetometers are the rule for Cesium magnetometers.

Note: The Cesium used here is not the radio-active sort that appears in nuclear waste. It is just an alkali metal much like sodium or potassium.

Preferred applications:

The Cesium, has all of the advantages of a self-oscillating magnetometer and thus is a good choice when a high performance magnetometer is needed. This is especially true in those applications where the field value may be rapidly changing. Cesium magnetometers have been the standard in airborne applications because of their superior noise performance and bandwidth. They are becoming common in marine applications because the orientation problems have been largely solved and the increasing demand for high resolution marine surveys.

Rubidium Magnetometers:

Rubidium magnetometers are nearly identical to Cesium magnetometers. The main difference is that the cell must be heated to a higher temperature to obtain the correct vapor pressure for proper operation.

Preferred applications:

If ambient temperatures of over 50 degrees Celsius are routinely experienced and the performance of a Cesium magnetometer is required a Rubidium magnetometer should be considered. At cooler temperatures there is no advantage and the more power needed for the heater is a disadvantage.

Potassium magnetometers:

In many respects Potassium magnetometers are very like Cesium magnetometers. Unlike Cesium the Potassium lines are narrow enough that they appear as discrete lines. This makes designing a Potassium magnetometer with good performance more difficult than the Cesium case. The multiple lines can cause the magnetometer to report one of several different field values for the same external field. This will typically happen when the sensor is rotated into and then out of a dead-zone or the external field changes rapidly. Swept magnetometers are the rule for Potassium magnetometers. The narrow line width of Potassium requires a slow sweep speed making the problems common to all swept magnetometers much worse.

Preferred applications:

The inability of the Potassium magnetometer to track rapid changes in the field, combined with the tendency to hop to a different line and thus start reporting erroneous values makes the Potassium magnetometer poorly suited to any situation where the field being measured is changing or the sensor may be rotated into its dead-zone.

Helium magnetometers:

No-one has yet produced a practical self-oscillating circuit for the helium magnetometer. Swept magnetometer designs are the rule for Helium. Both the Larmor frequency and line width of Helium are greater than for the others of this class. This means that the sweeping frequency can be several hundreds of Hertz somewhat mitigating the problems with slewing and aliasing.

In order for the gas cell in a helium magnetometer to function there must be a weak electrical discharge in it to elevate the helium atoms to the correct state. No heater is required because Helium is a gas at room temperature.

Because Helium is a gas at room temperature the exactly right amount of Helium must be put into the cell. In the other optically pumped magnetometers an excess of the material is put into the cell and then the correct amount is evaporated by the heater to create the correct vapor pressure. This fact combined with the great ease with which Helium can diffuse through glass makes it difficult to obtain a long life expectancy for a Helium magnetometer.

Preferred applications:

At the time of this writing, no Helium magnetometers are commercially available. Should someone begin producing them, Helium magnetometers should be considered for those cases where the polar dead-zone of the Cesium magnetometer makes it use impractical. The heading error, noise and bandwidth specifications of a Helium magnetometer should be better than that of the Potassium magnetometer, but not quite as good as that of a Cesium magnetometer.

SUMMARY:

Study and comparison of manufacturer data sheets can be confusing as each manufacturer tends to use different parameters to maximize their apparent performance advantages. Each sensor technology has its own positive and negative aspects as described above. In general, the industry has demanded increased sensitivity with increased sample rate, in effect, increased bandwidth. The end user will have to weigh the costs of each technology against the survey production rates, detection efficiencies and logistical deployment concerns. In general, we believe that optically pumped magnetometers offer the best sensitivity and sample rates, providing lowest cost per line kilometer of any other sensor technology.