GEOMETRICS

# Technical Report TR-120

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# Total Field Magnetometer Performance Published Specifications and What They Mean

## ABSTRACT:

This document is presented to aid users of total field magnetometers to better understand published system specifications and thus select the best equpment for their application. The report is divided into two main sections: the first defines typical specifications, precisely explaining their meaning and importance in practical usage. The second section describes the different types of total field magnetometers and in simple terms how they work so that a comparison of performance is possible.

## DEFINITIONS OF SPECIFICATIONS:

### Sample rate and Cycle time:

Sample rate is normally defined as the number of readings per second reported by the magnetometer. It is often reported as a frequency of reading in Hertz (Hz). Cycle time is one divided by sample rate and is the number of seconds per reading.

$$\text{Sample Rate} = \frac{\text{Readings}}{\text{Second}}\ (\text{Hz}) \qquad \text{Cycle Time} = \frac{\text{Seconds}}{\text{Reading}}$$

Importance:

Most magnetometers are used in surveys where they are transported over the earth's surface. Total field measurements are 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 "sampling" distance is small compared to the depth of the survey targets, the data will contain the information needed for proper calculation of the target location. In other words, the magnetic field needs to be sufficiently sampled (sampled often enough to properly represent the detailed shape of the anomaly and prevent "spatial aliasing") to be able to track even small variations. In hand carried applications, the user can walk slower and increase the data density at the expense of reduced production. In airborne and marine applications this option is often impracticable.

## Bandwidth:

The bandwidth of a magnetometer is in simple terms a measure of how well it can respond to rapid changes in the measured field. Higher bandwidth means better response. It determines in large part the ability of a given system to produce good data and faithfully reproduce the actual field. Not long ago, 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 apparent noise and bandwidth at the same time*.

All digital magnetometers report a value based on an average of the magnetic field sampled during a “read” period; there is no way to instantaneously sample the field strength with the high degree of accuracy required for geophysical survey. This reported value is normally the average value over a period less than or equal to the cycle time. In such cases it is the sample rate and not 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 the resulting bandwidth of the system because this determines the basic 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 high frequencies. Such a system can appear to have a sample rate many times higher than the actual frequency content of the data justifies, *but in reality the system is just reporting numbers that form a smooth curve, not the actual recording of the field variations*. 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.

## Resolution:

The resolution of a magnetometer is the smallest change in magnetic field the magnetometer can resolve or report. 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:

A magnetometer must have a counter resolution much smaller than the smallest change in magnetic field being detected or “quantization errors” will result, improperly defining the shape and character of the anomaly. 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 a system data sheet is unclear about the sample rate used for the determination of resolution, investigation as to the relationship between sample rate and bandwidth or sensitivity (discussed later) would be prudent.

### Absolute error and drift:

The absolute error is defined as the difference between the average of the readings of the magnetometer and the average of the field it measures. Drift is defined as the change in the absolute error with time. All magnetometers will have some absolute error and drift in their 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. For most systems a drift of less than 0.1 nT per day is acceptable. Values greater than this can cause artifacts in surveys such as survey block edge effects. Because other survey errors (positional inaccuracies, heading errors due to internal instrument and mobile platform effects, diurnal earth’s field variations) usually dominate 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 factors.

### Peak-to-Peak (P-P):

Peak-to-peak is a common term used to define amplitudes of signals or noise. The P-P value is simply the difference between the highest and lowest values. P-P is the usual method for specifying maximum heading error values. Peak-to-peak noise values are becoming a less popular metric because they are somewhat subjective, imprecise and because there is no standard for the amount of data that must be scanned to arrive at the largest and smallest values. Historically some makers used a relatively small amount of data (short good looking sections) while others used a large amount and discarded 10% of the “out-flyer” readings.

Importance:

Peak-to-peak specifications are ambiguous. If a peak-to-peak specification with no further explanation appears on the data sheet, it will usually be the system noise at some arbitrary cycle rate 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.

$$rms = \sqrt{(x_1^{2} + x_2^{2} + \ldots\ldots x_n^{2})\,/\,n}$$

Importance:

RMS values have properties that are useful when dealing with things of a statistical nature, such as noise. Statisticians term the RMS value the Standard Deviation which gives a measure of the variability of the data. When adding two sources of noise, the resultant RMS noise is the square root of the sum of the squares of the noise values (like adding two vectors at right angles to one another.)

**Noise:**

Noise by definition is simply any variation in the measurement not caused by actual variations in the external magnetic field. When considering the noise specification of a magnetometer, it is normally assumed that the sensor is not moving, so that the heading or motion errors are not included in the background system noise.

Importance:

The “system noise” specification of the magnetometer sets the lower limit of the noise in the data. This is important because during the performance of a typical survey, additional noise sources are encountered as noted above. 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 sample rate previously defined and faster sampling yields higher frequency numbers in Hz (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 by a factor of four will increase the noise in the data by a factor of two (noise goes up as the square root of the sampling rate increase.) *If a noise specification 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.

Noise values that are expressed only in NanoTeslas without sample frequency information can be misleading. Care must be employed when comparing noise specifications to ensure that the values reported have equal weight. Converting all noise values to nT/%Hz ensures this.

### Sensitivity:

The term "sensitivity" is becoming less common in the industry, partly because different manufacturers define the term dissimilarly. When comparing sensitivity specifications one cannot be confident that one is judging the two products on an equal footing. Therefore, it us usually best to ignore the sensitivity specification and refer to the resolution and noise specifications (in nT/%Hz). The most acceptable definition of sensitivity seems to be that the sensitivity is either 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. It is best to consider all three specifications.

### 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 magnetic permeability (or susceptibility) of the materials from 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 materials, means that no matter what technology is used to make the measurement, some heading error will always exist in a system.

Most manufacturers will specify the heading error for a sensor as a peak-to-peak value. The value is obtained by rotating the sensor 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 as a function of orientation angle.

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 its orientation angle to maintain the correct path over the ground. In marine systems, the sensor undergoes some change in orientation as it is towed. In land systems heading error is less apparent as a person tends to hold a sensor at a more or less constant angle.

Several low cost marine and land magnetometers do not specify a heading error value or claim to have none at all. Since all magnetometers have heading errors, the prudent user should question instrument specifications which do not report a heading error value. This heading error becomes an important factor when generating contour maps as data collected in alternate directions using systems with large heading errors will produce “striping” in the final result. There are some methods for post-acquisition removal of this artifact, but the better course is to minimize the error initially using systems with an absolute minimum of heading error.

### 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 published specifications. All optically pumped, proton free precession and Overhauser magnetometers experience some dead zone effects to a greater or lesser degree. In optically pumped systems an adjustable orientation fixture holds the sensor so that during maneuvers the sensor will not enter a dead zone. In proton and Overhauser systems, a three coil array or toroidal coil is employed to minimize or eliminate the dead zone effect .

Importance:

In some application the orientation of the sensor cannot be controlled. In that case, a sensor with dead-zones is not the best option. Usually, the orientation of the sensor can be controlled and dead-zones avoided.

## TYPES OF MAGNETOMETERS:

### Proton Magnetometers:

There are two types of proton magnetometers in common use, the free precession and the Overhauser magnetometer. Both rely on the fact that the proton has a well known mass, charge and spin which allows the gyromagnetic ratio to be calculated accurately 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 material.)

In proton magnetometers the signal is developed in a coil that surrounds the fluid rich in free hydrogen. In a single coil system, a dead-zone will appear when the coil's axis is aligned with the magnetic field vector. This dead-zone can be eliminated by using three coils and arranging them so that their axes are at 120° angles relative to one another.

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:

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

with a standard error of:

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

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 determined to 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 precessing. 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.

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.

It should also be noted that proton and Overhauser sensors have signal to noise ratios that are dependent upon the field strength they are measuring, meaning that in low field strength conditions (such as in the south Atlantic), their S/N ratio deteriorates making them more prone to system and survey noise.

## Optically Pumped Magnetometers:

There are two classes of optically pumped magnetometers, swept and self-oscillating. Each of these classes may use one of four active materials: Cesium, Rubidium, Potassium and Helium. 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 optically pumped magnetometers use the properties of the electron in their measurements. Light at a particular wavelength is radiated through a gas cell containing the working gas of the magnetometer and from there onto a photocell. A small “depumping” coil (H1) applies an RF field to this gas cell. See Technical Report ** *Optically Pumped Magnetometer Theory* for a more complete review of the physics.

Optically pumped systems will always out-perform proton and Overhauser systems by orders of magnitude because they employ an oscillating signal at between 70KHz and 350KHz as compared to 0.9KHz to 4.5KHz for proton/Overhauser systems. As information theory predicts, higher frequencies can carry more information, providing better response and more faithful reproduction of the original signal.

All 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 optical components. Most manufacturers have opted for the one time adjustment method as it generally produces better sensors. Once adjusted the setting is fixed 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 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 "lock" and begin producing values that are unrelated to the external field. This is referred to as "exceeding the slew rate limit". Another potential problem of swept magnetometer implementation is when the frequency modulation beats with external magnetic fields causing aliasing in the resulting data. This can be a problem when using swept magnetometers near large AC fields like those generated by power lines.

Swept magnetometers have more noise than self-oscillating magnetometers. In many electronic components, such as the lamp used in the magnetometer, there is an inherent noise (called $1/f$ noise) that varies 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 “optical absorption” 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.

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:

Each sensor technology has positive and negative properties as described above. Study of the technical data sheets are for many users the only “objective” means by which a comparison of system performance can be accomplished. Manufacturer use of dissimilar methods of specifying key parameters can be confusing, standardization is recommended.

The industry has demanded increased sensitivity with increased sample rate, in effect, increased bandwidth. The end user should weigh the costs of each technology against the survey production rates, detection efficiencies and logistical deployment concerns. In general, optically pumped magnetometers offer the best anomaly response and sample rate, providing the greatest detection capability any other commonly available sensor technology.