Fluxgate Magnetometers

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ABSTRACT

A wide variety of sensors are currently available and used to measure magnetic fields. Fluxgate magnetometers and gradiometers measure the direction and magnitude of magnetic fields. Fluxgates are affordable, rugged, compact and very low-power making them ideal for a variety of sensing applications. Fluxgate magnetometer sensors are manufactured in several geometries and recently have made significant improvements in noise performance, crossfield tolerance and power utilization

KEYWORDS

Fluxgate, sensor, magnetometer, gradiometer, Single Domain, crossfield

1. INTRODUCTION – FLUXGATE TECHNOLOGY

1.1 Theory of Operation

The typical fluxgate magnetometer consists of a "sense" (secondary) coil surrounding an inner "drive" (primary) coil that is wound around permeable core material. Billingsley currently manufactures four types of sensors: ring core, rod / Förster, racetrack and the recently developed Single Domain. Each sensor has magnetic core elements that can be viewed as two carefully matched halves. An alternating current is applied to the drive winding, which drives the core into plus and minus saturation. The instantaneous drive current in each core half is driven in opposite polarity with respect to any external magnetic field. In the absence of any external magnetic field, the flux in one core half cancels that in the other and the total flux seen by the sense coil is zero. If an external magnetic field is now applied, it will, at a given instance in time, aid the flux in one core half and oppose flux in the other. This causes a net flux imbalance between the halves, so that they no longer cancel one another. Current pulses are now induced in the sense winding on every drive current phase reversal (or at the 2nd, and all even harmonics). This results in a signal that is dependent on both the external field magnitude and polarity. [1]

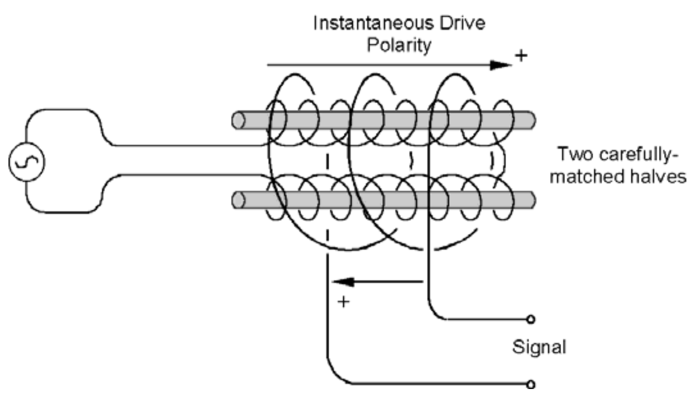

Figure 1 - Fluxgate Theory of Operation

There are additional factors that affect the size of the resultant signal. These factors include the number of turns in the sense winding, magnetic permeability of the core, sensor geometry and the gated flux rate of change with respect to time. Phase synchronous detection is used to convert these harmonic signals to a DC voltage proportional to the external magnetic field.[2]

High quality low noise fluxgates use a feedback loop to keep the core at zero field. The typical topology is shown in Figure 2 – Basic Fluxgate Block Diagram. The phase synchronous detector (or analog multiplier) is utilized to detect the even harmonics and these signals are integrated in an analog integrator to develop a voltage that represents the ambient field through the core. This signal is then fed back to the core to "null" the core to zero. The following paragraphs detail the level of complexity involved in the drive current circuit and at each step of the sense signal processing.

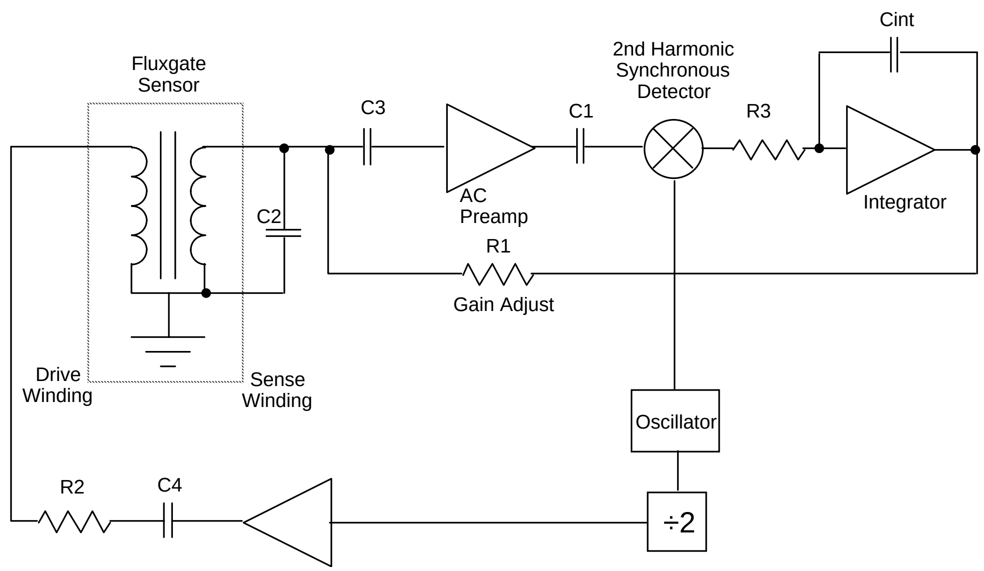

Figure 2 – Basic Fluxgate Block Diagram

1.2 Oscillator/Drive Circuit

To produce fluxgates with very low noise and stable zero offsets, it is necessary to drive the sensor core deep into saturation while minimizing power consumption. The core driver usually employed consists of an oscillator/divider, a low output impedance MOSFET driver and an R/C network R2, C4 shown in Figure 2. The drive waveform, typically in the 10 to 30 kHz range, is applied to R2, C4. As the core goes through the high permeability region of the B-H curve, the impedance of the drive winding connected in series with capacitor C4 is high and the capacitor charges through resistor R2. When the core reaches saturation, the impedance of the drive winding drops to a very low value and the capacitor discharges through the core winding. A large current surge of short duration will occur in the core winding, which will drive the core deeper into saturation. On the other half of the drive waveform, the core will be saturated in the other direction.

This topology drives the core into saturation while maintaining low average power consumption. It also ensures that the timing of the core saturation is very constant and is reasonably independent of drive voltage and core temperature effects. This timing of saturation is very important because it affects the phase of the generated second harmonic signal and it must be held constant for ideal operation of the magnetometer's synchronous detector. Any shift of the second harmonic signal phase changes the sensor's zero offset and to some extent the 1/f or "self noise" level.

1.3 Magnetometer Sense/Feedback Winding

The magnetometer sense or feedback winding is wound in a solenoidal form around the outside of the sensor core. This winding detects the even harmonics of the drive frequency, which are proportional to the magnetic field through the sensor, and are also used to feedback a current to null the core. Dual use of the coil is possible since the harmonics are AC signals and the feedback is near DC. Used as a sense coil, it is AC coupled via C3 to the sensor circuit's preamplifier. Capacitor C2, in parallel with the sense winding, tunes the winding whose inductance is being modulated at the core frequency by the second, and higher, even harmonics, of the drive frequency.

This coil is used with feedback to cancel the measured field, making the mechanical, electrical, and thermal characteristics are critical. The magnetometer output circuit provides feedback current to this coil, which creates a field in the opposite direction to the measured field, canceling the measured field at the sensor core. If the feedback current and the current to field relationship of this coil is known, then the field being measured is known. This coil's dimensions must not change with temperature, or must change in a predictable way, since the field it creates is a function of its dimensions and its input current.

1.4 AC Amplifier

The operational amplifier selected for the AC preamplifier has very low noise at the frequency of operation of the magnetometer circuit. Its wide bandwidth is necessary to prevent phase shift of the harmonic signals, which can cause an unstable sensor zero offset. The AC coupled gain of this stage is typically > 30 dB and reduces the DC errors of the following integrator stage by this amount.

1.5 Synchronous Detector

A synchronous detector is used to convert the harmonic signals from the sense coil to a DC voltage that is proportional to the integral of the even harmonic's magnitude. The voltage sign indicates the signal's phase. This switch must have low noise and low feedthrough of the switch's controlling signal to prevent unwanted sensor offsets.

1.6 Integrator

The amplifier used in the magnetometer circuit's integrator must have low 1/f noise as well as low current/voltage offsets and drifts. The integrator output is fed back to the sensors signal winding through a resistor. This feedback nulls the ambient field as seen by the sensor. The sensor's non-linearity is reduced, approximately, by the "open loop" gain factor (typically > 100 dB) of the integrator amplifier.

1.7 Noise

All sensors will exhibit some variability of their output even in an idealized completely static magnetic field. This sensor "self noise" is more or less white noise in spectral distribution but typically increases at about 6 dB per frequency decade below a "knee" point. This is known as 1/f noise. Standard fluxgate sensors' "knee" point tends to be > ≈ 1 Hz. Higher quality sensors such as the recently developed Single Domain sensors [have a "knee" point of ≈.2 to .5 Hz. This frequency point can be of critical importance in applications where the frequencies of interest are in the low milliHertz range.

1.8 Crossfield Effects

Fluxgate sensors, especially ring cores, are somewhat sensitive to crossfield effects. Cross field are magnetic fields perpendicular to the sensors sensing direction. We do not refer to the static deviation (misalignment) of the sensing direction from the geometrical axis, which may easily be corrected. The crossfield effects may appear as the change of sensitivity, decrease of linearity, change of the offset and change of the sensing direction caused by perpendicular field. Sensor geometry is a critical component of increasing crossfield tolerance. Rod (or Förster) sensors are the least susceptible to crossfield effects. [3]

2. FLUXGATE SENSORS

Billingsley manufactures four types of fluxgate sensors: ring core, rod / Förster, racetrack and the recently developed ultra low-noise Single Domain and selects sensor type based on application requirements.

A sensor's quality or performance is primarily judged by three criteria, broadband and 1/f noise, and zero-offset stability also referred to as accuracy. There are multiple contributors to noise and sensor zero offset stability. The source of noise is the sensor core itself. Careful selection of the sensor core's soft magnetic material and geometry are critical to the manufacture of low noise fluxgates. The processes used to fabricate the core have a significant impact the zero-offset performance of the sensor. Various electronics factors also affect low frequency noise, including thermal drifts that induce a zero drift, feed through of the second harmonic in the phase detector and offset drifts of the integrator circuit.

2.1 Sensor Core Materials

Historically Nickel/Iron/Molybdenum alloys have been used to fabricate sensors. The highest quality of these materials was developed by Dr. Dan Gordon at the U.S.Navy's NSWC facility during the 1960's. This material was known as 6/81 alloy and was capable of very low noise levels if carefully heat treated. This heat treatment consisted of raising the alloy to a very high temperature in a dry hydrogen atmosphere and then cooling at a pre-determined and tightly controlled rate until the sensor temperature passed by it's Curie point. This required a special oven and considerable skill to achieve the best results. In recent years, a class of amorphous metallic glass materials have become available (i.e.; METGLAS) and are widely used. These materials have outstanding magnetic characteristics. They are much simpler to heat anneal and much less expensive than the 6/81 alloys. This material has replaced the Nickel/Iron alloys in many applications where the low Curie point temperature (≈200C) is not a problem. This amorphous alloy can however re-crystallize if used continuously at temperatures of > 90°C. As a result, this would preclude use of amorphous alloys in sensors for some military and borehole applications.

2.2 Sensor Core Types

The following is a brief description of the Billingsley sensors, ring core, rod / Förster, racetrack and Single Domain and their respective applications.

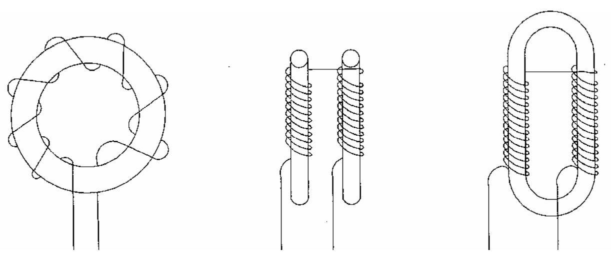

Figure 4 – Ring Core, Rod / Förster, Racetrack Sensor Geometries

Figure 3 - Fluxgate Sensors

2.2.1 Ring Core Sensors

Ring core sensors are the most commonly used because they are easily manufactured, extremely rugged, low- power and have relatively low noise levels. They are most frequently used where low power and low noise are the overriding considerations. Ring cores are less suitable for use in fields > ≈ 3 Gauss. Susceptibility to crossfield effects make this geometry less desirable for use in gradiometers or instruments where axial stability is paramount.

2.2.2 Rod / Förster Core Sensors

Rod / Förster core sensors or their variant, Vacquier sensors, are used when linearity and crossfield effect are the most important requirements and noise performance is not as critical. They are particularly well suited for use in gradiometers or in fields of > 3 Gauss.

2.2.3 Single Domain Rod Core Sensors

Single Domain[4][5] sensors are used when linearity and crossfield effects are important requirements and the lowest noise performance possible is critical. Figure 5 shows a typical spectral density noise plot of the Single Domain Sensor. The figure indicates the noise of this sensor of 1.3 pT/√Hz@ 1Hz. This particular sensor was ≈ 1.0" in length. Lower noise levels can be achieved by increasing sensor length.

The geometry of the Billingsley Single Domain sensor is similar to the rod / Förster sensors. Single Domain sensors are fabricated using amorphous materials which are annealed, and excited using a proprietary process.

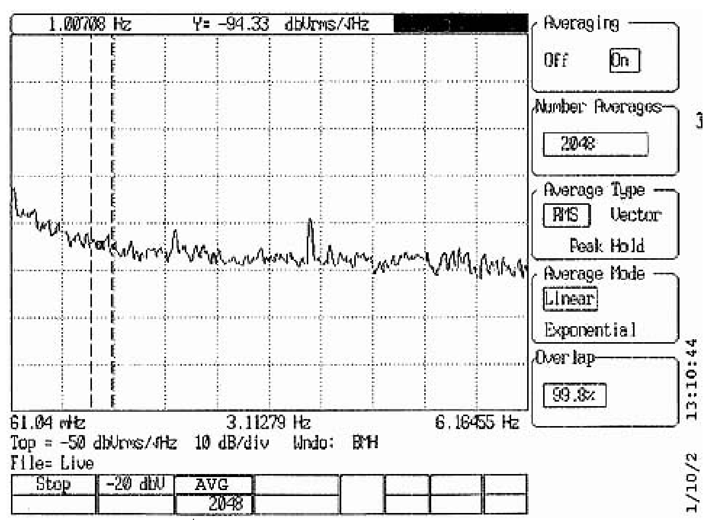

Figure 5 – 1.3 pT/√Hz@ 1Hz noise 1.0" Single Domain Fluxgate Sensor

2.2.4 Racetrack Core Sensors

Racetrack sensors are now rarely used due to the difficulty of manufacturing. The drive windings for this type must be hand wound due to the core shape. They have been largely supplanted by Single Domain sensors which have superior noise performance and are considerably easier to fabricate. They are still used in some instances because they require less power than the Single Domains and could be used where crossfield [6], low noise and low power are all considerations for the application.

2.3 Sensor Core Geometries Performance Comparison

Characteristic Evaluated	Fluxgate Sensor Type			
	Ring Core	Rod / Förster	Rod -Single Domain	Racetrack
Noise (RMS/√Hz @ 1 Hz)	6 - 20 pT <8-10 pT typical 0.7" dia. core*	15 – 50 pT < 25 pT typical, 1.25" L *	1.3 – 6 pT 3 – 4 pT typical 1.25" L *	4 to 12 pT < 10 pT typical 1.25" L*
Drive Power	Lowest 2 cores	Highest 3 cores**	Highest 3 cores**	Moderate 3 cores
Manufacturability	Best	More Difficult	More Difficult	Most Difficult
Zero Stability vs. Temperature	Good	Excellent	Excellent	Very Good
Ruggedness / Shock Resistance	Very good	Excellent	Excellent	Good
Temp. Coefficient -Scale Factor	Good	Excellent	Excellent	Very good
Full Scale Linearity	< ± .005% to 1 Gauss	< ± .0018% to 5 Gauss	< ± .0018% to 5 Gauss	< ± .0018% to 3 Gauss
Cost	Lowest	Intermediate	Higher	Highest
Crossfield Immunity	Good	Excellent	Excellent	Very good

* Noise performance is relative to sensor size, larger sensors are lower noise. ** Open magnetic path requires more drive power

Table 1 Sensor Geometry Performance Characteristics - Revised March 2003[7]

2. FLUXGATES VS. OTHER SENSOR TYPES

There is a significant need for small, low-cost, high-performance, low-noise and low-power magnetic sensors. There is no single magnetic sensor that meets all of these criteria. Numerous magnetic sensor technologies are available and selection of the most ideal sensor is contingent on an applications most critical requirements. We compared the key performance parameters of several magnetic sensor technologies to fluxgates.

Sensor Type	Vector / Scalar	Cost	Noise	Power	Linearity	Accuracy	Dynamic Range	Ruggedness	Size
Fluxgate	Vector	Moderate	Excellent to 1.3pT	Low-Moderate	Excellent	Good	Wide	Good	Medium
AMR	Vector	Low	Fair	Low	Poor	Poor		Good	Small
GMR [7]	Vector*	Low	Poor	Low	Poor*	Poor		Good	Small
GMI	Vector	Low	Poor	Low	Poor	Poor	Wide	Good	Small
SDT	Vector*	Low	Fair	Low	Poor*	Poor		Good	Small
Hall Effect	Vector	Low	Poor	Low	Poor	Poor		Good	Small
SQUID	Vector	High	Best sub pT	High	Fair	Fair	Narrow	Lab Environment	Large with Cryogenics
Overhauser [8]	Scalar*	High	Good	High-moderate	Excellent	Best	Low	Good	Large
Optically Pumped [9]	Scalar*	Highest	Good 10pT	High	Excellent	Very good	Moderate - Good	Good	Large

* Require DC bias to be linear Table 2 Magnetic Sensor Performance Comparison [10]

The cost and size of existing, commercially available AMR, GMR, and GMI sensors is appealing, but the poor 1/f noise performance and linearity, combined with the narrow dynamic range of these sensors makes them unattractive and unsuitable for many low noise applications as compared to fluxgates at the present time. Magnetoresistance (MR) sensors are currently being used to make magnetic compasses with accuracies of ≈0.5° to 2°. Significant development effort is being directed at magnetoresistive sensors so sizable improvements can be expected from this technology.

Overhauser scalar magnetometers have no heading errors (other scalars have low to moderate heading errors), good noise performance, excellent linearity and very good accuracy, but are limited in the area of vector measurements. They require a triaxial coil system to measure vector components. Many applications require vector information.

There have been significant advances in fluxgate magnetic sensor technology. Advances in sensor noise, linearity and crossfield immunity, combined with a wide dynamic range enable the fluxgate magnetometer to replace SQUIDS in some applications. They continue to be the ideal choice for magnetic vector field measurements. Fluxgates are easy to use, low-cost, low-power, low-noise and highly reliable.

3. FLUXGATE MAGNETOMETERS – CURRENT STATE OF DEVELOPMENT

Billingsley designs and manufactures fluxgate magnetometers and gradiometers for spacecraft attitude control, military and commercial applications. The following subsections detail the product features and applications of our most current analog and digital triaxial magnetometers and digital triaxial gradiometer.

3.1 Digital Triaxial Fluxgate Magnetometer – Billingsley DFMG28SD

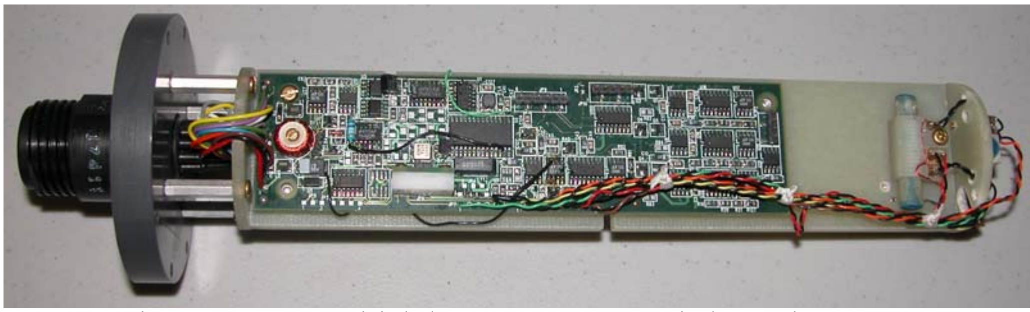

Figure 6 DFMG28SD Digital Fluxgate Magnetometer - Single Domain Sensors

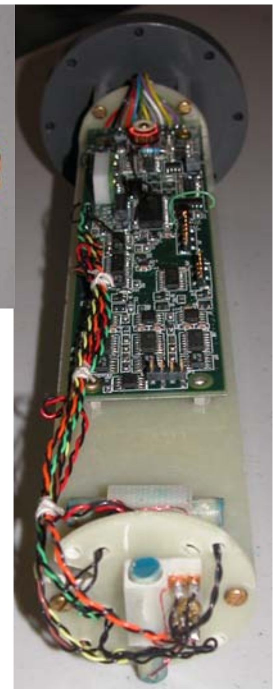

Figure 7 Single Domain Triaxial Sensor Assembly Rod / Förster Geometry

The DFMG28 is an ultra low noise, high resolution, very low power digital triaxial fluxgate magnetometer with Single Domain sensors. The DFMG28 was specifically designed for long term unattended operation in applications such as harbor protection, underwater degaussing systems where retrieval and repair cannot be readily achieved. The instrument is ideal for use in geomagnetic observatories as well. It features automatic cancellation of Earth's Magnetic field under software control. Null parameters are stored in flash memory preventing power outages from disturbing the instrument's magnetic baseline.

Specifications:

Data interface:	Serial interface 38.4K or 19.2K Baud, 8 Data, No Parity, 1 Stop Bit RS232C or RS485 serial interface. Can drive cable lengths >1000 meter.
Axial Alignment:	Orthogonality better than ± 0.1° (0.02 ° special)
Input Voltage:	16 to 34 VDC @ 750 mW constant power ideal for battery powered operation. AC mains operation as an option.
Field Measurement Range:	± 65 μTesla standard (other ranges on request)
Accuracy:	± .02 % of Full Scale
Digital Output Resolution:	28 bits at 4096 sample averaging. 26 ½ bits at 128 samples averaged.
Conversion speed:	25 microseconds per sample
Digital Linearity:	± .0015 % of Full Scale
Scale Factor Temperature Shift:	≤ .002 % / ° Celsius typical.
Noise:	≤ 3.5 picoTesla RMS/√Hz @ 1Hz (typical)
Zero offset:	≤ ± 5 nanoTesla
Susceptibility To Perming:	< ± 5 nanoTesla Shift with ± 5 Gauss applied
Digital sample rate :	> 100 conversions second / all 3 axes/ in binary mode ≈ 55 conversions second/ all 3 axes / second in ASCII mode, these data rates are with the A/D set to 128 samples/averaged. Faster data rates available.
Special features	Triaxial accelerometers for determining the sensor orientation relative to gravity. This enables arrays of the instruments to be used as a "virtual" gradiometer. Temperature and operating voltage also reported by software command.
Size of electronic card	Single card 15.24 Cm x 4.13 Cm, can be re-packaged in any user defined housing. All Analog and digital functions are contained on this single miniature electronics card.

3.2 Analog Triaxial Fluxgate Magnetometer – Billingsley TFM100G3

The TFM100G3 is an ultra miniature, analog, triaxial, fluxgate magnetometer that can be configured with any of sensor core type or geometry that Billingsley manufactures. The instrument was designed for spacecraft attitude control, general magnetic measurements in the laboratory or field applications such as remotely piloted vehicles, data buoys, sounding rockets, etc. The TFM100G3 is the successor to the TFM100G2. Design improvements include the addition of surge suppression circuitry for resistance to lightning strikes, temperature compensated scale factor and a highly efficient switching regulator. This series of magnetometers have been selected to fly on numerous commercial and government satellites for spacecraft attitude control, magnetometer arrays and science missions. The performance, flexibility, small size, and low cost of this magnetometer make the TFM100G3 the most common and ideal choice for applications that do not require an integrated digital interface.

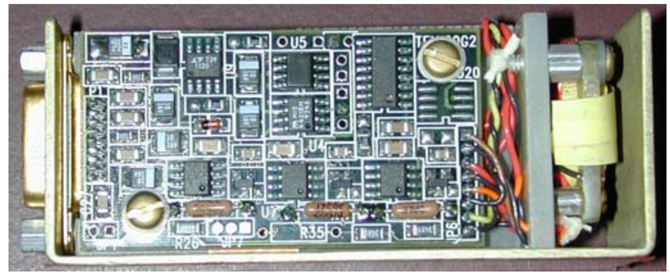

Figure 8 TFM100G3 Ultra Miniature
Triaxial Fluxgate Magnetometer
3.51 cm x 3.23 cm x 8.26 cm in aluminum chassis

Specifications:

Axial Alignment :	Orthogonality better than ± 1°
Input Voltage Options :	18 to 40 VDC @ 15mA (nominal) at constant power
Field Measurement Range	± 100µT = ± 10V or ± 100µT = 0 to 5V (other ranges and outputs available)
Accuracy :	± 0.75% of full scale (0.5% typical)
Linearity :	± 0.005% of full scale (18 to 40 VDC input)
Sensitivity :	100 µV/nT (or user specified)
Scale Factor Temperature Shift :	0.001% full scale/ Celsius
Noise :	≤ 10 picoTesla RMS/ Hz @1 Hz typical
Output Ripple :	3 millivolt peak to peak @ 2nd harmonic (30Khz)
Analog Output @ Zero Field :	± 0.025 Volt
Zero Shift with Temperature :	± 0.6 nT/ Celsius
Susceptibility to Perming :	± 8 nT shift with ± 5 gauss applied
Output Impedance :	332 Ω ± 5%
Frequency Response :	3 dB @ > 500 Hz (to > 4 kHz wideband)
Over Load Recovery :	± 5 Gauss slew < 2 milliseconds
E M I :	Designed to meet CEO1, CEO3, REO2, CS01, CSO2, CSO6, RSO1, RSO2, RS03
Random Vibration :	> 20G RMS 20 Hz to 2 kHz
Temperature Range :	- 55 to + 85 Celsius operating
Acceleration :	> 60G
Weight:	100 grams
Size in Aluminum Chassis:	3.51 cm x 3.23 cm x 8.26 cm

3.3 Digital Triaxial Gradiometer – Billingsley TRIGRAD

Figure 9 TRIGRAD Digital Gradiometer -1 Meter Baseline, Titanium Tube

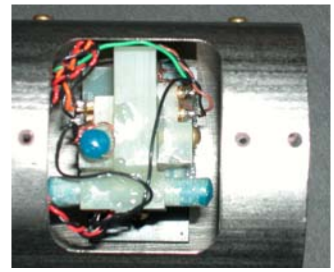

Figure 10 Triaxial Sensor Assembly Rod / Förster Geometry

The TRIGRAD is a 24-bit, low-noise, high resolution, very low power digital triaxial fluxgate gradiometer. It was designed for ROV magnetic surveys, component magnetic screening, general lab use and portable applications. All functions both digital and analog on a single miniature printed circuit board mounted in a lightweight, high stability titanium tube or underwater housing as required by user.

Specifications:

Gradiometer Baseline:	Two triaxial fluxgate sense heads spaced 91cm apart. User can specify baseline in most cases.
Data Interface:	Serial interface 38.4K or 19.2K Baud, 8 Data, No Parity, 1 Stop Bit RS232C or RS485 serial interface. Cable lengths >1000 meter.
Axial Alignment:	Orthogonality ± 0.01°
Input Voltage:	16 to 34 VDC @ ~ 900 mW constant power. Ideal for battery powered operation. AC mains operation as an option.
Field Measurement Range:	± 100 μTesla standard (other ranges on request)
High Gradient Tolerance:	Special geometry sensors operate in high gradients.
Outputs:	9 digital products which includes the six magnetometer outputs (corrected for slope and offset errors) and the digitized gradient information for each axis.
Scaling Accuracy:	<± .1 % of Full Scale
Digital Output Resolution:	24-bits at 4096 sample avg., 22½ bits (≈20 pT resolution) with 128 samples avg.
Conversion Speed:	25 microseconds/sample
Digital Linearity:	± .0015% of Full Scale
Scale Factor Temperature Shift:	≤ .002 % / ° Celsius typical.
Noise:	≤ 10 picoTesla Rms/√Hz @ 1Hz (special), < 25 picoTesla standard
Zero Field Offset Error:	< +/- 5 nanoTesla
Susceptibility To Perming:	< ± 5 nanoTesla Shift with ± 5 Gauss applied
Digital Sample Rate:	≈ 100 conversions/second / all 3 axes/ in binary mode ≈ 55 conversions/second/ all 3 axes / second in ASCII mode, these data rates are with the A/D set to 128. samples / averaged. Faster data rates achieved if fewer averages are taken. Software control allows the instrument to take averages from as little as two samples up to 4096 samples depending on the data acquisition speed requirement versus resolution requirement. The user can, by command, select the proper averaging/sample rate tradeoff for his particular application.
Special features	Pressure sensor (option) for measuring depth of the instrument in the underwater housing option. Greater than 70dB rejection of 60 Hz stray background fields in synchronous mode.
Size of electronic card	Single card 15.24 cm x 4.13 cm.
Packaging:	Can be packaged in many user defined housings and spacings.

4. Magnetometers - Future Development

Magnetoresistance:
We are currently developing improved electronics that will minimize power consumption and extract the best noise performance from this class of sensor. The goal in this effort is to fabricate very small, low cost sensors having the lowest possible noise and power consumption. There is great interest in this technology for use in battlefield surveillance applications as the low cost would permit large scale deployment of these devices.

Lower Power Optically Pumped Magnetometers:
Optically pumped magnetometers consume considerable power, in large part, due to method of generating the pumping light source. Historically this is done using an R.F. excitation source to ionize a buffer gas contained in a small bulb. This resulting light source then excites an isotope (Cs133 or Rb87 etc), causing it to emit light on specific lines. This light is used to pump an absorption cell (containing the same isotope as the bulb). These "lamps" have a finite operating life and are the predominant cause of instrument failure. The R.F source within the instrument can also cause considerable interference in the signal handling electronics. Replacing the R.F. source with a solid state laser would greatly reduce power, cost and eliminate the main source of instrument failure. Successful optical pumping of an absorption cell, using a solid state laser, was reported in the 1990's by Dr. M. Scully of Texas A&M University. The laser diode used in the experiment was a laboratory device that did not have the temperature stability required of a field deployable instrument. More recently the Polatomic Corporation has announced the development of a laser diode pumped Helium magnetometer of exceptional sensitivity for the U.S. Navy (SBIR90-064). Further improvements in solid state laser diodes will allow the commercialization of a class of Alkali vapor (or Helium) magnetometers which have greatly reduced power consumption, smaller size, lower cost and virtually unlimited operating life. Such an improved magnetometer would find a niche in airborne geophysical and other scalar field applications where the limited sample rate or resolution of Overhauser proton magnetometers are limitations.

Fluxgates
We continue to perform research and development on the Single Domain sensor technology with particular emphasis on improving the manufacturing process, reduction in sensor power consumption and lower noise levels. We are improving the dynamic range of our processing electronics. Our current level of performance in the digital electronics is achieved using high resolution "Delta-Sigma" type A/D convertors. This A/D topology is being rapidly developed, by the semiconductor industry. Our current design has a conversion speed of 25 microseconds/sample (Burr-Brown ADS1253) with a resolution of ≈17-18 bits. Oversampling by 4096 times allows a full 24 bits of resolution. Newer convertors such as the Linear Technology Corporation LTC2440, while slower at maximum speed, achieve roughly comparable resolution and conversion speed when both are compared at 128/samples averaged. The LTC 2440 in a practical implementation can be a bit simpler and lower in power. We anticipate faster parts in the future that will allow a greater oversampling ratio per unit time resulting in greater A/D resolution. These improvements are essential to keep pace with the progress we are making in sensor noise level reduction.

ACKNOWLEDGEMENTS

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