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High Accuracy Magnetic Measurements with the ASQ-81 Scalar Magnetometer

Brian S. Bourgeois, Jerry H. Ross, and Will Avera

Abstract—The Texas Instruments' ASQ-81 scalar magnetometer provides high resolution total field magnetic measurements. It uses an optically pumped metastable helium gas detector that has a range of 23 000 to 75 000 gammas ($1 \text{ gamma} = 1 \text{ nT}$) and a 0.016 gamma peak-to-peak noise level. Total magnetic field measurements can be made using the resonance oscillator output of the magnetometer. This output is a frequency modulated signal whose center frequency is Larmor frequency. For sampling rates slower than 0.5 Hz the Larmor frequency can be measured directly from the resonance oscillator using a frequency counter. At higher sampling rates the modulation of the resonance oscillator output can create measurement errors that exceed the instrument's noise level. This paper quantifies this measurement error and describes the circuitry and techniques required to reduce the measurement error to less than the instrument noise level.

Keywords—Scalar magnetometer, optically pumped magnetometer, helium magnetometer.

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I. INTRODUCTION

Optically pumped magnetometers use two common detection schemes: controlled oscillator and self-oscillating. The controlled-oscillator type modulates the Larmor frequency at a very low frequency and controls the Larmor frequency oscillator by phase detecting the low frequency output signal. The self-oscillating type uses the feedback from a tuned resonant absorption cell circuit to track the Larmor frequency. The discussion herein is directed toward magnetometers utilizing the controlled-oscillator type detection system. To be specific, the Texas Instrument's ASQ-81 helium magnetometer, used in the Geophysical Airborne Survey System (GASS) [1], is analyzed in this paper.

The controlled-oscillator type optically pumped metastable helium magnetometers, along with other types of optically pumped magnetometers, have been used in industry and research for many years. Scalar magnetometers of this type are used largely for geophysical mapping over large areas, for search type operations, and for monitoring the subtle variations in the Earth's background magnetic noise level. The popularity of the optically pumped magnetic sensors has come from its significant advantage in instrument noise level over most conventional vector fluxgate and proton precession type magnetometers. Additionally, in contrast to the self-oscillating optically pumped magnetometers, the controlled-oscillator optically pumped magnetometers enjoy insensitivity to sensor orientation.

For measuring the subtle variations in the Earth's magnetic field the optically pumped magnetometer is often operated at fairly low frequencies, on the order of 1 Hz. This is mainly due to the power spectrum characteristics of the earth's geomagnetic field. Fig. 1 is

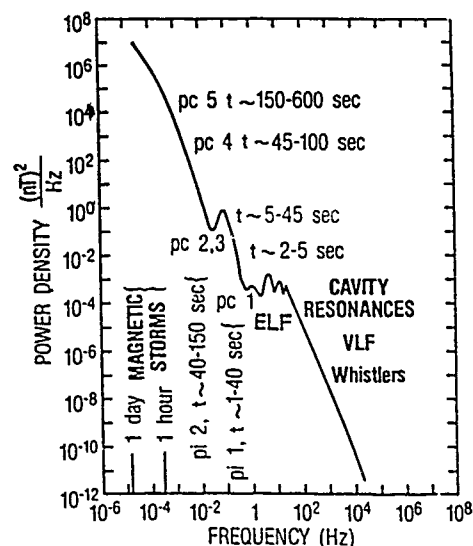


Fig. 1 Power spectrum of geomagnetic disturbance observed on the Earth's surface [2].

a typical example of a power spectrum for the distribution of geomagnetic activity for overland areas. In the frequency range less than 1 Hz, the Earth's magnetic field power spectrum decreases with increasing frequency. The spectrum decreases with a slope of approximately -6 dB/octave between 10^{-4} and 1.0 Hz. However, for the range from 1 to 40 Hz the field is dominated by the amplitude peaks of the Schumann resonances. Starting at approximately 80 Hz, the power spectrum again shows a decrease with frequency on the order of -6 dB/octave. For most optically pumped magnetometers, the sensor noise level is on the order of 0.01 nT. Based on these spectral amplitudes, natural variations in the geomagnetic field range from around 0.5 Hz to dc (0 Hz), depending on latitude and solar activity. Consequently, stationary optically pumped measurement systems have not required sample rates much above 1 Hz in order to study natural geomagnetic variations.

Mobile systems like those used for prospecting, search operations, and other mapping purposes do encounter magnetic field variations of a much higher amplitude for frequencies above 1 Hz. In a typical mapping system the magnetometer is towed (by aircraft or ship) over stationary geologic anomalies. The magnetic expression of these anomalies then becomes a time varying signal to the magnetic sensor, and the frequency of these variations depends on the tow speed and the size of the anomaly. Consequently, survey type operations often require data sampling rates higher than 1 Hz. For regional mapping purposes the data rates are still in the lower portion of the spectrum. However, for very precise detailed surveys a higher frequency data acquisition system (sampling rates above 0.5 Hz for the ASQ-81 helium magnetometer) must utilize the principles reported in this paper to accurately record the data from controlled-oscillator type magnetometers and avoid phase and amplitude error in the measurements.

This paper first discusses the theory of operation for the ASQ-81 helium, optically pumped, controlled-oscillator type scalar magnetometer. Following this discussion, the measurement error induced by high sampling rates for a controlled oscillator magnetometer is quantized. A scheme is then presented for making frequency measurements that are free of this induced error, by synchronizing the measurements with the modulation frequency of the controlled oscillator. While the ASQ-81 does provide an internal demodulator, a much improved signal noise level can be achieved by measuring the resonance oscillator signal directly.

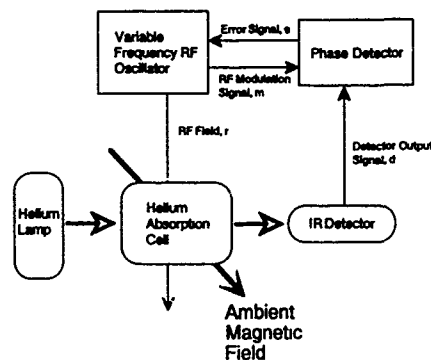


Fig. 2. Helium Magnetometer sensing element block diagram [3].

II. HELIUM MAGNETOMETER OPERATING PRINCIPLES

Fig. 2 illustrates the basic elements of a helium magnetometer sensing element. In the sensing element, spectral light from the helium lamp is detected by the infrared (IR) detector. The intensity of the light incident upon the detector is a function of the absorption characteristics of the helium absorption cell. The absorption characteristics of the cell are a function of the ambient magnetic field intensity and can be altered by subjecting the cell to radio frequency (RF) energy. Fig. 3(a) and (b) illustrates the absorption characteristics of the cell, and the IR detector output as a function of RF when the sensor is exposed to a fixed magnetic field. The Larmor frequency, f_o , is the RF at which the helium cell achieves maximum absorption of the light from the helium lamp. The Larmor frequency is proportional to the local magnetic field intensity as given by

$$f_o = gH_o$$

where H_o is the magnetic field intensity in gammas (1 gamma = 1 nT), and g is the gyromagnetic ratio of helium atoms. The nominal value for g is 28.024 Hz/gamma. The ASQ-81 magnetometer automatically tracks the local magnetic field intensity by frequency modulating the applied RF field. As shown in Fig. 3(c), 3(d), and 3(e), the output of the IR detector depends upon the applied RF field. If the center frequency of the modulated signal, f_i , of the variable frequency oscillator is exactly at the Larmor frequency, f_o , the frequency of the output of the IR detector is twice that of the modulation frequency of the oscillator. If f_i is not the same as f_o then the frequency of the output of the infrared detector is the same as the modulation frequency of the oscillator. For f_i not equal to f_o , the phase of the IR detector output depends upon whether f_i is greater than or less than f_o . As displayed by Fig. 3(d), if f_i is less than f_o then as f_i increases the detector output increases, so the RF modulation signal and the detector output are in phase. As shown in Fig. 3(e), if f_i is greater than f_o then as f_i increases the detector output decreases, so the RF modulation signal and the detector output are 180° out of phase. The phase of this signal is converted to a control voltage by the phase detector and this voltage causes the variable frequency resonance oscillator to automatically track the Larmor frequency. The modulation frequency used in the ASQ-81 magnetometer is 430 Hz, and the amplitude of frequency modulation is 1250 Hz. Thus the frequency of the variable frequency resonance oscillator is given by

$$f_r = f_o + 1250 \sin(2\pi\beta t)$$

where $\beta = 430$ Hz, and t is time in seconds. The oscillator center frequency (Larmor frequency), f_o , may range from 0.65 MHz (23000 gammas) to 2.1 MHz (75000 gammas) for the ASQ-81 magnetometer.

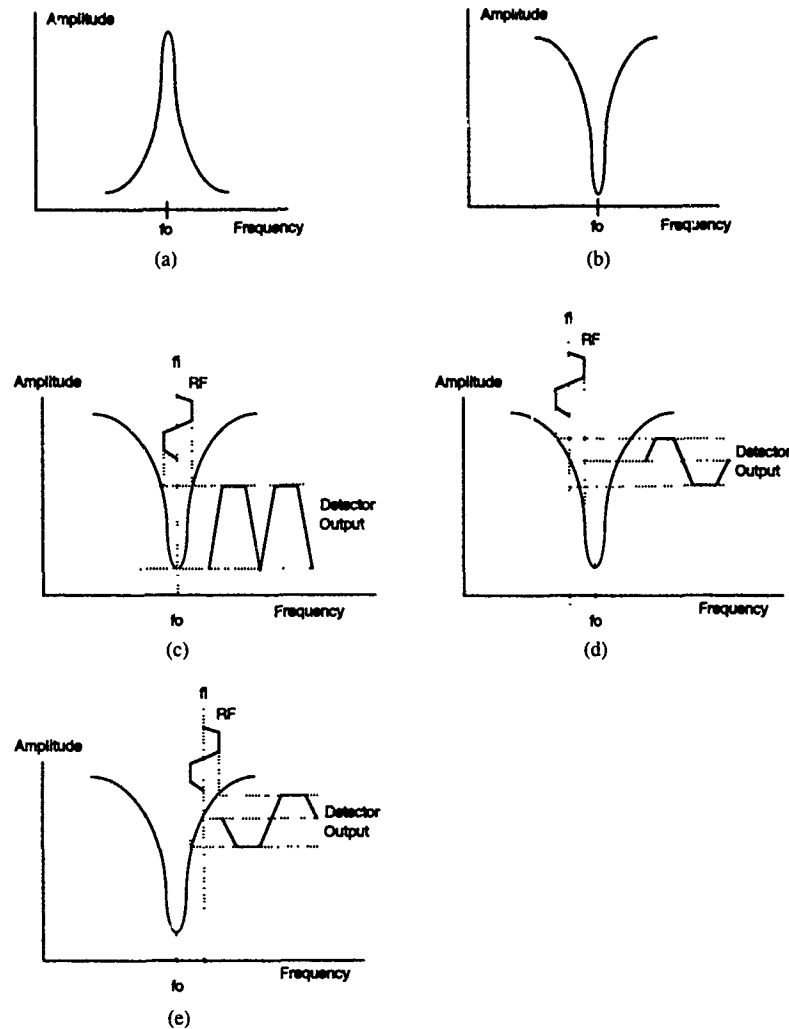


Fig. 3. Helium magnetometer absorption cell characteristics and detector output signal [3]. (a) Light absorption. (b) IR detector output (c) RF same as Larmor frequency. (d) RF less than Larmor frequency. (e) RF more than Larmor frequency.

III. MODULATION-INDUCED MEASUREMENT ERROR

The variable frequency resonance oscillator output is available for measurement on the ASQ-81, and can be measured using a frequency counter. The oscillator output is a squarewave with a variable cycle time since the frequency is being modulated. The frequency counter measures this signal's frequency by counting the number of edges (positive or negative transitions) over a period of time. Assuming a constant ambient magnetic field intensity, the actual measurement, f_a , given by the frequency counter is the time average of f_r :

$$f_a = \frac{\int_0^t f_r dt}{t}$$

If the measurement time is an integral number of modulation cycles, i.e., $t = n/430$ seconds, then the measured frequency is

$$f_a = \frac{430}{n} \int_0^{n/430} [f_o + 1250 \sin(2\pi\beta t)] dt.$$

Thus $f_a = f_o$ where $n \in \text{integers}$ and $\beta = 430$. When the measurement time is not an integral number of modulation cycles, a measurement error is introduced since the time average of f_r will not be f_o . The worst-case error occurs when the measurement time is

$n/430 + 1/860$, seconds, where $1/860$ seconds is one-half cycle of the modulation frequency. If a measurement begins at a zero crossing of the modulation frequency and continues for $n/430 + 1/860$, then one full positive lobe of the modulation frequency will be included in the measurement period. This results in a measured frequency of

$$f_a = \frac{860}{2n+1} \left[\int_0^{n/430} f_r dt + \int_{n/430}^{n/430 + 1/860} f_r dt \right]$$

$$f_a = f_o + \frac{2500}{\pi(2n+1)}$$

where the measurement error is given by

$$E = \frac{2500}{\pi(2n+1)}$$

which is an inverse function of n . In terms of sampling frequency, f_s , this yields

$$E = \frac{250}{86\pi} f_s$$

The noise floor for the ASQ-18 is about $0.016 \text{ gammas} \times 28.024 \text{ Hz/gamma} = 0.448 \text{ Hz}$ [2]. Thus for sampling rates slower than about 0.484 Hz , the worst case measurement error, E , is below the

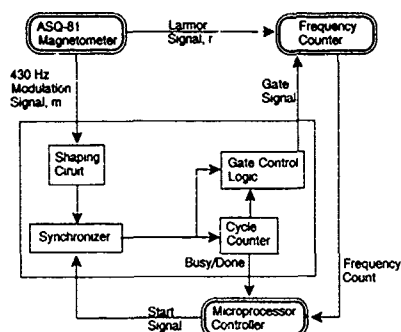


Fig. 4 Frequency counter synchronization circuit block diagram

instrument noise floor. As the measurement rate increases, however, the measurement error becomes very significant.

IV. ERROR COMPENSATION

The measurement error introduced by the frequency modulation of the resonance oscillator can be eliminated by synchronizing the measurement with the 430-Hz modulation frequency. This means that the measurement time will always be an integral number of modulation cycles, and the time averaged frequency that is measured will be the desired frequency f_0 . Fig. 4 is a block diagram of a circuit that can be used to synchronize these measurements. The 430-Hz modulation signal, externally accessible on the ASQ-81, is put through a shaping circuit to produce a 430-Hz squarewave. This squarewave and a "start" signal from the microprocessor controlling the measurement operation are inputs to the synchronizer circuit. When the microprocessor requests a measurement by asserting its start line, the synchronizer circuit delays the start of the measurement until the next edge (positive or negative) of the 430-Hz squarewave. At the next edge of the 430-Hz squarewave the synchronizer, through the gate control logic, asserts a gate signal to the frequency counter. This gate signal starts the frequency counter measurement. The cycle count circuit counts the number of 430-Hz cycles that have passed, and when the requested number of cycles have elapsed it instructs the gate control logic to de-assert the gate signal to the frequency counter. Also, the cycle count circuit notifies the microprocessor when the desired number of cycles have been counted. The number of 430-Hz cycles to count can be made switch or microprocessor selectable.

The number of count cycles desired depends upon the frequency resolution desired, the reference frequency of the frequency counter, and the frequency being measured. The frequency resolution of the measurement is given by

$$\text{freq. resolution} = \frac{\text{measured freq.}}{\text{measurement time (sec)} * \text{ref. freq.}}$$

where the measurement time will be the number of count cycles selected times 1/430 seconds. Since the frequency counter's reference frequency and the frequency of the signal being measured are typically predetermined, a tradeoff exists between the measurement time and the frequency resolution.

V. CONCLUSIONS

The ASQ-81 scalar magnetometer is used for total field measurements at sampling rates of up to 16 Hz in Navy systems like GASS [1]. At this sampling rate the worst-case induced measurement error is 14.5 Hz, well above the instrument's noise floor. A gate synchronization card was built and operated successfully for the GASS implementation, using a Hewlett-Packard 5370B universal time interval counter. Further work that is highly recommended would be to test the performance of a compensated magnetometer versus one that is not compensated with a known magnetic field. A magnetometer testing facility capable of testing the performance of the ASQ-81 was not locally available to the authors. The family of optically pumped controlled oscillator magnetic sensors offer a high sensitivity, low noise, and orientation independent measurement of magnetic fields. To truly take advantage of the sensor capabilities (for frequencies above 0.5 Hz for the ASQ-81), data recording systems for optically pumped magnetometers utilizing a controlled oscillator will have to incorporate the technology of synchronizing the measurement with the modulation frequency.

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