Self-Calibrating Vector Magnetometer for Space

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***Abstract* - A conceptual design is described for a miniature laser-pumped Self-calibrating Vector Magnetometer (SVM) for space applications. The SVM design incorporates a vector mode and a scalar mode that each extract magnetic field information from a single He^4 cell. The three-axis vector instrument is the Miniature Laser-Pumped Vector Magnetometer (MLPM) that is being designed fabricated and demonstrated under an OES IIP project. The scalar instrument is the Miniature Laser-pumped Scalar Magnetometer (MLSM) that is being developed under NASA/JPL SBIR sponsorship. The SVM combines the MLPM and the MLSM in a single instrument that both utilize a SVM single-cell sensor. The SVM scalar mode is included for pre-flight and in-flight calibration of the SVM vector mode in order to achieve an accuracy of 1 part in 100,000 for static and time-varying magnetic field components observed in Earth orbit. Laser pumped helium magnetometers developed for the U. S. Navy have demonstrated sensitivity of 0.1 pT/vHz in the scalar mode with an accuracy better than 1.0 nT. This technology is serving as a baseline for developing a low-power, miniature SVM instrument for use on a micro-satellite. Sensitivity and accuracy investigations of the MLPM and the MLSM and current status of the design effort for the miniaturized SVM will be reported. The three year effort will result in a small, low-power SVM breadboard instrument that will be evaluated for sensitivity, accuracy and stability over the Earth field range.**

I. INTRODUCTION

The Self-Calibrating Vector Magnetometer (SVM) instrument will provide accurate measurements of both the orthogonal vector components and scalar magnitude of magnetic fields using a single shared laser-pumped sensor. The SVM consists of a scalar mode, the Miniature Laser-pumped Scalar Magnetometer (MLSM) and a vector mode, the Miniature Laser-pumped Vector Magnetometer (MLVM). The great advantage is that the SVM can therefore replace with a single instrument the usual satellite or spacecraft magnetometer payload consisting of fluxgate vector magnetometers and a scalar magnetometer. The SVM design is made possible by two technical innovations developed by Polatomic, Inc. The first is laser pumping of the 2^3S_1 level of He^4 gas with tunable 1083 nm semiconductor lasers. The second is the Optically-driven Spin Precession (OSP) technique for producing magnetic resonance in optically pumped He^4. A major innovation achieved under the SBIR Phase I Project was the first demonstration of an OSP scalar magnetometer using OSP magnetic resonance in a sensor with a single helium absorption cell. Using a closed-loop tracking-oscillator magnetometer, sensitivity of 3.0 pT/vHz was observed.

II. SVM TECHNICAL INNOVATIONS

The SVM breadboard model will incorporate a number of innovative features. Single-line laser pumping in the SVM sensor permits reduction of the helium absorption cell volume by more than 75% compared to lamp-pumped cells. Single line laser pumping at the helium D_0 line permits reduction of light shifts to less than 20% of the value for a lamp pumped sensor. Laser pumping permits location of the laser in the Electronics Unit where it has increased radiation protection and permits further miniaturization of the sensor. The use of a laser pump source by the SVM will result in significant reduction in size power and mass, and achieve the scalar design goals of accuracy better than 1 nT and sensitivity better than 5 pT/vHz in a miniaturized sensor and the same vector performance through use of the scalar measurements for vector calibration. By locating the laser pump source and IR detector in the electronics package and coupling radiation by optical fiber, the boom mounted sensor is much less susceptible to radiation damage. The optical pumping radiation will be delivered to and received from the Electronics Unit by optical fiber, thus making possible remote location of the laser and electronics from the boom mounted sensor unit.

Use of an OSP closed-loop scalar magnetometer permits omni-directional scalar measurements at full sensitivity and accuracy for any orientation of the magnetic field relative to the sensor using a single miniature helium absorption cell. Use of the OSP resonance mode eliminates the RF resonance drive coil cable between the Electronics Unit and the Sensor Unit and eliminates the RF drive coil on the cell. The miniature SVM sensor consists of one helium absorption cell, a solid state non-magnetic exciter at the cell and fiber optic coupling to the IR detector and laser pump source in the Electronics Unit. The SVM self-calibration function improves the vector component calibration by using vector field measurements and scalar field measurements from the same helium absorption cell thus eliminating gradient effects due to spatial separation between the individual vector and scalar magnetometers. The principles of laser-pumping for both the scalar and the vector mode will be presented followed by a description of the OSP method of magnetic resonance and OSP magnetometer results.

III. PRINCIPLES OF OPTICAL PUMPING

An abbreviated energy level diagram for helium is shown in Fig. 1. Helium atoms in the 1^1S_0 ground state are excited by a weak RF discharge to the 2^3S_1 metastable level (+1, 0, and -1). Optical pumping occurs when 1083 nm radiation is unequally absorbed by helium atoms in each of the three magnetic states of the 2^3S1 level and, optical pumping changes the populations of these three states from an equal distribution to an unequal distribution. The larger the state's absorption cross section the more a state is depopulated, so that the gas becomes more transparent to the pumping beam in the pumped condition. When a circularly polarized beam is directed along the field, only atoms in the m = +1 state absorb pumping radiation and the atoms in that state are transferred to states m = 0 and -1. In the SVM, optical pumping radiation is produced by an InGaAs diode laser tuned to the D_0 absorption line shown in Fig. 1.

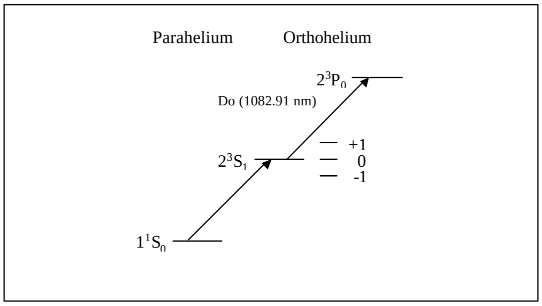

Fig. 1 Energy level diagram for helium.

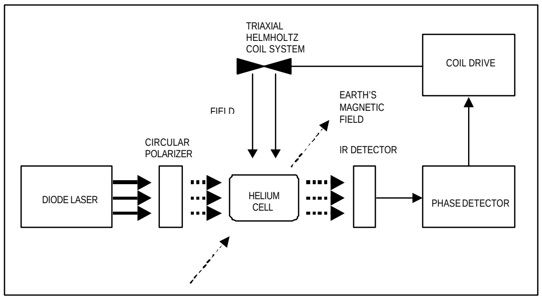

Fig. 2 Laser pumped sensor block diagram.

The SVM vector mode and the SVM scalar mode both utilize the laser pumping process in the SVM sensor with block diagram shown in Fig. 2. The scalar magnetometer mode utilizes the fact that optical pumping is destroyed by magnetic resonance in the three Zeeman-split states of the 2^3S_1 helium atoms. When resonance is induced in the cell, the magnetic resonance curve can be observed by monitoring the increased absorption of the gas. The block diagram in Fig. 2 shows a scalar magnetometer set up to drive magnetic resonance absorption by applying an electromagnetic field to the sample by means of a coil around the helium cell. This technique is Magnetically-driven Spin Precession (MSP) and is found in all conventional optically pumped resonance magnetometers. An error signal is generated which is proportional to the difference between the frequency of the digital oscillator and the true Larmor frequency of the helium resonance (28 Hz/nT). The tracking oscillator supplies an RF signal at the resonance frequency of the helium cell that drives an electromagnetic field into the sample. A low-frequency modulation of the resonance electromagnetic field produces an error signal at the modulation frequency, which is used to lock the resonance control loop. The error signal is used to lock the tracking oscillator to the helium resonance frequency, so the magnetometer readout is a digital frequency from the digital oscillator proportional to the magnetic field.

The SVM vector mode utilizes the same optical pumping apparatus as the scalar mode but extracts field information by an entirely different process - the variation of the absorption. The efficiency of optical pumping in a rotating field varies as $\cos^2$? where ? is the angle between the beam direction and the field. In the Bias Field Nulling (BFN) vector mode selected for the SVM, a rotating field is applied to the helium cell by means of a Helmholtz coil set. The field is biased to zero field so that any vector field component produces an optical error signal used to maintain zero field. The vector components are determined by reading out the three nulling currents in the three orthogonal Helmholtz coils around the cell.

As shown in Fig. 2, the SVM pumping radiation source is an InGaAs distributed Bragg reflecting (DBR) diode laser (DL) which is electronically tuned to the wavelength at 1083 nm. An infrared (IR) detector monitors light passing through the helium cell and monitors resonance absorption in the cell. The IR detector converts the light energy to an electronic error signal which is used to servo-lock the feedback loop. A scalar sensor model using optical fiber coupling to the laser and the IR detector is show in Fig. 3 with a schematic of the miniature SVM scalar sensor. Because the laser pumping process is 50 times more efficient than helium lamp pumping used in conventional helium magnetometers, performance requirements can be met with a 6 cm^3 absorption cell.

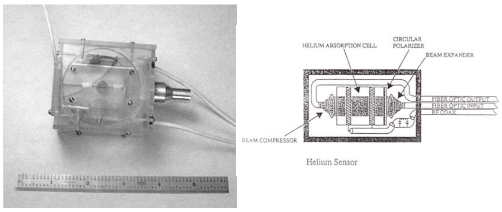

Fig. 3 Miniature laser sensor and schematic.

IV. OSP SCALAR MAGNETOMETER

A. Principles of OSP Magnetic Resonance

OSP magnetic resonance is produced by optically pumping the helium sample with a laser pump beam modulated at the Larmor frequency. The OSP resonance signal is proportional to $\sin^2\theta$ where θ is the angle between the pumping beam direction and the magnetic field direction in contrast to the MSP signal that follows a $\cos^2\theta$ dependence. For conventional MSP magnetic resonance, the spins of the atoms or nuclei are forced to precess in phase by a small magnetic field H_1 oscillating at or near the resonance frequency. For OSP magnetic resonance, the pumping light is modulated at the resonance frequency and the spins are forced to precess at the frequency of the light pulses that occur once per spin cycle. A proprietary modulation technique developed by Polatomic is used to modulate the pumping beam at the Larmor frequency and can cover the full range of He^4 resonance frequencies (up to 2.1 MHz in the earth's magnetic field). The beam emerging from the cell is detected with a photodiode as shown in Fig. 2 and monitors the error signals used by the digital resonance loop to lock the tracking oscillator to the Larmor frequency.

The OSP effect is described by the modified Bloch equations for the behavior of the bulk magnetization M in an optically pumped gas as it experiences magnetic resonance monitored by a photodetector with current $I_s(t)$. The time dependent magnetization $M_0(t)/t$ is given by

$$M_0(t) = A + B*\cos \omega t, \qquad (1)$$

where the OSP magnetic resonance drive frequency is $\omega = 2\pi\nu$ (ν is the actual Larmor frequency for the helium sample). The optically detected light beam intensity is given by

$$I_s(t) = KM_0(t)*M_\alpha(t), \qquad (2)$$

where K is a proportionality constant and Ma(t) is the magnetization along the optical axis. The Bloch equations can be solved for the case where the beam has 100% modulation (A = 0) to obtain the following expression for $I_s(t)$:

$$\begin{aligned} I_s(t) &= 1/4KB^2*\sin^2\theta / \{1 + (\omega - \omega_0)^2\tau^2\} + \\ &1/4\, KB^2*\sin^2\theta \ \{\cos 2\omega t \ / [1 + (\omega - \omega_0)^2\tau^2] + \\ &(\omega - \omega_0)\tau *\sin 2\omega t / [1 + (\omega - \omega_0)^2\tau^2]\}. \qquad (3) \end{aligned}$$

The current from the detector monitoring the pump beam exiting the cell $I_s(t)$ has a steady state term similar to that observed for conventional scalar MSP magnetometers. The high frequency term is similar to the self-oscillator terms in MSP resonance. The OSP signal appears on the modulated pump beam when the pump beam is directed perpendicular to the ambient magnetic field H_e. The orientation is set by θ, the angle between the pump beam and the ambient magnetic field. The laser frequency modulation technique was evaluated using a laboratory breadboard laser pumped sensor with a 33 cm^3 helium cell at the Polatomic Magnetic Test Facility. The signal amplitude follows $\sin^2\theta$ where θ is the angle between the light beam and the field direction and reaches maximum strength when the pump beam direction is perpendicular to the ambient magnetic field direction.

B. OSP Resonance Scalar Magnetometer

A test system was configured as an MSP/OSP single cell scalar magnetometer system, and was operated for both MSP and OSP scalar modes as a high performance closed-loop system.

For the OSP mode, the circularly polarized laser radiation is pulsed at the Larmor frequency. The absorption is minimum when the frequency of the pulsed laser light is at the Larmor frequency. For both MSP and OSP modes, the Larmor frequency is directly proportional to the ambient magnetic field with a proportionality constant of 28 Hz/nT. The output is the frequency of the digital oscillator tracking the helium resonance frequency.

The scalar feedback loop is a null sensing control loop that detects and tracks the Larmor frequency. Tracking the Larmor frequency is accomplished by frequency modulating the pulsed laser light in OSP mode at 432 Hz. When the control loop is exactly at the Larmor frequency, only the 2nd harmonic of the 432 Hz frequency is detected. The addition of a steady or slowly varying magnetic field generates a fundamental of the 432 Hz frequency along with the 2nd harmonic. Synchronously detecting the fundamental generates an error signal to draw the control loop back to the Larmor frequency. Noise spectral density plots of the single cell test system taken in the OSP mode is shown in Figure 4. The data was sampled at 432 Hz and 4096 points were collected. The noise levels decrease from 10 pT/√Hz at 1 Hz to 2 pT/√Hz at 10 Hz. The characteristic power spike can be seen at 60 Hz.

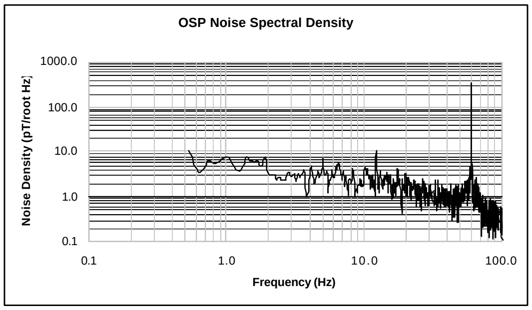

Fig. 4 OSP resonance mode magnetometer noise density.

The MSP/OSP magnetometer system was configured to run with a breadboard MSP magnetometer as a reference to remove geomagnetic noise. The single cell reference system noise level was the same as the MSP/OSP magnetometer system. Fig. 5 shows the gradiometer noise spectral density for the OSP mode. The data was sampled at 432 Hz and 10240 points were collected. The noise level is 3-5 pT/√Hz across the 0.1 to 50 Hz range. These closed-loop magnetometer tests verified the feasibility of developing a high-performance single-cell system operating in OSP mode. Noise levels of 3-5 pT/√Hz were obtained with a frequency response out to 50 Hz. The field value outputs between OSP and the reference system were within 1 nT.

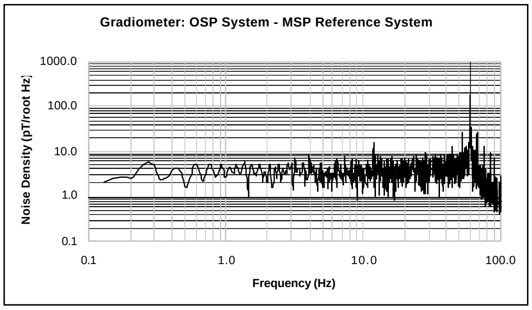

Fig. 5 OSP/MSP gradiometer noise density.

V. CONCLUSIONS

The major Technical Objective of the Phase I Project is development of a conceptual design for a Self-Calibrating Vector Magnetometer (SVM) that is capable of extracting tri-axial vector and scalar magnetic field values from a single sensor. The resulting SVM conceptual design is configured for space science applications and has the outstanding feature of replacing fluxgate vector magnetometers and a reference scalar magnetometer with the single SVM instrument. The scalar mode utilizes a unique resonance technique, Optically-driven Spin Precession (OSP), to achieve full sensitivity and high accuracy on all headings with a single helium absorption cell. A sensitivity of 3.0 pT/vHz for an OSP locked-oscillator single-cell magnetometer was demonstrated in Phase I . The scalar OSP mode is projected to have an accuracy of <1.0 nT and can be used to calibrate the vector field component measurements to an accuracy approaching 1 part in 10^5. The Self-Calibrating Vector Magnetometer constitutes a major instrumentation advance for the investigation of magnetic fields of the Earth and in space.

ACKNOWLEDGMENTS

The Miniature Laser-Pumped Vector Magnetometer project of is funded under NRA Contract Number NASS-01223 as a NASA ESTO Instrument Incubator Program. This Miniature Laser-Pumped Scalar Magnetometer Project is funded under NASA/JPL SBIR Contract Number NAS3-02053.