Development and Testing of a Compact Vector Helium Magnetometer

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Abstract

Many space missions include investigations into the magnetic fields present around planets and elsewhere in outer space. Scientific inquiries into the magnetic fields in outer space require instruments and techniques with which to measure and monitor magnetic fields on current and future missions. One such commonly used instrument is a Vector Helium Magnetometer (VHM), previously used on the Pioneer mission to Jupiter.[1] Previous versions of VHMs have been bulky in size and weight, posing challenges to their inclusion in the flight hardware of missions. This project aims to develop and test a new design for a compact magnetometer that is a fraction of the size of current models. Included in this report is a brief description of the compact VHM, a discussion of the LabVIEW data acquisition software developed to aid in assessing the performance of the VHM, and a review of the experimental procedures and results of completed and proposed tests used to determine the parameters necessary to optimize the operation of the VHM.

Introduction

Previous missions to outer space have included instruments for measuring the magnetic field present around objects in space. One such instrument used is a Vector Helium Magnetometer (VHM). This paper aims to discuss the development of a compact VHM intended for future space missions.

The approach to this instrumentation project is largely experimental. A new, compact design for a VHM has been proposed by this project group. The goal of this project is to develop a compact VHM that takes advantage of recent advances in laser technology to significantly reduce the size, weight and power requirements of the next generation of VHMs. In order to achieve this goal, is it necessary to evaluate the feasibility and reliability of such an instrument, as well as to define the operation parameters that are ideal for optimal performance of the compact VHM. In our definition, optimal performance is to be characterized by accurate measurements, reliable operation, a high signal-to-noise ratio, low power requirements, and overall efficiency of the system. In this project, we investigate many of the parameters that affect the performance of the VHM in order to achieve the aforementioned goals.

A brief description of the VHM is included for background information. The bulk of this paper discusses the experimental procedures and conclusions of tests undertaken to test the performance of the VHM under different conditions. The paper goes on to describe the future work that is yet to be completed in pursuit of the project goals.

Summary Description of VHM Operation

A detailed discussion of the operating principles of the VHM can be found in the paper by Smith, et. al.[1], and is recommended reading for anyone interested in a more exhaustive description of the device. This summary largely paraphrases the description in that paper:

In principle, the VHM measures magnetic fields by their effect on the efficiency with which metastable helium may be optically pumped (see ref. [2] for details on optical pumping). In our instrument, a circularly polarized 1083nm laser travels through a glass cell containing metastable helium gas. The laser optically pumps the metastable helium, resulting in high absorption of the laser by the metastable helium within the cell. A sensor on the opposite side of the cell measures the intensity of the beam, providing a measurement of how much of the beam has been absorbed by the gas. The lower the intensity of the beam reaching the detector, the more efficiently the helium has been optically pumped. The probability of absorption of the laser beam by the gas is significantly dependent on the angle between the optical axis and any magnetic field that may be present.

A rotating magnetic field of constant magnitude is applied to the helium cell by placing it at the center of a cage of Helmholtz coils in the *x-y*, *x-z*, and *y-z* planes which the magnetic field circulates through on alternating rotations. The equations relating changes in the sensor output to the magnitude of the rotating and ambient magnetic fields reveals a dependence on the first, second, and third harmonics of the sweep frequency of the rotating field. The second harmonic is especially significant in that its magnitude is directly related to the sensor's sensitivity to magnetic fields, where a larger magnitude corresponds with a more sensitive magnetometer. It is also important to note that when the average magnetic field on the sensor is zero, then only the second harmonic will be detected.

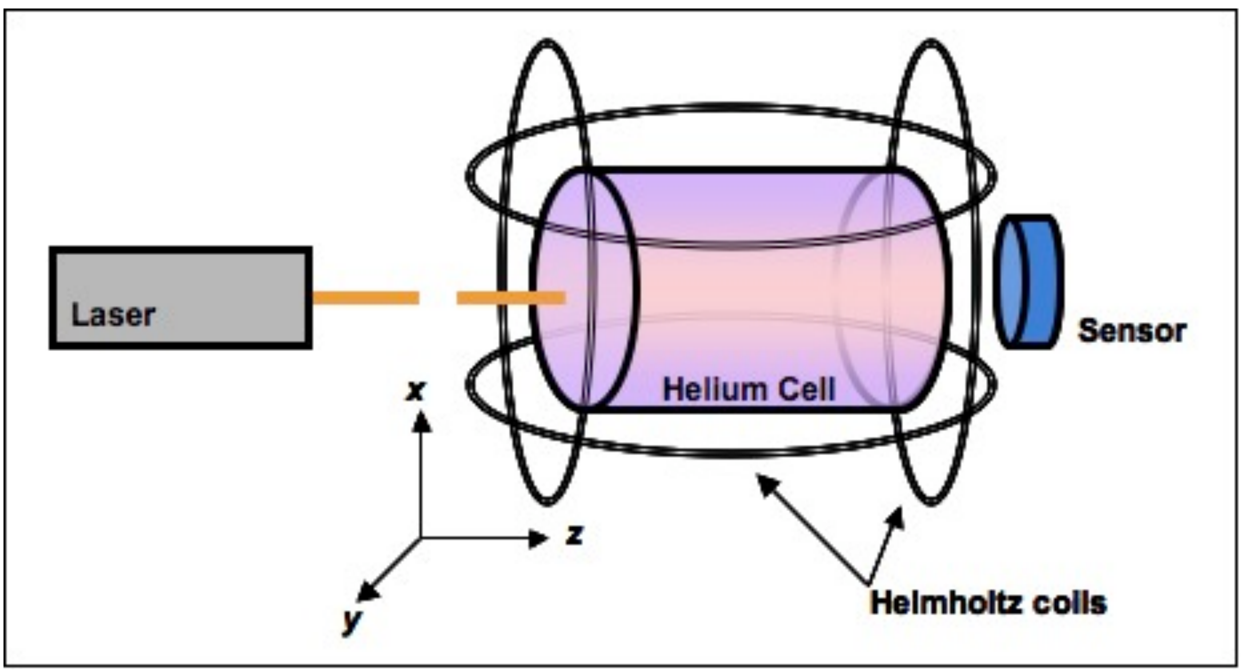

Figure 1: Partial diagram of Vector Helium Magnetometer. Pictured is the 1083nm laser traveling along the optical axis of the cell, two of the three pairs of Helmholtz coils, the glass cell of metastable Helium, and the magnetic field sensor. Not pictured is the computer control system and the RF supply that ignites the cell.

With the rotating field sweeping through each of the planes containing the three pairs of coils, feedback currents are meanwhile applied to these coils. It is possible to zero the field measured by the sensor with the feedback current that is applied to the coils encasing the sensor. The feedback current necessary to zero the field at the sensor is directly proportional to the magnetic field that is being measured. In this way, the system measures the magnitude of the magnetic field in the x, y, and z directions by measuring the amount of current that must be applied to each coil in order to maintain a maximum magnitude of the second harmonic. The amount of current applied to each coil is regulated by a PID control system with a servo loop that uses the magnitude of the first harmonic of the sweep as an error signal. When the magnitudes of the magnetic field in each direction are considered collectively, the VHM produces a measure of the magnitude and direction of the magnetic field.

Methods and Procedures

LabVIEW data acquisition system:

As discussed above, a VHM measures magnetic field strength by tracking changes in the voltage cycling through the coils surrounding the helium cell in the magnetometer, and this voltage data is converted to a measurement of magnetic field strength. Therefore, to monitor the conditions of our VHM, we required a method of viewing the continuous stream of the raw voltage data coming from the VHM. Doing so required the development of data acquisition software that would allow us to monitor in real time the instantaneous levels of the voltage cycling through the magnetometer coils.

LabVIEW was used to design an original program to display the analog input on graphs, as well as convert the voltage data to a measure of magnetic field strength, via multiplication by a predetermined scaling factor. The software was also designed to analyze the power spectrum of the voltage signal, a process that computes the Fourier transform of the input signal and displays its frequency spectrum on a graph. The display of the spectrum has been especially useful in monitoring the baseline noise in the signal.

A necessary step in the testing of the magnetometer was to properly calibrate its zero point, assuring that the VHM could properly measure zero magnetic field. To calibrate the zero point of the VHM, a mu-house, analogous to a Faraday cage that instead cancels exterior magnetic fields, prevents stray magnetic fields from interfering with the operation of the VHM, allowing us to assume that inside the mu-house there is zero magnetic field. With the VHM properly isolated from exterior magnetic fields, the magnitude of the voltage cycling through the coils in each direction was varied until the magnetic field produced by the components of the VHM was properly cancelled to give a zero-field reading.

Noise Reduction:

The first step undertaken by the project group, after the completion of the data acquisition software, was to eliminate as much noise as possible, before further fine-tuning of the instrument could take place. An exploration into the sources of noise in our signals affected the configuration of the equipment on the lab bench, involved grounding many of the devices, as well as eliminating the use of unnecessary wires and connections between equipment. An analog spectrum analyzer and an oscilloscope were employed to aid in this task, as well as the voltage data acquisition software, to monitor changes in the signal. In some cases, custom, nonmagnetic components were made to connect equipment, assuring that the wires were as short as possible, so that the connectors were not a point-of-entry for system noise.

Zero-field Calibration:

After a significant reduction in the noise was accomplished, we turned to the task of calibrating the zero-field point for the magnetometer. After a series of tests to determine which coil was wired to which N-S, E-W, and Z direction, the proper voltage levels were determined for each direction to obtain a measure of zero field. Testing was done with the magnetometer in the mu-house, safely shielded from any stray magnetic fields that would skew our calibration.

Laser Diameter and Power Density:

The following procedures were undertaken to measure the effect of laser beam power and power density on magnetometer performance:

A beam expander was introduced to the magnetometer, expanding the width of the laser beam entering the helium cell from the original width of ≈4mm to approximately 1cm in diameter.

The detector of a laser power meter was fitted with a standard ThorLabs lens cap, where an ≈1mm diameter aperture had been drilled into the exact center of the cap, drastically reducing the amount of laser light reaching the laser power meter. Taped to the lens cap was also a plastic card with an ≈3mm diameter hole in its center. The plastic card would fluoresce when the infrared laser was incident on the card. The purpose of this card was to allow the experimenter to know approximately when the laser was passing through the aperture in the lens cap.

The detector with the aperture cap was placed in the path of the laser beam, where the plane of the lens cap with the aperture was perpendicular to the incoming laser light. The power meter displayed the instantaneous power of the light incident on the detector, and a number of measurements of beam power were recorded. For comparison, the measurements of the laser power were also made without the lens cap, allowing the full beam to fall on the detector. Given the constant fluctuations in the power of the laser, the power measurements were made in successive pairs, first noting the laser power of total beam, and immediately thereafter the power measured through the small aperture.

To calculate the power density of the laser, we considered only the measurements of the laser power made while the aperture cap was on the detector, since the approximate area of the incident surface was known. The power density was calculated by dividing the laser power by the area of the aperture in the lens cap. These values were then graphed, Power Density vs. Laser Power; see *Figure 2* for the plot of this data.

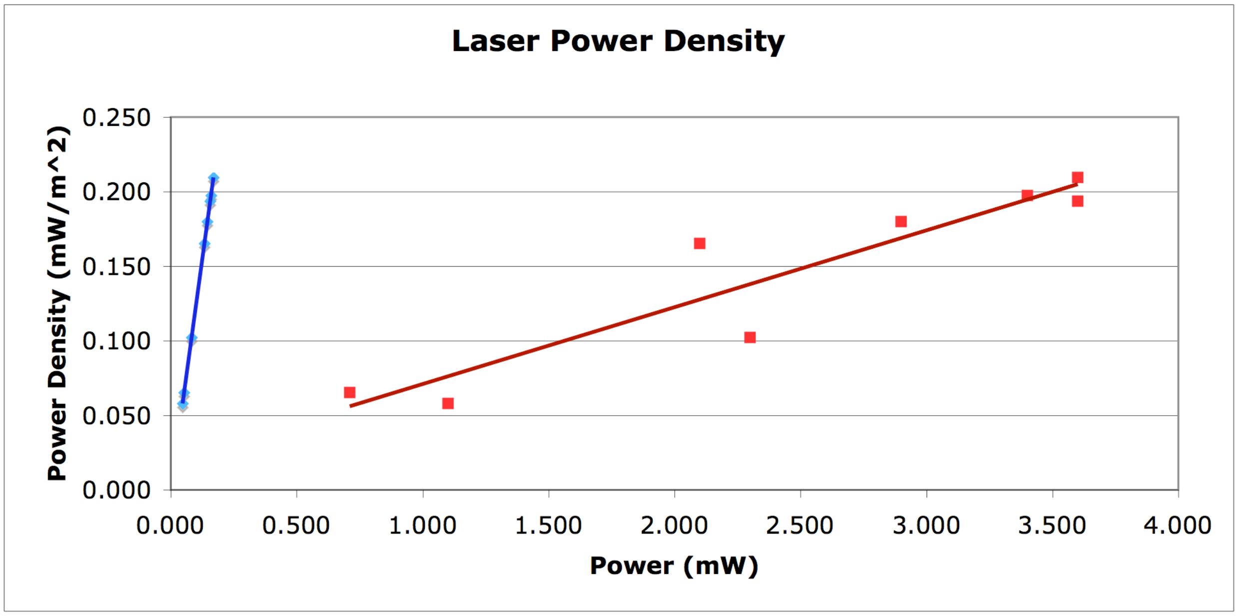

Figure 2: Graph of Power Density vs. Laser Power of the laser beam entering the helium cell. The line on the right side of the graph represents the correlation between beam power and power density of the expanded beam when measured without the lens cap aperture. The line of the left side of the graph represents the correlation between beam power and power density of the expanded beam when measured through a lens cap with a 1mm aperture.

In addition to a calculation of laser power density, a secondary procedure was followed to determine the relationship between beam diameter, laser power, and the magnitude of the second harmonic. The magnitude of the second harmonic, because of its correlation with the effectiveness of the optical pumping of the laser within the helium cell, is used as a relative measure of the performance of the magnetometer. A larger second harmonic corresponds to better functioning of the magnetometer.

The power of the laser, with and without the beam expander, was measured using a laser power meter, while the magnitude of the second harmonic (displayed on a spectrum analyzer) was simultaneously recorded for each power measurement.

The laser power was graphed against the magnitude of the second harmonic, with two data sets shown one the same plot: one data set of the power and magnitude of the expanded beam, the second data set of the power and magnitude of the original, unexpanded beam. See *Figure 3* for the plot of this data.

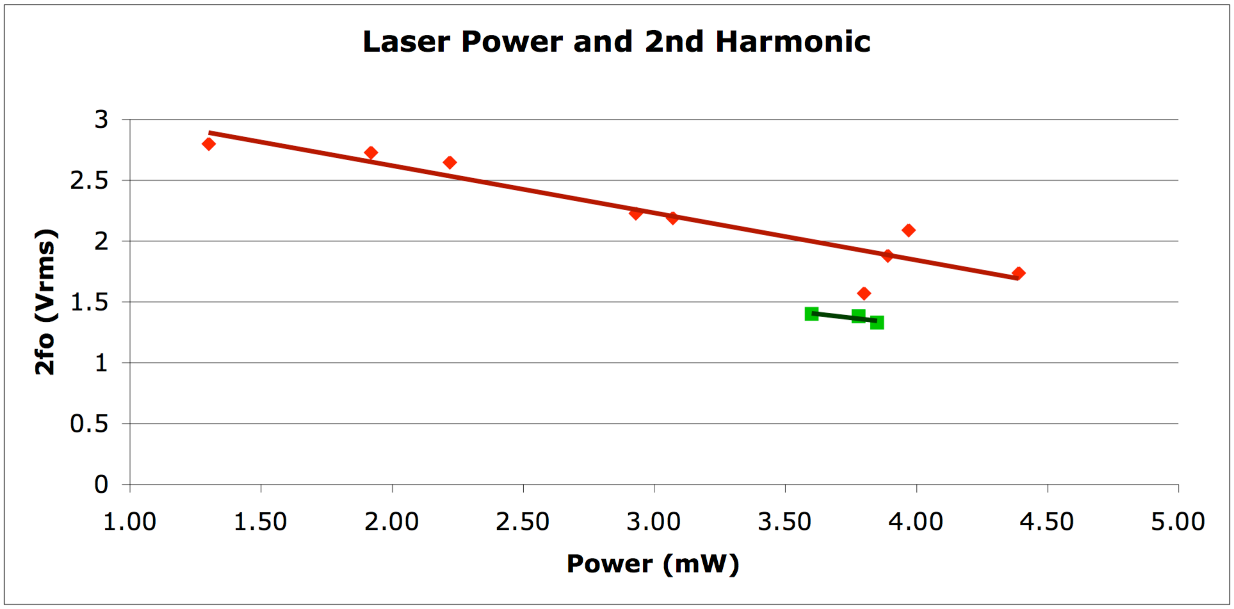

Figure 3: Graph of Magnitude of 2nd Harmonic vs. Laser Power. The upper line represents the power and 2nd harmonic magnitude relationship for the expanded beam, the lower line represents the same relationship for the unexpanded beam.

Current Results and Discussion

Progress on the project has seen the successful completion of the data acquisition software. Access to the information generated by the data acquisition program allowed the testing to proceed, as real-time performance of the instrument could then be monitored.

With the noise level successfully reduced to a workable level and the zero-point properly calibrated, we may proceed with further tests.

The graph of power density vs. laser power confirms that a positive linear relationship exists between the two parameters: the higher the power, the higher the density for both the expanded and the unexpanded beam. This experiment confirms that our expectations for this relationship were correct.

The graph of second harmonic magnitude vs. laser power reveals a negative linear relationship between the parameters: the lower the power, the higher the magnitude. This graph also reveals that the expanded laser beam is more efficient at optically pumping the helium than the narrower beam. This result correlates well with the theory behind optical pumping; the wider laser beam, while is delivers less power per unit area, can successfully perform optical pumping in a greater volume of helium atoms at one time. This greater volume of optically pumped helium atoms that is achieved with a wider beam counteracts the disadvantage of the beam having less power per unit area.

Future Work

Future work on this project will include an investigation of the effectiveness of the device when the laser that performs the optical pumping is either linearly polarized or circularly polarized. The project group is also presently configuring an alternate optical path of the laser that would pass the beam of the laser through the helium cell twice, hopefully attaining greater absorption of the laser and once again improving the amount of optically pumped helium atoms produced within the cell. The project group also hopes to continue its collaboration with a team of scientists at the University of California, Los Angeles, who are currently developing a new micro-computing system driver for the magnetometer that will replace the current, outdated Bench Control Equipment (BCE) that is pivotal in the operation of the magnetometer.

Conclusion

The goal of this project is to construct a reliable compact magnetometer to replace former magnetometer technology that takes advantage of recent advances in materials, laser, and computing technology. The goal is that the final design may be flight-ready, so that it may be included in the payload of scientific instruments of an upcoming mission to space. The experiments that are both in progress and that are planned for the future will provide crucial information about how to optimize the performance of the device. The information from these tests will ultimately allow researchers to collect new and more detailed data about the magnetic fields around planets and objects in outer space, which will no doubt lead to exciting discoveries.

Acknowledgements

Special thanks are given to the National Science Foundation for funding and supporting this research, as well as the Consortium for Undergraduate Research Experience (CURE) and the Jet Propulsion Laboratory, a CURE astronomy REU site. Thanks are also owed to Dr. Milan Mijic, the CURE director, to Dr. Neil Murphy, the principle investigator and primary research advisor, and to Dr. Alex Rudolph.

This work was supported by the National Science Foundation under REU Grant No. 0852088 to the California State University, Los Angeles.

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