Applications of Miniaturized Atomic Magnetic Sensors in Military Systems

21 October, 2012

Gregory Schultz[1], Vishal Shah[2], Jonathan Miller[1]

[1]White River Technologies, Inc.[†]
3 School House Lane, Hanover, NH 03750 USA

[2]QuSpin, Inc
10955 Westmoor Drive, Westminster, CO 80021 USA

ABSTRACT

A new generation of miniaturized ultra-high sensitivity atomic magnetometers is being developed and integrated into military systems. These new systems aggregate advances in micro-electromechanical systems, atomic physics, optics, electromagnetics, and data acquisition methodologies for record-level performance in terms of total magnetic field sensitivity while attaining large reductions in size, weight, and power. Very small scale sensors (on the order of a few cubic centimeters) have been demonstrated in both scalar and vector modes and integrated into designs for various defense applications. The focus of our work is on the practical integration of these sensors into operational platforms. There are a number of implications for utilizing these sensors in working environments such that signal-to-noise ratios, detection probabilities, and false alarm mitigation are optimized. The challenges of developing working sensor modules and platforms that operate effectively in the Earth's magnetic field for various military target detection, localization, and characterization missions are significant. We examine the mitigation of platform and environmental noise as well as the development of sensor arrays and associated data acquisition systems. Variations of and enhancements to conventional low frequency magnetometry are investigated through preliminary experimental data in addition to modeling and simulations. In particular, we discuss unique deployment concepts for sensor control, target geolocation, and data processing. Emphasis is placed on prototypes with specific bandwidth sensitivity tailored to a subset of platforms (small unmanned ground, unmanned undersea and unmanned aerial vehicles) and targets of interest. Applications include configurations for undersea and underground threat detection - particularly those associated with stationary or mobile explosives and compact metallic targets such as munitions, improvised threat devices, submarines, and other hazardous objects. We show the potential of current and future features of miniaturized magnetic sensors including very high magnetic field sensitivities, bandwidth selectivity, source field control, and array processing.

[†] formerly of Sky Research, Inc., Hanover, NH

Keywords: Magnetic Sensing, Magnetometers, Electromagnetic Induction, Nuclear Magnetic Resonance, Military Sensing

1.0 Introduction

Magnetic sensors have been used on military systems since the 1940's, however, the practical implementation of magnetic sensors on various platforms has many challenges. The general ruggedness, reliability, and high rate of productivity of commercial magnetic sensors, coupled with robust and simple data processing makes them a potentially attractive choice for military target detection and characterization applications - especially those for which an effective standoff sensing modality is required. Until recently, the most sensitive magnetometers have been prohibitively large and heavy, power hungry, and relatively expensive for anything other than niche applications. A significant progression in microsystems technologies has led to the development of numerous devices that have strong leveraging potential in the quest to reduce the size, weight, and power of magnetic sensors without a significant cost in terms of performance.

Driven by the use of micromechanical components over the past 6 or 7 years, a new generation of high performance miniaturized atomic magnetometers have been developed. Many of these technologies have been developed under the auspices of US DOD sponsorship and have been pioneered by academic (e.g., Princeton University, University of Colorado, and University of California-Berkeley) and government or non-profit R&D labs (e.g., National Institute of Standards and Technology, Sandia National Lab, and Draper Lab). More recently, sensor manufacturers (e.g., QuSpin Inc., Twinleaf, Physical Sciences Inc, and Geometrics) have begun to transition new systems from the benchtop to system integration and application specialists. These new systems aggregate advances in micro-electromechanical systems (MEMS), implementations of atomic physics, optical designs, electromagnetics, and data acquisition in various forms. Previous publications have detailed the development and designs of these new magnetic sensors (e.g., Moreland et al., 2005; Schwidt et al., 2005; Prouty, 2007). The focus of this paper is on the practical integration of developing or currently available miniaturized magnetic sensors into operational military platforms or systems.

2.0 Background

Highly sensitive magnetic sensors have broad and varied use in military applications. They are commonly used for detecting unexploded ordnance, landmines and other buried explosive hazards, delineating infrastructure and electrical power systems, and characterizing concealed weapons or other person-borne threats. Recent variations and enhancements have extended the conventional low frequency or DC magnetometry to higher frequencies leading to increased utility. AC-coupled magnetometers, for example, can be used with controlled electromagnetic sources for improved target characterization. Therefore, magnetic sensors are no longer used *only* for detection of ferrous or otherwise magnetic materials. Bandwidth selective sensing modes have been integrated with transmitters to enable magnetic resonance measurements. This is of particular interest because nuclear magnetic resonance is perhaps the only reliable technique that allows highly accurate identification of non-metallic solids and liquids containing hydrogen or nitrogen atoms.

2.1. Miniaturized Atomic Magnetometers

In non-zero magnetic fields, the theoretical sensitivity of atomic magnetometers is limited by spin-exchange relaxation in alkali atoms, which is approximately 1 $fT/\sqrt{Hz}$ $/cm^{3/2}$. However, commercial atomic magnetometers are generally three orders of magnitude less sensitive, primarily for two reasons: 1) Electronic and other technical noise from external sources such as temperature fluctuations, vibrations, and 2) commercial magnetometers rely on fifty year-old alkali vapor lamp technology, which has fundamental limitations due to the broad spectral width of the vapor lamps.

Recently highly miniaturized and ultra-low power chip-scale atomic magnetometers (CSAM) have been developed by leveraging the latest advances in vertical-cavity surface-emitting laser (VCSEL) technology and MEMS fabrication techniques. By virtue of their small size, weight, power consumption and low cost, the range of applications in which atomic magnetometer technology can be applied is now greatly expanded. MEMS advances have improved the fabrication of submillimeter mechanical structures through the use of lithographic patterning and chemical etching. Recently, these methods have been applied to the fabrication of chip-scale alkali gas cells with dimensions on the order of 1 mm. These MEMs-based designs provide for potential fabrication of a large number of cells simultaneously with the same process sequence, which will lead to a substantially reduced cost for large device volumes (Liew et al., 2004).

The application of MEMS technology to atomic magnetometers has been an active area of research in the last decade. Rapid progress is now being made to transition this technology from research labs to commercial domain. Based on the approaches used to fabricate chip scale atomic clocks, it has been demonstrated that the components of an atomic magnetometer can be fabricated and integrated into a chip-scale microsystem with superior performance characteristics. Atomic magnetometers have a particular set of advantages: 1) they are non-cryogenic, 2) do not require bulky microwave resonators for exciting atomic transitions, 3) measure the total field and are thus insensitive to alignment errors, and 4) are inherently accurate given a detailed knowledge of the gyromagnetic ratio of precessing atoms.

Aside from miniaturization and reduction in power consumption and cost, laser based atomic interrogation has also enabled new kinds of atomic magnetometers such as ultra-sensitive spin-exchange relaxation-free (SERF) atomic magnetometer and radio frequency (RF) atomic magnetometer. A SERF magnetometer operating in near zero-field environment can achieve magnetic field sensitivity three orders of magnitude greater than commercial atomic magnetometers. While potential of such high sensitivity for bio-medical applications such as magnetocardiography (MCG) and magnetoencephalography (MEG) is already becoming evident, military and space applications of this powerful technology are now only starting to be investigated. The RF version of the magnetometer can provide extreme sensitivity in a narrow frequency band of interest from 500 Hz to several 100 kHz. Applications of RF magnetometer range from extreme low frequency (ELF) communication for submarine and other underground applications to ultra-sensitive metal detection and non-destructive testing and evaluation.

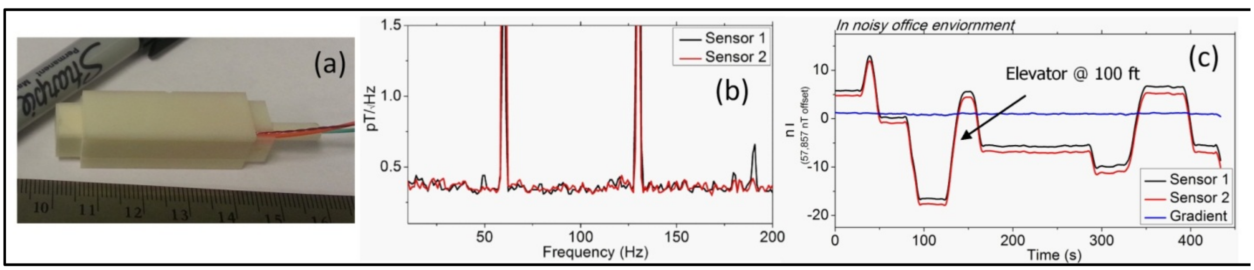


Figure 1: (a) A picture of QuSpin's scalar magnetometer prototype. (b) Magnetic sensitivity of the prototypes expressed in pT/√Hz. (c) Magnetometers operating in an office environment. The step like features are from magnetic fields from an elevator about 100 feet away from the office. The blue line is difference of the signal from the two identical magnetometers.

2.2. Sensing Modes

Miniaturized atomic magnetometers have been developed into sensor packages capable of multiple modes of operation including scalar mode, vector zero-field mode, and RF mode. In scalar mode, the magnetometer is sensitive to the DC changes in the magnitude of the total magnetic field. This has the particular advantage of being largely insensitive to changes in the orientation of the sensor within the ambient magnetic field (i.e., Earth's field). That makes this mode ideal for use on moving platforms or where total magnetic field sensitivity is paramount.

By nulling the magnetic field in the vicinity of the magnetic sensor and by increasing the temperature of the vapor cell, the magnetometer can be made to operate in SERF vector mode. This enables discrete measurements along focused axial directions, and ultimately a full three-axis measurement of the components of the magnetic field. In this mode, the sensitivity can be dramatically improved due to suppression of spin-exchange relaxation of alkali gas atoms. This SERF modality is simultaneously sensitive to magnetic fields along two independent axes.

To achieve wideband sensitivity or, conversely, narrow-band frequency selectivity, a SERF magnetometer can be tuned in the radio frequency band. This allows the sensor to be tuned to relatively narrow (~100 Hz) bands within the range of DC to 5 kHz. Bias fields required for tuning the magnetometer at frequencies above ~5 kHz suffer from higher spin-exchange relaxation, which degrades performance. A unique aspect of this feature is the ability to band select for magnetic resonance. For example, if a sample area is excited with a current pulse at the Larmor frequency, the nuclear magnetization of water (or other molecules) will generate a small relaxation field orthogonal to the

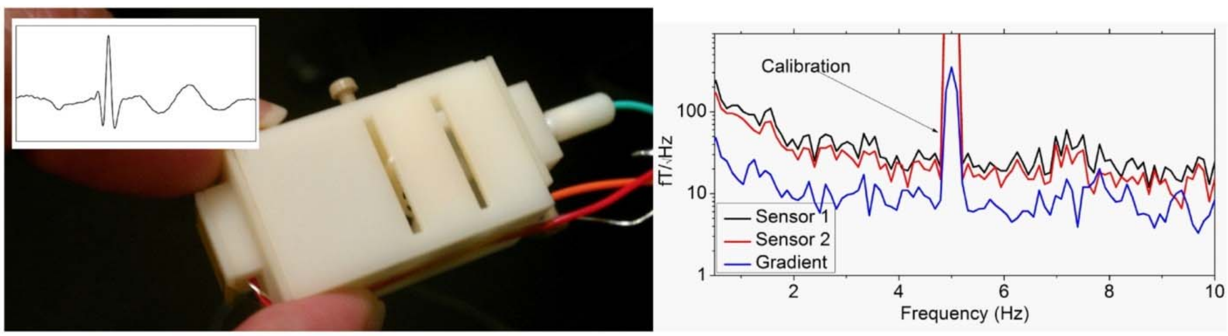


Figure 2: (left) A picture of QuSpin's ultra-sensitive SERF atomic magnetometer prototype. The inset in the picture is a magnetocardiogram (MCG) of a patient acquired using the prototype SERF magnetometer. **(right)** Sensitivity of the SERF magnetometer prototype expressed in fT/√Hz. The blue line is difference of the signal from the two identical magnetometers.

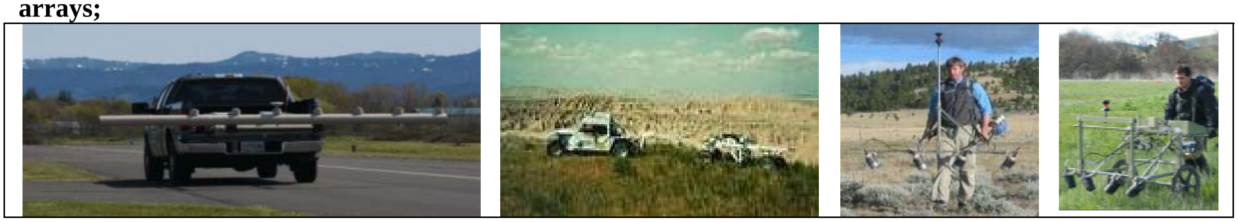
incident excitation.

3.0 Integration With Military Platforms

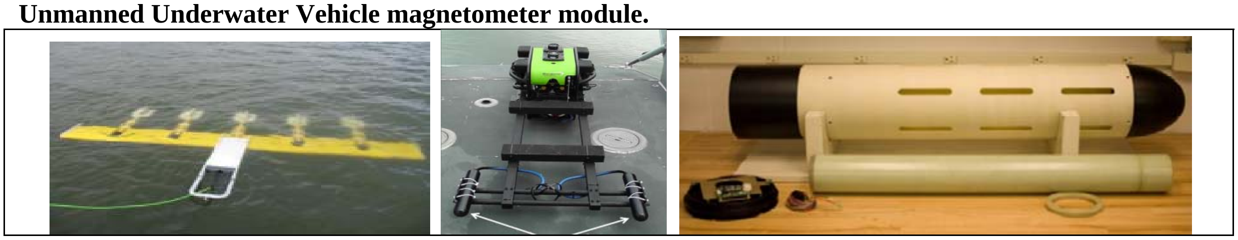
We have worked to develop operational sensing systems as modules on military platforms or within the layered defense family of systems. This has included self-contained unattended ground sensors and sensor arrays, implementations on manned and unmanned ground-based vehicles, on unmanned underwater vehicles, and airborne platforms. In many cases the size, weight, and power reductions enabled by the miniaturization of new atomic magnetometer technology has required significantly different or new system-level designs. The potential for very small and inexpensive sensors has also facilitated operational concepts not possible before. For example, we are developing compact magnetometer modules for unattended ground sensors (UGS) and small unmanned aerial vehicles that may be considered expendable under particular mission scenarios.

- **Airborne platforms:** **(i) Cessna Caravan 208 tail-boom, (ii) HeliMag array on Hughes 500 and (iii) Bell 206L helicopters, (iv) Mosquito rotocraft boom-mount, (v) Sick12 Mongoose unmanned rotocraft boom-mount;**

- **<u>Ground platforms:</u> (vi) Full-size pick-up truck direct mount for IED detection (vii) Multi-sensor Towed Array Detection System (MTADS), (viii) Cart-mounted UXO detection array, and (ix) Man-portable arrays;**



- **<u>Marine platforms:</u> (x) Marine towed magnetometer array, (xi) ROV-based magnetometer array, Unmanned Underwater Vehicle magnetometer module.**



Each platform has a unique self signature and noise environment that must be mitigated in order to optimize the sensor performance. To minimize platform noise levels and realize the best performance, noise reduction and compensation methods have been developed. Noise mitigation methods are designed to meet multiple requirements: 1) highly accurate and robust under varying conditions, 2) adaptable to multiple platform types, 3) comprehensive in mitigating the spectrum of noise sources - both platform and ambient, and 4) simple so as not to add significantly to the complexity of the overall system.

The total noise interference from a platform (Ash, 1997) comprises two main sources: (1) external natural environment and/or anthropogenic sources (Campbell, 1979) and (2) platform maneuver noise (Hardwick, 1984). The relative amplitude distribution of these noise sources can be categorized into distinct frequency bands. Platform noise can be classified into static and dynamic components:

1. Platform static magnetic signature (e.g., permanent magnetic moment, induced moment)
2. Static sources of magnetic noise and eddy currents (time rate of change of the magnetic field, e.g., changes in the induced moment as platform moves in earth's field, relative motion of UAV components, vibration and shock)
3. Dynamic sources of magnetic noise and eddy currents (e.g., from moving metallic parts, from current loops and integrated circuits, from switches).

3.1. Unattended Ground Sensors

Magnetic sensors have been an important component in unattended battlefield sensors to aid in target detection, localization, and characterization. They are unaffected by weather conditions, are extremely simple to use, and do require high bandwidth output for interpretation. Compact sensor modules can be used to track personnel and vehicles crossing secure or tactical borders, to detect concealed weapons or explosive hazards, and to characterize underground facilities. Current systems are bulky and require too much time to set-up, protect, sustain, and relocate.

In order to assemble small distributed sensor nodes in battlefield or forward operating areas where they may be left unattended for days at a time, it is advantageous to minimize their size, weight, and power consumption. The new generation of miniaturized magnetometers has great potential to facilitate more robust use in clandestine and unrestrained operations. This directly supports force protection and associated efforts to enhance situational awareness and secure tactical outposts as well as homeland installations.

Starting in 2009, we have been developing a remote unattended magnetic and electro-optical sensor array for securing entry control points and associated forward operating areas. The sensor modules are camouflaged in natural (rocks, buried) or engineered (traffic cones, curbs) structures to detect hazardous materials associated with person-borne improvised explosive devices (PB-IEDs). The security monitoring system was designed specifically for surveillance of PB-IEDs and employs embedded software that automatically compiles, processes, and analyzes sensor data providing a visual display of results as well as audible alarms to an operator control system. The system self-calibrates and performs adaptive corrections to remove ambient noise.

Figure 2. Left-to-Right: The SubtleMadness unattended ground sensor security system - sensors are obscured under traffic cones and laid out in an array depending on the protection scenario; The Operator Control Station tablet PC can be located up to 1000 meters from the sensor array providing safe standoff and automated alarm indications; A miniaturized magnetic sensor in the palm of the hand; The SubtleMadness physical security system protecting an entry control point in central Iraq.

The original systems utilized older, bulky and expensive atomic magnetometer technology. Our current efforts are focused on greatly improving the sensor size and power constraints through the implementation of new miniaturized atomic magnetometers. By driving the total system cost and complexity down (and size down to an equivalent hockey puck), we have opened new avenues for use of these modules in large array configurations and as expendable nodes in an UGS network.

3.2. Ground Vehicle-based Arrays

We have developed ground-based platforms utilizing arrays of magnetometers primarily for the detection of buried explosive hazards such as unexploded ordnance (UXO) and improvised explosive devices (IEDs). Beginning in 2008, we began developing a magnetic field change detection system for in-road IEDs. The activities performed under this project addressed the limitations of UXO detection technologies as applied to IED applications by exploiting two aspects of the IED problem. First, the detection of munitions (projectiles, rockets, bombs, etc.) is well understood and readily accomplished with magnetometers (e.g., Foley, 1994; Billings, 2004) through straightforward and well-established procedures. The main difficulty is not the IED detection, but in addressing the associated clutter that introduces prohibitive numbers of false alarms. Second, the presence of roadside IEDs changes with time. This condition is opposite from the UXO detection application, where munitions have been in the ground for years (often decades) prior to the detection and clearance effort. This time-variation in magnetic conditions associated with IED emplacement offers a unique aspect of the problem that can be exploited to facilitate IED detection, mitigate clutter-related false alarms, and support near-real-time implementation.

This system contains 5 key hardware elements including the magnetic sensor array, positioning sensors, data acquisition and processing units, telemetry subsystem, and the vehicle platform itself. This basic system has since been transitioned to an unmanned ground vehicle (UGV) platform. Atomic magnetometers are extremely sensitive instruments, capable of detecting ferrous material at distance. This extreme sensitivity also makes them susceptible to noise in close proximity to a vehicle. This is because they detect signals not only from subsurface metallic sources, but from any source that perturbs the Earth's magnetic field. Without sufficient attention to the data produced from a ground-vehicle system, the signature of the vehicle will surpass and mask the signals from anomalous sources in the ground. Therefore, we expended a significant portion of our engineering effort in assessing vehicle selection, sensor-to-vehicle separation, and data processing requirements.

The maximum effect of the vehicle bulk signature occurs when the orientation of the net magnetic moment vector is aligned with magnetic North or South. The rotation of steel beads and steel belts common in tubeless tires are also a significant contributor of vehicle-induced noise. We found that adaptive background subtraction methods that utilize specialized de-median filters were effective at removing the vehicle signature without making any modifications to the vehicle itself.

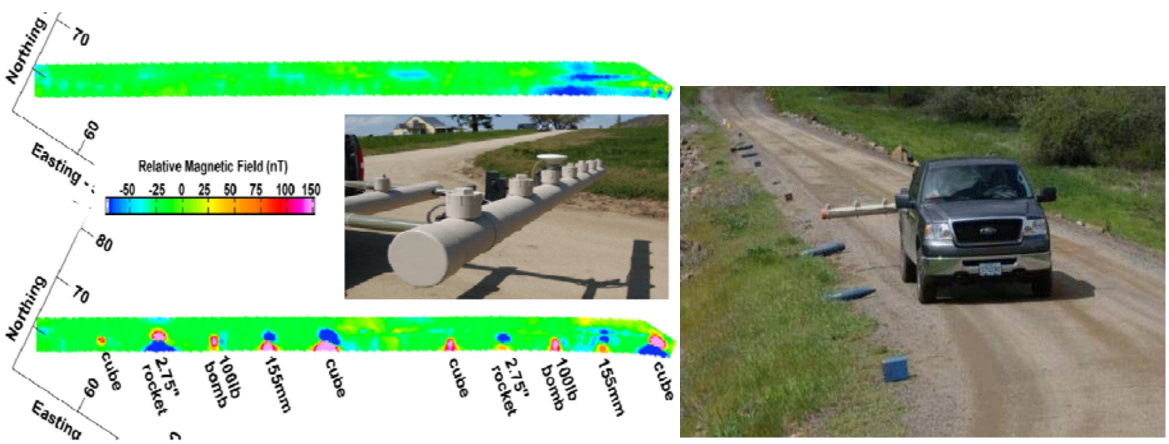


Figure 3. Left: Change detection map pairing - top figure shows the magnetic field anomaly experienced during a background pass and the bottom figure shows the map after IED surrogates were emplaced. Right: The magnetic field change detection platform mounted in the bed of a pick-up truck.

Our most recent work involves integration of wideband and RF-tunable miniaturized magnetometers with a controlled magnetic field source mounted on military vehicles. We are replacing multi-turn induction coil receivers with ultra-high sensitivity miniaturized atomic magnetometers. New designs lead to more complete sampling of the magnetic field response from objects, which enables greater ability to discriminate targets of interest from the pervasive clutter in either low- or high-intensity forward roadway operating areas. Additionally, since we are measuring the scattered magnetic field (*B*) with miniature magnetometers and not the time rate of change in the scattered magnetic field

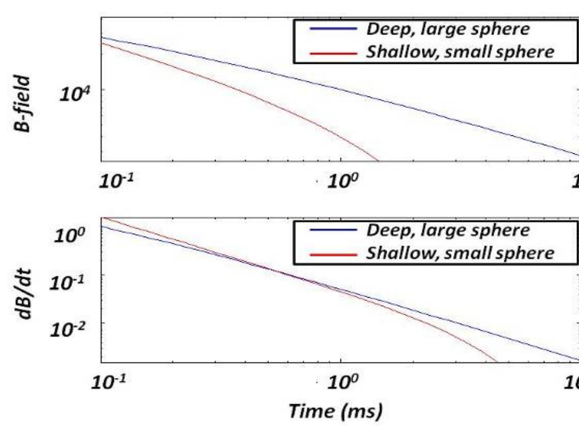


Figure 4. Effective sensitivity of *B* and *dB/dt* sensor modalities. At late times after cessation of the primary field discrimination of large/deep objects from small/shallow ones is more readily observed in *B* than in *dB/dt* simulated data.

(*dB/dt*) as with induction coils, we are able to exploit a wider range of target characteristics.

One of the key benefits associated with incorporating B-field measurements in an active source design is a higher sensitivity to large deep items compared to small shallow items. This effect is illustrated in Figure 4, which compares *B* and *dB/dt* responses of a 10 cm ferrous sphere at 1.3 m depth (a large deep item) to a 1 cm ferrous sphere at 30 cm depth (a small shallow item).

Another benefit of employing wideband B-field sensors is the ability to measure NMR, which has been shown to be effective for detecting and identifying the chemical compounds present in liquid explosives (Espy et al., 2010). Because the resonance of a particular substance is proportional to the magnitude of the applied field, NMR methods typically require very strong and homogenous static magnetic fields to generate signals at frequencies high enough to be within the *dB/dt* receiver sensitivity range; however, with the development of extremely sensitive chip scale atomic magnetometers, NMR spectroscopy is feasible using the earth's field in conjunction with modest pre-polarizing fields and compact magnetic field transmitters. It is possible to generate a NMR response in a liquid compound using an EMI transmitter coil and subsequently measure the NMR signal with a set of B-field receivers tuned for the specific resonance.

3.3. Underwater Sensor Configurations

Underwater threats and infrastructure are also readily detected by magnetic sensors mounted on unmanned or remotely operated vehicles as well as diver-based systems. For example, the U.S. Navy has been using magnetic sensors on unmanned undersea vehicles (UUVs) for a number of years to detect sea mines and other hazards. The recent integration of miniaturized atomic magnetic sensors into field-proven UUVs represents substantial progress in improving the probabilities of munitions detection, classification, and identification in difficult littoral environments. Integrated sensor and unmanned platform systems form a family of technologies that can be applied to mine countermeasures, port and harbor security, unexploded ordnance, and naval salvage and infrastructure characterization.

This next-generation atomic scalar magnetic sensing module is combined in a system design that can be readily adapted to numerous UUV form factors and original equipment manufacturer configurations. The integrated unit provides an internal sensor pressure vessel, flooded outer compartment shrouded with a hydrodynamic faring, and modular data interface module and bulkhead. The UUV-tailored miniature magnetometer array is configured into a gradiometer to reduce the influence of noise from UUV components and aid in localizing targets. Gradient noise rejection is on the order of the number of sensors N for coherent subtraction and order $\sqrt{N}$ for incoherent cancellation. By recording both the total magnetic field and total field gradients, we are able to use the Euler equation to compute the range and bearing to targets of interest. Pairs of sensors are arranged in close proximity to form gradient combinations. The elimination of induction coils that normally drive the "pumping" of alkali gas atoms in older units provides a simplified approach and allows sensors to be packed tightly without cross-talk.

We have performed platform signature studies of multiple types of UUVs where sensors are mounted internally near noise sources (Schultz et al, 2010). The simplest characterization test involves rigidly mounting an atomic scalar magnetometer on the nose of the UUV (Figure 5) and then systematically sweeping the vehicle and sensor through a 360 degree azimuthal rotation. As expected, the vehicle sweeps through the anomalous field to produce an approximate cosine functional behavior. The maximum measured anomaly occurs when the vehicle is aligned with magnetic North. Deviations from cosine behavior, such as the small peak near 180 degrees and some skewing of the anomaly with azimuth are due to the fixed (non-dipolar) distortion of the UUV signature. This distortion can be determined systematically and applied to new magnetic readings to eliminate the effects of the UUV.

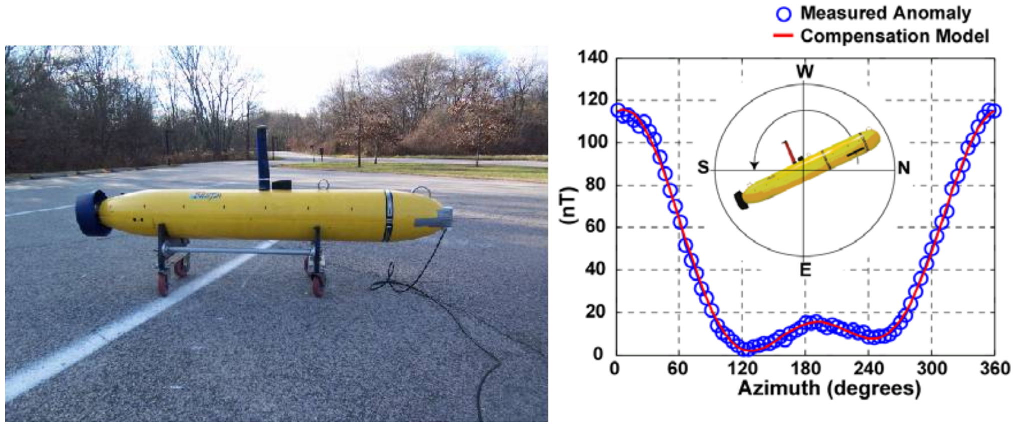


Figure 5. Example of the azimuthal response (blue circles) of an UUV produced by systematically spinning the vehicle 360 degrees through the Earth's field. A standard compensation model (red curve) was applied to fit the response with a high degree of accuracy.

3.4. Airborne Platforms

Amongst all the platform types, miniature atomic magnetometers have the greatest potential benefit for aerial platforms such as small unmanned aerial vehicles and small unmanned rotocraft. Payload capacity is especially limited on these platforms. These systems may also be placed at considerable risk during missions such that expensive sensor payloads may not be warranted.

Small UAV's are naturally low in ferromagnetic materials because of size, weight and power (SWaP) constraints. However, these UAV's contain a significant number of electrical and electronic components, including propeller motors, computers, power supplies, solenoids, and avionic actuators. The induced magnetic moment of the platform is proportional to the projection of the Earth's field on the ferromagnetic structures. This causes an induced field to turn at twice the angular rate of the platform, while the permanent field turns at the same rate as the platform. Eddy current fields occur in the skins and surfaces of conductive components. These fields do not depend on the ferromagnetic properties of components, but rather on the conductive properties. Since eddy currents are proportional to the time rate of change of flux, their amplitudes are proportional to accelerations that occur during maneuvers. This differs from the induced magnetic field, which only depends on the relative orientation between the Earth's field and the platform.

We have conducted a number of tests using various DC motor and other unmanned vehicle components similar to those used in small UAVs. For example, we recently conducted preliminary signature evaluations of a tactical micro-UAV, developed for forward Army reconnaissance missions. We performed motor signature and full integrated tests to assess both the static and dynamic noise signals as a function of distance and attitude of the UAV. A first-order analysis reveals the bulk UAV signature and the noise environment as a function of azimuth while the UAV was exercising flight operations (brushless DC motor running, tail avionics actuated, telemetry systems transmitting). We utilized a simple linear model to predict the variation in the bulk signature and variation of the signature (the noise environment) as shown in Figure 6. This exercise has given us useful knowledge of the noise environment, although the power spectra reveal that we are likely under-sampling the magnetic field environment.

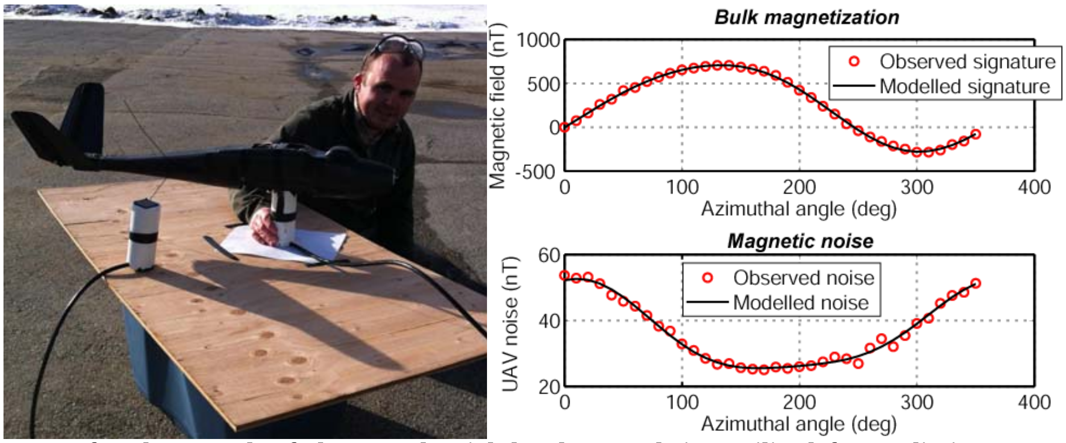


Figure 6. Left: Photograph of the Vertek Nighthawk UAV being utilized for preliminary magnetic signature tests. Right: Observed and predicted bulk magnetic signature and noise variation as a function of azimuth. The bulk magnetization contains both induced and permanent effects.

4.0 Synthesis

The new generation of miniaturized ultra-high sensitivity atomic magnetometers is relevant to a wide range of military sensing applications. An increasing reliance on unmanned reconnaissance platforms (including aerial, undersea, and ground vehicles) and discreet unattended ground sensors for critical information has generated a necessity for high-sensitivity, compact, and expendable sensors. Our work has focused primarily on the integration of these new miniature atomic magnetic field sensors with existing platforms to realize the full potential of these sensing systems. Specifically, we have applied several approaches to characterizing the magnetic signatures of different vehicle platforms to minimize their potential impact on magnetometer sensitivity and performance. Vehicle signatures typically comprise three main components: 1) permanent and induced magnetization resulting from the inherent ferromagnetic properties of different platform components; 2) eddy current effects caused by the movement of platform conductive components in the Earth's magnetic field; and 3) source current effects caused by powered electronic components within the platform. These different noise components contribute distinct characteristics to the overall platform magnetic signature. Mitigating their effect on sensor performance requires approaches that account for all aspects of the phenomenology associated with each noise source. For example, gradient sensor configurations can be effective for reducing noise associated with uniform fields emanating from distant sources; however, these configurations can also degrade sensitivity to distant targets. Band filtering is an effective method for reducing noise caused by active platform sources, provided that the spectral content of these sources does not overlap much with target frequency bands. In some cases, physics-based modeling is required to remove certain noise components. Induced magnetization is a well understood phenomenon, and its effects can be mitigated once sufficient characterization of the platform induced magnetization component is obtained. Physical models can then be applied to extract the induced and permanent magnetization parameters. With proper application of these mitigation approaches, it is possible to maximize the performance of these ultra-high sensitivity magnetometers when they are integrated with operational sensor platforms.

References

Ash, A. D., 1997, Noise and noise reduction techniques for airborne magnetic measurements at sea: International Conference on Marine Electromagnetics, UK, MARELEC.

Billings, S. D., 2004, Discrimination and classification of buried unexploded ordnance using magnetometry, IEEE Transactions on Geoscience and Remote Sensing 42, 1241 – 1251.

Billings, S. D., 2004, Discrimination and classification of buried unexploded ordnance using magnetometry, IEEE Transactions on Geoscience and Remote Sensing 42, 1241 – 1251.

Campbell, W.H., 1979, Introduction of Geomagnetic Fields: Cambridge University Press.

Espy, M., Flynn, M., Gomez, J., Hanson, C., Kraus, R., Magnelind, P., Maskaly, K., Maltshov, A., Newman, S., Owens, T., Peters, M., Sandin, H., Savukov, I., Schultz, L., Urbatis, A., Volegov, P., and Zotev, V., 2010, Ultra-low-field MRI for the detection of liquid explosives, Superconductor Science and Technology, vol. 23, no. 3, p. 034023, Mar. 2010.

Foley, J.E., 1994, STOLS: Magnetic survey at Sandia National Laboratory Technical area 2, in Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, March 27-31, 1994 Boston, Mass., edited by R.S. Bell and C.M. LEPPER, 895-907.

Hardwick, C.D., 1984, Important design considerations for inboard airborne magnetic gradiometers, Geophysics, 49, 2004-2018.

Liew, L.-A.; Knappe, S.; Moreland, J.; Robinson, H.; Hollberg, L.; Kitching, J., 2004, Micromachined alkali atom vapor cells for chip-scale atomic clocks Micro Electro Mechanical Systems, 2004. 17th IEEE International Conference on. (MEMS), 113 - 116

Prouty, M., 2007, Progress in Chip-Scale Total Field Magnetometers, Battlefield Acoustic and Magnetic Sensors, Laurel, MD, Aug 2007, BC01.

Schultz, G., Foley, J., Glenn, T, 2010, MM-1631 Underwater ordnance characterization using UUV technology, SERDP Final Report, 431 pp.

Schwindt, P. Knappe, S. Shah, V. Hollberg, L. Kitching, J. Liew, L. and J. Moreland, “2004, Chip-scale atomic magnetometers,” Appl. Phys. Lett. vol. 85, pp. 6409–6411, Dec. 2004.