The DARPA HUMS Program: Revolutionizing Magnetic Field Sensors Using Multiferroic Materials and Atomic Gas Vapor Cells

William S. Coblenz[*] and Scott A. Wartenberg[**]

[*]Defense Advanced Research Projects Agency, 3701 North Fairfax Drive
Arlington, VA 22203-1714
(571)218-4647
william.coblenz@darpa.mil

**Booz Allen Hamilton, 4001 North Fairfax Drive
Arlington, VA 22203-1714
(703)465-5834
wartenberg_scott@bah.com

Abstract

The Heterostructural Uncooled Magnetic Sensors (HUMS) program sponsored by the Defense Advanced Research Projects Agency (DARPA/DSO) is focused on developing magnetic field sensors that operate at room temperature with an ultra-sensitivity to enable applications such as through-wall imaging, perimeter fences, tagging/tracking, and other man-portable operations. Four teams of researchers are participating in the program, with Virginia Tech and University of Maryland leading multiferroic heterostructural materials development and Princeton University and the National Institute of Standards and Technology (NIST) leading atomic vapor cell development. Leveraging the strengths of these two technologies, each team has made advancements towards the program goal of ground-breaking sensitivity, reduced noise, and portability while operating under room temperature conditions. This paper summarizes the program's achievements so far and highlights the accomplishments made by each team.

Keywords: magnetic fields, sensor, photonic sensors, magnetometer, low frequency, sensitivity, SQUIDS, multiferroic materials, laser gas cells

1. INTRODUCTION

The DARPA HUMS program has explored two different technologies to produce imaging magnetic field sensors that enable warfighters to detect threats behind walls and to discern weapons from ordinary objects (see Figure 1).To meet such needs, deployable magnetic sensors must have extreme sensitivity ($\ll$pT/√Hz and $<$pT/m/√Hz) at low frequencies (10^{-3} Hz). This will allow sensors to resolve weak moving anomalies from actual magnetic signatures. For the greatest utility, the sensors should be mobile and be able to sample a broad field of view. Low power consumption will enable long deployments. The sensors must operate at ambient temperatures for simplicity. Each sensor should be small enough size that a large, portable imaging array system is feasible. In short, the program seeks to produce small, low-cost, low-power magnetic sensors that enable ground-breaking DoD capabilities in threat imaging.

Unattended Ground, Sea, and Air Sensor Technologies and Applications XIV, edited by Edward M. Carapezza,
Proc. of SPIE Vol. 8388, 838809 · © 2012 SPIE · CCC code: 0277-786X/12/$18 · doi: 10.1117/12.925247

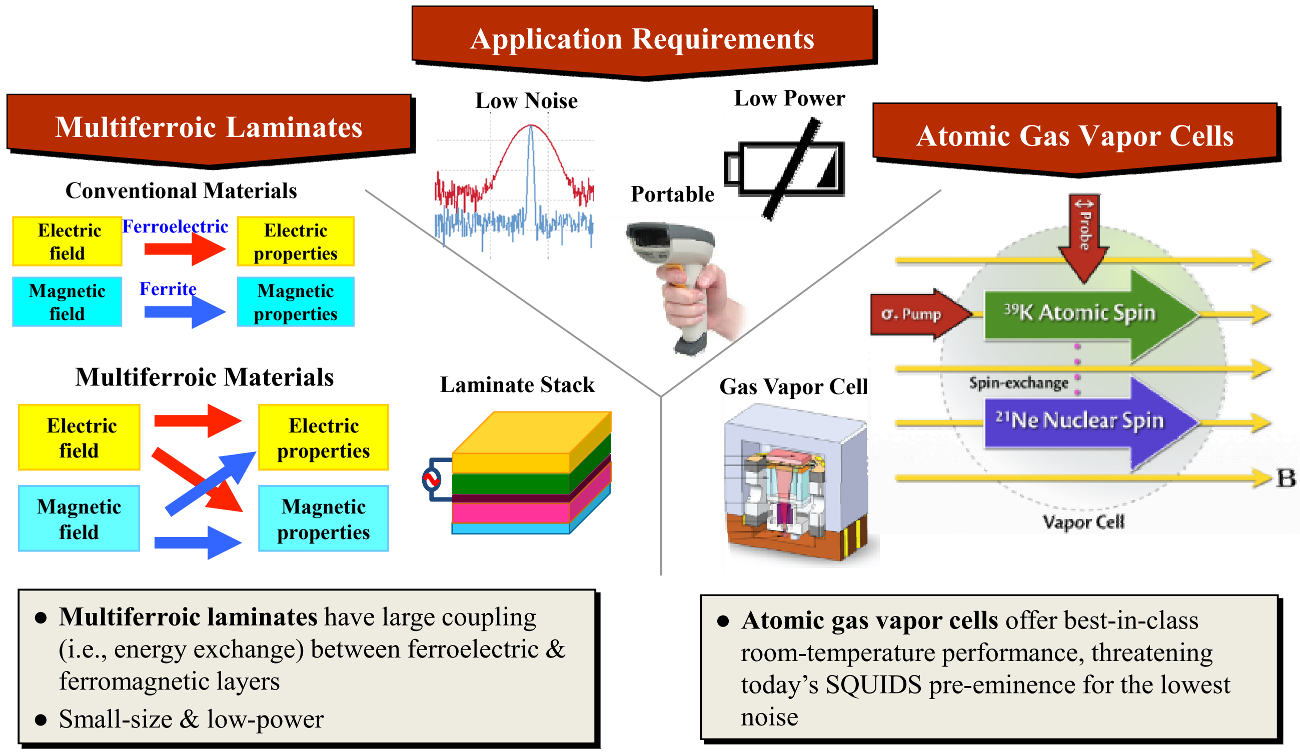

Figure 1. Major HUMS technologies and user application requirements.

2. PROGRAM OBJECTIVES AND CHALLENGES

Advances in magnetic sensor technologies are critical to reducing urban threats. Table I gives a comparison of popular magnetic sensors used today. Superconducting quantum interference devices (SQUIDs) are well-suited for the task, but require cryocooling and consume significant power. When used as a laminate/composite, multiferroic materials exhibit high magnetic field sensitivity. Similarly, gas vapor cells have been steadily progressing towards SQUID sensitivity. Both technologies have the potential to deliver a new generation of magnetic sensors that approach the performance of a SQUID while operating at room temperature. The HUMS program has several objectives: to field sensors with 10X better performance than state-of-the-art SQUIDs; room temperature operation (no cryogenic cooling needed); and reproducible, reliable manufacturing methods.

Technology	Detectable Field Range (Tesla) 10^{-16} 10^{-12} 10^{-8} 10^{-4} 10^{0}	Power Consumption	Frequency bandwidth	FOM*** (smaller is better!)
SQUID*		>1 W	>10^{-3}Hz	$2x10^{-15}$
Atomic Magnetometer		**50mW/head**	**10^{-3}Hz**	**$3x10^{-20}$**
Multiferroic Laminate**	R Broadband	**<1 μW, passive**	**>10^{-3}Hz**	**N/A below 100Hz**
Search Coil		<1 μW, passive	>100Hz	100Hz
Flux Gate		>100 μW	>10^{-2}Hz	$3x10^{-18}$
GMR		>100 μW	>10^{-2}Hz	$3x10^{-16}$
Hall-effect		>100 μW	>10^{-1}Hz	$3x10^{-15}$

*Notes: * SQUID temperature of 5K or 77K; ** R = resonant*
****** FOM = (Sensitivity limit) x (Power consumption) / (Temperature); FOM Units = Tesla-W/K-Hz1/2*

Table I. HUMS goals in relation to other magnetic field sensor technologies.

With this in mind, the HUMS program has three technical goals. The first is to demonstrate a magnetic sensor with a field sensitivity of 0.1pT/√Hz. This sensitivity is measured by a single sensor at an operating frequency of 1Hertz. The second goal is a 3x3 array of sensors should produce a 1pT/√Hz noise floor at 1Hz when the nine sensors are operated together. Manufacturing is important to fielding a useful system. Thus, the third goal is that manufacturing of the sensors should have >50% yield in lot sizes of 10 sensors, with a lot variability of <10%. There is at present no magnetic sensors that can fulfill these requirements. Successfully achieving these goals will result in passive sensors with milli-watt power consumption and a small form factor (<1 cubic centimeter) to enable portable, battery-powered magnetic field sensors.

Regarding multiferroic materials, the primary technical challenge is to reduce the noise factor while at the same time amplifying the magnetic-to-electric or magnetoelectric (ME) coefficient by orders of magnitude (see the top of Figure 2). It has been shown that dramatically enhanced magnetoelectric coupling coefficients in composites of magnetostrictive and piezoelectric layers arise due to elastic coupling (e.g., strain) between magnetostrictive and piezoelectric layers. When a magnetic field is applied from the bottom, a strain is induced in the ferromagnetic layer and transferred to the piezoelectric layer via elastic bonding. This generates an electric field across the piezoelectric layer due to piezoelectricity. Arriving at the most efficient heterostructural layer design becomes the challenge.

Most research in high-sensitivity magnetic sensors to-date has centered on developing vapor-phase magnetometers. For instance, the spin exchange relaxation-free (SERF) magnetometer is a type of vapor-phase magnetometer developed by Princeton University resesearchers. SERF magnetometers measure magnetic fields by using lasers to detect the interaction between atoms in a vapor and the magnetic field (see the bottom of Figure 2). Fiber optics detect changes in the magnetic polarization of the alkali metal vapor inside the cell.

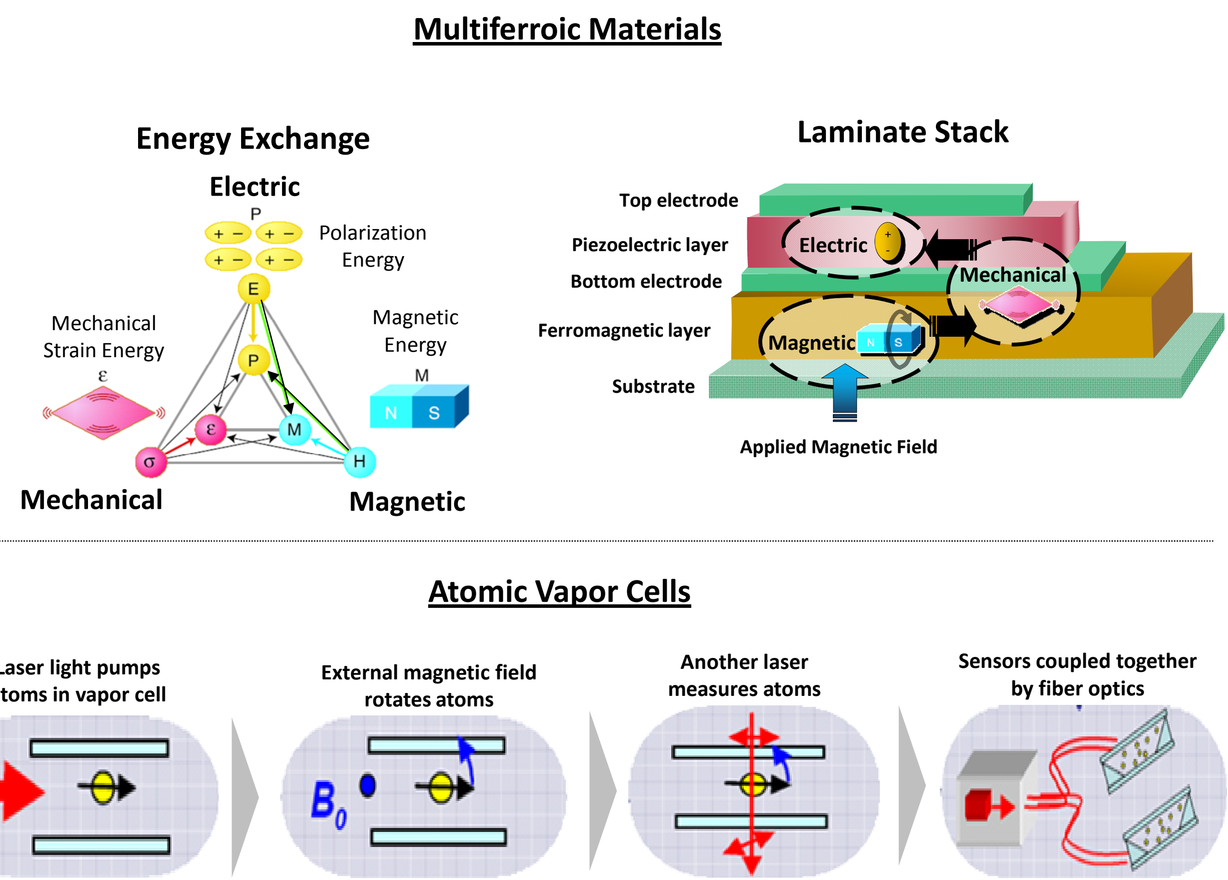

Figure 2. Theory of operation for multiferroic materials and atomic vapor cells.

3. PROGRAM TECHNOLOGIES AND ACHIEVEMENTS

As mentioned, two technological approaches are being pursued to develop highly-sensitive magnetic field sensors. A total of four teams are participating in the HUMS program, two in each technology (see Figure 3).

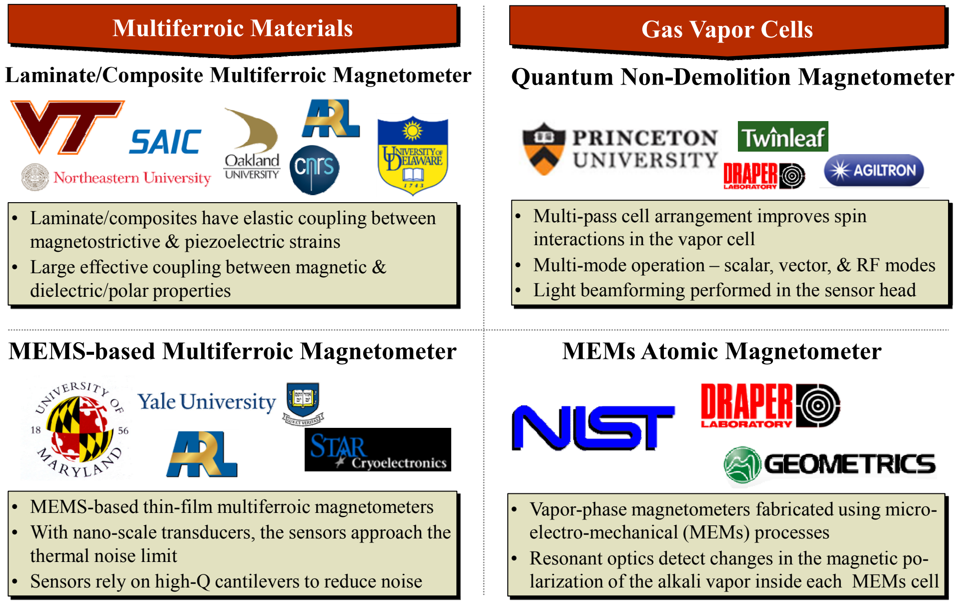

Figure 3. HUMS teams and their technological approaches.

3.1 Multiferroic Materials

Laminating magnetostrictive and piezoelectric materials together allows them to convert magnetic energy to electrical energy via a mechanical strain. By connecting a charge amplifier to the laminated stack, a magnetic field sensor results with unprecedented size, weight and power (SWaP). This enables a wide range of small, long-life, sensitive vector and gradiometer sensors. Defense applications include unmanned platforms, obscured target detection, unattended ground sensors (UGS) for vehicles, and personnel weapons detection for perimeter intrusion. The short detection range and high cost of today's sensors has made persistent and ubiquitous monitoring uneconomical. In addition to defense applications, a number of industrial and consumer products are also conceivable, such as traffic monitoring and security portals for baggage, parcel, vehicle, and people screening. In any case, there have been four challenges to implementing highly-sensitive magnetic sensors. One has been packaging the sensors to make them insensitive to external vibration. Another has been integrating the sensitive sensors with conventional electronics (e.g., charge amplifiers and signal conditioning circuits). To make the unit portable, it becomes necessary to integrate the field sensors alongside conventional electronics. The sensors must be isolated from the magnetic fields produced by the electronics. The third has been automated assembly (e.g., registration, lamination, curing, and testing). Fourthly has been the fabrication of materials with high Q in a favorable form factor.

3.2 Laminate/Composite Multiferroic Magnetometer – Virginia Tech Team

The Virginia Tech team uses laminated layers of magnetostrictive and piezoelectric materials to couple detected magnetic energy into electric energy via piezoelectric coupling. The goal is to build magnetometers with unprecedented low power, small size and sensitivity, deploying battery-powered sensors with micro-watt power consumption and a small form factor (e.g., volume of less than 1 cubic centimeters).

Drawing on their experience in multiferroic materials, Viginia Tech has led the investigation of several types of multiferroic laminates, experimenting with trilayers and asymmetric bending mode structures using Metglas/piezo-fiber. It also developed textured fibers made of Lead Magnesium Niobate-Lead Titanate (PMN-PT), a piezoelectric material. Similarly fielding a strong team in multiferroic materials research, Oakland University has investigated the combination of Permendur with Lead Zirconate Titanate (PZT). The GREYC (Research Group in Informatics, Image, Control and Instrumentation) Electronic group at CNRS-Caen has established a magnetic sensor test facility capable of characterizing magnetic sensors at low frequency (<0.1Hz) and low noise levels. GREYC brings their know-how in noise reduction techniques, in particular leveraging GREYC's 6-layer magnetic shielding room. The room's intrinsic noise room level was evaluated to be lower than SQUID sensitivity, essential for low intrinsic magnetic sensor noise measurements such as these. Next-generation low-noise op-amp detection methodologies were developed by team member Science Applications International Corp. (SAIC), with contributions on novel electronic modulation approaches by Northeastern University and flux concentrator developments from the Army Research Laboratory (ARL).

Virginia Tech's laminate development specifically focuses on layers of metglas/PZT-fiber/metglas [1]. The goal is to find the right mix of laminates delivering the lowest noise. This was obtained by reducing the loss tangent (tanδ) and electrical resistance of the materials in the stack. For instance, a loss tangent of tanδ=0.008 and a measured noise floor of 4 pT/√Hz at 1 Hz was obtained from a single layer of PMN-PT. Stacking multiple layers of PMN-PT yielded 2pT/√Hz. Applying additional noise-reduction methods such as flux concentrators and signal modulation is expected to further improve the noise performance. The Virginia Tech team has also used textured piezoelectric ceramics to improve the energy exchange efficiency of the sensor. Northeastern University demonstrated noise floor reduction by a factor of 3 using specific modulation techniques. In addition, noise statistics of the sensor's performance was calculated by the University of Delaware. These calculations served to further lower the noise floor of the measurements by applying statistical tools to de-embed the noise power fluctuations.

Measuring best-in-class field sensors requires a test system that performs better than the sensors themselves. CNRS-Caen approached the challenge in a segmented manner to quantify and de-embed specific sources of noise (the major sources are materials, control circuit electronics, and test system). All tests were conducted in a shielded room far from urban magnetic noise and under specific sensor operating conditions. The first step was to calibrate the test system using reference sources. The second step was to test the magnetometer with and without an electronic feedback loop. From there, a table of magnetometer measurements was built that fully characterized the magnetometer's performance. The sensor was measured both in a homogeneous magnetic field measurement (e.g., using a Helmholtz coil) and in an inhomogeneous magnetic field measurement. This gave the sensor's complete performance from which noise spectral density plots could be made.

The Army Research Laboratory has designed flux concentrators to shift the stack's operating frequency from 1 Hertz to a kilohertz frequency, offering less noise (see Figure 4). The flux concentrator enhanced the sensor's performance by a factor of 10. The concentrator shifts the operating frequency by modulating the magnetic field with a tensile force applied via an external magnetic bias field. This shifts the operating frequency by stimulating an acoustic force that modulates the measured magnetic field to a higher frequency.

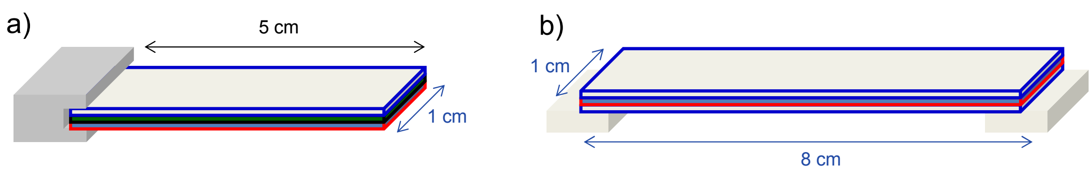

Figure 4. Two flux concentrator designs, (a) single-supported, and (b) double-supported.

Oakland University has contributed self-biased and symmetric magnetic field sensors [2]. Self-biased sensors operate without the need for an applied magnetic bias. The sensors are symmetric, one-dimensional arrays of Permendur-PZT-Permendur. The self-biasing is achieved by carefully grading the layers through adding nickel and metglas. Depending on the amount of grading, sensitivities of 25-100 pT/√Hz at 1 Hertz were demonstrated.

In summary, the Virginia Tech team has made significant advancements towards the goal of achieving enhanced sensitivity and reduced noise floors, including demonstration of magneto-electric (ME) laminates of Mn-doped PMN-PT single crystal fibers with Metglas, to achieve noise floors of 6-7pT/Hz√ at 1 Hertz. The team has developed a lamination process that produces eight sensors at a time with a yield of more then 50%. These have been used to build a 2x2 sensor array used in actual field testing.

3.3 MEMs-based Multiferroic Magnetometer – University of Maryland (U-MD) Team

Leading this team is the University of Maryland (U-MD), contributing its expertise in functional thin-film materials, combinatorial synthesis and characterization. The HUMS program builds on U-MD's past research in novel multilayered thin-film devices and combines it with Yale University's device and circuit nanofabrication, transducer development and integration expertise. Yale had performed extensive research in MEMs/NEMs, spintronics, nanophotonics, and optomechanics. Industrial contributor STAR Cryoelectronics uses its 30 years of experience developing SQUID-based magnetometers and low-temperature electronics to package the array of MEMs/NEMs-based multiferroic magnetic field sensors into a fieldable system.

The U-MD team's approach relies on using MEMs/NEMs devices as sensors to detect atto-meter displacement of cantilever transducers. An array of multiferroic magnetometer sensors was fabricated, with each sensor feeding either a thin-film PZT/FeGa piezoelectric cantilever or an optical signal read-out. In general, the materials research sought to investigate the limits of multiferroic/magnetostrictive thin-film magnetic field sensors using materials and devices designed for high-Q signal amplification at resonance and natural cooling at other frequencies. The sensor's design relies on a multiferroic magentostrictive layer to convert a detected magnetic field signal into a mechanical deflection which is then read out with high sensitivity using a nanoscale mechanical device. The readout was built from piezoelectric material Lead-Zirconate-Titanate (PZT). A large array of cantilevers and signal-averaging circuit served to reduce thermodynamics-related noise.

The cantilever design had two approaches. One was a piezoelectric cantilever made of a bilayer piezoresistive material stack. The top layer was made of Iron Gallium, FeGa (i.e., the magnetostrictive layer) covered by Silicon Nitride, SiN (i.e., the structural layer) [3]. The FeGa layer is magnetostrictive and actuates the cantilever. The high-stress silicon nitride has a high mechanical quality factor or Q. A high mechanical Q weakly couples to the enviroment and allows an uncooled sensor to receive a magnetic field. Using a stress concentrator improves the stress sensitivity to a magnetic field. During experiments, an external magnetic field was applied in different directions and the device's response measured. Both torque effect and magnetostrictive effect exhibited magnetic field sensitivity, but the magnetostriction effect was stronger. As the external magnetic field increases, the cantilever beam stretches and its resonant frequency increases. The result is that the tighter the frequency span of the applied field, the higher the magnetic field sensitivity of the cantilever. By adding a phase-locked loop to monitor the resonant frequency, 10^{-9} fractional frequency resolution was demonstrated. This corresponds to a field sensitivity of 40pT. While the piezoresistive device in the first approach showed good sensitivity, an optical transducer offers even better magnetic field sensing. The second cantilever approach was to build an optical device made of a bilayer of $CoFe_2O$ (i.e., the magnetostrictive layer) and SiN (i.e., the structural layer) [4]. The metal magnetostrictive layer was replaced with a transparent magnetostrictive layer to build an integrated optics readout that would achieve high sensitivity. The magnetic insulator was Cobalt Ferrite which has a magnetostriction coefficient approximately five times larger than FeGa, one of the highest to be found in thin-film materials. An important issue when fabricating piezoelectric cantilevers is optimizing the film stress in the hetero structural stack. One of the lessons learned has been that proper cantilever design should focus on the thickness of the first and last layers of silicon oxide. Alternating layers evenly distributes the stress in the stack and enables a planar cantilever structure.

To summarize, the U-MD team has thus far developed a set of MEMs/NEMs-based multiferroic field sensors that have shown a 4-5X improvement in the magnetostriction of quenched CoFe thin films. This has resulted in piezoelectric/magnetostrictive (PZT/FeGa) cantilevers with 40 pT at 600 Hz. Improving the performance at 1 Hertz will require adoption of new modulation schemes and employing a large array of sensors that significantly reduce the 1/f noise. Experimental work is on-going for an integrated photonic read-out, specifically, an interferometer with transparent magnetostrictive $CoFe_2O_4$, which should give an estimated ultimate dc field sensitivity of 20 fT. Separate experiments using piezoresistive FeGa cantilevers have indicated a sensitivity of approximately 20 pT at 20 KHz.

3.4 Atomic Gas Vapor Cells

During atomic magnetometer operation, alkali atoms precess in a magnetic field at a frequency and angle that can be optically measured. Held as a vapor in a small vacuum cell, atoms are polarized via an optical beam (e.g., laser). These polarized atoms precess at a measurable orientation when a magnetic field is applied. Using circularly-polarized light, the spin orientation can be accurately detected and measured, thereby using the orientation angle as a means to measure the strength of the applied magnetic field. Atomic magnetometers have well-known sensitivity limits. The sensitivity of the measurement is determined by the density of the alkali atoms, the volume of the cell, the optical probing technique, and the magnetic field gradients themselves. The measurement noise floor is determined by the atomic spin projection noise, the photon shot noise, and the laser's noise. The HUMS program required a signal-to-noise ratio of ~ 108 at one second to achieve a measurement sensitivity of 0.1 fT/√Hz.

Using novel designs, microfabrication techniques, and parallel cell manufacturing of an array of fT/√Hz, sub-milliliter-sized cells, the HUMS program has sought to dramatically improve the state of the art in atomic magnetometers. Encapsulation of alkali atoms in microfabricated vapor cells allows for a high degree of miniaturization and the potential for low-cost manufacturing. If sub-millimeter cell dimensions can be proven, then large-scale manufacturing at low cost will be possible.

3.5 Quantum Non-Demolition (QND) Magnetometer – Princeton team

SERF magnetometers are among the most sensitive magnetic field sensors in the world and in some cases exceed the performance of SQUID detectors of equivalent size. Originally developed at Princeton University, spin exchange relaxation-free (SERF) magnetometers use lasers to detect the interactions between alkali metal atoms held in a vapor during an applied magnetic field. The SERF approach achieves high magnetic-field sensitivity by monitoring the density of alkali metal atoms as they precess in a small, nearly-zero magnetic field. The technique improves upon traditional atomic magnetometers by eliminating the main cause of atomic spin decoherence – spin-exchange collisions among the alkali metal atoms themselves.

The Princeton University team has focused on improving sensitivity in three ways. The first is by using a Quantum-Non-Demolition (QND) approach. This technique has been shown to overcome sensitivity normally limited by quantum mechanical fluctuations. The second way is using multi-pass atomic vapor cells with integral mirrors. Increasing the path length of the laser beam through the atomic vapor can dramatically improve the signal strength. The third way is multi-mode operation of atomic magnetometers. Operating at different modes means that scalar and vector measurements of magnetic fields are possible using the same sensor. Princeton has previously demonstrated a scalar atomic magnetometer with improved sensitivity leveraging these three techniques. Along with Princeton, industrial partner Agiltron Inc. has developed the multi-pass cells and associated sensor electronics. Sensor maker Twinleaf fabricated and tested the cells in pulsed-mode operation. Draper Laboratories contributed the data acquisition and system control as well as application modeling. Thus far for the HUMS program, Princeton University has completed a first-generation sensor with noise of 50 fT/√Hz at 1 Hertz. The team has also completed construction of a second-generation sensor and has prepared for mass production to meet manufacturing and sensor array objectives.

The Princeton team's approach involves hybrid optical pumping to solve the problem of strong pump light absorption [5], [6]. This was done by separately optimizing pump and probe beam parameters, reducing the pressure of the buffer gas and increasing the optical rotation signal, and using pump and probe lasers at different frequencies so that both can be sent along the same fiber. Many commonly-available distributed-feedback diode (DFB) lasers are not reliable and have a short lifetime. Better to use are distributed Bragg reflector (DBR) lasers which have less intensity and wavelength noise than DFB lasers and are less susceptible to optical feedback. In general, each sensor is self-contained and magnetically quiet, with up to 64 channels and 12 sensor heads capable of reaching 0.1 fT/√Hz sensitivity. Assembled by Agiltron, the system has been tested at Princeton's laboratory. Noise cancellation achieved a noise floor of 15 fT/√Hz. Also, performance was measured at 100 fT/√Hz at 1 Hertz. Challenges to further improvement have included pump laser noise and pump-probe misalignment. When these were addressed, probe noise was further reduced down to 3 fT/√Hz. Decreasing the pump power further reduces the pump laser noise. Also, optimizing the temperature (~140°C) and testing in a ferrite magnetic shield resulted in the optimum sensor performance thus far (see Figure 5). A sensitivity of at least 5 fT/√Hz at 10 Hertz is sufficient to perform magnetoencephalography (MEG) studies. The sensor in its current configuration exhibits a number of limitations. For instance, the pump-to-probe beam alignment is sensitive to placement. When scanning the pump laser power up and down and with constant magnetic field modulation, the signal should remain flat when the beam is properly aligned. To address this, an improved alignment procedure is currently underway.

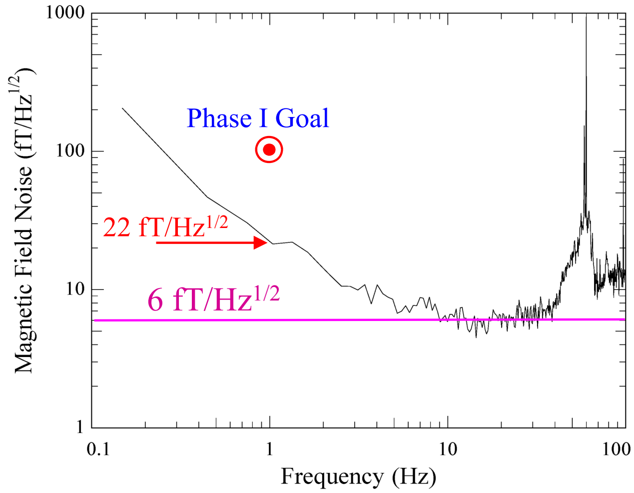

Figure 5. Quantum non-demolition (QND) magnetometer measured performance.

The Princeton team's approach leverages multi-pass cells in order to increase the optical path of the probe beam. The most common way of increasing path length is to use a resonant cavity. However, resonant cavities have many drawbacks. They have small mode volume, require a laser frequency lock with mode matching and coupling matching, and are sensitive to vibrations. In contrast, multi-pass cells increase the path length without many of these drawbacks. They are tolerant to misalignment, have a large interaction volume, and 100% power coupling. To fabricate the multi-pass cells, mirrors were pre-aligned and held together with alkali-resistant glue inside a glass cell as a multi-pass cavity with up to 160 passes. The multi-pass cell performs optical rotations of over 100 radians with multiple wrap-arounds of light polarization. This allows precise determination of precession zero-crossing time. Measurements were also made with a two-cavity cell containing two independent magnetometers in the same cell. This allows cancellation of current source noise and other ambient noise. Measurements showed sensitivity gains due to a large cancellation of common-mode noise.

In summary, the Princeton team has developed highly-sensitive, multi-pass atomic SERF vapor cell technology, thus far demonstrating an array of SERF magnetometers with a sensitivity of 22 fT/√Hz at 1 Hz and 5 fT/√Hz at 10 Hz. During the course of development, the team has established feasibility for economical commercial production of femto Tesla-level atomic magnetometers. The demonstrated sensitivity of <10 fT/√Hz exceeds current state-of-the art performance. These sensors are well-poised for applications such as radio-frequency (RF) detectors, gyroscopes, and magneto-encephalography (MEG) (see Figure 6). For instance, MEG with fiber-coupled atomic magnetometers can replace much larger cells that use fiber-coupled sensor arrays. This would offer a flexible sensor configuration adjustable to any head size and measure radial magnetic fields. HUMS vapor cells could also be integrated into a versatile atomic sensor platform. It is conceivable to scale down today's lab-sized apparatus to dime-sized sensor containing all the features of a state-of-the art magnetometer: miniaturized orthogonal pump and probe beams, and polarization sensing with modulation, with no loss in sensitivity.

	**Scalar Magnetometer**	**Vector Magnetometer**	**Tunable RF Detector**	**Nuclear Magnetic Resonance (NMR) Gyroscope**
Advantages	Insensitive to orientation & vibrational noise	Acts as a 3-axis SERF detector	Electronically tunable from Hertz to MHz	Two-spin species cancel out magnetic field noise
Applications	Calibrator with frequency resolution of 10^{-12}	Five-component vector gradient measurements	Explosives detection via nuclear quadropole resonance (NQR)	Smaller than fiber-optic gyros

Figure 6. Potential applications of quantum non-demolition (QND) magnetometers.

3.6 MEMs Atomic Magnetometer – NIST team

NIST has a history of leadership in atomic physics and advanced magnetometry. Leveraging its experience in chip-scale atomic clocks, the NIST approach combines micro-electro-mechanical systems (MEMs), atomic spectroscopy and advanced laser technologies into a sensor device. Team member Draper Laboratories brings expertise in MEMs, fiber optics and reliable manufacturing. Industrial partner Geometrics, Inc. has proven experience in sensor electronics and has successfully transferred advanced magnetometer technology to the commercial market.

The NIST team has developed a sensor system based on an array of compact, low-power atomic magnetometers fabricated using micro-electromechanical systems (MEMs) techniques [7]. MEMs is not used to micro-fabricate components such as switches or capacitors, but rather is used to micro-fabricate and encapsulate the sensor. Atomic (or optical) magnetometers are based on polarized atoms in the vapor phase which change their orientation in response to a magnetic field. The reorientation of the atoms is monitored using a resonant optical field. The use of atoms in the vapor phase allows for long coherence times and correspondingly high sensitivity. The use of MEMS micromachining allows for small size, low power dissipation and the possibility of mass parallel fabrication. The NIST system was designed with a number of performance goals in mind: small-size sensors (e.g., a volume of 10 cm^3); low power consumption per sensor (e.g., <50 mW); highly sensitive sensors (e.g., 0.1 fT/√Hz) when measured in a low-field, shielded environment; operation in the earth's magnetic field with nulling coils; suitability for array-based fabrication and low-cost manufacturing; and scalable array sizes from small numbers (< 10 sensors) to large numbers (>100 sensors). To meet these goals, the NIST system addressed the challenges via three innovations. The first was to operate the atomic magnetometer in the spin-exchange relaxation-free (SERF) regime where spin-exchange collisions are suppressed at low magnetic fields. This allows for very narrow magnetic resonance line widths to be generated with correspondingly high sensitivity to magnetic fields. The second innovation was to use micro fabricated alkali vapor cells, which allowed for large numbers of sensors to be fabricated using the same process sequence. The third innovation was the use of MEMs vacuum packaging for reduced power dissipation. The driving technical challenges were spurious magnetic fields generated by the sensor itself and the limited dynamic range of SERF magnetometers. This was tackled by transmitting the laser light from a single control box using fiber optics connected to each cell. This isolates magnetic-field-generating elements by locating them far from the sensors.

To accomplish these innovations and make a MEMs magnetometer with ground-breaking sensitivity, the NIST team followed a program plan consisting of five elements. The first was to improve field sensitivity by quantifying the basic factors limiting the sensitivity of chip-scale atomic magnetometers. To do this, the NIST team performed an initial set of experiments on first-run micro fabricated vapor cells to determine the optimum cell geometry. These experiments found that cells accepting a single laser beam were simple to build yet were less sensitive to detecting magnetic fields. Detection was on the order of 10 fT/√Hz. Two-laser-beam geometries, while more complex to implement, yielded better sensitivity, on the order of sub-fT/√Hz. The second element of the program plan involved sensor head fabrication. The team designed new sensor heads combining high performance sensitivity with low operating power and low production cost. This resulted in a suspended, thermally-isolated MEMs vapor cell. The third element was array fabrication. The team investigated numerous approaches to large-scale manufacturing of magnetometer sub-systems and found that the key sub-systems driving fabrication were the thermally-isolated vapor cells and the optics assembly. The fourth element was the electronic control system. Scalable optical and electronic subsystems (laser, optics, isolators, fiber optics, detection and processing electronics) can drive large numbers of sensor heads. The design emphasis was on portability and miniaturization. The fifth element of the program was the magnetic shield used for sensor testing. NIST constructed and tested a high-performance, magnetically-shielded chamber capable of measuring 0.1 fT/√Hz. To achieve this sensitivity, the chamber employed high-permeability shielding and an inner ferrite layer. Thermal noise from electron motion in metals was carefully quantified and de-embedded from the measurement (see Figure 7).

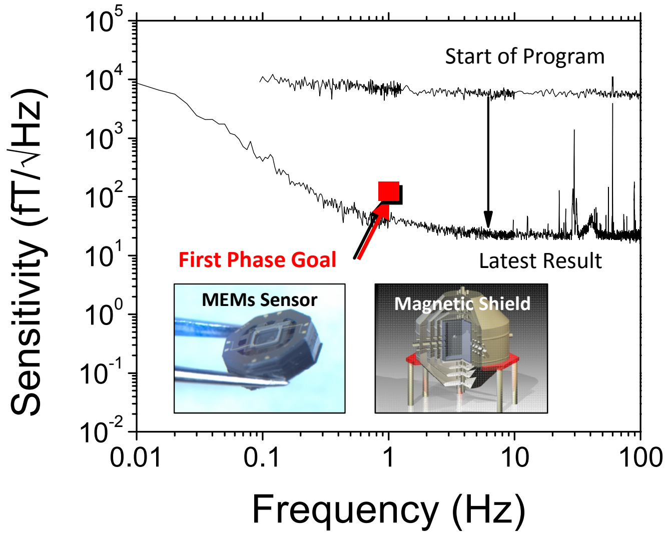

Figure 7. MEMs atomic magnetometer measured performance. Also shown are a MEMs sensor head and the magnetic shield testing chamber.

In summary, NIST has successfully assembled a set of atomic gas cells based on chip-scale atomic magnetometers. The magnetometers, made of micro fabricated Cesium cells on a thermal isolation suspension, have demonstrated advantages of small size, wafer-scale fabrication, and a planar structure.

4. SUMMARY

The HUMS program is developing magnetic field sensors with unparalleled small size and performance (resolution and range) for ground-penetrating and wall-penetrating imaging and expects to make a major impact on defense and national security. Each team of the HUMS program has demonstrated progress towards meeting the objectives of order-of-magnitude better performance than state-of-the-art SQUIDs, room temperature operation, and reliable manufacturing methods. The program has developed manufacturing capabilities in combination with functional state-of-the-art uncooled magnetic field sensors. This will enable HUMS technology to be more easily adopted by magnetometer makers who can quickly deliver HUMS devices to the field.

5. ACKNOWLEDGEMENTS

The author would like to thank the US Government technical team for their outstanding support, specifically Dr. Kent Averett (Kent.Averett@wpafb.af.mil) and Mr. John Blevins (John.Blevins@wpafb.af.mil) of the Air Force Research Laboratory, Dr. Daniel Green (daniel.s.green1@navy.mil) of the Office of Naval Research.

REFERENCES

[1] J. Petrie, D. Viehland, D. Gray, S. Mandal, G. Sreenivasulu, G. Srinivasan, A. S. Edelstein, “Enhancing the sensitivity of magnetoelectric sensors by increasing the operating frequency.” Appl. Phys. Lett. 110, 124506 (2011).

[2] G. Sreenivasulua, S. K. Mandala, V. M. Petrovab, A. Mukundana, S. Rengesha, G. Srinivasana, “Bending resonance in a agnetostrictive-piezoelectric bilayer and magnetoelectric interactions.” Int. Ferroelec. 126, 575010 (2011).

[3] H. Bhaskaran, M Li, D. Garcia-Sanchez, P. Zhao, I. Takeuchi, H. Tang, “Active microcantilevers based on piezoresistive ferromagnetic thin films.” Appl. Phys. Lett. 98, 013502 (2011).

[4] M. Li, W.P.H. Pernice, H. X. Tang, “Ultrahigh-frequency nano-optomechanical resonators in slot waveguide ring cavities.” Appl. Phys. Lett. 97, 183110 (2010).

[5] H. B. Dang, A. C. Maloof, and M. V. Romalis. “Ultrahigh sensitivity magnetic field and magnetization measurements with an atomic magnetometer.” Appl. Phys. Lett. 97, 151110 (2010).

[6] M. V. Romalis, “Hybrid optical pumping of optically dense alkali-metal vapor without quenching gas.” Phys. Rev. Lett. 105, 243001 (2010).

[7] R. R. Mhaskar, S. Knappe, J. Kitching, “Low-frequency characterization of MEMS-based portable atomic magnetometer,” IEEE Int’l Freq. Control Symp., 11488159 (2010).