Magnetic Sensors Project

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LONG-TERM GOALS

Clandestine mine reconnaissance is one of the Navy's highest MCM priorities. During the early 1990's, a helium-cooled superconducting gradiometer was demonstrated in the Magnetic and Acoustic Detection of Mines (MADOM) ATD to provide effective detection and classification, especially against buried mines, and to reduce acoustic false alarms significantly [1], [2]. This sensor utilized the low critical temperature (low Tc) superconductor niobium and required liquid helium for sensor cooling. Advanced approaches are being developed to transition this technology to the Fleet.

OBJECTIVES

The current focus of this project is to develop an advanced High Tc Superconducting Gradiometer (HTSG) prototype cooled by liquid nitrogen and to demonstrate it at sea. *This development will make it possible to provide localization and classification capabilities inconceivable using current Fleet magnetometers such as the ASQ-81/208 and to achieve the longer detection ranges previously reserved to low-Tc sensors.* In comparison to its low Tc counterpart, the HTSG can provide substantially reduced package sizes and minimal cryogen support requirements.

APPROACH

The technical approach for this project involves: (1) sensor development, (2) sensor evaluation in land-based motion studies simulating tow operation, and (3) sensor at-sea testing. In FY 1999, the work focused on evaluation and performance improvement of the HTSG prototype in motion. Final upgrade of the sensor to a field-deployable unit and a test at sea will be conducted in FY 2000.

WORK COMPLETED

Exploratory Research and Concept Development: In order to circumvent the current limitations in high-T_c fabrication technology, a HTSG sensor approach is being pursued which features the three-sensor gradiometer (TSG) concept [3]. Designs of nitrogen cooling units have been established and analyzed in order to provide a range of concepts appropriate for different missions [1]. A compact design with a 12" diameter and a 12" length consistent with desired performance is now being considered as feasible. Approaches are being developed to effectively eliminate a cryogen logistics trail. In one concept the sensor would be replenished from a small liquid nitrogen storage dewar housed onboard ship that is cryocooler-assisted in order to maintain a 6-month cryogen supply. Closed-cycle refrigeration is also becoming a more realistic possibility for this technology.

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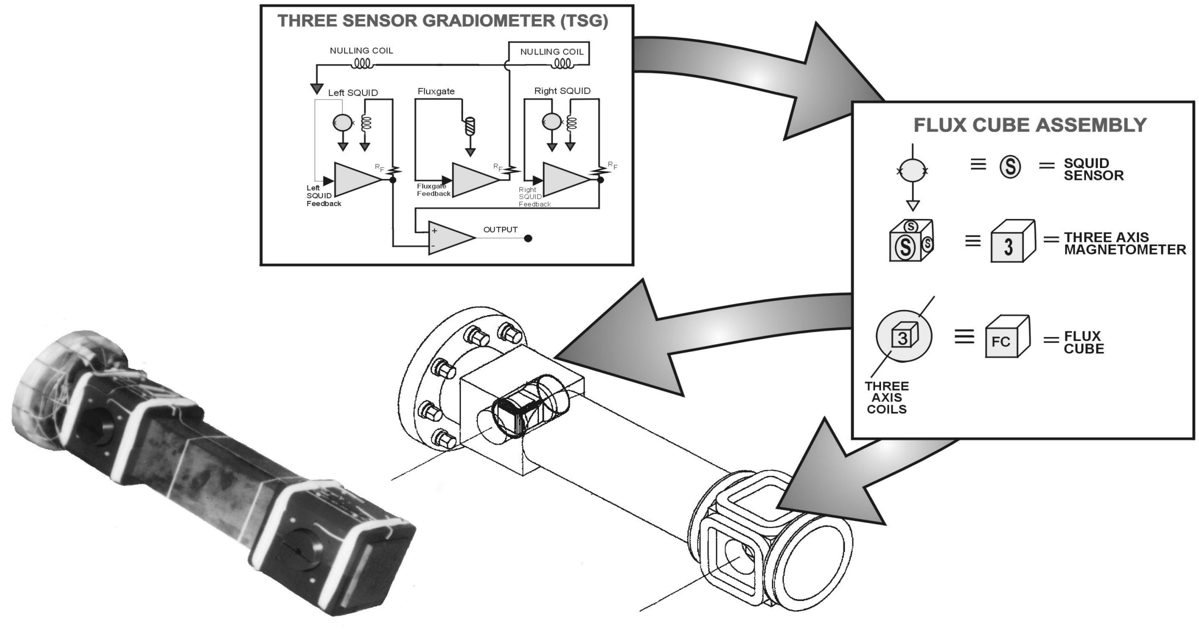

Figure 1. Concept of three-sensor gradiometer implemented in the high Tc superconducting gradiometer under development and photograph of prototype under evaluation.

HTSG Sensor Development: The feasibility prototype for a nitrogen-cooled HTSG has been developed by a team from the Coastal Systems Station, IBM, Quantum Magnetics, and Lockheed Martin and is currently being evaluated [4]. The HTSG prototype consists of cryogenic electronics, room temperature electronics and a dewar. This prototype has 6 SQUID-magnetometer channels configured to generate 3 independent tensor gradient components. 16-MHz Flux-Locked Loop (FLL) electronics have been developed to provide large bandwidth for electromagnetic interference immunity not possible using current commercial electronics [5]. Field-control electronics have been developed and tested to maintain constant field at the SQUID magnetometers. The field control is essential to provide the resolution and dynamic range required in the magnetometer subtraction and to minimize SQUID noise attributed to flux motion. A stringent design not to deteriorate the performance of the SQUID magnetometers has been validated through stationary and motion testing. A dewar, which was developed previously for high performance of low-Tc gradiometers cooled by liquid helium, is currently being used to cool the high-Tc electronics with liquid nitrogen and to evaluate sensor performance in motion.

Evaluation of the HTSG Superconducting Electronics Assembly: Testing of the HTSG using liquid nitrogen for cooling under both stationary and moving conditions has been completed at the CSS [4]. All major components of the sensor are functional and operating reliably and reproducibly. The HTSG has now demonstrated excellent performance in motion testing. Subsequent sensor upgrade to a field-deployable version and sea testing is planned in FY 2000.

RESULTS

Evaluation of the HTSG: HTSG performance stationary and in motion obtained from this sensor evaluation is summarized below [4]. *In totally unshielded field operation stationary,* a white noise floor of 0.5 pT/m-Hz$^{1/2}$ has been demonstrated (Fig. 2(a)). The corresponding magnetometer white noise in the field is 0.1 pT/Hz$^{1/2}$, essentially equal to the performance reported by the manufacturer under laboratory-controlled conditions. This sensor's performance stationary is better than the level attained typically by the helium-cooled gradiometer in sea testing. This spectrum at 0.1 Hz is 30 times better than the initial results obtained with the cryogenic electronics immersed directly in liquid nitrogen inside a metallic dewar. The following factors are significant in explaining this improvement: (1) operation in an exchange-gas environment in place of immersion in the cryogen, (2) field nulling to reduce thermally-activated motion of magnetic flux trapped in the superconducting material at cooldown, and (3) operation in a composite-material dewar to eliminate eddy currents that arose in earlier testing conducted inside a metal dewar from geomagnetic field fluctuations even in a stationary condition.

Excellent performance has now been demonstrated for this sensor in land-based motion testing. The sensitivity at 1 Hz is 5 pT/m-Hz$^{1/2}$, which corresponds to magnetometer noise of 1 pT/Hz$^{1/2}$ (Fig. 2(c)). This result represents performance better than that attained by any conventional non-superconducting technology identified and is approaching that of its helium-cooled counterpart. In fact, at frequencies above 3 Hertz, the sensitivity of the nitrogen-cooled sensor exceeds the performance of its helium-cooled counterpart as attained in sea testing (Fig. 2(d)). A 10-fold improvement in performance over results in initial testing was obtained. The challenge has been to obtain high resolution without aliasing in the signal condtioning electronics. The SQUID sensors, the FLL electronics and the dewar did not contribute to the noise issues encountered.

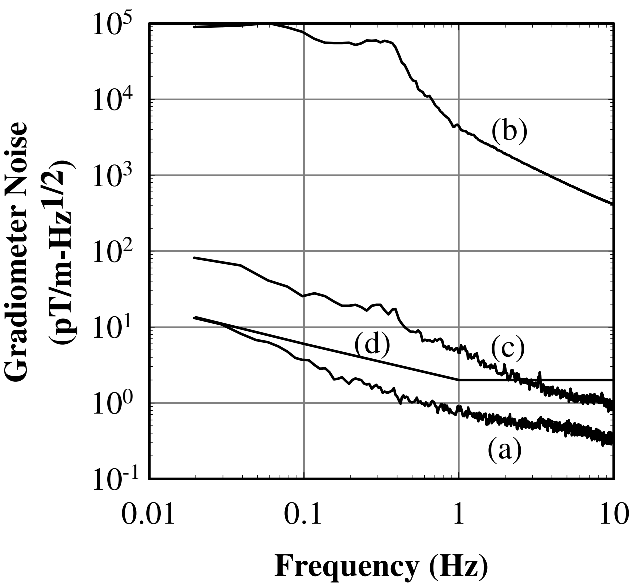

Figure 2. HTSG Spectra: (a) stationary, (b) uncompensated in motion, and (c) motion compensated. The performance of the low Tc gradiometer in sea testing is depicted in (d).

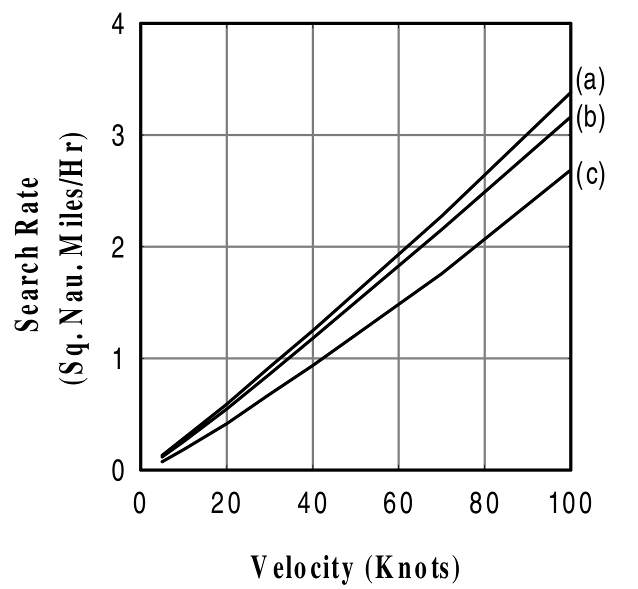

Figure 3. Nominal search rate as a function of velocity for a magnetic target with moment 60 A-m^2 for a vertical offset between sensor and target of (a) 20, (b) 40, and (c) 60 feet.

Assessment of Effective Performance: Unlike side scan sonars for which search rate is essentially independent of speed, search rate for a magnetic sensor increases with speed. Because the energy associated with target signals shifts to higher frequency as speed increases and HTSG sensitivity improves out to 10 Hertz, HTSG detection range increases with speed. In fact, a 20% increase in range can be realized at 30 knots over that at 5 knots. *Hence search rate increases at a rate better than linear as a function of speed, providing one means to accelerate mine reconnaissance missions.* Operation at 30 knots will provide search rates on the order of 1 sq. nmi/hr in very shallow water regions, an excellent capability for reconnaissance in that region.

Magnetic Classification: Magnitude of magnetic moment is the most basic classification parameter for magnetic sensing; i.e., to distinguish a magnetic contact as a target or clutter. This basic classification criterion can be improved using additional information of estimated target depth and statistical confidence. A technique using the vector information from target-moment predictions has recently been developed and demonstrated to improve classification capability. For the case in which the target magnetic moments are predominately induced (not permed), a criterion relating the scalar product

$$\frac{\vec{m} \cdot \vec{B}}{|\vec{m}| \cdot |\vec{B}|}$$

to clutter rejection ratio has been established. *A 70% reduction in the false alarm rate for magnetic targets was obtained using this criterion for data collected from a 1995 clutter survey [6].*

IMPACT/APPLICATIONS

The U.S. Navy has pioneered the 5-channel tensor-gradiometer approach to provide localization and classification capabilities inconceivable using current Fleet magnetometers such as the ASQ-81/208. The results from the MADOM ATD have provided proof of this enhanced capability. In FY 1999 the SGMS was the premiere sensor in an unscripted survey to locate unexploded ordnance in the Technology Demonstration of the Mobile Underwater Debris Survey System (MUDSS) [7]. It successfully detected buried targets and was effective in an environment that limited the performance of the acoustic and optic sensors utilized in the test.

We believe that a single nitrogen-cooled magnetic gradiometer can be flexibly integrated into various platforms in order to serve in a range of littoral warfare missions. Its capability in high speed operation meshes well with emerging interest in the use of high speed unmanned surface and aerial vehicles and the H-60 helicopter as one means to accelerate mine reconnaissance using magnetic sensors. This sensing capability is of particular value in the shallow water and very shallow water regions. It can also be applied to both mine and obstacle reconnaissance in the surf zone with search rates well beyond current capabilities. Airborne operations (using either unmanned aerial vehicles or the H-60) can also provide offboard sensing for ship self defense against near-surface mines and submarines. This sensing approach can also be applied to the military missions of nonacoustic ASW, the detection of underground facilities and hidden military targets, extremely low frequency communications, and torpedo homing. It can be utilized for dual-use applications of environmental cleanup, geophysical survey, police and rescue operations for the location of sunken or buried vehicles, archeology, treasure hunting, and civil engineering for the location of underground or undersea cables, pipelines, old foundations, buried gas tanks, and well heads.

The HTSG represents one of the major accomplishments in the area of high T_c superconducting electronics technology initiated a decade ago. The three-sensor gradiometer (TSG) concept has now been validated for high sensitivity operation in motion using high Tc SQUID technology [4] and using fluxgate technology for applications requiring less range [8]-[10]. *There is an excellent opportunity to commercialize TSG sensors in order to replace total-field magnetometers as the mainstay for magnetic anomaly detection in mobile applications.* Advanced flux-lock loop (FLL) electronics with a modulation frequency of 16 MHz, 30 to 100 times faster than conventional schemes, have been developed to improve cryogenic signal amplification and electromagnetic immunity essential for field operation [5]. The dewar technology has also been advanced for a number of applications requiring a high degree of thermal and magnetic stability in mobile operation. It provides the basis for the concept of a high performance, compact nitrogen-cooling unit for the HTSG.

Investments by this project have supported substantive refinement in high-T_c magnetic sensor technology. A number of high-Tc magnetic sensing circuits have been developed in conjunction with this project. This included a report of 0.026 $pT/Hz^{1/2}$ at 1 Hz for a 2x2-cm magnetometer, the magnetometers utilized in the HTSG prototype under development [1]. A 3-axis magnetometer prototype has been developed[11] and is now available as a commercial product from Tristan Technologies [11].

TRANSITIONS

One low-T_c sensor technology transitioned to the MADOM 6.3 Advanced Technology Demonstration in FY 1989 and to the Buried Mine Detector (BMD) 6.4 Program in FY 1992. Although the BMD Program is not currently funded, the HTSG developed in this project is available for transition to support reconnaissance operations, especially if a serious requirement for buried mine detection is established. The low-T_c technology has been successfully demonstrated in the FY 1995 Feasibility Demonstration of the Mobile Underwater Debris Survey System (MUDSS) and in the FY 1999 Technology Demonstration of MUDSS. Additional surveys at Fort Sheridan and Massachusetts Bay are currently under serious consideration. The nitrogen-cooled HTSG will be utilized in subsequent surveying for UXO cleanup and related applications. As mentioned previously, a 3-axis magnetometer prototype developed under this project is now commercially available from Tristan Technologies.

RELATED PROJECTS

This 6.2 exploratory development project has been supported by a contract to IBM Research sponsored by ONR 312 (Dr. D. van Vechten) and by CSS Internal Research to investigate noise mechanisms in high T_c SQUID magnetic sensors [12]. The Phase II SBIR to Conductus, Inc. sponsored by ONR 322 (Dr. J. Kravitz) has contributed directly to developments described in this report. The multi-channel tensor gradiometer approach initiated under this project is also being pursued for shorter-range, man-portable fluxgate gradiometers sponsored by ONR 322 (Dr. J. Kravitz) and the OSD SBIR program. The MUDSS Project sponsored by the Strategic Environmental R&D Program has provided the opportunity to demonstrate the capability of magnetic gradiometers for environmental cleanup, an application closely akin to mine reconnaissance.

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