Magnetic Sensors Project

Dr. Ted R. Clem
Code R22, Coastal Systems Station (CSS),
Dahlgren Division, Naval Surface Warfare Center,
Panama City, FL 32407-7001
Phone: (850) 234-4670 Fax: (850) 235-5462 Email: ClemTR@ncsc.navy.mil

Document Numbers: N0001401WX20286 and N0001401WX20843

LONG-TERM GOALS

Magnetic sensing can be used to enhance operations for mine hunting [1]-[3]. It is effective against totally buried ferrous targets since the magnetic signals generated by the target are neither attenuated nor distorted passing through the sea floor. Buried mine detection and significant reduction in false alarm rates were demonstrated in the Magnetic and Acoustic Detection of Mines (MADOM) Advanced Technology Demonstration using a 5-channel superconducting tensor gradiometer [1]. In the MADOM sea testing, more than 98% of the acoustically mine-like clutter was not magnetically mine-like. Requirements describing capability gaps for buried mine detection and false alarm reduction are documented in MNS-M042-85-93 (Mission Need Statement for Mine Countermeasures), MNS-M025-003-92 (Mission Need Statement for Shallow Water Mine Countermeasures), and OR 282-03-92 (Operation Requirements for Buried Mine Detector).

OBJECTIVES

Demonstrate a cryogen-free multi-channel magnetic sensor with the longer detection ranges, localization, and classification previously achieved by the 5-channel superconducting tensor gradiometer in MADOM. These localization and classification capabilities have not been achieved using conventional single-channel scalar magnetometers such as the USN ASQ-81/208. Demonstrate that this capability can extend into very shallow water and surf-zone regions, can provide search rates an order of magnitude greater than practical with UUV approaches, and can be effective against low ferrous targets.

APPROACH\WORK COMPLETED

A magnetic-sensing tow system for detection and localization of VSW/SZ mines was assembled and demonstrated [4]. The GEM Systems Model GSMP-2053, consisting of three highly sensitive total field magnetometers, was used as the primary sensor in this test. These magnetometers are high sensitivity scalar magnetometers based on the Zeeman effect for potassium vapor; i.e., the splitting of the potassium electron-spin spectral lines in a magnetic field [5].

The tow system, displayed in Fig. 1, consists of a sensor platform, a 7m Rigid Hull Inflatable Boat (RHIB) housing the magnetic sensors, towed 100 feet behind a second 11m RHIB. The 11m RHIB has two 350 hp diesel engines and water jet propulsors, capable of 40-knot operation (without heavy load or tow drag) into water depths as shallow as 5 feet. The 7m RHIB was selected as the towed sensor platform because it has a fiberglass hull and could be readily stripped of engines, steering

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2001**	2. REPORT TYPE	3. DATES COVERED **00-00-2001 to 00-00-2001**
4. TITLE AND SUBTITLE **Magnetic Sensors Project**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Code R22, Coastal Systems Station (CSS),,Dahlgren Division, Naval Surface Warfare Center,,Panama City,,FL, 32407**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S)
		11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Magnetic sensing can be used to enhance operations for mine hunting [1]-[3]. It is effective against totally buried ferrous targets since the magnetic signals generated by the target are neither attenuated nor distorted passing through the sea floor. Buried mine detection and significant reduction in false alarm rates were demonstrated in the Magnetic and Acoustic Detection of Mines (MADOM) Advanced Technology Demonstration using a 5-channel superconducting tensor gradiometer [1]. In the MADOM sea testing, more than 98% of the acoustically mine-like clutter was not magnetically mine-like. Requirements describing capability gaps for buried mine detection and false alarm reduction are documented in MNS-M042-85-93 (Mission Need Statement for Mine Countermeasures), MNS-M025-003-92 (Mission Need Statement for Shallow Water Mine Countermeasures), and OR 282-03-92 (Operation Requirements for Buried Mine Detector).

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a REPORT **unclassified**	b ABSTRACT **unclassified**	c THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

section, and other large magnetic fixtures to provide a low magnetic signature environment for sensor operation. More precise sensor positioning and hence more precise localization was obtained in this test than had been obtained in previous tests and surveys because a GPS station could be collocated with the sensor, which was not possible in MADOM because the sensors were operated in underwater vehicles.

A preliminary test was conducted to assess the suitability of this 7m RHIB as the towed sensor platform for this sea test. In this test, the 7m RHIB straightened out and began to handle well at speeds above 8 knots. It continued to handle well and to plane at higher speeds. The maximum speed obtained was 32 knots in 35' of water and 30 knots in 5-to-10' of water. Qualitatively the towed sensor platform appeared to provide a very stable platform for sensor operation, at least, in low sea states.

Both visual and magnetic surveys of the test area were conducted to select an area relatively free of magnetic clutter for the site of the target field. Five targets with magnetic moments ranging in magnitude from 0.1-to-10 A-m^2 were deployed in a straight line in water depths of 5 to 10 feet. Experiments were conducted to measure sensor performance as a function of target magnetic moment, standoff distance, speed, sea state, and water depth. At the completion of the test execution, the target field was removed and the system was disassembled.

The Vaizer-Lathrop (VL) algorithm, first developed for multi-channel tensor gradiometers and successfully validated in the MADOM project, was modified for this test to apply to multi-channel total-field gradiometers and to incorporate dGPS data for more accurate localization. Post-test data analysis was conducted using the VL algorithm.

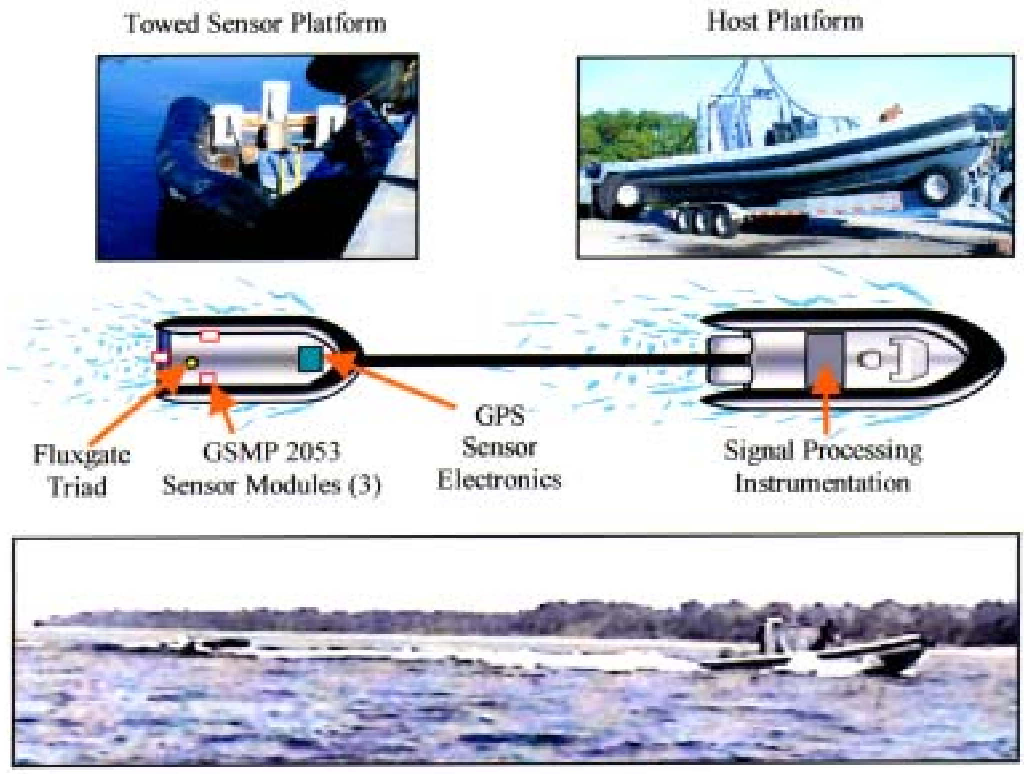

Figure 1. Tow system for sea test of magnetic sensor.

Following limited success with the VL algorithm, alternative data analysis using linear regression techniques was developed for the model in which the target is a magnetic dipole with unknown magnetic moment, but with position of the towed sensor platform relative to each target known throughout the sensor run from the dGPS data. These techniques were applied separately to fit (1) data from the three magnetometers and (2) data from the two gradiometers synthesized from the three magnetometers. Statistical estimates of the three magnetic-moment components and a measure of signal-to-noise ratio were obtained from this analysis.

RESULTS

Magnetic sensing was operated at speeds up to 30 knots and in water depths as shallow as 5 feet, successfully demonstrating one approach to increase the area coverage rate for magnetic sensors and a novel capability for VSW and SZ minehunting operations. One low-ferrous target with magnetic moment of 0.1 A-m^2, implanted in water as shallow as 5 feet, was detected at a standoff distance of 6m.

Sensor performance did not deteriorate appreciably compared to the more gentle conditions that characterized the MADOM testing, in which the sensor was operated in an underwater tow body at slow speeds in deeper waters, factors that substantially diminish vehicle motions and the strength of wave-induced MHP noise. Neither the functional form nor amplitudes of the target signals were modified from theoretical predictions under the extreme conditions tested. The tow system performed well at speeds exceeding 8 knots, the speed at which the towed sensor platform started to plane.

Unprocessed time series for the three total-field magnetometers and the two gradients synthesized from the magnetometers are displayed in Fig. 2 for a target run at 8 knots almost directly on top of the target field. The four larger targets are clearly discernable in both the total-field and the gradient signals. The magnetometer and gradiometer signals for the small target were discernable once the time series was blown up. The VL algorithm successfully localized all of the magnetic targets for this particular run.

In general, the classification and localization capability of the VL algorithm modified and applied to this 2-channel scalar gradiometer was less effective than when applied to 5-channel tensor gradiometers, largely as a result of the more limited information. To some extent, sensor-to-sensor decoherence in a configuration with baselines 4 times greater than those for the MADOM gradiometer impacted the algorithm's performance. Work will be required to improve the algorithm for this case using two scalar gradiometers instead of five tensor gradiometer channels. Addition of a third independent scalar gradiometer, in this case a vertical scalar gradiometer, is expected to improve the effectiveness of the VL algorithm.

As the result of the limited success of the VL algorithm, alternative data analysis using linear-regression described previously was pursued and proved to be far more effective. For example, all five targets were detected with good statistical fits of the magnetometer data for one run with the towed sensor platform moving at 24 knots with a nominal closest point of approach separation of 8 meters. In particular, the smallest target with moment magnitude of approximately 0.1 A-m^2, a magnitude comparable to that for a 81mm artillery shell, was detectable at a range of 6 meters. Fig. 3 displays the magnetometer and the two synthesized gradiometer empirical and model-predicted time series against one of the magnetic targets for this run.

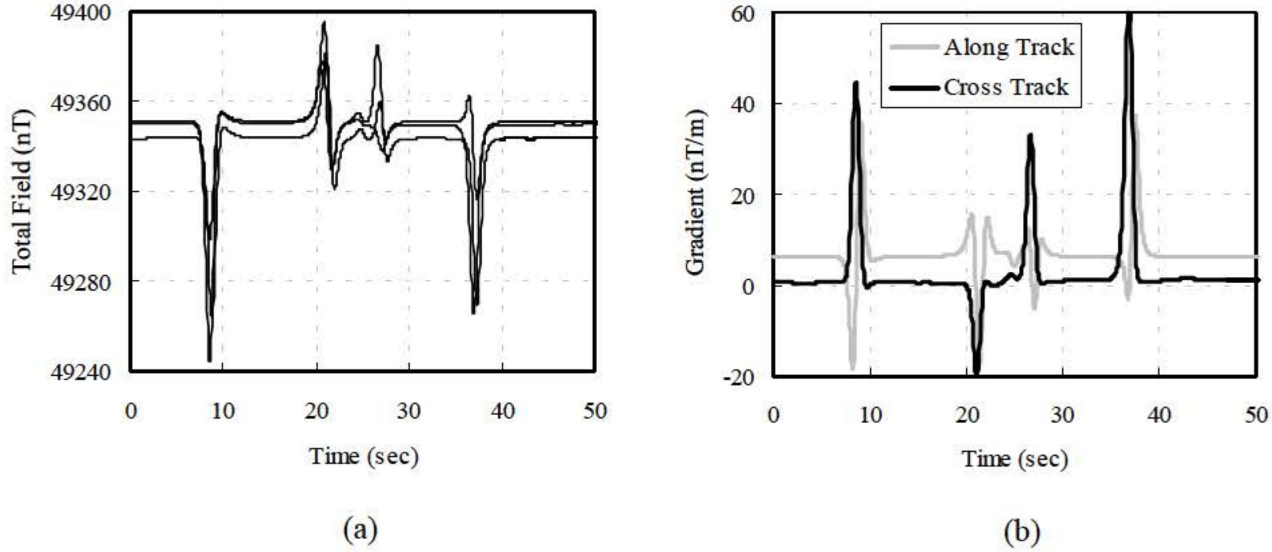

Fig. 2. Unprocessed time series for a run at 8 knots almost directly on top of the target field for (a) the three total-field magnetometers and (b) the two synthesized gradients. The four larger targets are clearly discernable in plots (a) and (b). The corresponding signals for the small target are discernable in a blowup of the data.

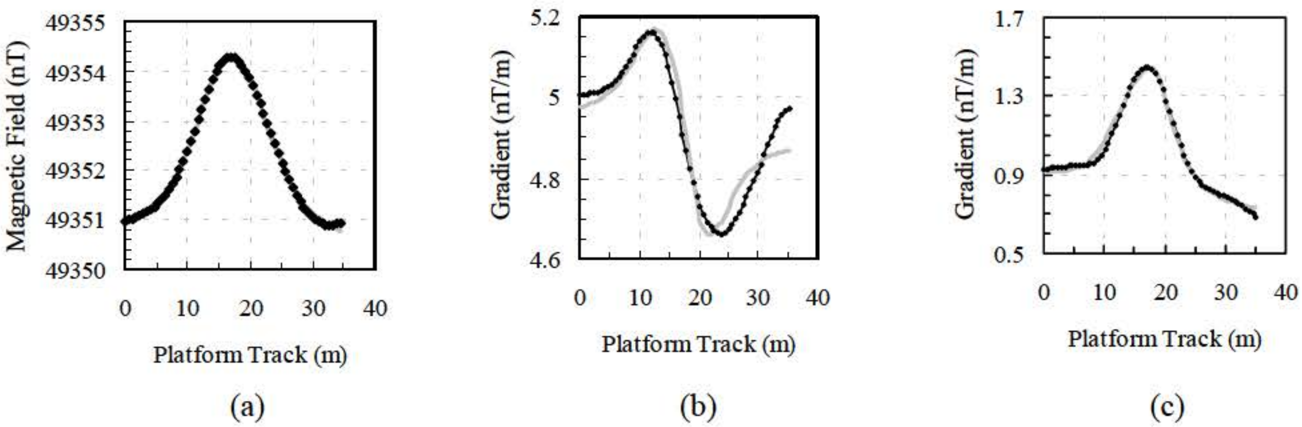

Fig. 3. Empirical and model-predicted time series for (a) one magnetometer, (b) the along-track gradiometer and (c) the cross-track gradiometer against a target with magnetic moment magnitude of approximately 10 A-m^2. The CPA separation for this run was approximately 6 meters. The lines without symbols display the empirical data and the lines with diamond symbols display model predictions.

IMPACT/APPLICATIONS

The U.S. Navy has pioneered the 5-channel tensor-gradiometer approach to provide localization and classification capabilities not achieved using conventional single-channel scalar magnetometers such as the USN ASQ-81/208. Results from the MADOM ATD provide demonstrative proof of this enhanced capability. Multi-channel gradiometers can be assembled from scalar magnetometers to provide localization and moment determination capability beyond a single scalar magnetometer alone. At this time we are unaware of any quantitative measure of the effectiveness of multiple-channel scalar gradiometers compared to the validated performance of tensor gradiometers. The test described in this report represents a first demonstration of this approach.

Magnetic sensing is also effective in high-speed operation. Unlike synthetic aperture sonars for which search rate is essentially independent of speed, search rate for a magnetic sensor increases linearly with speed. This capability meshes well with emerging interest in the use of high-speed unmanned surface craft and aerial vehicles as one means to accelerate mine reconnaissance. A search rate approaching 1 square nautical mile per hour against ferrous case mines may be attained for operations conducted at 30 knots, a factor of 6 greater than operations at 5 knots. This capability may be utilized in future systems for instride reconnaissance for ship transit (including defense against near-surface mines), for amphibious assault, and for rapid follow-on clearance following an assault. We believe that multi-channel magnetic gradiometers can be flexibly integrated into undersea, surface, and airborne system in order to serve in a range of additional littoral warfare missions, including nonacoustic ASW and the detection of and hidden military targets including underground facilities.

TRANSITIONS

The low-T_c superconducting sensor technology developed in the MADOM 6.3 ATD transitioned to the Buried Mine Detector (BMD) 6.4 Program in FY 1992. Although the BMD Program is not currently funded, the advanced magnetic sensing approaches developed under MADOM and continued under this project are available for the Buried Minehunting Project to be initiated in FY 2002. The basic tensor gradiometer concept pioneered under this project has been transitioned to a comparable fluxgate gradiometer, which is being pursued for demonstration for the VSW MCM mission.

In FY 1999 the low Tc superconducting gradiometer used in MADOM was the premiere sensor in an unscripted survey to locate unexploded ordnance in the Technology Demonstration of the Mobile Underwater Debris Survey System (MUDSS) [2], [6]. 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. Similar concepts are being proposed to SERDP for UXO cleanup and related dual-use applications using cryogen-free multi-channel magnetic sensors.

RELATED PROJECTS

Projects to develop shorter-range, man-portable fluxgate gradiometers based on the sensor and signal-processing concepts initiated under this project have been sponsored by ONR 322MG and the OSD SBIR program [7]- [9]. A project to integrate a fluxgate gradiometer into the Morpheus AUV developed by Florida Atlantic University was initiated in FY 2000 by ONR 321OE in conjunction with an SBIR “Integration of Advanced Magnetic Sensors into Underwater Vehicles to Provide High-Quality Spatiotemporal Magnetic Data” to Quantum Magnetics sponsored by ONR Code 322OM.

REFERENCES

1. T. R. Clem et al., "Superconducting magnetic gradiometers for mobile applications with an emphasis on ordnance detection," Chap. 13 in *SQUID Sensors: Fundamentals, Fabrication and Applications*, H. Weinstock, Ed., Kluwer Academic Publishers, Dordrecht, The Netherlands, 1996.

2. T. Clem et al., "Enhanced Magnetic Anomaly Detection using a Nitrogen-Cooled Superconducting Gradiometer," in *Information Systems for Navy Divers and Autonomous Underwater Vehicles Operating in Very Shallow Water and Surf Zone Regions II*, J. L. Wood (ed.), the International Society for Optical Engineering, Vol. 4039, pp. 70-84, 2000.

3. T. R. Clem et al., "High Tc SQUID Gradiometer for Mobile Magnetic Anomaly Detection," IEEE Trans. Appl. Sup., Vol. 11 (No. 1), pp. 871-875, Mar 2001.

4. T. R. Clem et al., "Magnetic Detection of Underwater Targets in Very shallow Water for Searches at High speeds," submitted for publication in *Oceans 2001*, Aug 2001.

5. GEM Systems, Inc., #14-52 West Beaver Creek Rd., Richmond Hill, Ontario, Canada, L4B 1L9, www.gemsys.on.ca.

6. D. C. Summey et al., "Mobile Underwater Debris Survey System (MUDSS)," *Oceans 99*, 1999.

7. G. I. Allen et al., "Operating a Sophisticated Magnetic Sensor Aboard a Standard AUV," 11th International Symposium on Unmanned Untethered Submersible Technology, 1999.

8. D. K. Lathrop et al., "Development of a Magnetic Tensor Gradiometer: Integration with an Autonomous Underwater Vehicle," in *Information Systems for Navy Divers and Autonomous Underwater Vehicles Operating in Very Shallow Water and Surf Zone Regions II,* J. L. Wood (ed.), pp. 85-92, 2000.

9. G. I. Allen et al., "Mitigation of Platform Generated Magnetic Noise Impressed on a Magnetic Sensor Mounted in an Autonomous Underwater Vehicle," submitted for publication in the Proceedings for Oceans 2001, Aug 2001.

PUBLICATIONS

T. R. Clem et al., "Magnetic Detection of Underwater Targets in Very shallow Water for Searches at High Speeds," submitted for publication in the Proceedings for Oceans 2001, Aug 2001.

T. R. Clem et al., "High Tc SQUID Gradiometer for Mobile Magnetic Anomaly Detection," IEEE Trans. Appl. Sup., Vol. 11 (No. 1), pp. 871-875, Mar 2001.