Portable Magnetic Gradiometer for Real-Time Localization and Classification of Unexploded Ordnance

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Abstract- We report progress toward achievement of a new magnetic tensor gradiometer technology that is being developed with support from the Strategic Environmental Research and Development Program (SERDP). The objective of this R & D effort is to provide a man-portable magnetic tensor gradiometer for real-time, point-by-point detection, localization and classification (DLC) of Unexploded Ordnance (UXO). The portable gradiometer processes data from triaxial fluxgate magnetometers to develop sets of rotationally invariant, "gradient-contraction-type" scalar parameters. The scalar parameters provide the basis for a unique "Scalar Triangulation and Ranging (STAR) method that determines the UXO's position and magnetic signature.

In particular, our paper presents: a) A review of the magnetic STAR concept, b) Details of construction and operation of the portable STAR-type gradiometer, c) Results of computer simulations of the effects of fluxgate noise on the gradiometer's target-tracking performance and d) Results of experimental measurements of uncorrelated fluxgate noise and correlated gradient channel imbalance errors, e) Preliminary results from a gradient imbalance noise compensation algorithm. The R & D results indicate that the magnetic STAR concept potentially will provide an exceptionally valuable, motion-noise-resistant magnetic sensing technology for real-time, DLC of Unexploded Ordnance, and buried mines.

I. INTRODUCTION

Hidden and buried Unexploded Ordnance (UXO) (e.g., bombs, artillery shells, mines, etc.) in formerly used defense sites and past and present war zones present huge humanitarian and economic problems. In order to help mitigate these problems, the Strategic Environmental Research and Development Program (SERDP) has been supporting the development of improved sensing technologies for Detection, Localization and Classification (DLC) of UXO. In principle, passive magnetic sensing systems that measure the static magnetic anomaly field (or signature) of magnetic UXO can be used to detect, locate and classify the UXO. Since the magnetic signatures are not significantly affected by intervening media such as soil, foliage and water, magnetic sensors can provide a unique modality for localization of underwater and buried UXO that would remain hidden to other sensor technologies. Many UXO-containing sites are characterized by difficult terrain and/or littoral underwater environments that are difficult or costly to survey with vehicle-based sensing platforms. Consequently, there is potentially a huge market for compact and effective man-portable magnetic sensor systems, that as indicated in the cartoon of Fig. 1, would be capable of real-time, point-by-point DLC of magnetic targets, be easily man-portable (even hand-held) and be generally adaptable a wide variety of highly mobile autonomous sensing platforms. However, in practice, conventional prior-art magnetic sensing technologies such as scalar total field magnetometry and tensor gradiometry have not been able to provide a portable magnetic sensing system that is capable of effective DLC of magnetic targets.

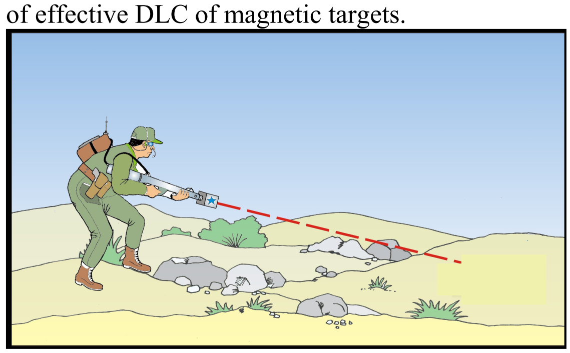

Fig. 1. Cartoon showing intended application of a land version of the STAR-type portable gradiometer sensor that is being developed. The portable STAR sensor will provide the operator with a stand-off capability for real time, point-by-point Detection, Localization and Classification of magnetic targets such as UXO, and buried mines.

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In response to the unmet need for a practicable magnetic sensing technology for DLC of underwater and buried mines using highly mobile sensing platforms, the Naval Surface Warfare Center Panama City has developed a new magnetic sensing system approach based on a magnetic Scalar Triangulation and Ranging (STAR) concept that was created to overcome many of the limitations of prior art approaches [1-3]. The STAR concept uses the magnitudes or "contractions" of magnetic gradient tensors to provide an intrinsically motion noise resistant magnetic sensing modality for DLC of magnetic targets.

The initial application of the STAR concept was a two-dimensional (2-D) magnetic anomaly guidance system for crawler-type Autonomous Underwater Vehicles (AUV) that would allow them to autonomously "home in on" magnetic targets [4-8]. More recently, the STAR concept has been shown to apply to the generalized problem of 3-D DLC of magnetic targets [2,3]. The generalized STAR concept provides the basis for the development of an improved man-portable magnetic sensing technology. The R & D effort reported here has the following objectives:

- To demonstrate that the STAR concept can be applied to provide an improved, intrinsically motion noise resistant magnetic sensing system and method for real-time, point-by-point Detection, Localization and Classification of magnetic targets.
- To construct a compact, self-contained magnetic gradient sensing system (STAR-type gradiometer) that easily can be carried by an individual operator and in real time provide the operator with an indication of the DLC parameters (e.g., range, bearing and magnetic signature) of magnetic targets.
- To provide improved modalities for compensation of residual "extrinsic" motion noise effects and thereby provide a portable magnetic gradiometer system and method that can perform effective real-time point-by point (stand-off) DLC of magnetic targets in environments characterized by difficult terrains.

On continuation, this paper describes the theory, means and methods that relate to the development of a STAR-type portable magnetic gradiometer.

II. STAR GRADIOMETRY

The use of magnetic sensors to determine the three components of a magnetic target's location vector $\boldsymbol{r}$ [m] and its magnetic dipole signature $\boldsymbol{M}$ [Am^2] is based on measurements of the magnetic induction field $\boldsymbol{B}_A(\boldsymbol{r},\boldsymbol{M})$ [Tesla, T], that emanates from the target; where,

$$\boldsymbol{B}_A(\boldsymbol{r}, \boldsymbol{M}) = (\mu/4\pi)[\, 3(\boldsymbol{M}\bullet\boldsymbol{r})\boldsymbol{r}/r^5 - \boldsymbol{M}/r^3] \quad \text{Eq. 1}$$

Where μ is the magnetic permeability of the surrounding media (typically $\approx 4\pi \times 10^{-7}$ Tm/A for non-magnetic media). Relative to the magnetic field of Earth ($\boldsymbol{B}_E$), the $\boldsymbol{B}_A$ field constitutes a magnetic anomaly whose amplitude drops off as the inverse cube of the distance r from the target. Thus at distances of only a few meters from medium sized UXO (e.g., with $M \sim 10$ Am^2) $B_A \leq$ nT.

The detection of nT-level target-vector signature components from mobile sensing platforms is made difficult by the presence of the relatively very large ($\approx$ 50,000 nT) Earth's background field, $\boldsymbol{B}_E$. The difficulty relates to the fact that each field-vector sensing element will experience a non-target-related field equal to $B_E \cos\theta$ where θ is the angle between $\boldsymbol{B}_E$ and a vector magnetometer's field-sensing direction. As a mobile vector magnetometer rotates it will measure non-target-related field components with amplitudes between +/- 50,000 nT. Since B_E has a small (~0.02 nT/m) gradient, accurate determination of the location $\boldsymbol{r}$ and magnetic signature $\boldsymbol{M}$ of magnetic targets from mobile sensing platforms generally requires the use of tensor gradiometer-type sensors that greatly reduce motion noise by measuring B-field gradients between multiple sensors.

The gradient of $\boldsymbol{B}_A$ ($\nabla\boldsymbol{B}_A$) is a tensor whose matrix elements (G_{ij}) are given by:

$$G_{ij} \equiv \partial B_i/\partial r_j = -3(\mu/4\pi)[\boldsymbol{M}\bullet\boldsymbol{r}(5r_ir_j - r^2\delta_{ij}) - r^2(r_iM_j + r_jM_i)]r^{-7} \quad \text{Eq. 2.}$$

As a result of Maxwell's Equations, measurement of just five independent tensor components is sufficient to determine the full, nine-component gradient tensor.

Prior approaches to tensor gradiometry that use Eq. 2 to solve for $\boldsymbol{r}$ and $\boldsymbol{M}$ have had two major problems: (A) Five independent equations are not sufficient to determine all six components of $\boldsymbol{r}$ and $\boldsymbol{M}$. (B) The G_{ij} components are intrinsically sensitive to motion noise. In practice, (A) and (B) result in limitations on sensing platform motion such that conventional mobile gradiometry requires the sensing platform's to be constrained to move at nearly constant velocity along straight-line paths with very little change in sensor orientation. Such constraints have greatly impeded the potential application of conventional tensor gradiometry for man-portable sensing systems and other highly mobile sensing platforms.

The magnetic Scalar triangulation and Ranging (STAR) concept was created to enable the development of man-portable and other high mobility sensing platforms by eliminating problems (A) and (B) and thereby removing limitations on the mobility of sensing platform.

The following very briefly highlights some details of the STAR concept [2,3]. The scalar magnitude of the magnetic gradient tensor **G** is given by the square root of the trace of the product **G•G***ᵗ* where *"t"* indicates the transpose of the matrix. In Cartesian coordinates, the trace or "contraction" (C_T^2) of $\mathbf{G}\bullet\mathbf{G}^t$ can be represented by the following expression.

$$C_T^2 = \Sigma (G_{ij})^2 = (\partial B_x/\partial x)^2 + (\partial B_x/\partial y)^2 + (\partial B_x/\partial z)^2 + (\partial B_y/\partial x)^2 + (\partial B_y/\partial y)^2 + (\partial B_y/\partial z)^2 + (\partial B_z/\partial x)^2 + (\partial B_z/\partial y)^2 + (\partial B_z/\partial z)^2 \quad \text{Eq. 3}$$

For a dipole field the relation between C_T, r and M can be represented by a central-potential-type function; namely:

$$C_T = k(\mu/4\pi)M/r^4 \quad \text{Eq. 4}$$

where "k" varies from 7.3 at r-points aligned with the target's dipole axis to 4.2 for points transverse to the dipole axis. Contours of constant C_T form concentric prolate spheroidal surfaces that are centered on a magnetic dipole target. C_T has the following very important characteristics:

- C_T is a rotationally invariant *and* robust scalar that is independent of gradiometer orientation and therefore, is therefore intrinsically resistant to motion noise.
- For a given value of k, differences in C_T-values relate only to differences in r-values between the target and the respective C_T-measurement points.

Thus, if a "snapshot" of C_T parameters is measured at multiple points within a multi-tensor gradiometer array in the far-field space of a target:

a) The value of k will be very nearly the same for all points within the array.
b) Different values of C_T –scalars relate only to different r-distances between the target and the respective measurement points.
c) The distances between C_T-measurement points constitute "triangulation baselines" within the array that are determined by the geometrical design of the gradiometer.
d) The triangulation baselines and their respective C_T scalar can be used by the STAR algorithm to determine ***r*** [2,3].
e) The r-components can be used in Eq. 2 to obtain the vector components of ***M*** that are so important for UXO discrimination and clutter rejection [9,10].

The STAR concept: a) Allows determination of all six components of ***r*** and ***M*** from a single sensor system position, and b) Uses intrinsically motion-noise-resistant C_T-type scalar parameters for DLC of magnetic targets. Therefore, the STAR concept should provide an exceptionally valuable technical approach for portable gradiometer development.

III. TECHNICAL DETAILS.

A design goal for overall operational sensitivity of the prototype man-portable sensor system is 0.2 nT/√Hz or better at 1 Hz. This level of sensitivity will allow detection ranges on the order of 10-m for medium size (i.e., with M ~10-20 Am^2) UXO. The STAR concept of using rotationally invariant scalars to triangulate UXO position addresses the major tensor gradiometry problems at a fundamental level and greatly simplifies the problem of development of a practical real time tensor gradiometer. Nevertheless, successful achievement of the design goal requires a significant hardware and software development effort to ensure that the following technical issues are properly addressed:

- The effects of all sources of noise, (in particular residual gradient imbalance errors) that can degrade sensor system performance must be minimized.
- Effective discrimination of pT-level target signatures that are embedded in the 50 µT B_E fields requires development/application of a unique data acquisition and signal processing system with (140 dB dynamic range) that can simultaneously discriminate multiple channels of pT-level analog signals.
- Interactive software is required to control data acquisition, process raw field data, adaptively compensate for residual gradient channel imbalances, apply the 3-D STAR algorithm and provide a near real-time output indicative of a magnetic target's position and magnetic signature.

The portable STAR gradiometer design is based on a cubic array ("STAR-Cube") of fluxgate-based magnetic gradient sensors (Fig. 2). B-field data from the sensors in each face of

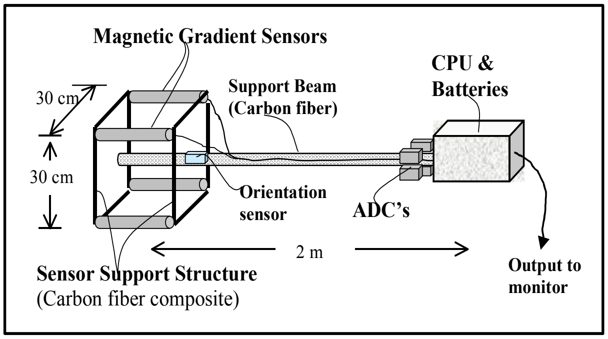

FIG. 2. Sketch of portable gradiometer configuration (not to scale). A cubic array of four magnetic gradient sensors is mounted on a carbon fiber composite support structure. The sensor's analog outputs are converted to digital words by 24-bit ADCs. The CPU processes *B*-field and orientation data and runs the STAR algorithm to provide a near real-time display of target DLC parameters to the operator's monitor & I/O unit. Currently, a heads-up display is being developed.

the cube is used to generate a complete gradient tensor and its corresponding C_T-parameter. The distances (30 cm) between C_T-parameters situated along the X,Y and Z coordinate axes respectively constitute XYZ "triangulation baselines" (ΔS_X, ΔS_Y, ΔS_Z) for target-ranging [2,3].

The portable gradiometer incorporates several unique design and construction features; namely:

1. A magnetic gradiometer comprised by a cubic array of 8 low-noise (<20 pTrms/√Hz) fluxgate-type Triaxial Magnetometers (TM). Paired sets of TMs comprise magnetic gradient sensor "axes" of the array that are rigidly mounted in carbon fiber composite tubes and held in place by a Sensor Support Structure made of extremely rigid and lightweight carbon fiber composite.
2. A set of unique, state-of the-art 24-bit digitizers provides near-simultaneous analog to digital conversion of the 24 channels of analog *B*-field data. The digitizers can be locked to the Global Positioning System to provide; a) Precise sensor channel timing, and b) Tracking of the portable gradiometer's position. Very importantly, the very wide dynamic range (140-150 dB) of the digitizers will allow discrimination of pT-level target signatures.
3. An orientation sensor comprised by a triaxial magnetometer, triaxial accelerometer and a triaxial rate gyro provides a reference frame for: a) Compensation of residual gradient imbalance errors, b) Indication of target position relative to the operator.
4. A single-board computer (SBC) that: a) Stores *B*-field, GPS and orientation data. b) Runs the imbalance compensation algorithm. c) Runs the STAR algorithm [2,3] d) Outputs the DLC parameters to the operator's monitor and I/O device (a laptop).
5. A set of very high power-density lithium-ion polymer batteries (of a type typically used to power model airplanes) will provide electrical power for the gradiometer system.

Construction of the portable gradiometer is expected to be completed in October 2006 pending delivery of additional components of the data acquisition system and fabrication of the Sensor Support Structure. The prototype gradiometer will have a mass of about 10 kg (including batteries), power requirement < 25 W and an operating time (while on batteries) of about 4 hours.

The gradiometer will perform the following operations in near real time while it is carried by an operator in search of hidden UXO:

1. Analog ***B***-field components are measured at each TM sensor position.
2. Analog ***B***-field data are digitized.
3. Gradient tensor components are calculated for each "face" of the cubic sensor array.
4. Residual gradient imbalance errors are removed from the "raw" gradient data .
5. A complete, nine-component gradient tensor and its respective $C_{T,i}$-parameter is calculated for each "*i*-th" face of the array .
6. The STAR algorithm calculates X,Y,Z components of target position. For example, the X-component of target position is $r_X = \{\Delta S_{+X,-X} [(C_{T,+X} / C_{T,-X})^{0.25} - 1] + 0.5\,\Delta S_{+X,-X}\}$ where $C_{T,+X}$ and $C_{T,-X}$ are C_T-parameters located, respectively, in the cube faces at $+ 0.5\Delta S_{+X,-X}$ and $-0.5\Delta S_{+X,-X}$, and $\Delta S_{+X,-X}$ is the triangulation baseline in the X-direction [2,3].
7. Target dipole moment components M_X, M_Y and M_Z are calculated using the results of step 7 in Eq. 2.
8. Target position (e.g., range and bearing) and magnetic dipole signature are displayed on the operator's display monitor-I/O unit. Target data can be stored in the SBC's 2-GB of compact flash-type memory.

RESULTS AND DISCUSSION

To date, a complete set of TM-based magnetic gradient sensors and a 24-bit digitizer

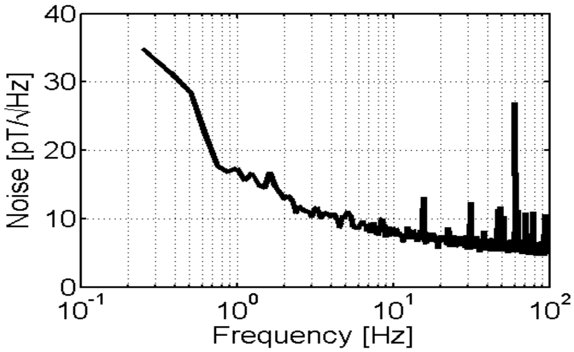

Fig. 3. Power spectral density of TM field sensing element noise showing an rms noise level of 17 pT/√Hz at 1 Hz.

have been delivered and are being characterized at NSWC PC prior to their being installed in the portable gradiometer system. Since gradiometer range and accuracy depend on sensor noise levels, measurements have been performed to characterize the uncorrelated noise levels of the STAR Cube's individual TM sensors and the correlated imbalance errors of its magnetic gradient sensors. Fig. 3 is a representative power spectral density of sensor noise from one signal channel of a magnetic gradient sensor. The averaged root-mean-squared (rms) noise level of 17 pT/√Hz at 1 Hz is fairly typical of the TM field-sensing elements and is within the manufacturer's specifications of < 20 pT/√Hz. In an otherwise perfectly balanced gradiometer, the uncorrelated TM sensor noise will impose a limit on the gradiometer's DLC range. Since the portable STAR sensor will take snapshots of *B*-field data with little averaging effects at 1 Hz, the TMs' peak-to-peak (p-p) noise will generate randomly varying gradient imbalance errors that will limit the sensor system performance. FIGs. 4-6 show the simulated performance of a STAR-Cube gradiometer with 120 pT(p-p) of

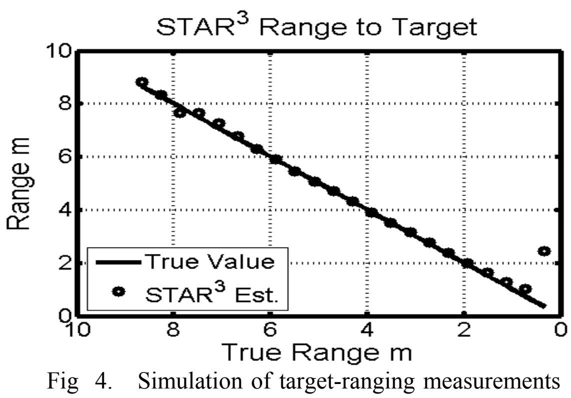

Fig 4. Simulation of target-ranging measurements from a STAR Cube gradiometer as it homed in on a 14.7 Am^2 magnetic dipole target. All 24 channels had 120 pT p-p random noise.

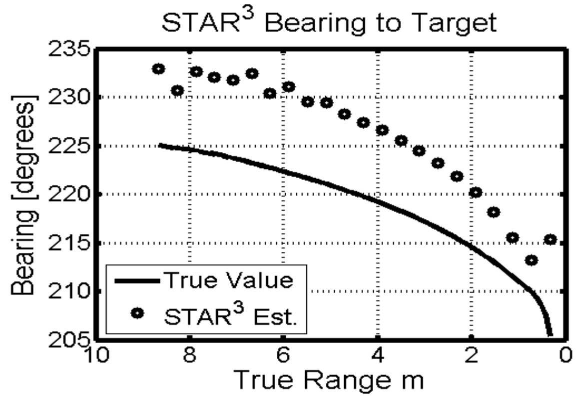

Fig. 5. Simulation of bearing-to-target measurements of a STAR Cube gradiometer as it homed in on a 14.7 Am^2 magnetic dipole target. All 24 channels had 120 pT p-p random noise.

uncorrelated random noise on all 24-channels. At distances of more than 9 m from a 14.7 Am^2 dipole target the simulated STAR-Cube gradiometer cannot detect/localize the target. However, at distances < 8.7 m, the simulated sensor performance is quite robust. The target-ranging performance is very accurate while the variances between true and measured values of bearing to target and target dipole signature are primarily related to "asphericity errors" [3] that will be eliminated by a least-squares-fit algorithm in the fully operational sensor system. (At the closest point of approach of about 0.37 m, sensor aperture effects cause the divergence between measured and true values of range, bearing and magnetic moment.)

Residual gradient imbalances due to, e.g., misalignment and cross-field effects in field sensing elements and variations in channel gain, linearity and offsets constitute a particularly insidious type of noise that depends on sensor system orientation in the Earths B_E field.

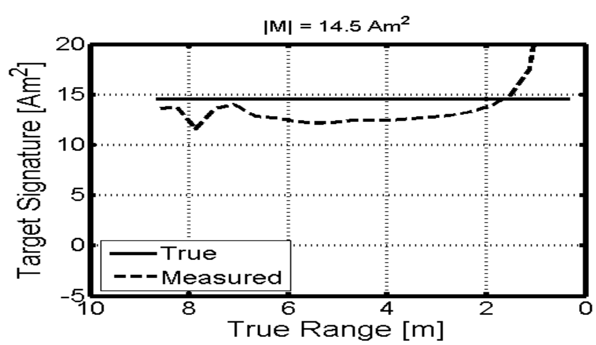

Fig. 6. Simulation of magnetic moment measurements of a STAR Cube gradiometer as it homed in on a 14.7 Am^2 magnetic dipole target. All 24 channels had 120 pT p-p random noise.

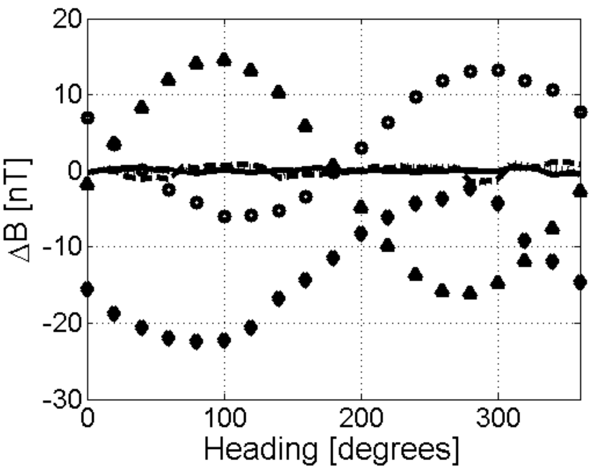

FIG. 7. Field-test data showing gradient imbalance errors versus heading of a 3-channel gradient sensor: Circles, triangles, and diamonds respectively indicate "raw" uncompensated ΔX, $\Delta Y/10$ and ΔZ errors. The Solid and dashed lines near B = 0 indicate ΔX, ΔY and ΔZ errors after application of an imbalance compensation algorithm to the raw data.

Unless they are properly mitigated, the gradient imbalance noise effects can constitute a *de facto* limitation on the 3-D mobility of a tensor gradiometer. Therefore, a very important part of the present R & D effort is the development of improved means and methods for characterization of, and real time compensation for, the effects of gradient imbalance noise. Fig. 7 presents field test data showing uncompensated and compensated gradient imbalance noise from a 2-TM magnetic gradient sensor element while being rotated in a gradient-free environment. Application of an "imbalance transformation matrix" to the uncompensated data results in a 20 dB reduction of imbalance errors. The imbalance transformation matrix is derived by application of a linear least squares fit algorithm to a previously determined set of calibration data that correlate gradient errors with B -field components measured by a reference TM sensor. Improved imbalance error compensation algorithms are currently being developed to further suppress the effects of motion noise.

CONCLUSION

The results of experimental characterization of gradient sensor noise levels and computer simulation of the effects of sensor noise on gradiometer performance indicate that the portable gradiometer being developed will function well with realistic levels of uncorrelated and correlated sensor noise. These results indicate that the STAR gradiometer concept can provide a uniquely effective magnetic sensing technology for Detection, Localization and Classification of Unexploded Ordnance, and buried mines.

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