ESTCP
Cost and Performance Report

(MM-0604)

Small Area Inertial Navigation Tracking (SAINT) System for Precise Location of Buried UXO

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ACRONYMS AND ABBREVIATIONS

2-D	two-dimensional
3-D	three-dimensional
APG	Aberdeen Proving Grounds
CF	compact flash
cm	centimeter
DGM	Digital geophysical mapping
DMC	digital magnetic compass
ESTCP	Environmental Security Technology Certification Program
IMU	inertial measurement unit
INS	inertial navigation system
m	meter
MEMS	microelectromechanical system
mm	millimeter
NMEA	National marine Electronics Association
PC	personal computer
R-T-S	Rauch-Tung-Streibel
RTS	robotic total station
SAINT	small area inertial navigation tracking system
SERDP	Strategic Environmental Research and Development Program
USACE	U.S. Army Corps of Engineers
UTM	Universal Transverse Mercator
UXO	unexploded ordnance
ZUPT	zero velocity update

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Technical material contained in this report has been approved for public release.

1.0 EXECUTIVE SUMMARY

1.1 BACKGROUND

Geophysical technologies for supporting munitions waste remediation have focused on the problems of detecting, locating, and mapping the presence of underground objects. Experience has shown that most underground objects detected by these systems present no safety hazard or need to be excavated. If reliable means of distinguishing hazardous from nonhazardous objects could be developed, significant resources for munition remediation programs could be saved and more effectively deployed to mitigate safety hazards.

Other researchers have shown a likelihood of being able to characterize buried targets via sophisticated inversion algorithms. These algorithms require high-fidelity sensor systems combined with high-fidelity positioning systems. Existing sensor technologies provide good quality sensor data, but practical high-resolution positioning systems (on the order of 1 cm error) remain a challenge.

ENSCO, Inc. conducted a demonstration at Aberdeen Proving Grounds (APG) on September 12-13, 2006, of the second generation small area inertial navigation tracking system (SAINT) technology integrated with an EM61-HH metal detector. The primary objective of this demonstration was to demonstrate a relative position accuracy of the EM61-HH sensor of less than 2 cm (one standard deviation) along each of the three axes of the local positioning reference frame.

1.2 OBJECTIVE OF THE DEMONSTRATION

This demonstration highlighted the integration of SAINT with a standard EM61-HH metal detector. The primary objective was to verify the three-dimensional (3-D) positioning accuracy of the EM61-HH sensor provided by SAINT. Because no communication is needed with auxiliary components or satellites, normal operation is not affected by heavy vegetation, elevation change, water, or tree cover, as is the case for most other positioning systems. During postprocessing, the EM61-HH data was merged with the SAINT position data; however, the overall performance of the EM61-HH was not assessed. The focus was on the position accuracy.

The demonstration was conducted in the calibration grid at APG and included the interrogation of 23 targets in the calibration grid. Postprocessing provided EM61-HH data merged with 3-D position data for the 23 targets in the calibration grid with all positions referenced in the Universal Transverse Mercator (UTM) coordinates.

Success was defined as demonstrating relative position errors of the sensor coil of less than 2 cm at 1 standard deviation along each of the three axes of the local positioning reference frame. Secondary demonstration objectives were to show robustness and reliability of the system, ease of use, and simplicity of postprocessing. Both objectives were met.

1.3 REGULATORY DRIVERS

This project was primarily motivated by the desire for more efficient and accurate munitions field operations to achieve better technical remediation performance and to reduce cost. Precise positioning technology is an important part of the infrastructure of munitions remediation efforts, an enabling tool to allow faster, better, and cheaper detection, characterization, and excavation. Thus, the need for this technology is not primarily driven by regulatory issues.

1.4 DEMONSTRATION RESULTS

SAINT was demonstrated to produce relative positioning accuracy of less than 5 mm and inversion fit quality consistent with a <1 cm positional accuracy. This accuracy is expected to be sufficient to allow target characterization based on the EM61-HH sensor data tied to accurate relative geolocation. During the demonstration, data were collected at a rate of six targets per hour for a single operator. In production use we anticipate a minimum rate of 12 targets per hour. This production rate is expected to result in an interrogation cost of $7 per target, thus potentially saving a substantial percentage of munitions remediation costs.

1.5 STAKEHOLDER/END-USER ISSUES

This demonstration report documents the relative positioning accuracy and land-area survey rate of the inertial navigation technology. Logistical issues (which are critical to munitions operations) were demonstrated by documenting activities required to complete the demonstration. Cost of the technology was estimated and compared to existing technology.

Thus, the outcome of this demonstration provides end users with an understanding of the technical, logistical, and financial impact of this technology, allowing them informed decision making.

2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY DEVELOPMENT AND APPLICATION

SAINT is a stand-alone unit that can be attached to virtually any system when a recorded free navigation position trace in 3-D is desired. In this demonstration, SAINT was attached to a commercially available EM61-HH (Mark-2) metal detector to record free-navigation position. The purpose was to record location and orientation of the metal detector sensor head as it was arbitrarily swept over a local area where an unexploded ordnance (UXO) was suspected to be buried. This allows a detailed map of metal detector and position data (digital geophysical mapping [DGM]) to be generated.

The primary positioning system consists of a Honeywell HG1900 inertial measurement unit (IMU) and a LEICA digital magnetic compass (DMC), as shown in Figure 1. SAINT also includes the following support hardware:

- Rabbit-embedded central processing unit (CPU)
- Weatherproof enclosure with mounting brackets
- Battery power-pack in satchel
- Compact flash (CF) card
- Cables for power and data.

IMU

DMC

Figure 1. Honeywell HG1900 IMU and LEICA DMC.

The Honeywell HG1900 IMU consists of orthogonally aligned microelectromechanical system (MEMS) accelerometers and gyroscopes that record 3-axis acceleration and rotation rates, respectively enclosed in an 8-cu-in container. The LEICA DMC is employed to aid the IMU and constrain heading drift. The DMC measures the strength and direction of a magnetic field and can be used to determine magnetic north in an environment free of additional magnetic fields. With the exception of batteries, a tripod stand, and the postprocessing personal computer (PC), all components of SAINT are packaged into a single enclosure. The enclosure clamps onto the shaft of the EM61-HH, needing no special modifications, as shown in Figure 2. An additional clamp is used to fix the sensor coil relative to IMU so the position and angle offset remain constant.

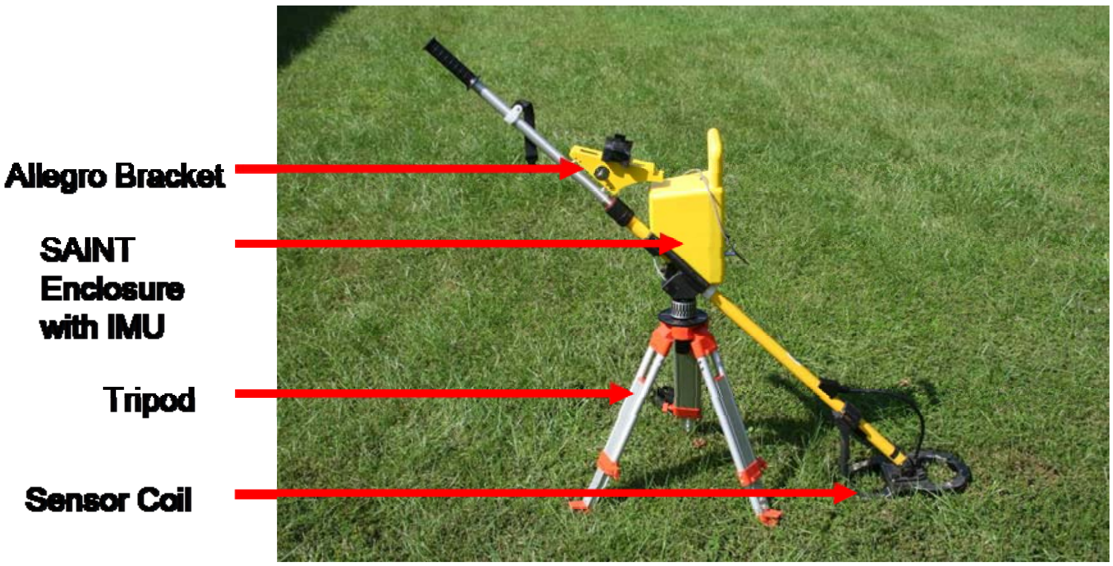

Figure 2. SAINT Integrated with the EM61-HH.

2.2 PROCESS DESCRIPTION

SAINT records all IMU data onto an internal CF. DMC data is recorded to the same CF card greatly simplifying user operation and data postprocessing. A schematic of the integrated system is shown in Figure 3.

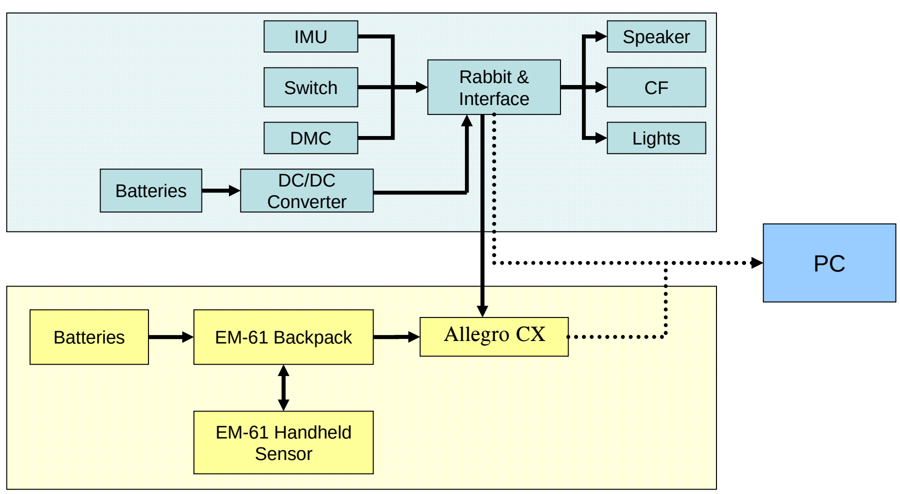

Figure 3. SAINT and EM61-HH Integration Schematic.
(Yellow Components are Part of the COTS EM-61 HH MK2.)

The Rabbit, a single board computer based on an extension of the z-80 processor, controls the data flow, buttons, and status lights. Lights and audible signals (speaker) aid the user for proper operation.

For a solely IMU-based positioning system, best case position errors will grow as a random walk due to accumulated errors in dead reckoning speed and heading, assuming all sensor biases are known and subtracted. Highly correlated errors (biases) will result in position errors that grow as a quadratic with time. The fundamental design goals for a dead reckoning system are to minimize the heading and speed error growth by using a combination of high quality (low noise) sensors and exploiting locally available information to remove biases from these sensors. By integrating a compass and requiring that the SAINT unit remains stationary over the same point for at least 15 seconds before and after each cycle of data acquisition, a Kalman filter and Rauch-Tung-Streibel (R-T-S) Smoother (Rauch et al., 1965) can be used to optimally estimate and remove sensor biases and minimize position and heading errors. In addition to the heading measurement provided by the compass, the software exploits the fact that during the stationary period the IMU occupies the same position and does not move, providing a zero-velocity update (ZUPT) and position update, respectively.

Data Acquisition

Geophysical data are acquired in 30-second cycles after which the IMU must be returned to its initial position. Each cycle consists of the following steps:

- Initial ZUPT period: The SAINT unit is set down on the tripod mount and remains stationary for 15-30 seconds.
- Operator picks up the unit and acquires geophysical data for approximately 30 seconds of free navigation over the area of interest.
- Final ZUPT period: The SAINT unit is returned to its original location on the tripod mount for about 15-30 seconds.

Lights and audible signals aid the user for proper operation. During the 30-second free navigation period, various audible chirps are sounded with 10, 5, and 0 seconds remaining before a new ZUPT is required. Adequate data density over a small area can be achieved by collecting multiple cycles of data.

Since there is no required infrastructure setup, a single operator can quickly and easily perform data acquisition over multiple points spread over large areas. Since the IMU rests directly above the center of the tripod, the location of the tripod defines the origin of the frame for the processed sensor position.

After all IMU data has been recorded, the SAINT CF card is removed and the data transferred to a PC using a USB CF card reader.

Data Processing

Prior to using the SAINT system for the first time, a measurement must be obtained of the 3-D position offset of the center of sensitivity of the EM61-HH, which is defined to be the physical center of mass of the figure-eight coil configuration, with respect to the IMU in the measurement frame of the IMU.

The data processing exploits the operational requirement that the start and stop locations of the SAINT hardware be identical. The operator can free-navigate for 30 seconds, at which time the unit must be returned to the same place it started. ENSCO has implemented a ZUPT-ing tripod to simplify the return of the hardware to the identical location. Upon completion of the ZUPT, a blue indicator light illuminates on the SAINT enclosure signifying the operator can free-navigate when ready.

The postprocessing software has been mostly automated and includes a GUI that requires the user to select the EM61-HH data and IMU data files for processing and the periods to process. The processing consists of the following components:

- A prefilter for detecting ZUPT intervals
- Navigation equations and a Kalman filter (Rogers, 2000)
- An R-T-S smoother
- A component to translate the IMU position and attitude to the geophysical sensor based on the static 3-D position and orientation offset vectors
- A component to interpolate the sensor position and attitude (recorded at up to 600 Hz) to the recorded EM61 times (recorded at approximately 15 Hz).

The error-state Kalman filter feeds corrections back into the navigation equations for both navigation errors and IMU sensor errors to optimally estimate the position and orientation of the IMU. The accuracy of these corrections is primarily a function of the quality of the IMU, the quality of the aiding measurements to the IMU, and the quality of the model defining the IMU in the Kalman filter. The accuracy of the reported errors is primarily a function of the quality of the model defining the IMU. For this project, the IMU was suboptimally modeled, and the Kalman filter error model (Rogers, 2000) was limited to the following 15 states:

- δr is a three-element vector of north, east, and down position errors
- δv is a three-element vector of north, east, and down velocity errors
- $\delta \psi$ is a three-element vector of infinitesimal angles describing the misalignment relative to earth
- δb^{acc} is a three-element vector of time-correlated accelerometer errors
- δb^{gyro} is a three-element vector of time-correlated gyro errors.

The Kalman filter provides an optimal estimate of position based on all measurements available until time t_k. However, additional information contained in the measurements after t_k can further improve the estimate of position. An R-T-S smoother was implemented as an algorithm to be used in postprocessing that computes an optimal smoothed path estimate utilizing all available measurements within the data set (Rauch et al., 1965).

In addition to the position and attitude estimates, the error estimates are provided for each of the components of position and attitude. Processing software outputs positions in a relative coordinate system with the origin at the ZUPT location and the orientation constrained by the compass.

Concept of Operations

The concept of operations assumes the operator has a sequence of target locations, likely marked by pin flags that need to be investigated. Data are collected separately for each pin flag location; a new ZUPT location may be chosen for each pin flag location. Assuming flags are used to mark the areas for interrogation during a survey, the procedure will consist of colocating the ZUPT position with the flags by placing the ZUPT stand directly on top of the flagged point. Processing software outputs positions in a relative UTM coordinate system with the origin at the ZUPT location and the orientation constrained by the compass. The intent of the SAINT system is to provide accurate positions in a relative frame for interrogation algorithms; hence, there is no requirement for knowledge of the UTM position of the ZUPT point. Knowledge of the UTM position of the ZUPT point simply provides a way to map these relative positions to a UTM frame during field operations.

2.3 PREVIOUS TESTING OF THE TECHNOLOGY

A demonstration of SAINT was performed at APG in Maryland in 2004 under ESTCP Project MM-0129. For that demonstration, a tactical grade Honeywell HG1700 IMU was paired with a G-858 cesium magnetometer.

Static inertial measurements were recorded at 36 marked locations within a one square meter grid, as shown by the asterisks in Figure 4. The sensor was placed in the grid locations using PVC standoffs of known length and placing the base of the standoff on marks on the plywood board defining the grid. The coordinate results recorded by SAINT were compared to actual coordinates of the fixed grid and are summarized in
Table 1.

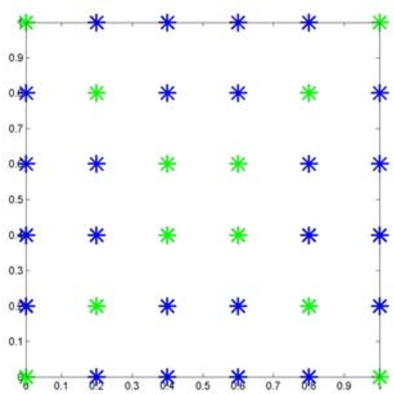

Figure 4. Static Test Grid Design with Multiple Elevations Recorded Across the Diagonals and Picture of Actual Operation Including SAINT System and PVC Standoff.

Table 1. Mean Errors from Static Fixed Grid Testing.
Two-Dimensional (2-D) Error is Defined to be the Square Root of the Sum of the Squares of the Errors in the Horizontal Axes.

Static	Mean 2-D Error (m)	Mean Altitude Error (m)
Inertial/G-858: 15-cm height	0.029	0.019
Inertial/G-858: 30-cm height	0.040	0.012
Inertial/G-858: 45-cm height	0.045	0.035

A substantial portion of these errors was likely due to the test methodology (warping of the plywood board, inaccuracy of placing the standoff fixtures on the board, etc.) and not the geolocation method; the position accuracy of the system could not adequately be measured by the test.

2.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The strength of SAINT is that it provides accurate positioning data over a localized area in a self-contained system. No satellites or external radios are used, so operation is not limited by any terrain or environment considerations. With accurate position data, it is expected that detailed sensor data analysis and inversion will allow buried objects to be characterized. Providing this accurate position data to support target characterization is the primary objective of SAINT.

The main limitation of SAINT is the duration of free-navigation time before the system must be set down and a ZUPT performed. Longer data collection times would facilitate use and decrease total operation time. IMU position errors grow quadratically with the duration of free navigation between ZUPTs. For a given IMU, shorter free navigation leads to smaller maximum errors, longer free navigation leads to larger free-navigation errors. A better quality IMU would extend the useable free-navigation time and/or reduce the maximum error. We selected the HG1900 as a tradeoff between price, size/weight, and performance of available IMUs.

An additional limitation to the current system that drives the positioning accuracy is the variable latency within the EM61-HH system. In standard UXO remediation, the cumulative latency is assumed to be fixed. While this may hold true at a macro level, at a millisecond level there are variable latencies within the EM61 that affect the time correlation between the calculated positions and the measured EM61 data. One primary source of variable latency is the clock in the Allegro, the EM61 data storage device, which has a 9 millisecond resolution. Additional variability between samples is generated by the EM61 operating system and processing load of the Allegro. This creates further difficulty in locating the actual sample location.

The IMU clock (stable to 1 ppm) is used for timing because it is the most precise in the SAINT system. Timing between the IMU and geophysical sensor is achieved using a National Marine Electronics Association (NMEA) GPGGA message for synchronization between the SAINT unit and the Allegro. The GPGGA message contains a time correlating to the IMU and is injected by the Allegro into the geophysical data stream with a time stamp. In postprocessing, the software correlates the time stamps between the Allegro data and the IMU data, then provides relative time offsets for samples based on Allegro times. This time correlation between the Allegro and the IMU is where the most significant timing errors occur because of cumulative and variable latencies within the Allegro and EM-61.

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3.0 DEMONSTRATION DESIGN

3.1 PERFORMANCE OBJECTIVES

Table 2 summarizes the performance objectives of SAINT.

Table 2. Performance Objectives.

Type of Performance Objective	Primary Performance Criteria	Expected Performance (Metric)
Quantitative	Location accuracy	$\le$ 2 cm (1 σ)
	Survey rate for 2 m x 2 m area	$\le$ 5 min
	Postprocessing time for 2 m x 2 m area	$\le$ 5 min
	Setup time (once per day)	$\le$ 5 min
	Density of coverage	EM sensor data on 10 cm or less increments
	ZUPT time	$\le$ 30 sec
	Free navigation time	$\ge$ 30 sec
	Total "on" time before CF download or batteries needed	2 hours
Qualitative	System easy to setup and calibrate by a two person team	Yes or No
	System easy to operate by a two person team	Yes or No
	Postprocessing software easy to operate by inexperienced user	Yes or No

The performance objectives were met as will be discussed in Section 4.3, Data Assessment. The location accuracy objective of <= 2 cm (1 σ) is a relative error. Location accuracy was assessed using the pen test method and by comparison to the relative positioning of the ArcSecond system. The ArcSecond system is a laser-based 3-D positioning system with cm-level positioning error. It was used as an independent ground truth system to establish location accuracy by SAIC (formerly AETC).

3.2 SELECTING TEST SITE

The criteria for selecting a test site were the following:

- Accessible to all project participants
- Buried metallic targets that can be used to compare sensor data with and without the presence of SAINT
- A controlled site with locations of items known so that it may be revisited to gauge improvement and the geophysical data and positioning data may be compared to previous geophysical surveys and technologies.

The selected test site was the APG UXO calibration grid demonstration site. Common limiting factors of navigation equipment, such as vegetation and tree cover are not a factor at the calibration grid, but they do not affect SAINT's performance.

3.3 TEST SITE HISTORY/CHARACTERISTICS

The Standardized UXO Sites Program has test methodologies, procedures, and facilities to help ensure that critical UXO technology performance parameters such as detection capability, false alarms, discrimination, reacquisition, and system efficiency are accurate and repeatable. The APG site is a 17-acre complex composed of five independently scored scenarios. The scenarios include calibration area, blind grid, wooded, moguls, and open field. Within the open field there are a variety of challenges, which include electrical lines, gravel roads, fence line, wet areas, and clutter fields. All grids have been surveyed many times with multiple instruments, including the EM61-HH.

This test utilized only the Calibration Area (#1), as shown in Figure 5.

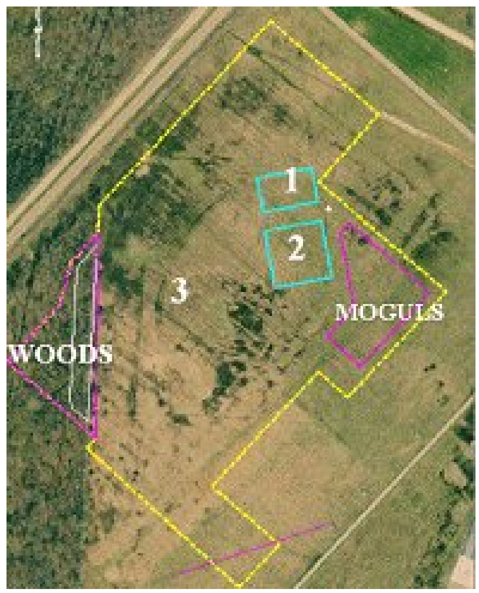

Figure 5. APG UXO Demonstration Site Layout
(#1=Calibration Area).

3.4 PHYSICAL SETUP AND OPERATIONS

The demonstration setup involves attaching SAINT to the EM61-HH, which includes the following:

- Attach SAINT to the EM61-HH shaft using the shaft clamp. (See Figure 6.)
- Lock the hinge of the EM61-HH using custom bracket (tie-straps and shaft clamp). (See Figure 7.)
- Connect data cable from SAINT to EM61-HH data hub (Allegro CE).
- Connect power cable from battery pack to SAINT. Turn the power switch on.
- Measure the offset between the EM61-HH sensor head and the inertial sensor of SAINT in the body frame of the inertial sensor.

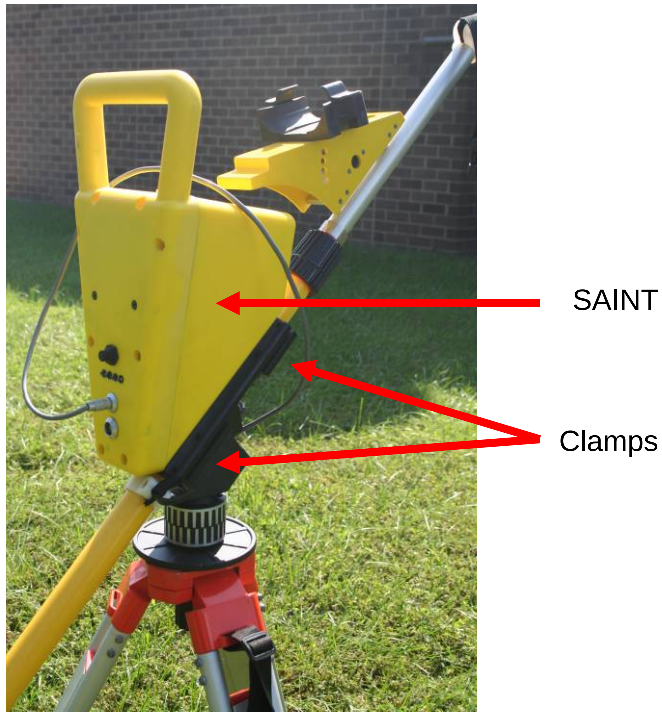

Figure 6. SAINT Attached to the EM-61 HH Handle.

Figure 7. Hinge Locking Mechanism for EM61-HH.

Once powered on, SAINT begins recording IMU and DMC data and will continue collection until the unit is powered off. All data is stored on a CF card, which can be downloaded once at the conclusion of collection or alternatively downloaded via serial port transfer.

Operation is intended for a single operator in possession of the SAINT metal detector system. During field collections it can be helpful to have a second operator to monitor the performance of the first, record notes about the survey, and provide relief when necessary.

Period of Operation

ENSCO's demonstration at APG occurred on September 12-13, 2006. Minor errors in the data acquired on the first day limited its use in demonstrating the system performance. On the second day, in addition to data acquisition over 23 targets in the calibration lane and a test to determine the effect of SAINT on the EM61, a pen test and an ArcSecond test were performed at the beginning and end of the day.

Area Characterized

This test utilized only the Calibration Area (#1), as shown in Figure 5. This area is seeded with inert munitions items ranging in size from small (20 mm) to large (155 mm) objects, 8# and 12# shotputs and loops of wire ranging in depth from 0.1 m to 2.0 m. We interrogated 23 items that include three each of 20 mm, 40 mm, 57 mm, 60 mm, 81 mm, 2.75", 105 mm, and 155 mm seeded items at different orientations/depths as well as one 8# shotput. The items are in lanes 3 A, C, and D; 4 A, C, and D; 6 A, C and D; 7 A, C, D, H, J, and K; 8 A, C, and D; 13 F and H; 14 F and H; and Shotput lane 10 G. These are the same items that were interrogated as in the previous demonstration with the addition of the smaller 20 mm and 40 mm items in lanes 3 and 4. These smaller items were added since the EM61-HH is more effective with smaller items than the G-858.

Operating Parameters for the Technology

All operating parameters are fixed during standard operation. The only requirement is for the operator to follow the routine procedure.

The desired coverage density of sensor data within the interrogation area limits the speed at which the device should be swept over the area. Since sensor data is collected at discrete time intervals, desired sensor data density along the path over which the sensor is swept can be obtained by regulating the speed at which the sensor is swept. Free navigation is limited to 30 seconds to minimize positioning error. To cover a larger area than can be swept in 30 seconds, two or more data sweeps must be performed in series (separated by a ZUPT). A sample sweep pattern is shown in Figure 8. Since the ZUPT locations are the same, no special operation has to be performed in the postprocessing software to overlay the adjacent collections.

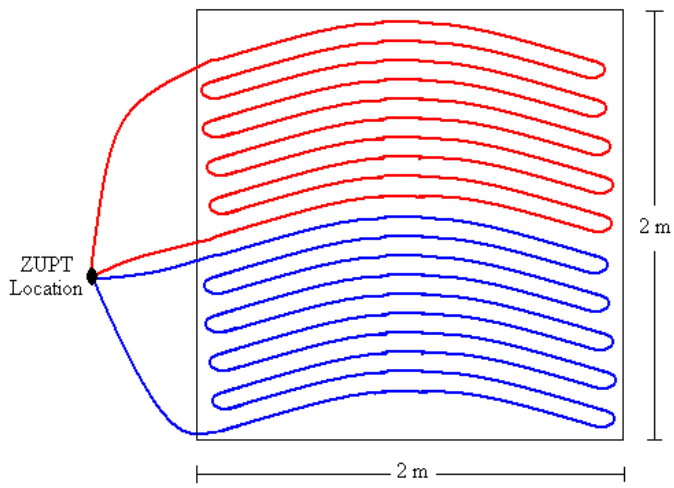

Figure 8. Sample Sweep Pattern to Cover a 4 m^2 Area in Two Passes.

3.5 ANALYTICAL PROCEDURES

ArcSecond Test

The ArcSecond system was operated by SAIC (formerly AETC, Inc.) working under Strategic Environmental Research and Development Program (SERDP) project MM-1381 as a ground truth system for a secondary evaluation of location accuracy. A special bracket was developed to mount the ArcSecond triad directly onto the EM61-HH shaft, as shown in Figure 9. The tests were performed at the start and end of the day to determine if environmental changes such as solar heating or battery discharge impacted the location accuracy. The ArcSecond error analysis performed by SAIC (formerly AETC, Inc.) concluded that "typically, agreement between the two systems was found to be good to within 1-3 cm. The fit qualities with each positioning system were consistent with a < 1 cm positioning accuracy, with the ArcSecond positioning giving noticeably better results."

Figure 9. ArcSecond System and SAINT Mounted on EM61-HH at APG Demonstration.

Collections

Geophysical data were collected in three successive passes over each of the 23 selected targets in the calibration grid with the integrated SAINT and EM61-HH system. SAINT position data are in an arbitrary, local-level reference frame by default. However, for archival and comparison purposes to other activities, position data from the demonstration were transformed to UTM based on the known coordinates where the IMU was located during a ZUPT. When the data were processed, the resulting position data and geophysical data were automatically saved to a separate tab-delimited text file for each pass over each of the 23 targets.

Figure 10. Data Collection over Geophysical Target at APG Demonstration.

4.0 PERFORMANCE ASSESSMENT

4.1 PERFORMANCE CRITERIA

Table 3 includes a summary of the evaluation data. Most of the quantitative objectives consisted of either acquisition or processing times and were simply confirmed based on acquisition times written in field notes and timing of the postprocessing software. The basis of location accuracy is provided in 4.3, Data Assessment.

Table 3. Self-Evaluation of Performance Objectives

Type of Performance Objective	Primary Performance Criteria	Expected Performance (Metric)	Actual Performance
Quantitative	Location accuracy	≤ 2 cm (1 σ)	3-5 mm
	Survey rate for 2 m x 2 m area	≤ 5 min	4.3 min
	Postprocessing time for 2 m x 2 m area	≤ 5 min	3.25 min
	Setup time (once per day)	≤ 5 min	< 5 min
	Density of coverage	EM sensor data on 10 cm or less increments	100% coverage <= 10 cm increments
	ZUPT time	≤ 30 sec	17 sec
	Free navigation time	≥ 30 sec	28 sec
	Total "on" time before CF download or batteries needed	2 hours	4 hours
Qualitative	System easy to setup and calibrate by a two person team	Yes or No	Yes
	System easy to operate by a two-person team	Yes or No	Yes
	Postprocessing software easy to operate by inexperienced user	Yes or No	Yes

4.2 PERFORMANCE CRITERIA

The primary performance criteria for this project are stated in Table 2. The successful demonstration of the SAINT technology at APG essentially consisted of collecting an adequate density of EM61-HH geophysical data (<= 10 cm between samples) while maintaining a relative location accuracy <= 2 cm (one standard deviation). Secondary demonstration objectives were to show robustness and reliability of the system, efficient data acquisition, ease of use, and simplicity of postprocessing

4.3 DATA ASSESSMENT

The SAINT system exceeded the project objective for location accuracy of 2 cm by a factor of four in both predemonstration testing and at the APG demonstration as verified by the pre- and post-survey pen tests. Analysis of the EM61-HH data merged with SAINT's position data using model-based EM inversion fits concluded that radial position errors were less than 1 cm for 21 of the areas interrogated. The remaining two areas were off by as much as a meter with the cause not identified. The location accuracy independently evaluated by SAIC (formerly AETC, Inc.)

using the ArcSecond system as ground truth concluded that the majority of the acquired ArcSecond and SAINT sensor position data showed agreement to within 1-3 cm. The inversion modeling results generally were better with the ArcSecond system than with the SAINT. The primary sources of location errors are the gyro and accelerometer biases. These biases change every time the unit is turned on and hence cannot be estimated just once and removed from the data but must be continually estimated inside the Kalman filter. The use of ZUPTs and position updates (when the unit is returned to the ZUPT stand after each free-navigation period) enable the Kalman filter and R-T-S smoother to estimate and remove these biases. These biases limit the length of free-navigation time for collecting data.

In addition to the demonstrated location accuracy, the system was shown to be easy to setup and operate and met the project objectives for survey rates and postprocessing times, which led to efficient field operations. The system routinely took less than 5 minutes to set up during testing. The free-navigation time was calculated as the average time during which the IMU was moving (start and stop times were extracted from the accelerometer data) for all 23 targets interrogated. The average time of 28 seconds is slightly lower than the objective of 30 seconds because the operator was returning the system to the ZUPT location when cued by the audible warning signals that the 30 seconds of free navigation was approaching.

5.0 COST ASSESSMENT

5.1 COST REPORTING

The major cost drivers for this system are the IMU and the quantity-one enclosure fabrication expense typical of prototype design. Larger production quantities will significantly reduce the cost per enclosure. The IMU used has not yet entered commercial production so price per unit at moderate and large quantities is not available.

The most significant factor affecting cost and performance is the data production rate: how many sites an operator can interrogate during a fixed period of time. It is expected that this method will show significant time and cost savings as compared to laser surveying or other manual methods.

For this demonstration, application costs and productivity are recorded and compared. This includes items such as a) daily/weekly/monthly technology costs for rental, purchase and maintenance; b) technology availability and downtime considerations; c) survey productivity factors that include setup, survey area limitations, operating personnel labor requirements, cost; and d) data processing considerations for position and geophysical instrument integration.

The SAINT technology is directed toward allowing more effective selection of which detected targets underground should be excavated at munitions sites. Because excavating nonhazardous objects can represent the majority of munitions remediation expenses, the potential impact of this technology is significant.

There are three primary cost factors associated with SAINT and its impact of munitions remediation: 1) the cost of the system, 2) the production rate (how fast and efficiently it can be operated), and 3) the effectiveness of the derived target dig lists.

The cost of a commercial SAINT system has not been determined. However, the critical component of SAINT, the Honeywell HG1900 IMU, has the largest part cost, approximately $10,000 at the time of this writing. Market forces indicate that IMUs in this MEMS line of products should decrease to approximately $5,000 per unit within 2-4 years. Other components of SAINT are much less costly. Therefore, the cost of a SAINT system is comparable to the cost of current geophysical sensor systems (EM-61, G858, etc.) or a commercial R-T-S system ($20,000-$30,000).

The production rate observed for SAINT operations at APG was approximately 4 hours for 23 targets for a single operator using a single system. Therefore, a single operator could interrogate approximately six targets per hour.

No effort was made under this project to evaluate the effectiveness of the target characterization algorithms. SAINT is designed as a tool for collecting data efficiently for target characterization; evaluation of the efficacy of these efforts is beyond the scope of this effort.

5.2 COST ANALYSIS

Cost to operate SAINT consists of a single operator employing a Geonics EM-61 integrated with the SAINT system. This operator can interrogate approximately six targets per hour, or 48 targets per day, at the production rate demonstrated. With experience and operating in a production setting, this rate is expected to double to 96 targets per day.

Given that an operator has been previously trained in using the EM-61 HH, SAINT-specific hardware instruction could be accomplished in less than 2 days. Improvements to hardware and software for ease of use in operational settings and system maintainability would reduce the instruction time to less than one day.

The primary cost driver to deploy SAINT is the production rate, which, given the EM-61 cost, SAINT cost, and labor cost, determines the interrogation cost per target. We can estimate this cost using the following rough order of magnitude estimates. Rental costs were taken from the web site of Exploration Instruments, www.expins.com:

Fully burdened daily labor cost (one person)	$500
EM-61-HH daily rental cost	60
SAINT daily rental cost (estimated)	100
PC daily rental cost	20
Total daily cost	$680

At 96 targets per day, the average interrogation cost is therefore $7.08 per target. Life-cycle costs are incorporated into the daily rental costs.

5.3 COST COMPARISON

There is no existing technology that SAINT is designed to directly replace. However, setup time and costing is similar to the R-T-S. This is the closest technology commercially available that can come close to the inertial navigation system (INS) accuracy. The RTS system demonstrated an average accuracy of 0.07 m in previous testing in 2004 (Millhouse: Innovative Navigation Systems to Support Digital Geophysical Mapping, ESTCP #200129 Phase III APG Demonstration and Phase IV Development Draft Final Report 17-Feb-2006). This test was performed in conjunction with the previous testing of this technology as outlined in Section 2.3, Previous Testing of the Technology. An accuracy of 0.07 m is not enough for interrogation data application. In that report only the ArcSecond system was demonstrated to provide an average accuracy appropriate for characterization. However, the manufacturer of the system, Metris, Inc. (formerly ArcSecond), made a decision in February 2007 to discontinue development of the ArcSecond system. The prototype ArcSecond system cost was $100,000.

The cost impact of SAINT depends on the efficacy of target characterization efforts, which are outside the scope of this effort. Therefore, the full impact of SAINT will not be known until the efficacy of characterization methods is better known.

6.0 IMPLEMENTATION ISSUES

6.1 COST OBSERVATIONS

The actual cost of a commercial SAINT system has not been determined. However, the critical component of SAINT, the Honeywell HG1900 IMU, has the largest part cost of approximately $10,000 at the time of this writing. Market forces indicate that IMUs in this MEMS line of products should decrease to approximately $5,000 per unit within 2-4 years. Other components of SAINT are much less costly. Therefore, the cost of a SAINT system is comparable to the cost of current geophysical sensor systems (EM-61, G858, etc.) or a commercial R-T-S system ($20,000-$30,000). A product unit cost will be driven principally by the cost of the IMU and by market size. Market size will determine if the units could be standardized and mass produced at reduced costs.

6.2 PERFORMANCE OBSERVATIONS

The system met all performance objectives except the 30 seconds of free navigation. The average time of 28 seconds is slightly lower than the objective of 30 seconds because the operator was returning the system to the ZUPT location when cued by the audible warning signals that the 30 seconds of free navigation was approaching. For location accuracy, the system was more accurate than the 2-cm objective with subcentimeter accuracy validated by the pen tests and the data inversion results.

6.3 SCALE-UP

More development effort is required prior to scale-up for data analysis, geophysical sensor synchronization, and for the SAINT processor upgrade. This unit is currently a unique one-of-a-kind prototype. Development effort is proposed as part of a new ESTCP project, Advancing Discrimination Performance by Integrating SAINT with Handheld EMI Sensors, by SAIC.

6.4 OTHER SIGNIFICANT OBSERVATIONS

Prior to commercializing this technology, additional effort will be required for geophysical instrument integration specifically for data synchronization and timing.

6.5 LESSONS LEARNED

None.

6.6 END-USER ISSUES

The SAINT system is an enabling technology to provide precise locations to support interrogation of a geophysical anomaly. For interrogation to be of value, there must be proven analysis techniques for discrimination and a market for their use. If it is ultimately cheaper to dig a suspected item rather then interrogate and discriminate then the techniques will never be applied. The end users must accept the process to create a market for these tools.

6.7 APPROACH TO REGULATORY COMPLIANCE AND ACCEPTANCE

This is not applicable since this is an enabling technology that is only part of a solution.

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7.0 REFERENCES

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APPENDIX A

POINTS OF CONTACT

Point of Contact	Address	Phone/Fax/E-Mail	Role in Project
Scott Millhouse, PE	U.S. Army Corps of Engineers Engineering & Support Center-Huntsville 4820 University Square Huntsville, AL 35816-1822	Ph: 256-895-1607 Fax: 256-895-1737 scott.d.millhouse@ usace.army.mil	Principal Investigator
David W.A. Taylor, PhD	ENSCO, Inc. 5400 Port Royal Road Springfield, VA 22151	Ph: 336-632-1200 Fax: 336-632-1225 taylor.david@ensco.com	Contractor Lead Scientist
Jane Bohlin	ENSCO, Inc. 5400 Port Royal Road Springfield, VA 22151	Ph: 703-321-4681 Fax: 703-321-4609 bohlin.jane@ensco.com	Contractor Task Manager

ESTCP Program Office

901 North Stuart Street
Suite 303
Arlington, Virginia 22203

(703) 696-2117 (Phone)
(703) 696-2114 (Fax)

e-mail: estcp@estcp.org
www.estcp.org