ESTCP
Cost and Performance Report

(UX-0129)

Innovative Navigation Systems to Support Digital Geophysical Mapping

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ENVIRONMENTAL SECURITY
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COST & PERFORMANCE REPORT
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ACRONYMS AND ABBREVIATIONS

CEHNC	U.S. Army Engineering and Support Center, Huntsville
CWM	chemical warfare material
DGM	Digital Geophysical Mapping
DGPS	Differential Global Positioning System
DSSS	direct sequence spread-spectrum
EM	electromagnetic
FUDS	formerly used defense sites
GPR	ground penetrating radar
GPS	global positioning system
IMU	inertial measurement unit
INS	Inertial Navigation System
MEMS	Micro Electro-Mechanical Systems
NP	navigation processor
OE	ordnance and explosive
POS/LS	Positioning and Orientation System for Land Survey
RF	radio frequency
RTK	real-time kinetic
RTS	Robotic Total Station
SMDBL	Space and Missile Defense Battle Lab
3D	three-dimensional
UTM	Universal Transverse Mercator
UXO	unexploded ordnance

ACKNOWLEDGEMENTS

The author would like to thank Jeff Marqusee and Anne Andrews of ESTCP for their continued support for the demonstrations. Thanks also to Sergeant Whittaker and the Redstone Arsenal McKinley Range, Huntsville, Alabama staff for graciously hosting the navigation demonstrations on their range.

1.0 EXECUTIVE SUMMARY

1.1 BACKGROUND

Unexploded ordnance (UXO) poses a threat to human life and to the environment. Millions of UXO may be located in the United States on active test and training ranges and formerly used defense sites (FUDS). Essentially, all project investigations addressing UXO involve the use of digital geophysical mapping (DGM). A major requirement with use of DGM is accurate navigation for sensor position, which becomes especially problematic with ground vegetation and tree canopies. Accurate, inexpensive, and easy-to-use navigation systems with consistent quality are needed for surveys in all terrain and vegetation cover. Navigation accuracy is critical in acquiring the DGM data required for anomaly discrimination.

1.2 OBJECTIVES OF THE DEMONSTRATION

The primary objective of this project is to demonstrate and compare multiple navigation systems to support DGM. Phase I demonstrations were performed to demonstrate navigation capabilities without geophysical sensors. In Phase II, promising systems are developed and integrated with geophysical equipment. Phase I demonstrations include eight navigation systems. The benchmark system for comparison is a typical $250 Garmin global positioning system (GPS) III handheld. The handheld unit was easy to use, readily available, inexpensive, and much more accurate than expected. Although ill-suited for direct usage to support geophysical mapping navigation, it did provide a navigation performance benchmark as a less accurate but inexpensive approach. This paper addresses the Phase I demonstration performed during October and November 2001 for concept study, presentation, and demonstration for navigation equipment. Future Phase II efforts planned for late 2002-2003 and Phase III efforts planned for 2003-2004 will develop and demonstrate the technologies integrated with typical geophysical equipment such as the electromagnetic (EM)-61 series and G-858 magnetometer sensors, with development towards commercial, integrated system approaches.

There are three levels of accuracy needed to support the ordnance and explosive (OE) program as outlined in the original request for proposals: screening level to determine areas of interest as implemented by airborne sensors, area mapping as performed by man portable and towed arrays, and interrogation, where highly accurate dense data is acquired to interrogate and discriminate a geophysical anomaly. Position tolerances of 0.5 m, 5 cm and 2 cm are desired for these scenarios. For this demonstration, tolerance is defined as the leeway for variation from a standard with the standard being the civil surveyed position of the known and unknown points and accuracy the demonstrated deviation from that standard. The following goals are desired for highly performing equipment:

- A 10-minute setup
- A 1,000'+ range per setup
- The ability to have multiple crews working in same area without interference
- Less that $20,000 per unit cost
- Voice communication
- Go-to point capability

- Real-time data transmission (could allow real-time geophysical analysis from a central location),
- The ability to capture the z or elevation data along with position
- The ability to determine relative position of individual sensor heads when coupled with geophysical instrumentation
- Flexible use with geophysical instruments [mag, electromagnetic (EM), ground penetrating radar (GPR), etc.]
- Selectable accuracy mode to get higher accuracy for interrogation of anomalies (most likely at slower rate of sensor travel speed)
- Heads-up track map display for surveyor
- The ability to support real-time grid generation and display of geophysical data when coupled with geophysical sensors.

Table 1 lists the demonstration vendors, their system type, and their technology.

Table 1. Demonstration Vendors.

Vendor	System Name	Technology
CEHNC	Garmin GPS III	Handheld GPS
ARINC, Inc.	LEOPARD Lite	GPS with satellite communications
Paper Pilot Research Inc.	New integration	GPS and inertia guidance
ENSCO	Tracker	Radio frequency
IT Group/Shaw*	Leica RTS	Robotic total station
ArcSecond, Inc.	Vulcan/LaserStation	Line-of-sight laser
Parsons	Trimble INS/GPS	DGPS and inertia guidance
Blackhawk	Applanix INS/GPS	DGPS and inertia guidance

*IT Group was purchased by Shaw Environmental.

1.3 PHASE I DEMONSTRATION RESULTS

The systems were deployed with varying degrees of success. The Phase I demonstration delineated the relative strengths and weaknesses of each system, the areas of application where each system would be beneficial, and the areas where each system required improvement.

Following compilation of the results, the most successful technology with the most value is the Robotic Total Station (RTS) as demonstrated by IT. It can easily meet all accuracy needs in the open to permit geophysical data analysis for discrimination. In addition, the integration of geophysical equipment was successfully demonstrated.

The ArcSecond System matches the RTS performance but it is greatly range limited. This system as it currently exists is perfectly suited for providing highly accurate three-dimensional (3D) data acquisitions for small areas desired for dense geophysical mapping to interrogate chosen anomalies.

2.0 TECHNOLOGY DESCRIPTION

2.1 U.S. ARMY ENGINEERING AND SUPPORT CENTER, HUNTSVILLE (CEHNC)

The baseline demonstration technology uses a commercially available, consumer level, handheld GPS available for approximately $250 (see Figure 1). Points are captured in Universal Transverse Mercator (UTM) coordinates by a 60-second occupation of a location, which is stored in the unit a waypoint. Analysis consisted of using the known locations of the monument points as a basis for the local adjustment of coordinates from the WSG84 standard used in the unit to NAD 27 site survey basis. This test was established not to compete with the demonstrated systems but as a baseline low accuracy, low-cost solution for comparison.

Figure 1. Typical Handheld GPS Unit.

Where ease of use and low cost is important and integration to equipment or position accuracy is not important, low-cost GPS units and their derivations, such as PC card GPS units for data recorders and laptops, do have an application. The principal application would be to acquire data for characterization of large areas to help determine areas of interest for further, more detailed investigations. The units' strengths are ease of use and low cost, and their weaknesses are their inaccuracy (especially without post processing corrections based on occupation of known points) and their inability to maintain accuracy without a clear view of the GPS satellites.

2.2 ARINC, INC.

The LEOPARD Lite system demonstrated by ARINC, Inc. originates from a prototype technology demonstration program sponsored by the U.S. Army Space and Missile Defense Battle Lab (SMDBL). The program is 3 years old, and the capability continues to evolve to meet military requirements. LEOPARD Lite can be used for surveillance and reconnaissance, UXO marking and reporting, position reporting, personnel and vehicle tracking, and situation awareness. The system is essentially an integration of GPS with mapping, display, and communications all in a backpack portable field system (see Figure 2).

Figure 2. ARINC System.

The LEOPARD Lite backpack system transmits data to a LEOPARD Lite base station for display and data archiving. The base station consists of two laptops in a ruggedized transit case.

One laptop is used as the communication processor and the other hosts the mapping and navigation software. The LEOPARD Lite system has the capability to create and send route plans, record a traveled path, and navigate using a variety of techniques. The moving map display allows the backpack operator's location to remain in the center of the map while he/she is traveling. Text messages may be sent from the LEOPARD Lite backpack configuration to the LEOPARD Lite base station in near-real-time via satellite. When the messages contain map data, the base station map is updated automatically. Waypoints and routes are easily entered and displayed on the Paravant palmtop computer to assist with navigation. The LEOPARD Lite system is easy to operate, easy to transport, and requires minimal training time for personnel familiar with GPS, Windows operating systems, and satellite communications devices. Accuracy is limited to direct unadjusted GPS. The technology was demonstrated because of its systemized approach and the unique use of the Iridium satellite system for data transfer and communications.

The demonstrated system is essentially a GPS engine similar to the handheld unit demonstrated by CEHNC. Captured points were significantly less accurate. This may be attributed to the age of the GPS unit but more likely to field procedures and a poor GPS satellite alignment. This unit captured an instantaneous point position rather than the 60-second count as used by CEHNC. Performance was typical of what is historically expected from standard GPS units.

The system was not specifically demonstrated for accuracy but for the rugged system approach and the novel communications methodology. Base accuracy can be improved by integrating DGPS or any of the demonstrated technologies. The advantage is data capture and transmission by the Iridium satellite system to display and process at a remote location anywhere in the world. Further development would be required to increase the data transfer rate to handle a real-time or near-real-time batch data transfer from the geophysical sensors. Unknown factors are the future availability and cost of using the Iridium communications system.

2.3 PAPER PILOT RESEARCH INC.

The prototype system is an integration of low-cost GPS/INS (Inertial Navigation System) hardware stowed in an equipment pack, with display and control by the handheld computer (see Figure 3).

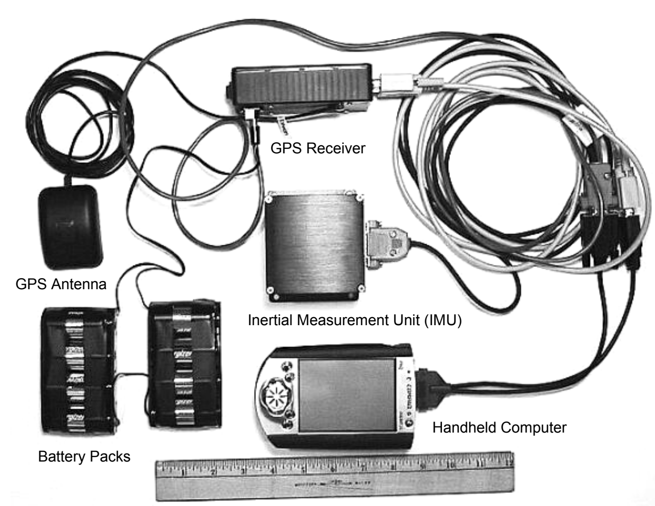

Figure 3. PaperPilot GPS/INS System.

The inertial measurement unit (IMU) is the IMU400CA-100 model from Crossbow Technology, Inc. The IMU400CA contains three Micro Electro-Mechanical Systems (MEMS) accelerometers and three solid-state angular rate gyros, for a total of six sensors. The MEMS terminology refers to a technology wherein very small mechanical devices, in this case vibrating beams, are constructed in silicon and mounted on a computer chip. The

IMU400CA sensors measure longitudinal, lateral, and vertical accelerations, as well as pitch, roll, and yaw angular rates. The Garmin GPS 25-HVS receiver tracks up to 12 satellites and provides position updates every second. The GPS and IMU sensor boards both have built-in RS-232 communication ports. The sensor boards are interfaced to the handheld computer via a two-port serial PC card manufactured by Quatech, Inc. The mobile host is a Compaq iPaq 3765 handheld computer. This computer has an ARM SA1110 32-bit processor, 64MB RAM, and 32 MB ROM. The operating system is Microsoft Pocket PC Version 3.0. A dual PC card expansion pack is used to house the multiport serial PC card and an extra 48 MB Compact Flash memory card.

There are two software programs that are used for data collection and processing. The PNAV program resides on the handheld computer and is intended mainly for data collection and providing real-time navigation information in the field. The second program, PSMOOTH, is used for data postprocessing, the binary data files generated by PNAV. The PSMOOTH program implements the complete six degree-of-freedom a priori navigation algorithm and generates estimates of 3D position and velocity. The final, smoothed position estimates can be provided in geodetic or local coordinates.

The demonstrator has assembled his system using the same low-cost GPS engine as in the handheld device but as packaged in PC cards. This is a low-cost "proof of concept" demonstration of INS integration and postprocessing software analysis. Assembling the GPS, INS, and computer/data recorder into a backpack system would permit easy integration with any geophysical instrument to create a low accuracy, low-cost system (approximately $5,000). The INS is the principal component cost. The INS maintains the base unit's accuracy when satellite lock is lost. The principal effort was to control errors using software to predict and test recorded position locations. The demonstration had some success and matched the accuracy of the CEHNC demonstrations, but it was not clear how much improvement was made by the INS integration. Errors from the low cost INS must be more tightly controlled by providing a vector of travel, which could be done with an inexpensive electronic compass.

The advantages are low cost, easy integration with geophysical equipment, and the potential to maintain accuracy in the woods. The principal disadvantage is low position accuracy and the need for future development and demonstration prior to fielding. The same concept should work to maintain accuracy with the more capable differential globe positioning system (DGPS) systems.

2.4 ENSCO

ENSCO's system is a local radio frequency (RF) positioning system (see Figure 4). It measures distances from a user to a suite of local RF transponders. The position is computed with measured distances from the transponders.

The unique aspect of this scheme is the one-dimensional distance measuring technique. The method relies on direct sequence spread-spectrum (DSSS) communications in the 2.4 GHz ISM band (the same band used by spread-spectrum modems, 802.11 communications, Bluetooth™, and microwave ovens). Distance measuring techniques using spread-spectrum communications

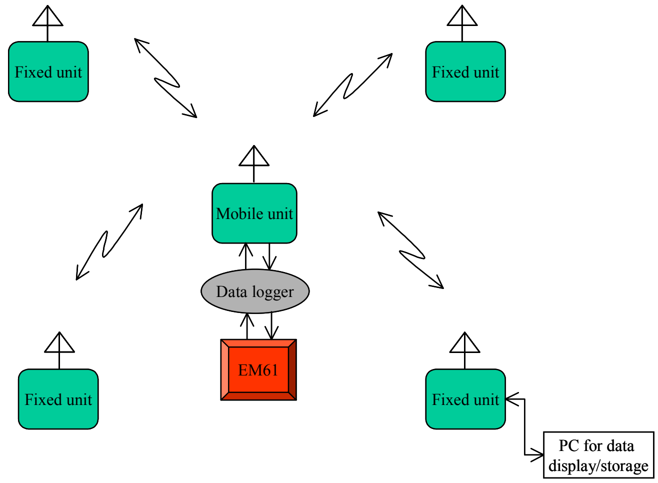

Figure 4. ENSCO Radio Navigation Concept.

are well known in literature and historically provide position uncertainties on the order of tens of meters, which is inadequate for DGM and UXO needs. The patented technique to improve accuracy exploits small intentional differences in the clock frequency between the user's DSSS radio (the mobile radio) and the fixed radio(s). There is a periodic "slip" in the DSSS signal that is a function of the difference in the two clock frequencies. This slip can be calibrated to acquire a fine resolution distance measuring capability to enhance the "coarse" resolution achievable by these prior well-known means.

Modifications to this system have improved accuracy from the previous systems and decreased cost. System cost when marketed should be moderate ($20,000-$30,000) and comparable to the laser measurement approaches such as the RTS and LaserStation. The advantages are ease of setup and the potential to cover a day's work area in a single setup in the open and in the trees. The demonstrated system automatically provided positions within the work perimeter and transmitted the tracking and geophysical data to the base computer. That data was automatically displayed as intensity track maps in real time. The system appeared to be very easy to set up and use. The disadvantage is the accuracy. The demonstrated system accuracy is less than would be desired for a man portable deployment, with positions within 0.25 m in the open and 0.9 m in the trees. Development to improve both would make this an excellent navigation solution.

2.5 SHAW ENVIRONMENTAL (IT GROUP)

An RTS operates under a different concept from the GPS and other technologies that measure from multiple known locations as established by base units or the GPS satellites (see Figure 5). It is essentially a laser-based survey station that derives its position from traditional survey methodology by measuring locations relative to known (or assumed) point locations, and then tracks the relative position of the sensor. The robotic portion maintains track

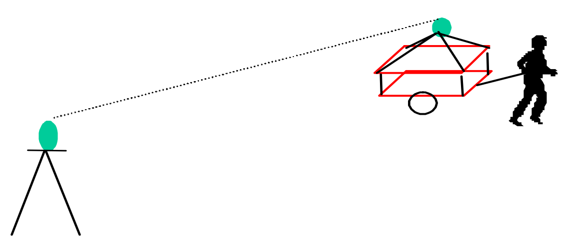

Figure 5. Shaw (IT Group) Robotic Total Station Concept.

on the moving object. The unique quality of this demonstration is the introduction of procedural and software modifications to allow the commercial RTS to maintain lock in heavy vegetation by predicting the location of the sensor and then reacquiring it when lost due to line-of-sight obstructions such as trees. The demonstrated geophysical mapping technology has both hardware and software components.

Hardware. System hardware consists of three integrated components: (1) geophysical sensors, (2) a composite-material cart survey system, and (3) the Leica TPS1100 dual laser RTS. The geophysical sensors (Geometrics G858) and cart-system have been engineered into an effective mapping device used for geophysical mapping at several UXO and non-UXO characterization sites. The LeicaTSP1100 is a motorized RTS that uses automatic target recognition to track the location of the prism and has a highly accurate distance/azimuth measurement system to produce +/-5 mm +2 ppm accuracy.

Software. Three software components are integrated in the demonstrated technology. First, modified firmware is used on the RTS base station to track the roving prism. This firmware was developed specifically for this application and allows for rapid collection of data at rates of up to 4 Hz, and serial output of solutions on both the base station and rover computing units. The new firmware also enables the user to optimize the prism tracking parameters for rapid recovery of lock if the signal is obstructed by trees during a survey. Second, time synchronization software was developed for determining precise clock slews between the RTS and sensor clock, ensuring accurate time representation of all collected data. Third, data-merge software is used to allow definition of the sensor geometry during collection. This software provides a robust framework to spatially configure sensors relative to each other and with respect to the prism location, resulting in accurate spatial representation of all collected data.

System costs are reasonable and accuracy excellent, as would be expected, since it basically is a surveying total station that automatically maintains a rover's position by continuous tracking. Performance was excellent in the woods with a high accuracy and distance measurement capability. The technology is pure line-of-sight, so it works around obstructions by reacquiring the prism when it reemerges into view. An obvious disadvantage is that this gap in position must be filled by interpolation from captured points. The denser the vegetation and the greater the distance from the rover, the more data gaps one would have to fill from the interpolations. This demonstration minimized line-of-sight problems by intelligent use and positioning of the equipment. Replicating performance in the woods may be more challenging on a typical site with typical field personnel but should remain very easy in the open. This system demonstrated accuracy of 0.004 m in the open and 0.09 m in the woods. The open accuracy easily meets our most challenging objectives.

2.6 ARCSECOND, INC.

ArcSecond's 3D measurement technology, which goes by the trade name of 3D-Intelligence®, consists of three primary components: (1) laser transmitters, (2) optical sensors, and (3) signal processing software and electronics (see Figure 6).

Figure 6. ArcSecond Vulcan LaserStation System.

Each laser transmitter creates a unique signature of light pulses that are broadcast throughout a workspace. The timing and duration of these light pulses varies depending on location within the workspace. The optical sensors detect the light pulses from the transmitters, then send signals to the software and electronics for processing. The timing information from the various pulses is decoded and converted into position coordinates for the point being measured. The position of each sensor is calculated 50 times a second (50 Hz).

The position calculation algorithms use triangulation principles, and no communication occurs between the sensors and the transmitters. Consequently, an unlimited number of receivers may work from as few as two transmitters. A minimum of two transmitters is required to triangulate, though one transmitter may give sufficient information for low-accuracy applications. This is the modern equivalent of the stadia method of traditional surveying. The user may also navigate to predefined locations using a real-time map screen.

System costs are reasonable and accuracy is excellent with demonstrated accuracies of 0.006 m in the open and 0.08 m in the woods. The technology is pure line-of-sight. If obstructed, the optical sensors are reacquired when they reemerge into view. During operation, the pole may be tilted to maintain view, and the system automatically calculates the point position. Track can be maintained although of lower accuracy if only one optical sensor is in view. Like the other line-of-sight equipment, where there is an obstruction, there is a position gap that must be filled by interpolation from captured points. All advantages are tempered by the low range of the demonstrated equipment (a maximum of 45 m). For small areas in the open, the system can easily meet our highest accuracy objective. The disadvantage is that the area is so small that it would require frequent set ups and known positions to work from to maintain a coordinate system. The range limitation is not perceived as a disadvantage for interrogation at high precision of an identified anomaly. Proposed enhancements could increase the coverage area to 5 acres, so that one setup could perform a day's efforts.

2.7 PARSONS

The real-time kinetic (RTK) GPS and ring laser gyro INS technologies both are proven methods of navigation. This integration of the two methods was undertaken as a joint venture between Trimble and a seismic acquisition company. The goal was to create a system capable of providing accurate positional information in areas of heavy tree canopy to support seismic 3-D surveys.

Figure 7. Parsons/Trimble DGPS/INS System.

The 4700 RTK GPS component evaluated in this project (see Figure 7) has been used in conventional surveying methods and for UXO removal activities. It uses carrier-phase processing in both the L1 and L2 channels to provide centimeter-level accuracy. The primary disadvantage of RTK GPS is that it does not function well when under even marginal tree cover.

The system tested was innovative because it combines the RTK GPS unit with a highly accurate INS that is small and lightweight. The INS unit chosen for integration with the Trimble GPS is the Honeywell Talin system. This is a ruggedized INS that is used in military vehicles such as the Bradley fighting vehicle to provide accurate positioning and targeting while the vehicle is moving.

An INS uses very accurate measurements of acceleration and changes in the azimuthal angle to compute the motion of the unit from a known starting point. The acceleration measurements are obtained by three orthogonally oriented accelerometers. They are sufficiently sensitive to allow accurate orientation of the system relative to vertical by measuring the earth's gravitational field.

The information from the all the sensors, including the GPS information, is integrated using an internal processing package that implements a Kalman filter. The Kalman filter attempts to predict the current state of the system (in the case of an INS system, the location and orientation of the system) using the sensor measurements and information on the noise and sensor errors. Any differences in the measured state and the predicted state are then used to recompute the filter parameters. As a result, the system is always adapting to current conditions. In practice, because the RTK GPS information has a much higher accuracy than the INS data, the GPS information is always used when an RTK GPS fixed quality position is available. When the system loses RTK GPS fixes, the system automatically switches to providing positional information from the INS system only.

Accuracy in the open was solely supplied by the DGPS and is typical of a high-end system. The INS attempted to maintain this accuracy with loss of DGPS navigation. Accuracies of 0.04 m in the open and 0.6 m when utilizing INS were demonstrated. The low INS accuracy shows that additional work is required to develop a field usable system for geophysical mapping. In addition, the INS portion of the system was extremely expensive and adding that component made a bulkier, heavier product with reduced productivity due to calibration and position updates. The current implementation is not recommended except for special applications for DGM usage due to inaccuracy and excessive cost. The demonstration gathered information to assist in developing a lower cost system using alternative INS components. The next generation may be a viable product. Note that Trimble manufactures the GPS units but purchases the INS units for integration.

2.8 BLACKHAWK

The Applanix Positioning and Orientation System for Land Survey (POS/LS) was used for the Phase I work. The system is similar to the Parsons-demonstrated GPS/INS. Where they differ is that Applanix is an INS specialist using purchased industry standard RTK GPS components for integration into their system.

The POS/LS is a man-portable INS that utilizes (where available) GPS data to improve position accuracy (see Figure 8). An INS contains two core components: an IMU and a navigation processor (NP). The IMU contains three accelerometers and three gyros, whose respective input axes form an orthogonal triad, plus digitization and digital interface electronics. The accelerometers measure the specific force that the IMU experiences, comprising accelerations and gravity with respect to an inertial reference. The gyros measure the angular rate that the IMU experiences, including its angular rate with respect to the earth plus the earth's angular rate with respect to the inertial reference. The NP receives the inertial data and performs two functions. First, it performs an *alignment*, during which it establishes an initial position and orientation using the local gravity vector as the vertical reference and North component of the earth rate vector as the heading reference. Having established a navigation frame of reference that is locally level and having a known heading with respect to North, the NP then transitions to its *free-inertial navigation* mode. It solves Newton's equations of motion in the navigation frame on the earth from the measured specific force and angular rate data to generate a current position, velocity, and orientation solution at a specified sampling rate.

Figure 8. Blackhawk/Applanix GPS/INS System.

Accuracy in the open should have been solely supplied by the DGPS but was instead generally provided by the INS component and was, therefore, lower than expected from a high-end DGPS system. This is most likely due to partial equipment failures during the demonstration of the DGPS integration that caused loss of the data. The INS attempted to maintain accuracy with loss of DGPS navigation. Accuracies of 0.2 m in the open and 0.6 m when utilizing INS were demonstrated. The low INS accuracy shows that additional work is required to develop a field usable system for geophysical mapping. In addition, the INS portion of the system was extremely expensive and adding that component made a bulkier, heavier product with reduced productivity due to calibration and position updates. This vendor demonstrated his equipment on an EM-61 chassis and emphasized an advantage of INS to capture the actual movement of the sensor position to tilt, twist, crab and lifting. This capture would permit processing out these errors and creating a more accurate geophysical data set. The current implementation is not recommended due to inaccuracy and excessive cost. The demonstration gathered information to assist in developing a lower cost system using alternative INS components.

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3.0 DEMONSTRATION DESIGN

3.1 SITE/FACILITY DESCRIPTION

The demonstration test site was the McKinley Range, Redstone Arsenal, Huntsville, Alabama.

3.2 SITE/FACILITY CHARACTERISTICS

CEHNC has established a series of test plots on a portion of the McKinley Range. The site is broken into five test areas with various objectives. The individual grids are defined by civil surveyed steel pin corner points outlining four 100′x100′ grids. The fifth area is a figure eight traverse into the woods (see Figure 9). An adjacent unseeded open area to the west provides a traverse extension for range evaluations along with an eastern traverse extension along the access road. The individual points for the grid corners and traverse were used as well as the six long range points to the west extension and the two long range points to the east extension in evaluations. These extensions provided individual clear line-of-sight distance measurements of over 1500′. Demonstrators were only provided with the locations of the corners of the 100′ x 100′ grids. All “figure-eight” traverse points were challenging due to a restricted view of the horizon and line-of-sight by either cultural or natural features.

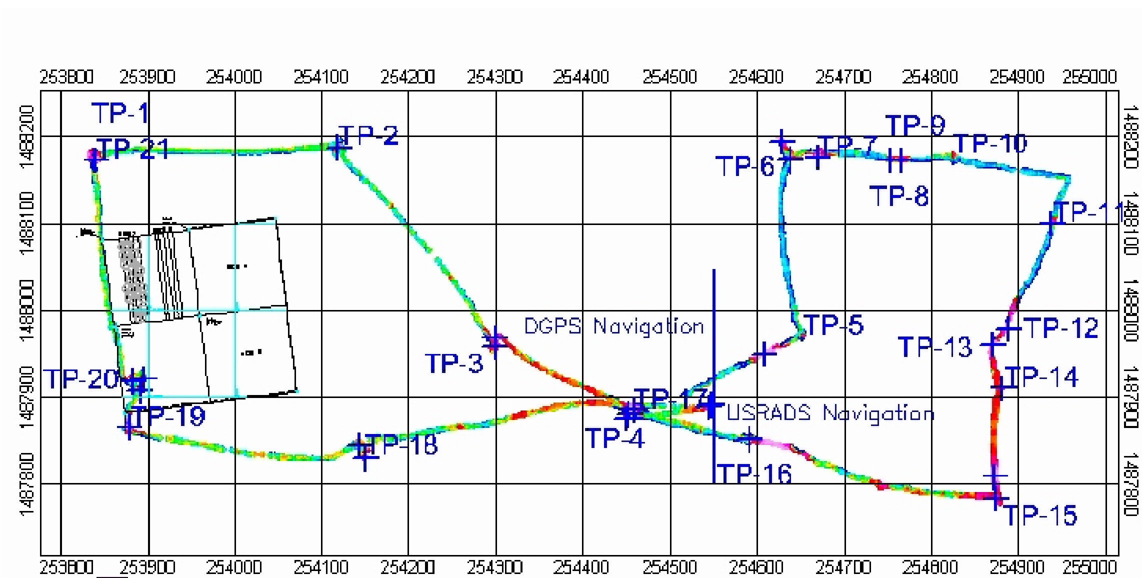

Figure 9. Figure-Eight Traverse — McKinley Range Test Site.

The following areas will be used predominately in Phase II, although the grid corner point locations were used in Phase I as the navigation basis for the demonstrations. Grid 1 is seeded with inert OE items from 20 mm to 2,000 lb bombs from a few inches to nearly 10-ft at depth. The grid is broken into two lanes, known and unknown. This grid has been used for instrument validation since 1994. Grid 2 is seeded with items typical for chemical warfare material (CWM) sites, including chemical test kits, pigs, and containers. Grid 3 is a series of sand trenches of various gradations that are also seeded with CWM stimulants. Grid 4 is seeded with traditional OE items but it is constructed to be more representative of an impact area. It has numerous areas of ferrous surface clutter. Area 5 is a figure-eight meandering path traverse that travels through open area into light and heavy canopy for use in determining navigation accuracy and reacquisition of anomalies. All grids have been surveyed many times with multiple instruments, including many examples using the EM-61 and magnetometers.

The corner points for the first four areas are perfect for determining navigation accuracy and the effects on the geophysical equipment. They are flat and open so the effects of the system components can be benchmarked against the known seeded item locations and the numerous geophysical equipment data sets for comparison. Area 5 allows assessment of the impact of vegetation and cultural obstructions.

4.0 PERFORMANCE ASSESSMENT

4.1 BACKGROUND

This performance assessment has been independently compiled by CEHNC from field observations, the demonstrator's reports, and independent comparison of demonstrator determined locations to the known and unknown survey points.

4.2 PERFORMANCE CRITERIA — UNOBSTRUCTED RANGE OF OPERATION

Expected performance is 50-1,000 m range with expected accuracy 1-20 cm (0.01-0.2 m).

Range is limited only by satellite view for the first three systems utilizing standard GPS. The last two with INS/GPS are limited by the DGPS base station radio link. The 450 m maximum tested was demonstrated. ENSCO maintained position lock to the western limit at the open area. IT could easily see the most distant points with the laser. ArcSecond was severely limited by the range of their base units. Only the DGP/INS by Parsons and the laser-based systems by IT and ArcSecond met our objectives for accuracy, with ArcSecond falling short on range (see Table 2).

Table 2. Unobstructed Range and Accuracy.

Vendor	System Name	Range	Accuracy
CEHNC	Garmin GPS III	Unlimited	0.7 m
ARINC, Inc.	LEOPARD Lite	Unlimited	11.7 m
Paper Pilot Research Inc.	New integration	Unlimited	1.0 m
ENSCO	Tracker	450 m demonstrated	0.25 m
IT Group	Leica RTS	450 m demonstrated	0.004 m
ArcSecond, Inc.	Vulcan/ LaserStation	45 m demonstrated	0.006 m
Parsons	Trimble INS/GPS	450 m demonstrated	0.04 m
Blackhawk	Applanix INS/GPS	450 m demonstrated	0.22 m

Table 3 groups the demonstrators loosely based on cost and accuracy for the known monument points in the open.

Note that Paper Pilot replicated and validated the performance of the CEHNC handheld. The minor difference can easily be explained by the satellite constellation. The performance for the GPS runs on the monuments is as expected, since essentially they use the same GPS engine and coordinate translation process. The INS does nothing to improve the accuracy, only to retain it in areas of GPS outage. The poor ARINC performance is attributed to the low accuracy of the military grade hardened GPS, using a single point capture, and perhaps to a coordinate translation error.

The ENSCO radio navigation improves accuracy to 0.25 m. Further development is needed to meet the more stringent objectives. Note that ENSCO was included in this evaluation, but it is an independent project. That project's goals were initially to provide 0.2 m accuracy, so the technology's first demonstration has come close to meeting the objectives. The two laser-based

Table 3. Demonstrator Performance — Known Points.

Cost	Monument Points (Unobstructed) in meters				
		Accuracy			
		Easting	Northing	Radial Offset	
$250	**Handheld**	-0.0069	-0.2830	0.8238	Average accuracy
	Average	0.4740	0.8324	0.3169	Standard deviation
$5,000	**Paperpilot**	-0.0001	-0.0326	0.9180	Average accuracy
	GPS/INS	0.7693	0.8052	0.4164	Standard deviation
$30,000	**ARINC**	5.0511	24.4097	25.1545	Average accuracy
	Leopard Lite	3.7738	6.4724	6.8772	Standard deviation
$25,000	**ENSCO**	0.0374	0.0260	0.2531	Average accuracy
(projected)	**Radio Navigation**	0.3659	0.3055	0.2445	Standard deviation
$25,000	**IT Corp**	-0.0022	-0.0027	0.0037	Average accuracy
	Robotic TS	0.0076	0.0031	0.0046	Standard deviation
$27,500	**ArcSecond**	-0.0012	0.0011	0.0056	Average accuracy
	LaserStation	0.0063	0.0069	0.0068	Standard deviation
$180,000	**Parsons**	0.0215	-0.0002	0.0402	Average accuracy
	DGPS/INS	0.0351	0.0330	0.0340	Standard deviation
$200,000	**Blackhawk**	-0.2160	-0.0300	0.2214	Average accuracy
	DGPS/INS	0.0866	0.0531	0.0894	Standard deviation

systems show good value with the expected high accuracy. They require line-of-sight and, in the case of ArcSecond, having only about a 45 m range. The two DGPS/INS systems displayed DGPS accuracy for this portion of the effort with the INS not adding anything where full satellite coverage is available. Blackhawk's lower accuracy can be explained by equipment failure on the GPS integration that dropped much of the GPS data.

4.3 PERFORMANCE CRITERIA — OBSTRUCTED RANGE OF OPERATION

Expected performance is 50-500 m with expected accuracy 5-20 cm (0.05-0.2 m).

Testing with obstructions was limited to 100 m. ENSCO's initial tests at that range were too inaccurate, so performance was achieved with multiple setups. ArcSecond's range in the woods is comparable to that where line-of-sight is available. The tree canopy was variable for the demonstrators with a slow loss of leaves over the demonstration period. All GPS demonstrators had sufficient multipath problems to limit their accuracy. The configuration of the GPS satellite constellation appears to have had a greater effect. The tests with the handheld by CEHNC over the demonstration interval did not show any accuracy improvements due to a reduced canopy. For the two laser line-of-sight systems and the radio navigation, the tree trunks and branches were the main obstructions. In the interior of the forest, there was little low vegetation to hamper visibility. Only the two laser-based systems used by IT and ArcSecond met our objectives for accuracy. Note that their accuracy could have been improved by a minimum effort of normal "line clearing" of brush and small branches to promote visibility (see Table 4).

Table 4. Obstructed Range and Accuracy.

Vendor	System Name	Range*	Accuracy
CEHNC	Garmin GPS III	100 m	2.1 m
ARINC, Inc.	LEOPARD Lite	100 m	25.9 m
Paper Pilot Research Inc.	New integration	100 m	3.3 m
ENSCO	Tracker	50 m	0.9 m
IT Group	Leica RTS	100 m	0.09 m
ArcSecond, Inc.	Vulcan/LaserStation	45 m	0.08 m
Parsons	Trimble INS/GPS	100 m	0.64 m
Blackhawk	Applanix INS/GPS	100 m	0.67 m

*100 m was the maximum range tested.

The following are observations regarding key evaluation parameters.

- All accuracies are shown for 2D position. 3D accuracies were not evaluated.

- All demonstrators could provide basic setups in 10 minutes. The INS systems required additional time for calibration and the ArcSecond system required multiple setups to maintain high accuracies over larger areas. No times were considered excessive for any demonstrators.

- None demonstrated multiple crew capability, but all had a procedure to make it possible using different codes or radio channels.

- The ability to capture data in 3D was demonstrated by all except ENSCO, but data was not specifically evaluated. 3D positions from all equipment were expected to be similar to the x-y position accuracy, with the laser systems also providing survey level accuracy for elevations.

- All systems demonstrated their most accurate capabilities. Lower accuracies would be expected with less care in setup and calibration, greater travel speed or more time between position updates. Reduced accuracy may be acceptable in some situations to enhance productivity with reduced performance requirements.

- Ability to display position data in near-real-time was demonstrated by ARINC, ENSCO, IT, and ArcSecond on remote computers. This capability was very mature and field-usable for the ENSCO and IT systems.

- All systems were relatively easy to set up and operate by a two-person crew.

- All demonstrators could reacquire points, but the two laser-based systems as demonstrated by IT and ArcSecond were the only systems that could do it quickly and easily.

Table 5 shows the real purpose of the demonstration — to determine how well the equipment works on unknown points and obstructed points in the woods. Performance of all systems was degraded. The two handheld GPS technology systems averaged about 0.3 m accuracy with the Radio Navigation within 0.1 m, the lasers within 0.1 m and the hybrid DGPS/INS systems within 0.6-0.7 m, and ARINC trailing with 26 m accuracy.

Table 5. Demonstrator Performance — Unknown Points.

Cost	Obstructed points (in meters)				
		Accuracy			
		Easting	Northing	Radial Offset	
$250	**Handheld**	0.9439	0.6760	2.1864	Average accuracy
	Average	1.4446	2.3250	1.9741	Standard deviation
$5,000	**Paperpilot**	0.0042	-1.5015	3.2893	Average accuracy
	GPS/INS	2.6178	3.2208	2.8730	Standard deviation
$30,000	**ARINC**	4.3312	24.6141	25.9338	Average accuracy
	Leopard Lite	6.8653	8.1810	7.9891	Standard deviation
$25,000	**ENSCO**	-0.0972	0.1766	0.9315	Average accuracy
(projected)	**Radio Navigation**	0.6921	0.8302	0.4876	Standard deviation
$25,000	**IT Corp**	0.0443	0.0861	0.0870	Average accuracy
	Robotic TS	-0.0134	0.0956	0.1049	Standard deviation
$27,500	**ArcSecond**	-0.0205	0.0263	0.0794	Average accuracy
	LaserStation	0.1083	0.0966	0.0936	Standard deviation
$180,000	**Parsons**	0.1123	0.1519	0.6386	Average accuracy
	DGPS/INS	0.7753	0.5639	0.7226	Standard deviation
$200,000	**Blackhawk**	0.3004	0.0762	0.6749	Average accuracy
	DGPS/INS	0.4750	0.4769	0.2734	Standard deviation

The obstructed points tested are where the INS in the DGPS/INS systems augmented the DGPS accuracy. It could be argued that the obstructed DGPS would be at the 0.2-0.3 m accuracy similar to the handhelds. The addition of the expensive (in excess of $100,000) military grade INS increases the accuracy to the demonstrated 0.6-0.7 m accuracy. Both vendors were using this high cost equipment to gain experience and characterize performance. A suitable final system would need to replicate performance with a complete package, most likely using an alternate INS, planned to fall in an intermediate price range ($40,000-$60,000).

4.4 TECHNOLOGY COMPARISON

In the previous discussion, the technologies were loosely ranked by cost and accuracy. The preferred ranking would be with a direct relationship between cost and accuracy. For accuracy we have the straight GPS systems: CEHNC Handheld, Paperpilot, and ARINC as the least accurate; then ENSCO radio navigation and the Parsons and Blackhawk DGPS/INS systems with moderate accuracy; and finally, the laser-based systems by IT and ArcSecond as the most accurate. Costing does not follow the order because of the extremely high cost of the INS portion of the Parsons and Blackhawk demonstrated hybrid systems. Those two systems are the most expensive and only moderately accurate in obstructed areas. Both need additional development to improve accuracy before they could become navigation tools of choice to support geophysical mapping.

The CEHNC unit and ARINC do not adequately meet the requested needs. The Paper Pilot low-cost system is worthy of further development when integrated with an electronic compass to provide a vector direction to help limit the low-cost INS errors.

The ENSCO demonstration generally met the independent project objectives. It shows promise as a low-cost, easy-to-use, moderately accurate system. It is recommended for further development and testing.

The GPS/INS systems as demonstrated by Parsons and Blackhawk are similar in performance and cost. Both had similar performance. When developed with less expensive INS equipment, they may become viable navigation systems, although questions of the draft rate of the INS remain to be addressed. Parsons is backed by Trimble, who creates the DGPS systems, and Blackhawk is backed by Applanix, who markets INS units. The hybrids have the potential to provide moderate to highly accurate navigation systems in all conditions at a moderate cost.

The most successful technology with the most value is the RTS as demonstrated by IT. It can easily meet all accuracy needs in the open to permit geophysical mapping and data analysis for discrimination. It also matched performance with the ArcSecond system without the range limitations. In addition, the integration of geophysical equipment was successfully demonstrated.

The ArcSecond System matches the RTS performance, but it is greatly range limited. It needs significant development to mature to a product with sufficient range. This system as it currently exists is perfectly suited for providing highly accurate, 3D data acquisition for small areas desired for dense geophysical mapping.

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5.0 CONCLUSIONS

Navigation in the open and in obstructed wooded areas, as demonstrated, is less accurate than expected or advertised by product vendors. Additional efforts are needed to develop most existing systems to meet desired accuracies to support geophysical mapping and reacquisition.

Where applicable, the line-of-sight laser-based systems have the best performance for the cost.

With postprocessing adjustment from known monument points, the inexpensive handheld and card based GPS units can provide reasonable accuracy for initial investigations where a large search radius can be tolerated. One has to balance the cost of a quick, inexpensive survey against the additional search cost during validations.

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