SAIC Marine Unexploded Ordnance (UXO) Survey System

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I. ABSTRACT

SAIC has developed a unique underwater UXO detection system for use in shallow water with typical depths up to 6m (~20ft) and a maximum depth of 10m (~30 ft).[1] This new system, known as the Marine Towed Array (MTA) has completed its first successful UXO survey on the Currituck Sound in Duck, NC in May 2005.[2] A perspective view of the sensor platform is shown in Fig. 1.

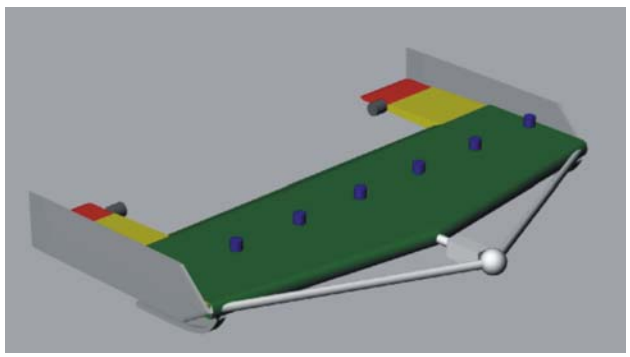

Fig. 1. Perspective View of the MTA Sensor Platform showing Cesium magnetometers (blue), stern planes (red) and the wing shaped body (green).

The MTA detection capability is derived from two primary UXO sensors, an array of Cesium vapor magnetometers and a Time Domain Electromagnetic Induction (EMI) system. There are eight Cesium magnetometers positioned to provide a cross-track spacing of 0.6 meters. The EMI system has one large rectangular transmitter (Tx) coil and an array of four receiver (Rx) coils. The layout of these sensors is shown in Fig. 2.

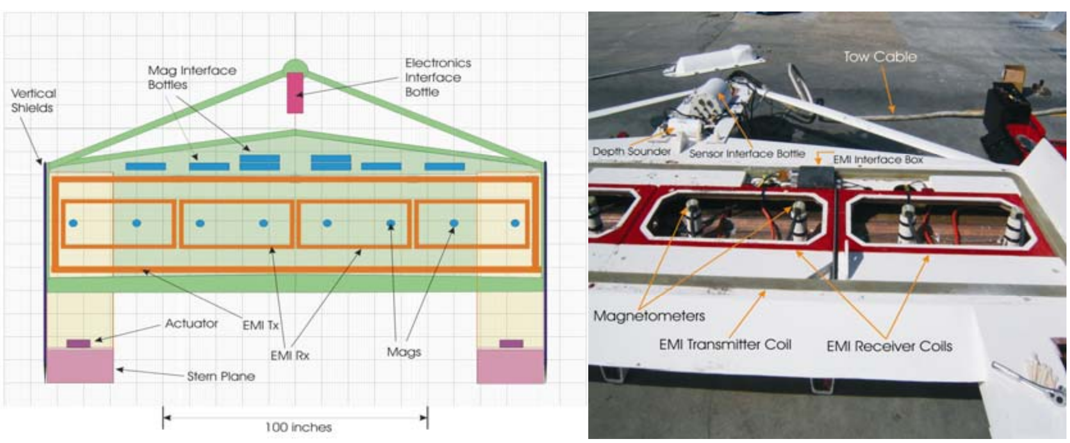

Fig. 2. Position of Cesium vapor magnetometers and Time-domain EMI transmitter (Tx) and receiver (Rx) coils.

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The sensor platform orientation is controlled by the two stern planes, which provide pitch and roll stability. The pitch setting also controls altitude above the bottom or depth below the surface. The stern planes are operated by an autopilot utilizing altitude or depth values from sensors on the platform as the command input into a multiple feedback closed-loop system. A platform mounted SONAR altimeter provides altitude above the bottom data and a pressure transducer supplies the depth below the surface. Other inputs affecting the closed loop are the pitch, roll and yaw angles of the platform, rates of change of these three angles, the platform velocity and the magnetic heading of the sensor platform.

The sensor platform is towed by a thirty foot, triple float pontoon boat with a 140 HP outboard engine. A pontoon boat design was selected for its shallow draft and good stability. It is outfitted to support all field UXO survey operations. Positioning and navigation is derived from a dual antennas (located at the bow and stern) real time kinematic (RTK) global positioning system (GPS). The tow vessel is shown in Fig. 3. Topside electronic instruments provide data acquisition, power distribution, autopilot operation, EM signal control/processing and ancillary sensor interfaces; these instruments are housed in two standard 19 inch racks with weatherproof enclosures.

Fig. 3 Triple float pontoon tow vessel outfitted with equipment for marine survey.

II. TECHNOLOGY

Sensor Platform and Sensor Design

Design of the complete survey system began with the sensor platform. Various possible approaches were considered: among them were a single platform with rigidly–fixed sensors; sensors mounted on a sled designed to tow along the bottom; a towed sensor platform with an above water GPS antenna mounted to the platform; and submerged sensor platform (towed with either a rigid boom or a flexible cable) without an above water GPS antenna. After extensive modeling, a (flexible cable) towed platform design without an above water GPS antenna was selected. The platform shape was selected to be a typical wing outline with a curved leading edge and a tapered trailing edge; the top and bottom surface contours are flat and parallel. The wing thickness is nominally 15 cm. The overall width of the sensor platform is 4.7 meters and the length is 4.15 meters. Rear body extensions were implemented to provide distance between the detection sensors and the actuators required to control the stern planes. These platform characteristics are shown in Figures 1 and 2. The sensor platform is manufactured of fiberglass to keep the overall metallic content to a minimum. Its dry weight is 1,300 lbs and it presents an underwater towing force of 350 lbs at 5 knots and 5 meters depth. The submerged platform is flooded; the combined weight of the platform and contained water is ~ 3,000 lbs.

The Cesium magnetometers are mounted with a spacing of 60 cm so that they do not interfere with the mounting of the EM Rx coils. The magnetometers' output data is received in 2 groups of 4 each at a synchronous rate of 20 Hz. This synchronized aspect is achieved by utilizing one magnetometer as a master and having its output daisy chained with the remaining 3 magnetometers in its group and then, again with the other 4 magnetometers in the second group. The magnetometers are individually connected to the Sensor Interface Pressure Vessel (SIPV). This SIPV is depicted as the Sensor Interface Bottle on the right side of Figure 2. This allows the SIPV diagnostic central processing unit (CPU) to separately monitor each magnetometer's current draw, to disconnect the magnetometer if excessive current draw is measured, and to report the operational status to the topside electronics.

The EMI system has one large rectangular Tx coil measuring 4.5 m by 1.0 m and four Rx coils measuring 1.0 m by 0.5 m. The EMI system has an interconnection box installed between the Tx coil and Rx coil. This interconnection box also contains the preamplifiers, one for each Rx coil. Each preamplifier conditions the raw Rx coil signal and outputs the signal differentially, which allows topside removal of all common mode noise that may have been picked up along the tow cable.

The stern plane positions are controlled by rotary actuators; they are coupled via a fiberglass linkage mechanism. Each actuator has an integrated optical encoder with a resolution of 0.00176º of output shaft rotation. The output shaft is coupled to the rotary actuator via 1:50 ratio harmonic drive gearing. This harmonic drive gearing produces a zero backlash because each gear is engaged on both sides of the tooth flank. It also has a very high torque/weight ratio because approximately 30% of the teeth are engaged at all times. The actuator mechanical output is rated at 60 Nm (45 lb-ft); it draws a maximum of 4 amps at a supply voltage of 28 Vdc. The actuators have 3 modes of control; position, velocity, or torque. Each primary control mode uses the other two as operational limits. All communications are handled via data commands and acknowledgements with integrated communication timeouts to prevent possible runaway conditions. Each actuator has mechanical rotation stops to prevent mechanical damage, which could result from malfunctions. During software initialization, the control interface routines command the actuator to rotate in one direction until no motion is detected. The software then determines the encoded position and commands the actuator to rotate in the opposite direction until no motion is detected. Once encoder positions for both mechanical stops are known, software limits are calculated, which are just inside the mechanical stop locations and then stored. After initialization is complete the control interface routines await position commands from the autopilot software module.

The SIPV contains all the ancillary sensors and interfaces for the sensor platform. These include a pressure transducer (for depth information), a tactical grade Inertial Measurement Unit (IMU), a platform magnetic heading compass, and internal pressure vessel temperature and humidity sensors. The IMU has an accelerometer bias of 1 milli-g and a gyro bias of 1º/hr. It performs internal raw sensor adjustments and compensations at 600 Hz. The IMU outputs flight control information at 600 Hz and inertial data at 100 Hz. An internal CPU constantly monitors mag sensor and actuator currents, as well as the various supply voltages. The supply voltages are +28 Vdc, +15 Vdc, -15 Vdc, and +5 Vdc. All diagnostic information is acquired at 10 Hz and serially transmitted topside for monitoring and recording via the Data Acquisition System (DAQ). All RS-232C sensor output signals are converted into RS-422 levels prior to exiting the SIPV to the tow cable.

Tow Cable

The tow cable has all of the electrical wiring embedded in addition to an integral Kevlar strain member, which has a working load rating of 1,000 lbs and a breaking strength of 5,500 lbs. The tow cable has two topside tow point connections, one at 16 m length and a second at 22 m. The 22 meter cable length allows routine submerged operation up to 7 m depths while the 16 m cable length is used for 5 m maximum depths. A stainless steel cable weak link is used as a safety release topside to connect the tow cable to the tow point on the vessel. This weak link is designed with a breaking strength of 1,350 lbs; this is approximately 4 times our operating force and ¼ of our tow cable breaking strength.

The tow cable connects to the tow point mounted at the stern of the tow vessel as shown in Fig. 4. The tow point is a specially designed fixture, which allows us to measure the tow cable azimuth angle with respect to our tow vessel heading. It is comprised of a free-wheeling arm coupled to an optical encoder via 2 spur gears of equal diameter. The arm is mounted on the shaft via 2 needle bearings with top and bottom thrust bearings yielding a very low resistance of movement. The optical encoder has a resolution of 0.1º and is read via a dedicated CPU which is used for positional calibration and output data formatting. Its output data are serially transmitted to the DAQ at 10 Hz.

Fig.4. Specially designed tow point mechanism to allow tow cable angle measurement and provide GPS equipment mounting. The optical encoder and the tow cable weak link are prominently displayed.

The tow point fixture also serves as the primary GPS antenna mounting location and provides the mounting for the two-way RF radio communications link to the RTK GPS base station. The tow cable topside connections are quick disconnect; they are designed to release at 50 lbs of pulling force. This feature prevents any permanent damage if the sensor platform is snagged and causes the stainless steel weak link to break. If the weak link breaks and the vessel operator is not able to stop the vessel fast enough, the tow cable becomes disconnected with a rope and a buoy attached to it for easy recovery.

GPS and Navigation

A dual antenna RTK GPS system provides positional control and navigation. The dual antenna setup has the primary antenna directly above the tow point and the second antenna mounted at the bow of the vessel. This arrangement provides a vessel heading measurement, a pitch measurement and the primary location measurement of our tow point. With the vessel tow point location, heading measurement, tow cable angle and the sensor platform depth we can use trigonometry to calculate our sensor platform tow point. After we have located our sensor platform tow point we use the sensor platform magnetic heading and the sensor mounting positions to determine the exact location of the magnetic sensors. This methodology can be seen in Figure 5.[3]

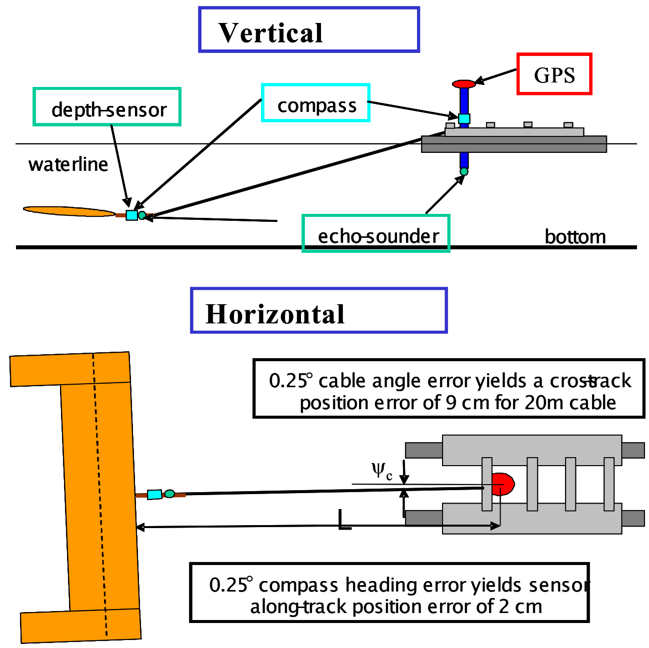

Fig. 5. Equipment locations and parameters required for positional calculations.

The RTK GPS system outputs positional information at 10 Hz. The horizontal positional accuracy is ± 1 cm while communicating with the stationary land based RTK base station. Wireless RF communication between the vessel and the base station is supported by Frequency Hopping Spread Spectrum (FHSS) radios. The GPS positional data are recorded by the DAQ and also used by the real-time navigation system.

The real-time navigation system is used to produce survey lines within an area of interest. All survey lines are pre-programmed with start and ending coordinates; this file is then transferred to the navigation system for pilot guidance. Line spacing is typically 4 m to minimize data gaps and maximize survey production rates. The navigation system also utilizes the tow cable angle information with a selectable fixed tow cable length to calculate the x,y location of our sensor platform as it is the primary vehicle that we are trying to steer for proper area coverage. The navigation system displays a line representing the tow cable with the vessel tow point at the beginning of the line and the sensor platform tow point at the end of the line. This display method allows the vessel operator to visualize the boat position along with the sensor platform position relative to the survey line. The survey line display shows the vessel and sensor tow point locations and also incorporates a left/right indicator bar showing the actual offset of the sensor platform from the planned survey line. The second navigational aid available to the driver is the vessel SONAR altimeter mounted at the bow of the vessel. It is mounted on a telescoping pivoting mount to allow easy recovery and storage when not surveying. This SONAR altimeter measures the depth of the water; the data are recorded by the DAQ; they are also displayed to the left of the operator for quick viewing. The water depth data is sample at 10Hz. These navigational aids are shown in Fig. 6 with the water depth indicator to the left of the steering wheel and the survey line display to the upper right of the steering wheel.

Fig. 6. Navigational aids. The water depth indictor is immediately left of the steering wheel: The survey line display is to the right (and above) the steering wheel.

The third navigational aid is a High Frequency Imaging SONAR system. This system operates at two discrete frequencies, 1.1 MHz and 1.8 MHz. The SONAR system is mounted at the bow of the tow vessel with a slight downward angle to produce an intersection point with the bottom forward of the vessel. Its mounting mechanism is similar in design to the vessel SONAR altimeter allowing easy recovery and storage when not surveying. It is set to scan at 5 Hz; all its imaging data are stored on its own individual 1U rackmount computer. This computer also controls all operating parameters of the SONAR imaging head via an ethernet communications link. Its control software allows for different frequencies of operation, selectable focal length, selectable field of view, and displays internal parameters such as temperature and supply voltages.

Data Acquisition

All data are stored on the DAQ. This DAQ is implemented via a dual Pentium 4, 4U rack mount computer, which operates at a 2.4 GHz clock speed and runs MS Windows XP Pro©. It stores all the acquired data onto a hard drive for later removal and archiving. One of the major design concerns was the accurate time stamping of all measured data because MS Windows© is not a real time operating system. Measured data are stored, along with the system time, which can drift throughout the duration of a survey. This time drift is not predictable or linear, which creates many problems. The most obvious time reference to use is GPS UTC time. In the past, our MTADS systems have used the 1 Pulse Per Second (1PPS) from the GPS system to trigger an interrupt routine that would automatically store the UTC time and the system time in one file. This file was later used to synchronize the two times to reduce timing errors between measured data and positional fixes. Accurate positional fixes alone are of no value if the fix cannot be accurately referenced to the measured data.

The SAIC MTA DAQ overcomes this problem by incorporating two novel methods. The first method employs a complete second GPS system with its own antenna. This GPS system is a short length PC interface card plugged directly into the PCI bus. Its purpose is to read and decode the GPS UTC and its software allows the MS Windows© system clock to be skewed, not jammed such that it tracks the GPS UTC. It is accurate to within 1 microsecond of GPS UTC. The second method that we implemented involves kernel level serial port drivers that timestamp each incoming byte as it arrives in the serial port input buffer. This time stamping is not affected by any Windows© latency and is derived from the 64 bit high performance counter that resides in hardware on the motherboard. This high-performance counter has a resolution of 1 nanosecond and is read at each integer second. When the DAQ software reads the serial port data, it also reads the time stamp and calculates the serial port time of arrival relative to the system clock, which is GPS UTC. This is the time that is stored in the data file, along with the sensor data. The DAQ and both instrument racks are pictured in Fig. 7.

Fig. 7. Instrument racks: Right rack: DAQ system with keyboard and LCD open, Left rack: DC power distribution unit (PDU).

Autopilot

The autopilot control software (developed for this project) is executed on its individual 1U rack mount computer. This computer interfaces to the sensor platform instruments and the vessel GPS. Its inputs are from the IMU, acknowledgment feedback from the rotary actuators, pressure transducer output for platform depth, sensor platform magnetic compass output, and topside GPS-derived velocity. The autopilot outputs data to the rotary actuators and to diagnostic files. It has two normal modes of operation and one “Emergency Rise” mode. The two normal modes of operation are altitude (above bottom) control or depth (below surface) control. When in altitude control mode, the autopilot maintains a constant distance above the bottom (as measured by the sensor platform SONAR altimeter). The altimeter has a resolution of ±1 cm. When in the depth control mode, the autopilot maintains a constant depth below the surface (measured by the sensor vessel pressure transducer). Units of control are in meters. The third mode is “Emergency Rise”. This mode is invoked when the large red “Emergency Rise” pushbutton is depressed. This push button can be seen in the left instrument rack in Figure 7. When “Emergency Rise” is initiated, the autopilot overrides all commands and executes a controlled (steep) upwards sensor platform pitch to bring the platform to the surface. This emergency mode must be reset by operator intervention on the autopilot graphical user interface (GUI). This GUI also displays operating parameters of the sensor platform such as pitch and roll angles, rate of change of pitch, roll and yaw, angle of the stern planes, and the platform depth and altitude.

III. ACCOMPLISHMENTS

The SAIC MTA UXO system completed its first UXO range survey in Duck, NC on the Outer Banks in May, 2005[4]. This range survey was conducted in the Currituck Sound offshore from the Former Naval Duck Target Facility. The average survey production rate varied from 3 to 9 acres/hr (1.2 to 3.6 hectares/hr) depending on survey line length, water depth, and the weather conditions. A total of 154 acres were surveyed between May 9 and May 18, 2005.

To determine the positional accuracy of the system, 23 rebar rods with dimensions of 18 in length x 3/8 in diameter were pushed into the sea bottom in a vertical orientation. The positions of the rebar rods were then surveyed using a Rover type RTK GPS utilizing the same base station as the survey vessel. The rods were then surveyed with the SAIC MTA UXO system and the data were analyzed as though they were ordnance anomalies using the MTA DAS. Plots were produced from the magnetic field readings, targets were analyzed and center positions of these analyzed targets were then compared to the surveyed in positions. The rebar positions were recovered to an average 22 cm from the target analysis. This comparison is shown in Table 1 below.

TABLE 1.
Comparison of rebar stakeout coordinates and analyzed measured coordinates.

Comparison of Rebar Stakeout Positions and Measured Positions

ID	HE (m)	Size (m)	Moment	Fit Quality	Analyst Comments	Measured Coordinates		Staked Out Coordinates			Miss Distance (m)	Easting Offset (m)	Northing Offset (m)
						UTM X(m)	UTM Y(m)	Easting (m)	Northing (m)	HAE (m)			
1	-42.78	0.183	3.2675	0.776	Rebar #1	431751.28	4003800.07	431751.15	4003799.98	-41.27	0.15	-0.13	-0.09
2	-42.74	0.183	3.2548	0.896	Rebar #2	431750.94	4003804.37	431750.97	4003804.01	-41.31	0.36	0.03	-0.36
3	-42.70	0.152	1.8492	0.913	Rebar #3	431750.33	4003808.94	431750.24	4003808.79	-41.32	0.18	-0.09	-0.15
4	-42.76	0.185	3.3234	0.925	Rebar #4	431749.85	4003813.63	431749.54	4003813.41	-41.34	0.39	-0.31	-0.23
5	-42.77	0.227	6.2274	0.917	Rebar #5	431749.27	4003817.83	431749.08	4003817.70	-41.34	0.23	-0.19	-0.14
6	-42.75	0.233	6.7297	0.938	Rebar #6	431748.59	4003822.75	431748.43	4003822.60	-41.40	0.22	-0.16	-0.15
7	-42.80	0.238	7.1657	0.869	Rebar #7	431748.12	4003828.91	431748.03	4003828.76	-41.38	0.18	-0.09	-0.15
8	-42.86	0.152	1.8587	0.844	Reabar #8	431747.84	4003834.38	431747.71	4003834.47	-41.38	0.16	-0.13	0.09
9	-42.96	0.179	3.051	0.670	Rebar #9	431747.54	4003839.66	431747.85	4003839.77	-41.35	0.33	0.31	0.11
10	-42.81	0.164	2.3149	0.812	Rebar #10	431747.46	4003845.51	431747.60	4003845.54	-41.35	0.14	0.13	0.03
11	-42.96	0.227	6.158	0.781	Rebar #11	431747.38	4003851.16	431747.59	4003851.04	-41.36	0.24	0.21	-0.12
12	-42.98	0.247	7.9884	0.741	Rebar #12	431747.08	4003856.67	431747.29	4003856.63	-41.33	0.21	0.21	-0.04
13	-42.88	0.225	6.0604	0.804	Rebar #13	431746.92	4003861.84	431747.02	4003861.93	-41.44	0.13	0.10	0.09
14	-43.06	0.178	3.0023	0.840	Rebar #14	431746.74	4003866.75	431746.80	4003866.65	-41.33	0.11	0.06	-0.10
15	-42.78	0.23	6.4742	0.846	Rebar #15	431746.49	4003871.69	431746.58	4003871.62	-41.29	0.12	0.09	-0.07
16	-42.77	0.267	10.1039	0.836	Rebar #16	431746.17	4003876.85	431746.27	4003876.69	-41.31	0.19	0.10	-0.16
17	-42.73	0.211	4.9436	0.804	Rebar #17	431745.95	4003881.70	431746.02	4003881.46	-41.26	0.25	0.07	-0.24
18	-42.59	0.133	1.2429	0.801	Rebar #18	431745.68	4003886.82	431745.78	4003886.76	-41.27	0.12	0.10	-0.06
19	-42.66	0.177	2.9581	0.934	Rebar #19	431745.51	4003892.23	431745.51	4003891.88	-41.25	0.36	0.00	-0.35
20	-42.58	0.192	3.7376	0.916	Rebar #20	431745.36	4003896.54	431745.24	4003896.23	-41.25	0.33	-0.12	-0.31
21	-42.56	0.148	1.7247	0.949	Rebar #21	431745.31	4003901.58	431745.03	4003901.39	-41.23	0.34	-0.28	-0.19
22	-42.81	0.19	3.6296	0.861	Rebar #22	431744.76	4003906.77	431744.76	4003906.78	-41.26	0.01	-0.01	0.01
23	-42.89	0.241	7.4097	0.716	Rebar #23	431744.34	4003911.56	431744.61	4003911.23	-41.95	0.43	0.27	-0.33
										Average Offset	0.22	0.14	0.16

As shown above in Table 1, the average positional accuracy was within 0.22m. This level of accuracy allowed the recovery team of Explosive Ordnance Disposal (EOD) divers to directly stake out targets from the target list provided without the use of an underwater magnetometer for precise location.

This positional accuracy has shown the SAIC Marine Towed Array to be a very efficient underwater surveying system with the ability to search for and precisely locate UXO.

IV. CAPABILITIES

Deliverable products of an SAIC MTA survey include magnetic anomaly (Fig.9), magnetic total field, bathymetry (Fig 8) and electro-magnetic anomaly maps. There is also a target dig list produced with locations and calculated target parameters of size, inclination, azimuth, and depth. See TABLE 2 for a typical target dig list. The high frequency SONAR imager data is stored on DVD discs and available for playback along all of the surveyed paths. See the figures below for examples of these maps.

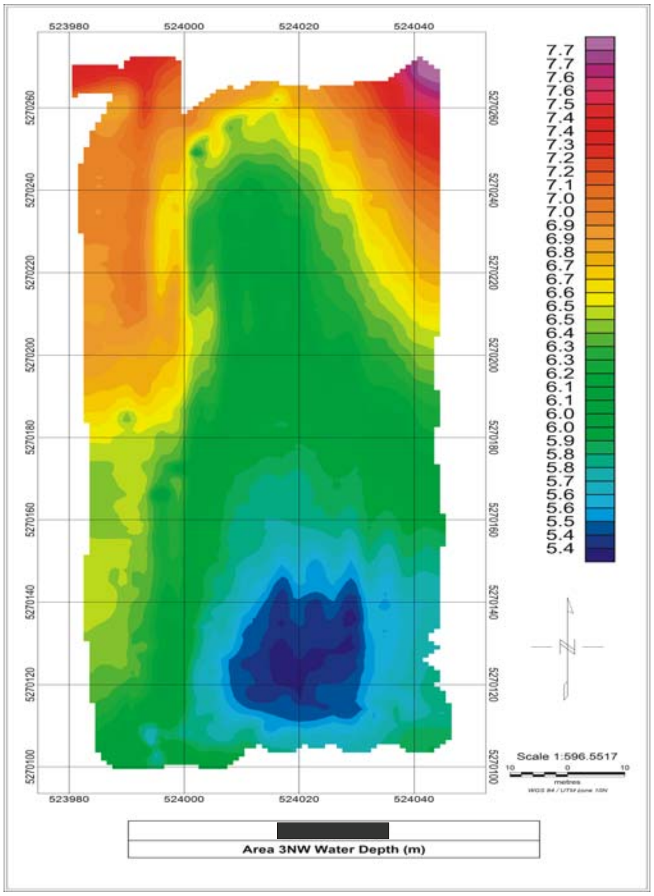

Fig. 8 Bathymetry Map

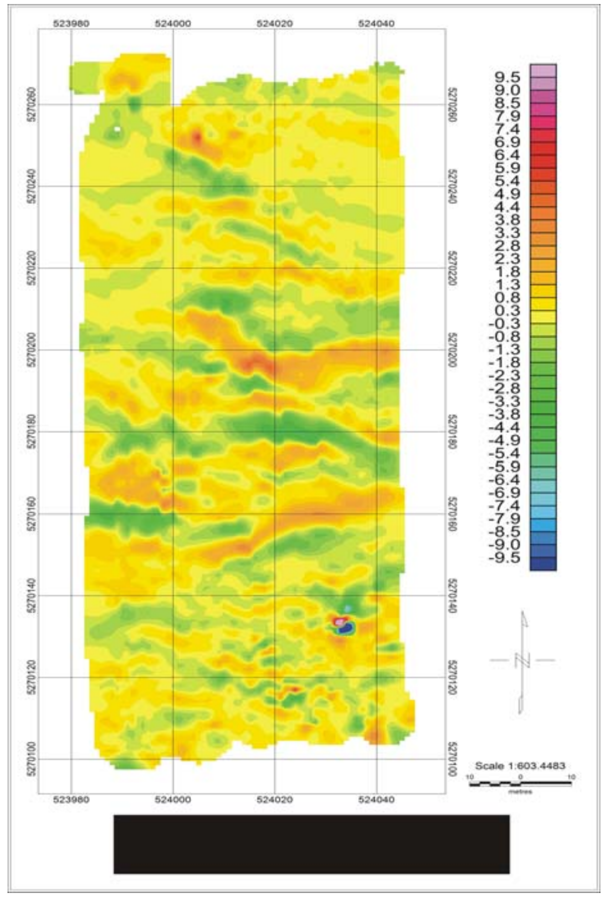

Fig. 9 Magnetic Anomaly Map

TABLE 2.
Typical Dig List produced from software analysis

DIG LIST FOR THE FIRST SIX SHALLOW TARGETS

ID	Local X (m)	Local Y (m)	UTM X(m)	UTM Y(m)	Size (m)	Incl (deg)	Azi (deg)	Target Depth (m)	Water Depth (m)	Peak Pos Signal (nT)	Peak Neg Signal (nT)	Analyst Comment	Dig/Don't Dig
399	724.19	1176.94	431724.19	4004176.94	0.158	13	13	0.08	1.20	569.10	-430.50	Large target on surface in 4 ft of water, DIG THIS	Yes
400	732.74	1170.94	431732.74	4004170.94	0.132	14	12	0.16	1.20	258.60	-249.20	Good target on surface in 4 ft of water, DIG THIS	Yes
401	726.28	1162.48	431726.28	4004162.48	0.249	57	85	0.12	1.21	3440.90	-534.10	Rocket sized target on surface in 4 ft of water, DIG THIS	Yes
412	736.22	1056.83	431736.22	4004056.83	0.183	32	346	0.43	1.26	271.00	-119.20	3 in rocket 1.5 ft in mud in 4 ft of water, DIG THIS	Yes
416	723.53	1012.01	431723.53	4004012.01	0.103	50	310	0.05	1.27	184.70	-57.30	Good target on surface in 4 ft of water, DIG THIS	Yes
424	663.28	888.03	431663.28	4003888.03	0.196	77	1	0.04	2.95	241.80	-51.40	large target on surface, DIG THIS	Yes

A typical port or harbor survey is normally divided into two areas, one area that can be surveyed with the MTA at 4 meter line spacing and another area which will include tight, small spaces such as around piers, docks or shoreline construction. This second area is typically surveyed with a 14-18 foot boat with a minimum 2 and possibly 3 magnetic sensors mounted on vertical poles or rigidly fixed inside on the bottom of the boat. GPS, vessel SONAR, navigation instruments and any other ancillary equipment is also mounted onto the boat. This allows very tight turns and much better maneuverability than the 30 ft pontoon boat with the MTA. See Fig. 10 for typical survey lines to cover a port area.

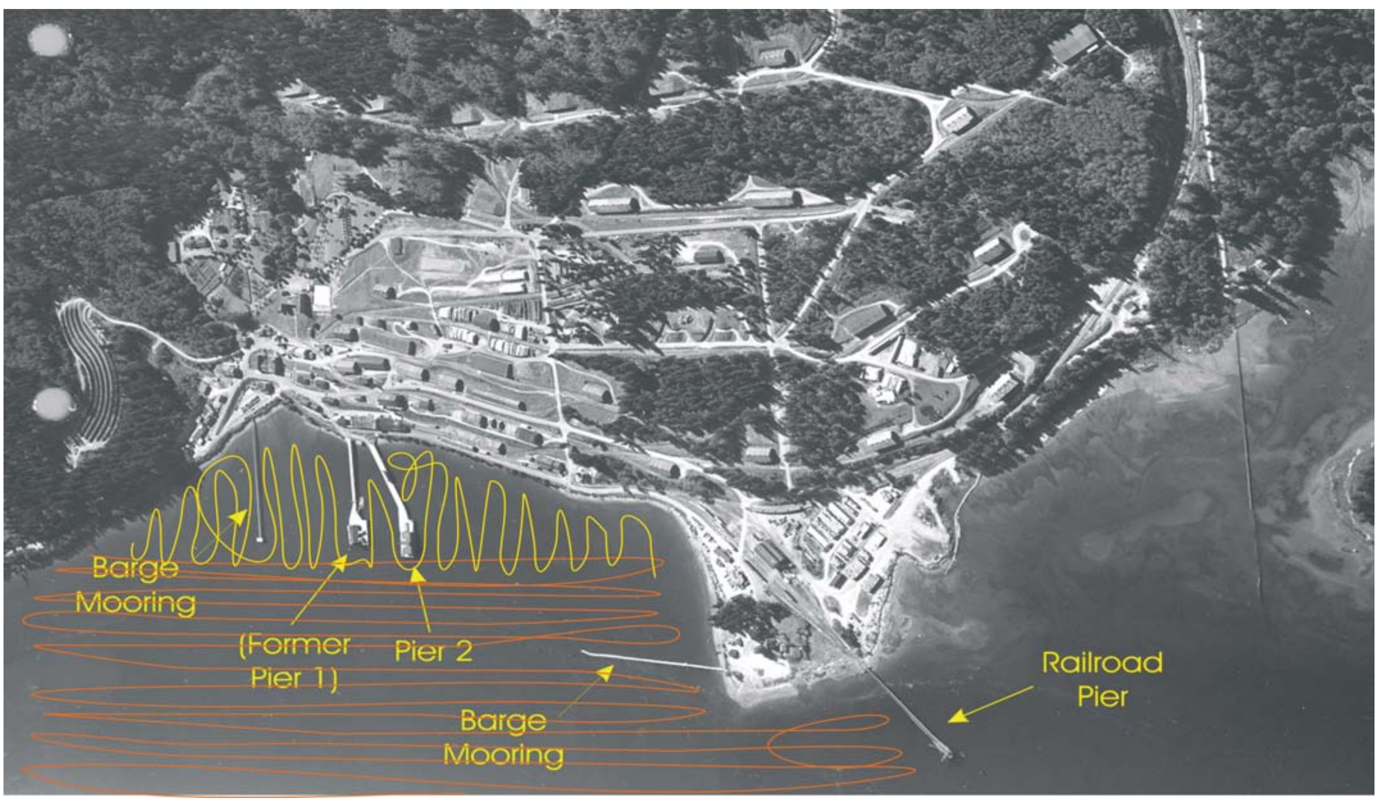

Fig. 10. Typical port survey lines, orange is with the pontoon boat and MTA, while yellow is with a smaller 14-18 ft boat.

REFERENCES

1. "Technology Needs for Underwater UXO Search and Discrimination," Final Report SERDP Project UX-1322

2. ESTCP Project 200324

3. SERDP Project UX-1322

4. Marine Towed Array Technology Demonstration at the Former Naval Duck Target Facility. J.R. McDonald, AETC Incorporated, August 20, 2005