FINAL REPORT

Underwater (UW) Unexploded Ordnance (UXO) Multi-Sensor Data Base (MSDB) Collection

SERDP Project MM-1507

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Dr. Paul J. Carroll

Naval Surface Warfare Center – Panama City
Code T12
110 Vernon Avenue
Panama City, FL 32407-7001

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This paper describes the Multi-Sensor Data Base (MSDB) Collection, a two phase project to collect quality acoustic and electromagnetic (EM) detection and mapping data of underwater (UW) unexploded ordnance targets and demonstrate the value of data fusion from three sensors detecting independent phenomena. The MSDB project initially used a suite of acoustic, passive magnetic and active EM sensors deployed from a surface catamaran and a wide area augmentation system (WAAS) global positioning system (GPS) to measure the detected target position locations. Phase I MSDB tests conducted in October 2005 included over 75 search runs over the UXO target fields at two shallow water sites in St. Andrews Bay, FL. Phase I tests demonstrated that the acoustic (Buried Object Scanning Sonar) and EM sensors (Realtime Gradiometer and GEM-3 array) could detect proud and buried UXO-sized targets at both sites but only BOSS had sufficient detection range to reliably detect UXO targets during a single search track run. Phase I tests also showed that WAAS GPS was not suitable for detailed target mapping and did not permit meaningful fusion of the UXO detection data from the three different sensors. Phase II tests were conducted in September 2008 with a modified goal of collecting quality detection and mapping UW UXO with only a BOSS sensor using an Real-Time Kinematic (RTK) GPS with higher mapping accuracy. Phase II tests demonstrated that BOSS acoustic sensor could detect and map all UW UXO targets within 25 cm of ground truth and reliably detect UXO targets buried 30

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Acronyms

AFB	Air Force Base
BMH	Buried Mine Hunting
BOSS	Bottom Object Scanning Sonar
cm	Centimeter
CW	Continuous Wave
DGPS	Differential Global Positioning System
DRUM	Dynamically Responding Ultrasonic Matrix
DVL	Doppler Velocity Logger
EM	Electromagnetic
EMIS	Electromagnetic Induction Spectroscopy
ESTCP	Environmental Security Technology Certification Program
FAU	Florida Atlantic University
FM	Frequency Modulation
FOV	Field of View
GEM	Geophex Electromagnetic
GPS	Global Positioning System
IMP2	In-situ Measurement of Porosity 2
IMU	Inertial Measurement Unit
LSG	Laser Scalar Gradiometer
mm	Millimeter
MSDB	Multi-Sensor Data Base
MTA	Marine Towed Array
MTADS	Multi-sensor Towed Array Detection System
MUDSS	Mobile Underwater Debris Survey System
NAEVA	North American Exploration of Virginia, Inc
NAVFAC	Naval Facilities Engineering Command
NRL SSC	Naval Research Laboratory-Stennis Space Center
NSWC PC	Naval Surface Warfare Center Panama City
ONR	Office of Naval Research
PCSWAT	Personal Computer Shallow Water Acoustic Toolbox
QM	Quantum Magnetics, Inc
RMS	Root Mean Squared
RTG	Real-Time Gradiometer
RTK	Real Time Kinematic
SAIC	Science Applications International Corporation
SAS	Synthetic Aperture Sonar
SERDP	Strategic Environmental Research and Development Program
SNR	Signal to Noise Ratio
SSS	Side Scan Sonar
STMS1	Sediment Transmission Measurement System
TD	Technical Demonstration
TV	Towed Vehicle

UUV	Unmanned Underwater Vehicle
UW	Underwater
UW/APL	University of Washington/Applied Physics Laboratory
UXO	Unexploded Ordnance
WAAS	Wide Area Augmentation System

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Executive Summary

Detection and identification of underwater (UW) Unexploded Ordnance (UXO) is a significant problem in remediation efforts to reclaim formerly used defense sites. Presently there is no system available that can accurately survey and map the location of UXO at UW sites and reliably discriminate UXO from UW debris. The UW UXO survey problem is complicated by a wide range of targets (e.g., magnetic and non-magnetic, metallic and non-metallic) that are often buried. Sensor detection concepts are currently being developed for UW UXO detection and mapping including multi-sensor systems capable of independently measuring different target physical characteristics. UW detection sensors and systems tested to date have had limited measurement capability versus buried UW targets and there is no set of quality data from independent detection sensors to assess the value of new detection and identification sensors and algorithms.

The objective of the Multi-Sensor Data Base (MSDB) project was to collect a data base of high quality UW UXO sensor data from multiple sensors on a range of UW buried UXO targets deployed in shallow water (10-15 feet) at a variety of environmental sites and to perform data fusion analysis of independent sensor target detections to assess the improvement in UXO target location and discrimination of multiple sensor data versus single sensor data. The MSDB was collected using a set of state-of-the-art acoustic, passive magnetic and active electromagnetic (EM) sensors deployed from a catamaran in two UW towed vehicles at positions above or on the sea bottom within detection range of each sensor. The UW sensor platforms were deployed in fixed positions with respect to the catamaran to permit co-registration of the sensor responses during the search operations. MSDB data was collected and is available to the SERDP community to permit study and evaluation of UW UXO sensor detection techniques and UW UXO sensor phenomenology that can lead to successful approaches to UW UXO mapping.

The MSDB project was conducted in two Phases in FY06 and FY08. The goal of the FY06 Phase I MSDB project was to integrate the selected sensor suite in a configuration deployable from the catamaran and to conduct search tests versus UW UXO target sets deployed UW at shallow water sand and mud bottom sites at St. Andrews Bay, FL. The Phase I MSDB tests were designed to perform search operations versus a set of simulated UXO targets of different sizes. The UXO targets were deployed in sets of straight line configurations with targets alternately proud and buried in the sea bottom. Multiple UXO target lines were deployed at each site with target orientations varied to assess the potential impact of target aspect on target detectability. Target ground truth positions were established by divers during target emplacement using Wide Area Augmentation System (WAAS) differential global positioning system (DGPS) techniques. The MSDB search tests focused on driving the catamaran in a series straight line search tracks over the UXO target areas and measuring the sensor responses and GPS position of the catamaran and sensors during the search tracks. Sensor outputs were post processed to determine estimates of detected target positions for each sensor, the first step in assessing data fusion.

The Phase I MSDB project successfully integrated a unique set of three sensors, a bottom-penetrating acoustic Bottom Object Scanning Sonar (BOSS), a passive fluxgate magnetic sensor, the Real-Time Gradiometer (RTG), and an active EM GEM-3 array and deployed the sensors in

two separate vehicles towed from a catamaran. The MSDB project performed detection tests in October 2006 versus several simulated UXO target sets at two shallow water (~ 10 ft) test sites, one a sand bottom and one a mud bottom, where targets were both proud and shallow buried (~ 1 ft). The Phase I tests included over 50 search track runs over the test sites during a week long test period. Measurements of the acoustic parameters of the water and sea bottom in the sand and mud bottom test areas were performed by University of Washington/Applied Physics personnel approximately one week after MSDB sensor tests.

Phase I MSDB sensor test data were processed and results confirmed that the simulated UXO targets were successfully detected by all three sensors during the search runs. The BOSS sensor was the most successful sensor in detecting the UXO targets and BOSS images of the targets were obtained from processed data for essentially all UXO targets, both proud and buried. The GEM-3 array was the next most successful sensor detecting virtually all targets from Line 1 at the sand site and detecting a number of UXO targets in Lines 3 (sand site) and Lines 1 and 2 (mud site). The RTG sensor was only partially operational (three of five channels) and several UXO targets were detected in all lines but with RTG in a degraded mode, target positions could only be estimated.

The BOSS sensor typically detected most targets during a single search track. The RTG and GEM-3 sensors generally required multiple search tracks to detect more than one target in a given target line. This was primarily due to the limited ranges of the RTG and GEM-3 sensors and the difficulties in navigating the catamaran/towed vehicles over the target sets when significant tides and current were present.

Phase I MSDB sensor detection data was used to develop maps of the locations of the detected targets which were compared to ground truth UXO positions determined by divers using WAAS GPS. The results showed that BOSS data was typically most complete and accurate. Processed BOSS images of detected targets showed clearly the position of each target and the depth at/below the bay bottom. BOSS target detections were generally within a few meters of the target ground truth position and the buried targets were visible below the bottom interface. Processed BOSS images also showed evidence of specular reflection scattering effects which masked the detected targets when they were directly below the BOSS towed vehicle (TV). Analysis was performed that indicates that the specular reflection scattering could be reduced by extending the length of the wings/receivers of the BOSS sensor to eliminate specular reflection regions under the present BOSS TV. The GEM-3 array successfully detected the UXO targets that it passed over.

The number of targets detected in a single search track was determined by the success of the catamaran pilot in steering over the targets. Catamaran navigation during the tests proved more difficult than anticipated primarily due to wind and cross-track tidal currents.

Fusion of the Phase I UXO target detection positions from the BOSS, RTG and GEM-3 sensor was performed. The results demonstrated that UXO targets were detectable by the different sensors but that target coincidence was generally limited to agreement within several meters. This was primarily due to the limitations in the accuracy of the WAAS GPS navigation systems employed during UXO target deployment and during MSDB sensor data collection. Tests

performed with WAAS GPS sensors verified that the position of a stationary point varies up to several meters within a period of minutes or hours.

Phase I site environmental measurements were performed at the sand and mud bottom test sites by UW/APL employing specialized measurement systems to estimate sea bottom parameters. The parameters are available for analysis of the BOSS results using models such as the PCSWAT.

Phase I target detection position accuracy was judged as insufficient to meet UXO target mapping requirements and limited the utility of the Phase I acoustic, passive magnetic, and active magnetic sensor in evaluating data fusion techniques. Land target UXO mapping performed using Real Time Kinematic (RTK) GPS equipment typically achieves target position accuracy of a few centimeters. This is the degree of target position accuracy required by SERDP for UW UXO mapping and data fusion studies.

The limitations of selected Phase I sensor detection range and target position measurement techniques were re-evaluated prior to Phase II MSDB operations in FY08. The goal of Phase II MSDB was reestablished at a more modest level. The Phase II goal was to collect high quality acoustic detection data and mapping of a set of simulated and real UXO that were flush buried and shallow buried at the sand bottom St. Andrew's Bay site. A key factor in achieving the Phase II goal was to improve target mapping accuracy. In Phase II, RTK GPS equipment and techniques were employed to measure UXO test target ground truth position and BOSS acoustic sensor position during target search operations.

Phase II MSDB tests were conducted in September 2008 with the BOSS acoustic sensor deployed in the BOSS vehicle towed from the front of the catamaran. Passive and active magnetic sensors were not deployed during Phase II operations. During the Phase II tests the position of the BOSS sensor was measured to higher accuracy (~ 10cm) by installing an RTK GPS antenna directly over the BOSS vehicle and sensor. The lateral movement of the BOSS sensor was limited by adding a harness to the BOSS TV mount which restricted the vehicle lateral motion during towed search operations. Output of the RTK GPS position was recorded in the BOSS data stream at 5 Hz to insure that BOSS sensor position was well measured during Phase II search operations. RTK GPS was also used to measure ground truth position of the UW UXO targets during target deployment of the shallow water Phase II test field. Diver measurement of target ground truth was estimated to be accurate within 25 cm for the UXO targets that were deployed in ~ 10 foot water.

Phase II tests were conducted over several days in September 2008. Phase II tests were conducted at a shallow water St. Andrew's Bay site where 56 test targets were deployed in multiple lines approximately 50 meters long. The Phase II test field primarily included sets of inert UXO ordnance (81 mm mortar, 100 mm rounds, and 4.2-inch mortar) and small simulated ordnance (10 cm and 5 cm cylinders) that were flush buried or buried 10-30 cm below the sand bottom. Several other target types including tires, concrete clumps, and icosahedron shapes were deployed in the test area to simulate naturally occurring non-UXO debris.

BOSS data were collected on nearly 100 search sorties over the test area during three days of Phase II testing. All search sorties were straight line catamaran paths that were parallel, perpendicular or at a 45 degree angle with respect to the test field. A limited number of search runs were also performed over the Phase I test field that was deployed in 2006. The 2006 test field which was near the 2008 test site included simulated buried UXO targets (2", 3", 4", and 6" diameter cylinders), most targets larger that the 2008 test targets.

The BOSS sensor was calibrated versus a standard spherical target prior to Phase II test runs. Also the sea bottom environmental parameters in the test area were characterized by personnel from NRL Stennis. They collected 10 core samples of the bottom test area two weeks before the Phase II BOSS tests and performed analysis to estimate the sea bottom parameters. Selected sea bottom parameters were used inn the BOSS detection analysis of buried targets.

BOSS detected all UXO in the 2008 target field and all 3, 4 and 6 inch cylinders in the 2006 UXO target field. BOSS detected the position of UXO targets with an error of about 1 foot rms, a major improvement over Phase I results and within the SERDP UW mapping requirements. The BOSS sensor configuration generated imagery of the flush buried and fully buried targets with detail sufficient to estimate the depth of buried targets beneath the sea bottom and general shape features. Although BOSS provided high position and burial depth accuracy, the current generation BOSS sensor did not provide sufficient target imagery detail to accurately measure UXO shape and dimensions to perform target identification. The conventional synthetic aperture sonar (SAS) method of sweeping the synthetic aperture along-track frequently does not allow specular illumination of the UXO targets at aspects that generate echo levels with adequate signal-to-noise ratio (SNR) for unambiguous target imaging. Specular echoes from the sediment-water interface also prevent detections of targets with grazing angles greater 60 degrees.

Based on the FY06 and FY08 MSDB tests several recommendations are proposed. The FY08 tests demonstrated that the BOSS acoustic sensor can detect and map a UXO target set to a suitable accuracy level (several centimeters) employing the MSDB catamaran configuration and RTK GPS equipment. FY06 MSDB testing demonstrated that a passive magnetic sensor with higher sensitivity is required to obtain adequate range to detect UXO-sized magnetic targets, especially the smaller UXO targets. Significant advances in passive magnetic sensor technology have occurred since the FY06 MSDB tests. The U.S. Navy has tested UW target detection employing an advanced total field magnetic sensor array built by Polatomic, Inc. which has demonstrated detection ranges comparable to the BOSS acoustic sensor. The BOSS acoustic and Polatomic magnetic array should be integrated in a single TV to be operated from the catamaran. This sensor suite can be the basis of a multi-sensor system that can provide independent UXO target detection data for evaluating sensor fusion techniques. The BOSS sensor should be upgraded to provide higher resolution imaging. FAU, developer of BOSS, has proposed a set of hardware and processing techniques for generating high resolution imagery of buried UXO that allows accurate estimation of the dimensions and shape of buried or proud UXO.

BOSS data from the Phase II tests have been recorded and documented and are available to other researchers for analysis.

Objective

The objective of the MSDB project was to collect a data base of high quality UW UXO sensor data from multiple sensors on a range of UW buried UXO targets deployed in shallow water (10-15 feet) at a variety of environmental sites and to perform data fusion analysis of independent sensor target detections to assess the improvement in UXO target location and discrimination of multiple sensor data versus single sensor data. The MSDB was collected using a set of state-of-the-art acoustic, passive magnetic and active EM sensors deployed in two UW platforms from a catamaran at positions above or on the sea bottom within detection range of each sensor. The UW sensor platforms were in fixed positions with respect to the catamaran which permitted co-registration of the sensor responses during the search operations. MSDB data can be utilized by the SERDP community to study and evaluate UW UXO sensor detection techniques and UW UXO sensor phenomenology that can lead to successful approaches to UW UXO mapping.

The major goal of the MSDB project in Phase I was to integrate the selected sensor suite in a configuration deployable from the catamaran and conduct search tests versus UW UXO target sets deployed UW at shallow water sand and mud bottom sites at St. Andrews Bay, FL. The MSDB tests were designed to perform search operations versus a set of simulated UXO targets of different sizes which were deployed in straight lines configurations. The UXO targets were deployed in straight lines with targets alternately proud and buried. Multiple UXO target lines were deployed with targets orientations varied to assess the potential impact of target aspect on target detectability. Target ground truth positions were established by divers during target emplacement using WAAS DGPS techniques. The MSDB search tests focused on driving the catamaran in a series of straight line search tracks over the UXO target areas and measuring the sensor responses and GPS position of the catamaran and sensors during the search tracks. Sensor outputs were post processed to determine estimates of detected target positions for each sensor, the first step in assessing data fusion. MSDB data sets were designed to include documentation of the UXO target positions, sensor configurations, test conditions, and environmental data to permit independent analysis and use by other investigators.

A significant secondary objective of MSDB project was to provide other investigators with sensor and test data to support validation of sensor performance models. For example, the acoustic sensor MSDB data was intended to provide well documented sensor and environmental data to evaluate the SERDP UW UXO Panama City Shallow Water Acoustic Toolkit (PCSWAT) acoustic modeling project. The MSDB project intended to analyze sensor performance/sensor phenomenology directed at target detection and classification utilizing models and techniques developed primarily for buried mine hunting applications. The MSDB data base would ultimately include buried UW UXO targets of different sizes, magnetic and non-magnetic targets, metallic and non-metallic targets and a range of environments (e.g., salt water, fresh water, sand bottom, mud bottom, muck bottom, rocky bottom, etc.).

Background

Several sensor systems have been developed and tested in the past few years that demonstrated significant capability for mapping UW UXO under selected conditions. SERDP sponsored the development and testing of the Mobile Underwater Debris Survey System (MUDSS) in 1995-1998[(1)]. MUDSS demonstrated ability to utilize a suite of surface towed sensors (acoustic, magnetic, and electro-optic) and to develop maps of detected UW objects. MUDSS successfully mapped a 2 sq. nautical mile site in shallow water (20-25 ft) in Choctawhatchee Bay near Eglin AFB during a five-day MUDSS Technical Demonstration (TD) in fall 1998. During the TD, MUDSS detected approximately 150 targets with magnetic signatures corresponding to a 250-lb bomb (target of interest) and a similar number of acoustic targets. Data fusion techniques were applied that showed that a small number of targets (~10) were co-located - detected within ten meters by both acoustic and magnetic sensors. A significant number of magnetic targets were buried and were not detected by the acoustic sensor. The MUDSS electro-optic sensor was generally not useful for target reacquisition and identification during the TD survey since water visibility near the bottom was poor and detected targets were commonly located in heavily silted and muddy bottom areas. The majority of the detected UW targets were buried in silt. A select number of MUDSS targets were relocated and verified by Navy divers using hand held sensors.

Five contractor-developed prototype UW sensor systems were tested at Mare Island, CA in 1999 under a demonstration project sponsored by NAVFAC [(2)]. Several of the selected systems tested at Mare Island demonstrated significant detection capability against a variety of proud and buried UXO in very shallow water (~ 6 ft. deep). The Mare Island test included search of a 30 meter x 50 meter area seeded with approximately 90 UXO and simulated UXO targets positioned singly and in clusters. UXO target size varied from 20mm ammunition to 6-inch projectiles. Search rates were modest. Contractors typically collected search data from one to several hours, and maps of the UXO locations were developed during overnight post processing. Sensor swath widths were typically of the order of 6 feet and sensor search platforms operated at a few knots. All sensor systems employed some form of Differential Global Positioning Sensor (DGPS).

Environmental Chemical Corporation, an independent NAVFAC contractor, independently evaluated the five contractor Mare Island test results. Geophex and North American Exploration of Virginia, Inc (NAEVA) Geophysics scored high in successful UXO detection; both contractors detected greater than 84 % of the UXO targets. Geophex search system measurements were performed using two sensor systems: (1) an array of four total field magnetometers and (2) an array of two GEM3 active EM sensors. NAEVA measurements were performed using a single Geonics EM-61 active EM induction sensor. All Geophex and NAEVA searches were performed with the sensors deployed within a few feet of the bottom.

Subsequent to the MUDDS and Mare Island tests, SAIC developed a Marine Towed Array (MTA) survey system under SERDP and ESTCP sponsorship that includes a towed array of total field Cesium vapor magnetometers and EM sensors. The MTA system which incorporates RTK GPS and Data Acquisition (DAQ) subsystems has been successfully used to magnetically

detect, survey, and map several UXO sites including Duck, NC, and Erie Army Depot, PA[3,4]. MTA surveys were subsequently used to recover selected UXO at the test sites. The MTA system was developed and tested during the period of the MSDB project so that lessons learned during MTA development and demonstrations had minimal impact on the MSDB system.

Several valuable lessons were learned during the earlier MUDSS demonstration and Mare Island tests which provided guidance to the design of the MSDB collection system employed in the MSDB project. They included:

- The MUDSS demonstration included a test target field and an area of unknown targets. The MUDSS demonstration would have benefited from focusing on a test with a larger number and variety of test targets with well documented ground truth (target size, precise position, orientation, etc.) as there were in the Mare Island tests. In the muddy bottom conditions of the MUDSS demonstration, divers were not able to verify the ground truth on numerous targets and thus these data were not particularly valuable.

- The multi-sensor data fusion technique was proven to a modest degree for UW UXO detection but the utility of multi-sensor data is only valuable to the degree to which the multi-sensor data is accurately correlated and co-registered. The MUDSS sonar and magnetic sensor target data was collected from separate vehicles and there was significant uncertainty (meters) in the correlation of the data. A quality data set from multiple sensors requires accurate co-registration of data from the different sensors in order to maximize the power of data fusion from independent sensors.

- In the MUDSS tests the acoustic and magnetic sensors had different capabilities against buried targets. The MUDSS side scan sonar (SSS) had buried target capability operating in the low frequency mode (20 KHz) but the SSS was primarily a longer range device and did not generally detect buried targets on the same search run as the superconducting passive magnetic sensor. This exacerbated the correlation issue.

These observations and shortfalls motivated NSWC PC and several sensor developer partners, FAU, Quantum Magnetics (QM), and Geophex, Ltd., to propose an upgraded suite of sensors selected specifically to detect UW buried targets at comparable ranges and configured for operation at fixed relative positions from a single platform. In this configuration the sensor results could be correlated more closely and UXO detection data could be collected from all sensors during the same test run. This approach was the basis of the MSDB project which focused on collection of robust, high quality data from a state of the art sensor suite. This suite consisted of UW buried target detection and classification sensors that had been developed and tested by the US Navy and were available to the MSDB project at zero development costs.

MSDB Phase I Test Materials and Methods

MSDB Phase I Sensor Configuration for UW UXO Data Collection

Figure 1 shows the sensor and catamaran platform configuration that was employed during Phase I MSDB testing in St. Andrews Bay, FL. The MSDB sensor suite included a BOSS acoustic sensor, an RTG passive magnetic array, and a GEM-3 active EM sensor array. The sensors were deployed from a 46 ft long catamaran, as shown in Figure 1, to measure the acoustic and EM database on the UXO test target sets. The MSDB sensors were mounted in UW towed vehicles/housings as described below. The sensor UW towed vehicles/housings were mounted to a set of rigid support structures attached to the catamaran. The BOSS and RTG sensors were located in a single BOSS TV which was deployed from a vertical tow pole mounted on the front of the catamaran. The position of the tow pole was adjustable to permit deployment of the acoustic and passive magnetic sensors at selectable altitudes below the catamaran and above the sea bottom. The active EM sensor was towed on a separate sled behind the catamaran. The sled was towed from a fiberglass pole attached to the rear of the catamaran. During test operations, the catamaran executed straight line tracks over the target test field at modest speeds (2-3 knots). The position of the catamaran (and attached sensors) was measured using a WASS GPS located on the catamaran deck. The catamaran also served as the platform for sensor data collection systems.

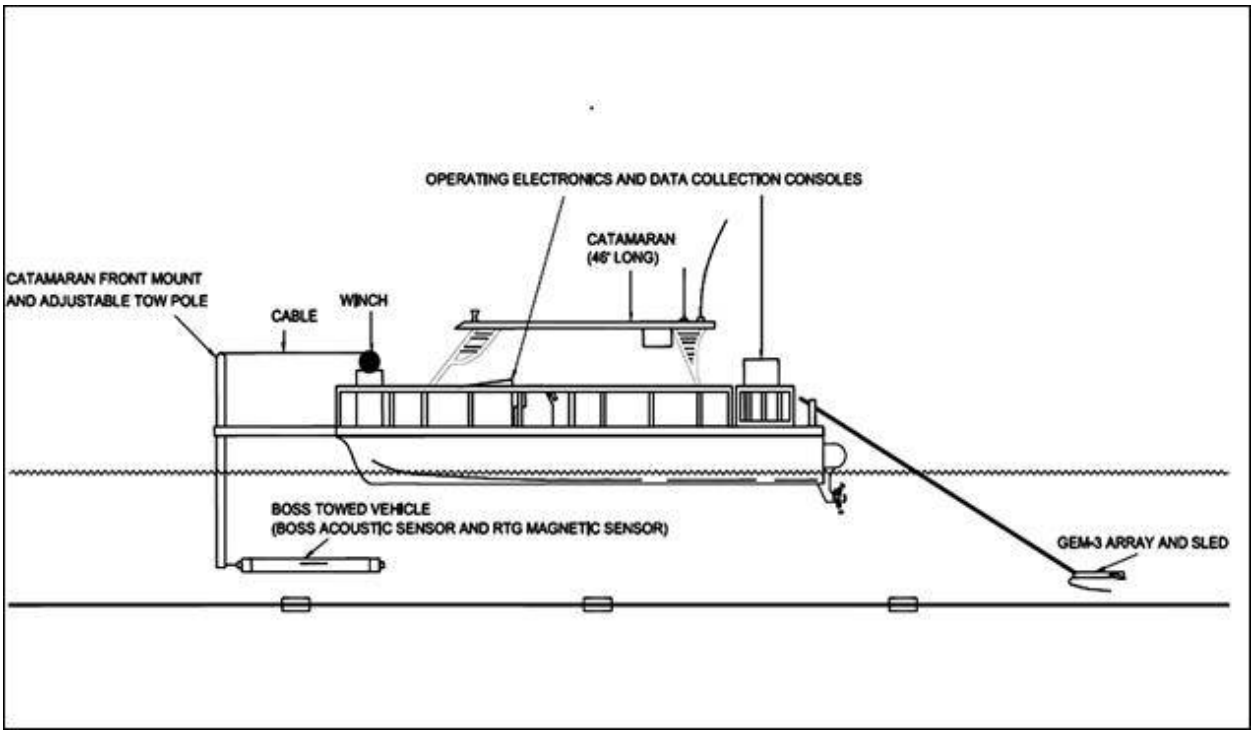


Figure 1 Phase I MSDB Sensor Deployment Configuration from Catamaran

BOSS-Wing Sonar

The MSDB BOSS acoustic sonar is a wideband FM sonar that generates multi-aspect imagery of buried, partially buried and proud targets[5]. An omni-directional spherical projector transmits a FM pulse to illuminate the seabed in all directions. Hydrophone arrays encapsulated in vehicle wings measure the backscattering from the seabed. The hydrophone outputs are digitized, matched-filtered and coherently summed using time-delay focusing to form an image of the seabed [6]. The focused data are stored in a 3D matrix where matrix indices correspond to focal points under the seabed. Maximum intensity projections of the 3D matrix data onto orthogonal planes form three views of the seabed. The maxima of a sequence of overlapping projections form a multi-aspect image projection. The sonar operator uses the three orthogonal multi-aspect image projections to view top and side views of buried targets.

Figure 2 shows the dimensions of the BOSS sonar vehicle used in the October 2006 experiments in St Andrews Bay near Panama City FL. The sonar vehicle is approximately 2.7 meters long with a wing span of approximately 3.5 meters. The vehicle is neutrally buoyant in water and has a dry weight of 500 lbs.

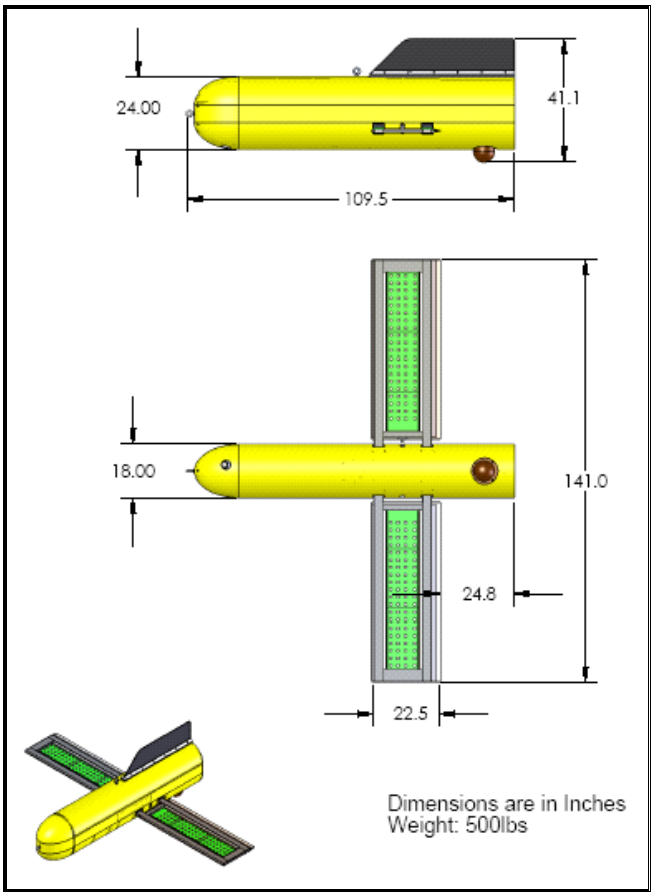


Figure 2 Dimensions and dry weight of BOSS-160 Sensor and BOSS TV

The BOSS-wing system uses the same type of acoustic transmitters employed in a BOSS-disk sonar that was previously successfully demonstrated during FY 2004 field tests over another St. Andrew Bay target field at NSWC PC. FAU developed a new BOSS system, and all associated electronics and signal-processing equipment, and operated the BOSS sensor/TV during the Phase I tests. Illustrations of the BOSS-wing sonar are shown in Figure 2.

A photo of BOSS-160 vehicle in Figure 3 was taken during mobilization for the St Andrews Bay experiment. The vehicle contains a spherical acoustic projector, two wings each with a 4 by 20 element hydrophone array, a side scan sonar (not used), a Doppler Velocity Logger (DVL) for measuring 3 axis velocities over the seabed, an Inertial Measurement Unit (IMU) for measuring 3-axis angular rates and 3-axis acceleration, a sonar computer for data acquisition and storage, and the RTG for passive magnetic detections.

Figure 3 BOSS-160 vehicle with aft mounted RTG

The photo shows the spherical projector protruding below the aft end of the vehicle and one of the 1.5 meter long wings containing a 4 by 20 element hydrophone array.

A block diagram of the processing for the BOSS data collected is shown in Figure 4. After the hydrophone data from the 160 hydrophone channels are matched-filtered, the transmitter to surface to bottom to hydrophone multiple is removed from each channel. Focusing generates a 3D matrix of image pixels where each pixel location corresponds to a focal point. Each image pixel is calculated using data from N hydrophone channels for M transmissions, starting at ping m_1 and ending at ping m_2, using the expression

$$A(x,y,z) = \left| \frac{1}{NM} \sum_{n=1}^{N} \sum_{m=m_2-M+1}^{m_2} s_{n,m}(t_{TFn}) R_{TFm} R_{Fn,m} \right| \qquad (1)$$

where $s_{n,m}(t_{TFn})$ is the analytic signal for the nth hydrophone channel for ping m where t_{TFn} is the sample time associated with the path from the transmitter to the focal point $\vec{X}_F$ to receiver n, R_{TFm} is the path length from the transmitter to the focal point for ping m, and $R_{Fn,m}$ is the path length from the focal point to the nth hydrophone for ping m. Figure 5 contains a schematic of the position vectors that are calculated during focusing and synthetic aperture processing. Unless otherwise in the analysis section of this report, the number of hydrophones N=160 and the number of pings in the synthetic aperture M=30. Because the BOSS-160 data was collected at a transmission rate of 30 pings per second and the vehicle speed was approximately 1m/s, the length of the synthetic aperture was about 1 meter.

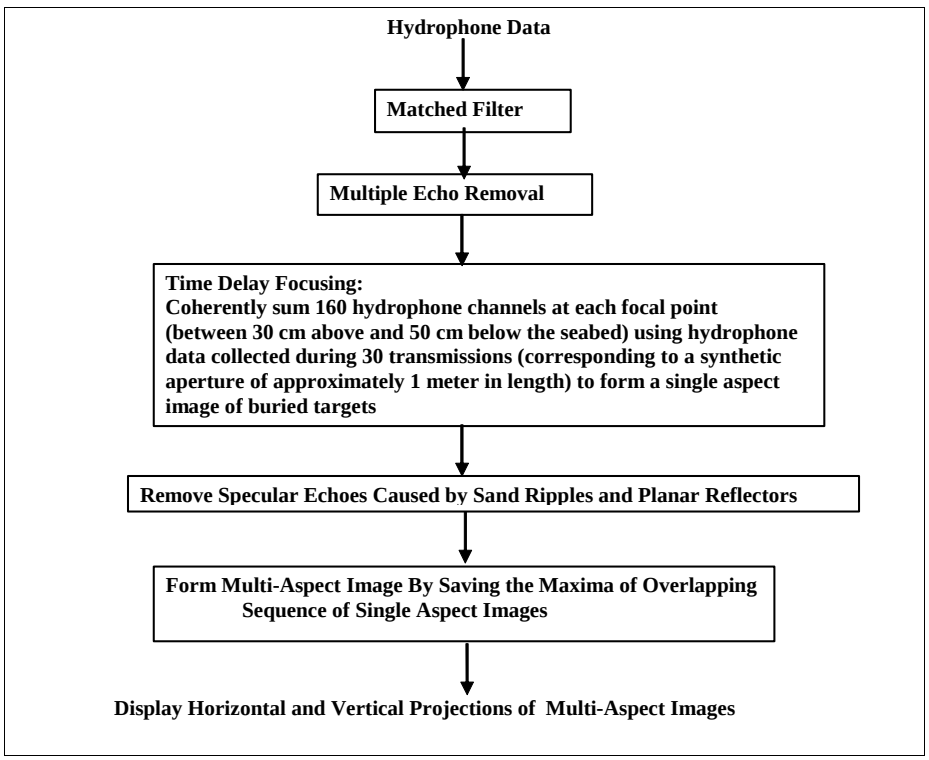


Figure 4 Flow Chart Showing Processing of Buried Object Scanning Sonar Data

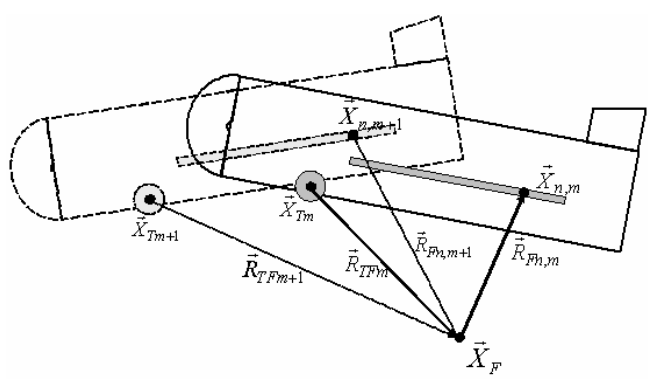


Figure 5 Positions of projector and hydrophone n with respect to a single focal point $\vec{X}_F$ for transmissions m and $m+1$

A single aspect 3D matrix of image pixels is produced by focusing using 160 channels of hydrophone data for a set of 30 transmissions. After focusing, the region of the signal aspect image containing specular reflection from seabed ripples and layering is set to zero. A multi-aspect image is formed for each trackline by taking the maxima of the overlapping single aspect images generated along the trackline. The projections of the multi-aspect images onto the z=0 plane (plan view) and x=0 and y=0 planes (across and long track views) form the multi-aspect image display for each trackline.

RTG Sensor

The RTG is a compact, passive magnetic sensor configured to measure five tensor gradient components of the magnetic field of magnetic dipole targets. RTG uses fluxgate triads and subtracts the outputs of three spatially separated triads to form the tensor gradient sensors. RTG traids employ a feedback approach to measure the ambient magnetic field components at the site of each triad. Figure 6 shows four fluxgate triads used by RTG to measure the gradients. Each triad includes a 3-axis fluxgate magnetometer and a set of feedback coils. The outputs of three triad magnetometers are subtracted to form the tensor gradient sensors measuring the five gradient components of the magnetic dipole target. The component magnetic field outputs of one triad (the fourth triad on the top/left in Figure 6) are used as references to set currents in the feedback coils of each magnetometer to levels that null out the Earth's magnetic field at the triad. This feedback approach reduces dynamic range requirements that would otherwise limit gradient sensitivity when two vector magnetometers are rotated in the Earth's magnetic field. The RTG gradient baseline is approximately 6.5 inches and gradient sensitivities of ~ 0.5 nTesla/meter-$Hz^{1/2}$ are achieved [(7)].

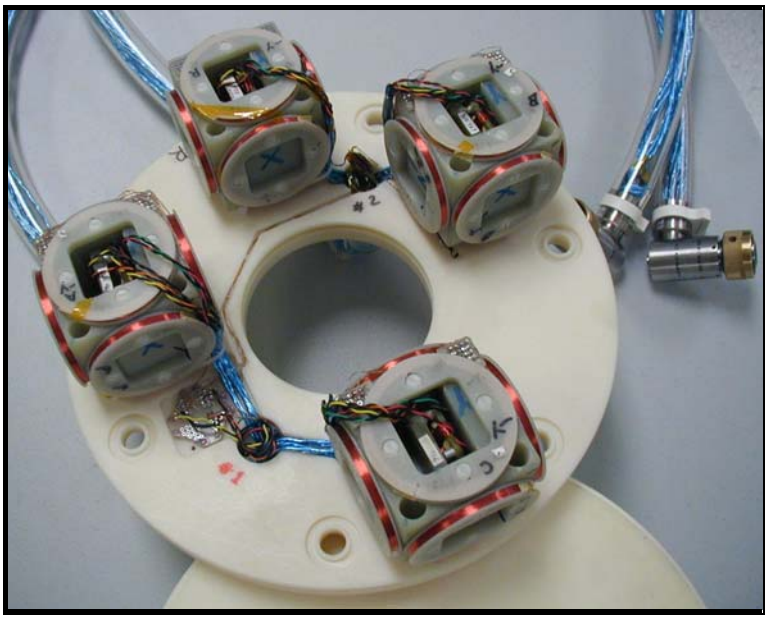


Figure 6 RTG Sensor. Four sensor triads are shown, each with a 3-axis fluxgate magnetometer (internal, not clearly visible) and a set of 3 feedback coils. The upper triad 3-axis magnetometer regulates the feedback currents to null the magnetic field at the center of the other three triads. Gradients are measured by subtracting the outputs of the component magnetometers in the three lower triads

During search operations RTG measures a time series of five target gradients. The gradient-time series data are processed to determine the position and magnetic moment vectors of detected targets. Detection range of RTG is dependent on target size and magnetic material composition. The RTG detection range for the simulated UXO targets in Phase I varied from 2 -4 meters.

During Phase I tests the RTG sensor was packaged in a watertight housing shown in Figure 7 and integrated into the aft section of the BOSS TV as shown in Figure 8. The RTG is operated via electronics mounted on the catamaran during search operations. RTG uses the BOSS tow cable and an Ethernet network to operate the sensor and to pass RTG measurement data to the catamaran for data storage. During the MSDB target testing the BOSS TV was deployed at altitudes such that RTG sensor is within detection range of the UXO targets.

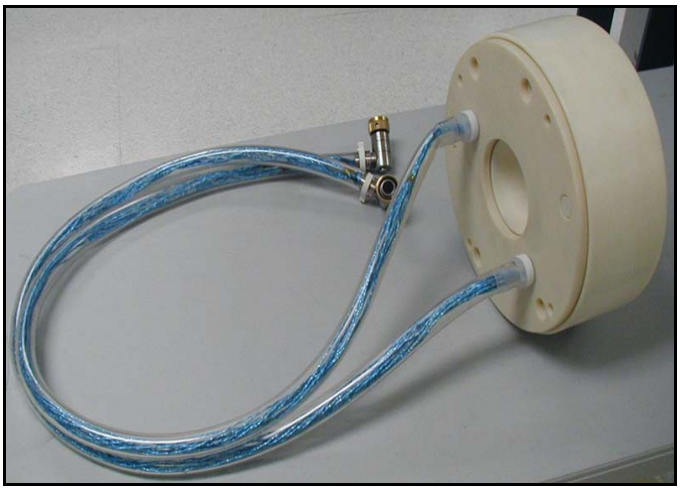


Figure 7 RTG in Watertight Housing

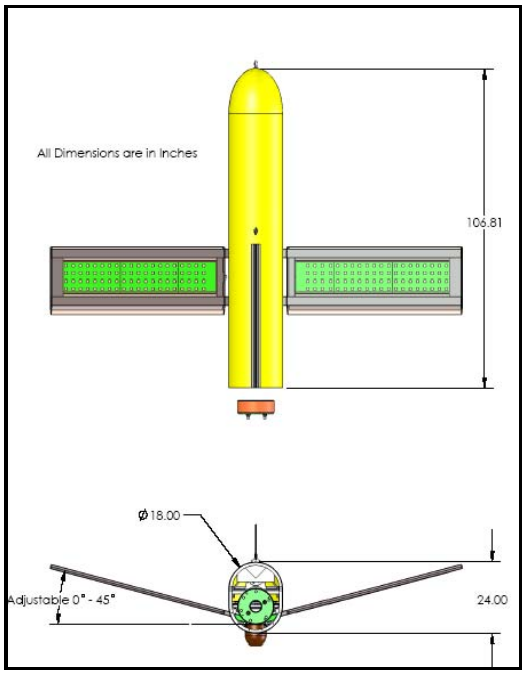


Figure 8 BOSS TV with RTG Sensor Installed

GEM-3 Sensor Array

The GEM-3 sensor array is an active broadband EM sensor used to detect and classify buried metallic UW targets. The sensor operates at multiple programmable frequencies and detects the eddy current scattering from conducting portions of each target[8]. Once the sensor detects a potential target, it measures the target's spectral responses over the entire operating bandwidth. The sensor measured spectrum can then be compared with a library of spectra stored for known targets to aide in classifying the identity of the detected target.

The GEM-3 sensor array consists of three GEM-3 sensor units and an electrical unit. The array is towed along the seafloor during search operation. Figure 9 illustrates the configuration of the GEM-3 sensor array that utilizes three GEM-3 style sensors positioned side-by-side in a single UW housing. The triple GEM-3 coil design yields a search width of approximately 7-8 feet.

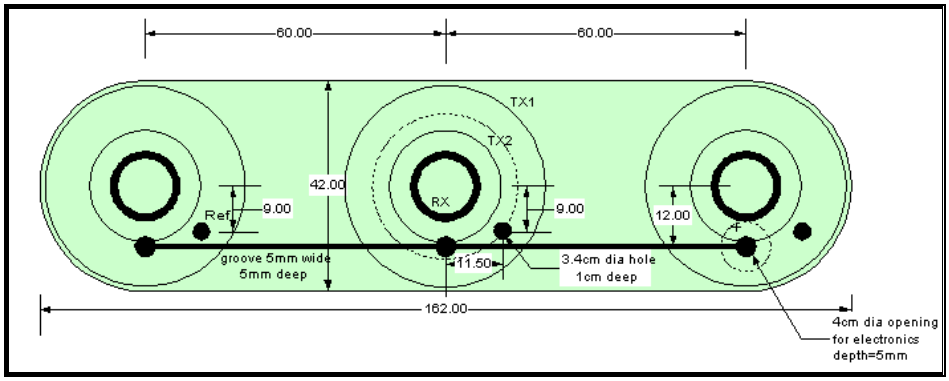


Figure 9 GEM-3 Sensor Array with Three GEM-3 Sensors

For simple UXO detection, the GEM data is processed using a composite frequency channel referred to as "qsum + ipdif", which consists of the sum of all quadrature components plus inphase component differences from the lowest frequency inphase (subtracting the lowest frequency from the others desensitizes the response to geologic magnetic susceptibility). Anomaly maps are developed plotting the intensity of the "qsum + ipdif" versus the position as determined from measured GPS location of the GEM-3 towed sled position.

MSDB Craft and Mechanical Design

The MSDB craft and mechanical design concept were shown in Figure 1. The catamaran is 46 feet long, 12 feet wide and is operated and propelled by twin 110 HP outboard motors. The craft has a very low magnetic signature. The catamaran is the platform for the MSDB sensors/sensor structures, ancillary sensors (DGPS system, depth altimeter), and deck/shelter space for the sensor electronics, displays and data collection equipment. The catamaran also carries up to seven craft, sensor and test personnel during the UW UXO Site I test operations.

The BOSS acoustic and RTG magnetic sensors are housed in the BOSS TV and are operated remotely via cable from separate sensor electronics mounted on the catamaran. Sensor control and data transfer to/from the sensor electronics are via Ethernet. The depth of the TV/sensors below the catamaran is controlled by the position of the vertical tow pole mounted on the front of the catamaran. Figure 10 shows the mount and the adjustable pole. The pole vertical position is adjustable which permits flexibility so that the TV can be positioned at shallow depth

during transit to test areas and at search depths of 3-7 feet during test operation. During search operations the BOSS/RTG sensors are positioned 3-6 feet off the sea bottom to achieve a 12-15 foot search swath width.

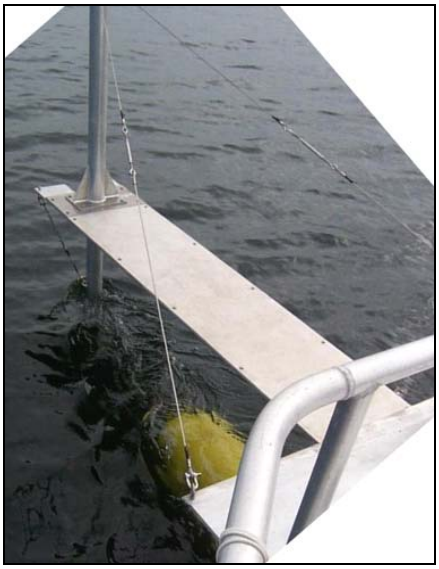


Figure 10 Photo of bow mounted pole used to tow the BOSS-160 sonar at a depth of approximately 1 meter during transit.

The GEM-3 array sensor package was mounted onto a fiberglass frame with cement filled (for ballast) tubular sled rails in a 3-point configuration, attached to a 40' long towing pole. Figure 11 shows the GEM-3 array mounted on the triangular sled that was towed behind the catamaran.

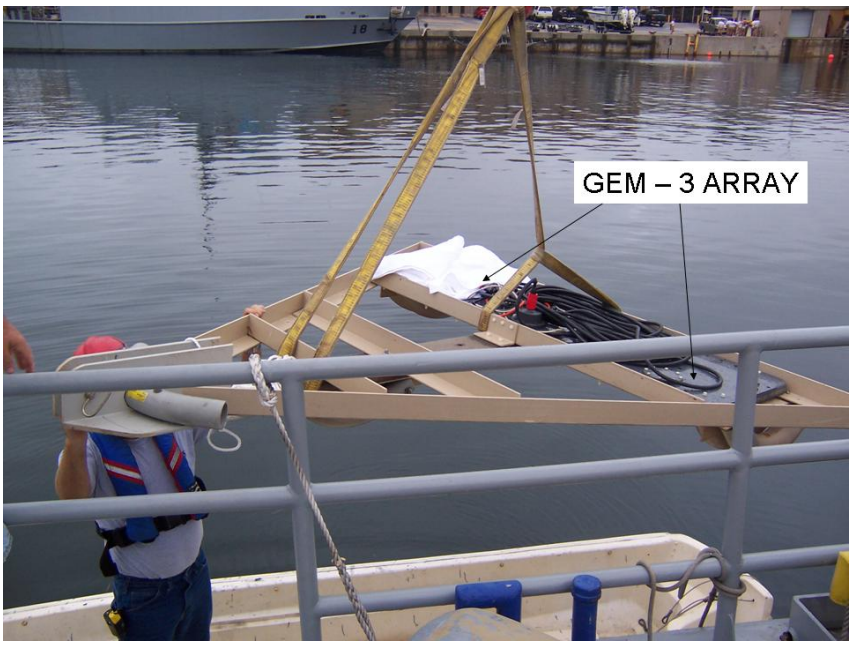


Figure 11 The GEM-3 sensor array (see Figure 9) is deployed in the rear of the triangular towed sled. The horizontally oriented GEM-3 coils pass ~ 6in above the sea floor during search operations.

The UW data acquisition is performed in a bottom dragged/surface towed method. Navigation is accomplished by extrapolating two differential global positioning systems (DGPS) mounted at the surface end of the tow shaft about a meter apart.

MSDB Data Collection Issues

MSDB testing was conducted with attention given to the data collection protocol to insure that comprehensive high quality data were recorded using a well-documented format that allows the data to be easily accessible to other SERDP UW UXO investigators who may use it in their own analyses. Several key elements were emphasized in the MSDB experiment design including:

- Target Ground Truth - Precision deployment of the test target field by divers to insure that the characteristics of the targets in our test field (target position, burial depth, orientation) were validated and documented. WAAS GPS techniques were employed to determine an UW marker set defining the endpoint locations of each test field leg. Individual target locations were measured referenced to the marker set via a line connecting the marker set. Light monofilament line connecting the buried targets and the marker line were used to verify target positions.

- Environmental Ground Truth – Collection of acoustic environmental data to permit other SERDP sensor modelers to validate their models. SERDP expressed interest in the MSDB project collecting acoustic sensor and environmental data to permit other SERDP sensor modelers to test and validate their models. As an example, SERDP funded an NSWC PC modeling effort under a separate SERDP project (MM-1506) to evaluate PCSWAT capability to predict sonar sensor detection performance versus buried UW UXO targets. SERDP requested that MSDB collect BOSS acoustic sensor detection data *and appropriate environmental data* to permit SERDP project MM-1506 to evaluate PCSWAT capability to predict BOSS performance. The PCSWAT evaluation would be performed under SERDP project MM-1506.

  The SERDP project MM-1506 principal investigator identified several acoustic environmental parameters to be measured for SWAT validation of BOSS. These included measurement of several bottom parameters (e.g., sound speed, attenuation, density, and scattering caused by gas) as well as surface roughness, and water speed profile [(9)].

  The MSDB project chose to employ two methods to measure the acoustic environmental parameters requested by the PCSWAT SERDP project. Method 1 employed chirp sonar techniques developed by Shock of FAU to estimate selected bottom parameters [(10)]. Acoustic inversion techniques can be used to estimate sound speeds and densities of the sea bottom by collecting pulses reflected from the water/bottom interface and using a layered bottom model to find the set of layer parameters that best reproduces the measured reflected signal. Method 2 employed University of Washington/Applied Physics Lab equipment, In-situ Measurement of Porosity – 2nd generation – IMP2- conductivity probe techniques and Sediment Transmission Measurement System – STMS1 – transmission techniques, to measure the sediment interface roughness and sediment sound speed and attenuation.

- Application of precision navigation techniques on the catamaran platform that insures precise knowledge of the position of each sensor at all times during each test run. In the MSDB

sensor suite design each sensor is in a fixed, known position with respect to a point on the catamaran. The catamaran position (and reference point on the catamaran) was measured applying WAAS GPS techniques.

- All sensor data was time stamped with a common clock. This was accomplished by use of time code generator techniques that permitted time correlation of different sensors.

MSDB Phase I Test Preparations/Test Methods

MSDB Phase I testing focused on conducting UW UXO detection tests versus two fields of simulated UXO targets deployed at a sand bottom and a mud bottom site in St. Andrews Bay, FL. Several candidate sites were surveyed in St. Andrew Bay to identify suitable test areas with desired water depth and bottom type for deploying the UXO test targets. The primary site criteria was to identify a flat bottom area with water depth of 10 ft (+/- 2 ft) which was debris free and large enough to deploy up to three lines of simulated UXO targets.

Surveying was performed by personnel operating from a support pontoon boat equipped with WAAS GPS navigation and depth measurement devices. Equipment used included a Furuno sounder, a Trimble GPS device, a Trimble antenna, and an Amrel laptop computer. The specifications for the Trimble AgGPS 132 are in Table 1 and the frequency for the Furuno sounder ranges between 50–200 kHz. Figures 12 and 13 show maps of the St. Andrews Bay area and identify several candidate sand and mud bottom sites that were surveyed for the MSDB project.

Table 1 Trimble AgGPS 132 Specifications

Physical Characteristics	
Size	14.5 cm W x 5.1 cm H x 19.5 cm D (5.7 in. W x 2.0 in. H x 7.7 in. D)
weight	0.76 kg (1.68 lb)
Power	7 W (max), 10 to 32 Vdc
Operating Temperature	-20ºC to +65ºC
Storage Temperature	-30ºC to +85ºC
Humidity	100% condensing, unit fully sealed
Casing	Dust proof, waterproof, schock resistant
Compliance	FCC Class B, CE
Performance Characteristics	
General	12 channel L1 code phase receiver
Maximum update rate	10 Hz
Position Accuracy	
Static (year-to-year)	submeter differential
Dynamic (pass-to-pass)	4–12 in. (10–30 cm) RMS 15 min pass-to-pass accuracy
Time to first fix	<30 s, typical
NMEA message	GGA, GGL, GRS, GTS, VTG, RMC, GSA, GSV, XTE, ZDA, ALM, MSS
Communication Ports	2 x RS-232, 2 x J1939 (CAN 2.0B)

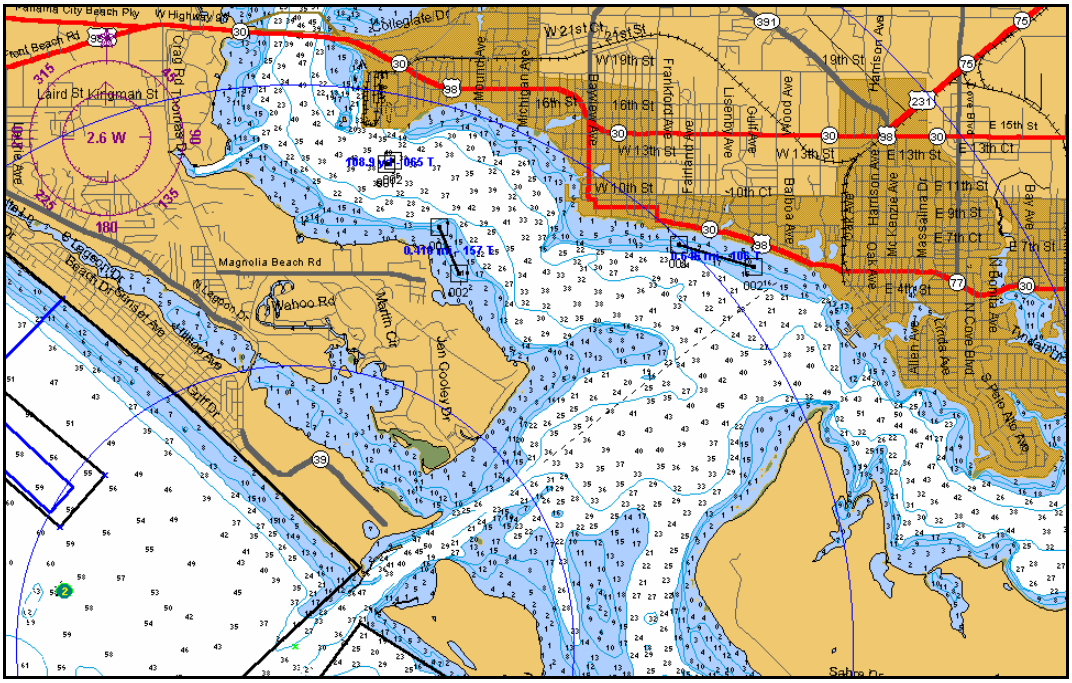


Figure 12 Phase I St. Andrew Bay Test Area Sand Seafloor

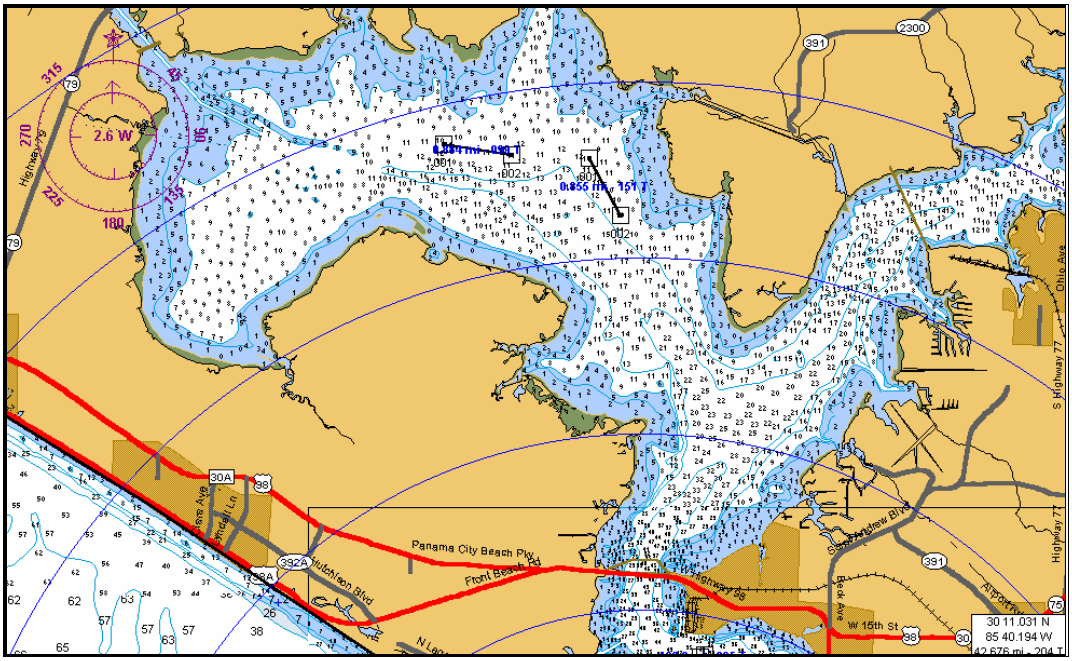


Figure 13 Phase I West Bay Test Area Mud Seafloor

Based on the water depth survey and subsequent diver inspection of the bottom, two Phase I sites were selected: 1) a sand bottom site southeast of the Navy center and 2) a mud bottom site in the West Bay portion of St. Andrew's Bay. Positions of the selected sites are illustrated in Figure 14.

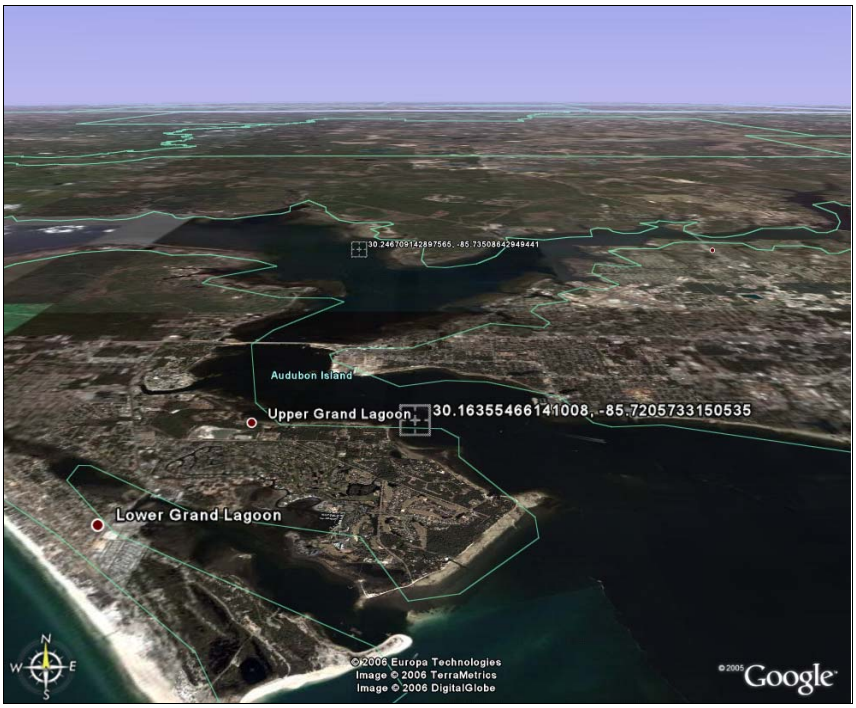


Figure 14 Selected Phase I MSDB Sand and Mud Test Sites

A set of simulated UXO targets were fabricated for deployment as UXO test targets for the MSDB tests. The targets fabricated for MSDB included four different cylinders sizes shown in Figure 15 which were intended to simulate 50mm to 150mm UXO shells.

Figure 15 MSDB Phase I UXO Target Set

UXO targets were machined from mild steel and were capped at both ends and filled with concrete. Thirty-two UXO target were fabricated and deployed by Navy divers at the two sites.

The UXO targets were deployed in multiple straight line rows at each site. Figure 16 illustrates the UXO target layout for the sand site which included three target rows. Each target line included two targets of each of four sizes (eight targets per line) with one target of each size proud and a second target buried. The targets were deployed from South to North starting with the smallest targets and alternating proud – buried – proud - buried. The deployment procedure for each line and set of UXO targets was identical. Initially, two screw anchors were deployed and installed. The position of each anchor was measured by the divers using GPS equipment. Divers deployed the UXO targets at 10 meter intervals securing each UXO to the line with parachute chord. Divers buried the proud targets flush to the bottom (half buried) and the buried targets 1 foot below the bottom.

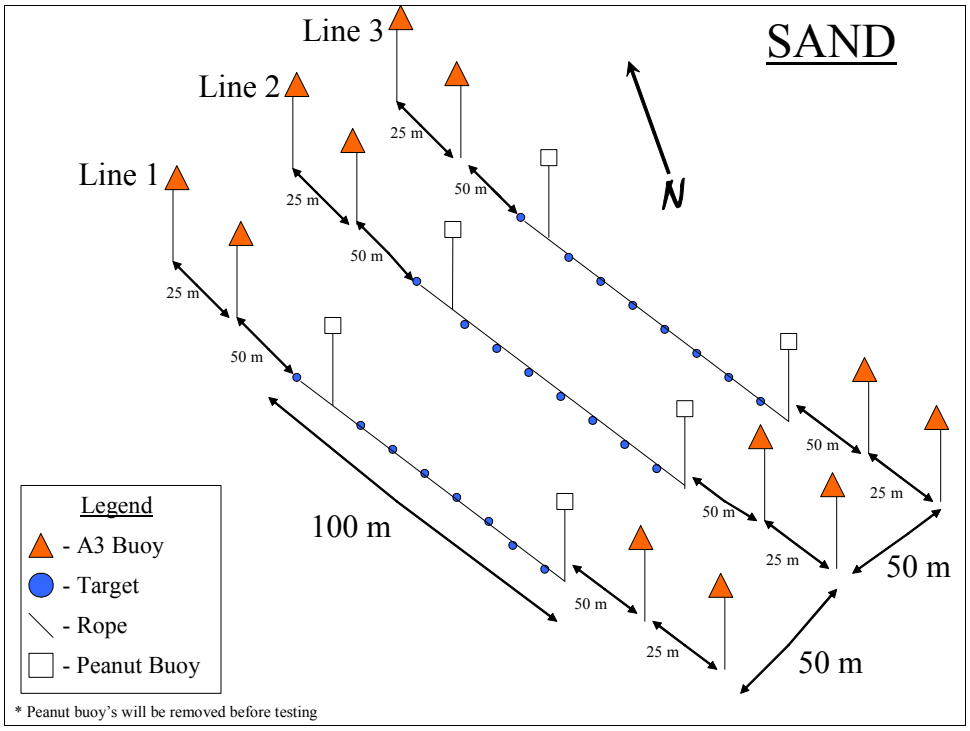


Figure 16 UXO target/buoy configuration at the Phase I sand site

Additional surface buoys were deployed in line with each target line to assist the boat pilot in steering the catamaran over a given line during search operations. The horizontal orientation of the UXO targets differed from line to line. In the sand field all targets in line 1 were parallel to the line direction. Targets in lines 2 and 3 were oriented at 90° and 45° with respect to the line direction. The difference in target orientation for each line was selected to permit evaluation of target detection with target aspect angle, a factor that was expected to be important for the BOSS acoustic UXO detection. Lines 1, 2, and 3 were laterally separated by 50 meters to insure that only targets from a given line would be detected during a search run.

Figure 17 shows the target configuration at the St. Andrews Bay mud site. Two target lines were emplaced at the mud site using identical techniques as at the sand site. The target orientation at the mud site include a line 1 with targets horizontal and oriented parallel to the target line and a line 2 with targets horizontal and oriented perpendicular to the line direction.

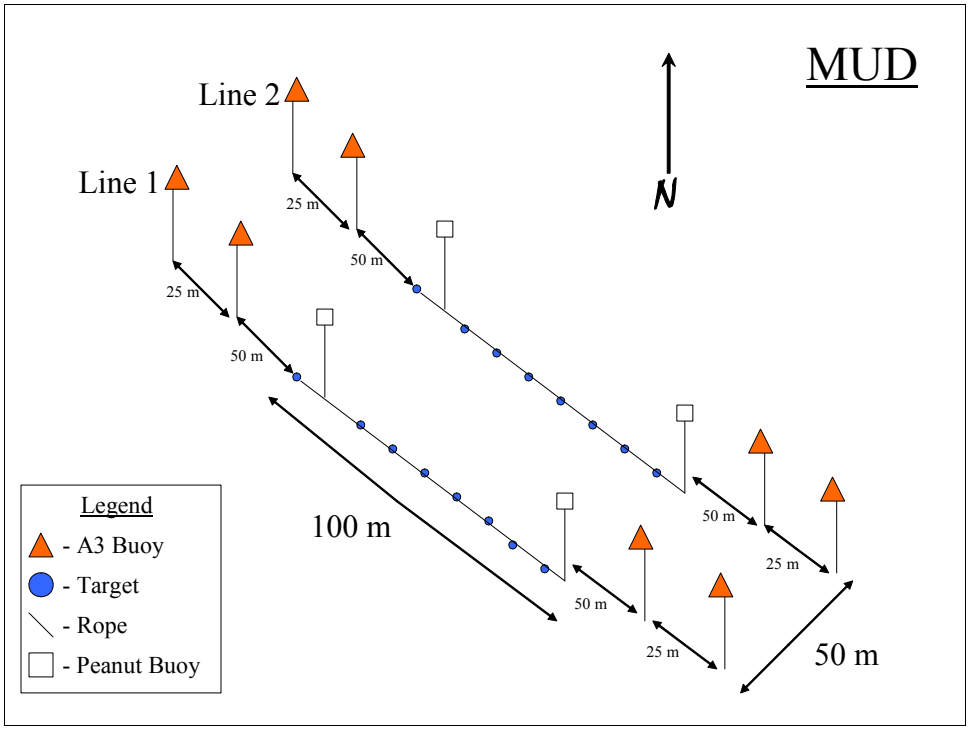


Figure 17 UXO target/buoy configuration at the Phase I mud site

Deployment of the UXO target lines was performed at the St. Andrews Bay sand bottom and mud bottom sites by Navy divers in late September 2006, approximately three weeks prior to MSDB search tests.

Procedures were developed and implemented for conducting the UXO search tests at the two sites. Figure 18 shows the RTG sensor being installed in the BOSS TV at the west dock at the Naval Surface Warfare Center – Panama City during pretest preparations. Figure 19 shows the BOSS TV being deployed in the water at the front end of the catamaran during pretest dock operations. The BOSS TV tow/electronics cable was threaded through the adjustable vertical pole to permit pretest checkout of the BOSS and RTG sensor operation. The GEM-3 array was assembled and attached to the rear mounting assembly for electrical pretest checkout. Figure 20 shows the GEM-3 array in a small whaler boat which was used during dockside checkout and was the platform for transporting the array to the test sites. Figure 21 shows the GEM-3 array being towed from the catamaran rear mounting assembly during egress to a test site. The GEM-3 array was deployed from the whaler during test operations.

Figure 18 RTG sensor is installed in the BOSS towed vehicle during Phase I pretest operations

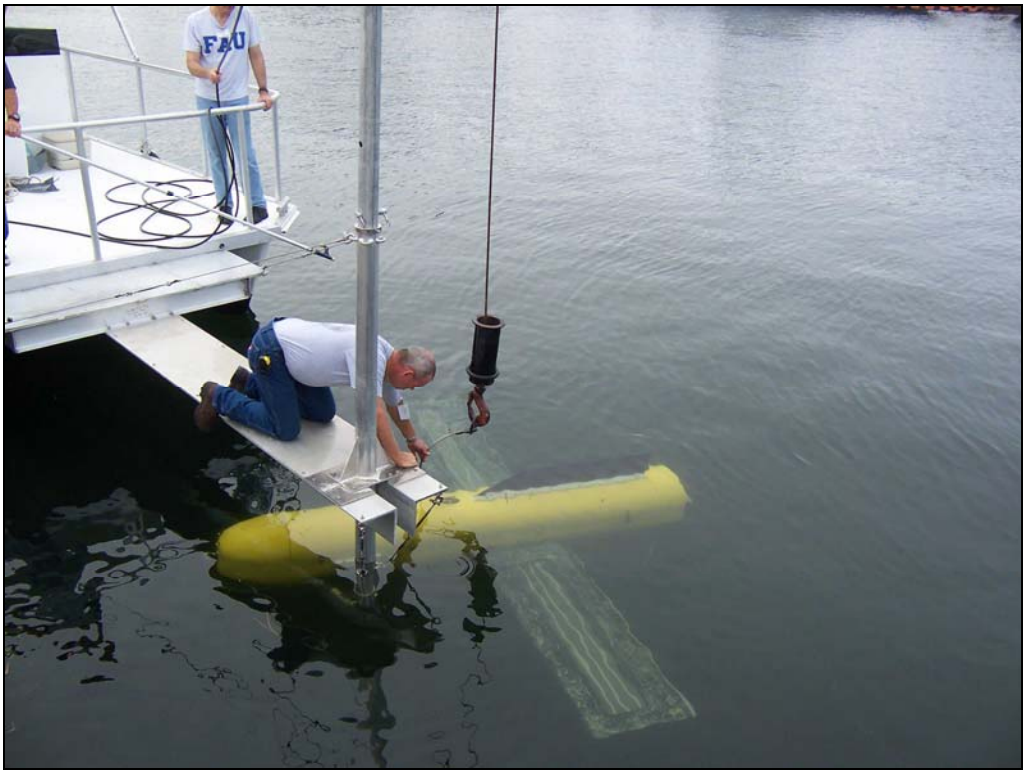


Figure 19 Deployment of BOSS/RTG TV from catamaran during Phase I pretest preparation

Figure 20 GEM-3 array mounted on whaler for transit to test area

Figure 21 GEM-3 array configuration during transit to test area

During the St. Andrews Bay tests the WAAS GPS antenna was mounted directly above the sonar vehicle as shown in Figure 22. The antenna served as the fixed reference point on the catamaran during the experiments. The antenna was directly above the BOSS wings. The WAAS GPS pair mounted on the GEM-3 tow pole was located 13.1 meters aft of the BOSS GPS. The maximum deviation between the center of the sonar and the GPS antennae during the survey was observed to be less than 1 meter. This offset between the antennae and vehicle centerline was caused by course alterations as the catamaran maneuvered to stay on track.

Figure 22 Photo of WAAS GPS antennae mounted directly above the sonar vehicle being towed from the pole. The GPS was aligned to a point above the center of the two sonar vehicle wings.

The GPS navigation data was logged simultaneously with chirp sonar data. The accuracy of the WAAS enabled GPS was measured over 6 days with the GPS stationary and is given in Table 2. The table shows that 95% of the WAAS GPS location measurements have an error less than 3 yards.

Table 2 WAAS GPS error reported for 70, 95 and 99 % confidence limits

70% CL	95% CL	99% CL
1.62 yards	3.0 yards	4.2 yards

MSDB Bottom Sediment Parameter Measurement Techniques

Two methods were employed during MSDB testing to measure the sediment acoustic bottom parameters at the sand and mud bottom test sites. Bottom sediment acoustic parameters were measured to provide accurate site data to evaluate PCSWAT acoustic model image results with target images calculated directly from BOSS measured data[9].

One technique required BOSS calibration measurements that were performed daily during catamaran transit to the St. Andrews Bay tests sites; the second measurements were performed by UW/APL using the IMP2 and STMS1 instruments in measurements conducted at the St. Andrews Bay sand and mud test sites one week after the MSDB search tests. Both methods are described below.

During the transit BOSS calibration measurements were performed to generate the calibrated reflection coefficient measurements needed for sediment property estimates [10]. The sonar was calibrated using a 4 inch stainless steel calibration sphere. The reflection coefficient is defined as the pressure amplitude of the reflected wave divided by the pressure amplitude of the incident wave measured just above the sediment-water interface.

The system response of the sonar was measured using the known backscattered response of a solid sphere and was used to correct the measured spectrum of the seabed echo. The exact solution for the amplitude and phase response of a solid sphere with known properties (compressional and shear velocities, bulk density and Poisson's Ratio) as a function of the length and direction of the acoustic source to sphere position vector and the sphere to field point position vector, is given by Hickling (1962) and was verified experimentally by Nuebauer (1974). An example of the amplitude response of a stainless steel sphere is shown in Fig. 23.

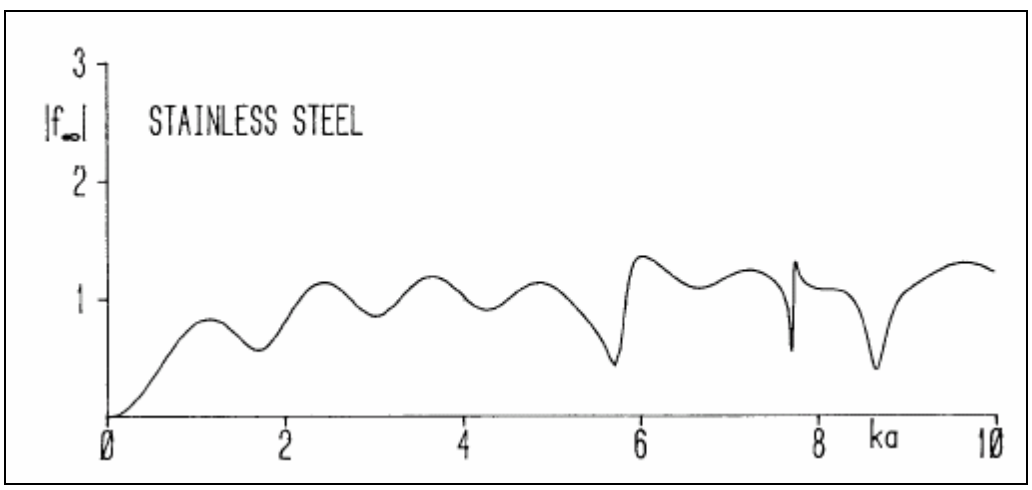


Figure 23 Amplitude response of stainless steel ball as a function of fluid wave number - ball radius product for large ranges and for a co-located transmitter and receiver. (MacLennan, 1981)

With the reflection profiler at the operating depth of the survey, a solid sphere was lowered from the bow to various depths below the sonar where backscattering from the sphere was measured by all 160 channels. The known response of the sphere and the FM pilot signal are de-convolved from the backscattered signal to measure the frequency response of the sonar system. Temperature measurements are made to correct the properties of the sphere to ensure the sphere's response is known within 0.1 dB. The calibration sphere was deployed at each site during the survey to compensate for changes in system response during the survey. The system response must be measured with a 1% accuracy to obtain a reflection coefficient measurement accuracy of 0.1 dB.

To ensure that the frequency response of the sphere was not altered by the calibration procedure, the calibration sphere was not rigidly mounted below the sonar vehicle, but was tethered below the sonar with a monofilament line that has no significant effect on the acoustic field. Because the sphere's range and the projector-sphere-hydrophone angle must be known to calculate the theoretical frequency response of the sphere, the position of the sphere must be measured during the calibration procedure. The position was measured by beam forming the output of the 4 by 20 element array of hydrophones contained in each of the vehicle wings.

The objective in the St. Andrew's Bay UW/APL measurements was to estimate the sediment sound speed and attenuation, and the water column sound speed profile at the two St. Andrews Bay test sites (the "sand" site and the "mud" site). In addition at the sand site the sediment/water RMS roughness and roughness interface spectrum were to be measured. The mud site was to be examined to decide on whether the interface roughness could be measured.

All sediment interface measurements were performed with the In-situ Measurement of Porosity - 2nd generation (IMP2) system. The IMP2 translates a conductivity probe in 1 mm increments vertically and 1 cm increments horizontally. The change in conductivity as the probe enters the sand allows identification of the sand/water interface over a total horizontal range of 4 m in 1 cm increments. This interface topography is then Fourier transformed to give the sediment interface roughness spectrum[1].

All sediment sound speed and attenuation measurements were performed using the Sediment Transmission Measurement System – 1st generation (STMS1). This system includes a diver deployable "attenuation" array that has two transmitters and two receivers. These sensors were inserted into the sediment and transmission measurements made in order to obtain sediment sound speed and attenuation[2].

The water column sound speed in St. Andrew's Bay was measured using a Seabird CTD Model 19-03.

MSDB Phase I Test Results

The MSDB Phase I UW UXO target tests were performed primarily during a three day period 18-20 October 2006. UW UXO target search data was collected by the MSDB three-sensor system at the sand site on October 18th and 19th with a total of 48 runs over the three lines of target fields. MSDB search data was collected at the mud site on October 20th with a total of 19 runs over the two lines of target fields.

Representative sensor UXO target detection results are presented for selected search runs. Briefly, data was collected on Lines 1 and 3 with all three sensors (BOSS, RTG, and GEM-3) deployed at the sand site. The search runs at the sand site over the Line 2 target set were performed with the BOSS and RTG sensors deployed but not the GEM-3 array. The GEM-3 array was not deployed during Line 2 search runs because the Line 2 area included a known debris target (e.g., an oil drum) and there was concern that the GEM-3 sled would snag on the debris. Data was collected on both Lines 1 and 2 with all three sensors at the mud site.

This section reports the search navigation data and target detection results at each Phase I test site as determined by each sensor. The results presented in this section are representative of MSDB sensor detections at each site but details of target detection results for other runs are provided in the Appendices. Appendix A details results from October 18; Appendix B presents the results from October 19; and Appendix C presents the results from October 20.

Navigation Data

The navigation data for the 3 days of surveys are presented in Appendices A, B, and C. An example of the navigation data for a portion of day 1 at the sand site is shown in Figure 24. Figure 24 is a plot of the position of the GPS antenna onboard the catamaran during each of the track runs specified in the color coded legend on the top left of the figure. The red crosses in the plots of the data sets correspond to the marker buoy locations shown in the target layout plans. The northern red cross is located half way between the buried and half buried 6 inch diameter UXO targets. The southern red cross is located 10 meters south of the southernmost target, the proud 2 inch diameter UXO target. Each track shows the catamaran captain's best attempt to follow a navigation line that would pass directly over the deployed target field. Variations in a straight line track are the result of the captain's response to steering the catamaran in the prevailing currents and wind conditions.

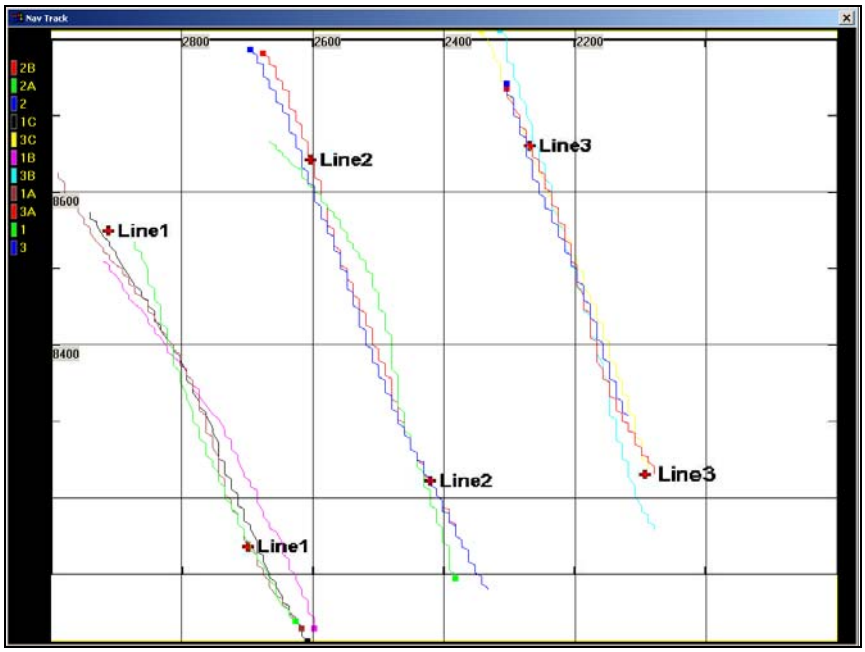


Figure 24 Tracklines for BOSS-160/RTG data collection at the sand site on 18 October 2006 with the BOSS at a towing depth of 3 feet.

Phase I BOSS Target Imagery

Appendix A contains multi-aspect images for all missions conducted at the sand site on 18 and 19 October and at the mud site on 20 October 2006. This section presents representative multi-aspect images of target UXO that were generated from selected missions using the data processing procedure described in the flow chart from Figure 4. Figure 25 presents imaging results and target mapping in the horizontal plane from a run on 18 October over Line 3 in the sand field. A more complete example of analysis of horizontal and vertical mapping results for another search run is presented and explained in greater detail in a later section.

In Figure 25, the BOSS images of sonar detected flush buried and fully buried targets are displayed as dark objects in the horizontal plane; the positions of the marker buoys and targets are displayed as circles. The BOSS images indicate that objects are detected at or within a meter or two of the ground truth target circle positions for virtually all UXO targets, both proud and buried, from the 2" diameter cylinder to the 6" diameter cylinder. Other objects are observed that appear as distinct as some of the targets, especially the buried targets (see for example the object between the 2" proud and 2" buried target, or the object to the right of the 3" buried target). It is not clear whether these are real target or not. Additional diver inspection of the target area would be required. It is clear that BOSS has detected the majority of the simulated UXO targets in Line 3 on this search run.

An inspection of the multi-aspect images shows that not all targets are detected on each pass. As described in the following analysis, there are several factors which determine if the target will be detected on a given pass including 1) across track range to the target, 2) which section of the hydrophone array is being processed, 3) interference from grooves in the seabed caused by the

GEM3 sled and 4) target orientation and interference from the surface-bottom multiple reflections. The analysis also shows that with a modified array geometry and an improved transmitter baffle, all targets would be detected on every pass.

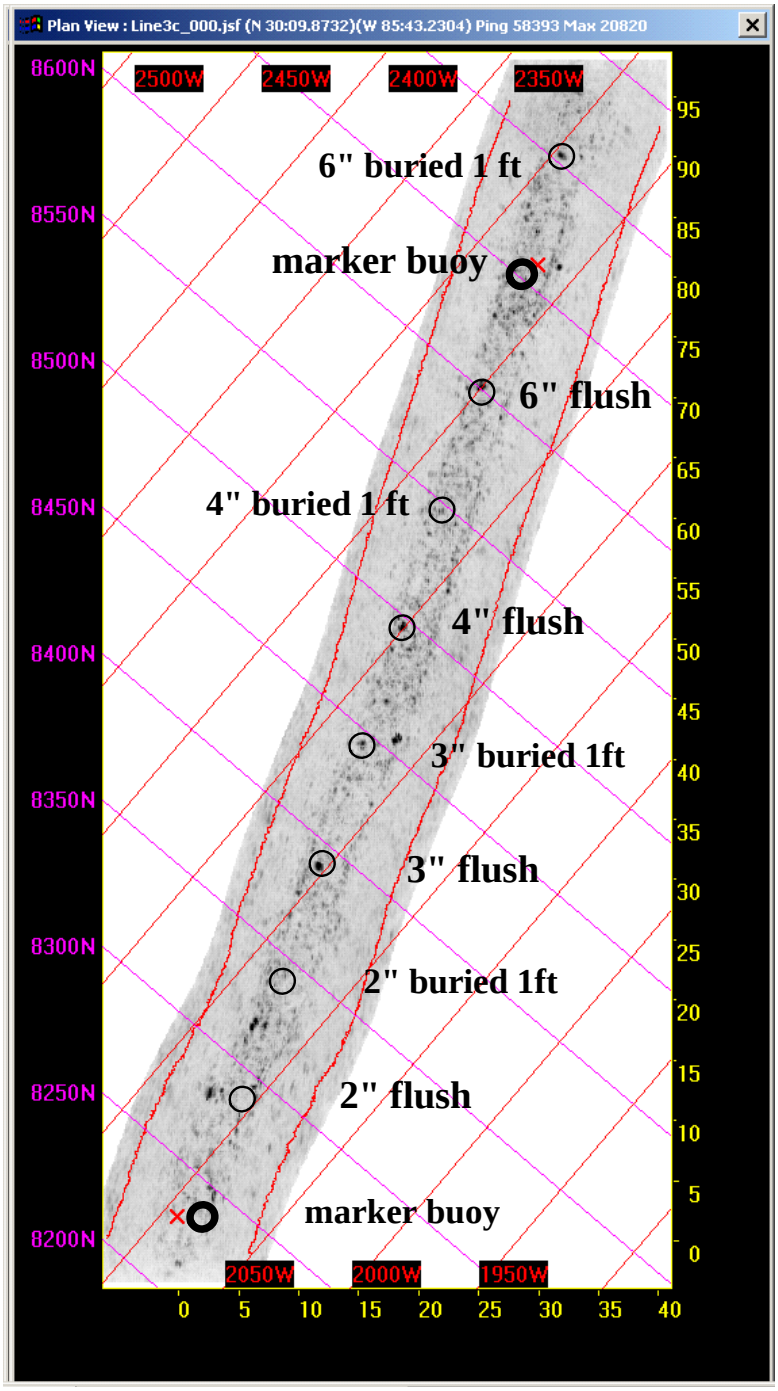


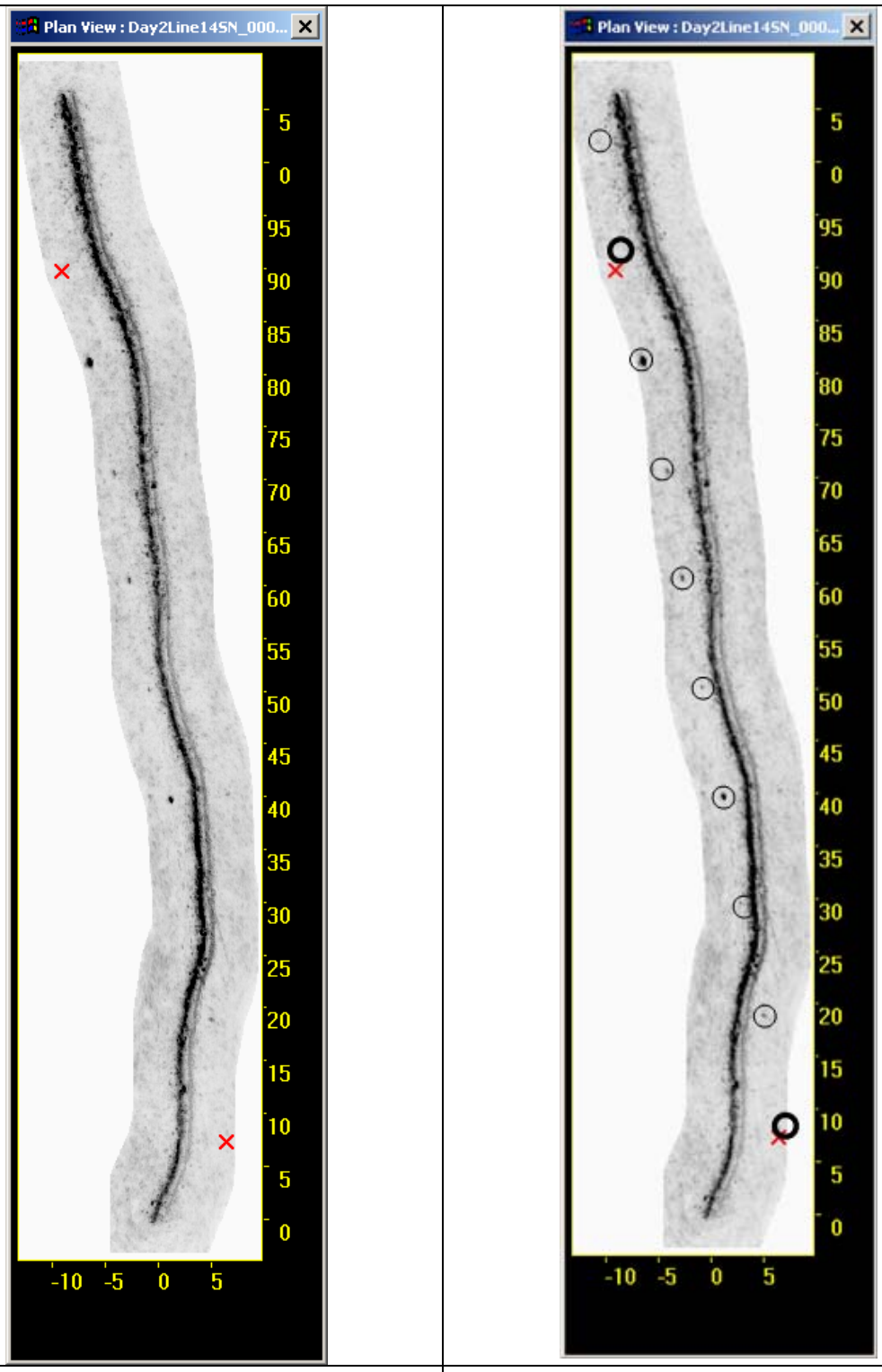
Figure 25 Multi-aspect image of trackline Line3c collected on 18 October 2006 at sand site with target overlay

Although BOSS detected all cylinders buried in the mud and sand sites, the targets were not detected on every pass and the target images did not always appear to be cylindrical in shape in

the imagery. Sonar-target geometry is an important factor controlling image quality. Only specific target-sonar geometries can detect all the targets and produce cylindrical like images. Detailed analyses of the BOSS imagery a) show the sonar-target geometries that yield the best imagery and b) yield a methodology for deploying BOSS so that all targets will be detected on every pass and the target imagery will be sufficient quality for visual classification.

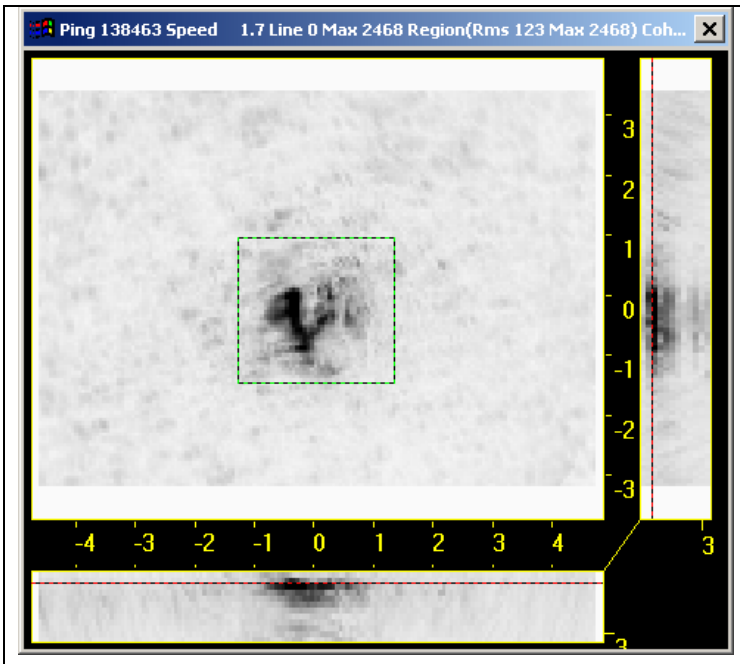
The most significant problem that prevented detections on every pass by a given target was interference caused by specular sediment-water interface and sediment layer reflections. The multi-aspect image of the seabed along Line 1 of the sand site is shown in Figure 26. The dark bands down the center of the image are caused by the specular seabed echoes. When a target falls within the dark band, it usually cannot be detected. All cylindrical targets buried along Line 1 are visible in Figure 26 with the exception of the uppermost target which is the 6 inch diameter cylinder which is buried 1 foot. As described later, that target is obscured by the specular reflections.

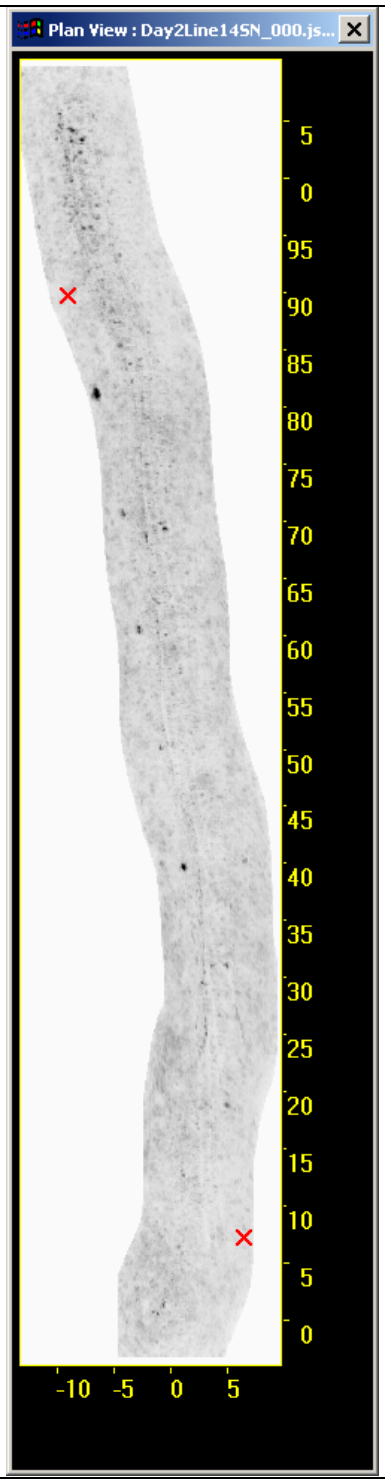
The standard procedure for mitigating specular reflection interference in BOSS data is to eliminate the specular reflections from the data just before forming the multi-aspect image. As previously indicated in Figure 5, a multi-aspect image is the maxima of all overlapping single aspect images. Therefore the multi-aspect image contains the entire history of all echoes measured by the sonar. Specular seabed echo interference in the center of single aspect image is removed before generating the multi-aspect image in Figure 27. The removal area is indicated by the green box in the single aspect image. This removal process reduces the specular interference (dark bands) shown in Figure 26. All BOSS multi-aspect images shown in the Appendices of this report were generated with specular echo removal enabled (removing the dark bands). The problem with the removal algorithm is that targets falling under the dark bands are also removed.



Line1 of sand site	Line1 showing target overlay

Figure 26 BOSS multi-aspect image of Line 1 (Run# Day2Line14SN). Right hand image contains an overlay of circles showing planned target locations. The red x's are the locations of the end markers which have the same navigation coordinate as the bold black circles in the template.

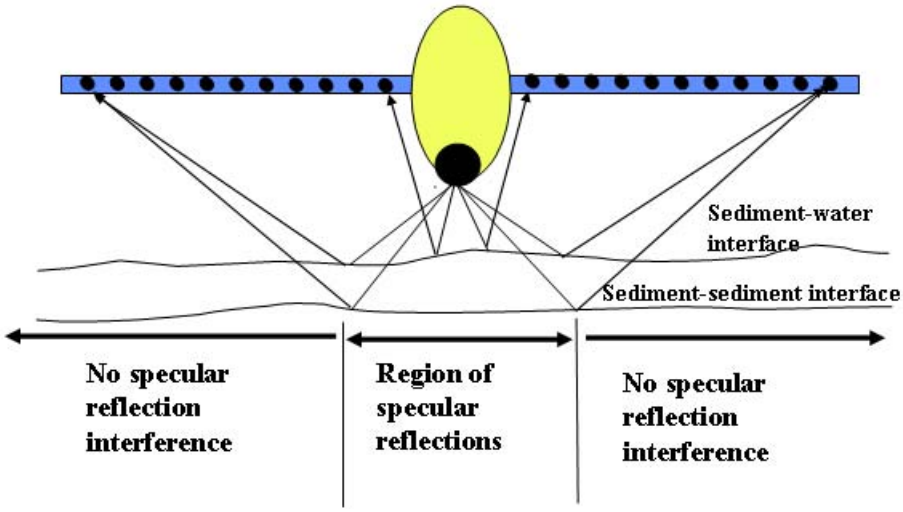




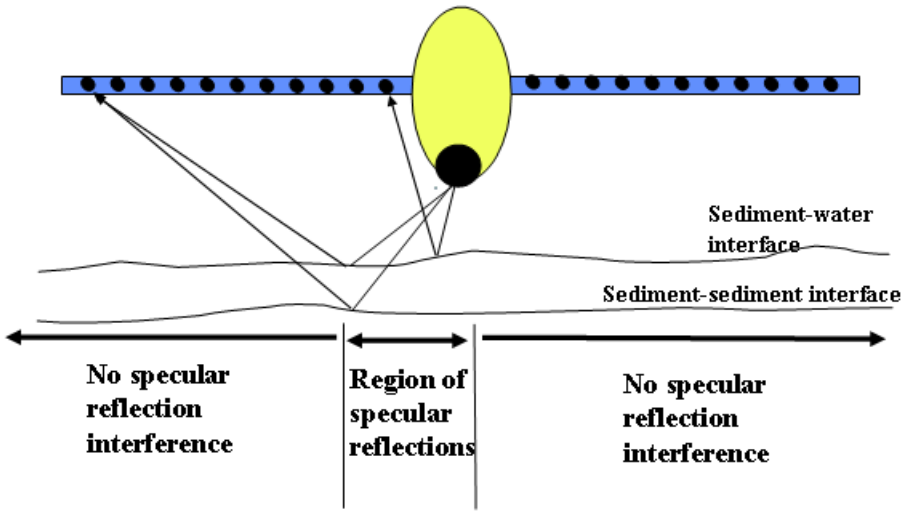
Example of single aspect image formed by synthetic aperture processing of 30 transmissions	Multi-aspect image with specular reflections removed

Figure 27 The interference from the specular sediment-water interface reflection in the center of each single aspect image is zeroed before the forming the multi-aspect image.

A study of the BOSS geometry and imagery shows that generation of images without specular reflections is possible if the length of the vehicle wings is extended. Figure 28 shows the sonar-seabed geometry creating the specular interference occurring in the center of the single aspect image (Figure 27).



A. Front view of BOSS showing region of specular reflections when processing data from both wings (normal mode)

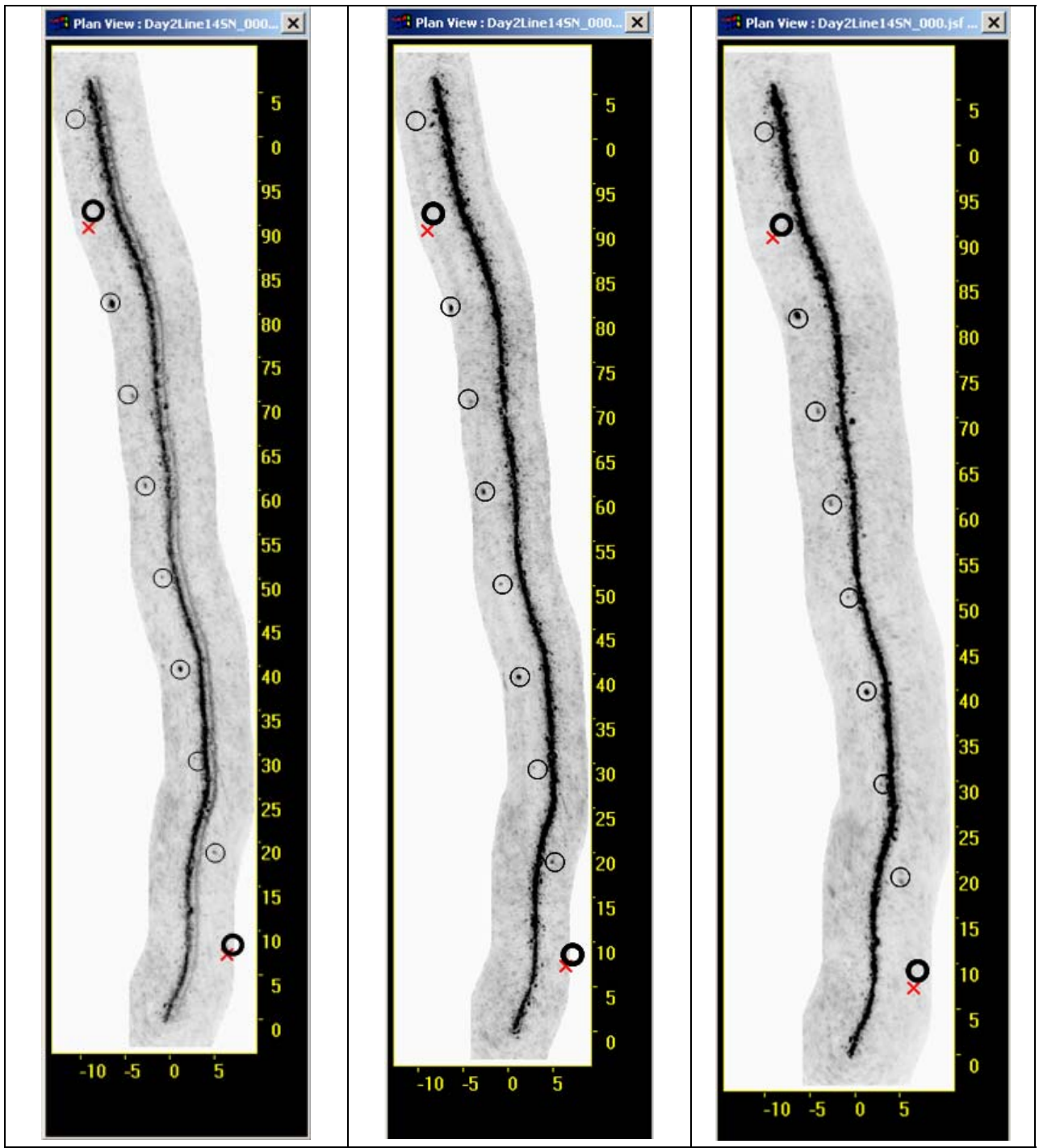


B. Processing data from one wing (reduced resolution mode)

Figure 28 The region of specular reflections is reduced by processing one wing at a time

To confirm this potential method of specular interference reduction, a multi-aspect image was generated for each wing as shown in Figure 29. The port wing generated an image with a dark band slightly to the left of centerline. Similarly the starboard wing generated an image with a dark band slightly to the right of centerline. A new image could be formed by selecting portions of the 2 images that do not contain specular interference. However the wings are not long enough so there is still a small region of overlapping specular interference. The wing would have to

double in length to eliminate all specular interference in the combined image. Figure 29 shows that processing one wing at time has the potential of eliminating the specular interference. For example, by comparing the targets just to the right of the uppermost circle in each of the images,



Both Wings (160 hyd)	Starboard Wing (80 hyd)	Port Wing (80 hyd)

Figure 29 Comparison of images generated with all hydrophone channels (both wings), starboard wing channels and port wing channels. (Run # Day2Line14SN)

it is clear that a target that is obstructed in the port wing data is clearly seen in the starboard wing data. To improve the effectiveness of BOSS for buried ordnance detection the length of the wings should be doubled and the image pixels remapped to eliminate the specular reflection interference.

An analysis of data collected along line 1 of the sand site shows the effect of target-sonar geometry on image quality. Each target measured during run # Day2Line14SN is analyzed for target shape information by zooming in on the multi-aspect image. Figure 30 is a multi-aspect image that was generated using the 4x20 element array in the starboard wing of BOSS. All UXO targets can be seen in the circles of the target overlay with the exception of the 6”D x 27”L cylinder which appears to be buried about 2 meters to the east of the planned position. Each target is annotated with the diameter and length of the cylinder and the burial depth.

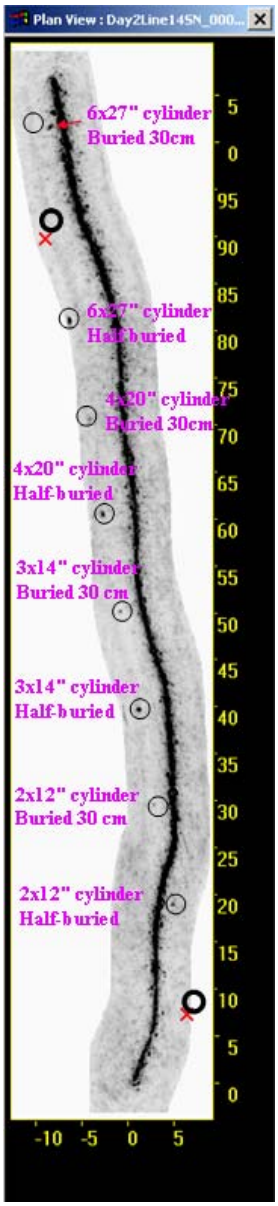


Figure 30 A multi-aspect image of line 1 at sand site developed using starboard array data

A zoom feature in the BOSS software provides more detailed shape information and burial depth information than shown in Figure 30. Figure 31 shows images of the 2” D x 12” long half-buried cylinder generated using starboard wing BOSS data. In Figure 31 the single aspect image (left) shows the target position associated with the reception of the strongest echo. The multi-aspect image (right) shows the history of echoes from the target at all aspects as the sonar approaches and passes the target. The target appears to be at the sediment-water interface as expected. Figure 32 shows the corresponding images as calculated from port wing BOSS data.

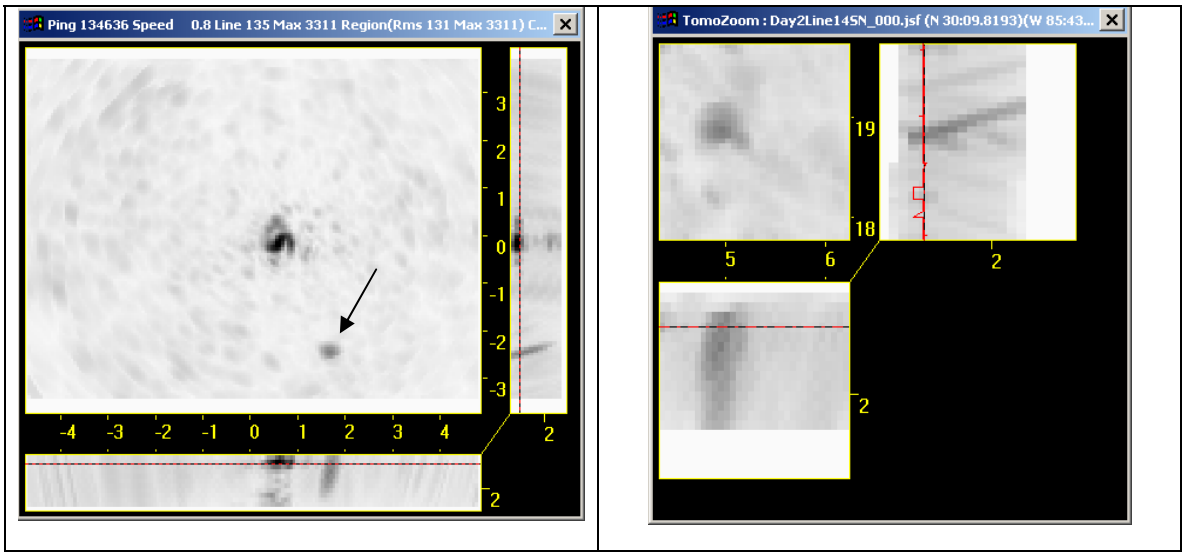


Figure 31 Images of 2”D x 12” long half-buried cylinder generated using starboard wing data.

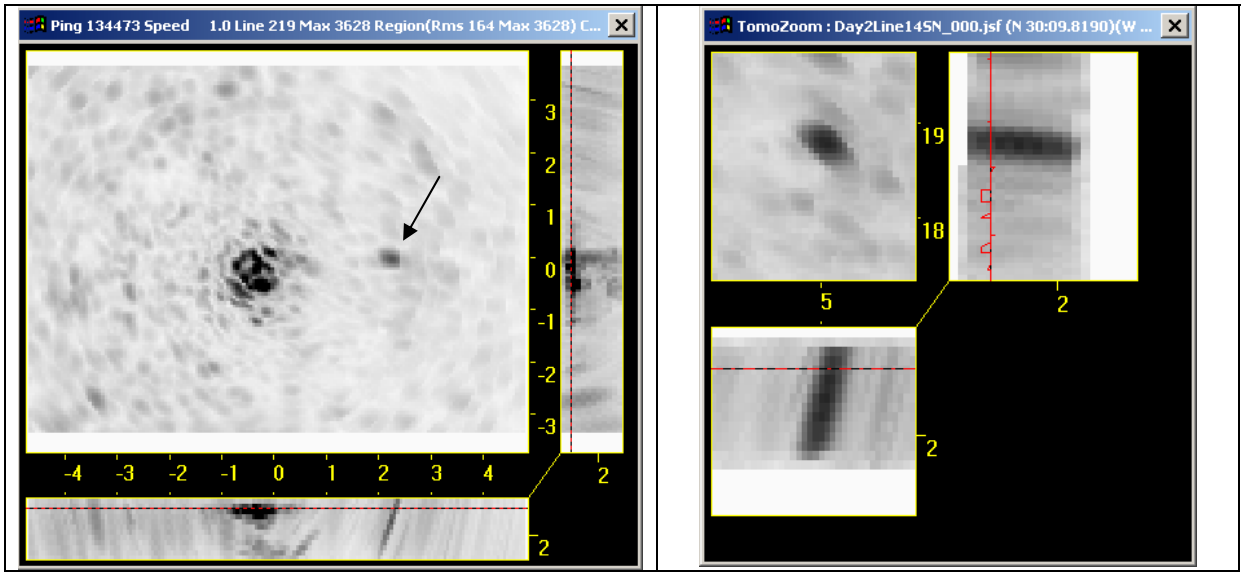


Figure 32 Images of 2”D x 12” long half-buried cylinder generated using port wing data

In Figure 32, the single aspect image (left) shows target position associated with the reception of the strongest echo and the multi-aspect image (right) shows the history of echoes from target at

all aspects as the sonar approaches and passes the target. Scales are in meters. The target appears to be at the sediment-water interface as expected and the angle of incidence for the target in single aspect image is 55 degrees.

Figures 33 and 34 show single aspect and multi-aspect image data generated from starboard and port wing data for the 2”D x 12” long cylinder in line 1 that was buried 30cm below the bottom.

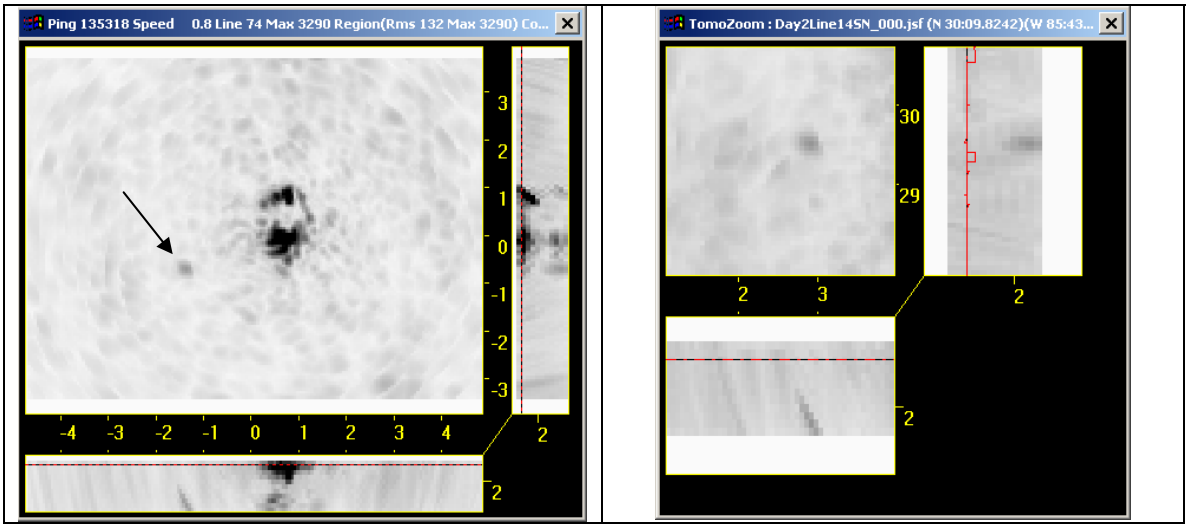


Figure 33 Images of 2”D x 12” long cylinder buried 30 cm generated using starboard wing data.

In Figure 33 the single aspect image (left) shows the target position associated with the reception of the strongest echo. The multi-aspect image (right) shows the history of echoes from target at all aspects as the sonar approaches and passes the target. Scales are in meters. The UXO target appears to be buried 30 cm consistent with ground truth data. The angle of incidence for the target in the single aspect image is 44 degrees.

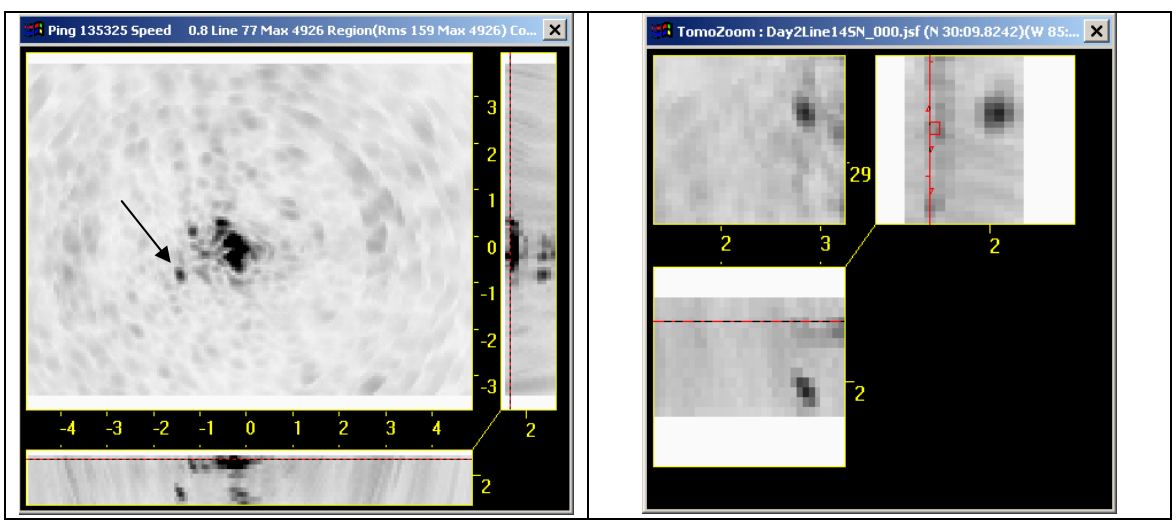


Figure 34 Images of 2”D x 12” long cylinder buried 30 cm generated using port wing data.

Figure 34 shows the same single and multi-aspect images generated using port wing data. The UXO target appears to be buried at 30 cm as expected.

In the following figures 35-40, the analysis of single and multi-aspect images are continued for the 3”D, 4”D, and 6”D simulated UXO targets.

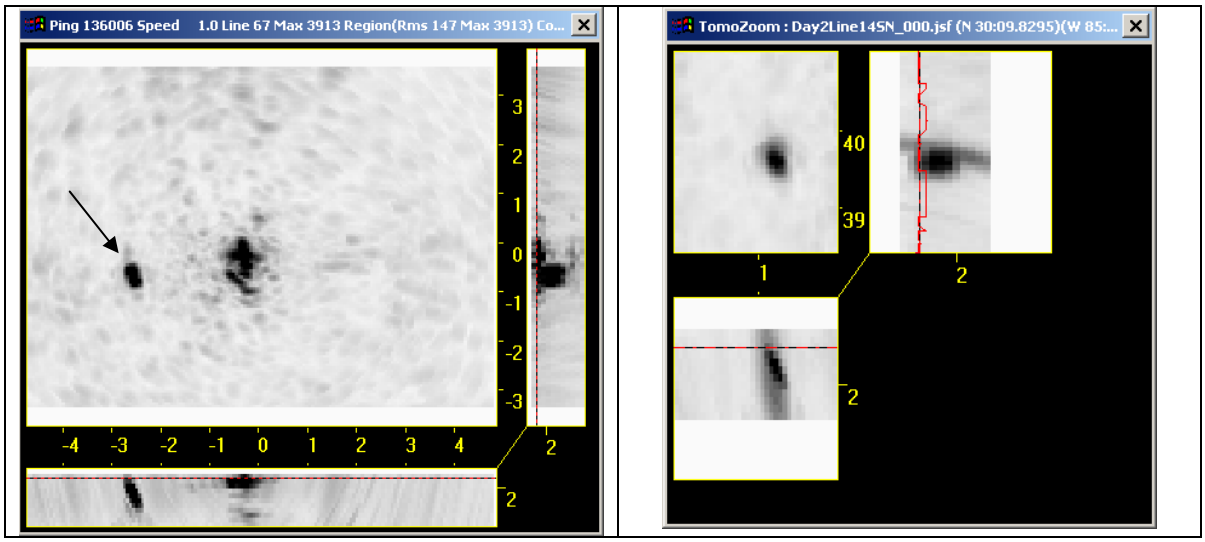


Figure 35 Images of 3”D x 14” long half-buried cylinder generated using port wing data

Single aspect image (left) in Figure 35 shows target position associated with the reception of the strongest echo. Multi-aspect image (right) shows history of echoes from target at all aspects as the sonar approaches and passes the target. Scales are in meters. The target appears to be ~ 10 cm below sediment-water interface. Angle of incidence for target in the single aspect image is 59 degrees.

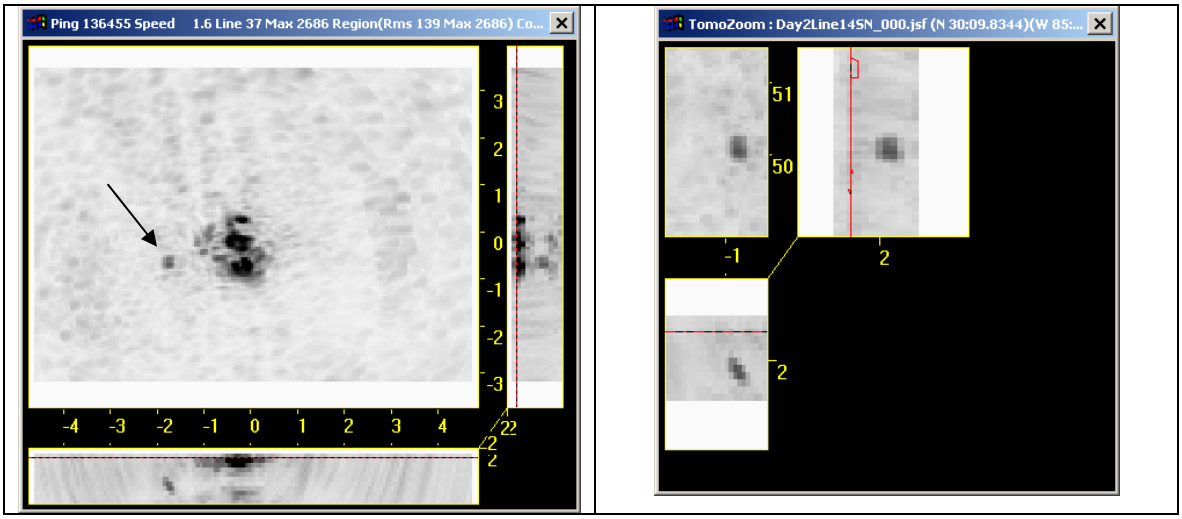


Figure 36 Images of 3”D x 14” long cylinder buried 30 cm generated using port wing data.

Single aspect image (left) in Figure 36 shows target position associated with the reception of the strongest echo. Multi-aspect image (right) shows history of echoes from target at all aspects as the sonar approaches and passes the target. Scales are in meters. The target appears to be ~ 30 cm below sediment-water interface. Angle of incidence for target in the single aspect image is 46 degrees

.

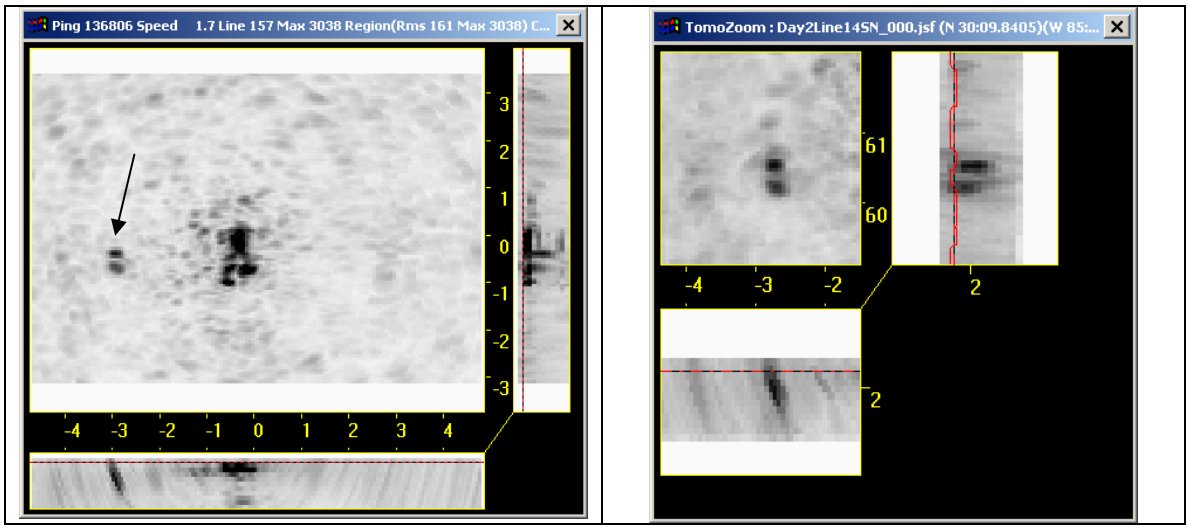


Figure 37 Images of 4”D x 20” long cylinder half-buried 30 cm generated using port wing data.

Single aspect image (left) in Figure 37 shows target position associated with the reception of the strongest echo. Multi-aspect image (right) shows history of echoes from target at all aspects as the sonar approaches and passes the target. Scales are in meters. The target appears to be ~ 10 cm below sediment-water interface. Angle of incidence for target in the single aspect image is 58 degrees.

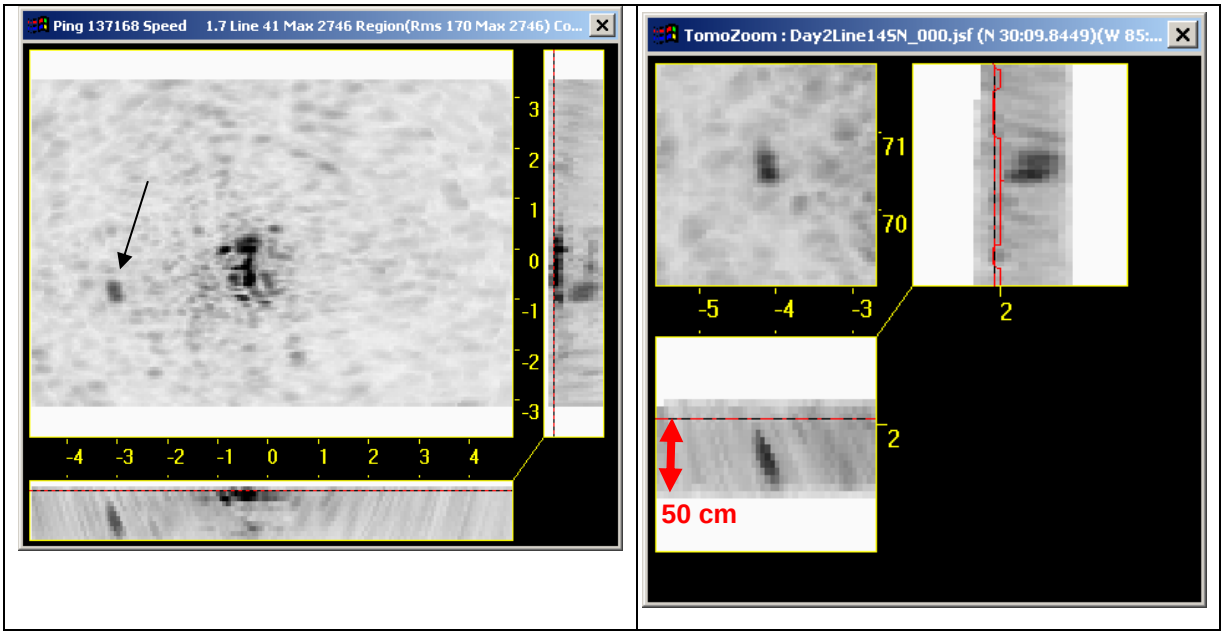


Figure 38 Images of 4”D x 20” long cylinder buried 30 cm generated using port wing data.

Single aspect image (left) in Figure 38 shows target position associated with the reception of the strongest echo. Multi-aspect image (right) shows history of echoes from target at all aspects as the sonar approaches and passes the target. Scales are in meters. Target appears to be about 30 cm below sediment-water interface. Angle of incidence for target in the single aspect image is 57 degrees.

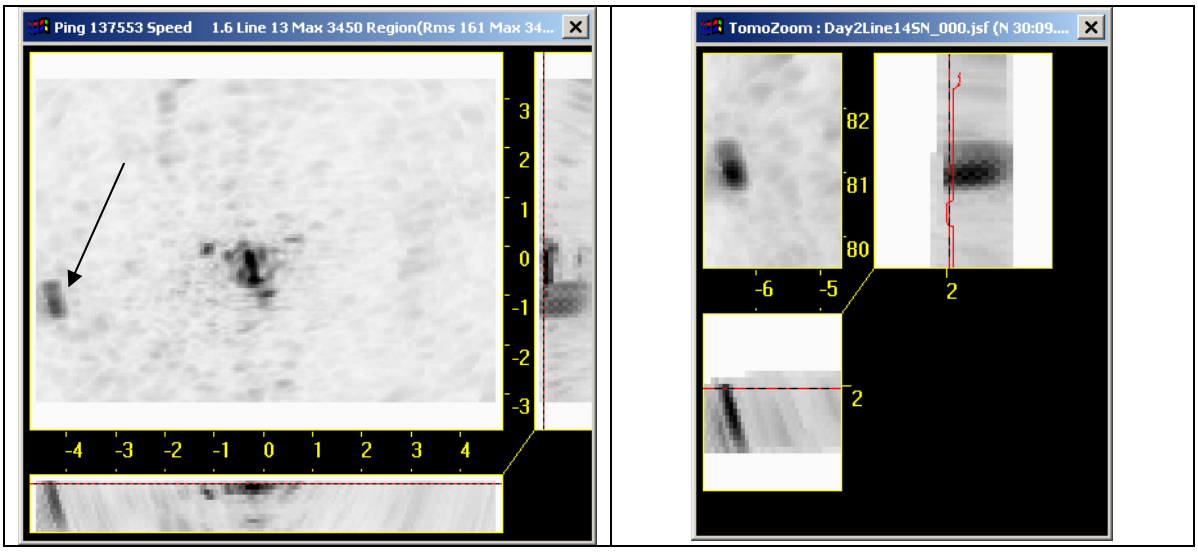


Figure 39 Images of 6”D x 27” long half-buried cylinder generated using port wing data.

Single aspect image (left) in Figure 39 shows target position associated with the reception of the strongest echo. Multi-aspect image (right) shows history of echoes from target at all aspects as the sonar approaches and passes the target. Scales are in meters. The target appears near the sediment-water interface. Angle of incidence for the target in the single aspect image is 65 degrees.

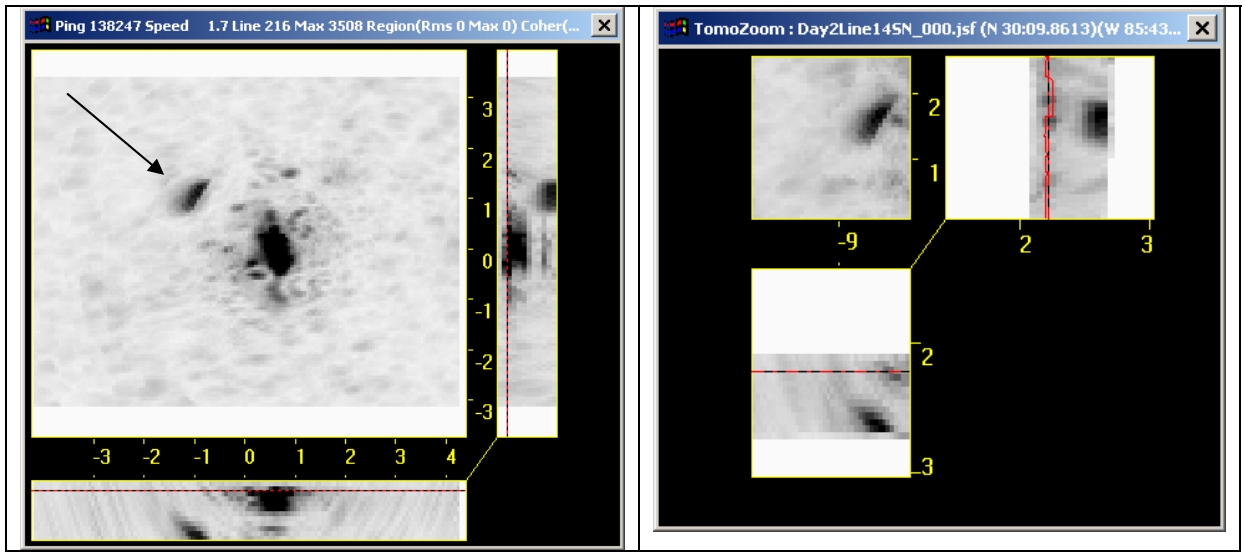


Figure 40 Images of 6”D x 27” long buried cylinder.

Single aspect image (left) in Figure 40 shows target position associated with the reception of the strongest echo. Multi-aspect image (right) shows history of echoes from target at all aspects as the sonar approaches and passed the target. The target appears to be buried 30-50 cm below the seabed.

The above set of single aspect and multi-aspect images show that even for the smallest (2x12") cylinder, the image SNR exceeds 6dB when the sonar measures the specular reflection off the side of the target. Comparing port wing and starboard wing images, Figures 31-34 show that port wing generates a superior image of the half-buried 2x12" cylinder. When the cylinder passed 1.6 m under the starboard wing, the target strength decreased and the cylinder was barely detectable. Illuminating the broadside of a cylinder with the sonar in the near field of the cylinder results in a curved wave front hitting the side of the cylinder such that the phase of the back scattered waves generated along the length of the cylinder is not in phase. As the target range decreases, the wave front curvature at the surface of the target increases and only a small portion of the side of the cylinder will be in phase. Hence, the distorted multi-aspect image and the odd location of the strongest single aspect echo for the 2 x 12 inch cylinder in Figure 31 is caused by near field interference preventing strong specular echoes of off the side of the cylinder. This results in the image being dominated by echoes off the end of the cylinder as shown in Figure 31. The center of the starboard wing is offset by about 2 meters from the center of the port wing. The range of the target from the port wing is 2 meters greater such that the effect of wave front curvature is reduced and the strength of the specular echoes off the side of the cylinder has increased to provide a much better image of the half-buried 2"x12" cylinder (Figure 32). Note the cylinder is not oriented along track as planned, but it has an orientation error of about 30 degrees. In summary, while the 1 meter long synthetic aperture is ideal for point targets with ranges of 1 to 2 meters, that aperture length results in suboptimal imagery for linear targets. A future improvement is to adjust the length of the aperture as a function of range and object shape.

Images of the 2x12" cylinder, buried 30 cm, in Figure 33 and 34, show continued problems with imaging linear targets with a long synthetic aperture and the difference in target image quality from one wing data set to the other. Due to the proximity to the bottom and the 2 meter separation between wing centers, target-receiver propagation paths are significantly different causing differences in wing image quality and target SNR. A good quality image of the 2x12 inch cylinder was generated using starboard wing data with a reduced synthetic aperture length of 75 cm and an incident angle of 30 degrees as shown in Figure 41.

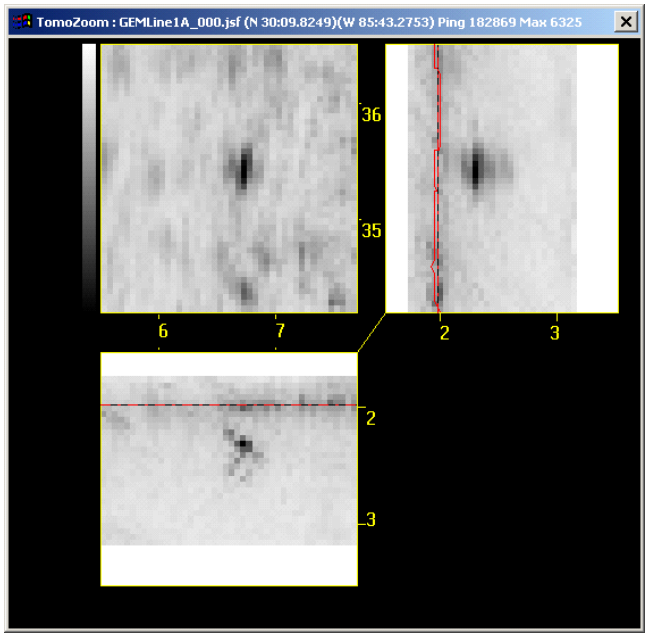


Figure 41 An improved image of the 2x12" cylinder that was buried 30 cm.

Figures 35, 37 and 39 show the loss in vertical resolution with increasing sonar range. As sonar range increases it becomes more difficult to determine burial depth of the target due to the vertical broadening of the focused echo. The wings are line arrays which have poor resolution in end fire. Figure 42 shows the variation in target resolution as a function of position with respect to the center of a line array. Target images show that when the path of the target to wing center is within 45 degrees of vertical, target burial depth can be resolved within 10 cm. Another factor to consider when measuring burial depth with increasing sonar range is that the echo moves from the top to the side of the target with increasing range which causes an apparent increase in burial depth.

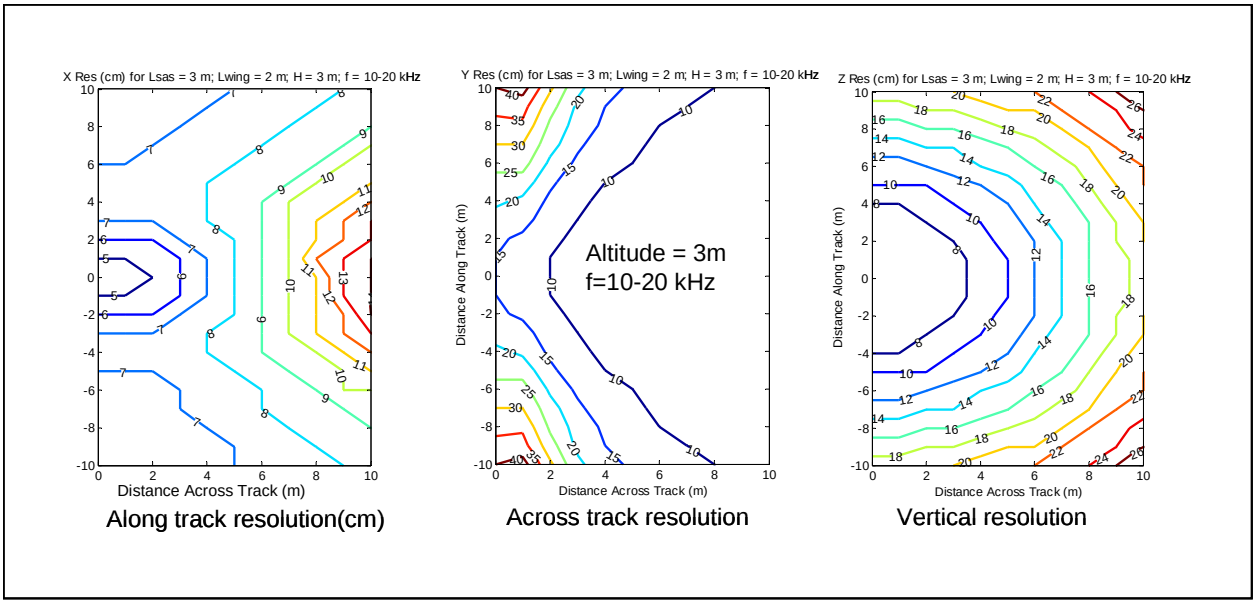


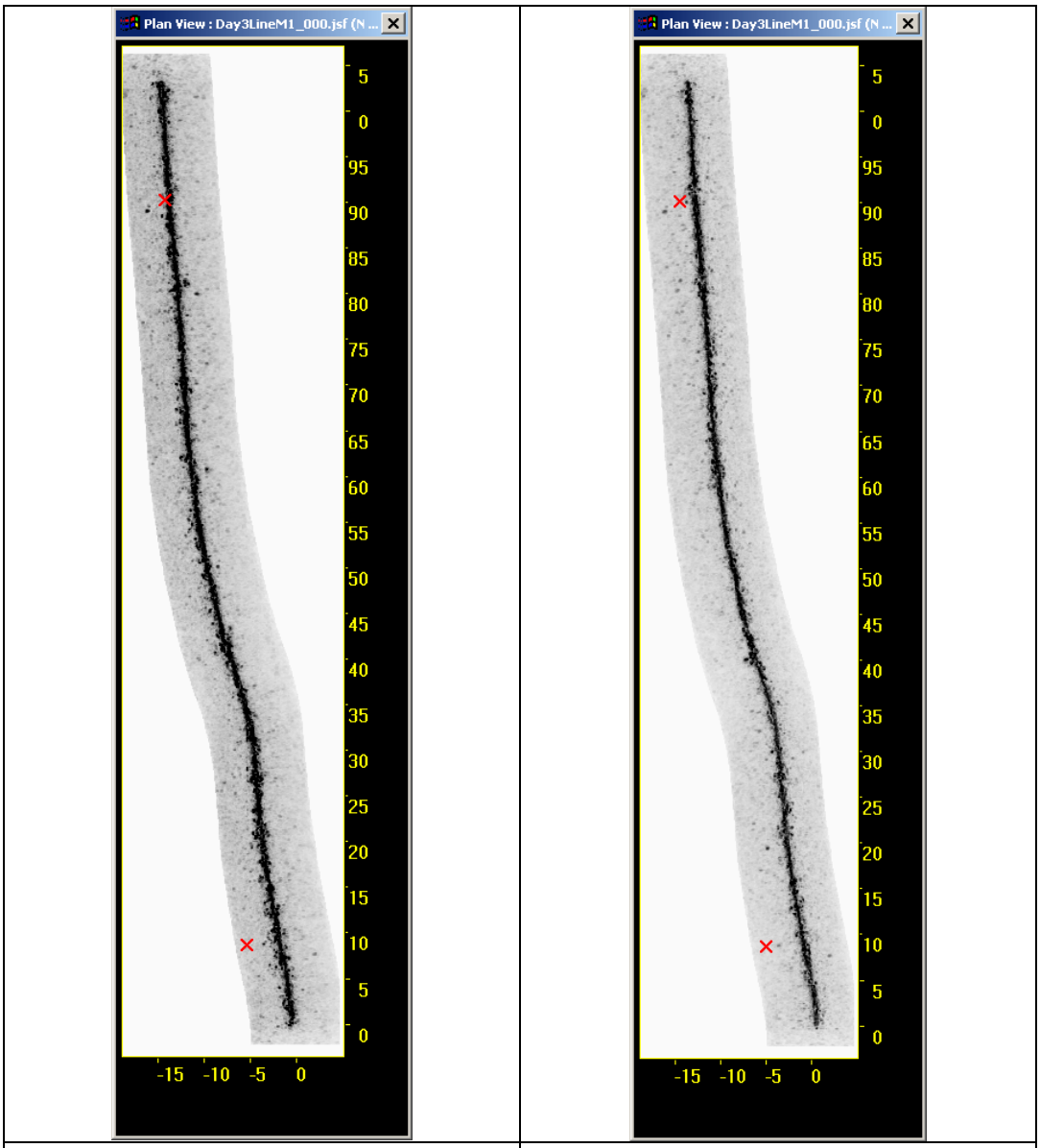
Figure 42 Resolution of BOSS in imaging band of 10-20 kHz using 2 meter synthetic aperture.

In Figure 42 the sonar altitude above the point target is 3 meters. Only the resolution on the starboard side of the sonar is shown. Note the degradation in vertical resolution with increasing across track horizontal range.

The last observation in the data analysis of line 1 at the sand site is that the 6” by 27” cylinder appears to be buried about 2 meters to the east of the planned position and has an orientation of about 45 degrees with respect to the axis of the target field. Its burial depth appears to be 40 cm.

In summary, while the current BOSS array configuration and signal processing procedures perform well for buried mine hunting, it is not the optimal configuration for imaging small buried cylinders (diameters as small as 2 inches) in water depths less than 10 feet. Specular echo interference due to the sediment-water interface, ripples, and sediment layers cause interference that prevents targets from being detected at certain sonar-target geometries. The imagery shows that there is a fixed range of transmitter to target and target receiver paths that generate optimal imagery. The images also demonstrate the need to adjust the length of the synthetic aperture to compensate for near field wave front curvature. An effective survey tool for mapping buried ordnance can be developed by modifying BOSS using the above considerations. The modified BOSS system would use longer receiver arrays and several acoustic sources to eliminate the blind spots caused by the current array configuration and to optimize image quality.

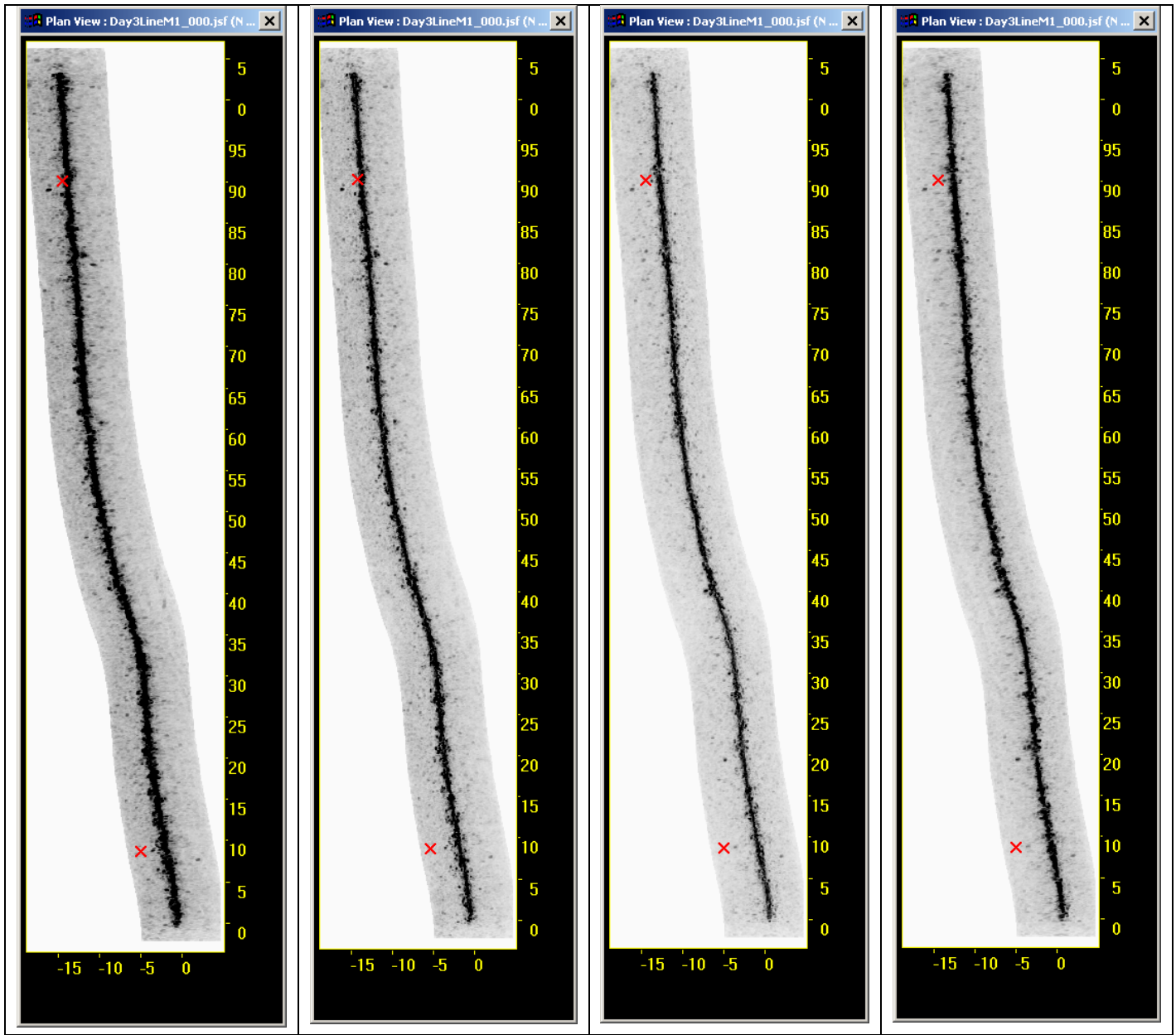
An analysis of data collected along line 1 of the mud site also shows the effect of target-sonar geometry on image quality. Run # Day3LineM1 provides a good example of the difficulty in imaging targets that the sonar passes directly over. As shown in Figure 43, the specular interference from the sediment-water interface reflection prevents detection of targets directly under the vehicle path. Generating images using the one vehicle wing at a time reduces the size of the blind region (as discussed in some detail in the sand site analysis).



Port Wing Channels Mud Field Line 1	Stbd Wing Channels Mud Field Line 1

Figure 43 These multi-aspect images were generated with the 4x20 element arrays embedded in the port and starboard wings of the BOSS. The vehicle track was from bottom to top.

In an attempt to increase the across track offsets of the specular interference regions, the multi-aspect images were also formed using the outer half (4x10 channels) of each wing. As shown in Figure 44, the across track offset of the specular interference region has increased as expected; however, the width of the region has doubled because the across track resolution of the receiver array was reduced by a factor of two. This analysis supports the need for longer wings to allow formation of images with longer across track offsets of the specular scattering region without loss of across track resolution.



Outer Port 4x10	Port 4x20	Stbd 4x20	Outer Stbd 4x10

Figure 44 Multi-aspect images generated using the indicated array segments in the port and starboard wings of BOSS. Note that the across track offset of the interference region moves from port to starboard in the above imagery.

The planned positions for targets buried along mud site line 1 are shown in Figure 45. The figure also provides the diameter, lengths and planned burial depths of the cylinders.

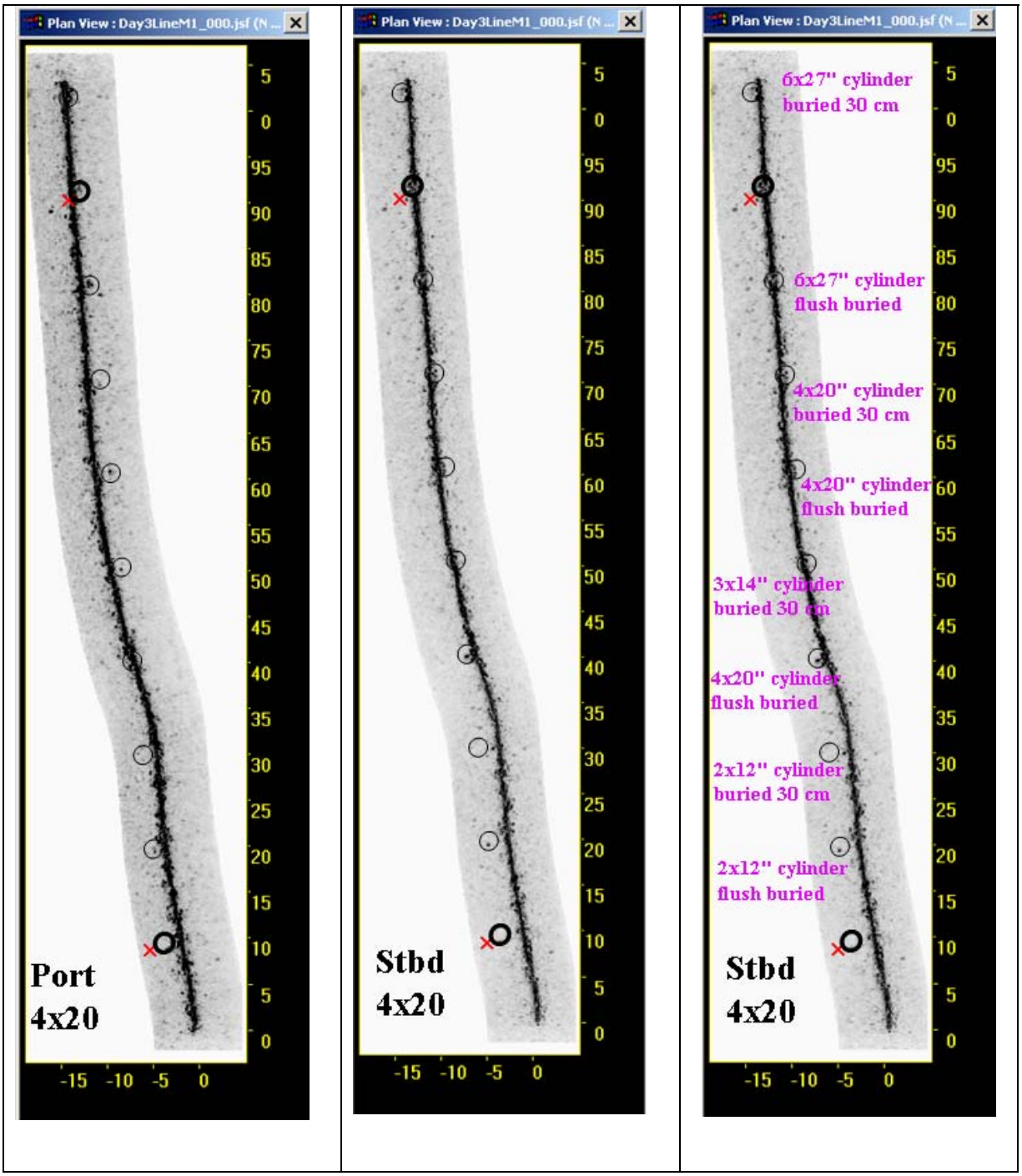


Figure 45 Multi-aspect images generated with the 4x20 element array in the port and starboard wings of BOSS. The overlay circles show the planned positions of the cylinder targets.

Because most of the targets appear in the port wing data image, that data is used to analyze each target. Each target measured during run # Day3LineM1 is analyzed for target shape information by zooming in on the multi-aspect image.

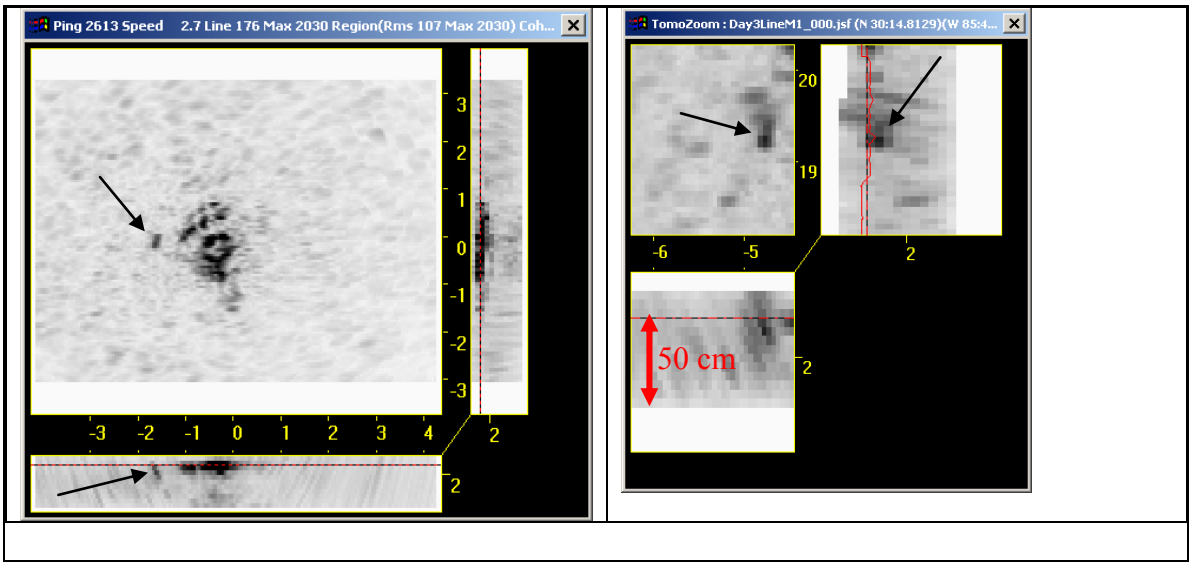


Figure 46 Images of 2”D x 12” long half-buried cylinder generated using port wing data.

In Figure 46, the single aspect image (left) shows target position associated with the reception of the strongest echo. Multi-aspect image (right) shows history of echoes from target at all aspects as the sonar approaches and passes the target. Scales are in meters.

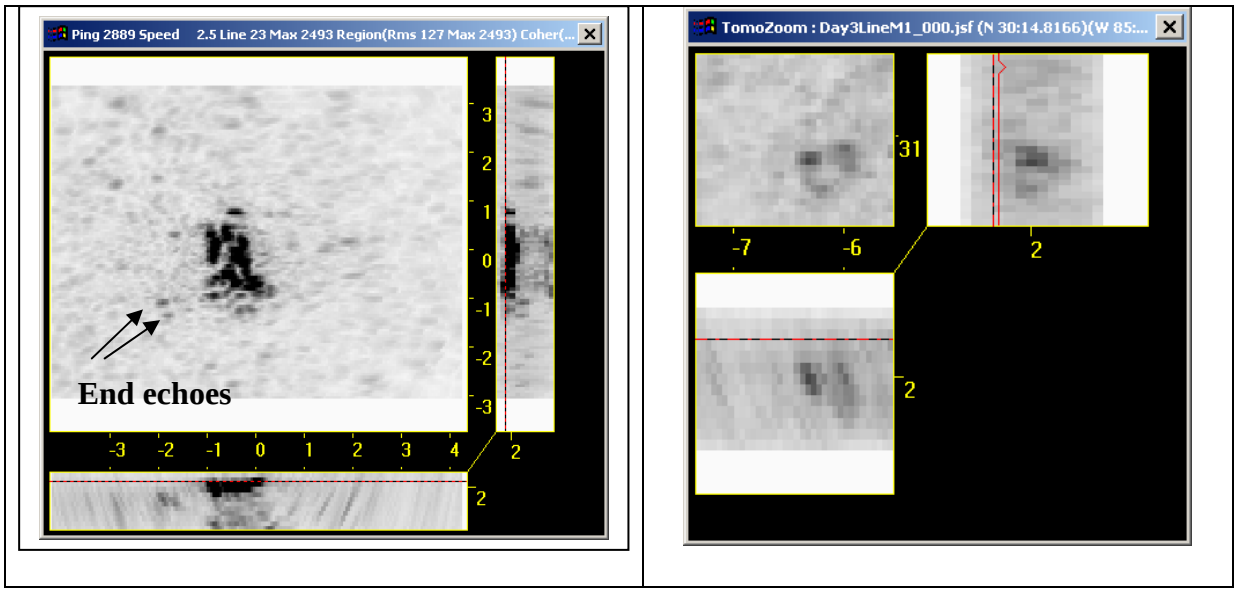


Figure 47 Images of 2”D x 12” long cylinder buried 30 cm generated using port wing data.

In Figure 47, the single aspect image (left) shows target position associated with the reception of the strongest echo. Multi-aspect image (right) shows history of echoes from target at all aspects as the sonar approaches and passed the target. Scales are in meters.

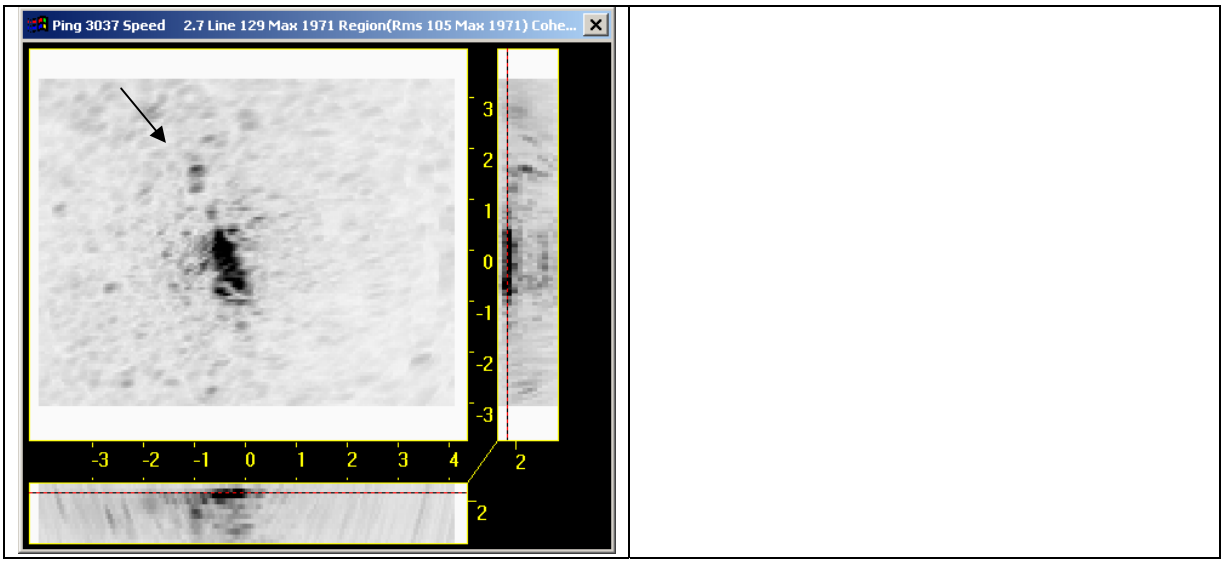


Figure 48 Image of 3”D x 14” long half-buried cylinder generated using port wing data.

In Figure 48, the single aspect image (left) shows target position associated with the reception of the strongest echo. The multi-aspect image (right) showing history of echoes from target at all aspects was not generated due to specular scattering interference (which occurs when the sonar passes directly over the target with the current array geometry).

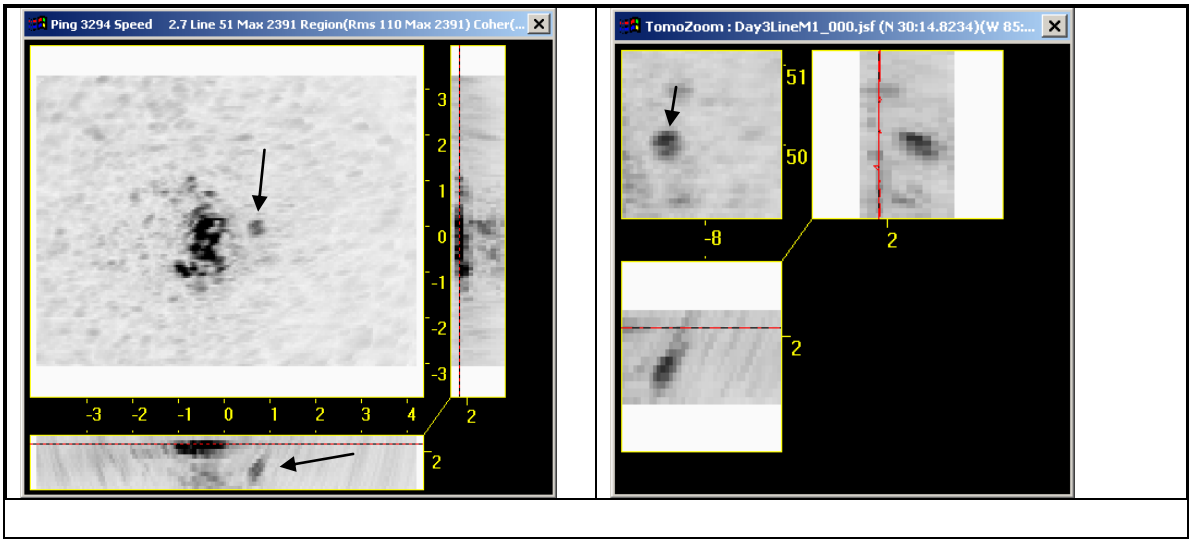


Figure 49 Images of 3”D x 14” long cylinder buried 30 cm generated using port wing data.

In Figure 49, the single aspect image (left) shows target position associated with the reception of the strongest echo. The multi-aspect image (right) shows history of echoes from target at all aspects as the sonar approaches and passes the target. Scales are in meters.

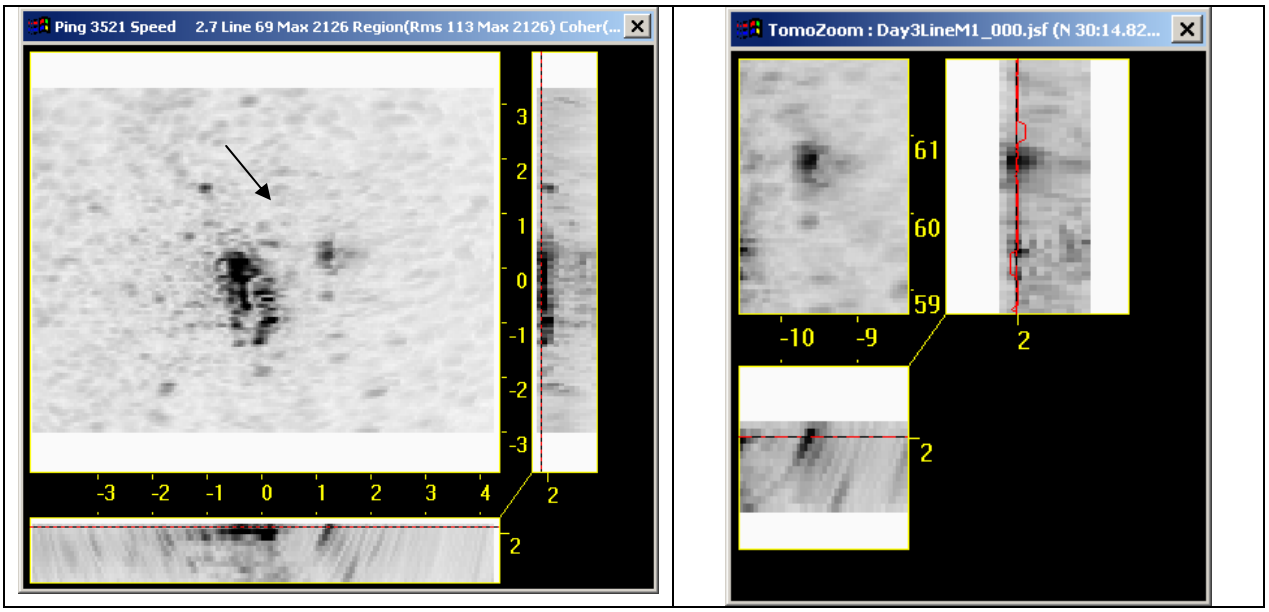


Figure 50 Image of 4”D x 20” long half-buried cylinder generated using port wing data.

In Figure 50, the single aspect image (left) shows target position associated with the reception of the strongest echo. The multi-aspect image (right) shows history of echoes from the target at all aspects as the sonar approaches and passes the target.

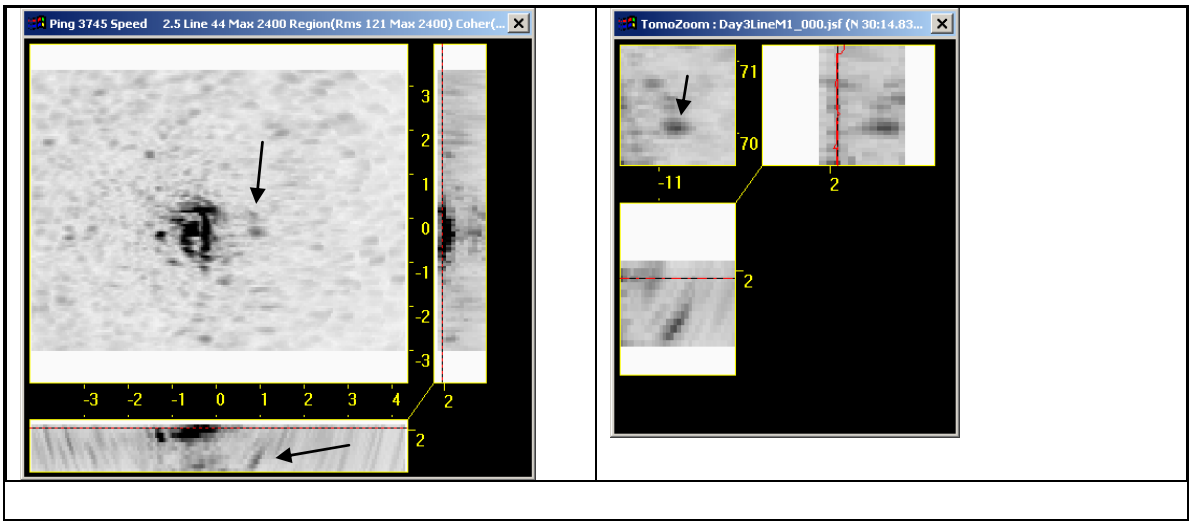


Figure 51 Images of 4”D x 20” long cylinder buried 30 cm generated using port wing data.

In Figure 51, the single aspect image (left) shows target position associated with the reception of the strongest echo. The multi-aspect image (right) shows history of echoes from target at all aspects as the sonar approaches and passes the target. Scales are in meters.

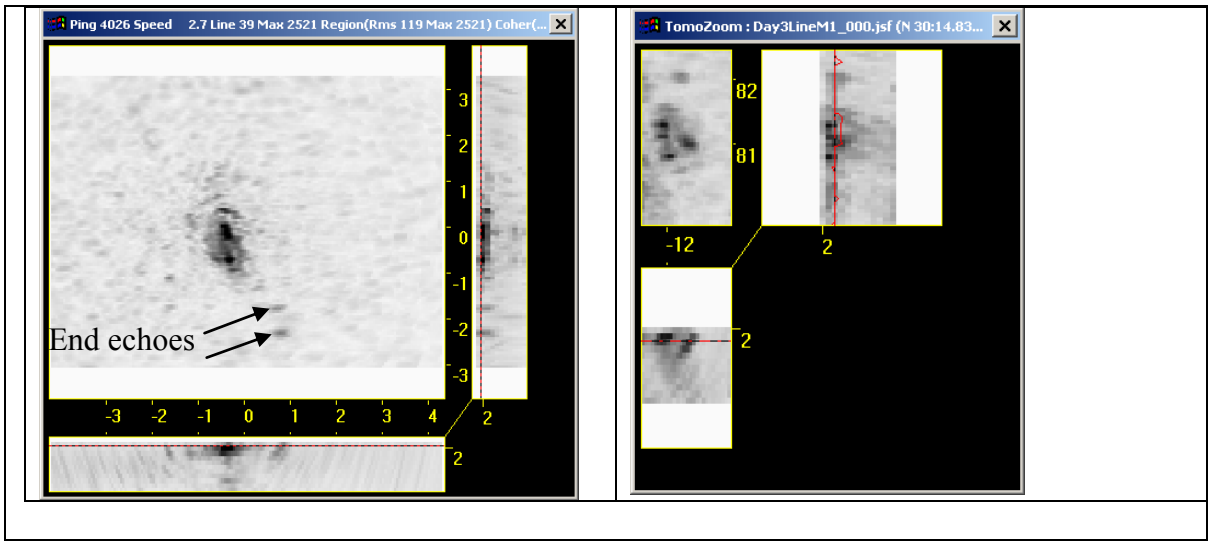


Figure 52 Image of 6”D x 27” long half-buried cylinder generated using port wing data.

In Figure 52, the single aspect image (left) shows target position associated with the reception of the strongest echo. The multi-aspect image (right) shows history of echoes from the target at all aspects as the sonar approaches and passes the target.

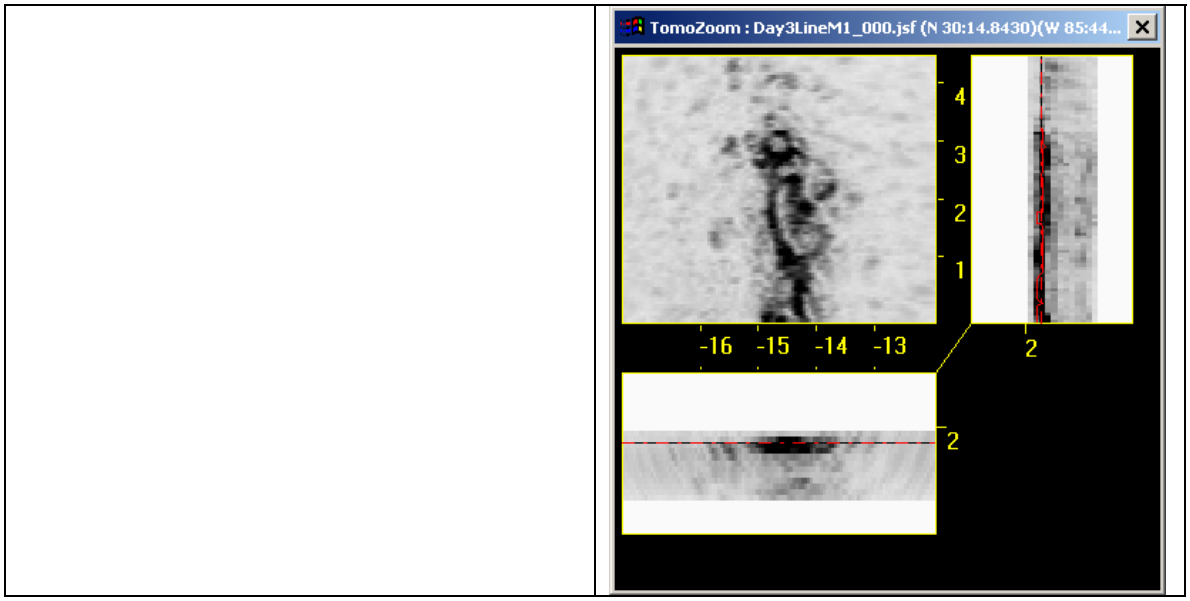


Figure 53 Multi-aspect image of planned location of 6”D x 27” long cylinder buried 30 cm (generated using port wing data).

In Figure 53, the multi-aspect image which provides the history of all echoes from buried targets shows that there is no 6” buried cylinder within 2 meters of the planned location. The image only shows interference due to sediment-water interface and seabed roughness echoes.
In contrast to the sand site where target echoes where frequently generated by specular reflections off the side of the cylinder, the target echoes measured during run # Day3LineM1 at the mud site were dominated by end echoes. Hence, the target images appeared less cylindrical-

like. Possible reasons for lack of specular echoes off the side of the cylinders include 1) suboptimal target-sonar geometry for imaging and 2) the cylinders not lying horizontal. One end of the cylinder may have settled deeper into the mud. Running past the target at a larger offset can provide better target-sonar geometry for imaging than passing directly over the target. A longer term solution is to make improvements to the sonar arrays so the sonar always uses optimal sonar-target geometry to generate the best imagery.

As shown by the imagery above, the best imagery is not generated when the sonar passes directly over the target. By increasing the horizontal offset, target imagery can greatly improve as seen in Figure 54 which contains comparisons of the half-buried 3 x 14' cylinder images generated using 2 passes along mud line 1.

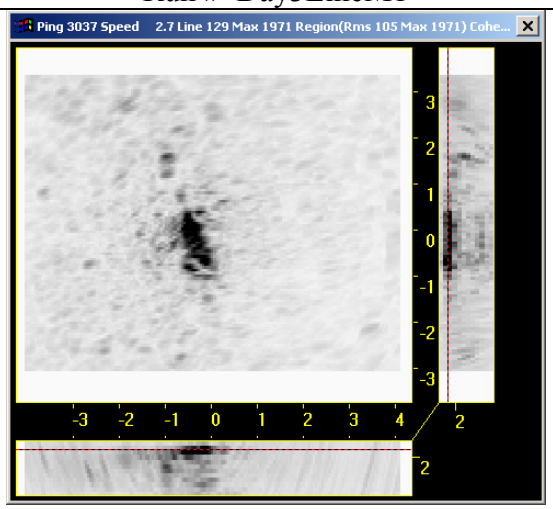
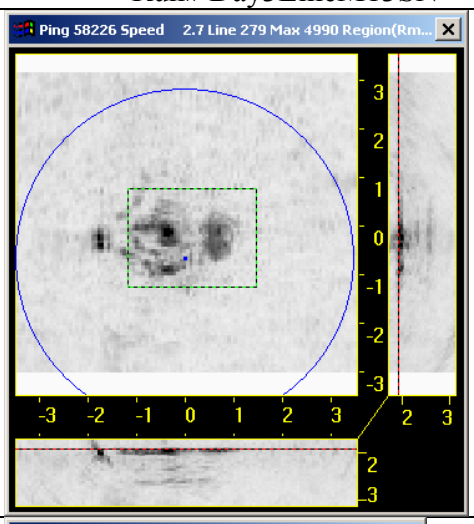
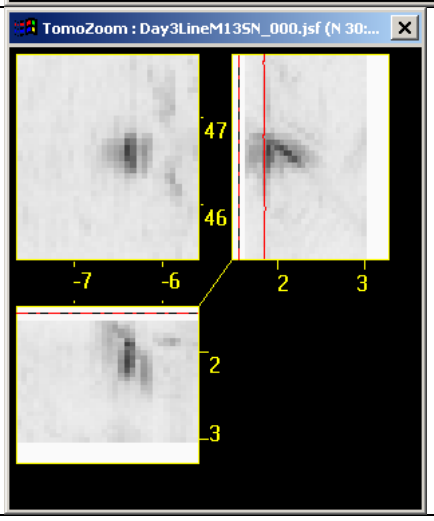
Run # Day3LineM1	Run# Day3LineM13SN
	
Sonar passed over target causing a poor imaging geometry where the specular interference prevented target from appearing in multi-aspect image	

Figure 54 Comparison of images of half buried 3x14" cylinder for 2 runs along mud line 1 shows the effect of sonar-target geometry on image quality

In Figure 54 the increase offset of LineM13SN clearly shows that the target is oriented along track as planned but one end has dropped about 20 cm below the sediment-water interface. The upper images are single aspect images. The lower right hand image is a multi-aspect image.

A similar improvement in the imagery for the 3'x14" cylinder, buried 30 cm, was observed while comparing data from runs Day3Line M1 and Day3LineM13SN as shown in Figure 55.

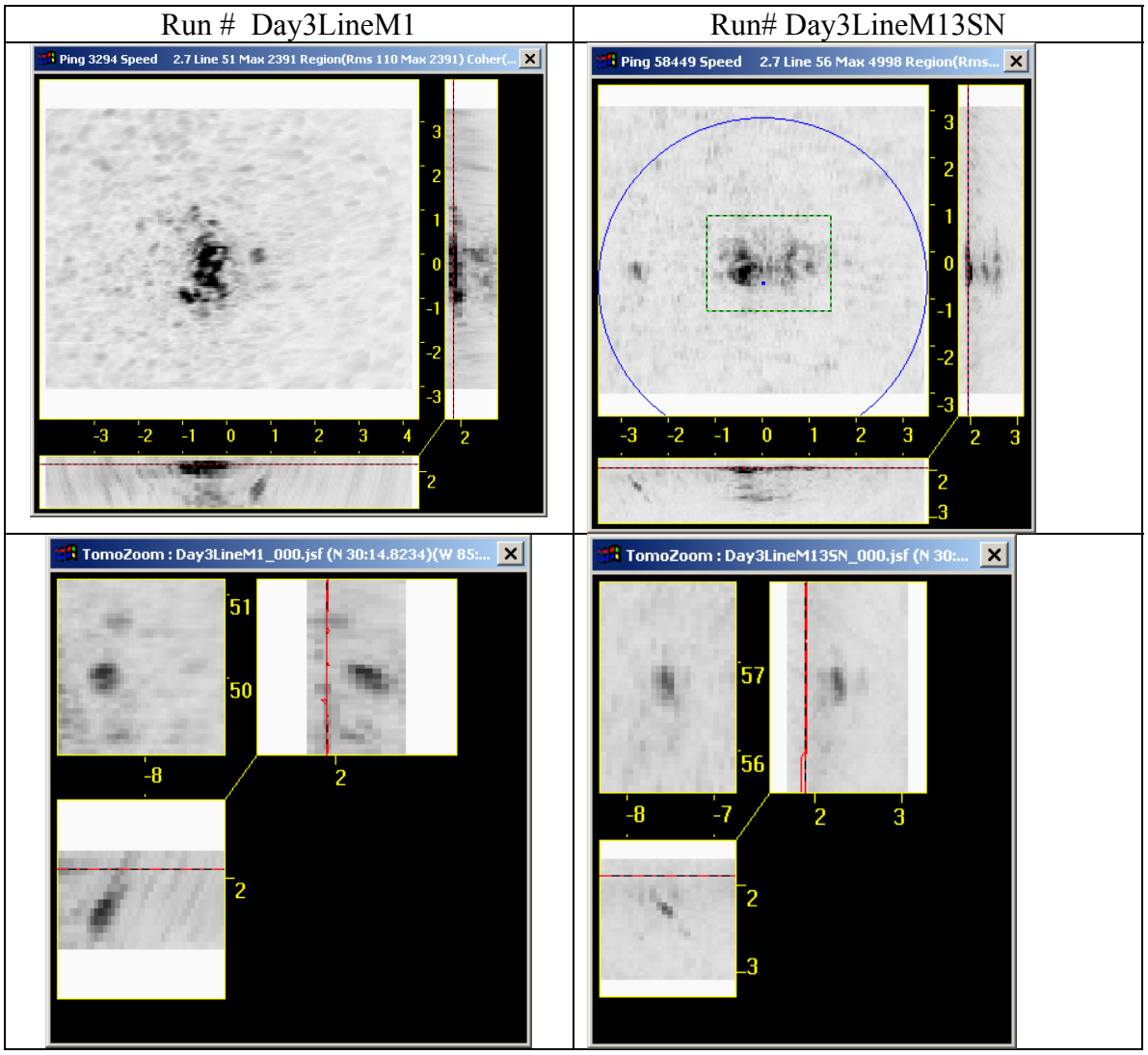


Figure 55 Comparison of images of 3x14" cylinder buried 30 cm for 2 runs along mud line 1 showing the effect of sonar-target geometry on image quality.

In Figure 55 the increased offset of LineM13SN clearly improved the image quality. The upper images are single aspect images. The lower images are multi-aspect images.

Phase I Acoustic Environmental Data

Personnel from the University of Washington/Applied Physics Laboratory collected bottom environmental data at the Phase I sand and mud sites using the IMP2 and STMS1 measurement units.

St. Andrew's Bay – Sand site

The RMS height and the small scale roughness parameters measured using IMP2 at the sand site in St. Andrew's Bay are listed in Table 3:

Table 3 RMS height and small scale roughness parameters

DATE	RUN Number	RMS roughness (cm)	γ_2	w_2 $\left(cm^{4-\gamma_2}\right)$
Oct 25 2006 Sand Site	194	0.77	5.19	3.22×10^{-4}

In Table 3, γ_2 and w_2 are parameters designating the power-law exponent and the power-law strength of the power spectrum of the roughness interface. The STMS1 attenuation array was moved to 20 different positions. The attenuation array transducer insertion depth into the sediment was 16.5 cm. The sound speed ratio and attenuation measured as a function of frequency are shown in Fig. 56. The plot lines display the best linear fit to the data.

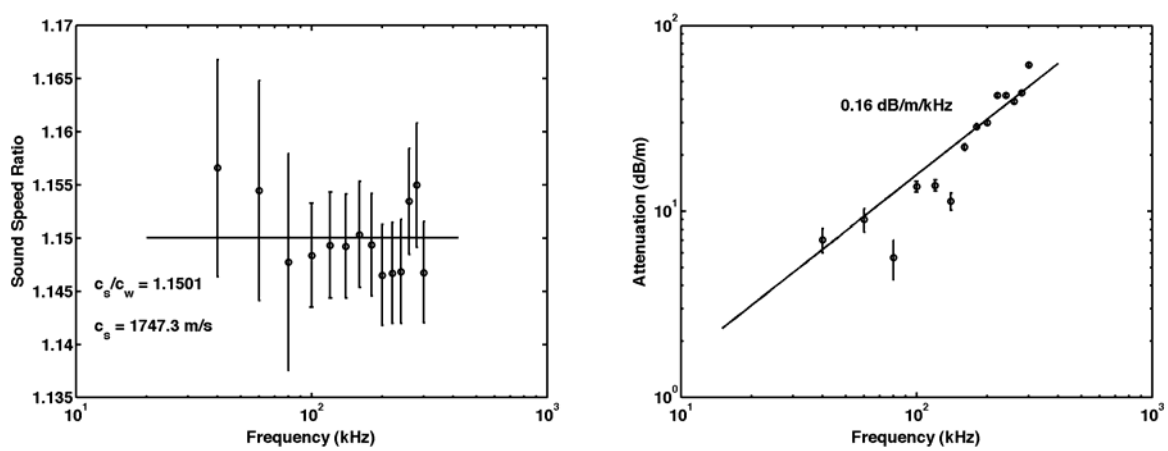


Figure 56 Sediment sound speed ratio (sediment sound speed/water sound speed) and attenuation measured at the sand site.

Two separate CTD casts (taken within two minutes of each other) at the sand site gave the water column sound speed profiles shown in Fig. 57.

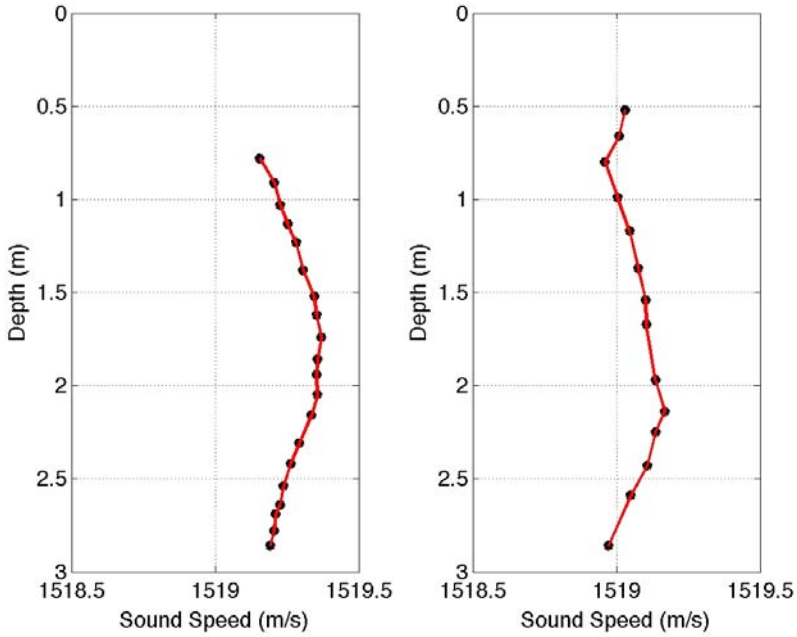


Figure 57 Water column sound speed profiles on Oct. 25th at the St. Andrew's Bay sand site. Two separate casts are shown.

St. Andrew's Bay – Mud site

An initial dive at the mud site indicated a very soft top layer of sediment. The interface roughness would not be important for determining the backscattering strength and thus IMP2 interface roughness measurements were not carried out.

The sediment sound speed measurements using STMS1 showed considerable coda after the initial direct path energy from buried source to receiver. This implies a large amount of sediment heterogeneity (most likely shells) and also implies that sediment volume scattering would likely be the main contributor to backscattering in sonar systems operating below 50 kHz. We believe a box core type sampling of the area would be useful in determining the type of volume scatterers. The results from this type of coring could be used in volume scattering models to determine backscattering levels. In absence of this type of effort we suggest that volume scattering parameters in a fundamental scattering model be adjusted to match acoustic backscattering data acquired within the area away from the buried targets.

The STMS1 attenuation array was again moved to 20 different positions. The attenuation array transducers are deep enough (16.5 cm) that they are sampling a stiffer layer of sediment (a mix of mud and sand) than the initial several inches of soft sediment. The sound speed ratio and attenuation measured at the mud site are shown in Fig. 58.

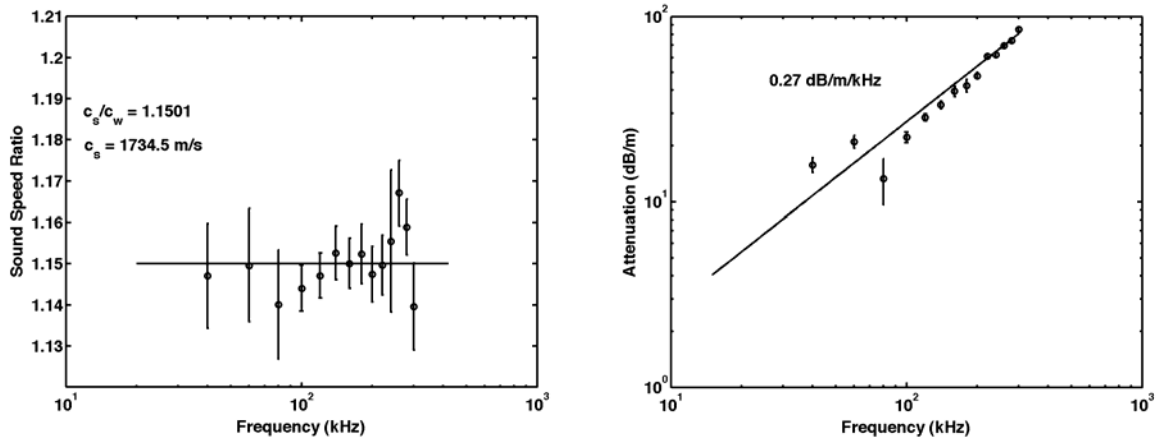


Figure 58 Sediment sound speed ratio and attenuation measured at the mud site.

Two separate CTD casts (again taken within two minutes of each other) at the mud site gave the water column sound speed profiles shown in Fig. 59.

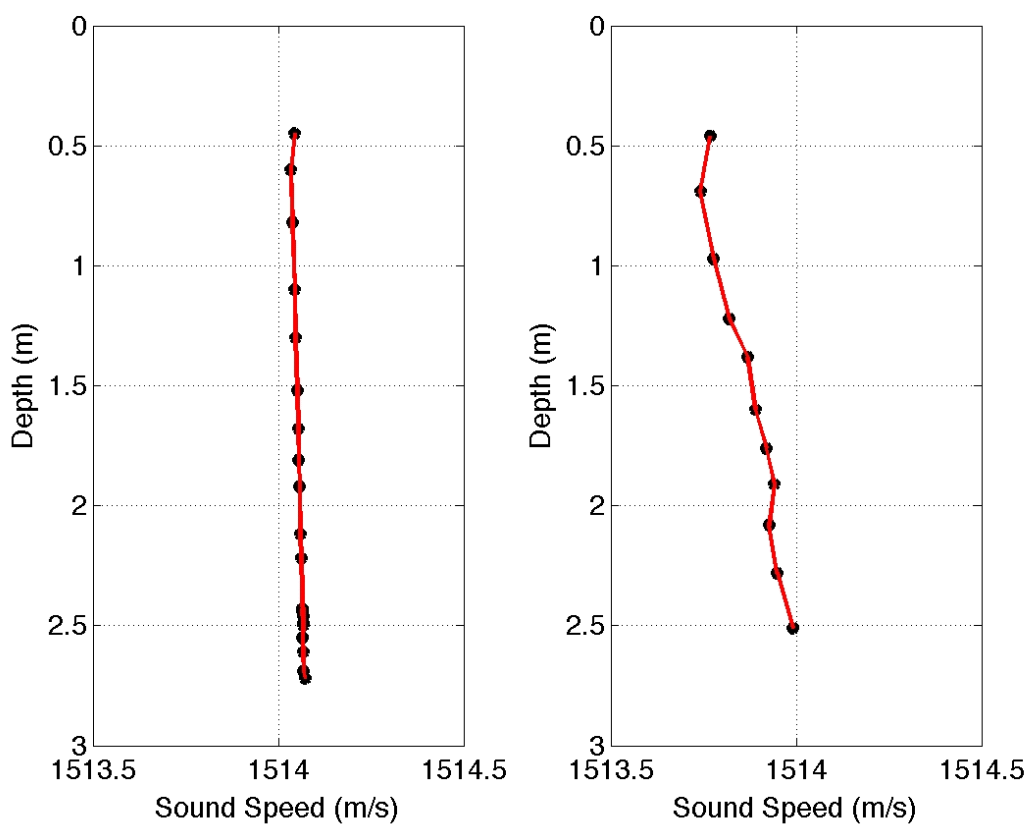


Figure 59 Water column sound speed profiles on Oct. 26th at the St. Andrew's Bay mud site. Two separate casts are shown.

Phase I RTG Target Detection

The RTG magnetic sensor was operated from the BOSS TV during all tracking runs during the three days of operation at the St. Andrew's Bay UXO target sites. RTG operation was validated during dockside checkout each day and the RTG data was recorded on all BOSS TV search tracks. However, the RTG noise performance was not evaluated until after the test period. Post test analysis revealed that the RTG performed in a degraded mode during the search tracks at the sand and mud sites. RTG develops five independent magnetic gradient measurements used in target localization by electronically differencing the outputs of a set of three orthogonal tri-axial magnetometer cubes mounted on a base plate internal to the RTG sensor. Examination of the five magnetic gradient channels revealed that the noise level of two of the five gradient channels was 5 times larger that on the other three channels. The higher noise level on the two gradient channels made it impossible to detect the magnetic gradients from any of the UXO targets and thus the magnetic localization algorithm yielded no useful results. Subsequently, post test sensor analysis revealed that the problem was related to the signals from the magnetometers in one of the three magnetometer cubes. Signals from those magnetometers were excessively noisy primarily due to degraded electrical contacts in an oil-filled cable connecting that magnetometer to the RTG computer. The net result was that gradient signals developed using magnetometer components from the defective cube/cable connector were much noisier than gradient components calculated from the other three RTG magnetometer cubes. Thus, for virtually all search runs, only three of the five required target gradients were measured and recorded.

Although RTG sensor operation was significantly degraded during the search tracks, limited target information was obtained from the three gradient channels that were performing well. Specifically, the gradient measurements from the three well-behaved gradient channels can be used to estimate the closest points of approach on targets detected during a given run. Also, the noise levels of the well-behaved gradient channels can be used to estimate the range of RTG versus the UXO target set.

Figure 60 shows the time series magnetic field gradient data for five independent gradient RTG channels for one of the UXO search tracks – Line 03-02 - at the sand site on 18 October. The noise on two channels, Gxx and Gxz, is of the order of 5-10 nanoTesla/ foot which is considerably larger than the background noise on the other three gradient channels, Gxy, Gyy and Gyz. Figure 61 displays the time series magnetic field gradient data from the three quieter channels of the five channels for the same search run, Line 03-02. Figure 61 shows that the average background noise on these three gradient channels is of the order of 2-3 nanoTesla/ foot, several times lower than Gxx and Gxz and, at these levels, signals from two, possibly three, distinct targets are clearly visible above the noise (distinct targets at t ~ 1800 sec and t ~ 2800 sec; possible additional target at t ~ 1600 sec.). Three gradient channels are not sufficient to determine the precise position of the detected targets but we can estimate the position along the search line from the time of closest approach.

This approach was employed on several time series search track runs conducted at the sand site on days 1 and 2 and the results are plotted (along with the BOSS TV track) in Figure 62. These results demonstrate that the RTG sensor is capable of detecting the UXO targets but the data is

not concrete enough to demonstrate that data fusion of BOSS and RTG target detections is useful in distinguishing between known targets and debris or other detected artifacts.

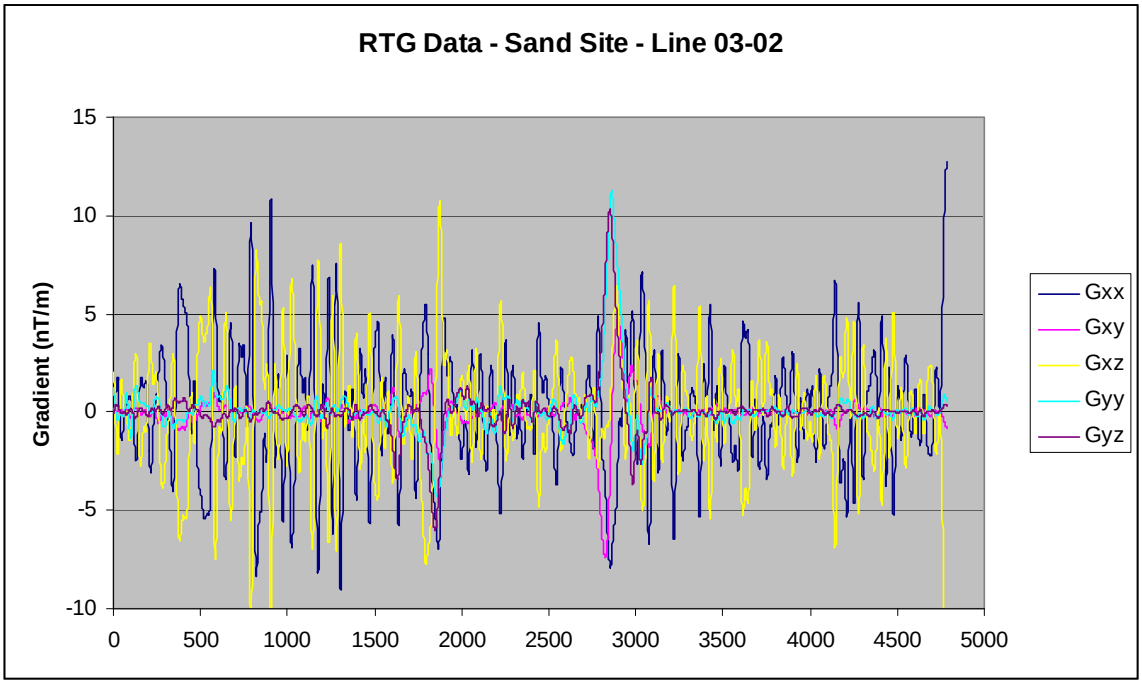


Figure 60 RTG time series for five gradient channels – Line 03-02 – Sand Site

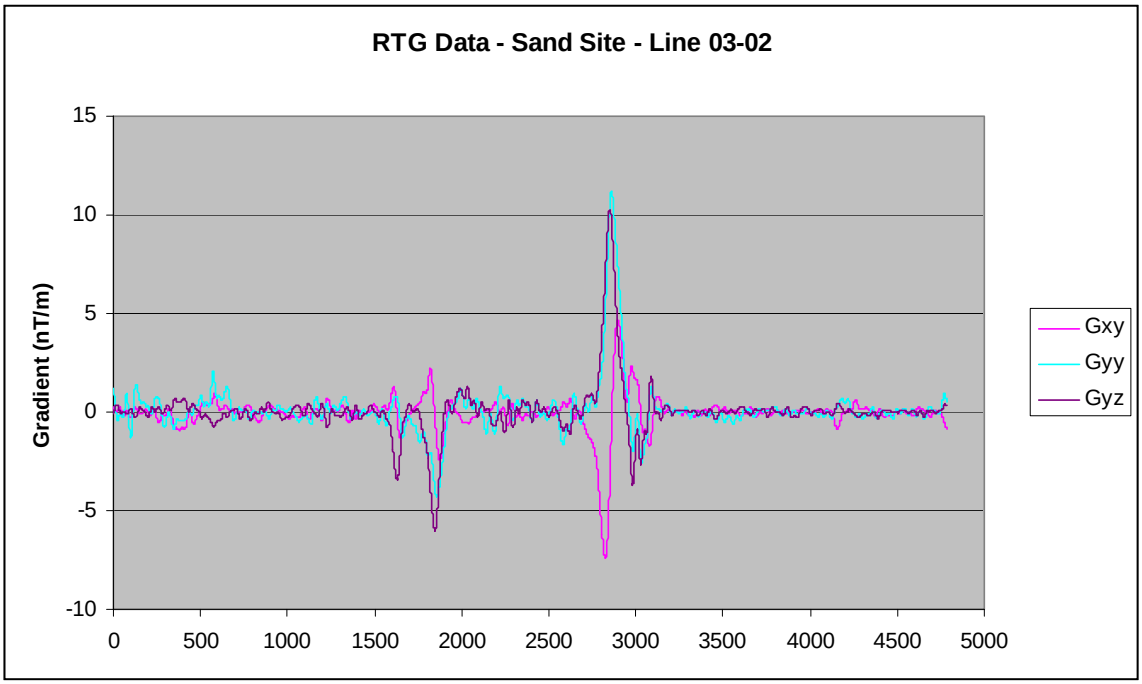


Figure 61 RTG time series for three gradient channels, Gxy, Gyy, and Gyz – Line 03-02 – Sand Site

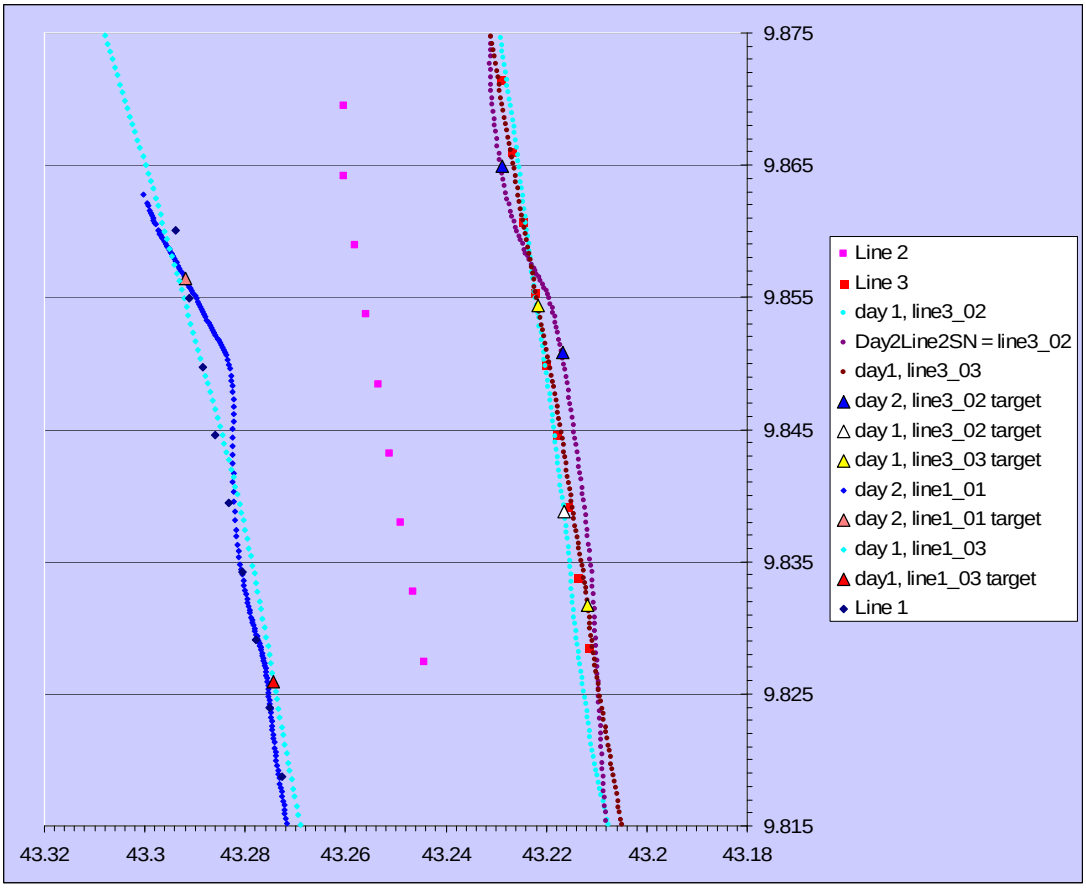


Figure 62 BOSS/RTG Tracks and RTG Targets for Selected Sand Site Search Tracks from days 1 and 2

Post test analysis of RTG sensor performance corroborated that there was a cable problem which was the likely source of noise contamination in the two other magnetic gradient channels. This problem has been corrected and should not pose a threat in future measurements.

Phase I Active EM GEM-3 Array Target Detection

For simple UXO detection, we used a composite frequency channel referred to as "qsum+ipdif", which consists of the sum of all quadrature components plus inphase component differences from the lowest frequency inphase (subtracting the lowest frequency from the others desensitizes the response to geologic magnetic susceptibility). Anomaly maps are presented in Figures 63-66 in which the detection channel is contoured for all runs over each of the four UXO target lines surveyed by the GEM-3 array. Line 2 at the sand site was not surveyed by the GEM-3 array because of known obstacles (partially buried large drums) that posed a damage risk. Target positions are plotted with small black circles, and data-point locations with colored dots.

Figure 63 shows a map of a set of "bulls-eye" anomalies composed from several track runs along Line 1. A number of targets are detected which form a straight line pattern which runs parallel to

the ground truth target positions. There is at least one target detected near each ground truth position. The spacing of the anomalies is approximately consistent with the target separation distance (10 m) for much of Line 1. The difference in detected and ground truth positions varies from less than a meter to more than five meters. Uncertainty in the GEM-3 sensor navigation make it difficult to determine if there are unknown targets in the area or whether some targets are the same targets detected at slightly different positions on different search tracks.

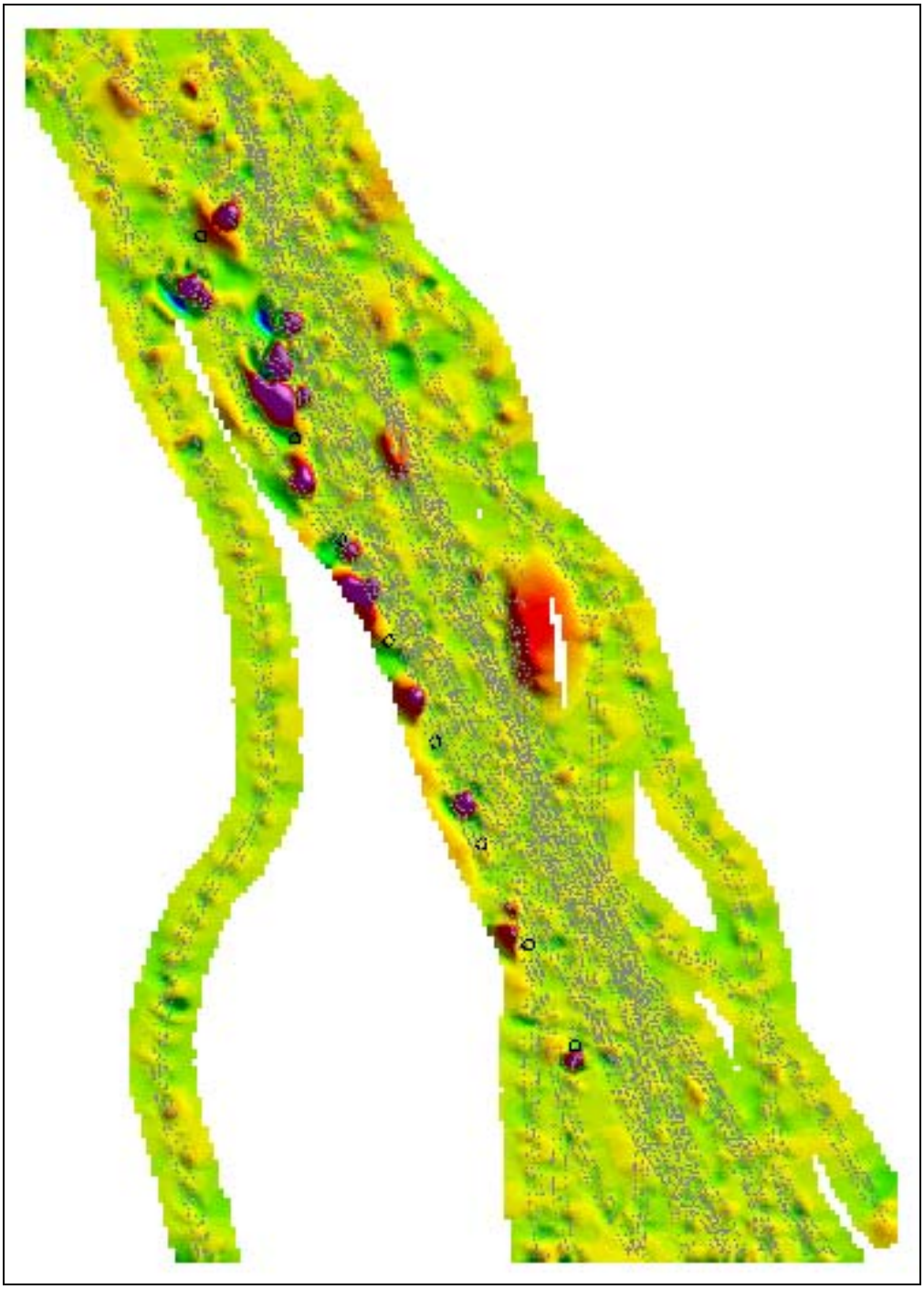


Figure 63 Detection channel ("qsum+ipdif") contour map over sand area line 1

Composite contour maps of GEM-3 detections at Line 3 (sand site) and Lines 1 and 2 (mud site), Figures 64, 65, and 66, respectively, show results which demonstrate GEM-3 detection of targets at sand and mud sites but the number of detected targets is much more scarce. This is significantly due to the inability to navigate the catamaran/GEM-3 array sled over the targets (see Line 3).

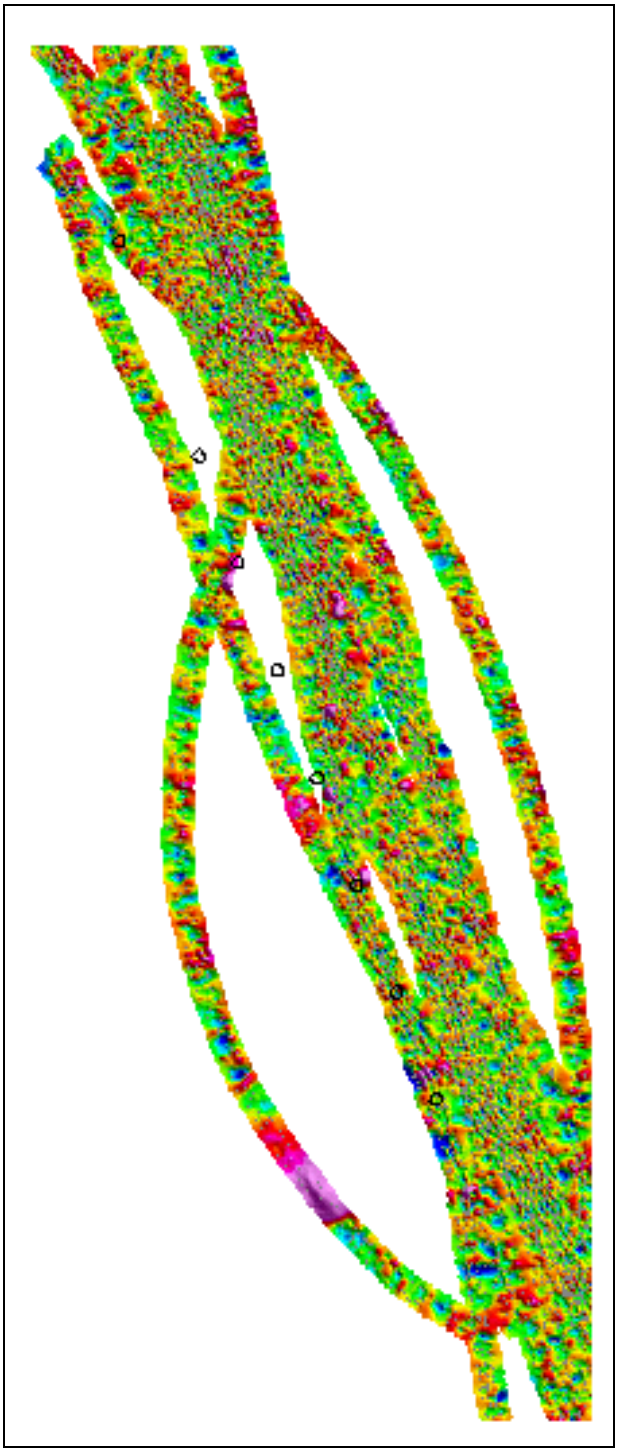


Figure 64 Detection channel ("qsum+ipdif") contour map over sand area Line 3

GEM-3 data from Line 1 and 2 at the mud site also demonstrate successful detection of seeded targets but the number of data runs at the mud site was limited due to GEM-3 GPS equipment problems. Figures 65 and 66 are composites of only 3-4 track runs. Both composite maps show several detected targets along the seeded target line within 3-5 meters of ground truth target positions but uncertainty in sensor navigation prevents convincing analysis to confirm seeded target detection.

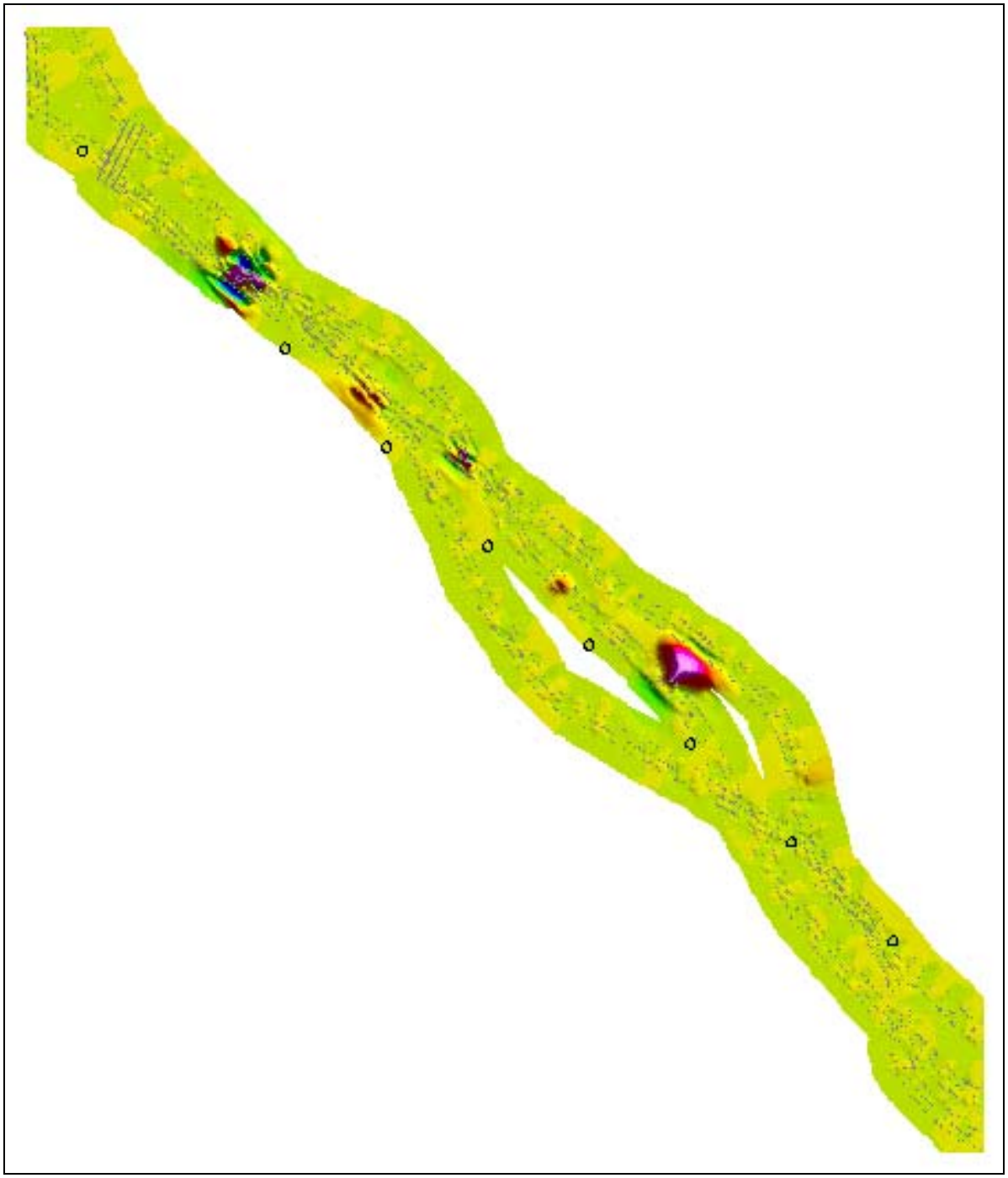


Figure 65 Detection channel ("qsum+ipdif") contour map over mud area line 1

Figure 66 Detection channel (“qsum+ipdif”) contour map over mud area line 2

Accurate sensor positioning relative to target location during the survey was problematic for a number of reasons, and that many detection channel anomalies were in fact responses to the seeded targets even though they do not coincide precisely on the maps. It is noted that in past surveys using essentially the same equipment (except for the towing boat) and platform, GEM-3 successfully located seeded targets (proving grid at Mare Island, and ATC UW test site at

Aberdeen proving ground), so it is expected that there are differences in the acquisition and navigation scenarios of past sites versus the MSDB site. The following lists known issues:

- In previous tests, both the DGPS deployed and the DGPS used to emplace targets utilized a local real-time kinematic (RTK) base station with accurately surveyed (USGS) base-station position. RTK DGPS can achieve a few centimeters accuracy (relative to base station). The DGPS employed for the Phase I survey incorporated WAAS satellite supplied regional base station corrections, which claim an accuracy of 1 - 2 meters; the error is somewhat systematic and slowly varying except for jumps when the available satellite constellation changes. The error results in a shift or distortion of the data point positions rather than random scatter, and a similar uncorrelated shift in target positions.

- The error sited above can be geometrically amplified by the extrapolation from two closely spaced DGPS antennas to the end of the 40' tow shaft.

- There was likely greater tow-shaft flexure in this environment than previous tests, adding to extrapolation error. This was because the cross currents and wind forced large "crabbing" lateral displacements of the sled, and also, the deeper water resulted in vertical flexure.

- In the mud search area the tow-shaft mounted DGPS data was not recorded due to human error, and an alternate DGPS, mounted at the front of the catamaran, was used as a substitute to estimate GEM-3 array position. This estimate was performed for the along-track direction but no measurement was available to account for crabbing angle, and using a tow-shaft dip angle estimate, and the extrapolation distance was double that of the shaft mounted DGPS. As a note, using both sets of DGPS for the sand area to check for consistency revealed a large (~12 m) down-track discrepancy between the two.

Phase I Problems

Data positioning and navigation

The most serious problem related to navigation difficulties was described above. A related problem was the difficulty in piloting the catamaran so that all the sensors tracked over the target line within detection range for each sensor. The pilot used the front-mounted DGPS, and focused on steering the front mounted sonar and magnetic sensors over the target line. Cross currents and wind made the pilot's job difficult, and the GEM-3 crabbing offset the EMI sensors from the track line even when the pilot succeeded in driving the BOSS TV directly over the target line.

Potential remedies include the use of a local base-station RTK DGPS for both locating the seeded targets, and for surveying (including pilot navigation DGPS); this may prove impractical at this site, which does not have a conveniently available USGS survey reference position for the base station within range of the target sites. Use of a non-surveyed position can suffice if it is used consistently for both seeded target positioning and the mission, resulting in a common offset relative to absolute global position.

Extrapolation errors can be reduced by increasing the antenna separation on the shaft. This entails a little mounting difficulty but doable. Of course, care must be taken to ensure all GPS data are being recorded during the mission.

A more advanced pilot navigation aid can be developed where the display includes both the real-time position of the catamaran and the sensor so that he can see the crabbing offset, superimposed on the target line.

Sled lift

Another problem encountered was the tendency for the sled to "fly" off the bottom when the tow speed exceeded about two knots. This was not initially recognized and one full day of surveying turned out to produce no useable data. Once the problem was understood, lead weights were added to the front of the sled, which helped but did not eliminate the need to tow at less than two knots, and real-time monitoring of EMI sensor data clearly showed when the sensor began to lift (the bottom response changes drastically).

This should be remedied with some sled design changes; incorporating the lead weights as a permanent addition, and relocating the towing point further back (it is currently at the very nose of the sled) towards the center of mass may suffice. An alternative approach would be based on adding down-pushing fins to the front of the sled

Site deployment difficulties

Towing the platform out to the site was somewhat inconvenient. Initially, a small boat carried the sled/senor package while towed by the survey boat; this prove impractical as it is heavy and not easily lifted off or back on. A better method floated the sled with buoys for transport, but it was still somewhat difficult to detach and reattach at sea. Some scheme for building in floats that can be remotely deflated and re-inflated should be designed.

Phase I Comparison of BOSS, RTG and GEM-3 Array Target Detection

A major objective of the MSDB project was the comparison of target position data from the tracking tests at the sand and mud sites and evaluation of data fusion techniques that can increase the probability that UXO targets can be identified and distinguished from other debris in a search area. The initial data fusion techniques were based on simple mapping of the target detection results from the three independent sensors. Figure 67 presents mapping results from BOSS, RTG, and GEM-3 data at Line 3 of the sand site. The left hand image contains the latitude / longitude grid overlay. Units are in 1/10000 minutes. The image was created from BOSS datafile: Line3c_000.jsf . The RTG detections were generated from RTG datafile: Day1, line3_03. The figure also shows the GEM3 detections above a response level of 200 (collected over several runs).

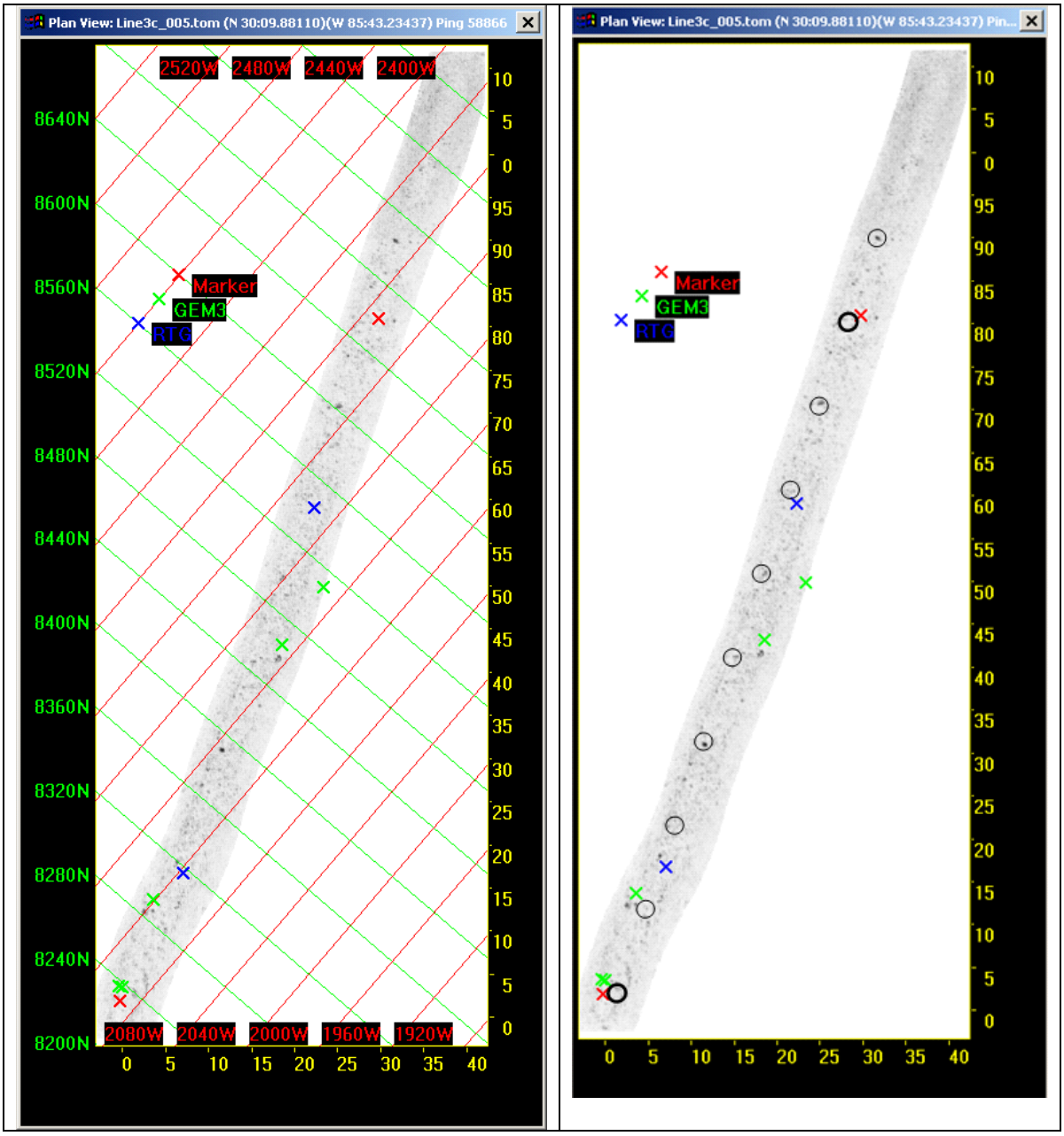


Figure 67 BOSS, RTG, and GEM-3 target position data from Line 3 at Sand Site. BOSS detected objects - black dots; RTG detected objects – blue cross; GEM-3 detected objects – blue cross; Marker position – red cross; target lay down position – black circle

Figure 67 shows that only a few targets were detected by RTG and GEM-3 during search tracks over line 3 and there is rough coincidence of BOSS, RTG, and GEM-3 targets within a few meters. The level of target position coincidence is not surprising as the accuracy of the WAAS GPS-determined positions of each sensor likely include uncertainty of a few meters. However,

the fusion results are difficult to interpret as the target detections are not what might be expected from this sensor set deployed in the two sensor vehicles as in the MSDB test configuration. Specifically, the RTG is expected to detect the same targets as BOSS (they are in the same vehicle) *if* the target is within range. This would most likely be the case for the larger targets during track runs where the BOSS TV passed directly over the targets. Data from line 3 does not indicate RTG detections of the large targets, specifically the 6" targets on the North end of line 3. The data indicates that the detected RTG targets are nearest the buried 4" target location and the proud or buried 2" targets on the south end. Target results from GEM-3 are also sketchy but this can be explained in part by an inability to consistently steer the GEM-3 array over the targets. The fusion results could not be interpreted more clearly with the Phase I data due to limitations in target ground truth accuracy and measured senor/vehicle position accuracy.

MSDB Phase I Test Conclusions

The MSDB project conducted a test in October 2006 and collected a data base of UW sensor detection data from a multiple sensor system versus a set of simulated UXO targets. The MSDB sensor suite which included an acoustic BOSS sensor, a fluxgate RTG magnetic sensor, and a GEM-3 active EM sensor array was deployed from a single craft, a 46' catamaran, in two UW vehicles, a towed vehicle housing the BOSS and RTG sensors and a towed GEM-3 array sled. The catamaran deployed the UW vehicles on or near the bottom and conducted a series of search tracks versus several lines of proud and buried UXO at two different test sites in St. Andrews Bay, FL. The UXO target lines included simulated cylindrical UXO targets of four different sizes (2"-6" diameter) which were deployed in approximately 10' feet water at a sand bottom and a mud bottom site. Positions of the sensors during the search runs were determined by WAAS GPS measurements of the catamaran position and known position of the sensors with respect to the GPS catamaran position. Data from all sensors were digitally recorded.

MSDB test results confirmed that UXO targets were successfully detected by all three sensors during the search runs but generally multiple search runs were required to detect more than one target in a given line. This was primarily due to the limited ranges of the RTG and GEM-3 sensors and the challenge of navigating the catamaran/TVs over the target sets when significant tides and current were present. The BOSS sensor was the most successful sensor in detecting the UXO targets and BOSS images were obtained from processed data for most every UXO target. The GEM-3 array was the next most successful sensor detecting virtually all targets from Line 1 at the sand site and detecting a number of UXO targets in Lines 3 (sand site) and Lines 1 and 2 (mud site). The RTG sensor was partially operational (three of five channels) and several UXO targets were detected in all lines but target positions could only be estimated with RTG in a degraded mode.

The MSDB sensor detection data was used to develop maps of the locations of the detected targets which were compared to ground truth UXO positions determined by divers using GPS. These results showed that BOSS data was typically most complete and accurate. Processed BOSS images of detected targets showed clearly the planar position of the targets and the depth at/below the water bottom. BOSS target detection positions were generally within a few meters of the target ground truth positions and the buried UXO were visible below the bottom interface.

Processed BOSS images also showed evidence of specular reflection scattering the bottom surface which can mask the detected BOSS targets. Analysis has been performed that indicates that the specular reflection scattering can be eliminated by extending the length of the wings/receivers of the BOSS sensor to eliminate specular reflection regions that presently exist under the BOSS TV. The GEM-3 array successfully detected the UXO targets that it passed over. The number of targets detected in a single search track was determined by the success of the catamaran pilot in steering over the targets. Catamaran navigation during the tests proved more difficult than anticipated primarily due to effects from tides and currents.

Initial fusion of the UXO target detection positions from the BOSS, RTG and GEM-3 sensor was performed. The results demonstrated that UXO targets were detectable by the different sensors but that target coincidence was generally limited to agreement within several meters. This is primarily due to the limitations in the accuracy of the WAAS GPS navigation systems employed during target deployment and during sensor data collection. Tests performed with WAAS GPS sensors verified that the position of a stationary point varies by several meters in periods of hours.

Site environmental measurements were performed at the sand and mud bottom test sites by UW/APL employing their IMP2 system to estimate sea bottom parameters. These parameters are available for analysis of the BOSS results using models such as the PCSWAT.

Track data from the MSDB sensors was recorded during the FY06 St. Andrews Bay tests and is available to other UW UXO researchers upon request through the SERDP program office.

Based on the Phase I MSDB St. Andrews Bay tests several recommendations were proposed. The MSDB tests demonstrated that the sensor suite can detect a representative UXO target set employing the MSDB catamaran configuration. It was proposed that the MSDB tests be continued at the same St. Andrews Bay test sites with several key improvements in test/measurement techniques. The primary improvement was to employ RTK GPS navigation techniques to determine target ground truth and to accurately determine the position of the three sensors during the search runs. Employment of RTK GPS would permit reduction of position uncertainties by one order of magnitude. This improvement would reduce the uncertainties and ambiguities in detected target identities and locations that will be vital in accurately evaluating the value of multiple sensor detection and data fusion. Other proposed improvements included: modification of the BOSS wing design to permit elimination of specular reflection scattering effects; changes in RTG sensor calibration and performance validation during pretest procedures; and detailed independent identification of extraneous targets and debris by divers in target search areas.

MSDB Phase II Test Materials and Methods

MSDB Phase II Sensor Configuration for UW UXO Data Collection

The limitations of selected Phase I MSDB sensor detection range and target position measurement techniques were revaluated by SERDP Munitions Management program personnel. It was determined that the Phase I data was not of sufficient mapping quality to warrant continuation of the data fusion effort. The goal of Phase II MSDB was reestablished at a more modest level. The Phase II goal was to collect high quality BOSS acoustic detection data and mapping of a set of simulated and real UXO that were flush buried and shallow buried at the sand bottom St. Andrew's Bay site. A key factor in achieving the Phase II goal was to improve target mapping accuracy.

The MSDB project employed RTK GPS equipment to improve measurement accuracy of UXO test target ground truth positions and BOSS acoustic sensor position during Phase II target search operations. BOSS vehicle stabilization techniques were also employed to insure that the RTK GPS equipment accurately measured the BOSS vehicle and sensor position during UXO target search and mapping operations.

Figure 68 shows the modified MSDB catamaran and BOSS vehicle sensor configuration employed during Phase II target search operations. Figure 79 shows the BOSS acoustic sensor deployed in the BOSS UW vehicle which is towed from a mount on the front of the catamaran during UXO search operations. This configuration is near identical to the Phase I configuration except that the BOSS vehicle housed the BOSS sensor only.

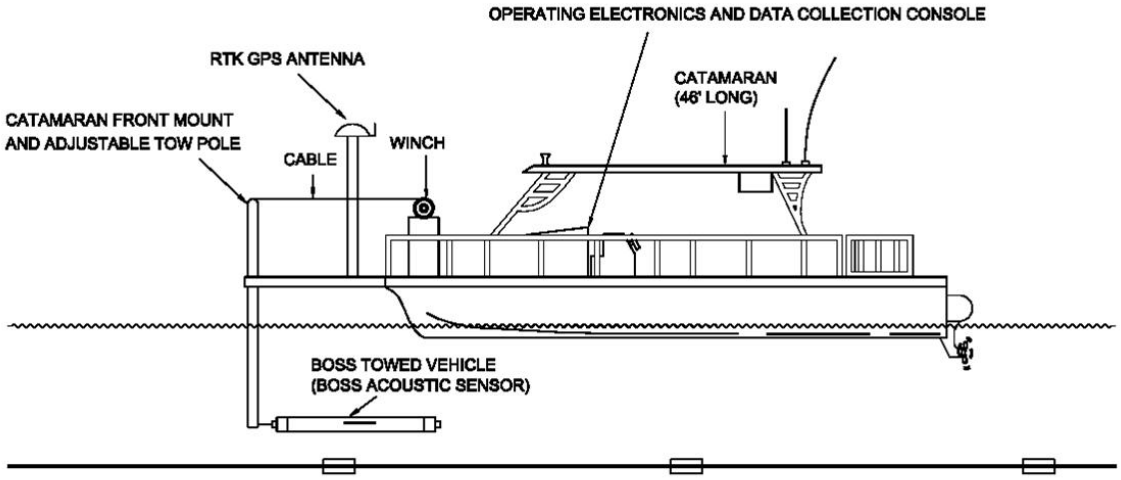


Figure 68 Phase II MSDB Sensor Deployment Configuration from the Catamaran

Two other Phase II modification were employed: 1) The BOSS sensor position was measured with an RTK GPS antenna positioned directly over the BOSS sensor and 2) the lateral motion of the BOSS vehicle and sensor were restricted during search operations by a vertical harness installed on the front mount. Figure 69 shows the location of the RTK GPS antenna and the vertical BOSS vehicle harness during Phase II operations. It was estimated that the RTK GPS antenna measurement was within 10 cm of the lateral BOSS sensor position.

Figure 69 RTK GPS antenna and vertical BOSS vehicle harness in the Phase II configuration

NovaTel RT2 equipment was used to perform the RTK GPS measurements. The shore-based reference NovaTel RT2 unit was located on the roof of an NSWC PC building ~ 1.5 kilometers from the shallow water test site.

MSDB Phase II Test Preparations/Test Methods

MSDB Phase II testing focused on conducting UW UXO detection tests versus a single field of real and simulated UXO targets deployed at a sand bottom site in St. Andrews Bay. The target site was in the same general area of St. Andrew's Bay as the Phase I sand test site. The primary site criteria was to identify a flat bottom area with water depth of 10 ft (+/- 2 ft) which was debris free and large enough to deploy up to three lines of real and simulated UXO targets plus additional selected debris targets.

A target field of 59 objects was deployed three weeks prior to Phase II search tests. Figure 70 shows the target layout which consisted of rows of real, inert UXO (81 mm and 4.2" mortar projectiles), simulated UXO (5x30cm and 10x30cm steel cylinders), concrete markers (6" diameter x 12 inch long) and assorted debris (concrete clump, tire, aluminum icosahedron, etc.). The rows of inert and simulated UXO were flush buried or buried up to 30 cm deep. The targets

in each row were separated by 1 meter. The target field included 4.2” mortar at several penetrating angles (45/75 degrees from horizontal) and piles of several 4.2” mortar flush buried or buried up to 30 cm deep. The concrete markers were deployed vertically and were hemi spherically-shaped on the top end to provide acoustic reflection at any lateral aspect angle.

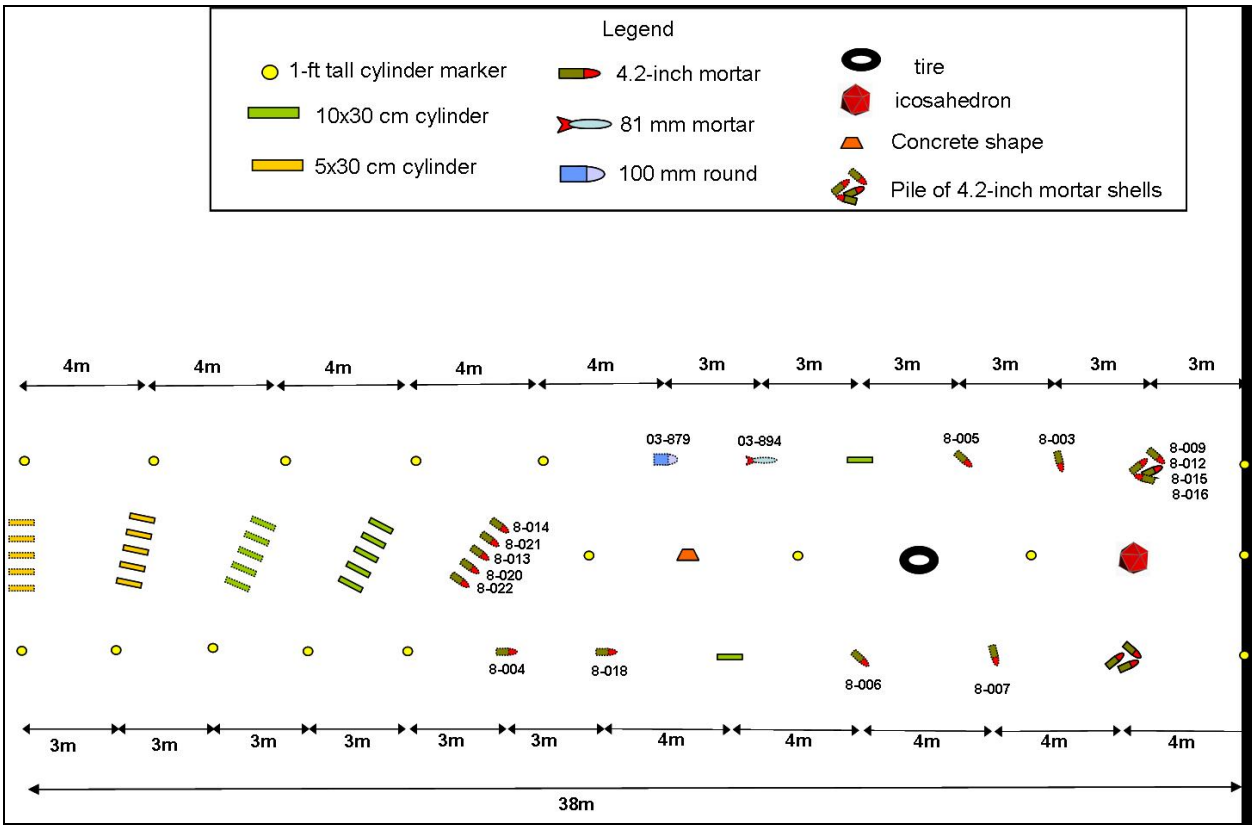


Figure 70 Phase II Target Laydown at St. Andrew’s Bay Sand Site

Figure 71 shows the inert UXO targets onboard the dive boat prior to deployment.

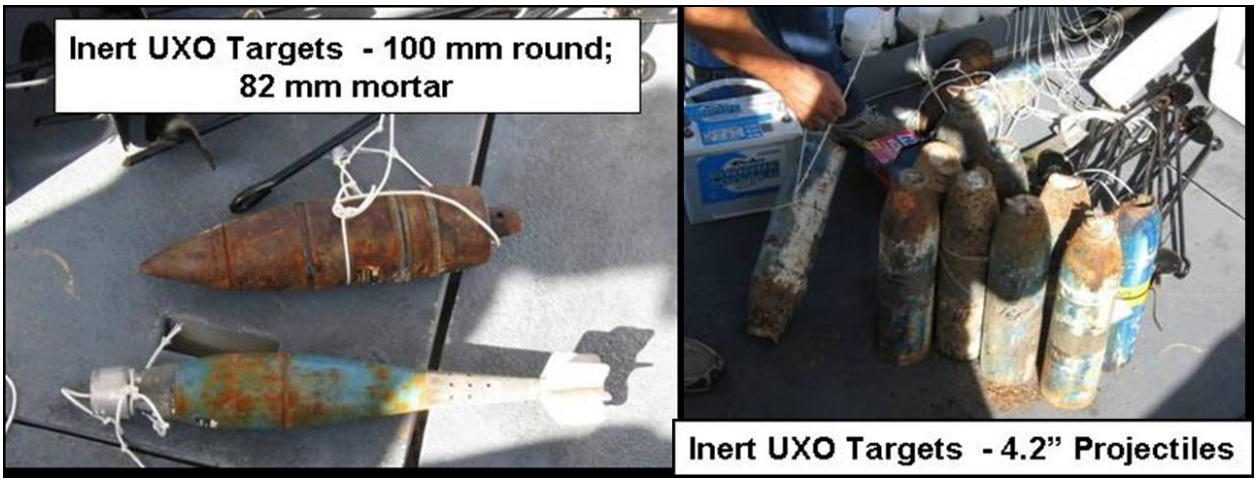


Figure 71 Phase II inert UXO Targets

The ground truth position of each target in the Phase II target field was measured by divers using an RTK GPS antenna mounted on a stadia pole. The orientation of the GPS antenna was monitored during ground truth measurements. Wind and currents caused some variation in the angle of the pole during ground truth measurements but averaging techniques were used to minimize these effects. Figure 72 shows the ground truth target locations of the markers and UXO/debris determined by averaging the ground truth data on three measurement days, 8/18/08, 9/15/08, and 9/22/08. Figure 72 plots the ground truth locations of only outermost UXO targets in lines 1 through 5. Figure 72 also correctly shows the geographic orientation of the laydown field which is deployed northwest to southeast in order to maintain the targets at a specified water depth.

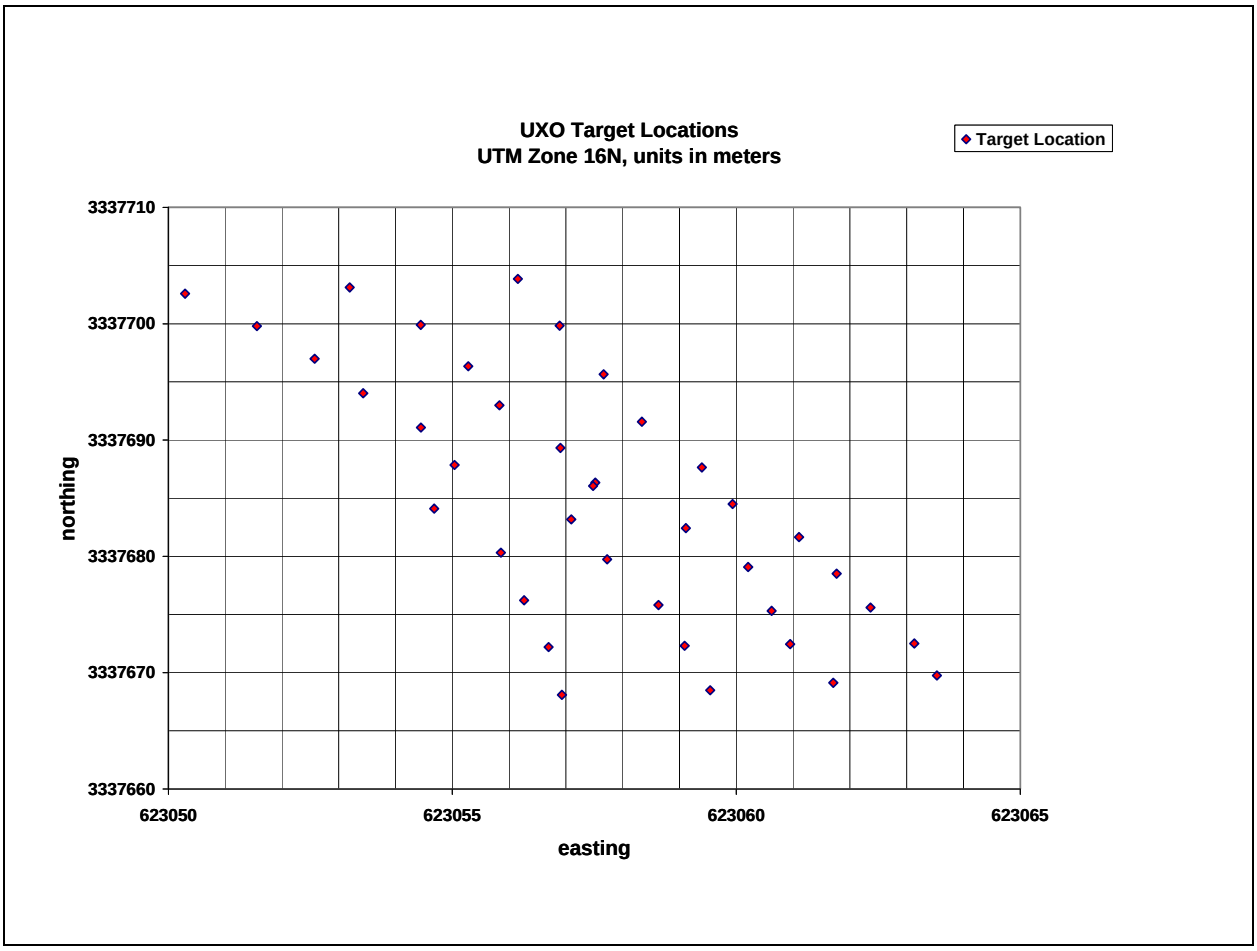


Figure 72 Average Ground Truth Phase II Target Locations calculated from 8/18/08, 9/15/08 and 9/22/08 RTK GPS data

MSDB Phase II Bottom Sediment Parameter Measurement Techniques

The bottom sediment parameters in the St. Andrew's Bay Phase II target area were evaluated by NRL SSC personnel. NRL divers collected 12 core samples at sites within the tests area approximately three weeks prior to the Phase II MSDB search tests. Samples of surficial sediment varying from 8 to 34 cm in depth were collected in standard "NRL" cores 5.9 cm in inside diameter and 45 cm in length. At four of the locations within the MSDB target site,

smaller (13-cm length) NRL cores were collected for the purpose of measuring sediment permeability.

All cores were logged intact for sediment sound speed at 100 and 400 kHz directly through the plastic core wall using oil-filled rubber transducers that fit snugly on either side of the cores. Acoustic measurements of the sediment cores were made at 1-cm increments on NRL cores 24-36 hrs after collection. Physical properties of bulk density and porosity were measured on all 12 cores. Five of the 12 NRL cores were sectioned at 2-cm intervals, with the remaining cores assayed whole for porosity and bulk density (*in toto*). The cores showed that the sediment is a medium sand with a mean grain size of approximately 0.28 mm and a sound speed of 1760 m/s at 100 kHz.

MSDB Phase II Test Results

Navigation Data

On 18 Sept 2008, BOSS-160 was towed across the 2008 UXO target field shown in Figures 70 and 72. Sonar tracklines lines were oriented parallel, 45 degrees, and perpendicular to the axis running through the center of the field. The tracklines generated from RTK data, stored in the sonar data header, are plotted in Figure 73.

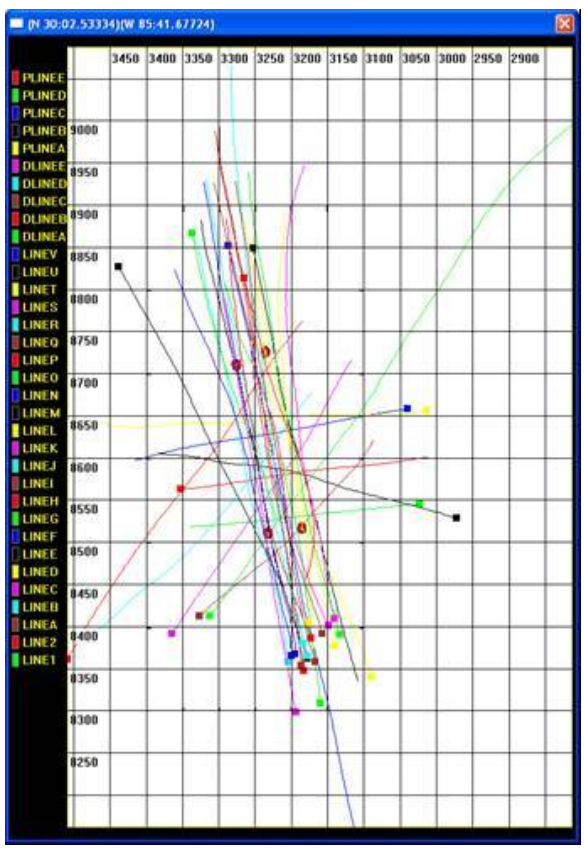


Figure 73 Tracklines generated from RTK data for BOSS survey of 2008 UXO field on 18 September 2008. The scale shows fractions of a minute of latitude and longitude. For example, the value of 8500 shown along the left hand edge of the figure marks the latitude of 30d 09.8500 min North. The red circles mark the corner markers of the UXO field.

On 20 Sept 2008, BOSS-160 system was towed across the 2008 UXO target field shown in Figure 81 and 83 and the 2006 UXO field shown in Figure 16. In the 2008 UXO field, tracklines were oriented parallel, 45 degrees, and perpendicular to the axis running through the center of the field. For the 2006 UXO field, tracklines were run only parallel to the 3 lines of targets. The tracklines collected on 20 September 2008 for both UXO fields, generated from stored RTK data, are plotted in Figures 74 and 75.

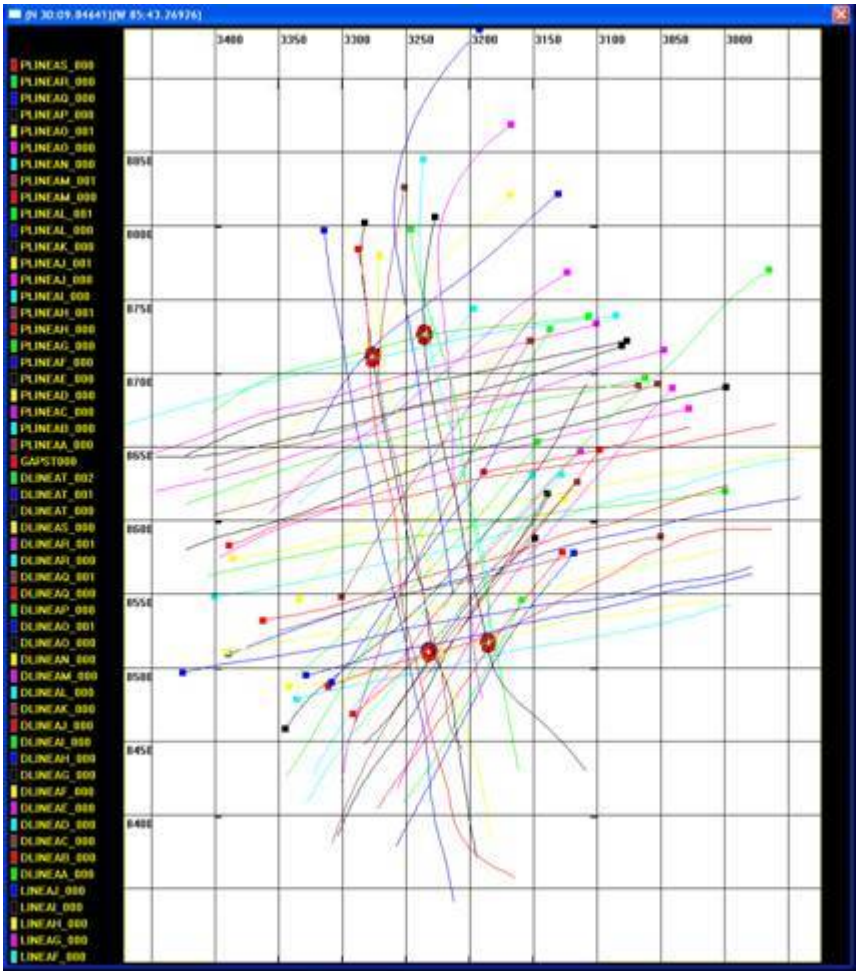


Figure 74 Tracklines generated from RTK data for BOSS survey of 2008 UXO field on 20 September 2008. The scale shows fractions of a minute of latitude and longitude. . For example, the value of 8500 shown along the left hand edge of the figure marks the latitude of 30d 09.8500 min North. The red circles mark the corner markers of the UXO field.

The accuracy of the RTK GPS data varied throughout the survey. The variability in RTK's fix quality factor correlated with the degraded target positions in BOSS imagery. End markers, proud concrete hemispheres, marking the corners of the field, were used to assess the variability in RTK GPS position data. When the RTK GPS was reporting a fix quality factor of 4, the ground truth measurements (made by divers) usually fell within one foot of the position of the hemisphere in the image. When the fix quality factor was 5, the errors between the ground truth measurements and the position of the hemisphere in the image were a large as 6 feet. Figure 76 provides examples of the magnitude of position error caused by degradation in RTK fixes.

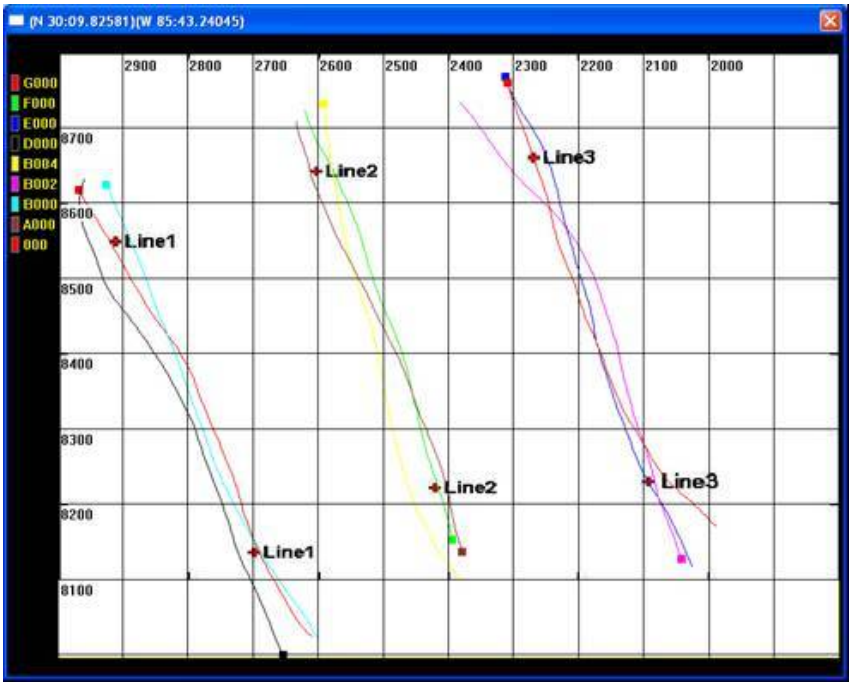


Figure 75 Tracklines generated from RTK data for BOSS survey of 2006 UXO field on 20 September 2008. The scale shows fractions of a minute of latitude and longitude. . For example, the value of 8500 shown along the left hand edge of the figure marks the latitude of 30d 09.8500 min North. The red crosses mark the ends of each line of targets.

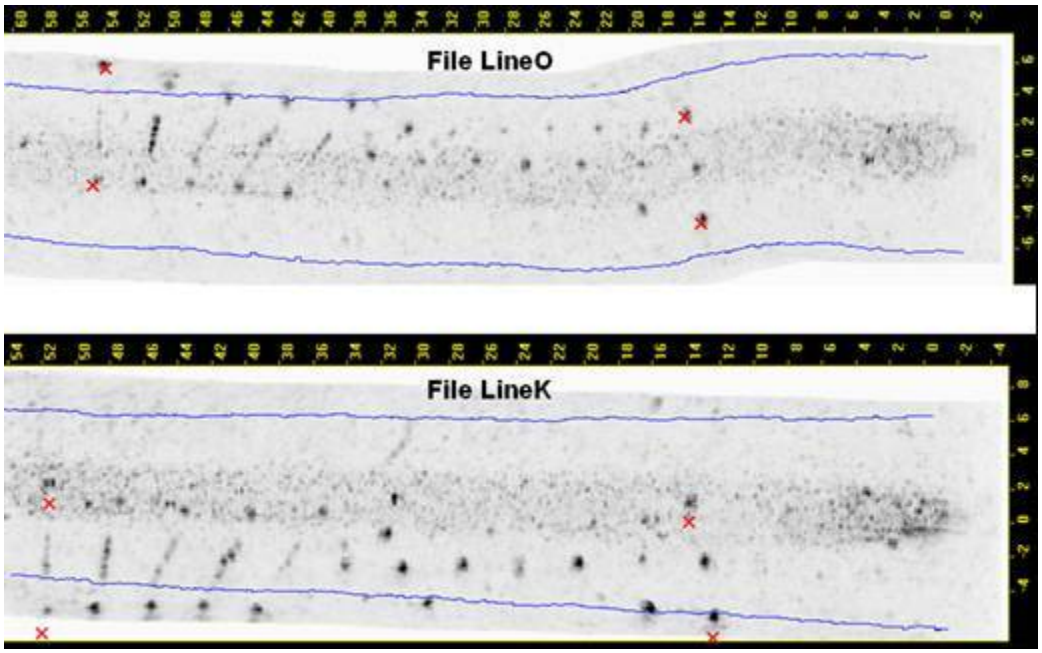


Figure 76 Example of BOSS imagery produced using degraded and accurate RTK GPS position data. During track LineO, the RTK GPS reported a fix quality factor of 4. Note that for LineO, the red ground truth makers fall on top of the images of the corner markers showing the image-based positions and ground truth positions of the corner markers agree. During Line K, the fix quality factor was frequently reported to be 5. The error between the red ground truth markers and the concrete markers in the imagery is about 1.5 meters.

The reason for poorer GPS fixes observed on selective search runs (see Line K, Figure 76) is not clearly understood. One explanation is that the combination of the low GPS antenna position and satellite clustering leads to lower quality GPS fixes. The GPS fix quality may be improved by raising the position of the GPS antenna from ~ 1 foot to 6-8 feet above the front mount.

Phase II BOSS Target Detection

Detection of 2008 UXO Target Field

During the 2008 surveys BOSS-160 was towed across the target field 24 times on 18 September 2008 and 60 times on 20 September 2008. Tracklines were oriented in 3 directions with respect to the longitudinal axis through the center of the field: 000, 045 and 090 degrees. Acoustic data collected during each pass was stored with RTK GPS data in one or more files. Along the left hand edge of trackline plots in Figures 84, 85 and 86 list the filenames for each of the runs.

All targets were detected in the 2008 UXO target field. In general the targets were detected when they were illuminated at grazing angles between 70 and 45 degrees. At lower grazing angles, SNR was too poor for detecting or imaging fully buried targets because transmission losses through the sediment-water interface. At higher grazing angles, SNR was also too low because scattering from sediment-water interface ripples and other specular surfaces was higher than echo levels from targets.

The sequence of images in Figure 77 shows detections of all targets in the 2008 UXO field. Unless otherwise stated, BOSS imagery in this report was generated using a 1 meter long synthetic aperture and the pass band of 8 to19 kHz.

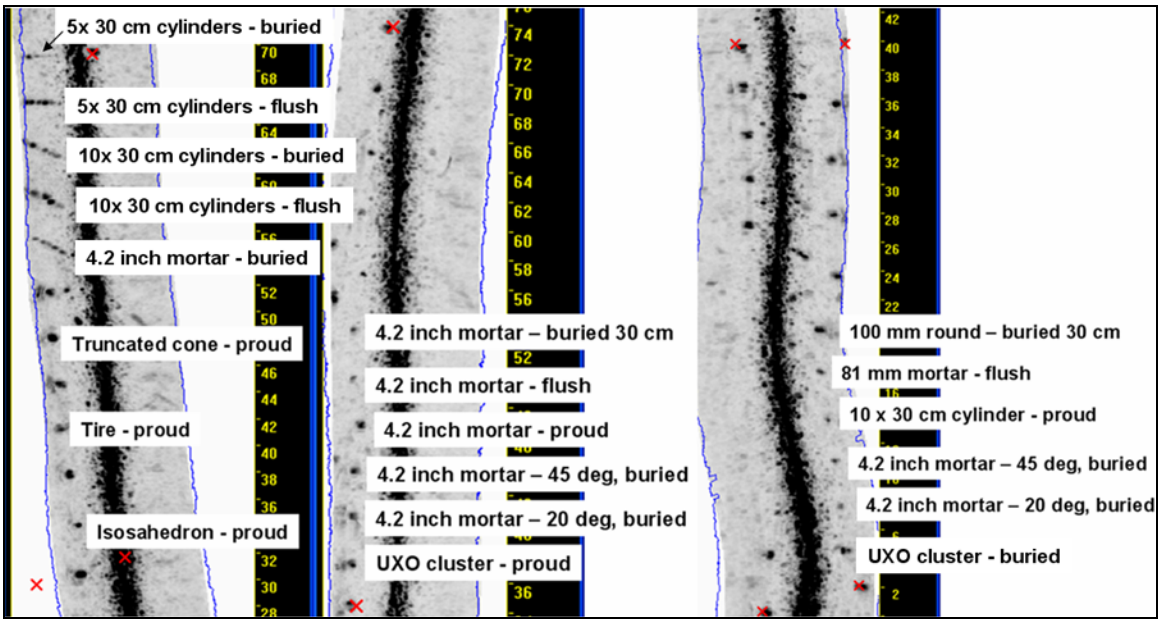


Figure 77 Representative lines parallel to axis of target field showing that all targets were detected. The planed layout of the 2008 UXO field is in Figure 81. The scattering noise in the center of each image is due to specular scattering off the sediment-water interface directly below the sonar.

Accuracy of Target Positions in Imagery

Positions of the targets measured by divers (ground truth) and positions of the targets measured from BOSS images of targets are plotted in Figure 78. With the exception of targets 11 and 51 and the rows of 5 cylindrical targets, the BOSS measurements of target positions agree with the ground truth positions. Imagery in Figures 79, 80 and 81 show that the discrepancies between BOSS measurements of target positions and ground truth may be due to errors in measuring the ground truth.

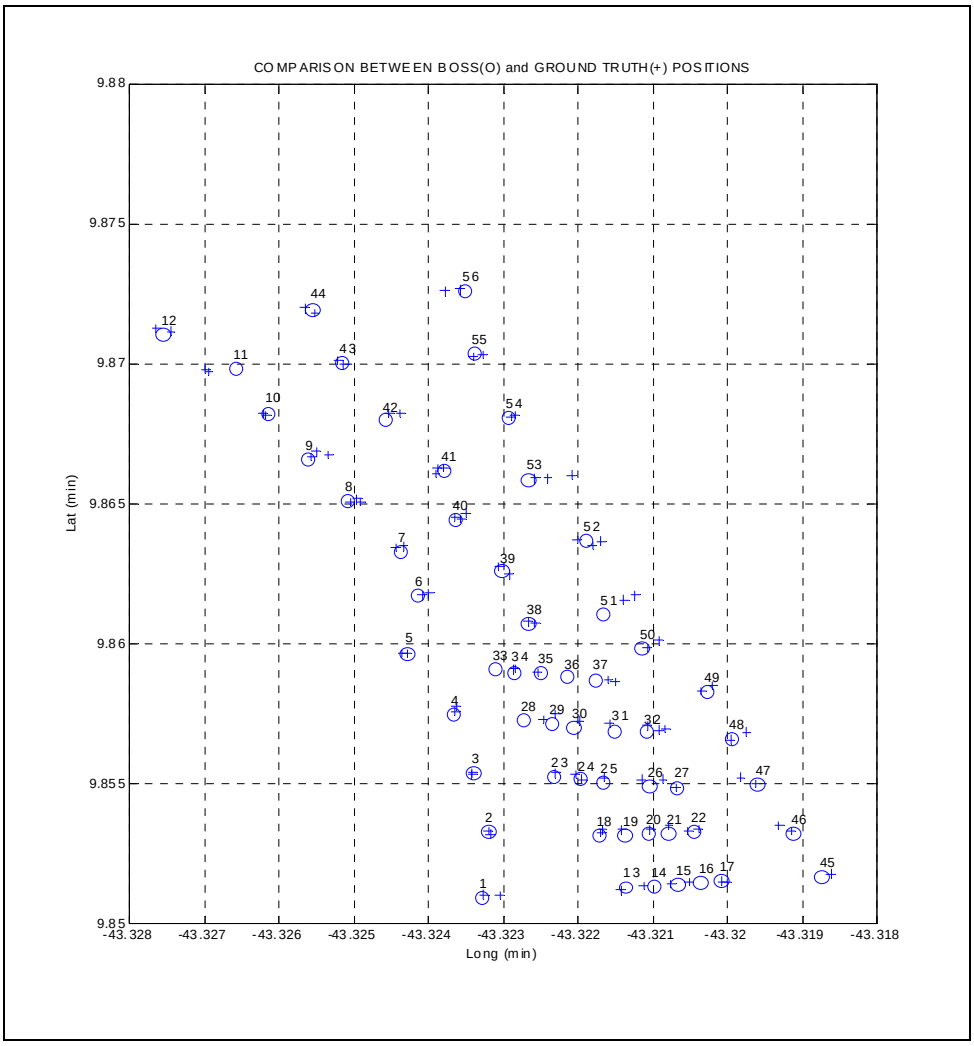


Figure 78 Positions of targets measured by BOSS and divers at 2008 UXO field. The crosses indicate the positions of ground truth measurements made by divers. The circles indicate the positions of targets in the BOSS imagery.

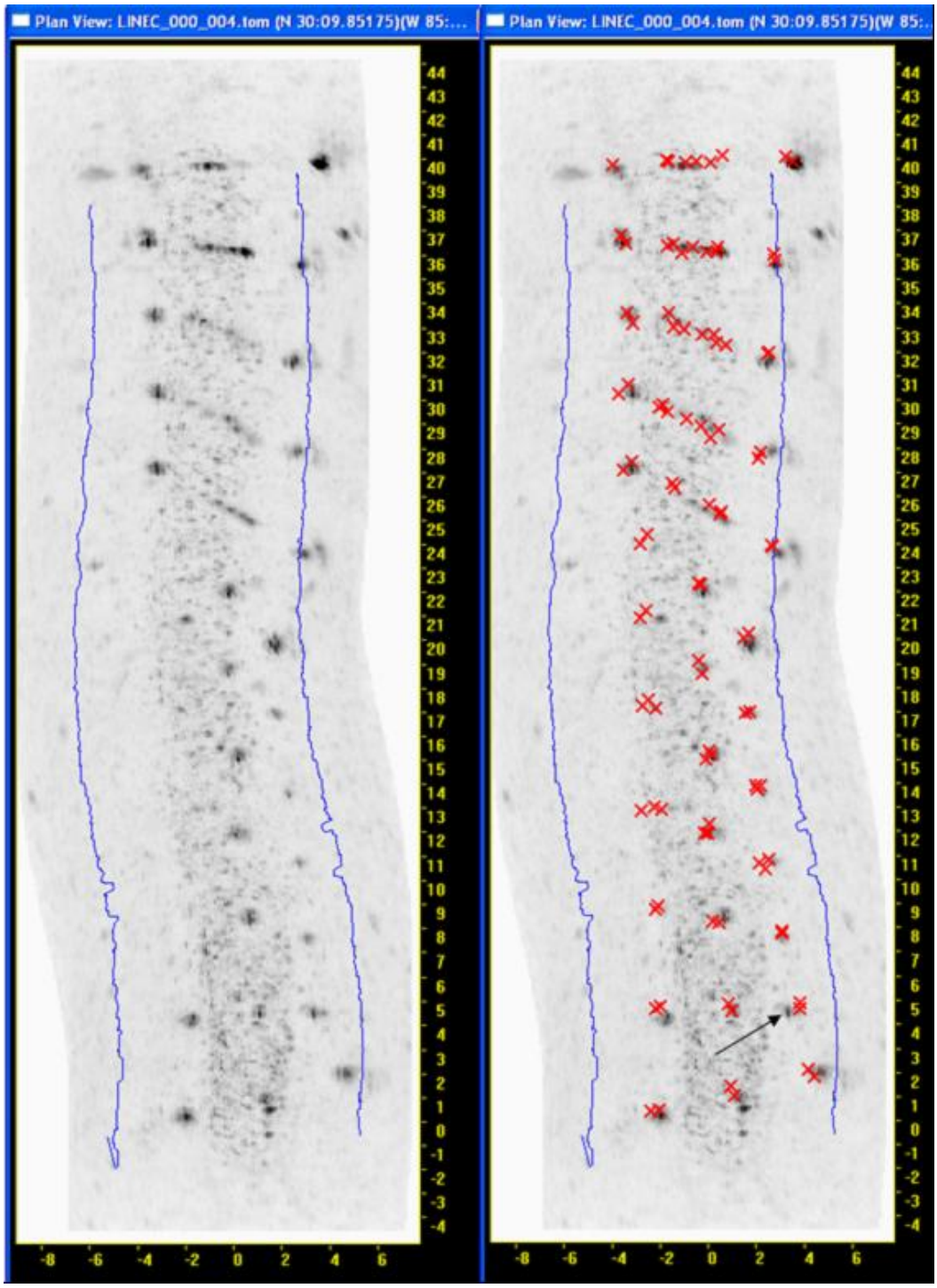


Figure 79 Ground truth measurements of target positions plotted on BOSS image of 2008 UXO field (file LineC). Arrow points at pile of random UXO (Target #11). Position of strongest echo off the UXO pile is offset from the diver's measurement point. Right hand image of 2008 UXO field is identical to the left hand images with the exception the ground truth positions of UXO are marked with a red x in the right hand image.

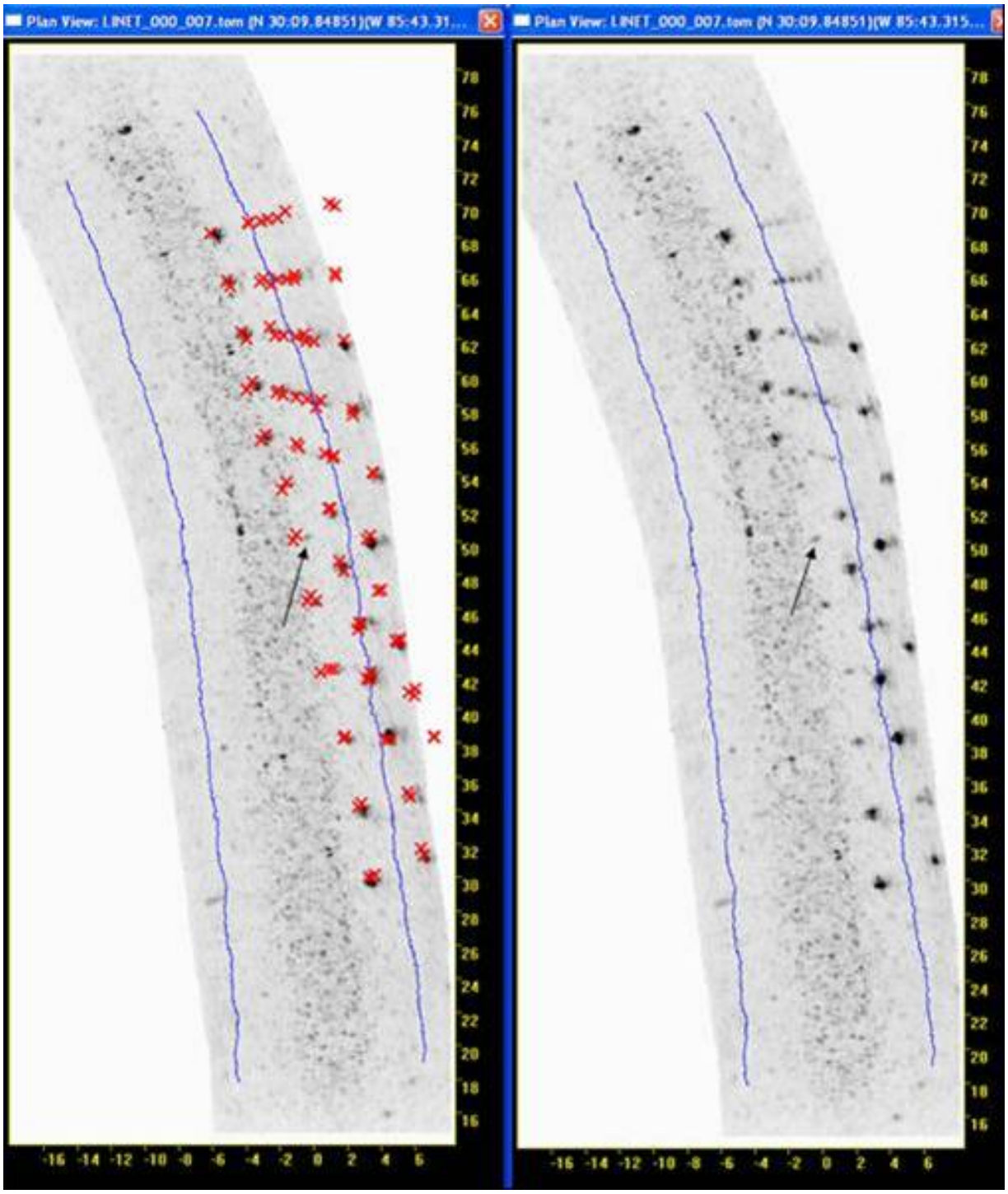


Figure 80 Ground truth measurements of target positions plotted on BOSS image of 2008 UXO field (file LineT).Arrow points at a flush-buried 4.2 inch mortar(Target # 51). It appears that the divers may have been measuring position of a marker along a string between targets instead of the position that the target was buried.

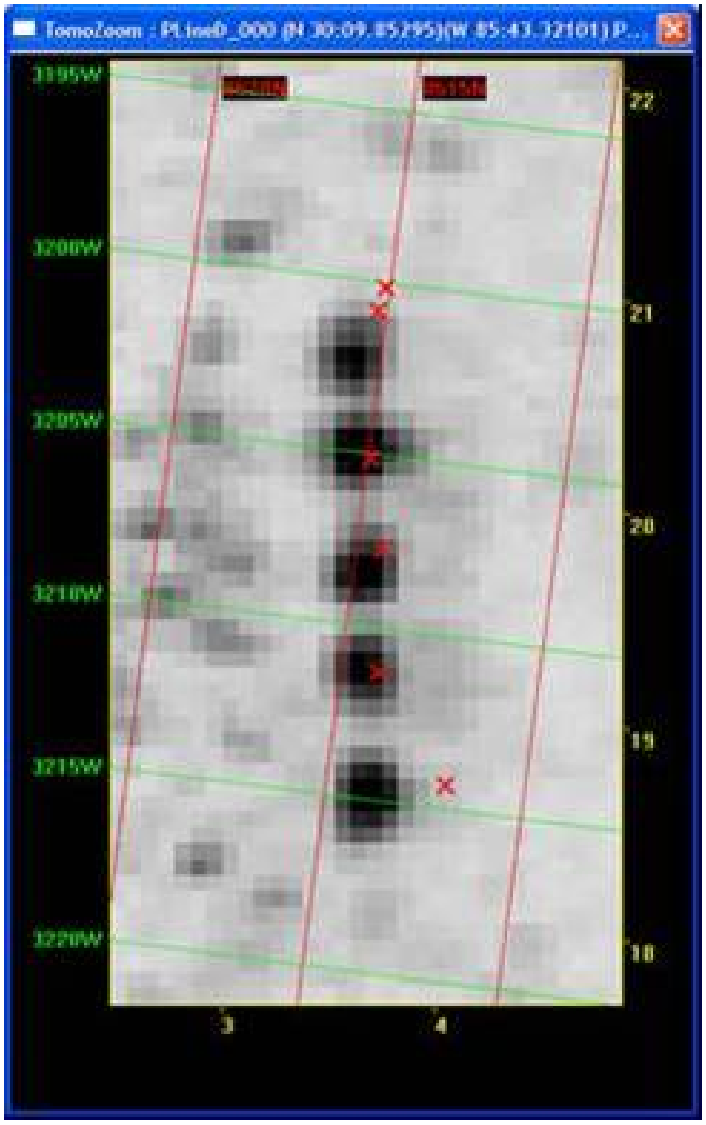


Figure 81 Image of southernmost line of cylinders (5 x 30 cm, buried). Image shows cylinders have equal intercylinder spacing as planned. Ground truth positions (red x's) agree with only 3 out of 5 targets in the line of targets suggesting that target positions derived from BOSS imagery may be more accurate than the ground truth measurements made by divers. BOSS positions of targets are derived from the latitude/longitude grid overlay. Units for latitude and longitude grid are decimal minutes. Horizontal and vertical scales are in meters.

3D Images of Targets Showing Burial Depth

A zoomed view of the multi-aspect image generated for each trackline was used to produce a 3D view of the seabed that showed UXO burial depth. The burial depth is measured using the vertical scale in the 3D image. The distance between the center of the target echo and the sediment-water interface detection (made by the DVL) is the reported depth of the target. The burial depths of all targets are shown in the captions of the 3D images in Figures 82-87.

A) B)

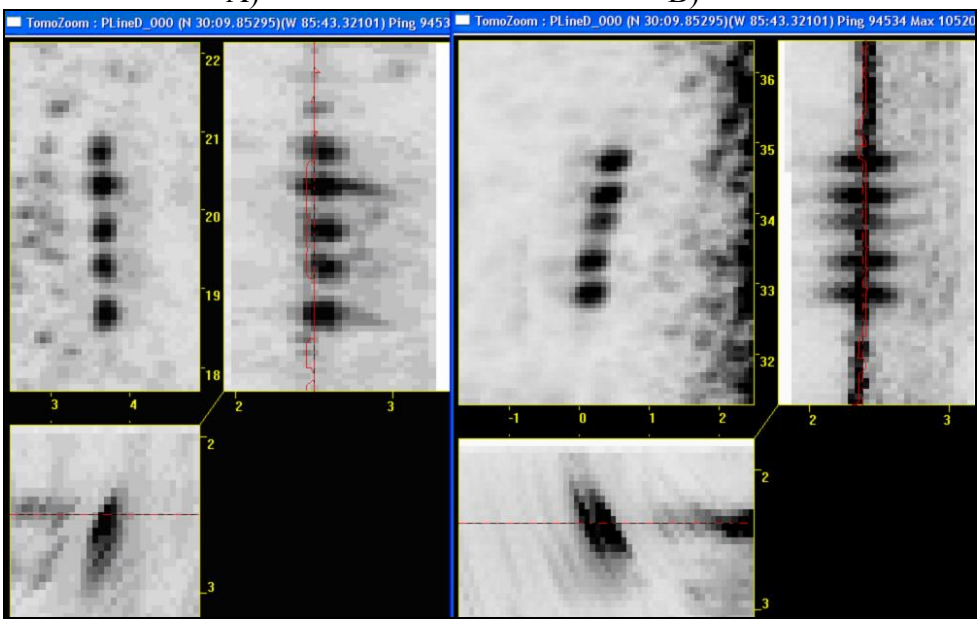


Figure 82 A) Left hand image: 3D image of 5x30 cm cylinders buried 30 cm. Image shows burial depth is actually about 10 cm. B) Left hand image: 3D image of flush-buried 5x30 cm cylinders. Images confirm cylinders are flush-buried. Vertical scale has a 2:1 exaggeration. The horizontal red line is the position of the seabed detected by the DVL.

A) B)

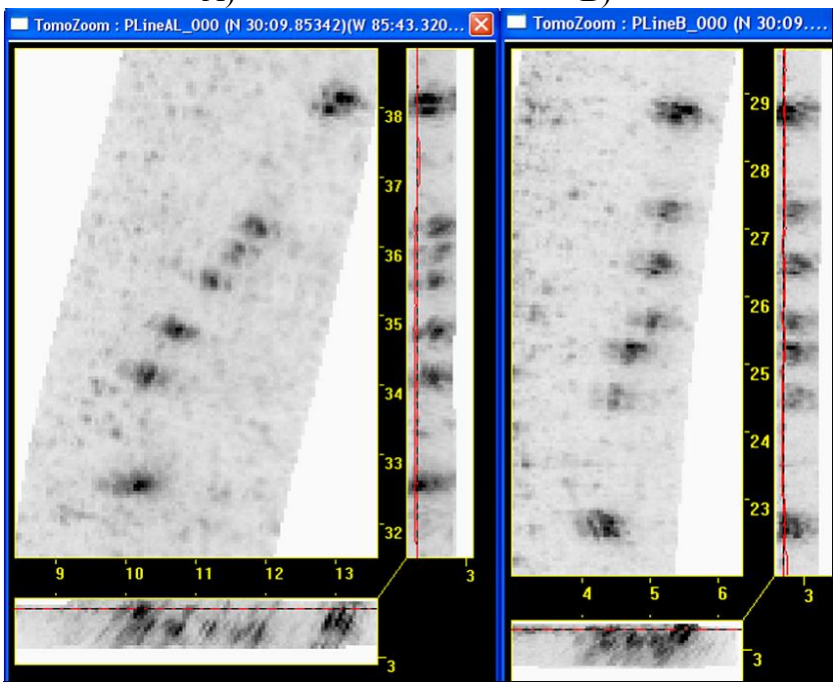


Figure 83 A) Left hand image: 3D image of 10x30 cm cylinders buried 30 cm. Image shows burial depth is about 30 cm. B) Right hand image: 3D image of flush-buried 10x30 cm cylinders. Images show the cylinders are flush-buried. Vertical scale has no exaggeration. This figure was generated using high resolution mode processing. The horizontal red line is the position of the seabed detected by the DVL.

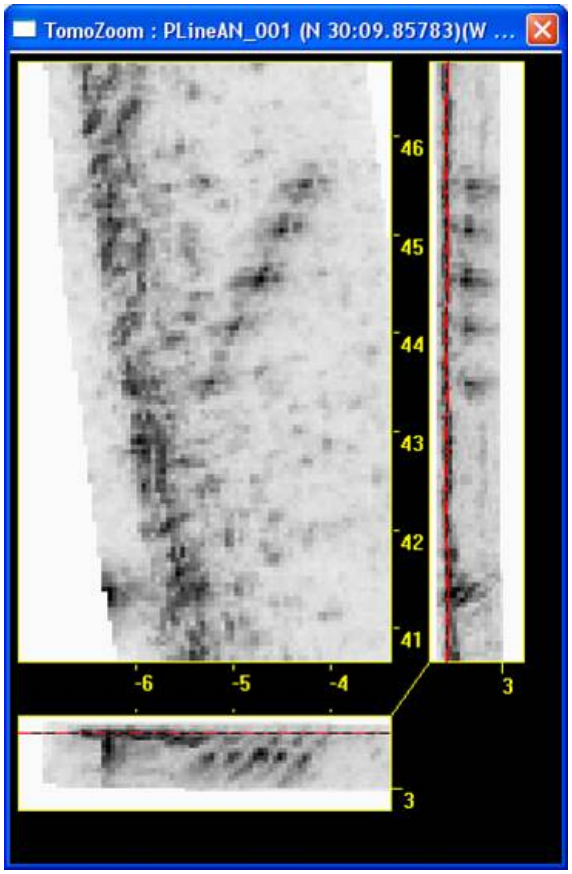


Figure 84 3D image of line of 4.2 inch mortars buried 30 cm. Image confirms burial depth is about 30 cm. This figure was generated using high resolution mode processing. The horizontal red line is the position of the seabed detected by the DVL.

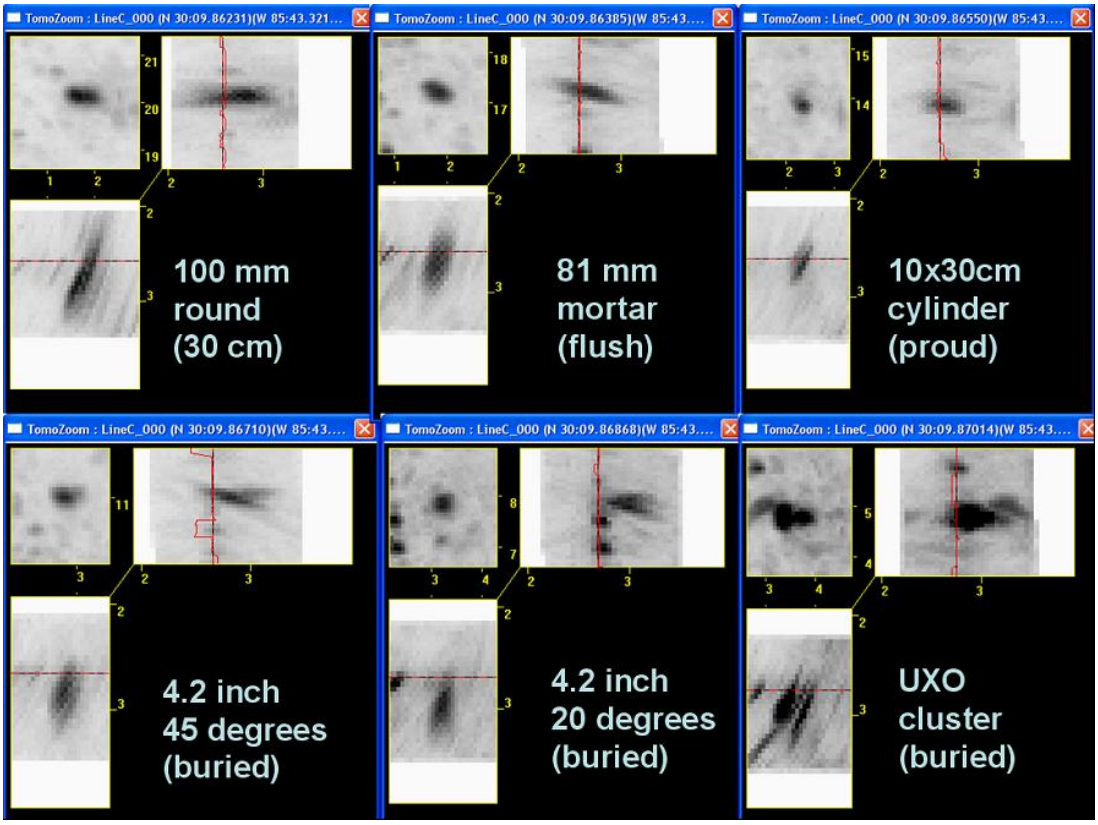


Figure 85 3D images of targets 6-11 (Fig. 78). Planned burial depths are shown in parentheses below each target description. The measured burial depths are the following: 100 mm round (30 cm) – 30 cm; 81mm mortar (flush) – 10 cm; 10x30cm cylinder (proud) – 5 cm; 4.2 inch mortar (45deg, buried) – 10 cm; 4.2 inch mortar (20deg,buried) – 15 cm; UXO cluster (buried) - 15to 25 cm. The horizontal red line is the position of the seabed detected by the DVL.

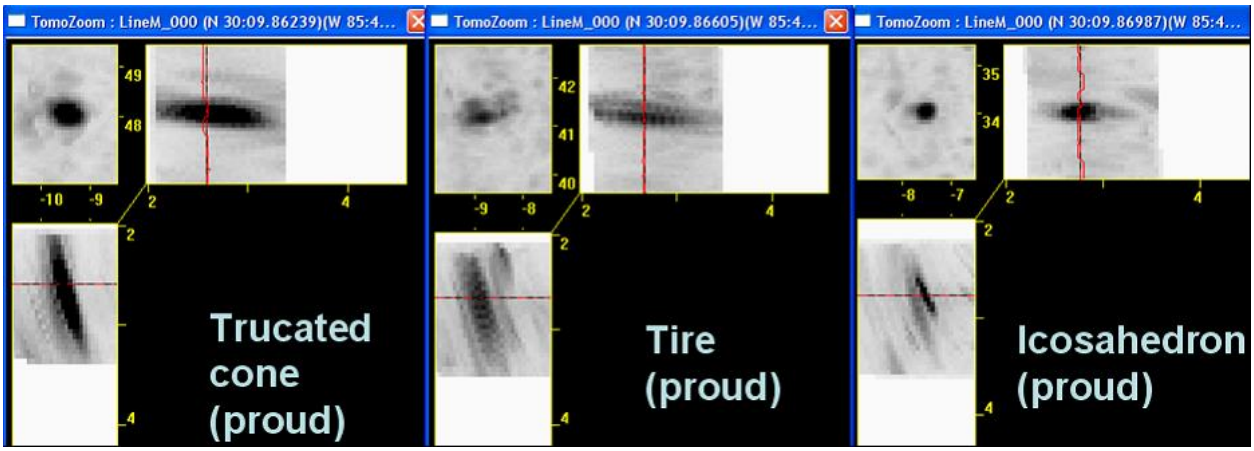


Figure 86 3D images of targets 39, 41 and 43 (Fig. 78). The targets in these images had a range of 3 meters off the port side of the sonar. At this elevation angle, it appears the echo from the cone originated off the lower edge which is about 5 cm under the seabed. Echoes from the tire appear at the seabed and 30 cm above the seabed. The echo from the icosahedron appears to arrive from the part of the target that is at the sediment-water interface. The horizontal red line is the position of the seabed detected by the DVL.

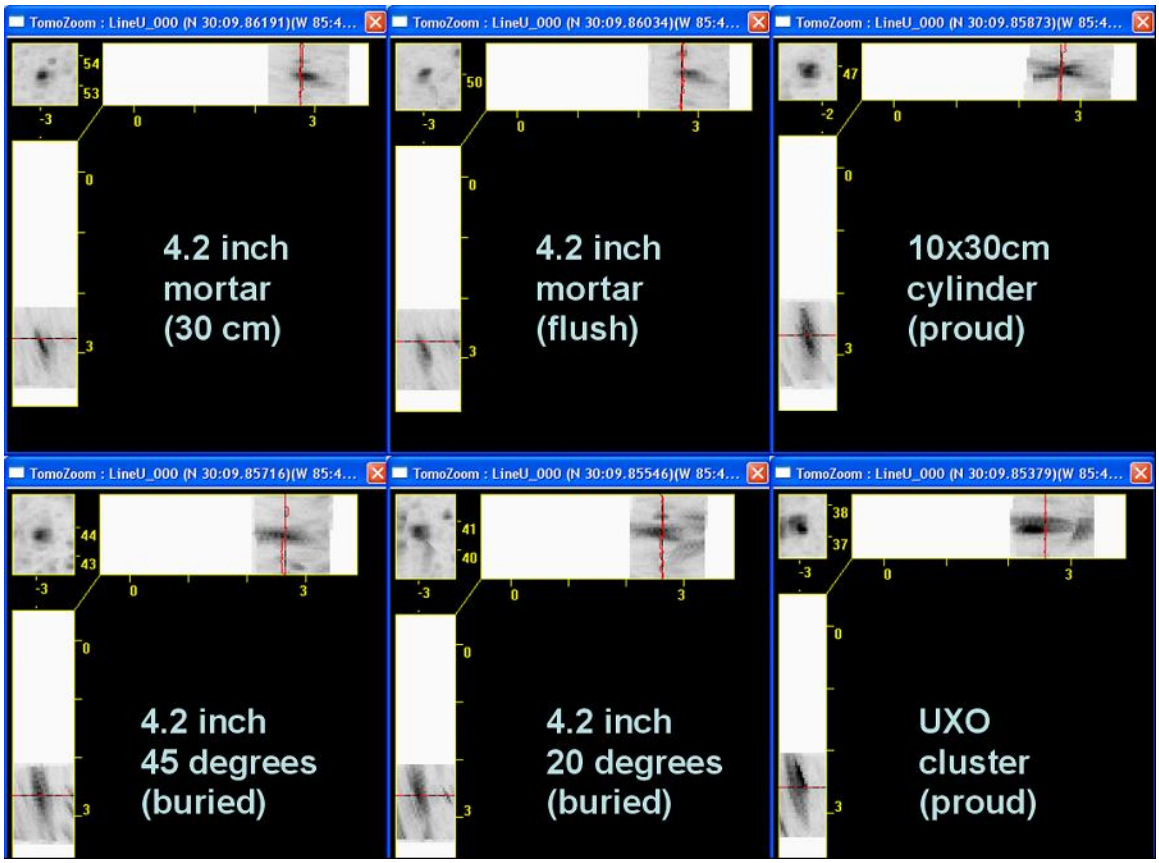


Figure 87 3D images of targets 50-55 (Fig. 78). Planned burial depths are shown in parentheses below each target description. The targets in these images had a range of 3 meters off the port side of the sonar. The measured burial depths are the following: ; 4.2 inch mortar (30 cm) – 10 cm; 4.2 inch mortar (flush) – 10 cm; 10x30cm cylinder (proud) – proud; 4.2 inch mortar (45deg, buried) – flush; 4.2 inch mortar (20deg,buried) – flush; UXO cluster (proud) - 20 cm proud. The horizontal red line is the position of the seabed detected by the DVL.

Analysis of buried cylinders to determine effective range & swath width of BOSS

NRL velocity measurements on sediment cores yielded a velocity ratio of 1.15. Assuming phase dispersion results in the sound speed being about 1% less at 10 kHz than at 100 kHz, the sound speed at 10 kHz, the velocity ratio at 10 kHz should be approximately 1.14 [(11)]. The critical angle for a sediment sound speed that is 1.14 times higher than seawater is 61 degrees. BOSS imagery shows that buried 5 cm and 10 cm cylinders have higher SNRs than most random scatterers for angles of incidence less than 67 degrees (slightly higher than the 61 degree critical angle). Therefore buried UXO targets can be detected beyond the critical angle to ranges up to a grazing angle of 23 degrees. Note that the cylinders are oriented end to end, so target echoes are originating from the end of the cylinder. Consequently, one could expect greater detection range if the echo originated off the side of the cylinder. Figure 88 shows that the range for end detection of buried 5x30 cm cylinders is approximately 2.25 times the vehicle altitude (6.75 meters for 3 meter vehicle altitude).

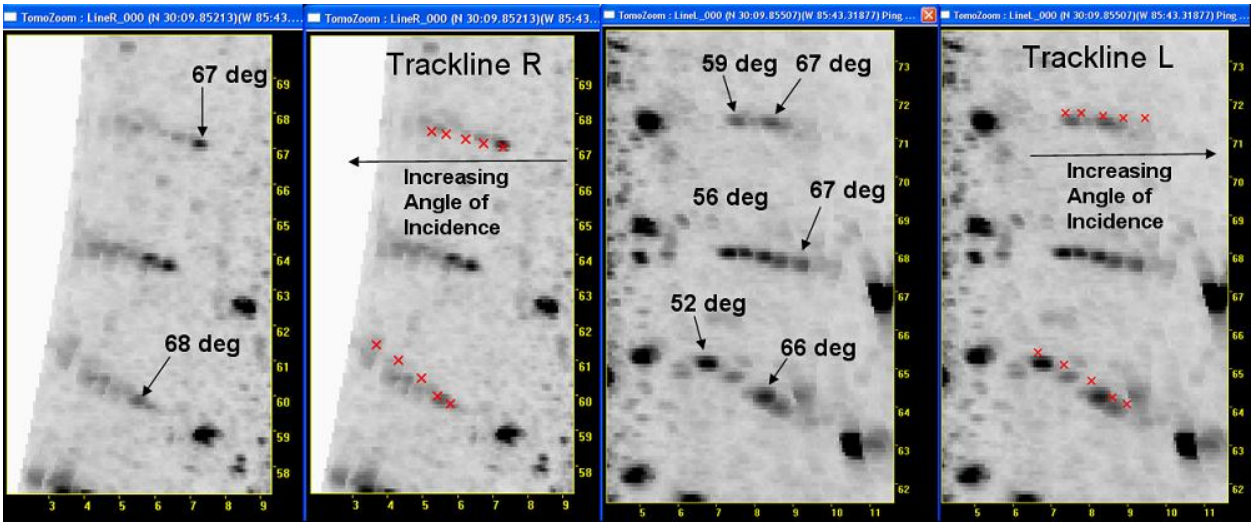


Figure 88 BOSS images of buried cylinders (top line – buried 5x30cm cylinders; second line – flush-buried 5x30 cm cylinders; third line – buried 10x30cm cylinders. These images show that the fully buried cylinders were not detectable at ranges beyond an angle of incidence of 66-67 degrees (a grazing angle of 23 to 24 degrees). A 24 degree grazing angle corresponds to a swath range of 4.5 times vehicle altitude. For example, for a vehicle altitude of 3 meters, the search swath is 13.5 meters.

High resolution imagery mode for determining target shape and orientation

Most imagery in this report used a 1m long synthetic aperture and a 3D pixel spacing of 10 cm (low resolution mode). To obtain the best possible resolution, the half-wavelength resolution, the synthetic aperture should subtend an angle of 40 degrees with respect to the target. Longer synthetic apertures, forming a subtended angle greater than 50 degrees, will improve resolution but at the expense of higher side lobe levels. For a 7.5 – 19.5 kHz FM pulse, the center frequency is 13.5 kHz. Therefore, half-wavelength along track resolution is 5.5 cm. The length of the synthetic aperture should be about 2/3 of the slant range to obtain an along track resolution of 5.5 cm. The temporal resolution of a pulse with 12 kHz of bandwidth is about 5 cm.

The images in Figure 89 through 92 were generated in the high resolution mode, e.g., with a pixel spacing of 5 cm and full length synthetic aperture. The processing time for the high resolution mode is about 24 times greater per unit volume of sediment than for the low resolution mode.

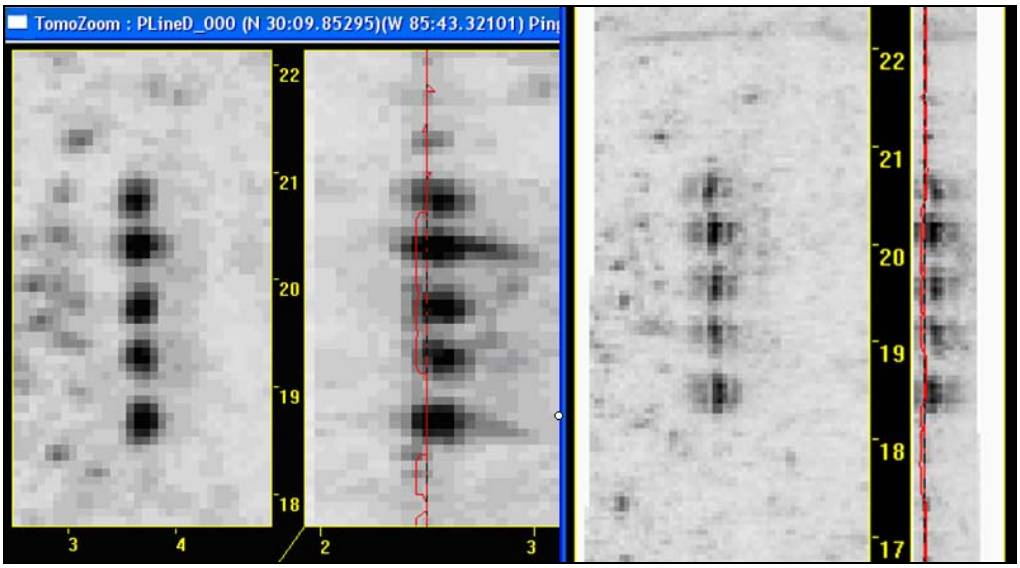


Figure 89 Comparison between low resolution (left) and high resolution (right) processing modes for line of buried 5x30cm targets. The images show the high resolution mode is required to show target length and orientation. Note there is a 2x vertical exaggeration of the seabed cross section in the low resolution image. The horizontal red line is the position of the seabed detected by the DVL.

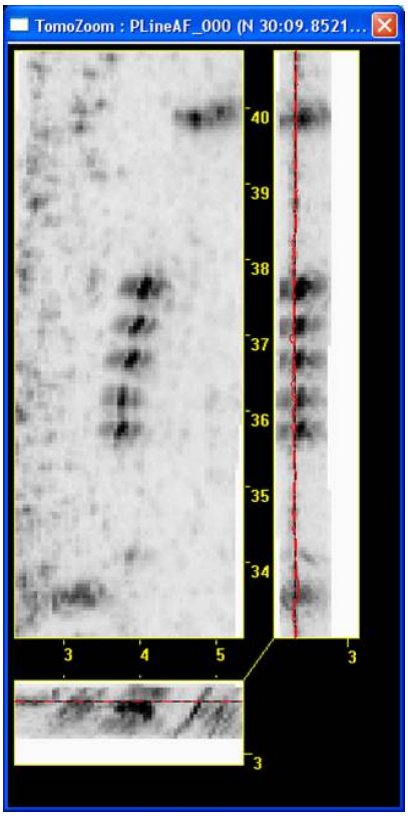


Figure 90 The high resolution 3D image of flush-buried 5x30 cm cylinders show small variations in the end-to-end orientation of the buried cylinders. The horizontal red line is the position of the seabed detected by the DVL.

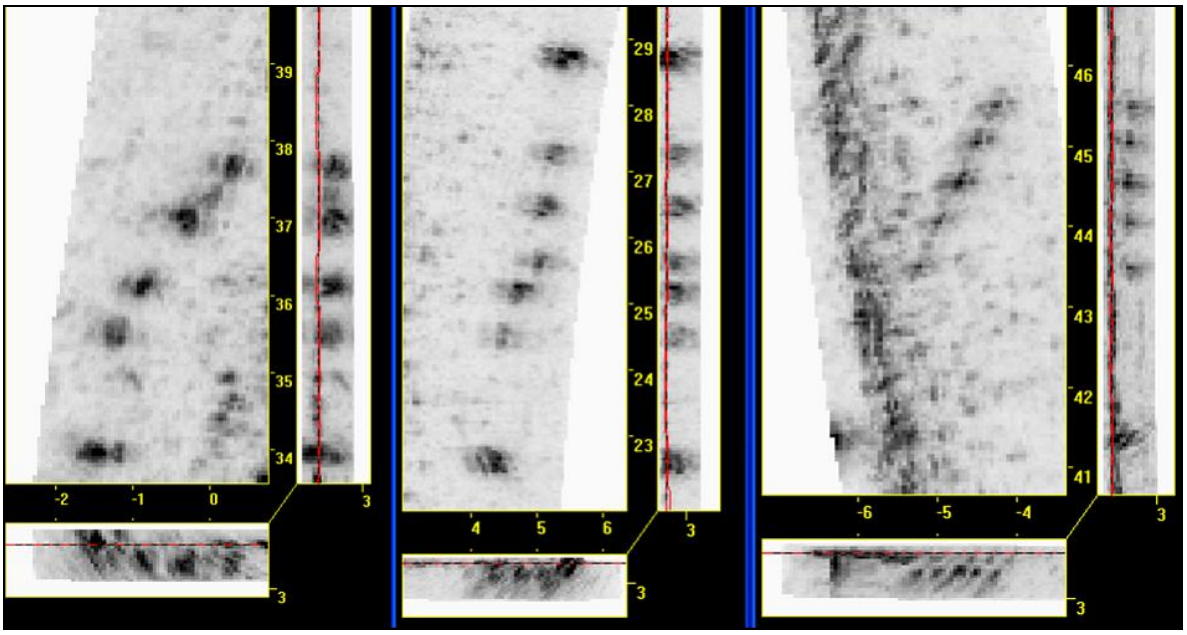


Figure 91 High resolution 3D images of buried 10x30 cm cylinders, flush-buried 10x30 cm cylinders and 4.2" mortars. It is difficult to determine orientation and target shape of many of the targets in the above images. This is due to using the conventional method of SAS processing where the aperture is only swept along the track. Adaptive mixed physical/synthetic aperture processing that resolves this problem is proposed in (1). Note that disturbed sediments may also be contributing to the distorted imagery.

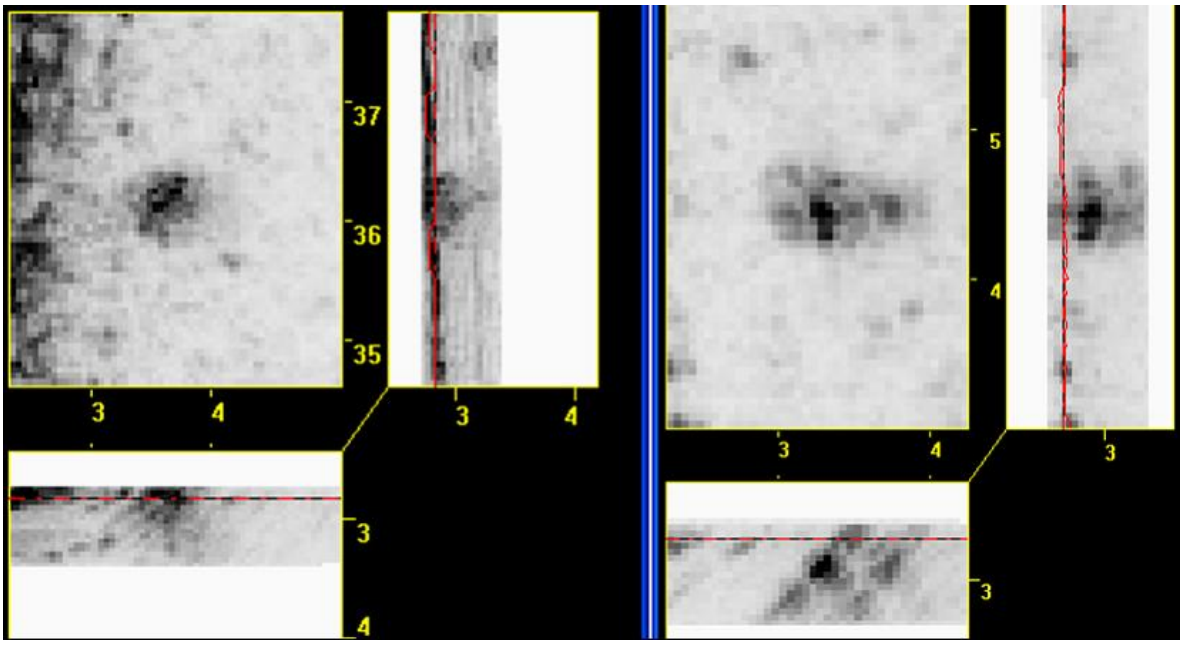


Figure 92 High resolution images of proud (left) and buried (right) clumps of 4.2" mortars. For this conventional method of synthetic aperture processing, the sonar acquires echoes off only one side of the target. Therefore the closer targets in a clump will obstruct the sonar from imaging target at greater ranges within the clump. The adaptive mixed physical/synthetic aperture processing and the distributed source sonar geometry proposed in (1), resolves this problem.

Detection of 2006 UXO Target Field

The 2006 UXO field, a field of 24 concrete-filled cylinders varying in diameter from 2 inches to 6 inches were buried in medium sand in September 2006 in the configuration shown in Figure 16 and in detail below in Figure 93. The cylinders were buried at two depths, flush-buried and buried 30 cm, and at three aspects, parallel, diagonal, and perpendicular to the long axis of the 100 m long field. A quick survey (3 tracklines for each line of targets) of the 2006 UXO field using BOSS with RTK GPS was conducted on 20 September 2008. This field was previously surveyed with BOSS-160 in October 2006. The results of that survey are described in Phase I results. During the 20 September 2008 survey of the 2006 UXO target field, all targets were detected in Line 1 (parallel target orientation) as shown in multi-aspect image in Figure 94. Multi-aspect images in Figures 95 and 96 show that all targets with the exception of the 2" cylinders were detected.

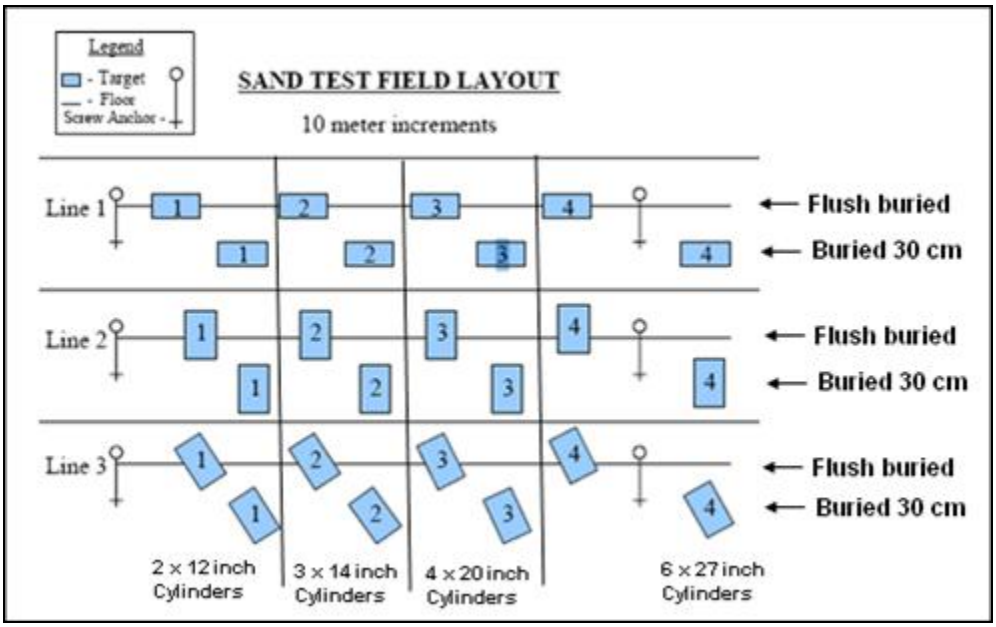


Figure 93 Layout of 2006 UXO target field in St. Andrews Bay. This field contains concrete-filled steel cylinders with dimensions and burial depths as indicated above.

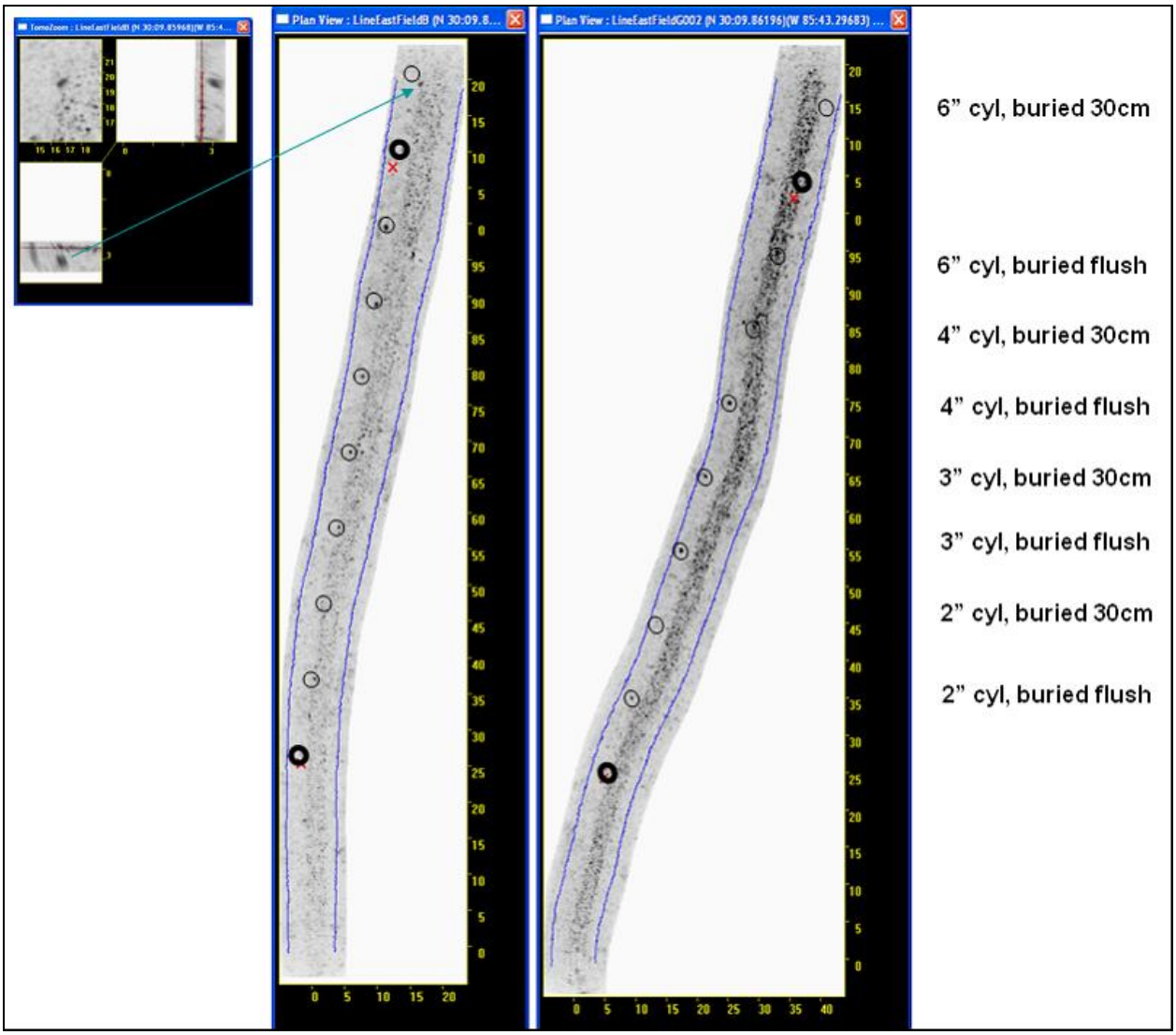


Figure 94 Results from the 20 September 2008 survey of the October 2006 UXO site, Line 1. With the exception of the 6 inch, 30 cm deep, cylinder, BOSS imagery showed that all cylinders buried along Line1 were at the expected locations (indicated by circles). The 6 inch diameter cylinder, buried 30 cm, was approximately 1 to 2 meters from the expected position. The 3D view of the 6 inch cylinder (top left) shows that the cylinder was buried about 30 cm.

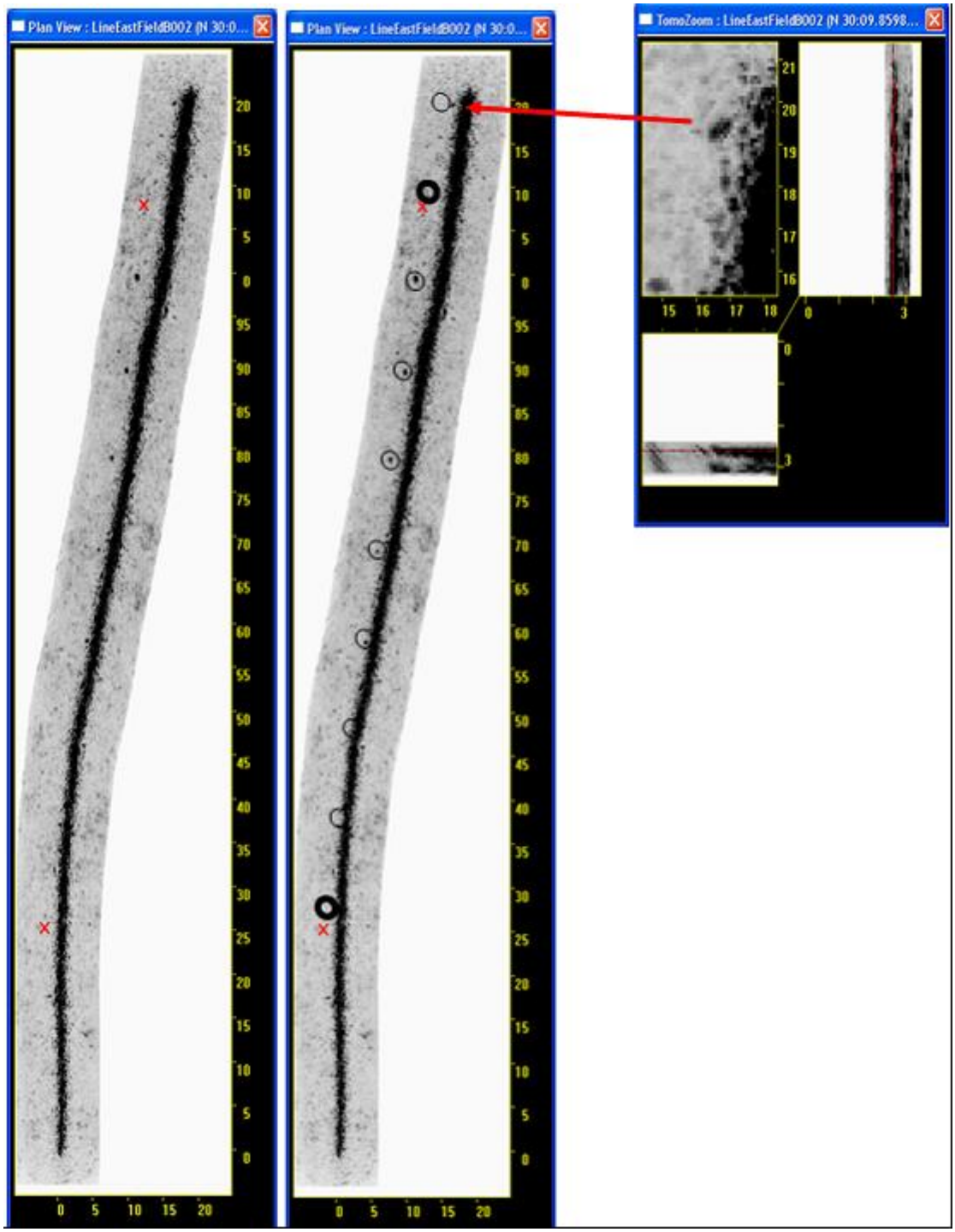


Figure 95 Results from the 20 September 2008 survey of the October 2006 UXO site, Line 2. The 6 inch diameter cylinder, buried 30 cm, was approximately 1 meter east of the planned burial position. The 3D view of the 6 inch cylinder (top left) shows that the cylinder was buried about 30 cm. The flush-buried and fully buried 2”cylinders were not detected due to specular scattering interference.

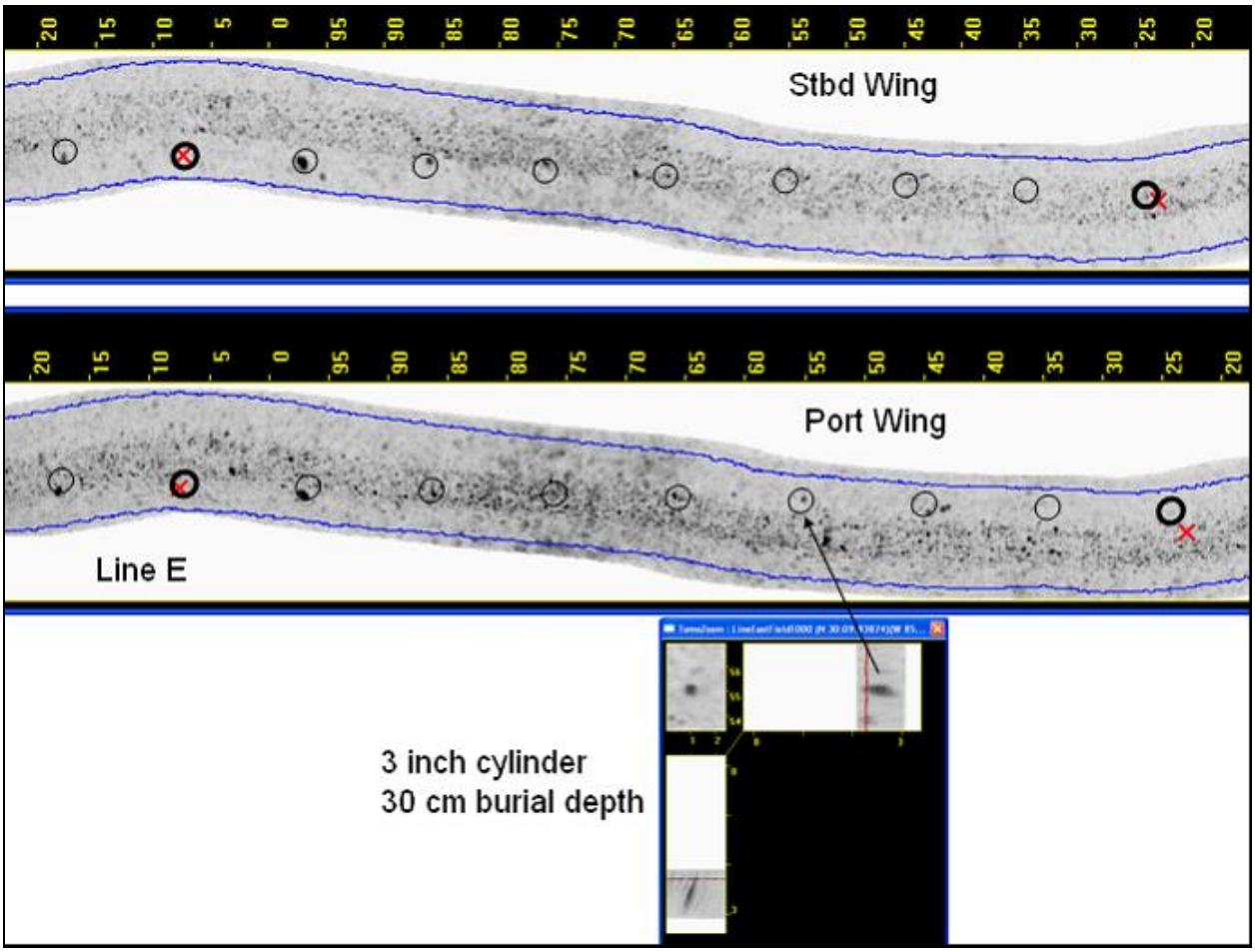


Figure 96 Results from the 20 September 2008 survey of the October 2006 UXO site, Line 3. With the exception of the 2 inch, 30 cm deep cylinder, BOSS imagery showed that all cylinders buried along Line1 were at the expected locations (indicated by circles). The buried 2 inch diameter cylinder was not detected due to the targets end aspect.

MSDB Phase II Test Conclusions

The results of the MSDB Phase II UXO surveys are summarized as:

- BOSS imagery provided the positions of UXO with an error of about 1 foot rms. The position accuracy of BOSS derived positions could not be measured because of the variability of the ground truth.

- BOSS-160 detected all UXO in the 2008 target field and all 3, 4 and 6 inch cylinders in the 2006 UXO target field.

- BOSS-160 measured the burial depth of all targets in the 2006 UXO field.

- BOSS-160 has temporal and azimuthal resolutions of about 5 cm in the high resolution mode.
- BOSS-160 used the high resolution processing mode to measure the burial orientation of cylinders.

The data in this report and in ref. 12 show that imagery of relatively smaller UXO targets do not have sufficient detail for target identification. The multi-aspect imaging procedures used by BOSS-160 cause image distortion for some target aspects that prevent accurate measurement of target shape. Using BOSS-160 for UXO imaging is inefficient because several sonar runs are needed to capture the information needed to analyze a single line of targets. In order to produce a usable UXO image, BOSS-160 needs to pass a target such that the target has a broadside target aspect and has a range window between the critical angle and the region of near nadir specular scattering interference. The conventional SAS method of sweeping the synthetic aperture along track frequently does not allow specular illumination of the UXO targets at aspects that generate echo levels with adequate SNR for imaging. Specular echoes from the sediment-water interface also prevent detections of targets with grazing angles greater 65 degrees. Reference 12 proposes hardware and signal processing techniques for generating high resolution imagery of buried UXO that allow measurement of the dimensions and shape of buried or proud UXO. The proposed design uses 1) increased system bandwidth, 2) a new adaptive mixed physical/synthetic aperture processing technique, and 3) distributed sources along the wings. The design allows the sonar to produce an all-aspect target image with a 2 to 3 cm resolution, thereby capturing the shape information of the target. This is done using a focusing technique that processes data from a single run to produce a mixed adaptive physical/synthetic aperture that essentially moves around each target that passes between the tips of the vehicle wings. Sources distributed along the wing provide the all-aspect illumination needed for the all-aspect adaptive mixed physical/synthetic aperture processing that generates an all aspect high resolution image of each target thereby providing target shape.

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(1) "Mobile Underwater Debris Survey System (MUDSS) Final Report", SERDP Project MM-52, March 2000

(2) Validation of Detection Systems Final Report – Mare Island Naval Shipyard, Vallejo, California, Environmental Chemical Corporation, Burlingame, CA, Contract No. N62742-98-D-1809, CTO 0001, November 24, 1999 prepared for Commander, Pacific Division, Naval Facilities Engineering Command, Pearl Harbor, HI

(3) "Marine Towed Array Technology Demonstration at the Former Naval Duck Target Facility," ESTCP Project MM-2003-24 Interim Report, AETC, Inc., November 2005

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(5) D.D. Sternlicht, D.W. Lemonds. R.D. Dikeman, and S.G. Schock, "Detection and Classification of Buried Objects with an Adaptive Acoustic Mine-hunting System," MTS/IEEE Oceans 2001, pp. 212-219, Nov 2001

(6) S.G. Schock and J. Wulf, "Sonar for Multi-Aspect Buried Mine Imaging," MTS/IEEE Oceans 2002, pp. 479-484.

(7) G.I. Allen et al., "Initial Evaluation and Follow On Investigation of the Quantum Magnetics Laboratory Prototype, Room Temperature Gradiometer for Ordnance Location," in *Information Systems for Navy Divers and Autonomous Underwater Vehicles Operating in Very Shallow water and Surf Zone Regions,* J.L. Woods (ed.), the International Society for Optical Engineering, Vol. 3711, pp. 103-112, April 1999.

(8) I.J. Won, D.A. Keiswetter, and E. Novikova, 1998, Electromagnetic Induction Spectroscopy, *Jour. Environmental and Engineering Geophysics,* Vol. 3, Issue 1, pp. 27-40.

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(10) S.G.Schock, "A Method of Estimating the Physical and Acoustic Properties of the Sea Bed Using Chirp Sonar Data," IEEE Journal of Ocean Engineering, Vol. 29, No.4, October 2004, pp 1200-1217.

(11) S.G.Schock, "Synthetic Aperture 3D Buried Object Imaging, , Int. J. Soc Underwater Tech., 27(4), pp. 185-193, 2004

(12) S.G. Schock, "Synthetic Aperture 3D Buried Object Imaging," Int. J Soc Underwater Tech., 27(4), pp.185-193, 2008

A Appendix A

Table A-1 MSDB Search Tracks at Sand Site, October 18, 2006

Multi-Sensor DataBase						
Test Location: St. Andrews Bay Sand Site						
Date	**Run**	**Vehicle Tested**	**Test Line**	**Time**	**Heading (°)**	**Speed (knots)**
10/18/2006	Line1A	BOSS, RTG	1	1228 - 1230	170	2.7
10/18/2006	Line3B	BOSS, RTG	3	1234 - 1236	334	1.7
10/18/2006	Line1B	BOSS, RTG	1	1240 - 1242	170	2.7
10/18/2006	Line3C	BOSS, RTG	3	1248 - 1250	334	1.7
10/18/2006	Line1C	BOSS, RTG	1	1254 - 1256	165	2.7
10/18/2006	Line2	BOSS, RTG	2	1419 - 1421	330	1.7
10/18/2006	Line 2A	BOSS, RTG	2	1426 - 1428	190	2.7
10/18/2006	Line 2B	BOSS, RTG	2	1433 - 1435	320	1.7
10/18/2006	GEMLine3	BOSS, RTG, GEM	3	1541 - 1543	325	2.0
10/18/2006	GEMLine1	BOSS, RTG, GEM	1	1552 - 1554	170	2.0
10/18/2006	GEMLine1A	BOSS, RTG, GEM	1	1602 - 1604	330	2.0
10/18/2006	GEMLine3A	BOSS, RTG, GEM	3	1608 - 1610	180	2.0
10/18/2006	GEMLine1B	BOSS, RTG, GEM	1	1616 - 1618	330	2.0

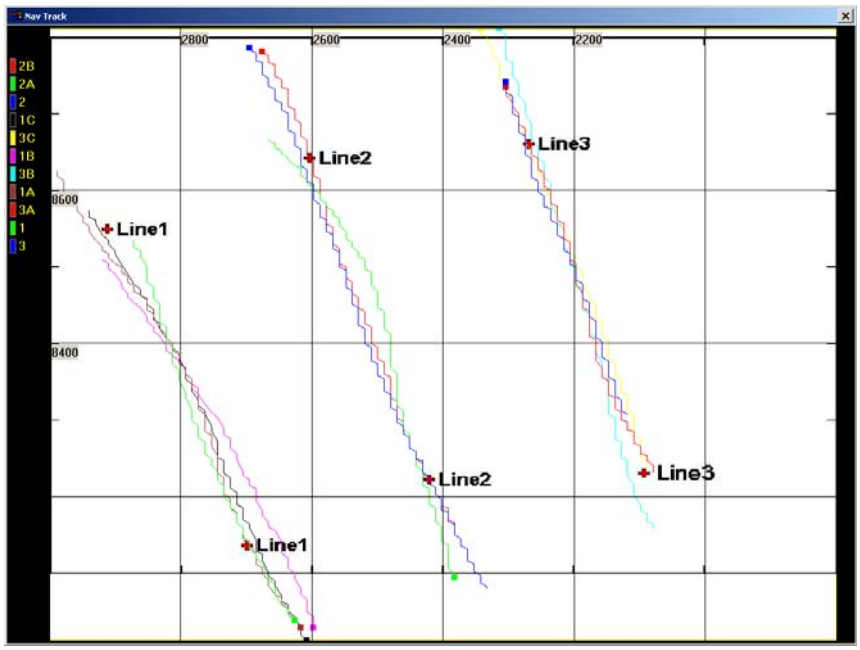


Figure A - 1. Tracklines for BOSS-160/RTG data collection at the sand site on 18 October 2006 with the BOSS at a towing depth of 3 feet.

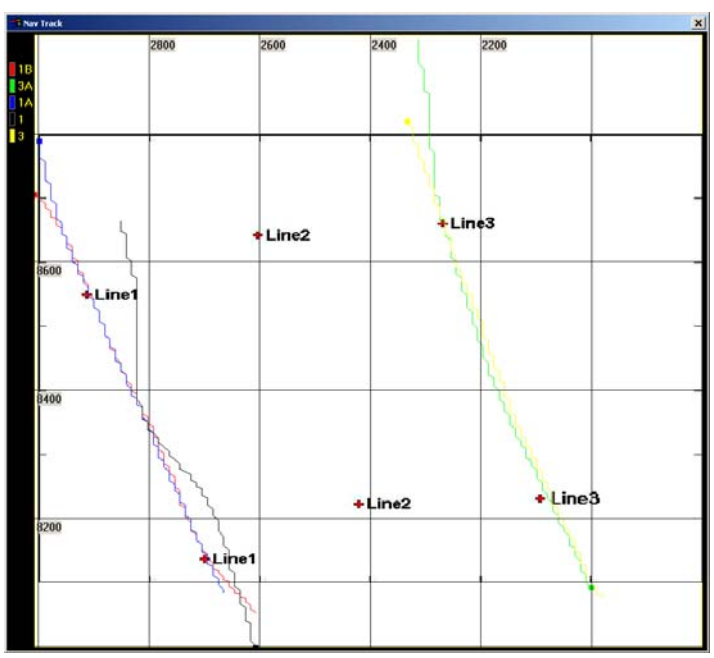


Figure A - 2. Tracklines for simultaneous BOSS-160/RTG and GEM3 data collection at the sand site on 18 October 2006 with the BOSS at a towing depth of 6.2 feet

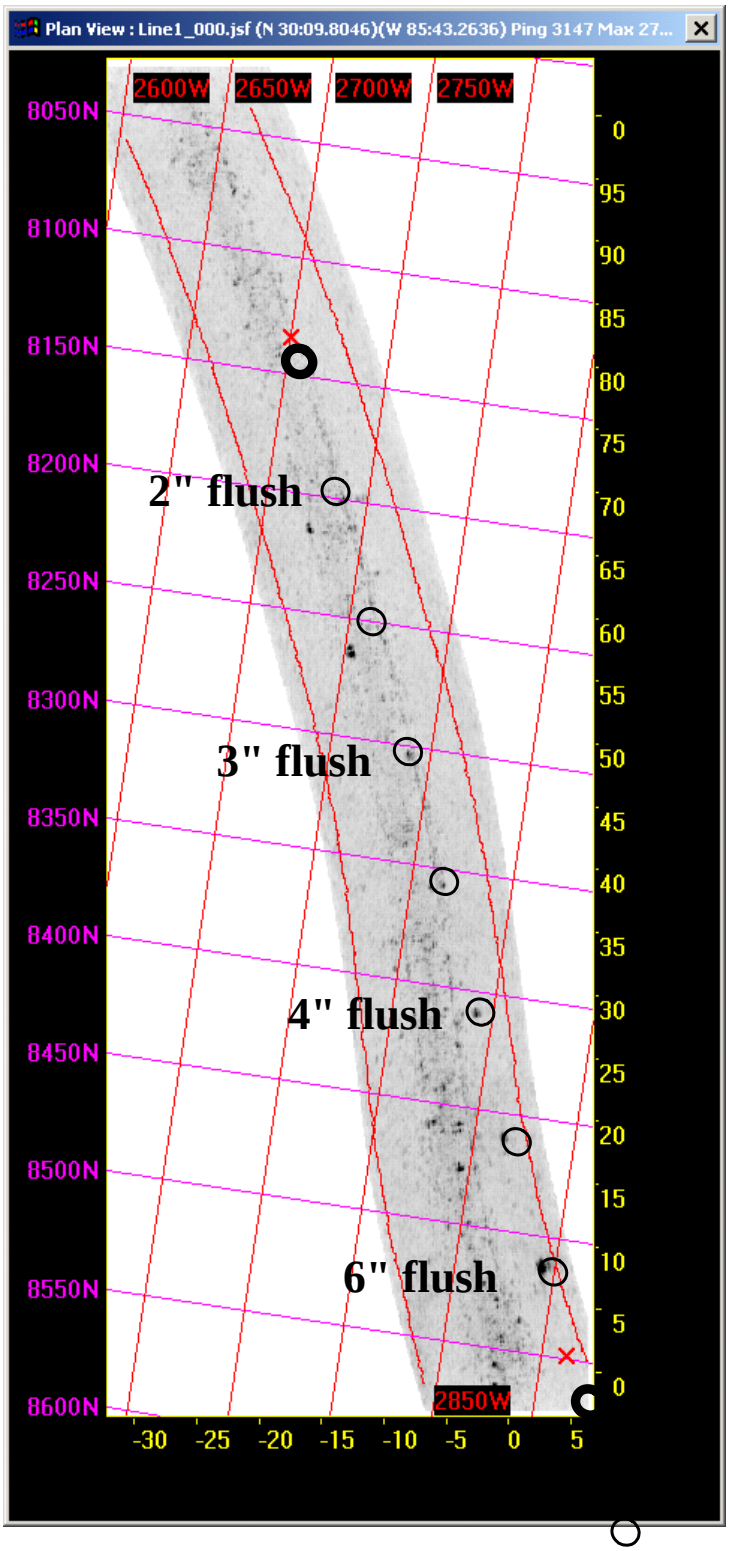


Figure A - 3. Multi-aspect image of trackline Line1 collected on 18 October 2006 at sand site with target overlay

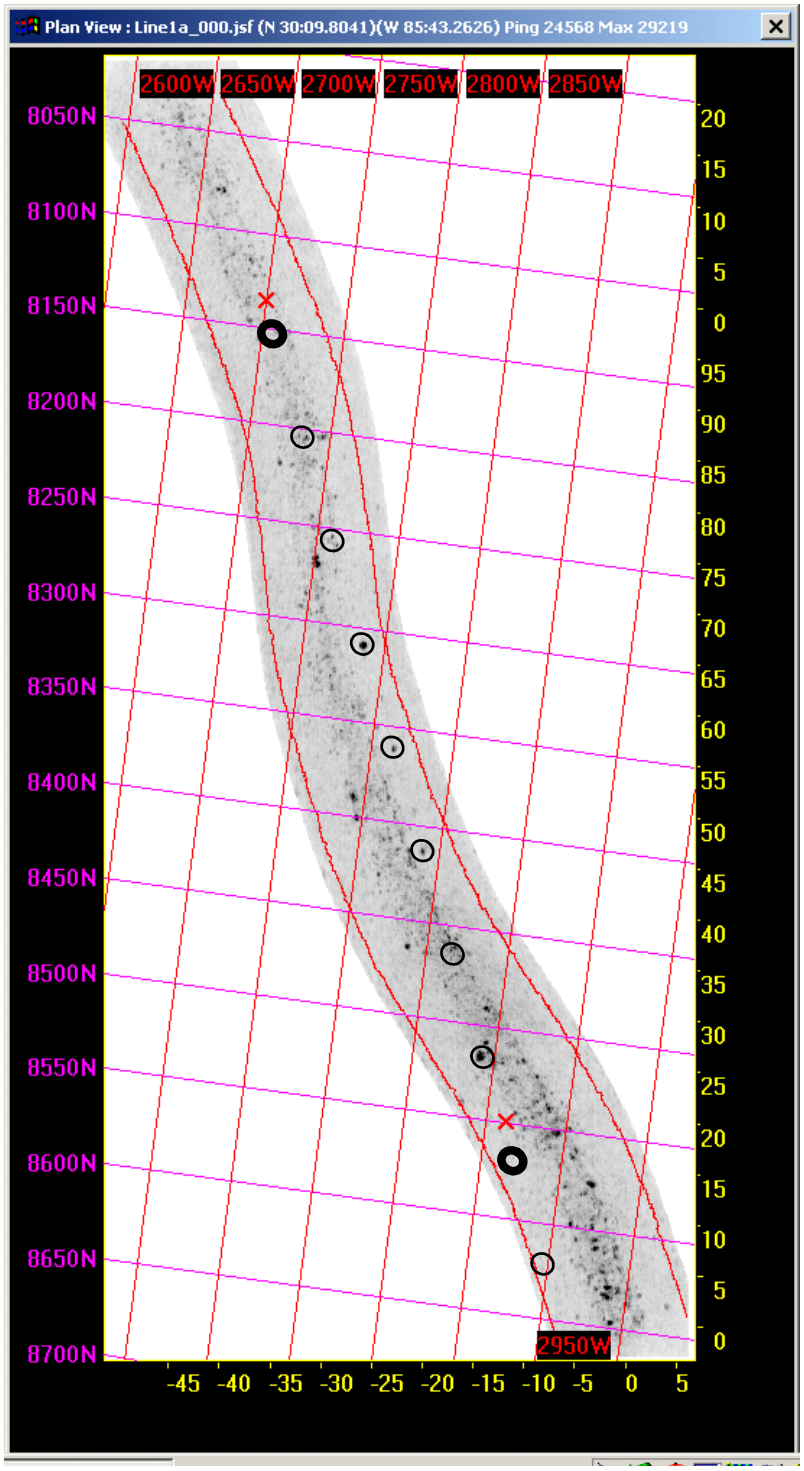


Figure A - 4. Multi-aspect image of trackline Line1a collected on 18 October 2006 at sand site with target overlay

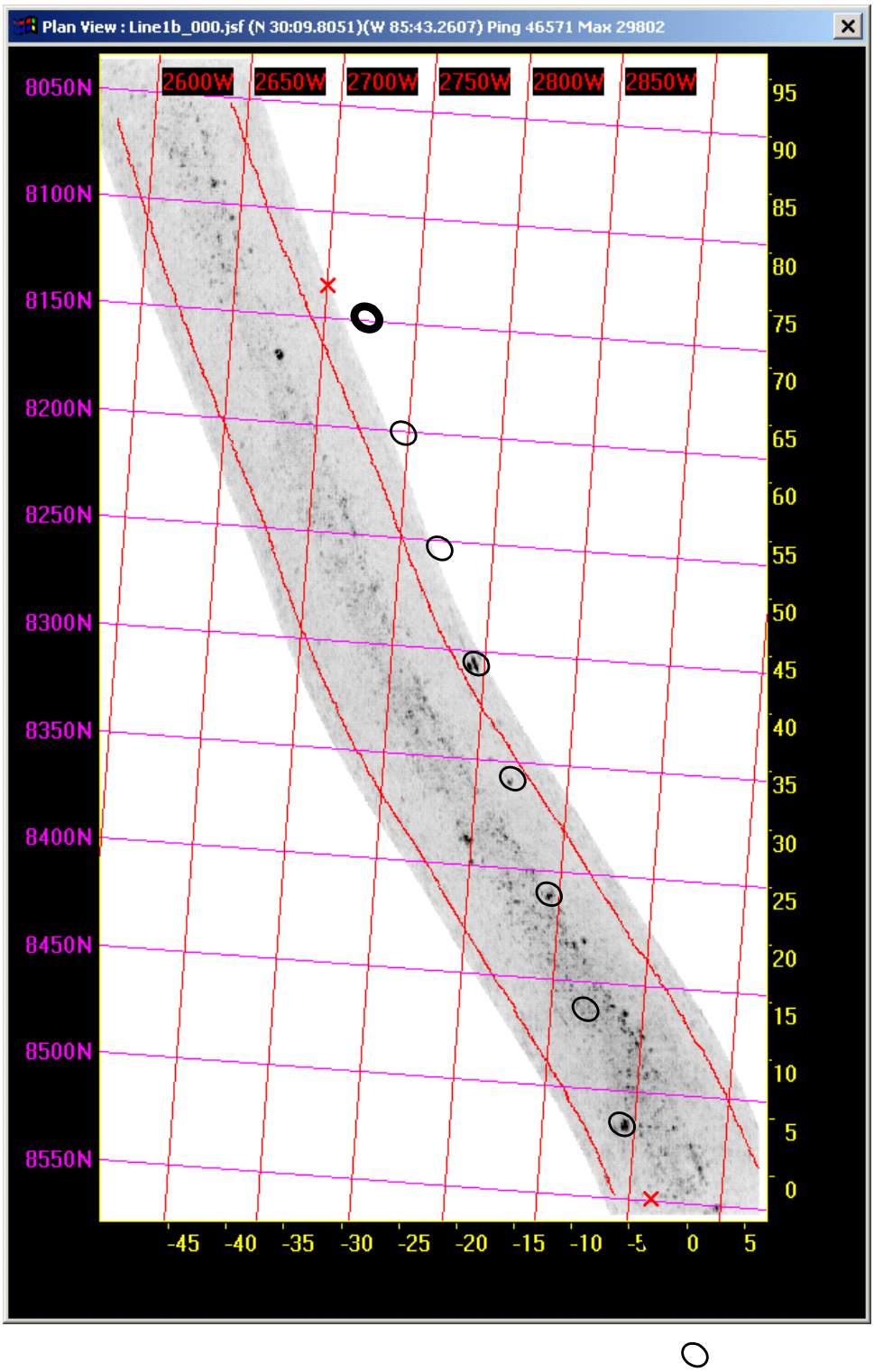


Figure A - 5. Multi-aspect image of trackline Line1b collected on 18 October 2006 at sand site with target overlay

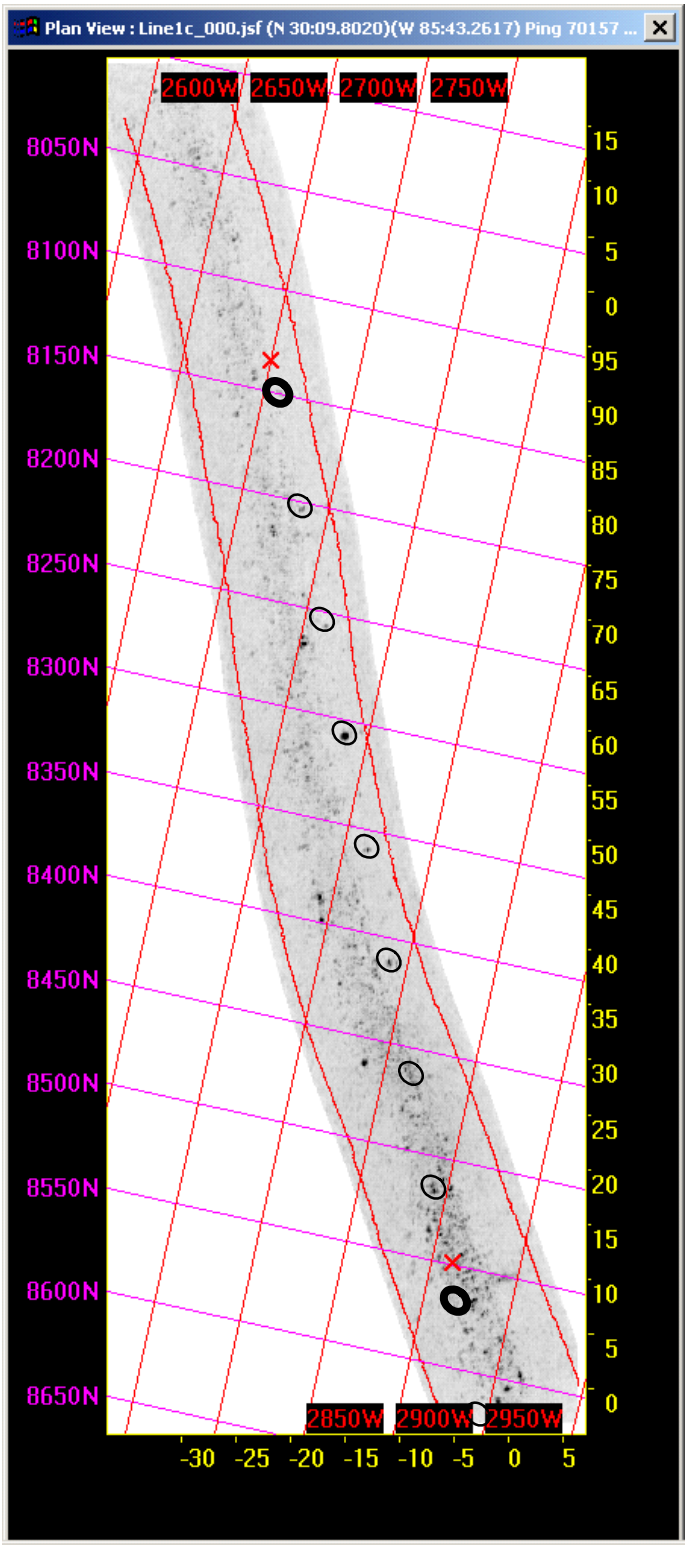


Figure A - 6. Multi-aspect image of trackline Line1c collected on 18 October 2006 at sand site with target overlay

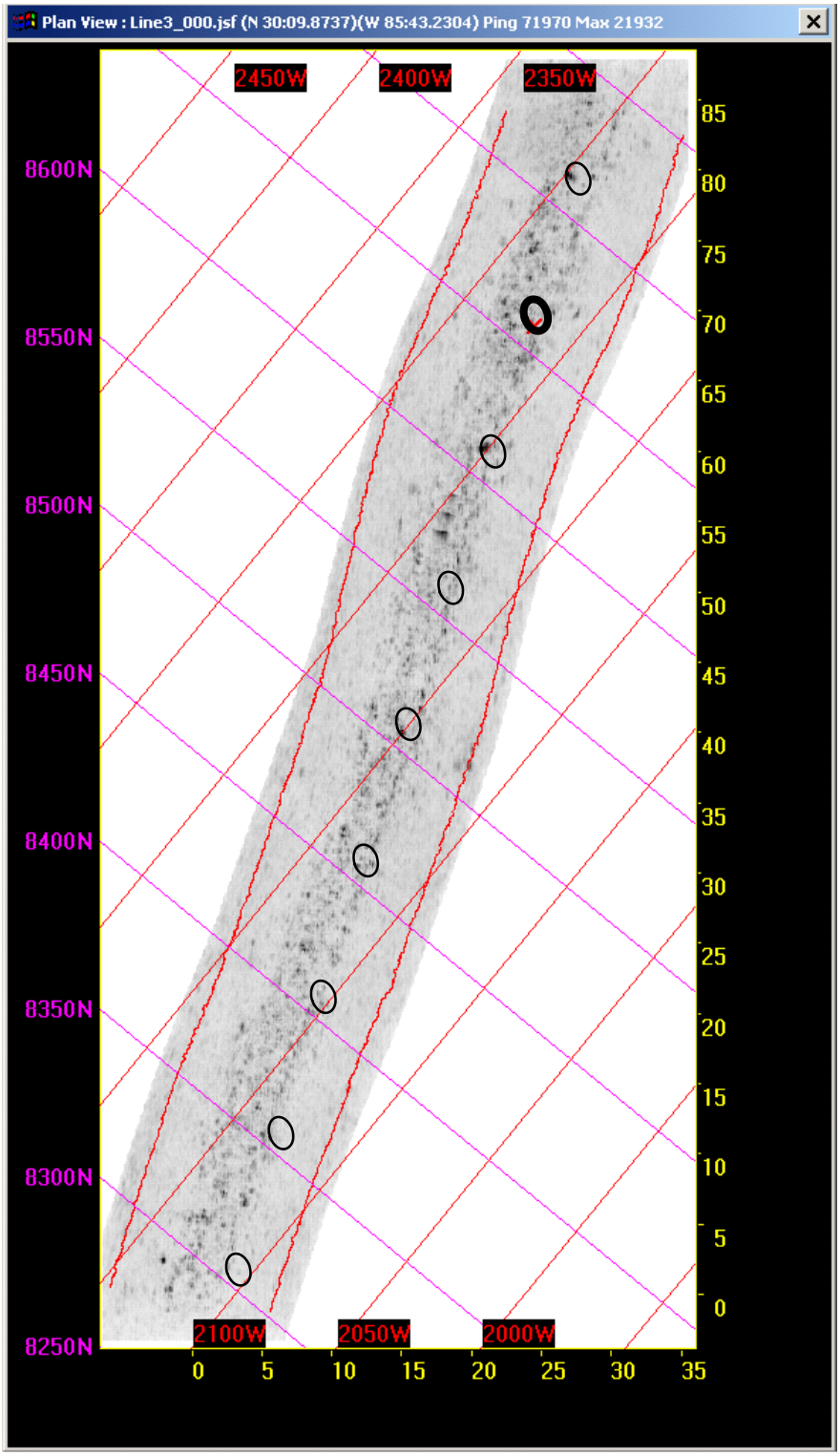


Figure A - 7. Multi-aspect image of trackline Line3 collected on 18 October 2006 at sand site with target overlay

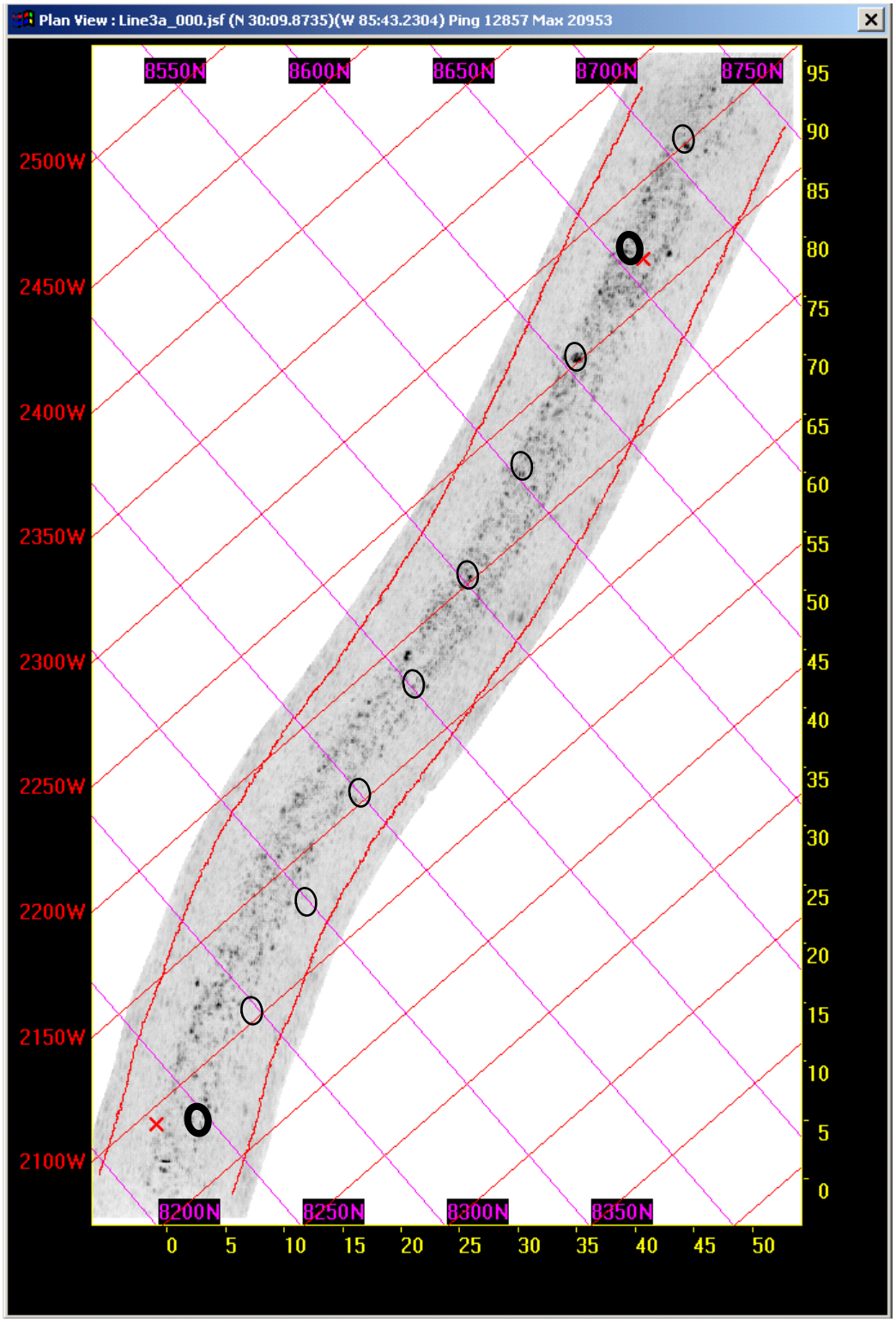


Figure A - 8. Multi-aspect image of trackline Line3a collected on 18 October 2006 at sand site with target overlay

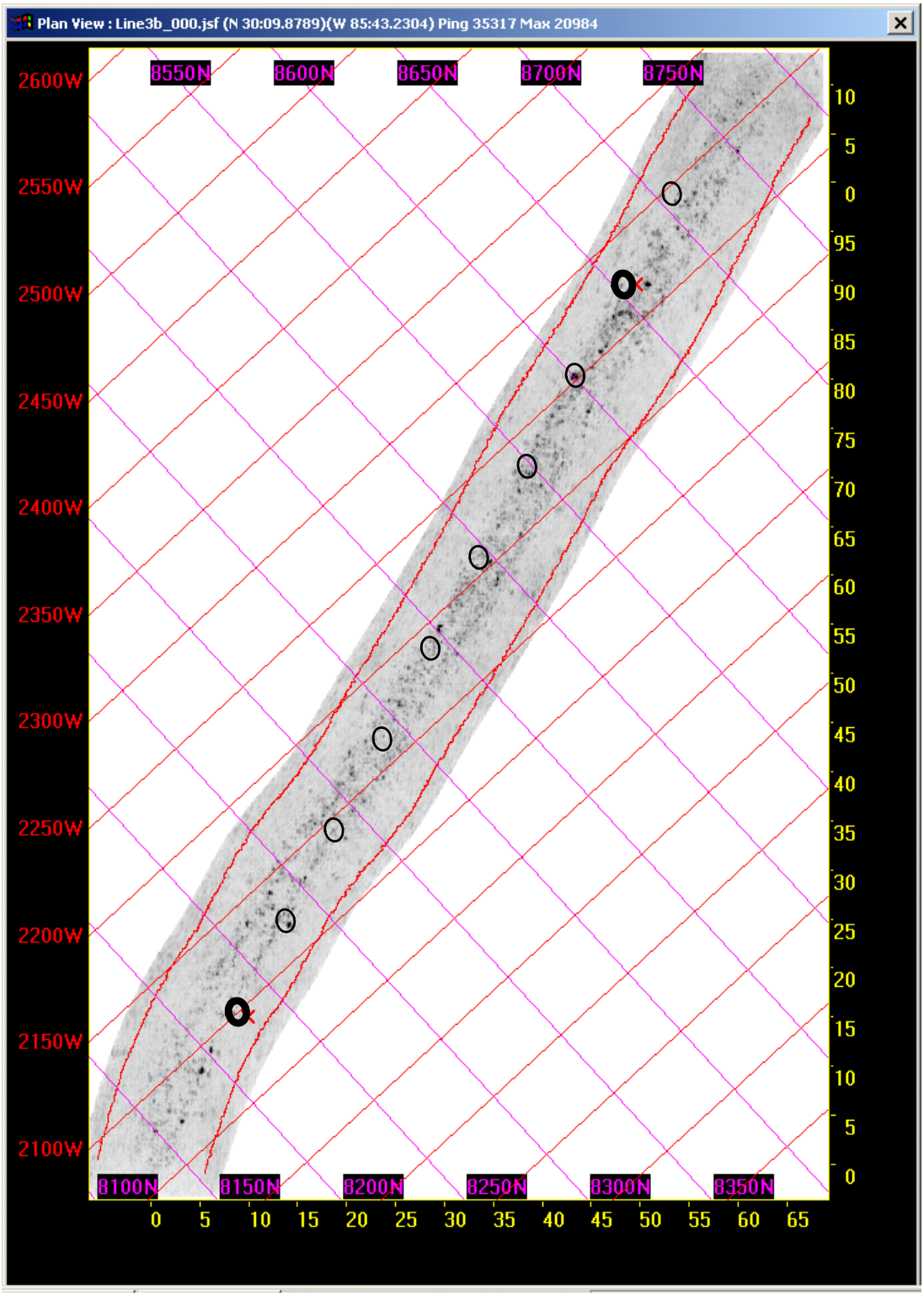


Figure A - 9. Multi-aspect image of trackline Line3b collected on 18 October 2006 at sand site with target overlay

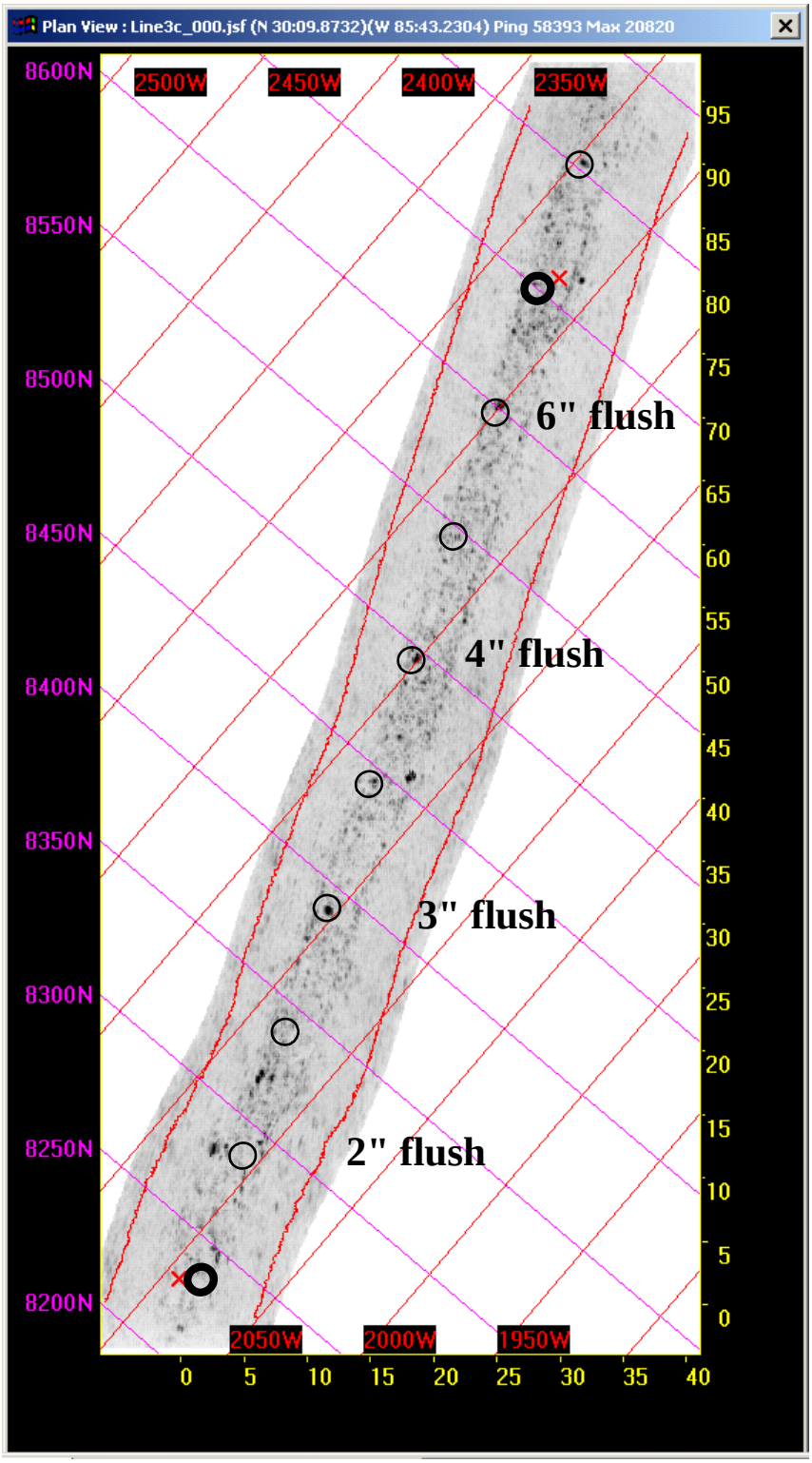


Figure A - 10. Multi-aspect image of trackline Line3c collected on 18 October 2006 at sand site with target overlay

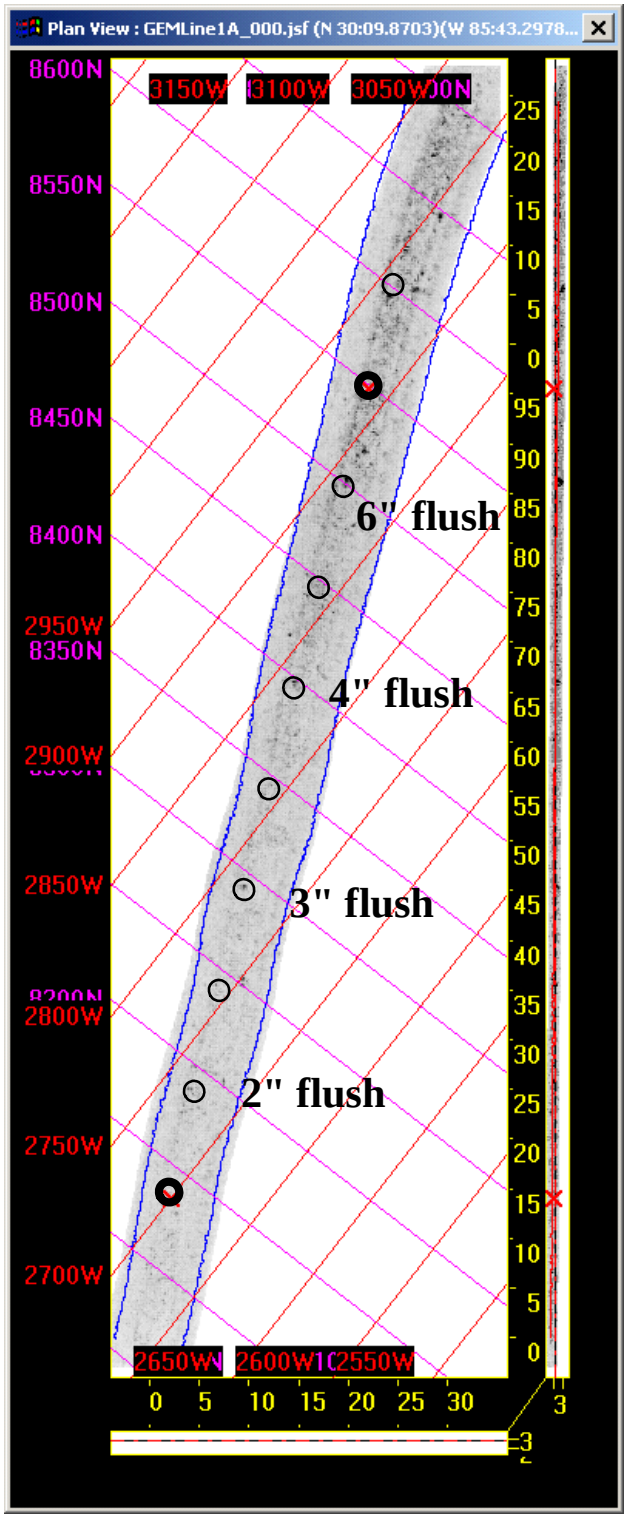


Figure A - 11. Multi-aspect image of trackline GEMLine1A collected on 18 October 2006 at sand site with target overlay

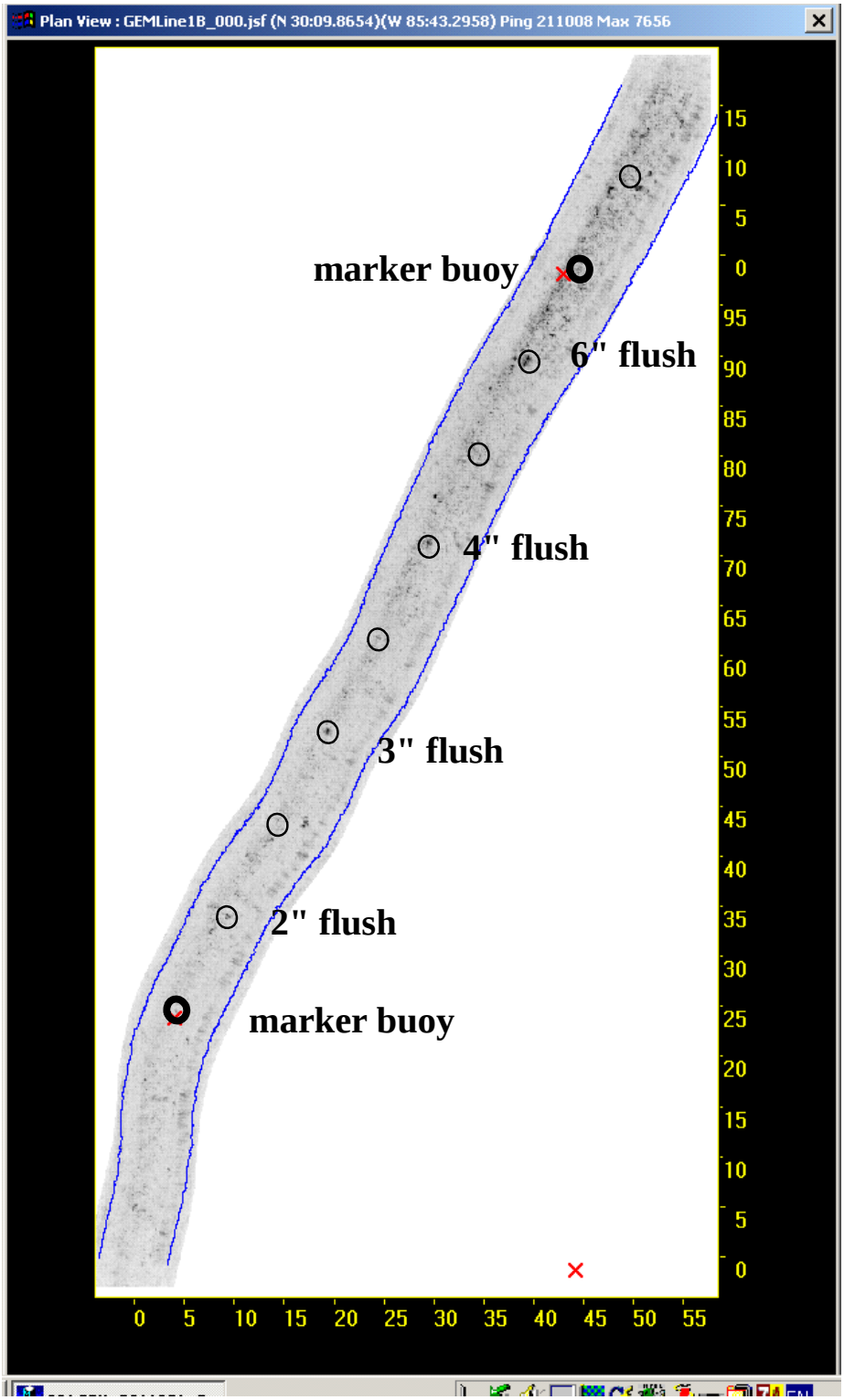


Figure A - 12. Multi-aspect image of trackline GEMLine1b collected on 18 October 2006 at sand site with target overlay

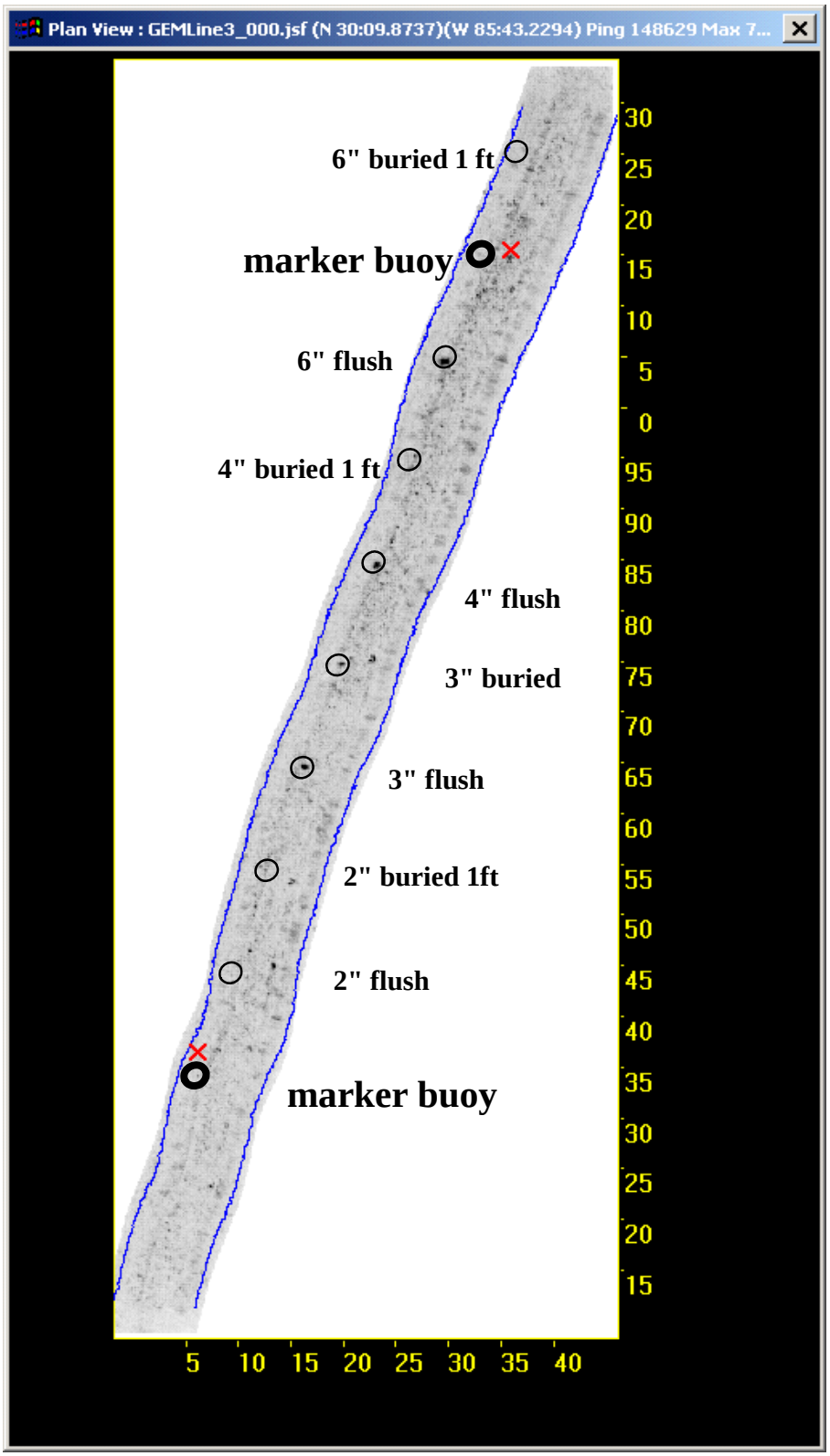


Figure A - 13. Multi-aspect image of trackline GEMLine3 collected on 18 October 2006 at sand site with target overlay

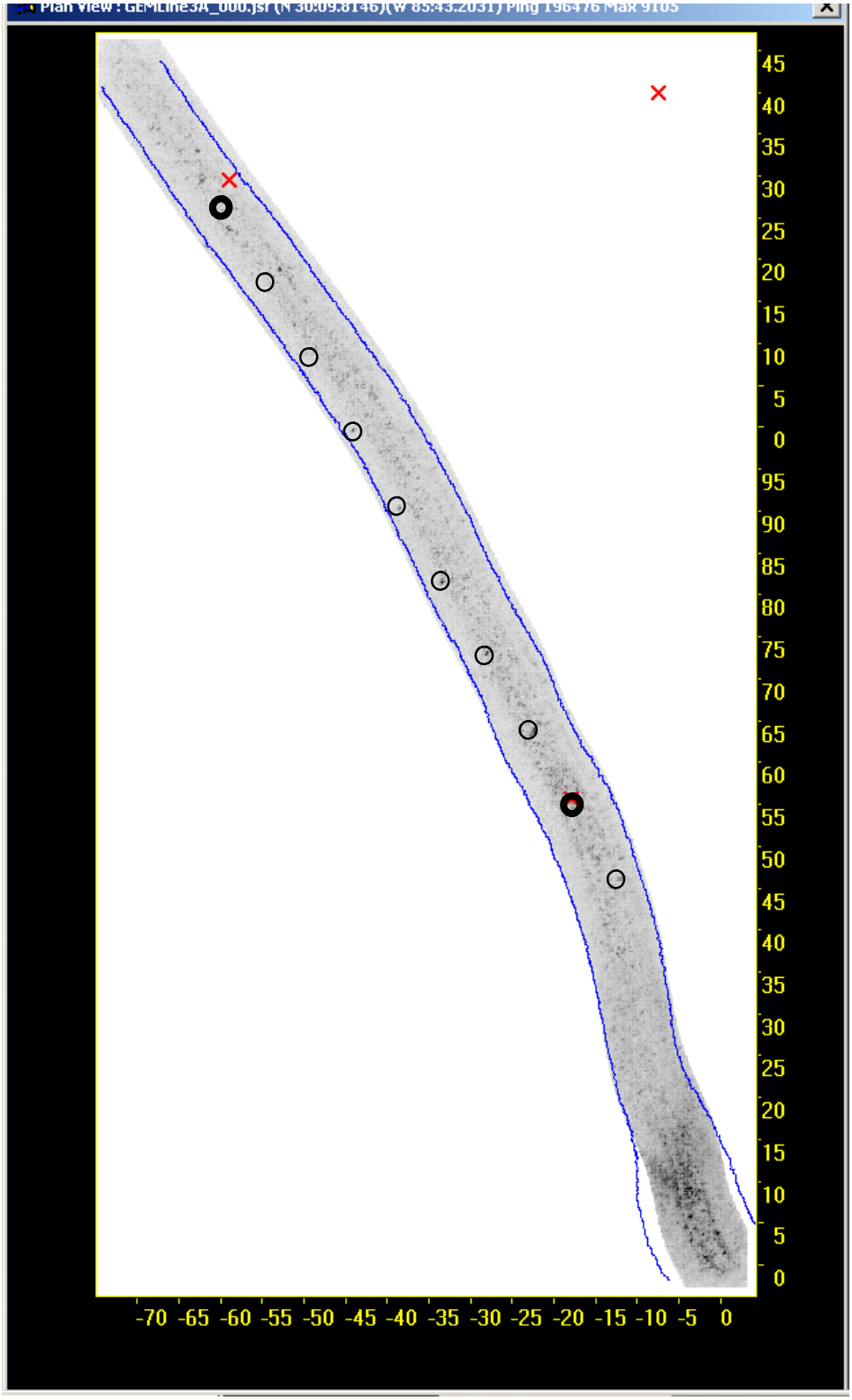


Figure A - 14. Multi-aspect image of trackline GEMLine3a collected on 18 October 2006 at sand site with target overlay

B Appendix B

Table B - 1. MSDB Search Tracks at Sand Site, October 19, 2006

Multi-Sensor Database						
Test Location: St. Andrews Bay Sand Site						
Date	**Run**	**Vehicle Tested**	**Test Line**	**Time**	**Heading (°)**	**Speed (knots)**
10/19/2006	Line1	BOSS, RTG, GEM	1	1155 - 1159	335	1.5
10/19/2006	Line3	BOSS, RTG, GEM	3	1203 - 1207	180	1.5
10/19/2006	Line3	BOSS, RTG, GEM	3	1213 - 1217	310	1.5
10/19/2006	Line1	BOSS, RTG, GEM	1	1220 - 1223	185	1.5
10/19/2006	Line31	BOSS, RTG, GEM	3	1226 - 1229	320	1.5
10/19/2006	Line11	BOSS, RTG, GEM	1	1232 - 1235	170	1.5
10/19/2006	Line11	BOSS, RTG, GEM	1	1239 - 1241	330	1.5
10/19/2006	Line31	BOSS, RTG, GEM	3	1248 - 1250	185	1.5
10/19/2006	Line14	BOSS, RTG, GEM	1	1256 - 2159	330	1.5
10/19/2006	Line34	BOSS, RTG, GEM	3	1304 -1307	185	1.5
10/19/2006	Line34	BOSS, RTG, GEM	3	1314 - 1317	320	1.5
10/19/2006	Line14	BOSS, RTG, GEM	1	1321 - 1323	165	1.5
10/19/2006	Line32	BOSS, RTG, GEM	3	1329 - 1331	320	1.5
10/19/2006	Line12	BOSS, RTG, GEM	1	1335 - 1338	185	1.5
10/19/2006	Line12	BOSS, RTG, GEM	1	1344 - 1347	315	1.5
10/19/2006	Line32	BOSS, RTG, GEM	3	1352 - 1354	185	1.5
10/19/2006	Line13	BOSS, RTG, GEM	1	1358 - 1402	315	1.5
10/19/2006	Line33	BOSS, RTG, GEM	3	1407 - 1410	187	1.5
10/19/2006	Line33	BOSS, RTG, GEM	3	1415 - 1418	320	1.5
10/19/2006	Line11	BOSS, RTG, GEM	1	1420 - 1423	185	1.5
10/19/2006	Line1A	BOSS, RTG, GEM	1	1428 - 1430	325	1.5
10/19/2006	Line3B	BOSS, RTG, GEM	3	1435 - 1437	200	1.5
10/19/2006	Line3B	BOSS, RTG, GEM	3	1443 - 1445	325	1.5
10/19/2006	Line1A	BOSS, RTG, GEM	1	1449 - 1451	185	1.5
10/19/2006	GEM3SN	BOSS, RTG, GEM	3	1502 - 1504	310	1.5
10/19/2006	GEM1NS	BOSS, RTG, GEM	1	1507 - 1511	185	1.5
10/19/2006	GEM1SN	BOSS, RTG, GEM	1	1518 - 1521	324	1.5
10/19/2006	Gem3NS	BOSS, RTG, GEM	3	1527 - 1530	N/A	1.5
10/19/2006	GEM1BSN	BOSS, RTG, GEM	1	1535 - 1539	N/A	1.5
10/19/2006	Line2NS	BOSS, RTG	2	1627 - 1630	180	2.0
10/19/2006	Line21	BOSS, RTG	2	1641 - 1642	327	2.0
10/19/2006	Line24	BOSS, RTG	2	1647 - 1650	175	2.0
10/19/2006	Line22	BOSS, RTG	2	1700 - 1702	345	2.0
10/19/2006	Line2NS	BOSS, RTG	2	1706 - 1708	165	2.0
10/19/2006	Line23	BOSS, RTG	2	1713 - 1714	345	2.0

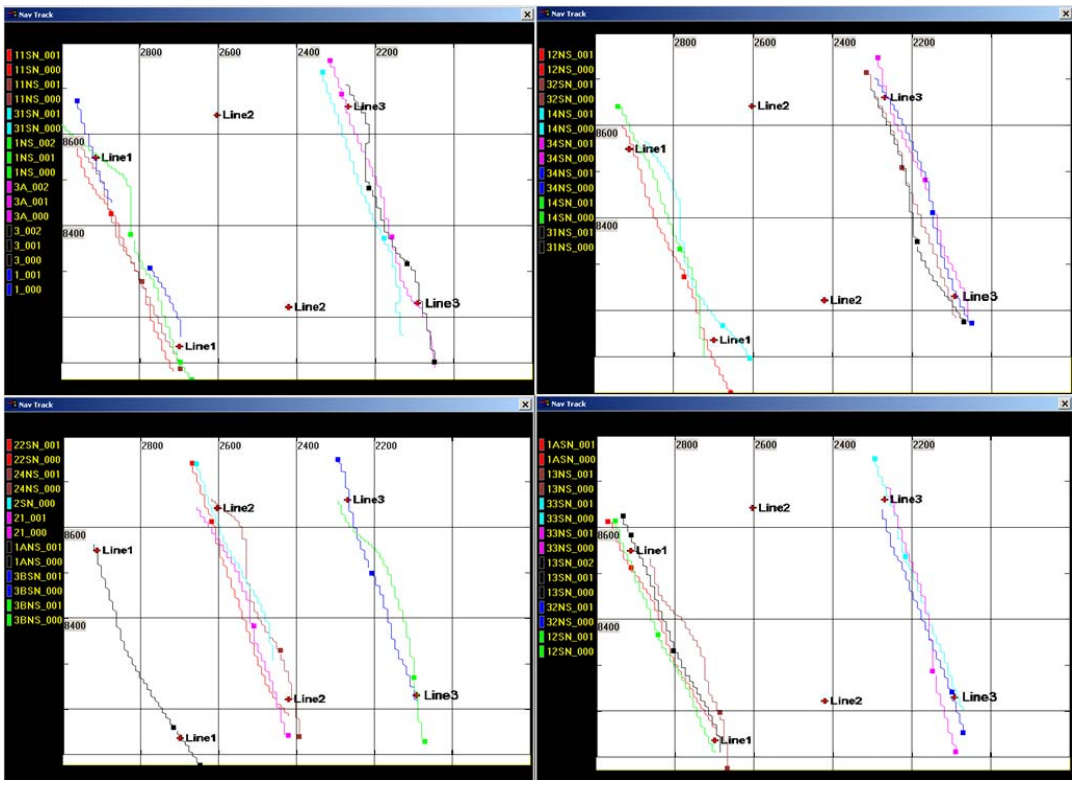


Figure B - 1. Tracklines for simultaneous BOSS-160/RTG data collection at the sand site on 19 October 2006 with the BOSS at a towing depth of 6.2 feet. The planned tracklines were at 2 and 4 meter offsets to the centerline.

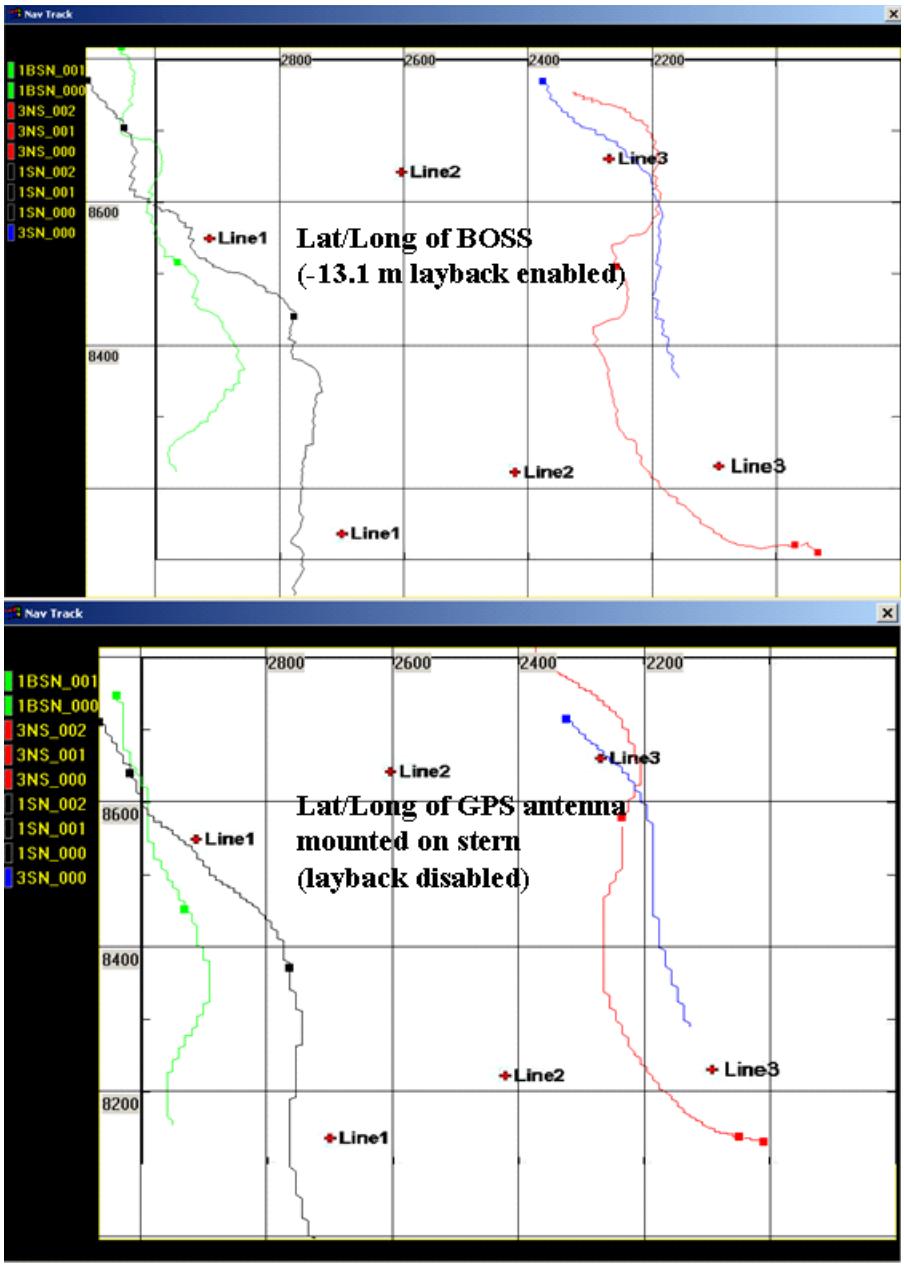


Figure B - 2. Tracklines for simultaneous BOSS-160/RTG data and GEM3 data collection at the sand site on 19 October 2006 with the BOSS at a towing depth of 6.2 feet. The GPS antennae was moved to the rear of the catamaran (13.1 meters aft of BOSS-160) for these tracklines in order to minimize the offset of the aft mounted GEM3 sled as the boat captain maneuvered the catamaran to stay on track. The upper plot provides the trackline of the sonar based on the layback and GPS generated course over ground. The low plot is the trackline for the stern of the catamaran.

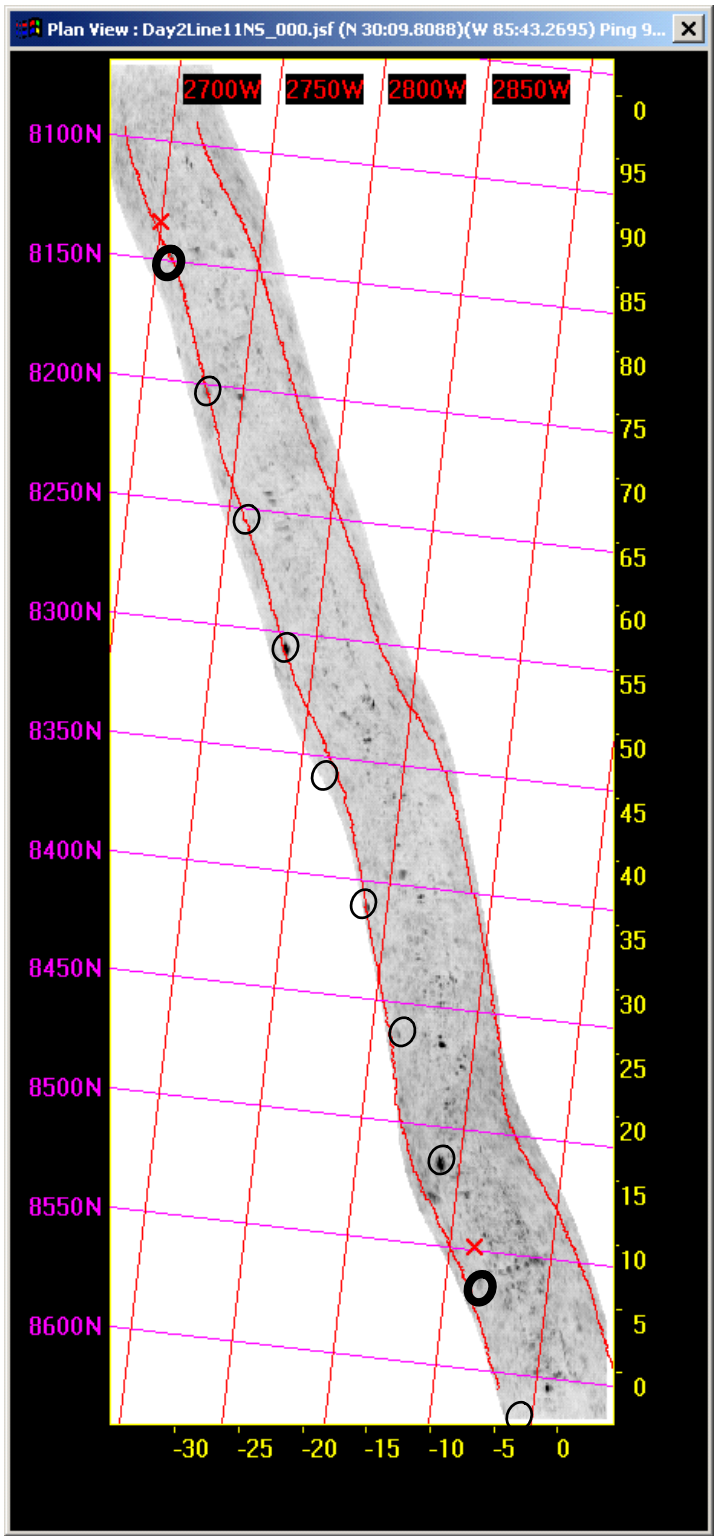


Figure B - 3. Multi-aspect image of trackline Day2Line11NS collected on 19 October 2006 at sand site with target overlay

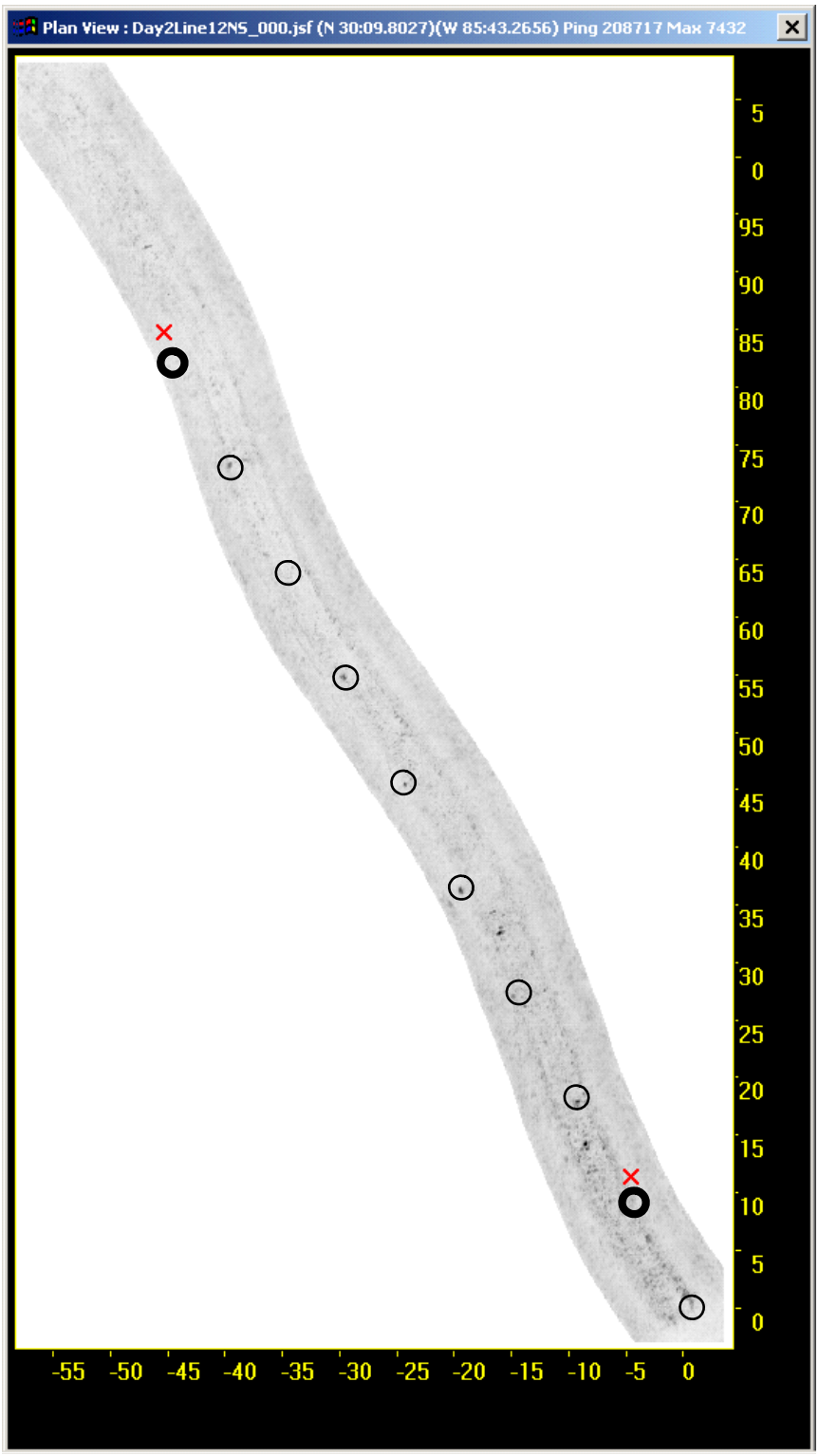


Figure B - 4. Multi-aspect image of trackline Day2Line12NS collected on 19 October 2006 at sand site with target overlay

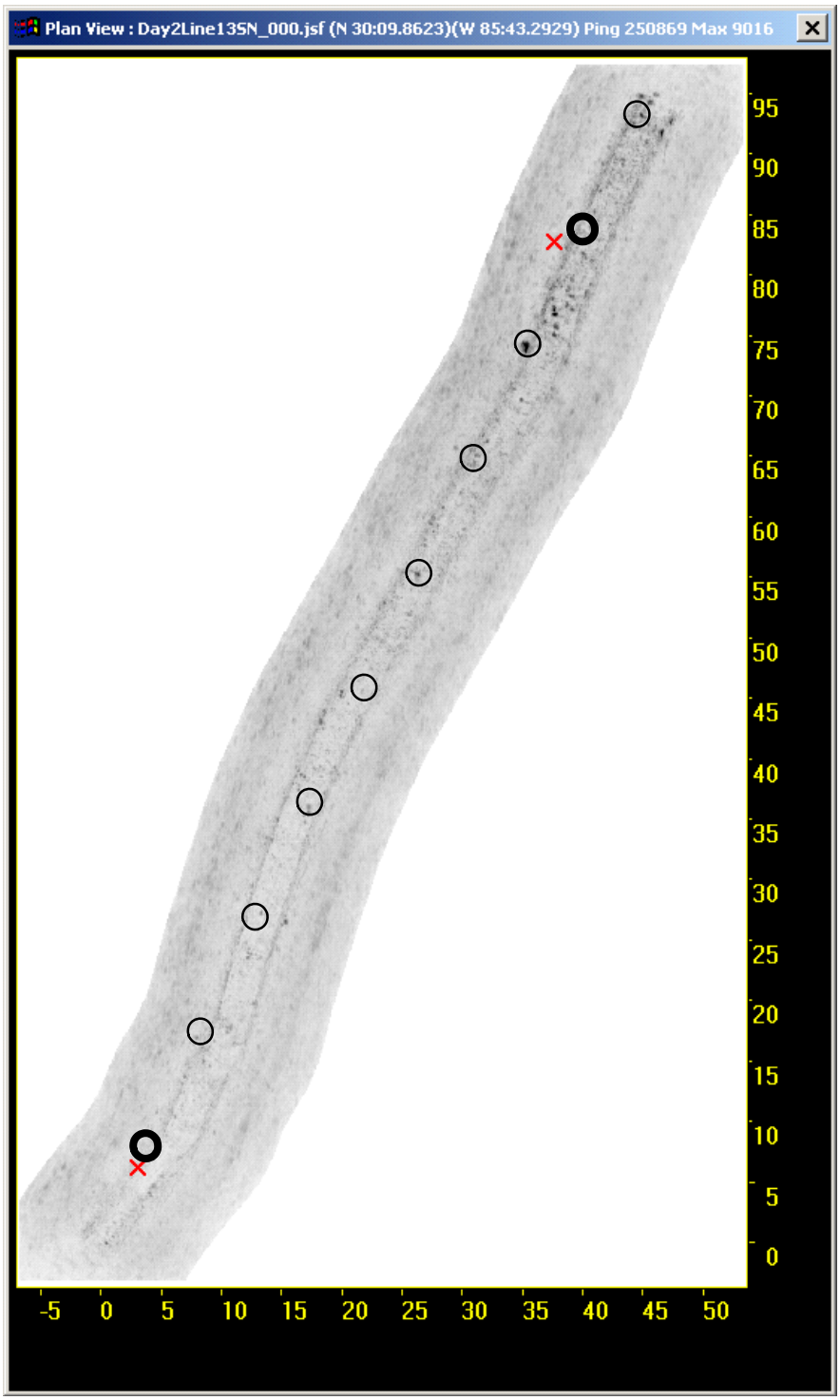


Figure B - 5. Multi-aspect image of trackline Day2Line13SN collected on 19 October 2006 at sand site with target overlay

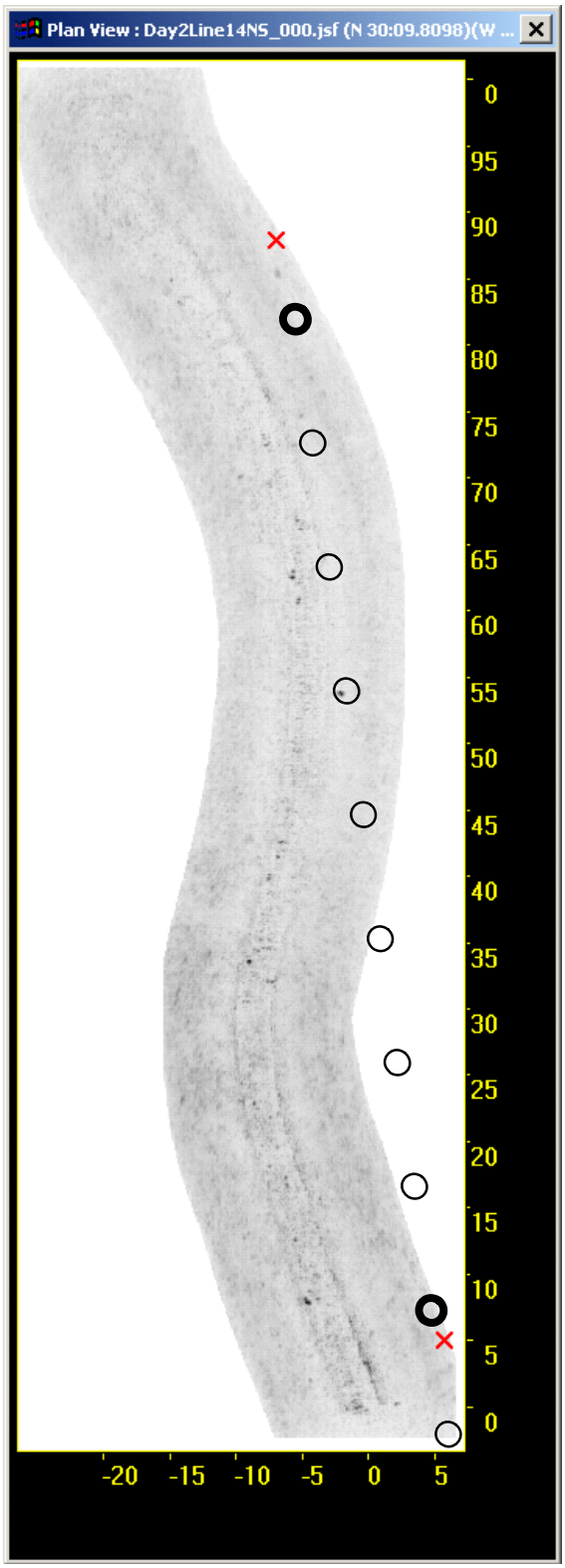


Figure B - 6. Multi-aspect image of trackline Day2Line14NS collected on 19 October 2006 at sand site with target overlay

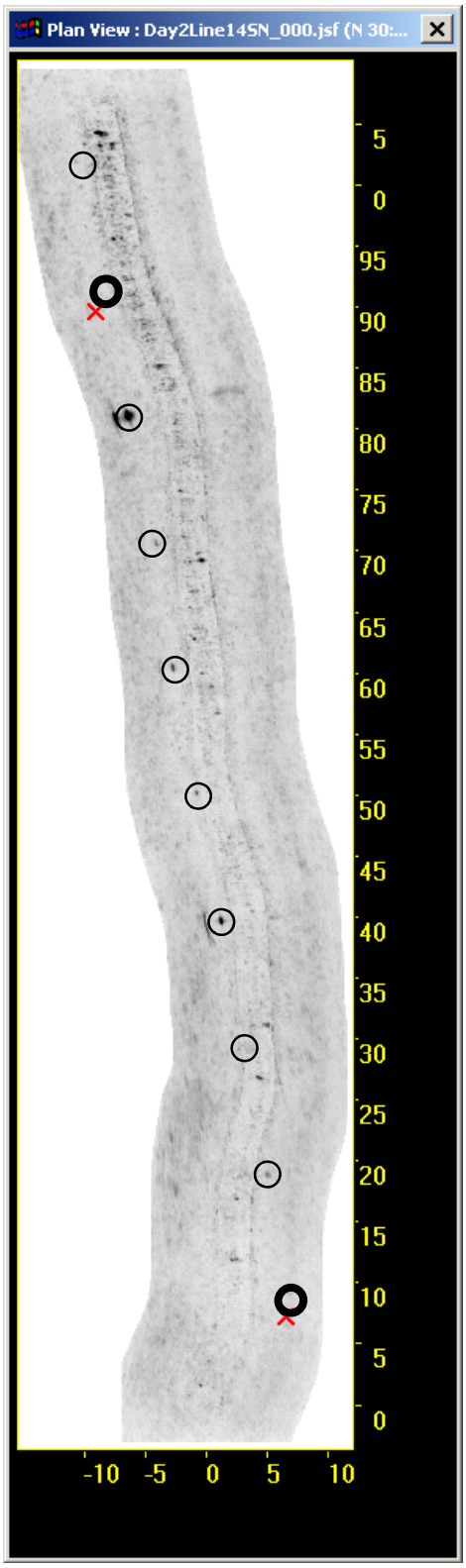


Figure B - 7. Multi-aspect image of trackline Day2Line14SN collected on 19 October 2006 at sand site with target overlay.

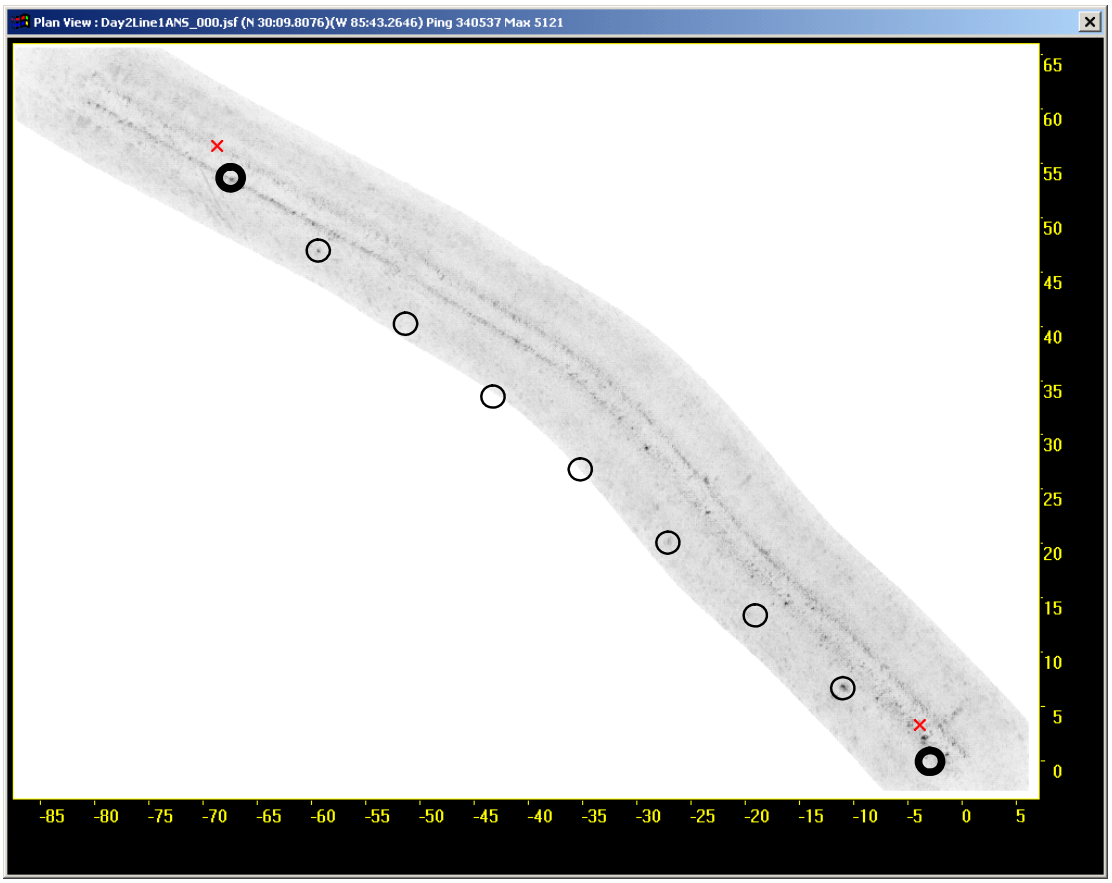


Figure B - 8. Multi-aspect image of trackline Day2Line1ANS collected on 19 October 2006 at sand site with target overlay

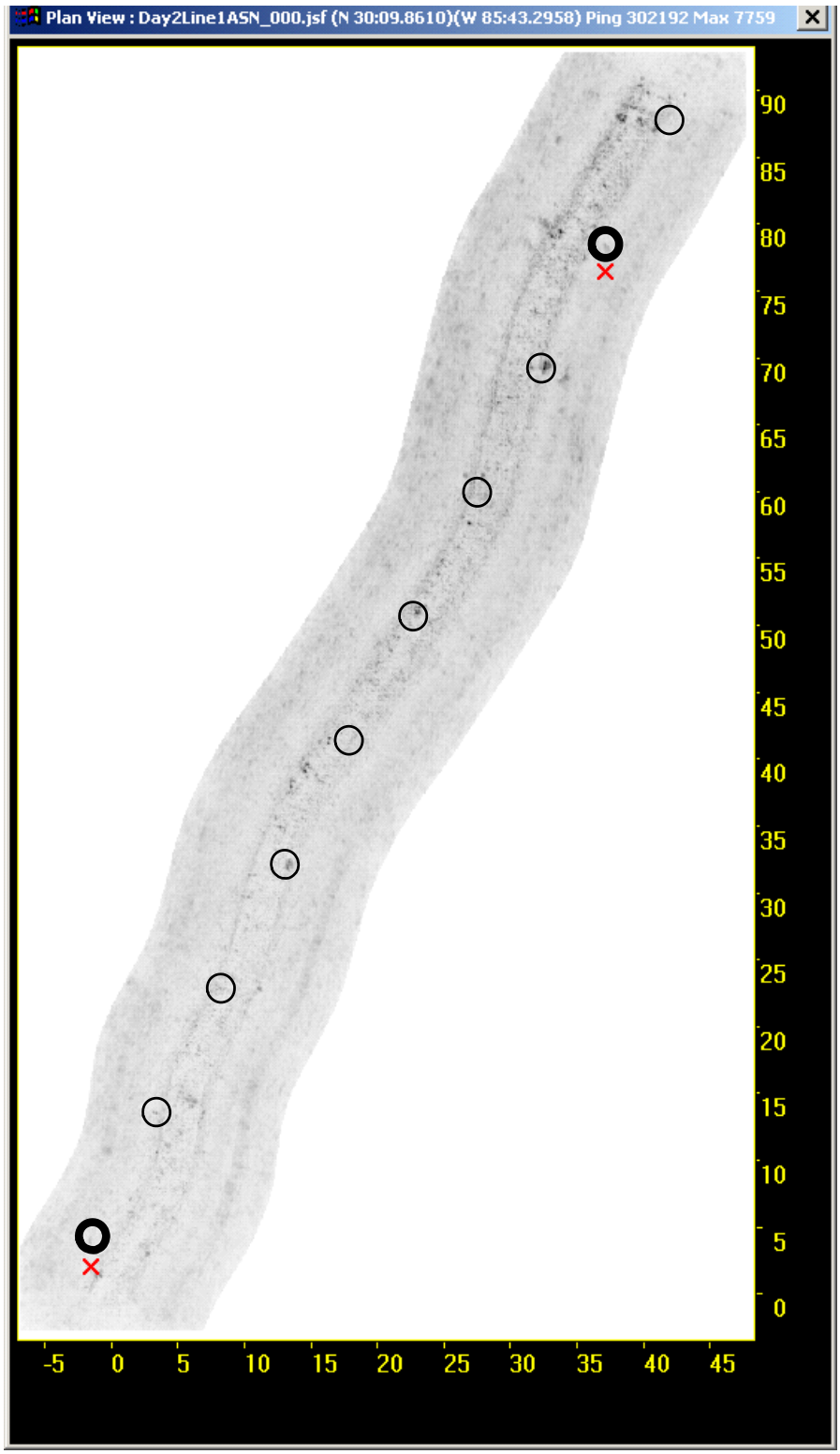


Figure B - 9. Multi-aspect image of trackline Day2Line1ANS collected on 19 October 2006 at sand site with target overlay

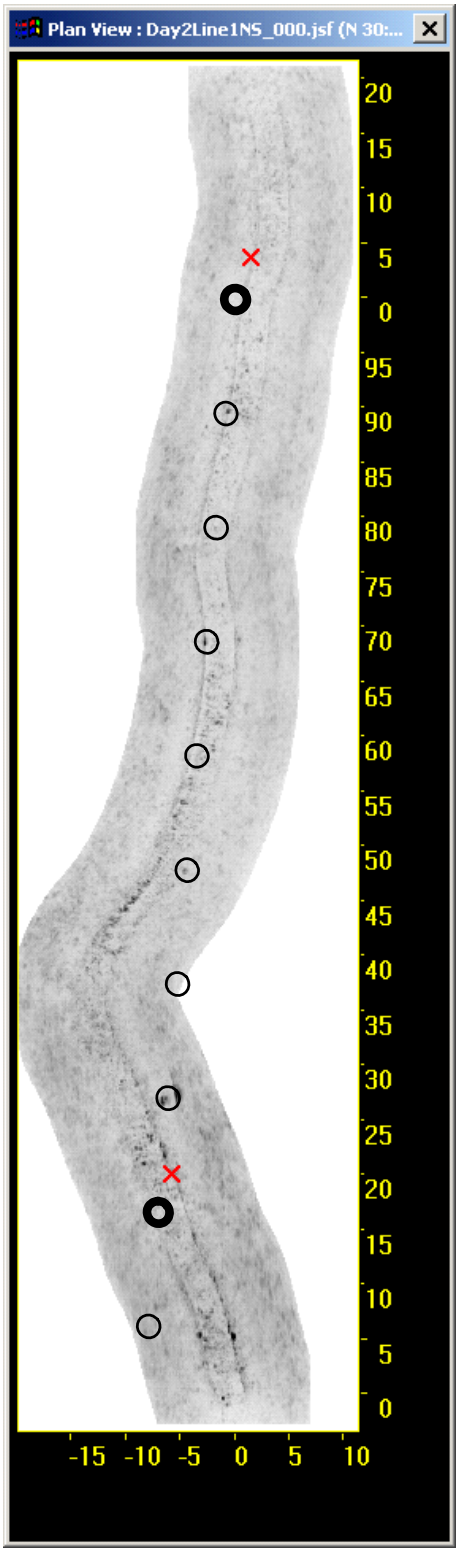


Figure B - 10. Multi-aspect image of trackline Day2Line1NS collected on 19 October 2006 at sand site with target overlay

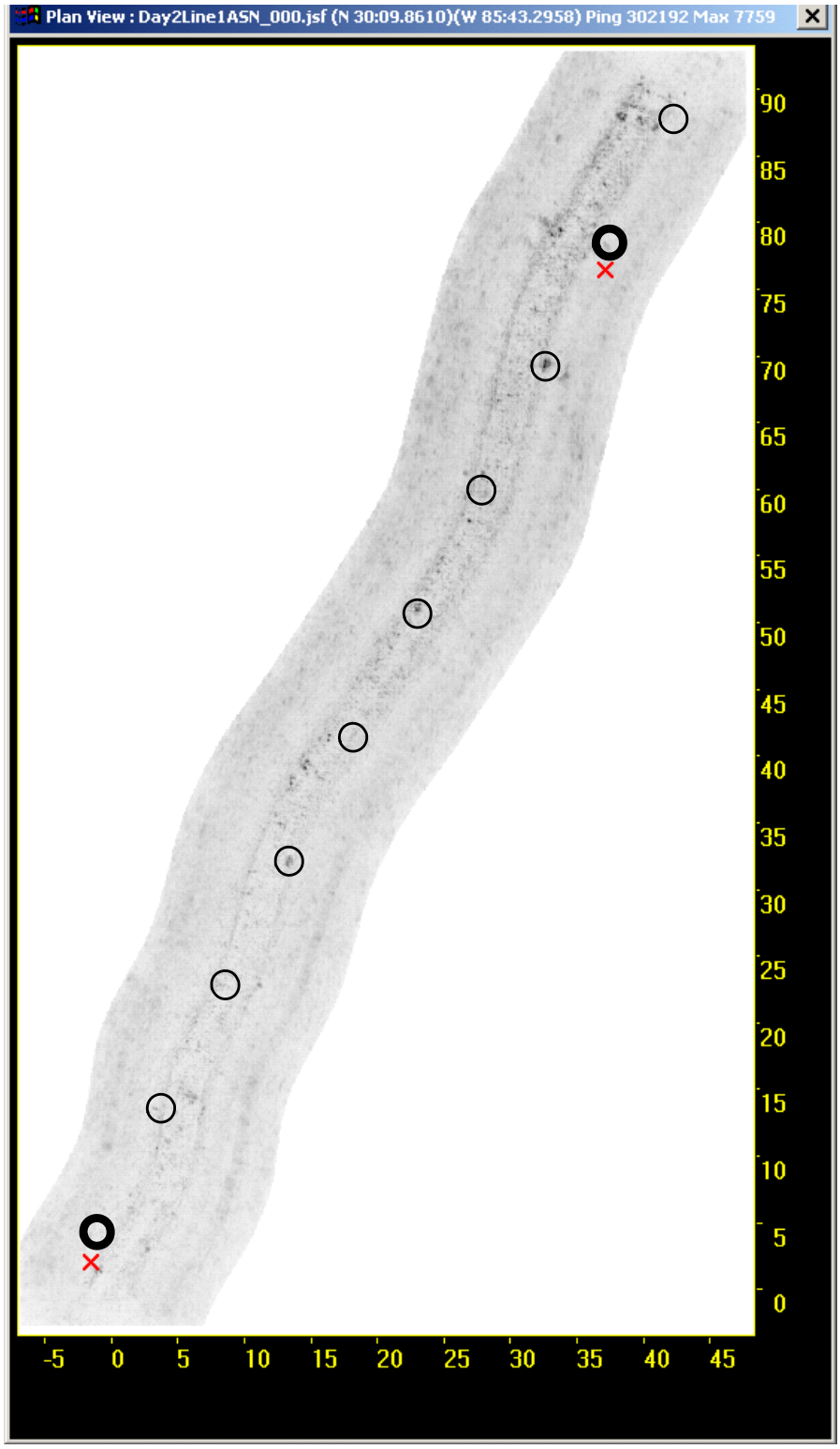


Figure B - 11. Multi-aspect image of trackline Day2Line1ASN collected on 19 October 2006 at sand site with target overlay

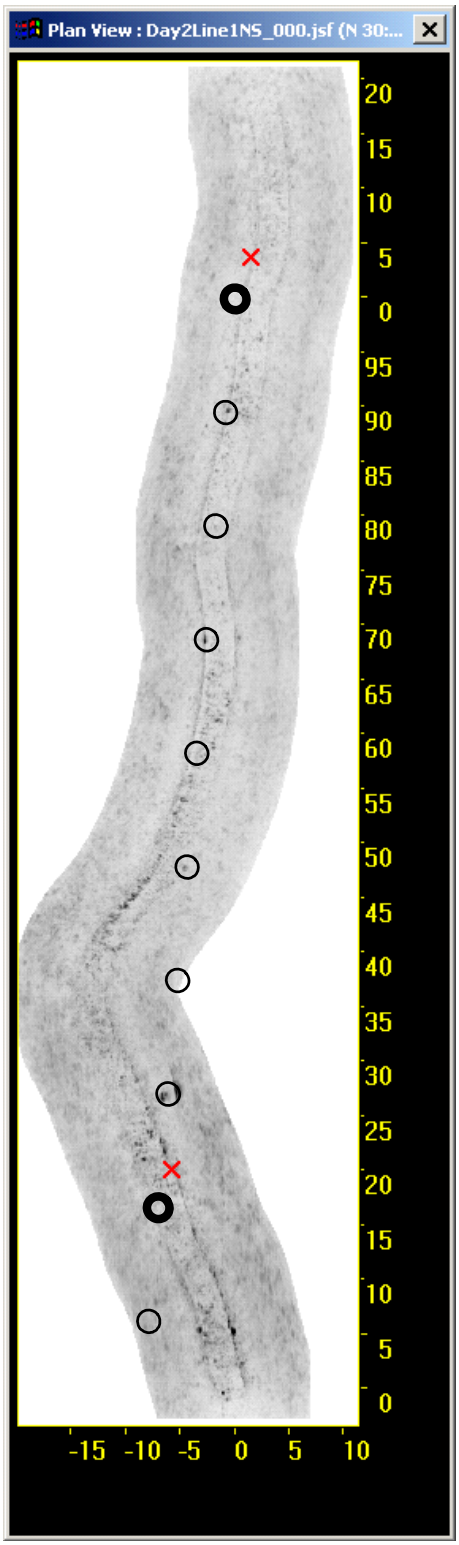


Figure B - 12. Multi-aspect image of trackline Day2Line1NS collected on 19 October 2006 at sand site with target overlay

Figure B - 13. Multi-aspect image of trackline Day2Line21 collected on 19 October 2006 at sand site with target overlay

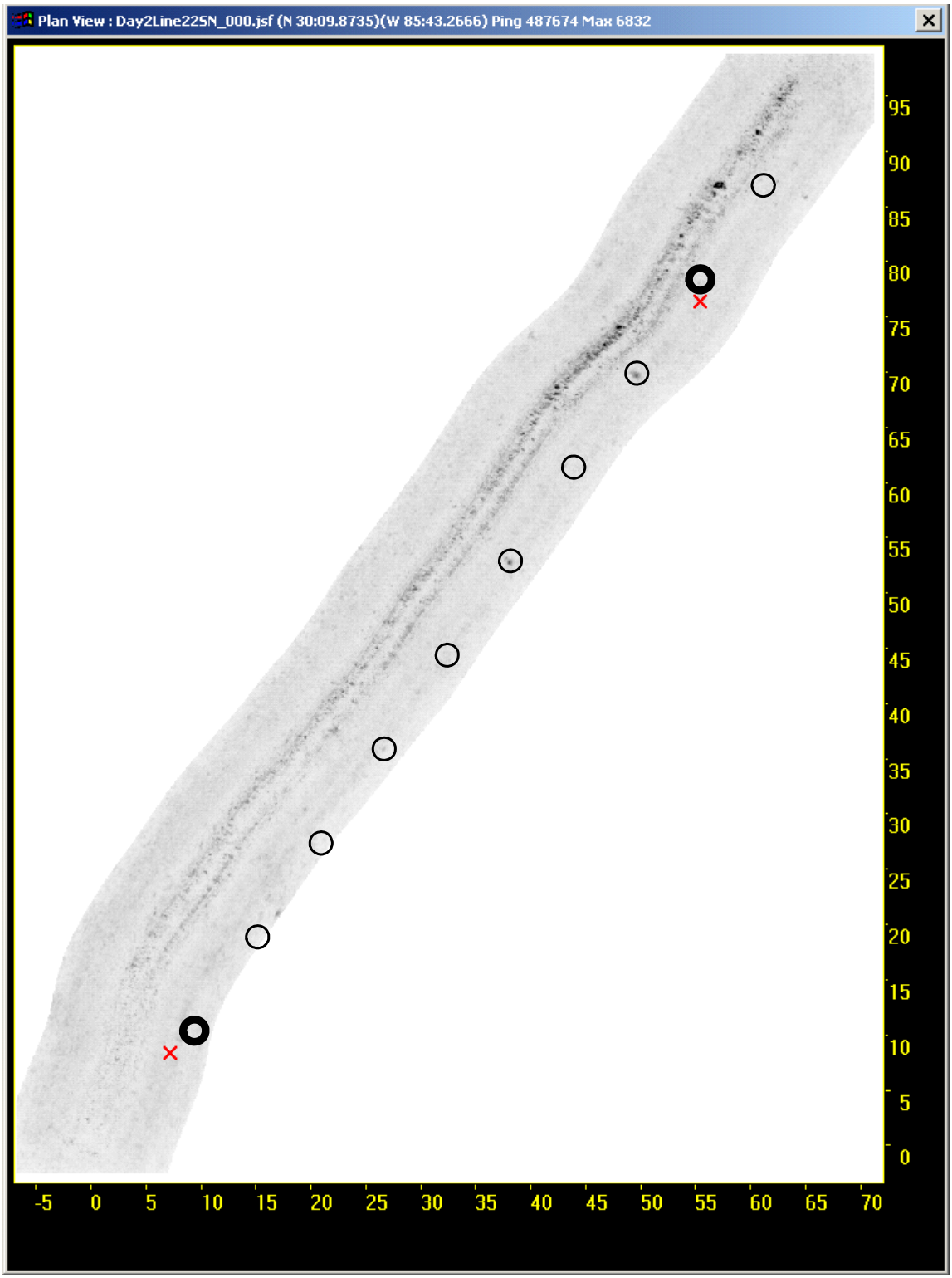


Figure B - 14. Multi-aspect image of trackline Day2Line22SN collected on 19 October 2006 at sand site with target overlay

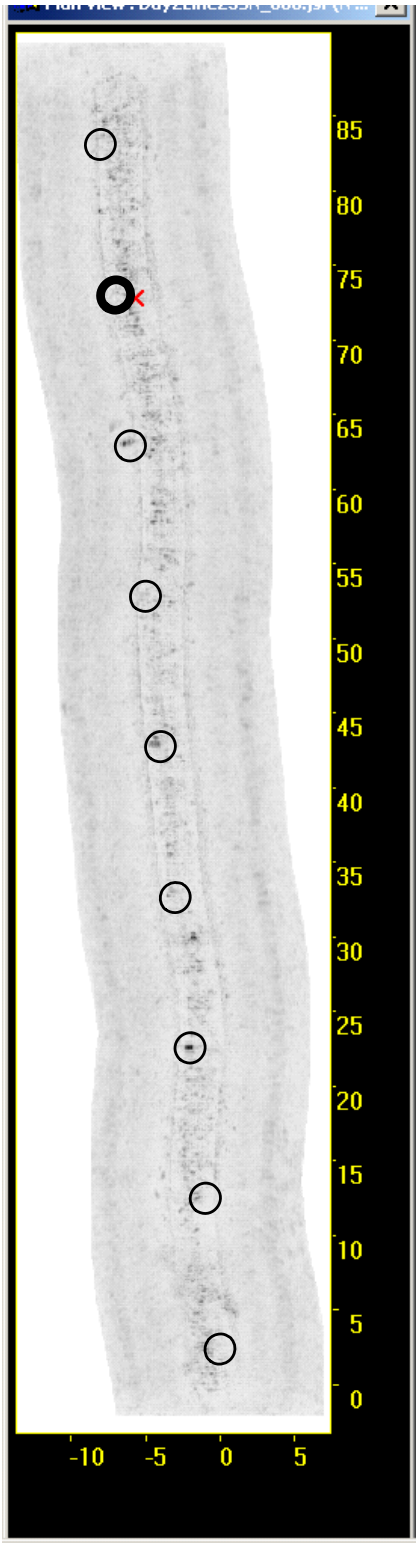


Figure B - 15. Multi-aspect image of trackline Day2Line23SN collected on 19 October 2006 at sand site with target overlay

Figure B - 16. Multi-aspect image of trackline Day2Line24NS collected on 19 October 2006 at sand site with target overlay

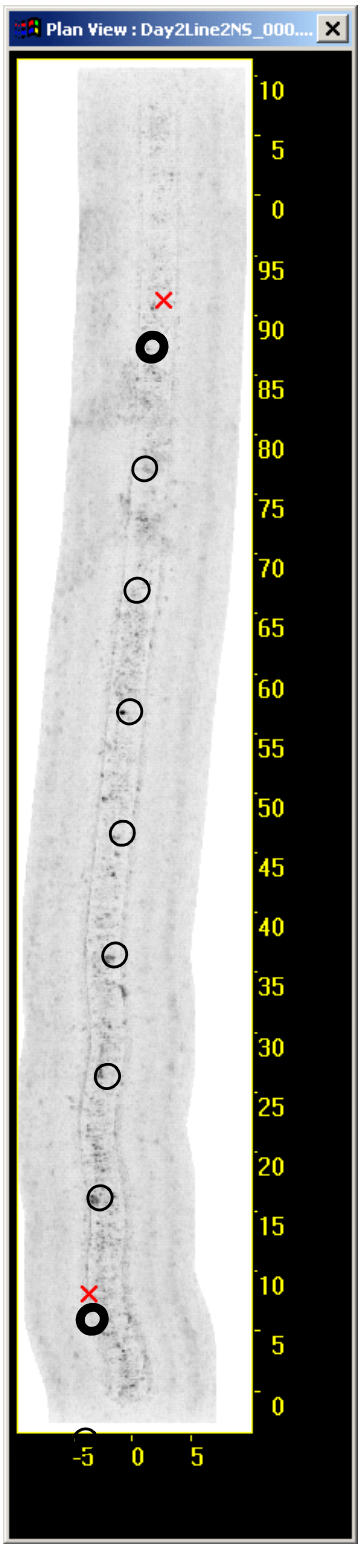


Figure B - 17. Multi-aspect image of trackline Day2Line2NS collected on 19 October 2006 at sand site with target overlay

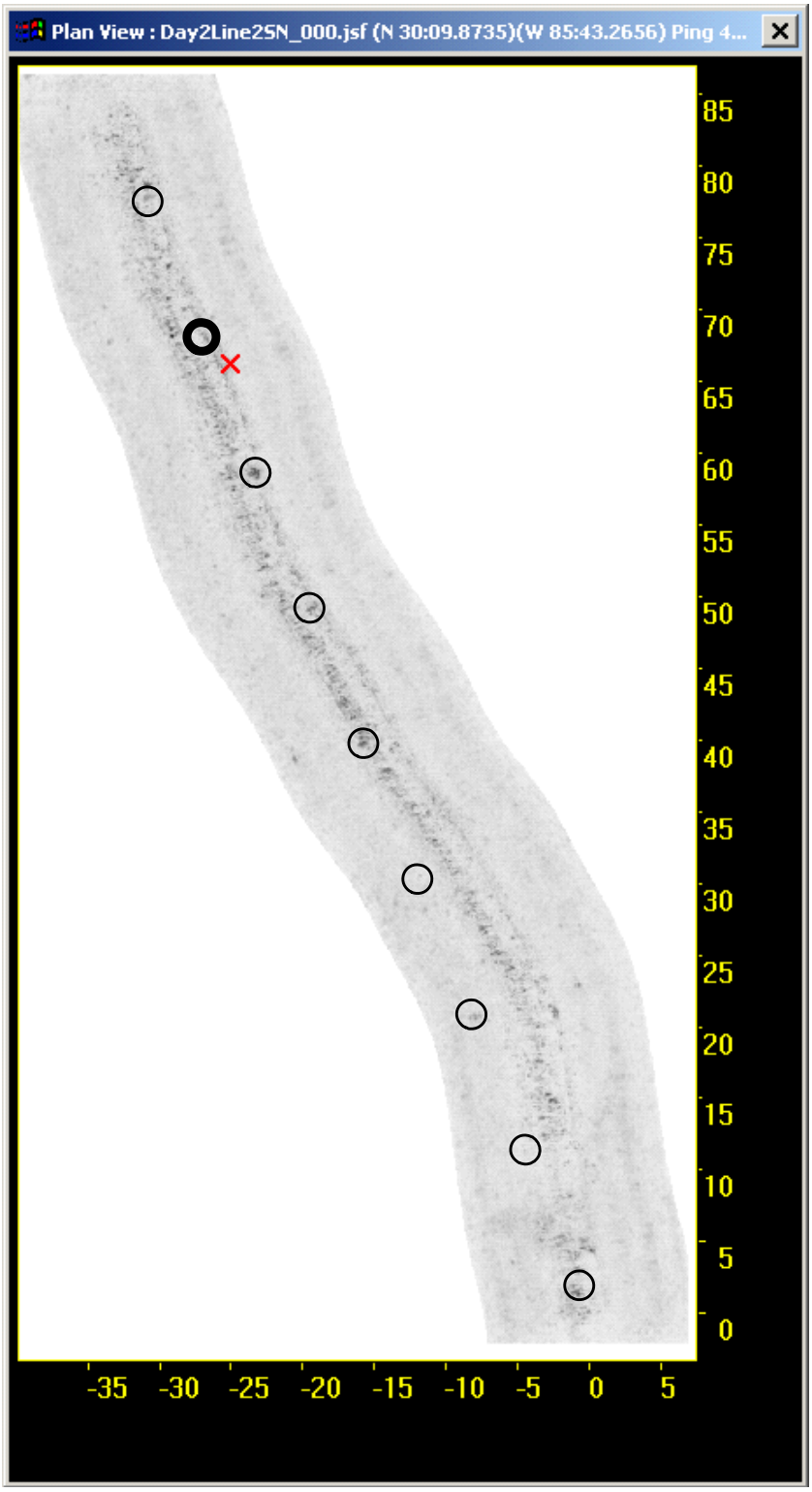


Figure B - 18. Multi-aspect image of trackline Day2Line2SN collected on 19 October 2006 at sand site with target overlay

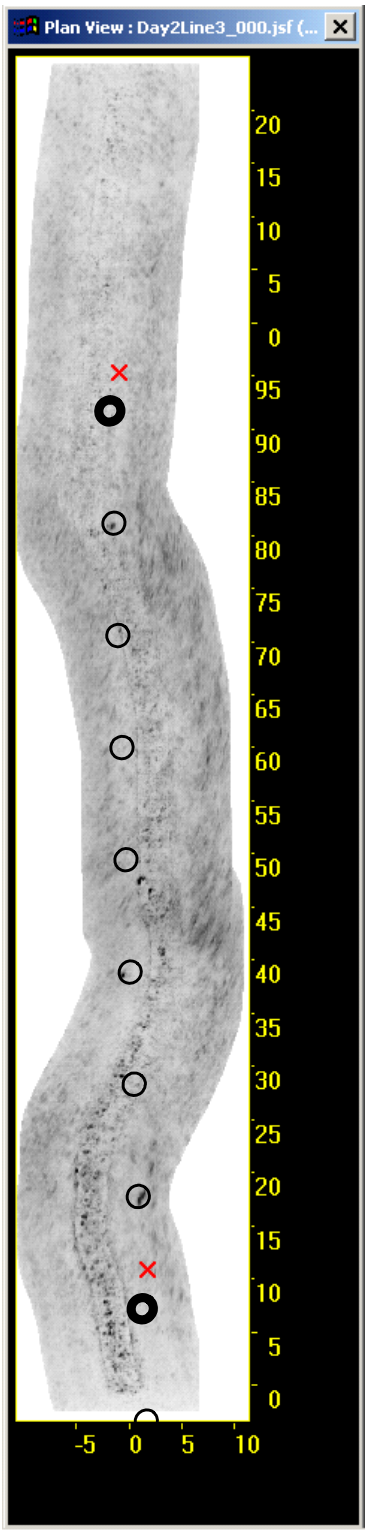


Figure B - 19. Multi-aspect image of trackline Day2Line3 collected on 19 October 2006 at sand site with target overlay.

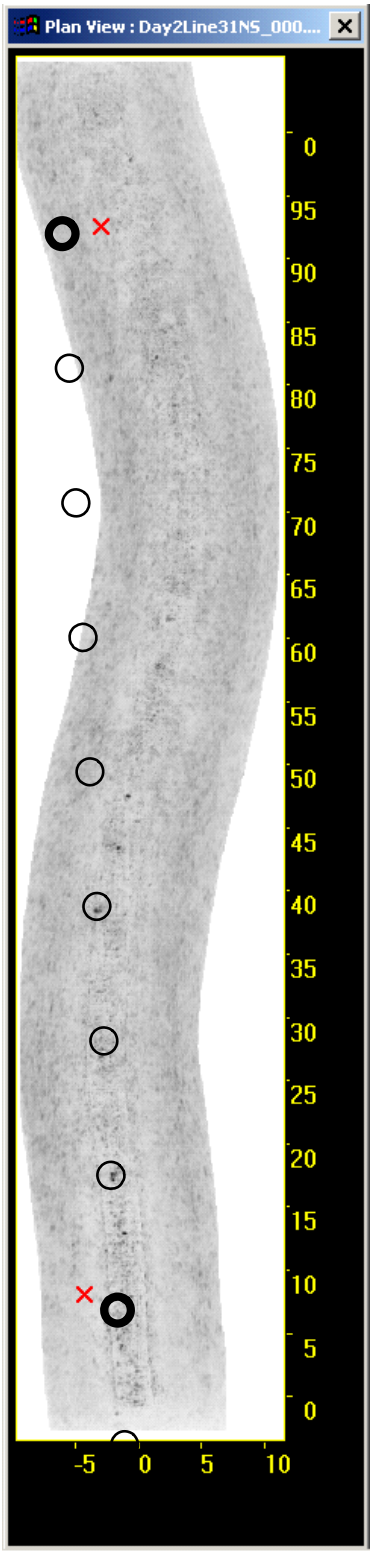


Figure B - 20. Multi-aspect image of trackline Day2Line31NS collected on 19 October 2006 at sand site with target overlay.

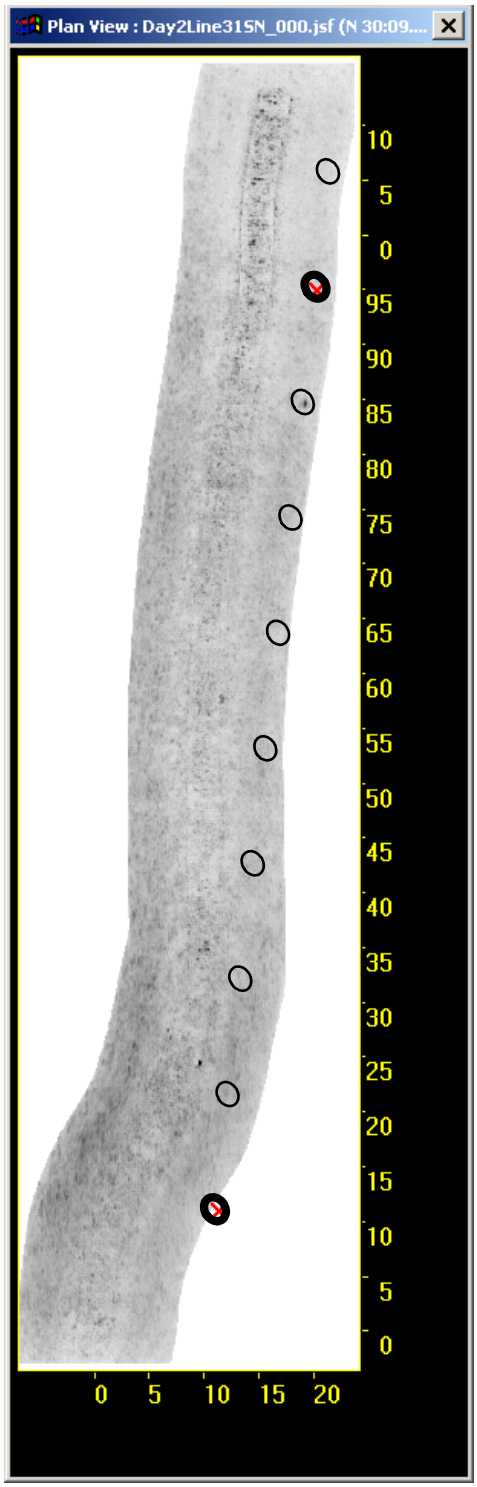


Figure B - 21. Multi-aspect image of trackline Day2Line31SN collected on 19 October 2006 at sand site with target overlay.

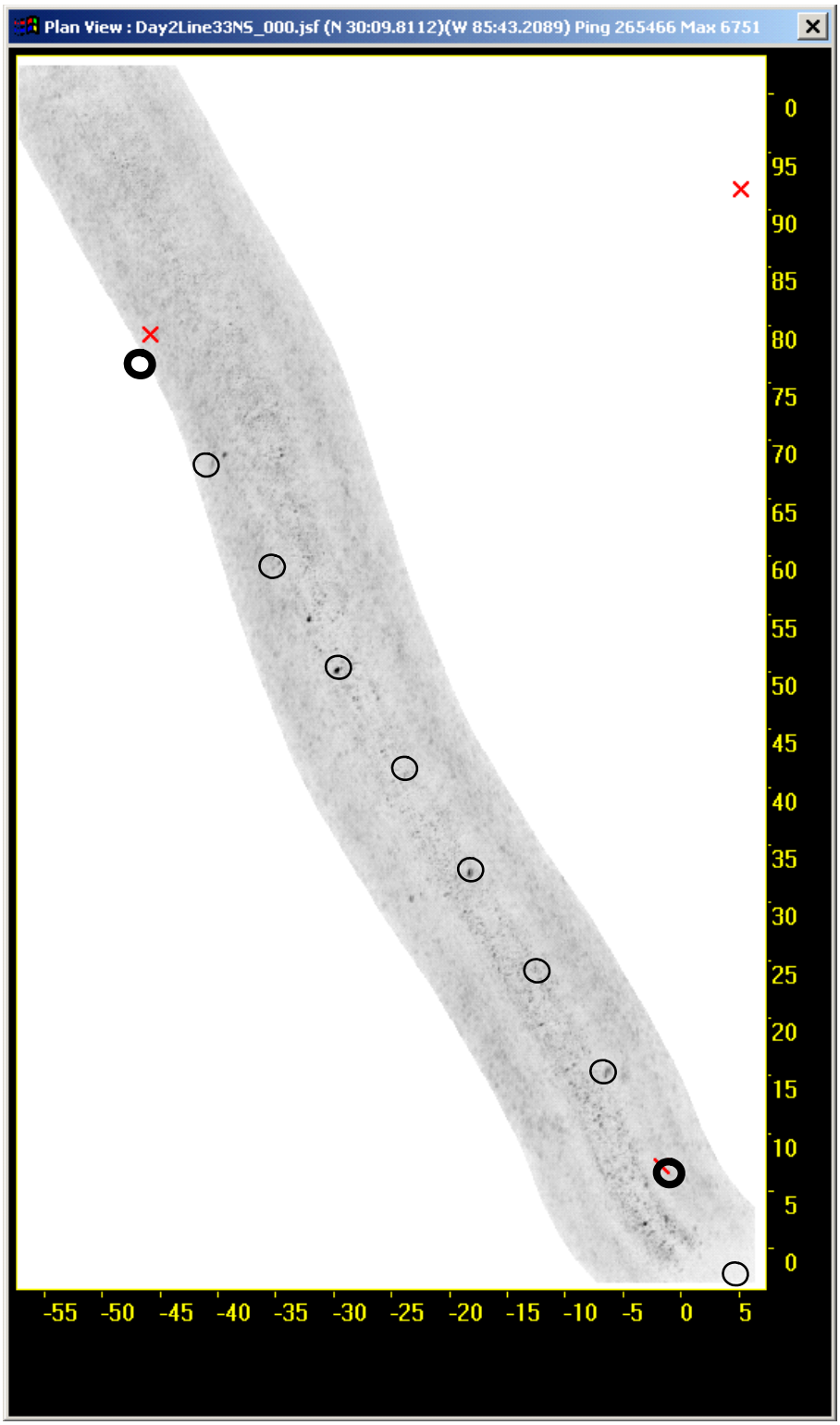


Figure B - 22. Multi-aspect image of trackline Day2Line33NS collected on 19 October 2006 at sand site with target overlay.

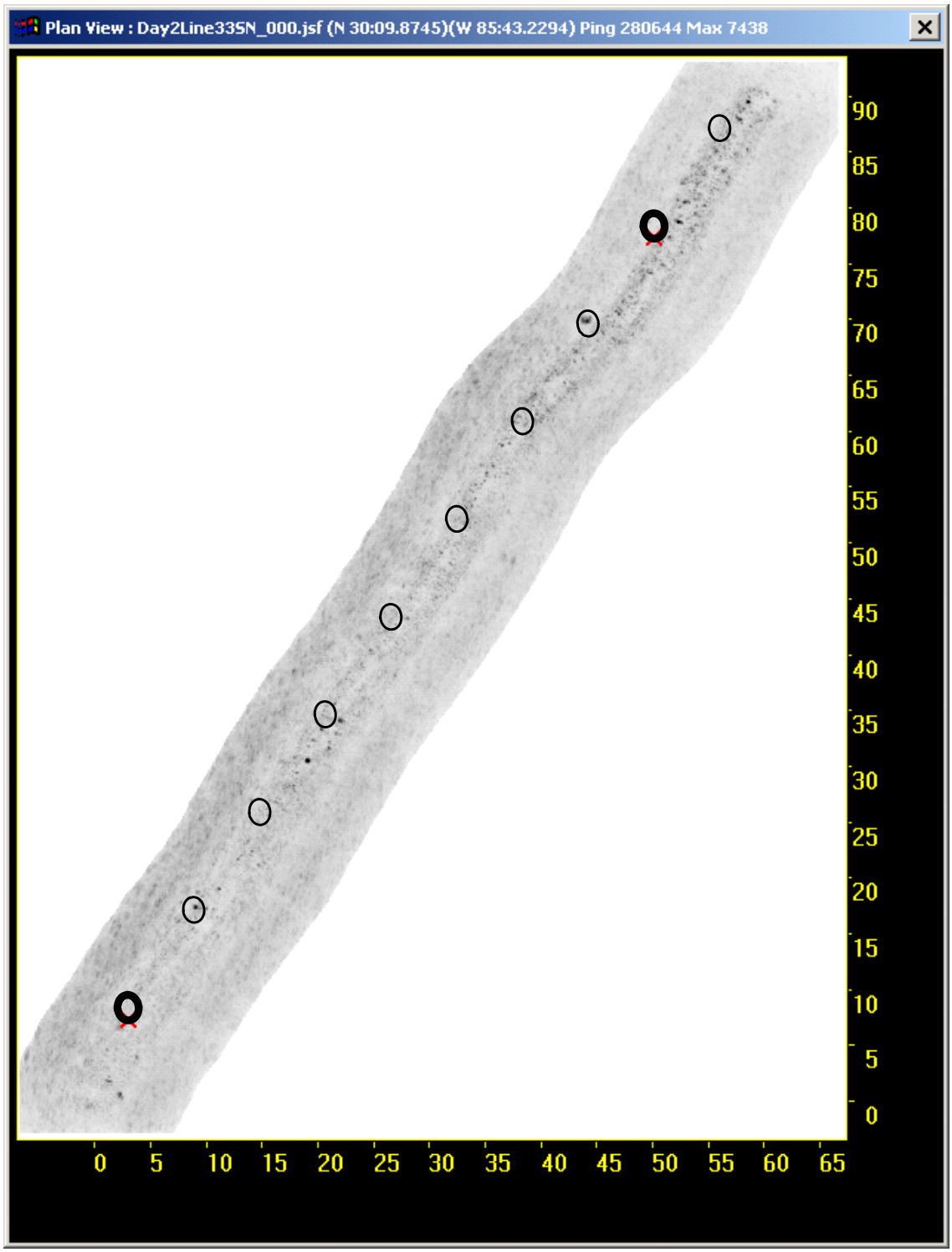


Figure B - 23. Multi-aspect image of trackline Day2Line33SN collected on 19 October 2006 at sand site with target overlay.

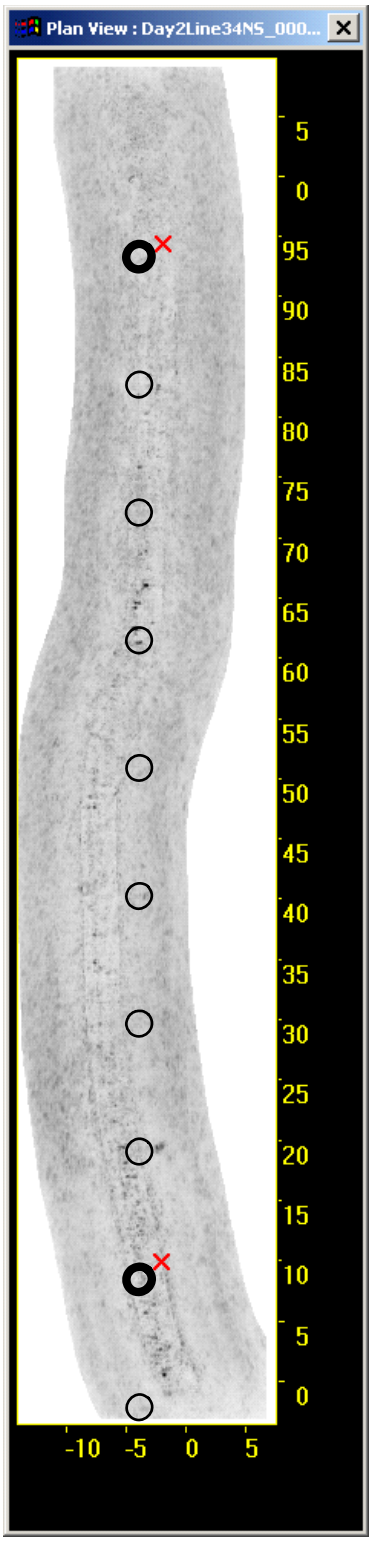


Figure B - 24. Multi-aspect image of trackline Day2Line33SN collected on 19 October 2006 at sand site with target overlay.

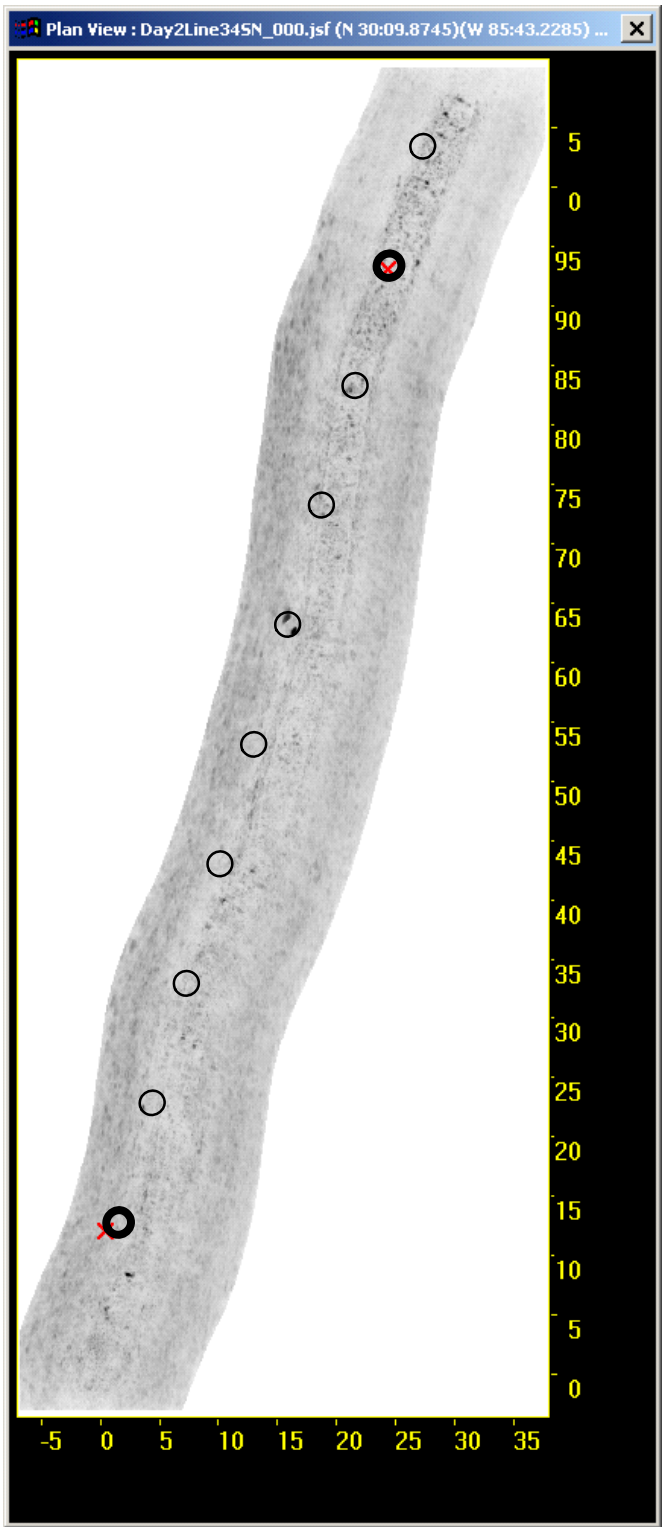


Figure B - 25. Multi-aspect image of trackline Day2Line34SN collected on 19 October 2006 at sand site with target overlay.

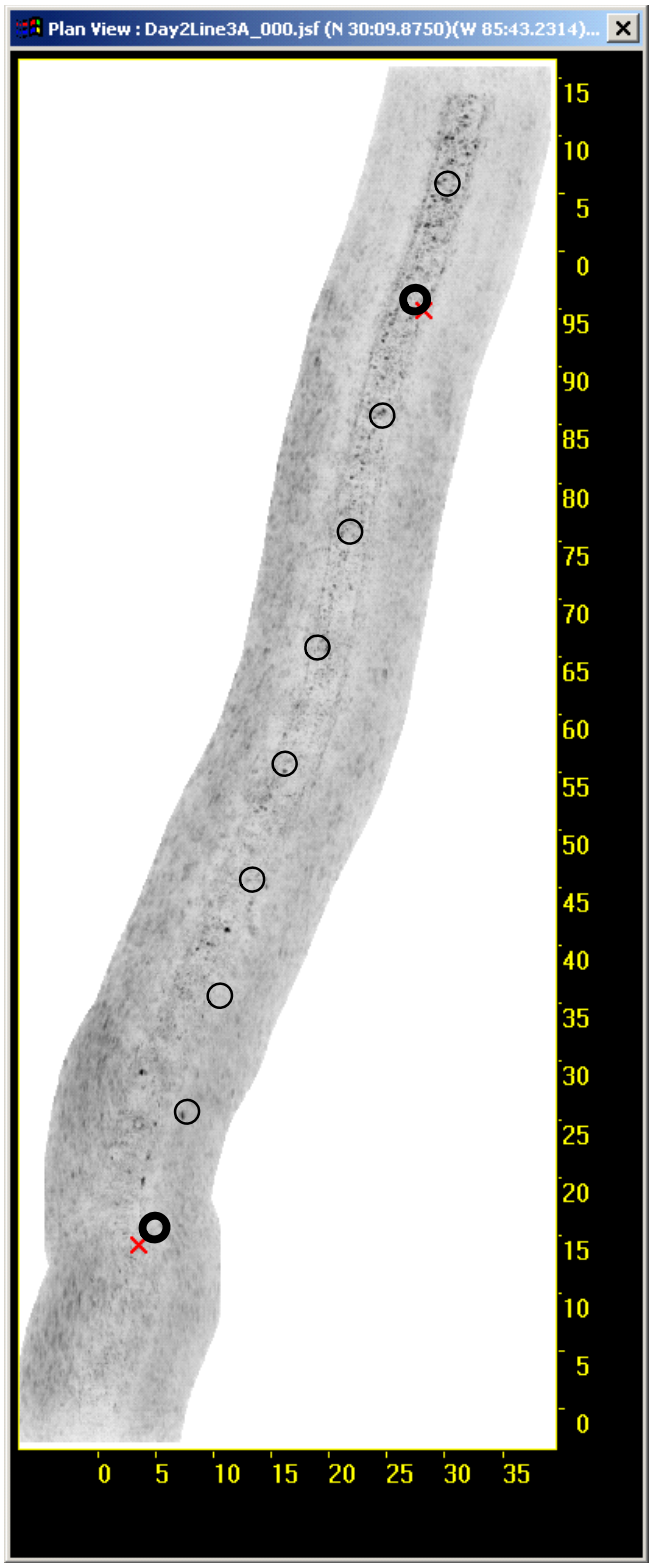


Figure B - 26. Multi-aspect image of trackline Day2Line3A collected on 19 October 2006 at sand site with target overlay.

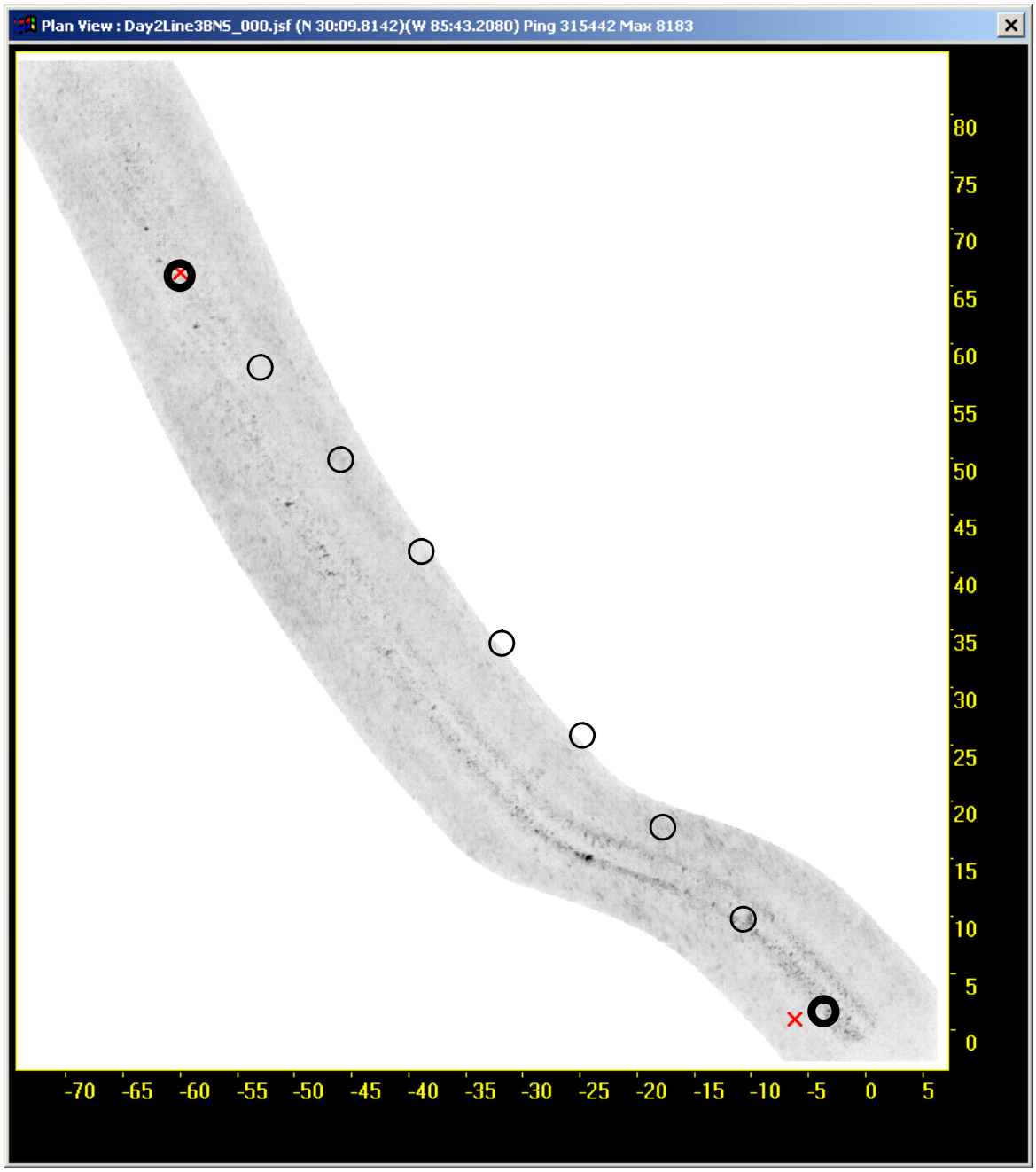


Figure B - 27. Multi-aspect image of trackline Day2Line3BNS collected on 19 October 2006 at sand site with target overlay.

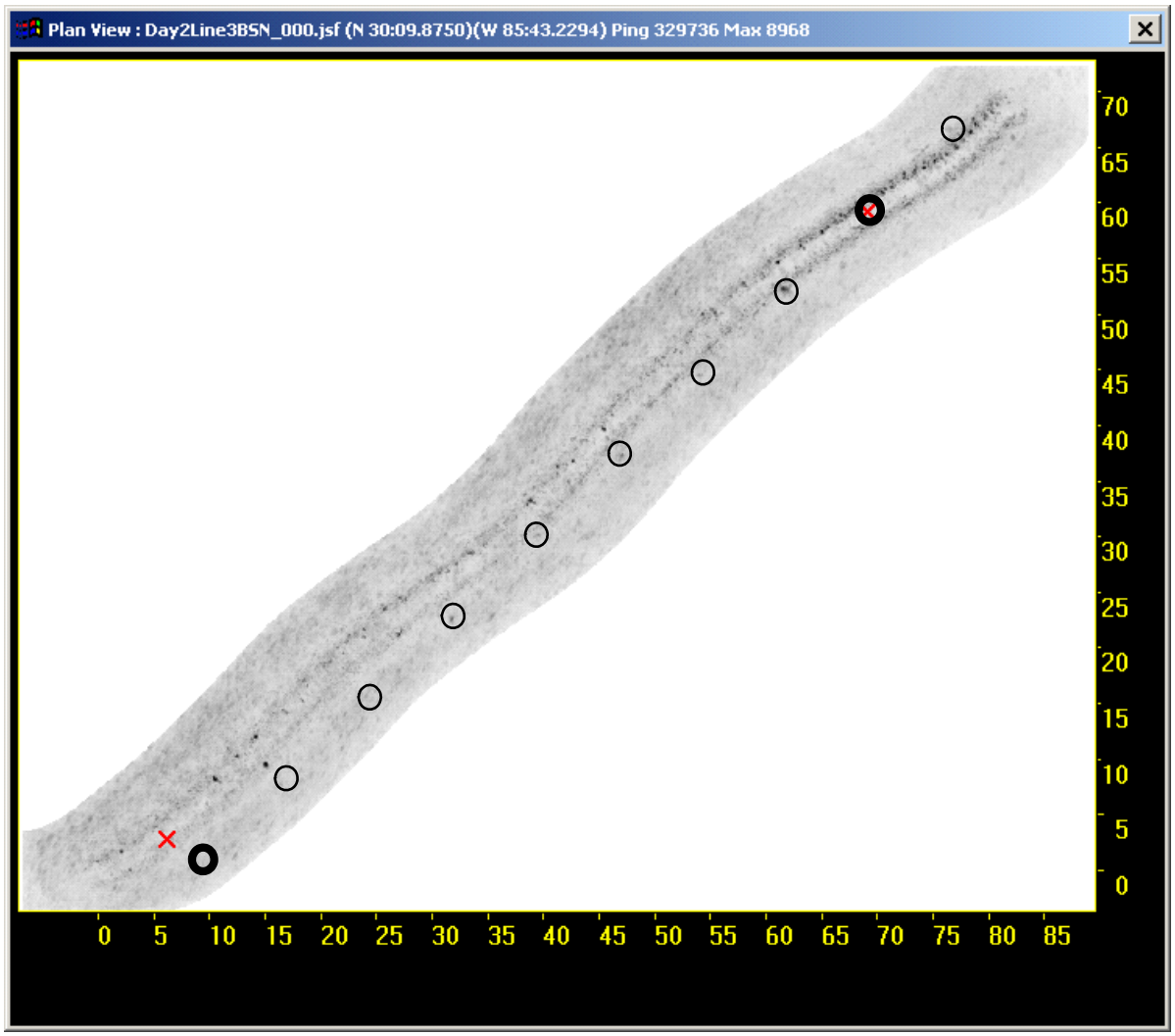


Figure B - 28. Multi-aspect image of trackline Day2Line3BSN collected on 19 October 2006 at sand site with target overlay

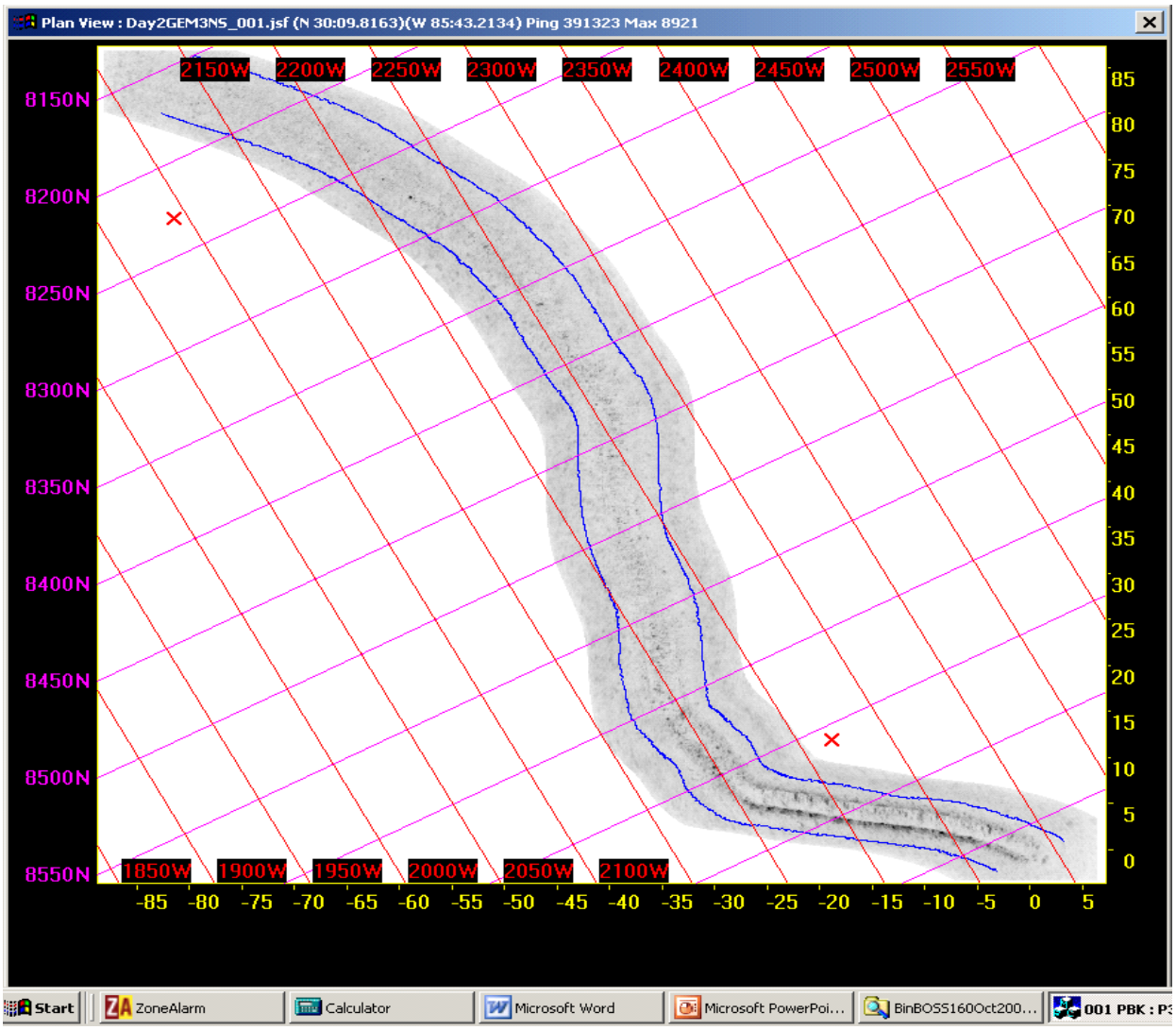


Figure B - 29. Multi-aspect image of trackline Day2GEM3NS collected on 19 October 2006 at sand site with target overlay.

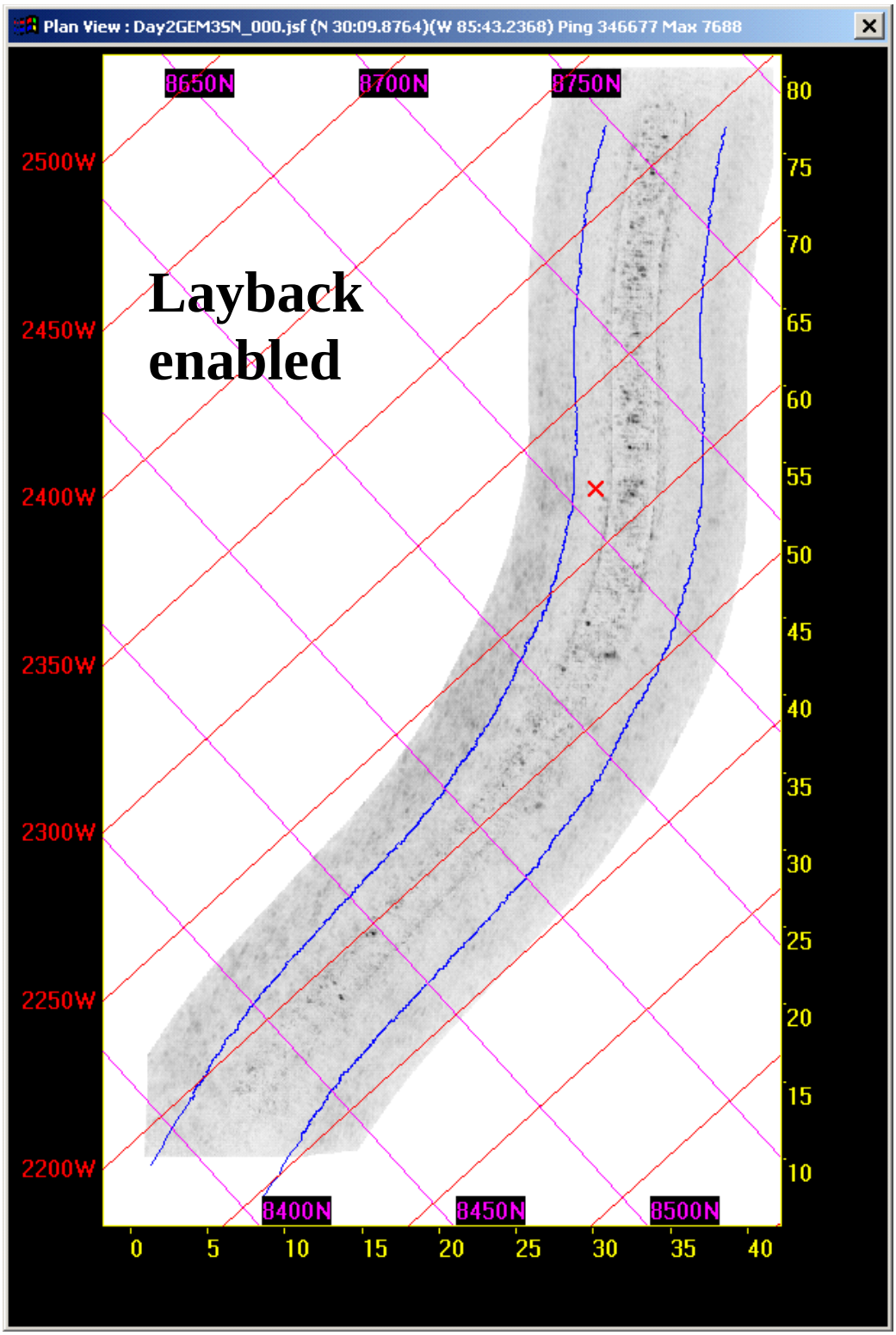


Figure B - 30. Multi-aspect image of trackline Day2GEM3SN collected on 19 October 2006 at sand site with target overlay.

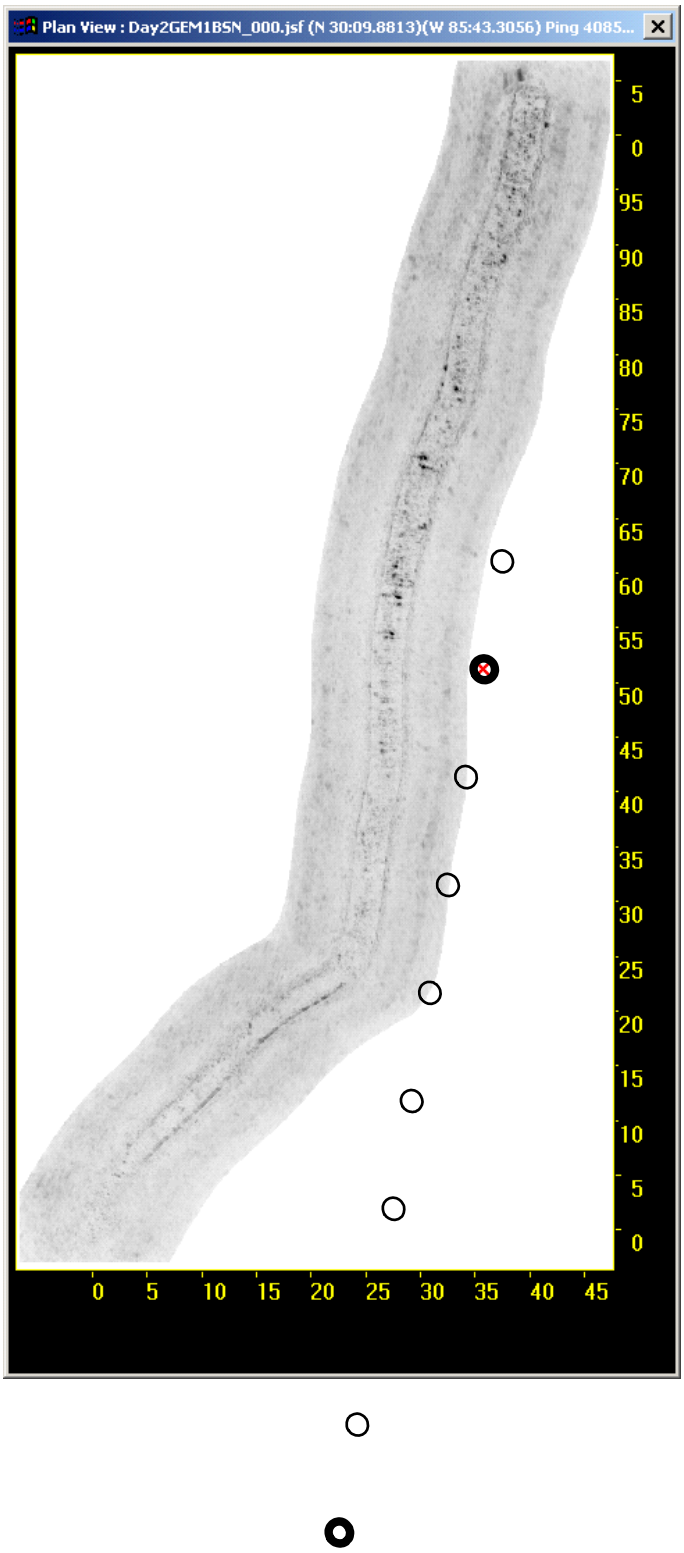


Figure B - 31. Multi-aspect image of trackline Day2GEM1BSN collected on 19 October 2006 at sand site with target overlay.

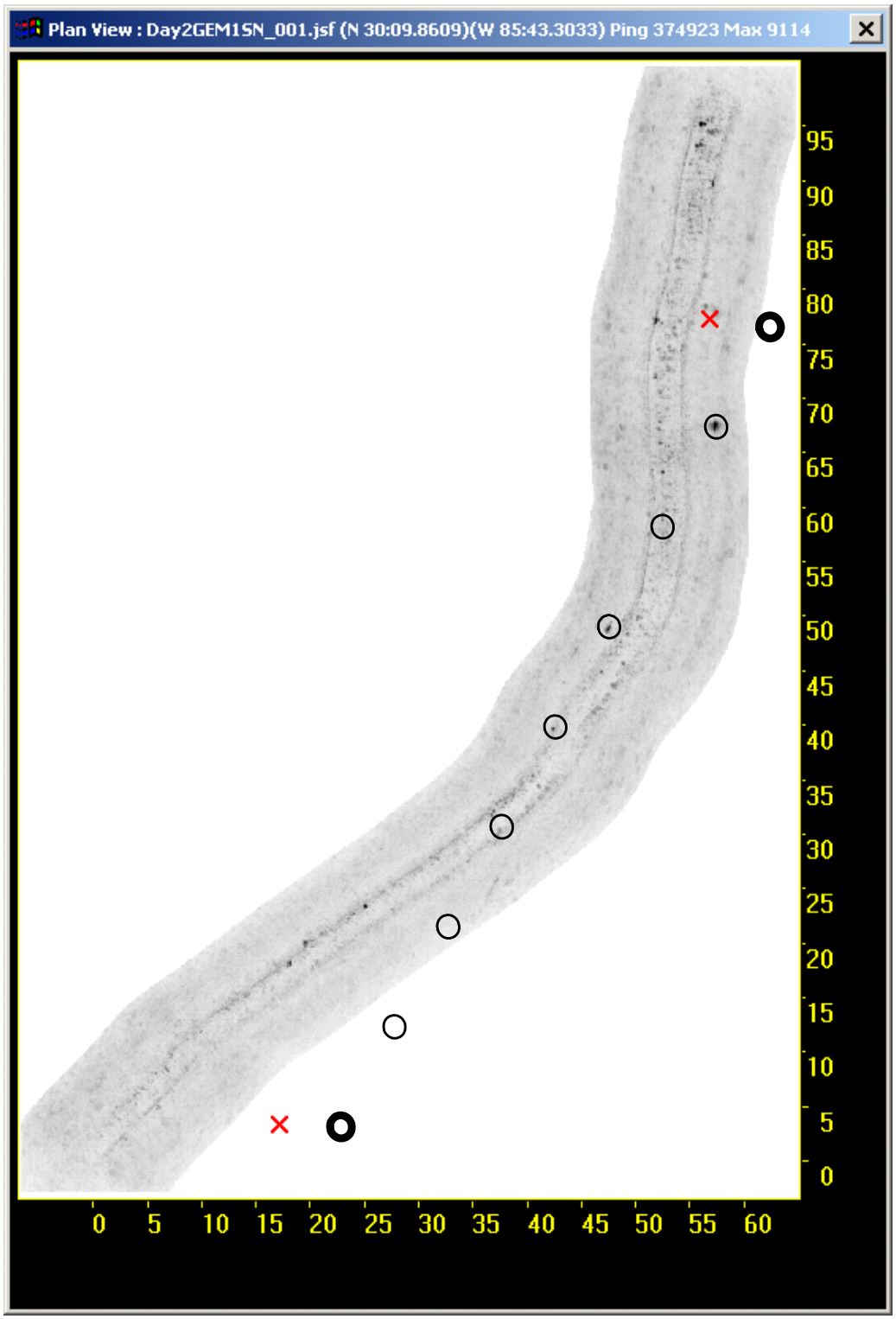


Figure B - 32. Multi-aspect image of trackline Day2GEM1SN collected on 19 October 2006 at sand site with target overlay.

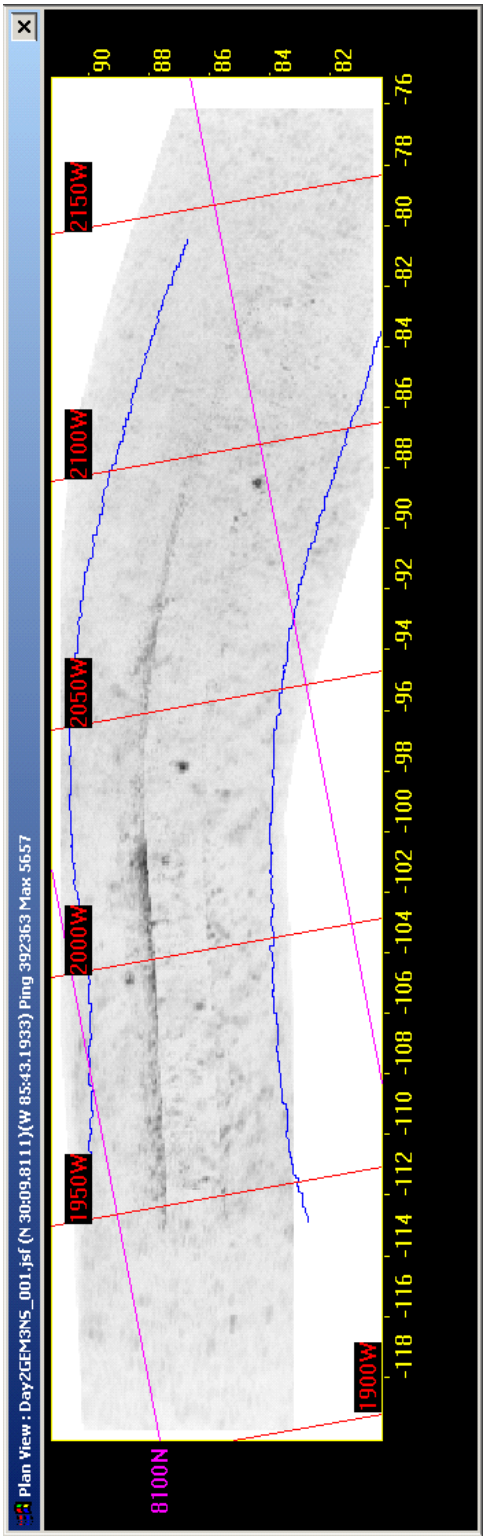
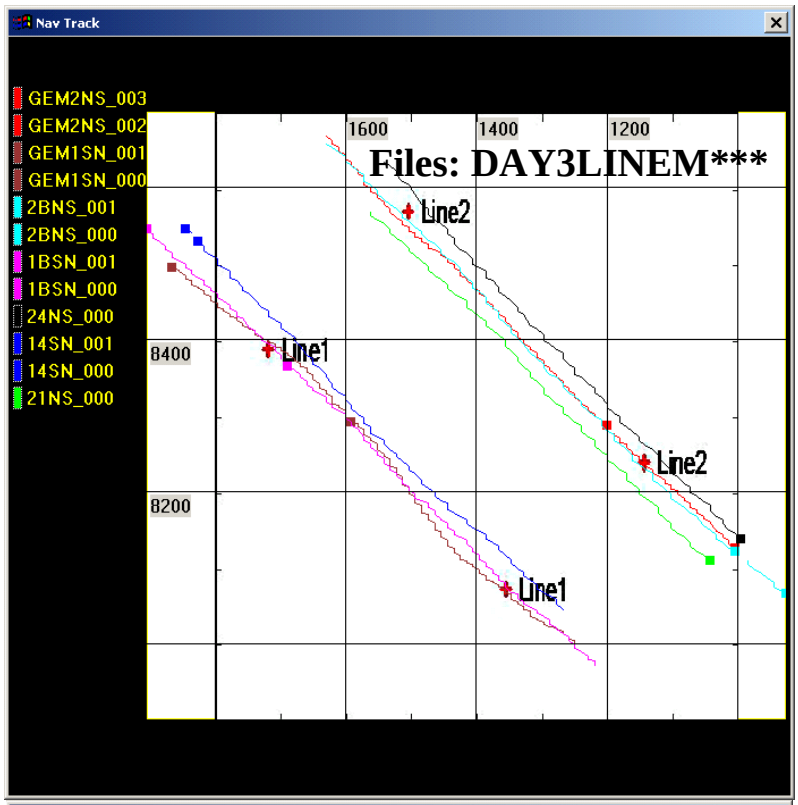


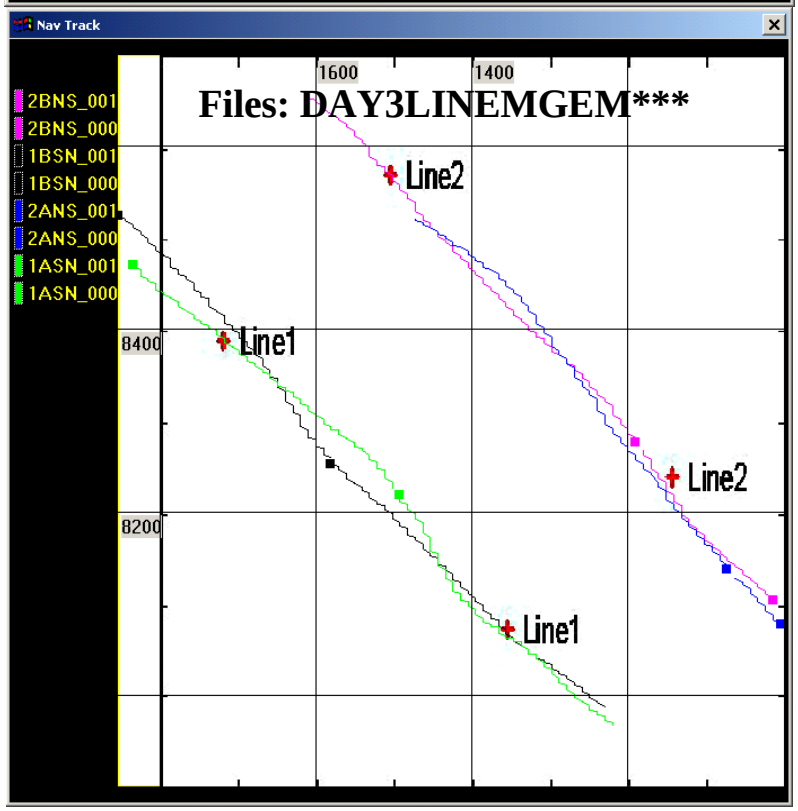
Figure B - 33. Multi-aspect image of trackline Day2GEM3NS collected on 19 October 2006 at sand site with target overlay.

C Appendix C

Table C-1 MSDB Search Tracks at Mud Site, October 20, 2006

Multi-Sensor Database						
Test Location: St. Andrews Bay Mud Site						
Date	**Run**	**Vehicle Tested**	**Test Line**	**Time**	**Heading (°)**	**Speed (knots)**
10/20/2006	LineM1	BOSS, RTG	1	0939 - 0941	315	2.6
10/20/2006	LineM2	BOSS, RTG	2	0945 - 0946	130	3.2
10/20/2006	LineM22	BOSS, RTG	2	1000 - 1001	145	3.0
10/20/2006	LineM12	BOSS, RTG	1	1005 - 1007	315	2.3
10/20/2006	LineM13	BOSS, RTG	1	1019 - 1021	315	2.6
10/20/2006	LineM23	BOSS, RTG	2	1024 - 1026	140	3.2
10/20/2006	LineM11	BOSS, RTG	1	1030 - 1032	315	2.8
10/20/2006	LineM21	BOSS, RTG	2	1035 - 1037	140	3.2
10/20/2006	LinwM14	BOSS, RTG	1	1041 - 1043	320	2.8
10/20/2006	LineM24	BOSS, RTG	2	1047 - 1049	140	3.1
10/20/2006	LineM1B	BOSS, RTG	1	1053 - 1055	318	2.2
10/20/2006	LineM2B	BOSS, RTG	2	1059 - 1101	125	3.2
10/20/2006	LineMGEM1	BOSS, RTG, GEM	1	1144 - 1147	325	1.7
10/20/2006	LineMGEM2	BOSS, RTG, GEM	2	1150 - 1153	145	2.3
10/20/2006	LineMGEM1A	BOSS, RTG, GEM	1	1202 - 1205	325	1.7
10/20/2006	LineMGEM2A	BOSS, RTG, GEM	2	1209 - 1211	145	2.3
10/20/2006	LineMGEM1B	BOSS, RTG, GEM	1	1219 - 1222	325	1.7
10/20/2006	LineMGEM2B	BOSS, RTG, GEM	2	1226 - 1228	140	2.1
10/20/2006	LineMGEM1C	BOSS, RTG, GEM	1	N/A	N/A	N/A


Nav Track
GEM2NS_003
GEM2NS_002
GEM1SN_001
GEM1SN_000
2BNS_001
2BNS_000
1BSN_001
1BSN_000
24NS_000
14SN_001
14SN_000
21NS_000
1600
1400
1200
Files: DAY3LINEM***
Line2
Line1
8400
8200
Line2
Line1


Nav Track
2BNS_001
2BNS_000
1BSN_001
1BSN_000
2ANS_001
2ANS_000
1ASN_001
1ASN_000
1600
1400
Files: DAY3LINEMGEM***
Line2
Line1
8400
Line2
8200
Line1

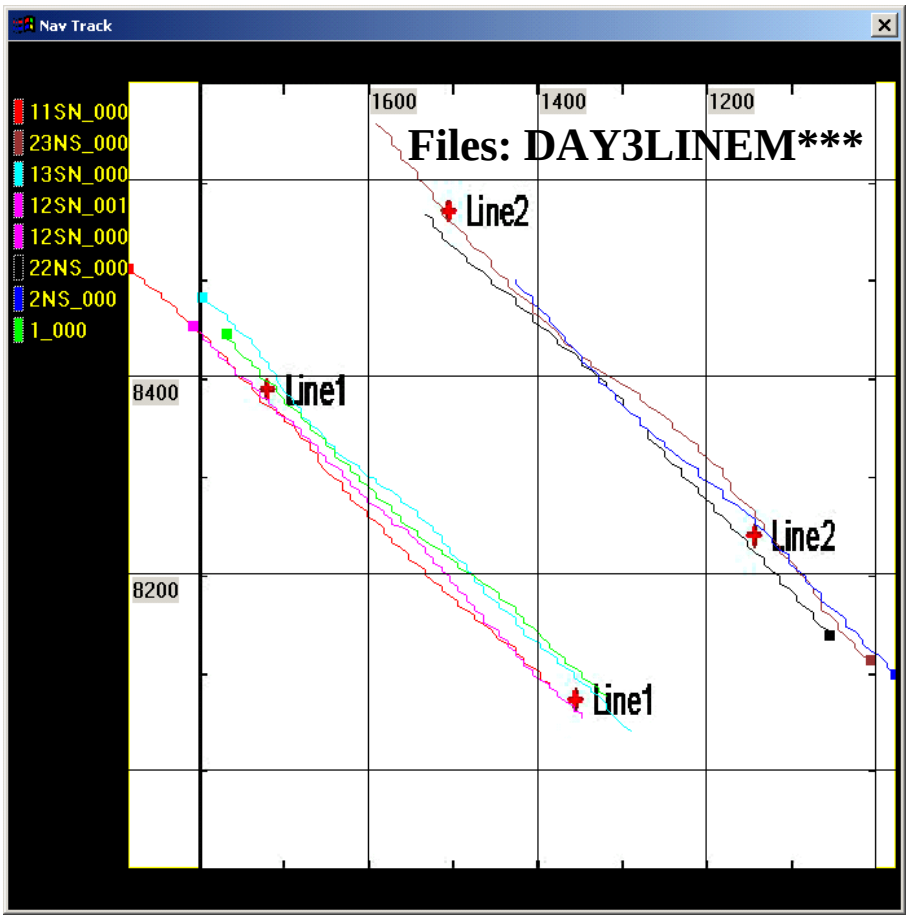


Figure C - 1. Tracklines for BOSS -160/RTG data collection at the sand site on 19 October 2006 with the BOSS at a towing depth of 6.2 feet. The planned tracklines were at 2 and 4 meter offsets to the centerline.

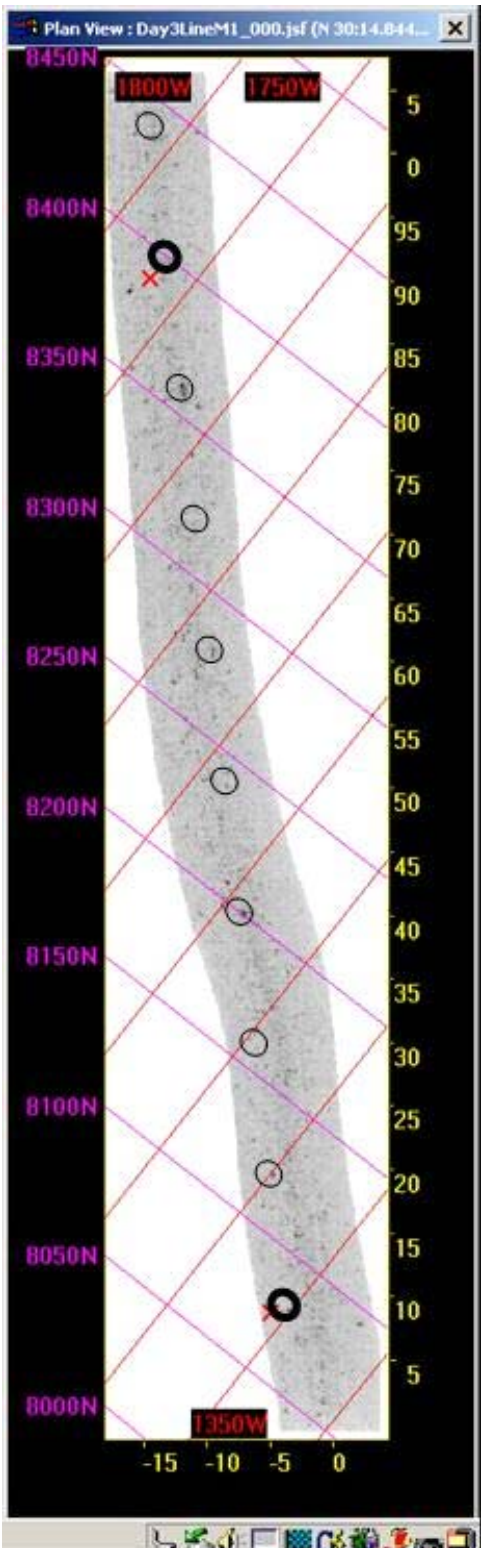


Figure C - 2. Multi-aspect image of trackline Day3LineM1 collected on 20 October 2006 at mud site with target overlay

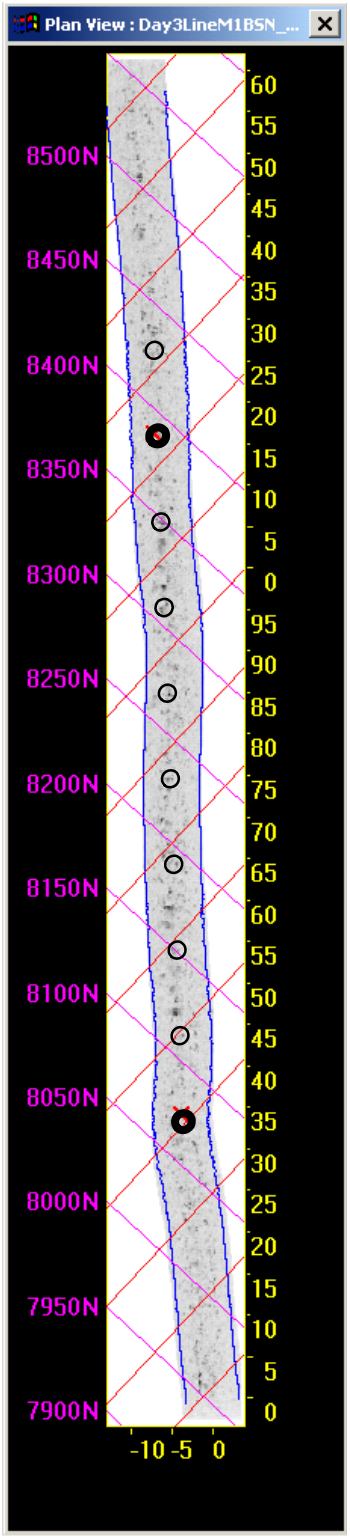


Figure C - 3. Multi-aspect image of trackline Day3LineM1BSN collected on 20 October 2006 at mud site with target overlay

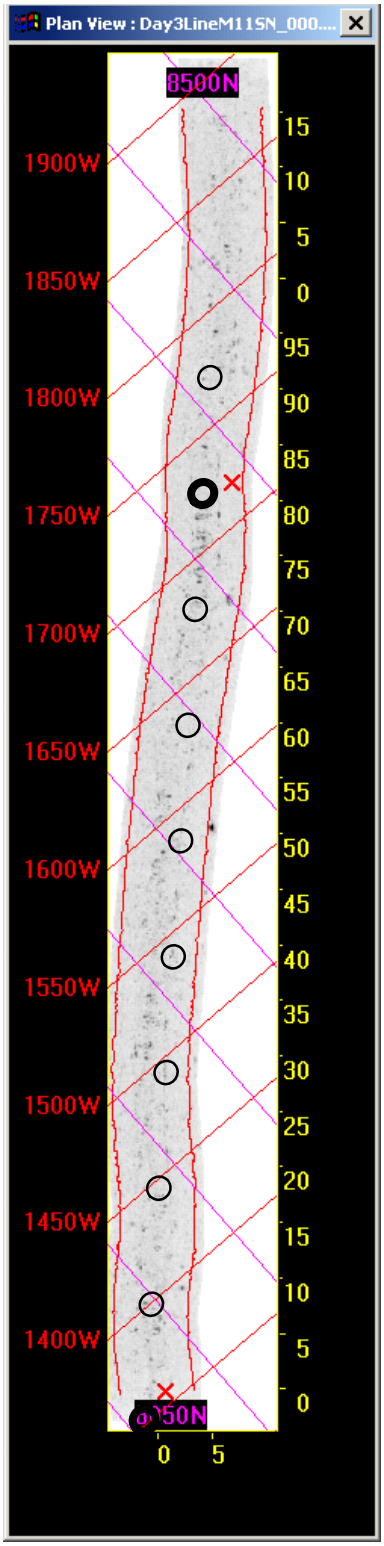


Figure C - 4. Multi-aspect image of trackline Day3LineM11SN collected on 20 October 2006 at mud site with target overlay

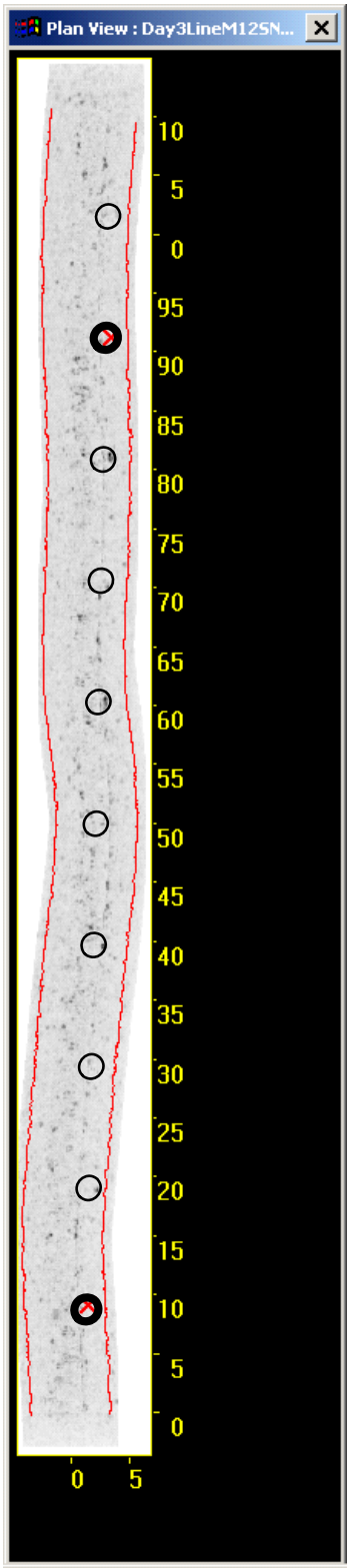


Figure C - 5. Multi-aspect image of trackline Day3LineM12SN collected on 20 October 2006 at mud site with target overlay

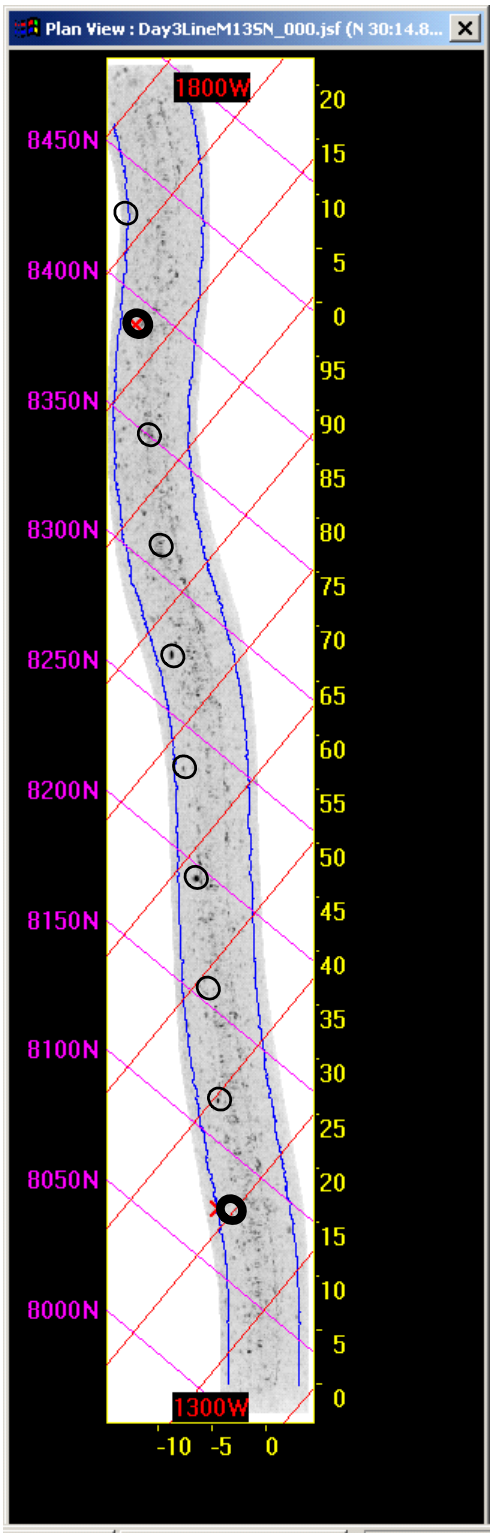


Figure C - 6. Multi-aspect image of trackline Day3LineM13SN collected on 20 October 2006 at mud site with target overlay

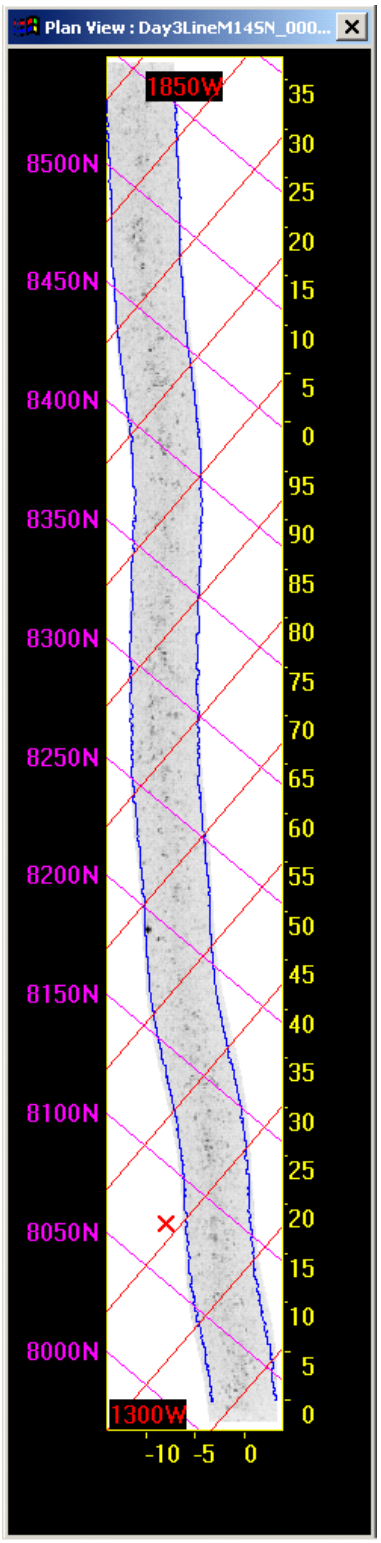


Figure C - 7. Multi-aspect image of trackline Day3LineM14SN collected on 20 October 2006 at mud site. Targets are not within sonar range.

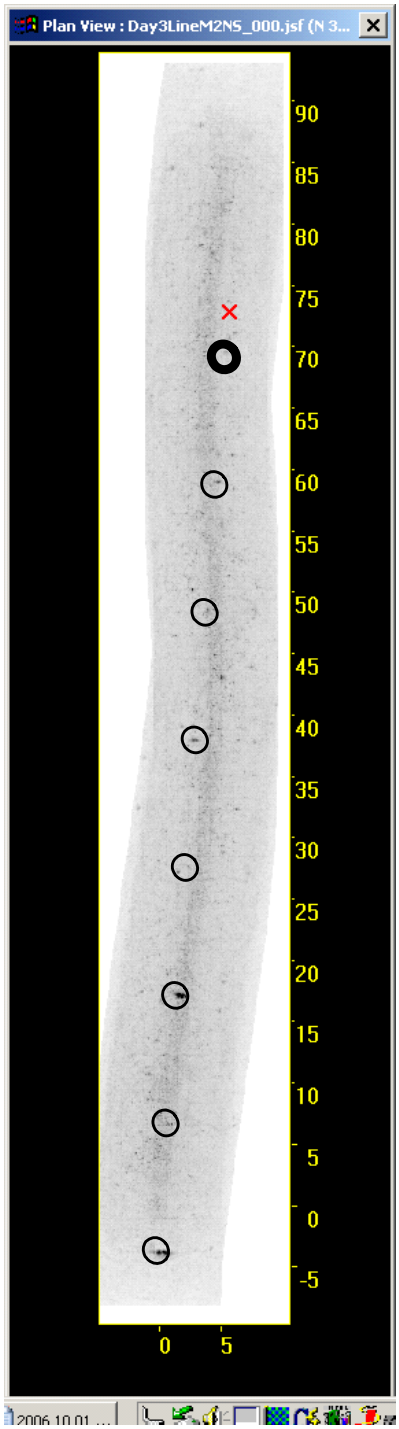


Figure C - 8. Multi-aspect image of trackline Day3LineM2NS collected on 20 October 2006 at mud site. Line was aborted before completion.

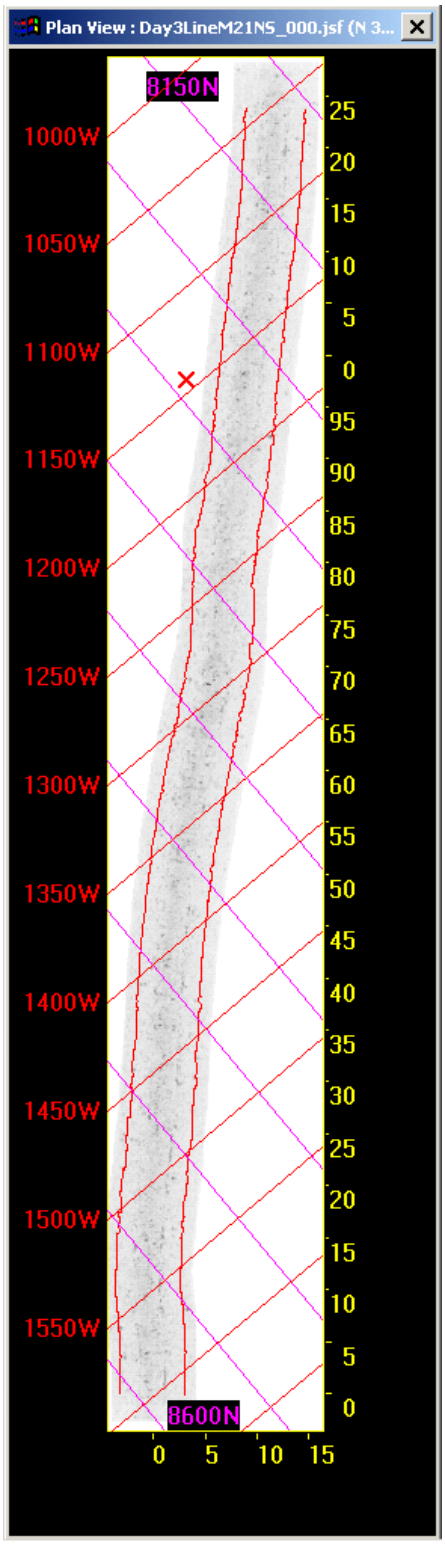


Figure C - 9. Multi-aspect image of trackline Day3LineM21NS collected on 20 October 2006 at mud site. Targets are not within sonar range.

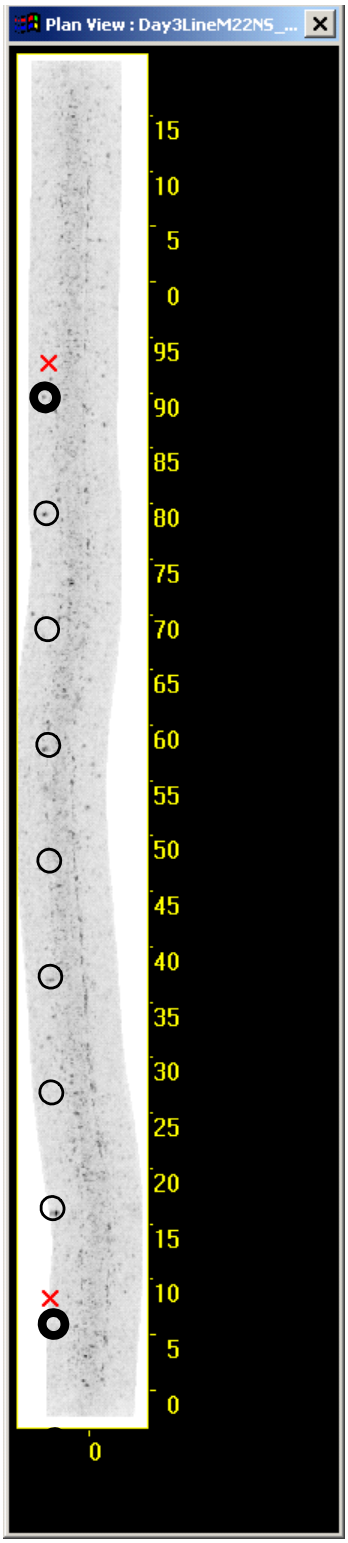


Figure C - 10. Multi-aspect image of trackline Day3LineM22NS collected on 20 October 2006 at mud site with target overlay.

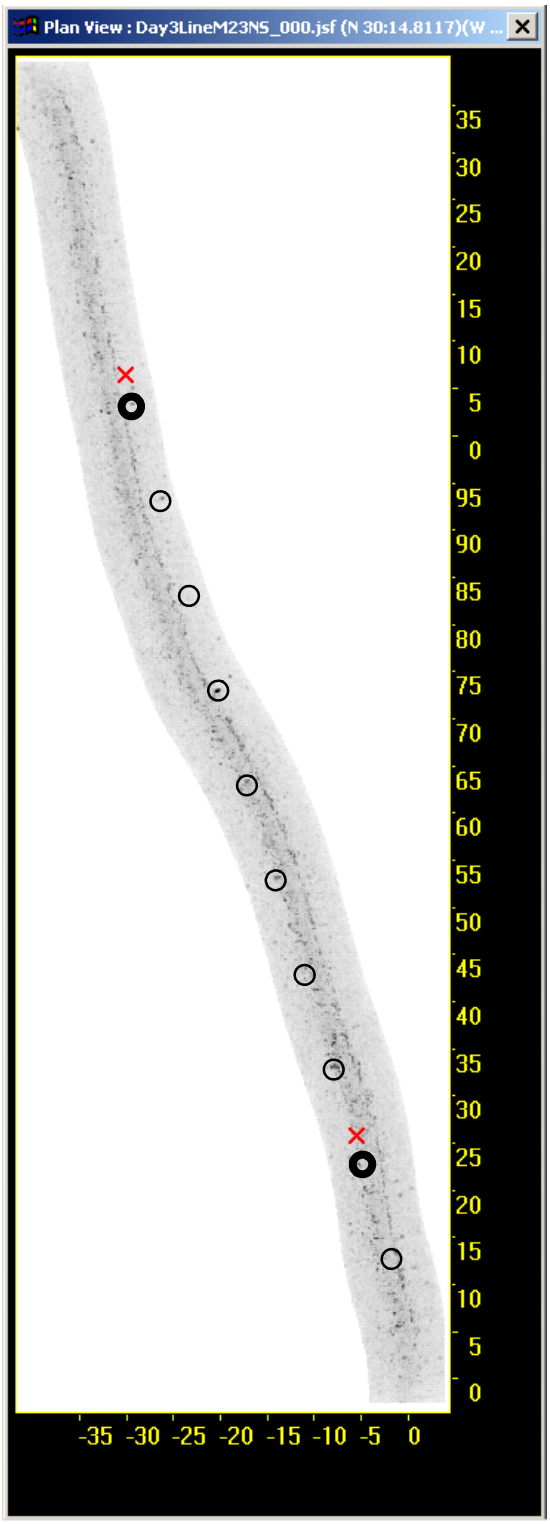


Figure C - 11. Multi-aspect image of trackline Day3LineM23NS collected on 20 October 2006 at mud site with target overlay.

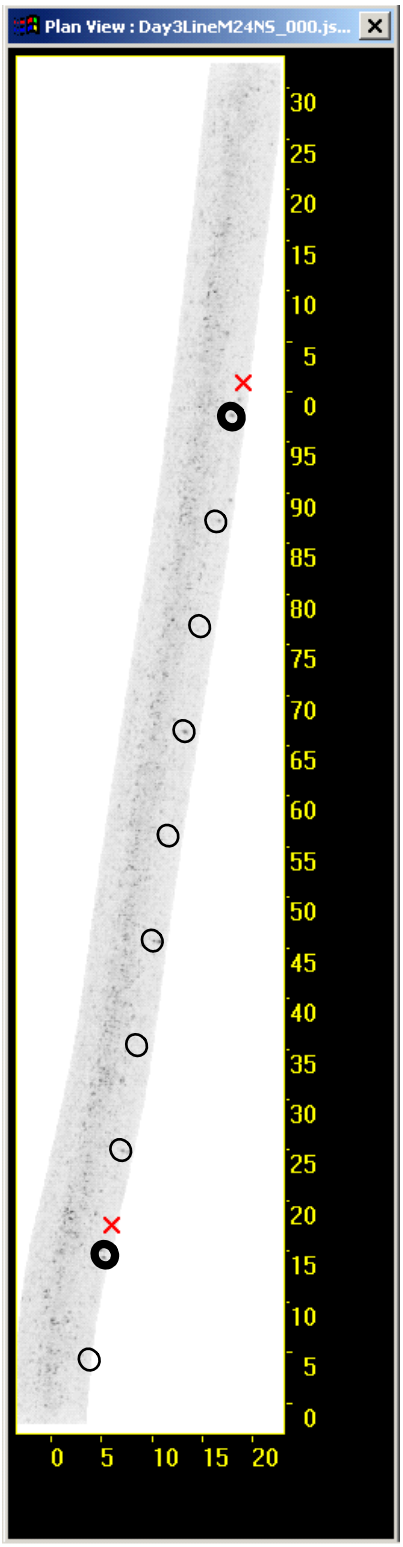


Figure C - 12. Multi-aspect image of trackline Day3LineM24NS collected on 20 October 2006 at mud site with target overlay.

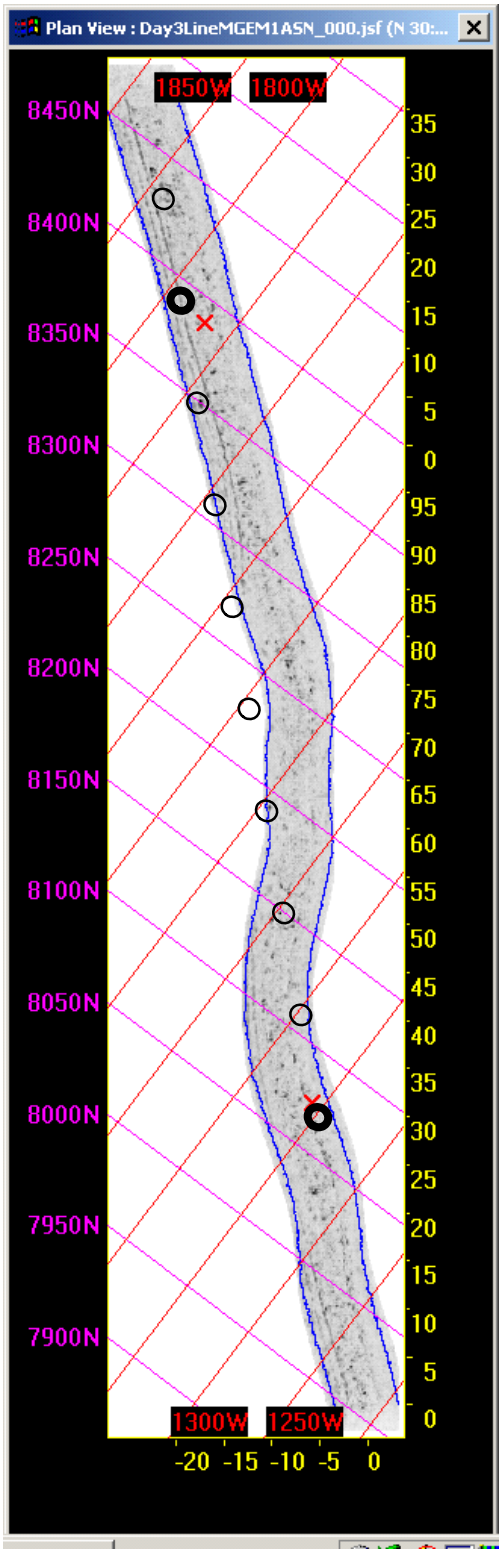


Figure C - 13. Multi-aspect image of trackline Day3LineMGEM1ASN collected on 20 October 2006 at mud site with target overlay. Notice that the GEM3 sled has produced grooves in the sediment-water interface which interferes with BOSS imagery.

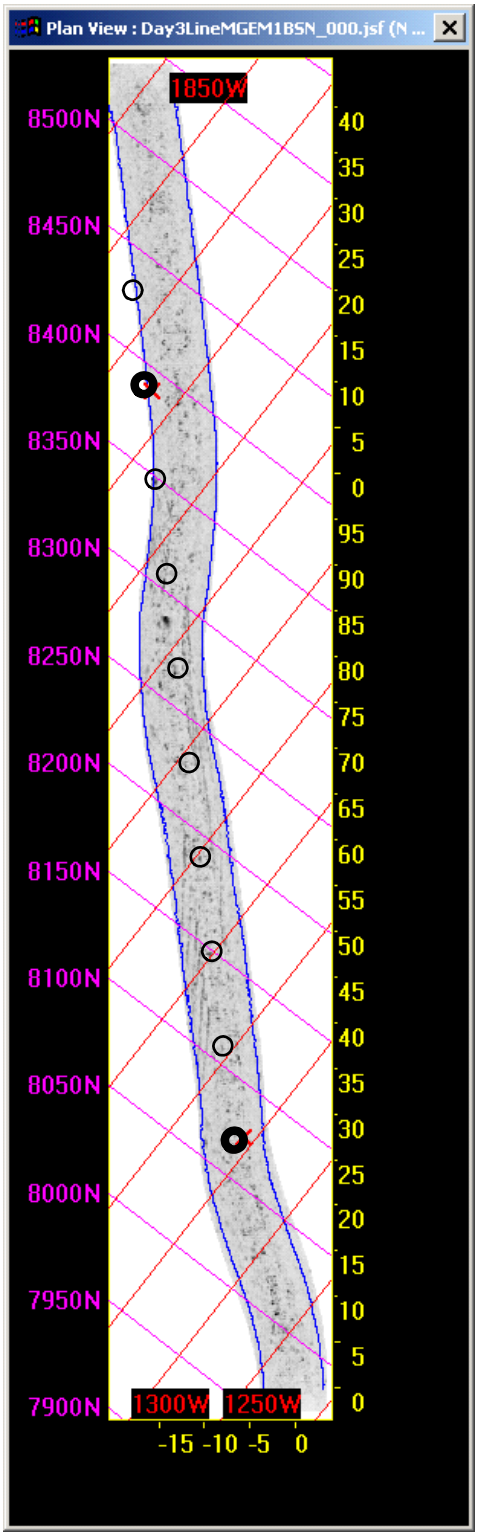


Figure C - 14. Multi-aspect image of trackline Day3LineMGEM1BSN collected on 20 October 2006 at mud site with target overlay. Notice that the GEM3 sled has produced grooves in the sediment-water interface which interferes with BOSS imagery.

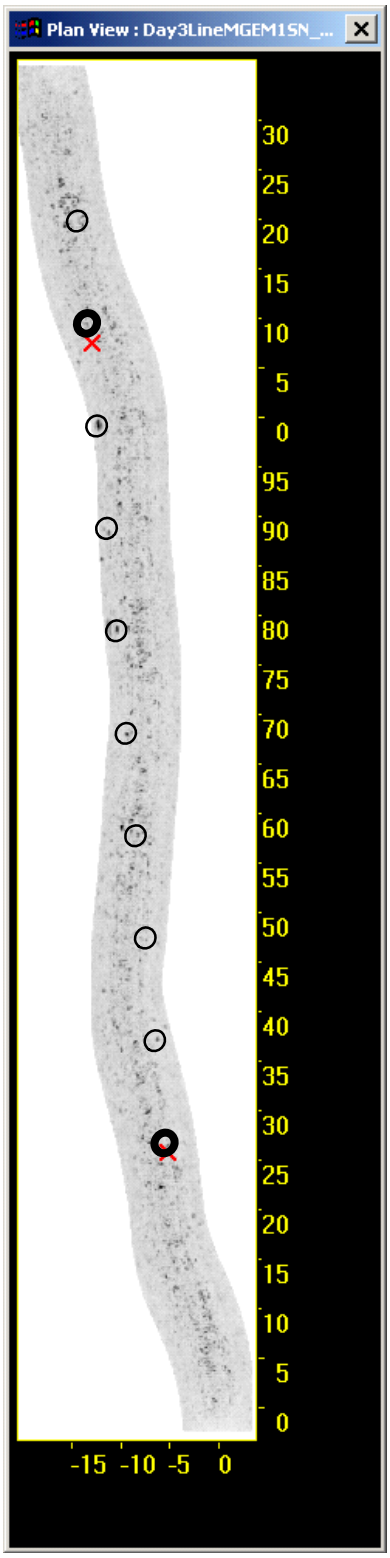


Figure C - 15. Multi-aspect image of trackline Day3LineMGEM1SN collected on 20 October 2006 at mud site with target overlay.

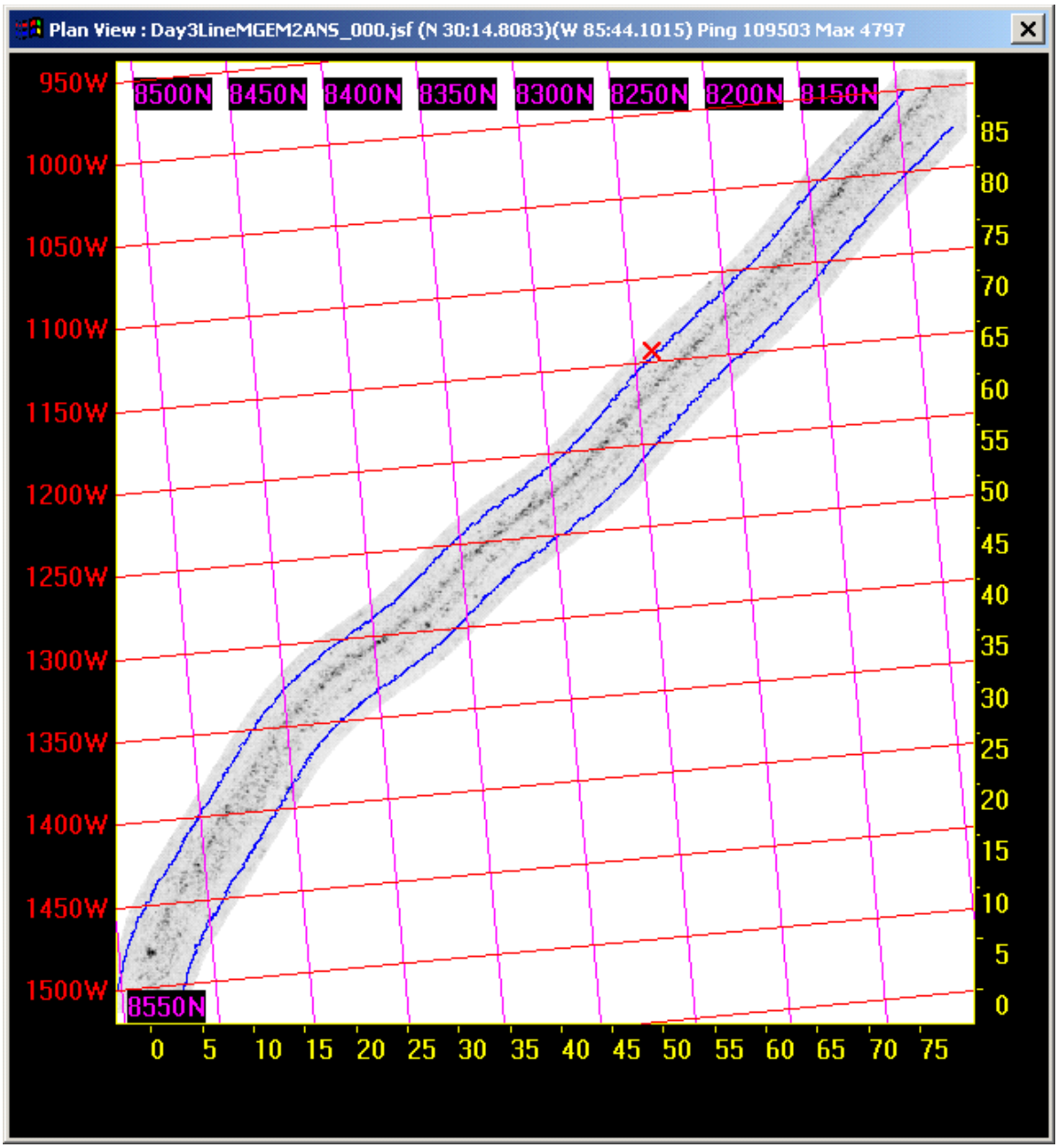


Figure C - 16. Multi-aspect image of trackline Day3LineMGEM2ANS collected on 20 October 2006 at mud site. Line was aborted before completion.

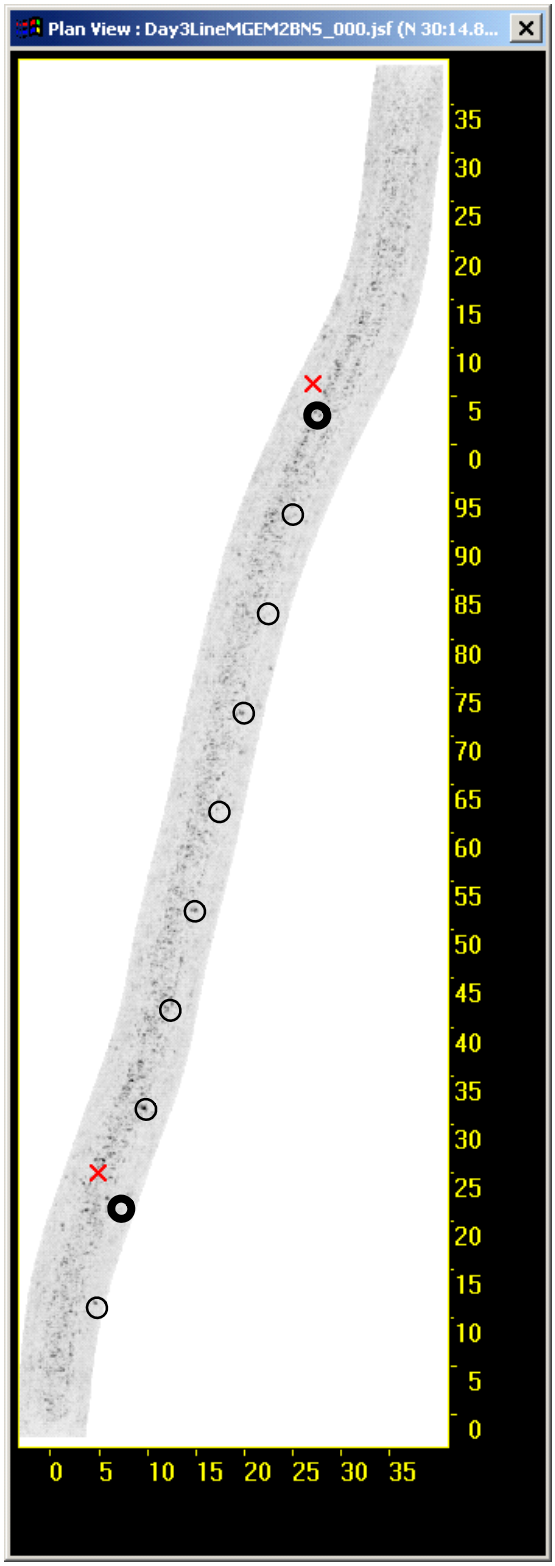


Figure C - 17. Multi-aspect image of trackline Day3LineMGEM2BNS collected on 20 October 2006 at mud site with target overlay

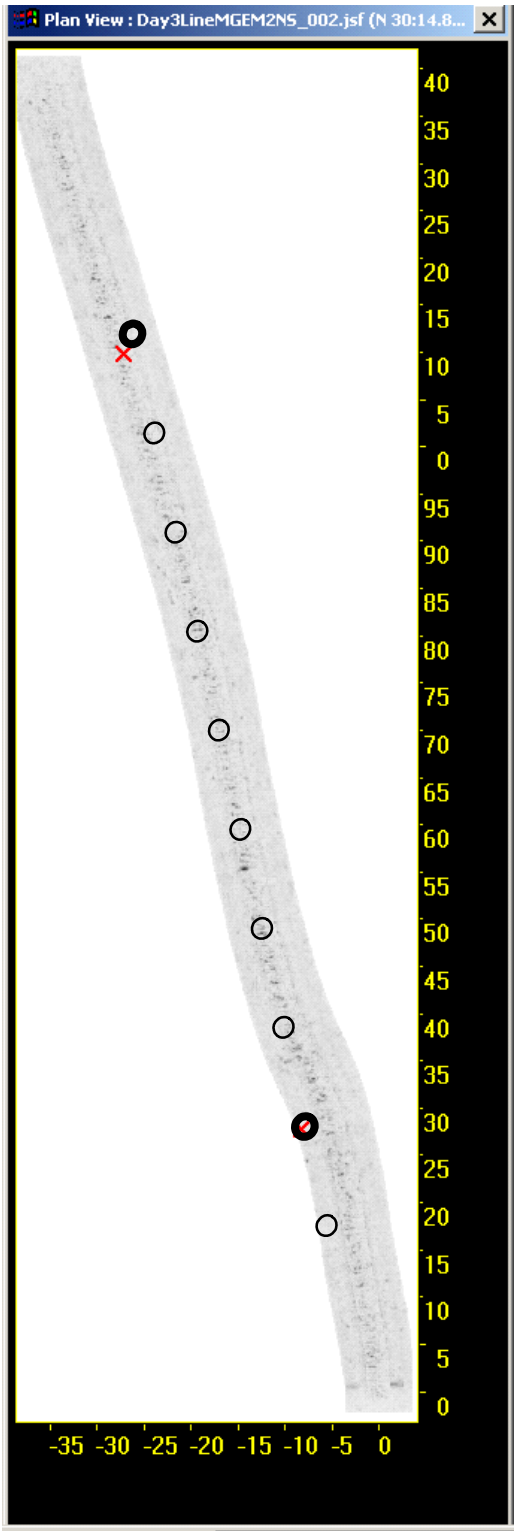


Figure C - 18. Multi-aspect image of trackline Day3LineMGEM2NS collected on 20 October 2006 at mud site with target overlay