FINAL REPORT

Development and Testing of an Engineering Prototype for a Marine Version of the Berkeley Unexploded Ordnance Discriminator (BUD): Phase II

SERDP Project MR-2321

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H. Frank Morrison
Marine Advanced Research, Inc.

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14. ABSTRACT

An operational marine version of the Berkeley Unexploded Ordnance Discriminator [BUD] has been built and tested in shallow seawater. The system was built in response to a need to develop a geophysical system for detecting and characterizing UXO in the marine environment. Such a system must detect a metallic object, provide its depth and symmetry properties that allow it to be identified as an intact UXO. A three-component transmitter is mounted on a planar base and four three-component receivers are mounted on the same base and on the corners of a square pattern centered on the transmitter. Differences in field at symmetrically located receivers cancel the response of the seawater and of the air-sea interface above the system. A marine sled-like vessel provides complete enclosure of the electronics in sea-water without exposing the sensors to turbulent flow. The vessel displayed excellent stable motion when towed on the bottom. New air-cored induction coils coupled with low noise amplifiers provide high stability and a critically damped response. The coils are mounted orthogonally in rigid sealed blocks to provide three-component sensor modules. A first stage of amplification at the sensors provides a high level signal from a low impedance source to carry the signals, without added coupling noise, over cables to the data acquisition module where the signals are differenced in software processing. The current pulse in the transmitter coils is a bipolar half-sine of 5 msec. duration with a repetition rate of 12.5 Hz. A new pulser, based on the BUD pulser provides a peak moment of 2000 Amp turns m^2 with current pulses of 200 A and a net power consumption of 400 Watts. Tests of the prototype on land showed that the system recovered the diagnostic polarizabilities of a 6 inch (152.4 mm) steel test ball to over 57 cm depth and a typical 105mm UXO to over a meter. The tests yielded identical difference transients in air and in seawater in the absence of the target showing that the effects of the seawater and the air-sea interface were canceled. The marine tests with the 105mm target were not successful: the polarizability curves were relatively correct but their amplitudes were in error as were the estimates of depth and orientation.

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Acronyms

ADC	Analog to digital converter
BUD	Berkeley Unexploded Ordnance Discriminator
FPGA	Field programmable gate array
LBL	Lawrence Berkeley National Laboratory
MBUD	Marine version of BUD
UXO	Unexploded ordnance

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Abstract

An operational marine version of the Berkeley Unexploded Ordnance Discriminator [BUD] has been built and tested in shallow seawater. The system was built in response to a need to develop a geophysical system for detecting and characterizing UXO in the marine environment. Such a system must detect a metallic object, provide its depth and symmetry properties that allow it to be identified as an intact UXO.

A three-component transmitter is mounted on a planar base and four three-component receivers are mounted on the same base and on the corners of a square pattern centered on the transmitter. Differences in field at symmetrically located receivers cancel the response of the seawater and of the air-sea interface above the system. A marine sled-like vessel provides complete enclosure of the electronics in sea-water without exposing the sensors to turbulent flow. The vessel displayed excellent stable motion when towed on the bottom.

New air-cored induction coils coupled with low noise amplifiers provide high stability and a critically damped response. The coils are mounted orthogonally in rigid sealed blocks to provide three-component sensor modules. A first stage of amplification at the sensors provides a high level signal from a low impedance source to carry the signals, without added coupling noise, over cables to the data acquisition module where the signals are differenced in software processing.

The current pulse in the transmitter coils is a bipolar half-sine of 5 msec. duration with a repetition rate of 12.5 Hz. A new pulser, based on the BUD pulser provides a peak moment of 2000 Amp. turns m^2 with current pulses of 200 A and a net power consumption of 400 Watts.

Tests of the prototype on land showed that the system recovered the diagnostic polarizabilities of a 6 inch (152.4 mm) steel test ball to over 57 cm depth and a typical 105mm UXO to over a meter. The tests yielded identical difference transients in air and in seawater in the absence of the target showing that the effects of the seawater and the air-sea interface were canceled. The marine tests with the 105mm target were not successful: the polarizability curves were relatively correct but their amplitudes were in error as were the estimates of depth and orientation.

Objective

The objective of this research is to build and test a fully operational marine version of the BUD system, and to demonstrate its discrimination abilities over seeded UXO targets. BUD has a fundamental transmitter-receiver configuration that inherently cancels the seawater response and this project uses a modified BUD system that is optimized for marine use. The major questions are how well a sled structure can be towed over an uneven, obstacle strewn, sea bottom, how well the paired receiver concept will cancel the seawater response, what the noise level of the system will be while being towed, and how well the system can be positioned (both for towing over a known target and for precisely locating targets found in a survey). The marine version that has been developed will henceforth be referred to as MBUD. In Phase I of this project a rough prototype of MBUD was developed for static tests and used a simple frame structure with simple electronic connections. *The prototype developed in Phase I proved that MBUD effectively cancels the seawater response and the sea-air interface response and yields the free-air target response.*

Background

The Berkeley unexploded ordnance discriminator (BUD) was designed from first principles using numerical models of simple shapes to determine the optimum configuration of transmitters and receivers needed to obtain the principal polarizabilities of a buried conductor. The goal was to use the symmetry properties of intact UXO to distinguish them from scrap.

BUD was designed for transient measurements: the secondary fields from the body were measured after the primary energizing magnetic field pulse (in this case series of alternating polarity half sine pulses) was terminated. Generally transient methods are used in EM systems where the transmitter and receiver are close together and the desired secondary fields from a target are very small compared to the direct primary field but are easily measured after the primary field is turned off. It was found that if a target body is illuminated with fields of different polarizations, provided by three orthogonal loop transmitters, and multiple transient field measurements are made with receivers close to the system, then the three orthogonal equivalent dipole polarizabilities of the target can be determined. A complete theoretical explanation can be found in published papers 1 – 10 in Literature Cited. BUD has been successfully demonstrated at a number of

munitions sites around the country. Its fundamental configuration can be modified so that it will function in seawater as well as it does on land. It avoids a fundamental problem that has not been addressed by other marine electromagnetic UXO systems that have simply been waterproofed versions of land-based systems.

The fundamental problem with marine detection/discrimination is that the response of the seawater itself is comparable to, or larger than, the response of the target. If the seawater response were cancelled to 1 % of its value by the differencing scheme discussed below the target response rises well above the difference response for most of the useful time window of the transient.

The unique feature in the BUD system of measuring the differences of receivers placed symmetrically on either side of the transmitters cancels the seawater response because the induced currents in the seawater are also symmetric with respect to the transmitters. If all the symmetric receivers are in a single horizontal plane parallel to the air-sea interface and to the sea bottom then the layered response of these interfaces is also cancelled in the differences. The UXO target closer to one of the receivers then stands out against a null field background with essentially the same response as it would have in the land-based system. MBUD has capitalized on this unique feature of the BUD system and appears to have the same discrimination abilities as BUD for objects larger than 60 mm on or beneath the ocean bottom.

This report details the steps leading up to the marine tests of an operational prototype of the MBUD system.

The response of a conducting object in a conducting medium

The presence of highly conducting seawater introduces three phenomena that are not noticed when the conducting target is embedded in the relatively modest conductivity of typical land soils. The first is that there is a large transient response from the conducting seawater itself. The second is that there is some attenuation of the primary field at the target and further attenuation of the target signal back to the receiver. In the frequency domain this is manifested as a change in amplitude in phases of the primary field as it reaches the target and a further change in amplitude and phase as it returns to the receiver. In the transient this can cause a reversal in sign of the transient, called a cross-over, at some, usually early, time in the transient.

Again this is not noticed in land-based systems because the soil conductivity is not high enough to introduce appreciable attenuation at the late times that are typically measured. Finally there is an electric dipole moment induced in a conducting target by the currents flowing in the conducting seawater. This is shown schematically in the two modes of induced fields shown in Figure 1.

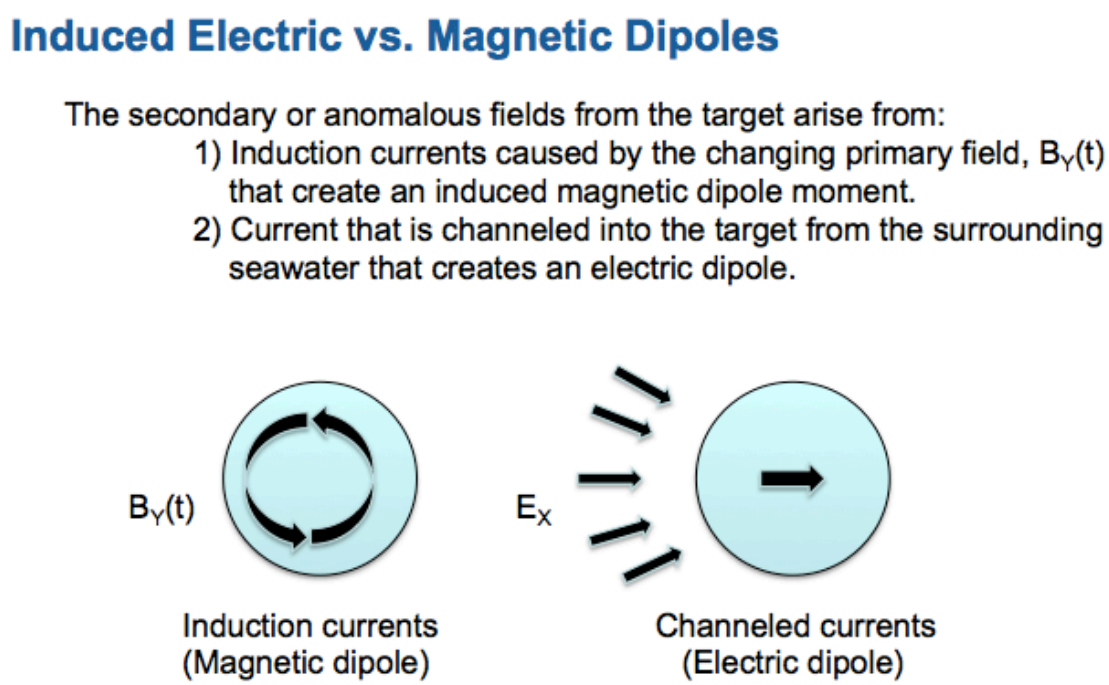

Figure 1. Induced magnetic and electric moments in conducting objects in seawater.

These currents are channeled into the conductor and they produce magnetic and electric fields from the induced electric dipole. The induced electric dipole moments are in general orthogonal to the induced magnetic moments and the secondary magnetic fields they produce at a receiver can be in the same direction as common orthogonal to or opposite to the secondary fields from the magnetic dipole. The induced electric dipole depends very much on the surface condition of the target; for example an insulated steel ball would have no induced electric moment and would behave very much as it would in free space albeit with a slight attenuation caused by the seawater between the transmitter and receiver. In Phase I of this project it was shown that under the assumption that the electric moments were negligible the response of a typical UXO in sea water was simply the addition of the sea water response with the target response in air: there was

no effective coupling of the two. Some of the results obtained in the first marine tests suggested that the induced electric dipole might be important. The numerical program for calculating the magnetic fields from an arbitrary loop source was rewritten to obtain the fields in a conducting medium including the induced electric moment. Figure 2 shows the transient response of a 15.24 cm steel ball 1.0 m away from the MBUD transmitter in air, in seawater without the electric dipole (as previously modeled) and in seawater including the electric moment. For practical UXO systems the effects of the induced electric moment occurs at early times and are probably not seen in the window used for interpretation. Future systems might use very early time measurements to characterize additional surface properties of the object although as a practical matter it is technically very difficult to completely shut off the current in the coil. Small leakage currents through the SCRs persist after shutoff and consequently create a field at the receivers that distorts the target secondary field at early times.

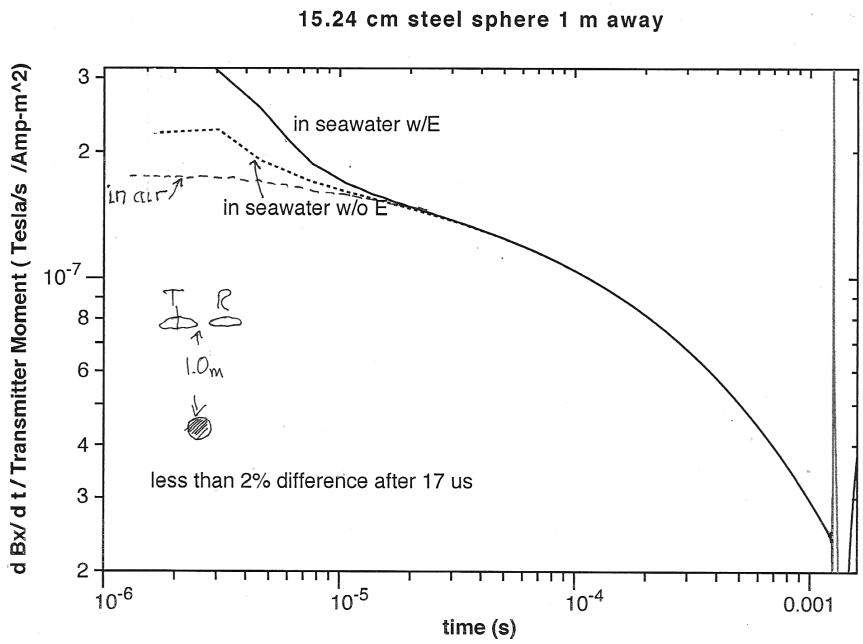

Figure 2. Transient response of target in air and in seawater with and without induced electric dipole contribution.

Optimum transmitter receiver configuration

The configuration selected for MBUD in Phase I is shown schematically in Figure 3. It uses three orthogonal transmitters with four three-component receivers arranged on the base plane of the transmitter

‘cube’. This configuration was reanalyzed and the design represented by Figure 3 was selected for MBUD.

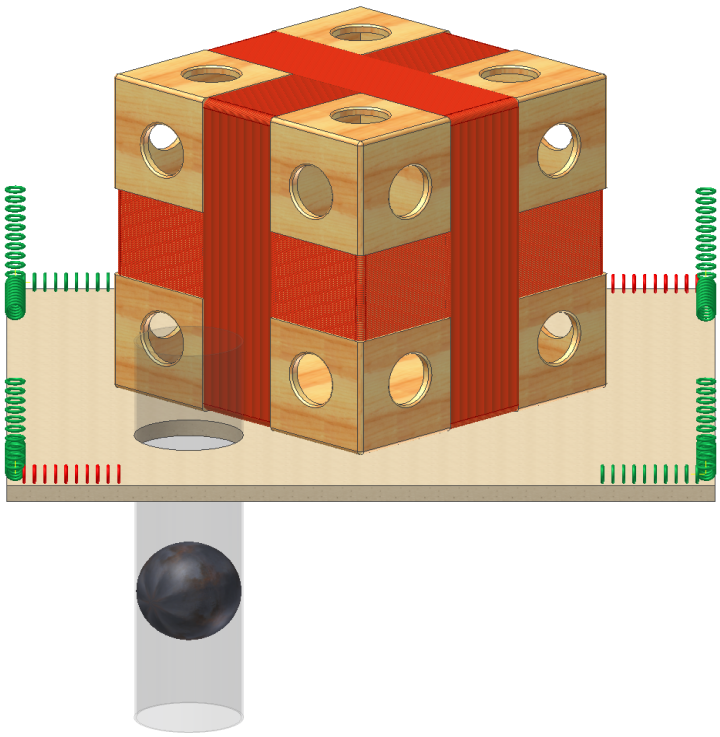

Figure 3. Schematic transmitter-receiver configuration for MBUD

In the MBUD configuration four 3-component receivers are placed on horizontal plane beneath a three-component transmitter cube. Diametrically symmetric receivers see the same response from the seawater *and from the horizontal air-sea interface* and both responses are cancelled in the difference. In some cases the receiver outputs of a particular pair for one transmitter coil are of the same sign and must be differenced by the acquisition for another coil they are of opposite sign and must be summed. Figures 3 also shows schematically the position of a target relative to the structure.

Based on this analysis the MBUD system was designed to have a 5.0 msec. pulse length. It will be seen in the section below on the design of the pulse forming circuit that this has the added advantage of reducing the demands on the switches in that circuit.

MBUD Receiver sensors

It was intended that ferrite cored feedback coils be used for MBUD but a problem was identified in the preparation of the proposal for the current project indicating that the sensor would saturate when exposed to very large fields directly from the transmitter during the current pulse. In relaxing from saturation the ferrite produced an unacceptable transient in the receiver. Further testing in the current project showed that the ferrite transient was time varying and it became evident that these sensors were unsuitable for transient UXO characteristics.

New air core multi-turn induction sensors were designed based on the design used in the original BUD system. The wires are spaced apart to form a flat winding, a single layer solenoid, on a square form13.6 cm on a side. A prototype single coil is shown in Figure 4.

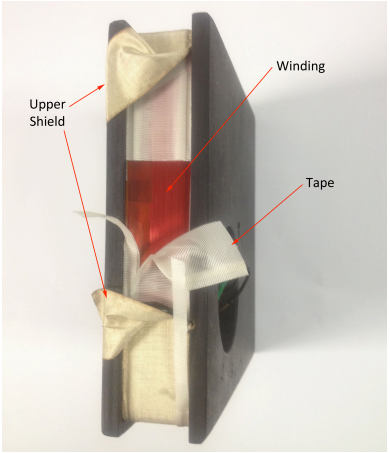

Figure 4. A prototype single solenoidal coil receiver.

The winding is covered with an insulating tape and then covered with an electrostatic shield. The properties of a single such coil are:

Turns: 80
Turns-area product: 1.48
Resonant frequency: 1.2×10^5 Hz
Inductance: 1.8×10^{-3} Henry

Because of the high resonant frequency these coils, when critically damped, have a very fast transient from the primary field shutoff: the response is essentially zero past 30 μsec.

The final configuration for installation in the MBUD vessel is shown in Figure 5. The three orthogonal coils were wound around the sides of a cube and the amplifiers for each coil were placed in recesses in the cube. Traces of the flat solenoids are faintly visible in the photo below.

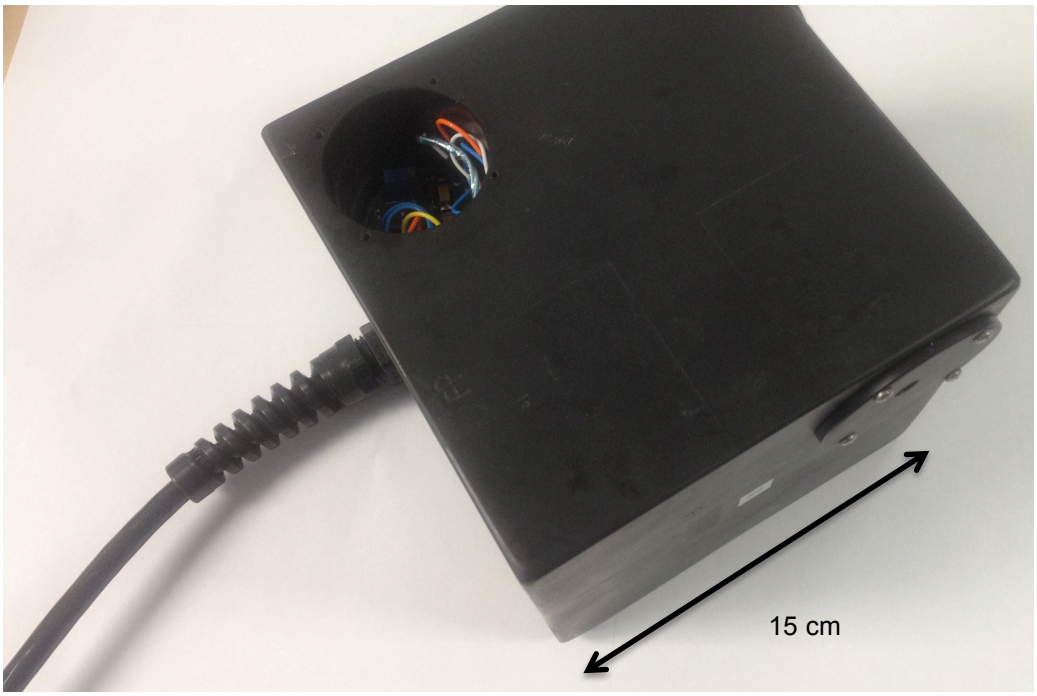

Figure 5. The 3-component cube receiver.

These sensors are very sensitive and, without the weight limitations of BUD, have much higher sensitivity than the receivers previously used in the BUD system. In addition the cube shape lends itself to efficient mounting in a rigid frame.

A problem with the BUD circuit was that although it was fairly easy to achieve critical damping with the adjustable external resistor, the very small change in resonant frequency made it difficult to tune two resonant circuits to achieve accurate analog cancellation in difference mode. As the components of the sensing loop changed slightly in response to temperature variations the corresponding differences of the transient signal became a significant source of noise. In the final system used in this project each coil has its own amplifier and has an individual channel in the data acquisition unit.

The new MBUD sensors have about half the noise of the BUD sensors. This is a significant improvement: in practice it translates into a signal to noise gain of two, equivalent to doubling the source moment. Since the

MBUD moment is already four times larger than that of BUD, the signal to noise for MBUD is considerably better than BUD.

The individual coil/amplifiers are each connected to the central acquisition unit. It is important to note that this scheme removes the spurious coupling issues that plagued the BUD system wherein the coils were wired in opposition and then fed to the amplifiers of the ADC over long wires snaking across the transmitter coils. In MBUD the initial gain at the coil provides a low impedance source and relatively high level signal that is relatively immune to spurious coupling on the connecting cables. The new configuration is only possible because in MBUD the amplifiers can sustain higher voltages before saturation, the sensor/amplifiers are relatively farther from the transmitter (in BUD the flat air-core sensors were mounted *on* the transmitter frame and some were maximally coupled to one or more of the transmitter windings) and the orientation and location of the sensor 'cubes' could be adjusted to minimize the direct primary field coupling.

Data acquisition system

A new digital acquisition and control system has been designed, built and incorporated in the Phase II MBUD. It was found in Phase 1 that the FPGA controlled data acquisition and control system developed for BUD was too specialized and it was cumbersome to adapt to the new MBUD system. The FPGA system itself was 10 years old, the software was not familiar to, or easily modifiable by, MAR personnel. Continued dependence on assistance from personnel at Lawrence Berkeley National Laboratory was problematic and not likely to continue into the future. The new system consists of a simple computer on a chip to provide switching control to the pulser and synchronizing pulses to a commercially available, fast, 24-bit digital to analog converter: Data Translation DT9847. This new system was assembled quickly, tested on the MBUD prototype and interfaced to the data processing and interpretation routines on the external control laptop computer.

The final version of the data acquisition system developed and tested in this project consists of three 4 channel DT9847 data acquisition modules. The three acquisition modules are mounted in a separate sealed container shown in Figure 6. Sampling, triggering and control of the acquisition units was effected from the small microcomputer that also controlled the pulse timing and sequencing for the transmitter: the common timing and control

unit assured synchronization of the transmitter pulses and the recorded transients. This data–control synchronization is a non-trivial problem that has not been fully resolved in the final system. The digital files of the transients from the acquisition unit were passed through a USB cable to the controlling PC computer. Initially the data acquisition unit was placed in the marine sled and only digital data was sent to the tow vessel on the surface. Serious leakage problems, of even small amounts of moisture, caused many failures of the data communication system during field tests. In the end the entire system was reconfigured so that the analog signals from the receiver cubes were sent to the surface and digitized there. Unfortunately this modification to the system did not solve the synchronization problems and control pulse problems have resulted in serious problems in signal averaging the transients as can be seen in the marine tests described below.

The acquisition module itself, though not used in the vessel, was not modified for surface operation. It is shown in the photo of figure 6 below.

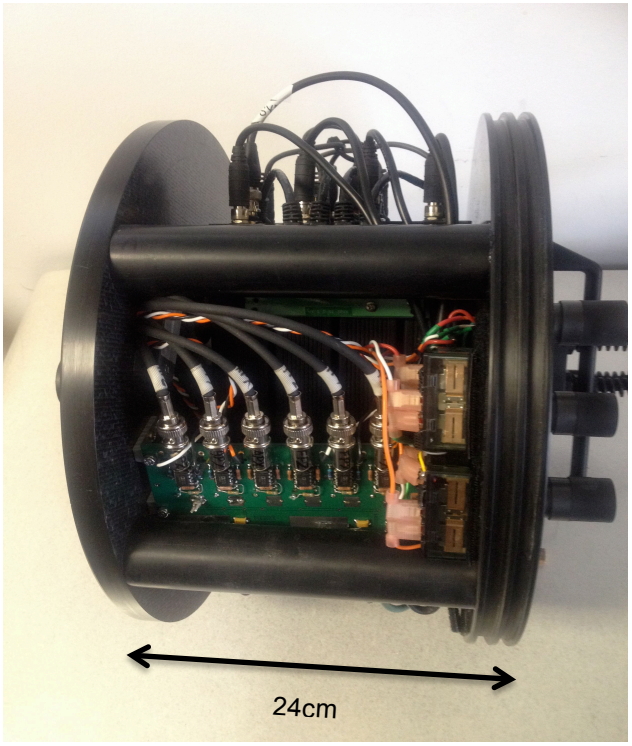

Figure 6. The 12 channel data acquisition module

High-power pulser and transmitter cube

The pulser design for MBUD is a modified version of the BUD design. The MBUD coils have a different inductance than BUD and the pulse length is 5 msec. rather than 1.0 msec. necessitating different capacitors. Because of higher design current pulses the SCR switches also had to be different.

The basic MBUD pulser was built and described in Phase I. It was rebuilt with new components for the current project but the technical description, component specifications etc. are the same as described in the Phase 1 Final Report. It is shown in Figure 7 below.

The low voltage triggers for the SCRs are generated by a commercially available microcomputer that is programmed by a PC through a USB interface. Once the microcontroller board is programmed, the role of the PC in changing the pulsing configuration can be substituted with a switch array attached to the microcontroller's I/O port. These triggers are inputs to the gate drivers that generate the required transmitter coil current pulse format.

The current through the transmitter coils is measured with a current transformer so that the appropriate power supply voltage can be determined. The current monitor uses a separate channel of the data acquisition system. This channel also has sufficient bandwidth to characterize transient behavior during the turn-off of the transmitter coil current.

In general, it is preferred to run an adjustable power supply in a voltage regulating mode after setting the current limit to just above what is required to meet the pulse format requirements. The current limit can then be used as a fault indicator and can also limit energy that can be deposited into a fault such as a short circuit. For a single output level during marine tests, a DC battery is used as the primary power source.

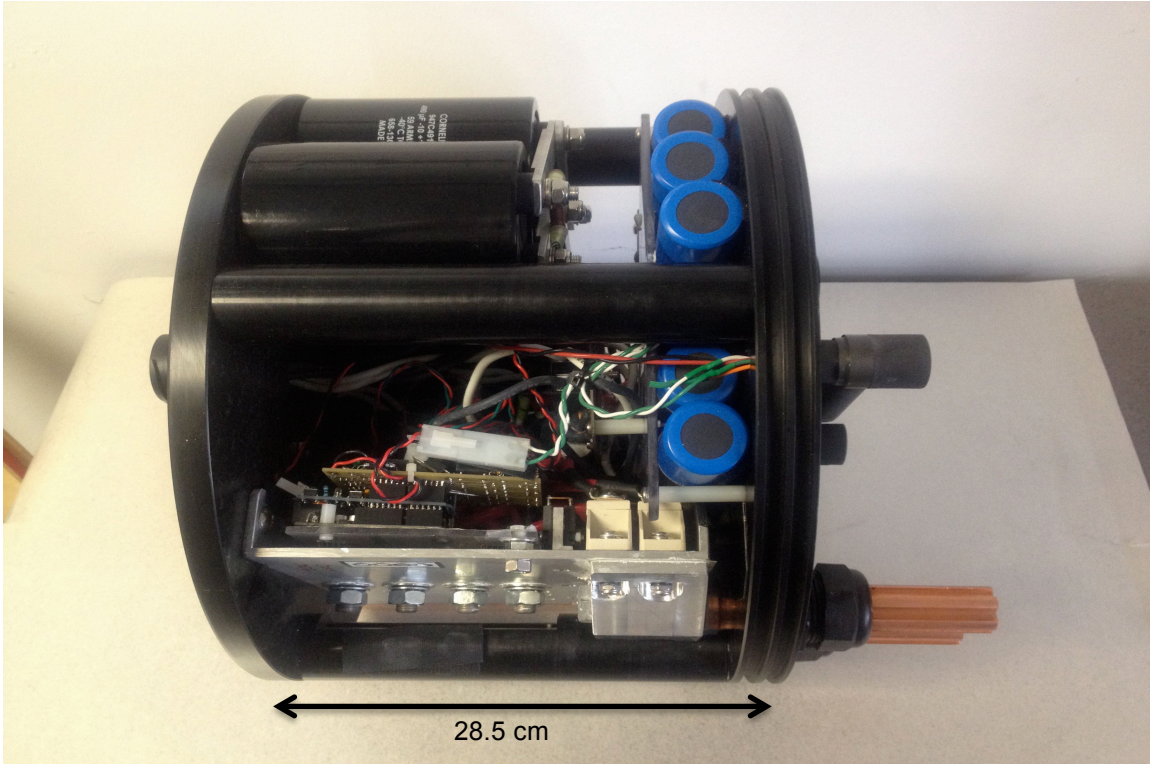

Figure 7. ¢KŜ a . ¦5 tdzfăŜℕ

The pulser module is compact and requires some heat exchangers that are visible in Figure 7 as the copper rods extending from the right hand side of the unit.

The three axis transmitter is shown in Figure 8. The transmitter coils are wound as flat solenoids around the cube form. The final specifications are shown with the photo below.

Specs:

20” (0.508m) cube
40 turns/coil
Peak current: 200 A
Peak moment: 2000 Am^2 [BUD peak moment: 500 Am^2]
Half-sine pulse width: 5 msec
Pulse repetition freq: 25 Hz

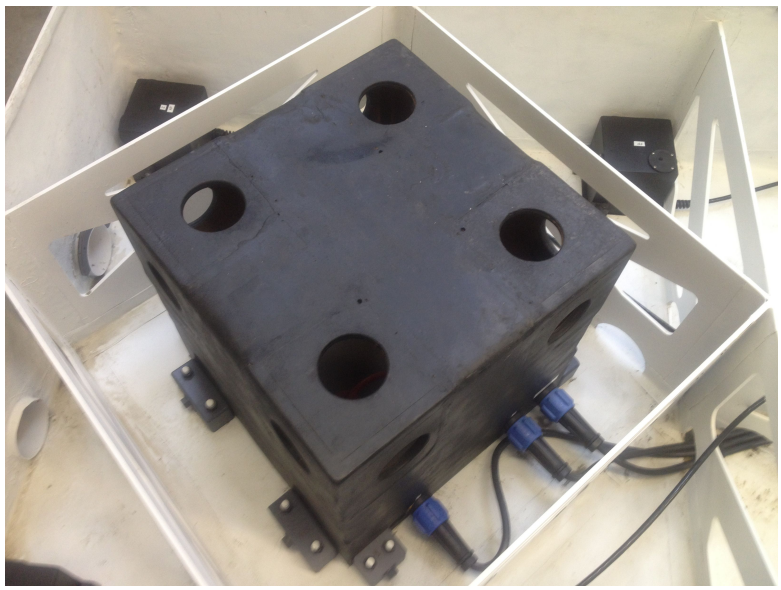

Figure 8: The 3 axis transmitter cube

The pulser-receiver system developed for the MBUD system, like that in its predecessor BUD system, displays a transient signal after turn-off that is unrelated to secondary fields from conductors but seems to arise from within the system. An example of this transient is shown in Figure 9. This plot shows the transient response of a steel ball target and the transient response with no ball present. The various traces before 10^{-4} seconds are related to early time shut-off transients that are irrelevant because only the transients after 10^{-4} seconds are used in the inversion for polarizabilities. The large transient in the absence of the ball target has been present in all the versions of BUD and MBUD that have been built. To overcome this problem in field surveys the transient data is differenced; transients in areas clear of conductors are recorded and subtracted as the system is moved over the target area.

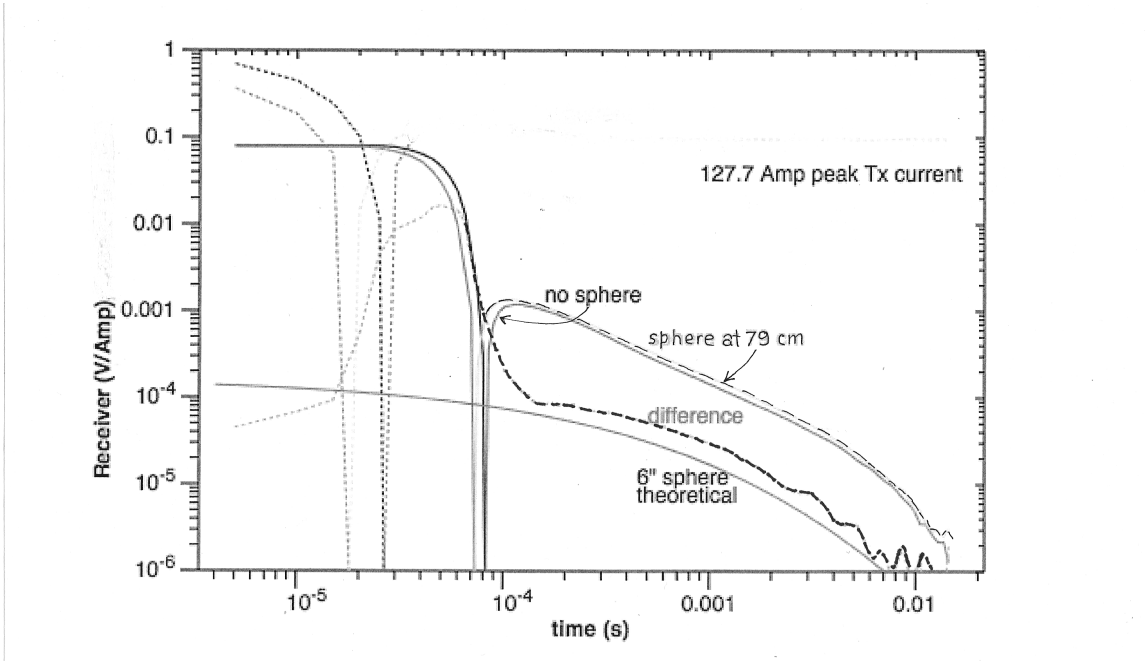

Figure 9. Differencing of residual transients to reveal target response

The differencing procedure is very effective. The difference transient is very close to the predicted transient.

The MBUD underwater sled

It had been planned to do scale model tests in the Berkeley test tank to select an appropriate shape for the MBUD vessel. On careful review of the hydrodynamics of the underwater sled two things became evident: 1) the prototype marine sled will be towed very slowly, at approximately 2 knots. At such slow speeds the only hydrodynamic variable of import is the upward sweep of the underside of the bow [needed to raise the sled above objects on the sea bottom]; 2) it was originally planned to have slight positive buoyancy for the vessel so that it would rise easily in case of running into a submerged object. Under such conditions it is difficult to model either numerically or in a scale model tank the dynamics of the vessel-bottom interface. Instead it has been realized that at low speeds the vessel will have to be negatively buoyant and be towed firmly on the bottom. In which case, except for the easily modeled up-swept bow, the hydrodynamics are quite simple and easily calculated. Consequently the plan was revised to go directly to the full-size model, where weight versus tow characteristics can be determined experimentally.

A design drawing of the MBUD sled is shown in Figure 10 the drawing also shows the layout of the modules described above.

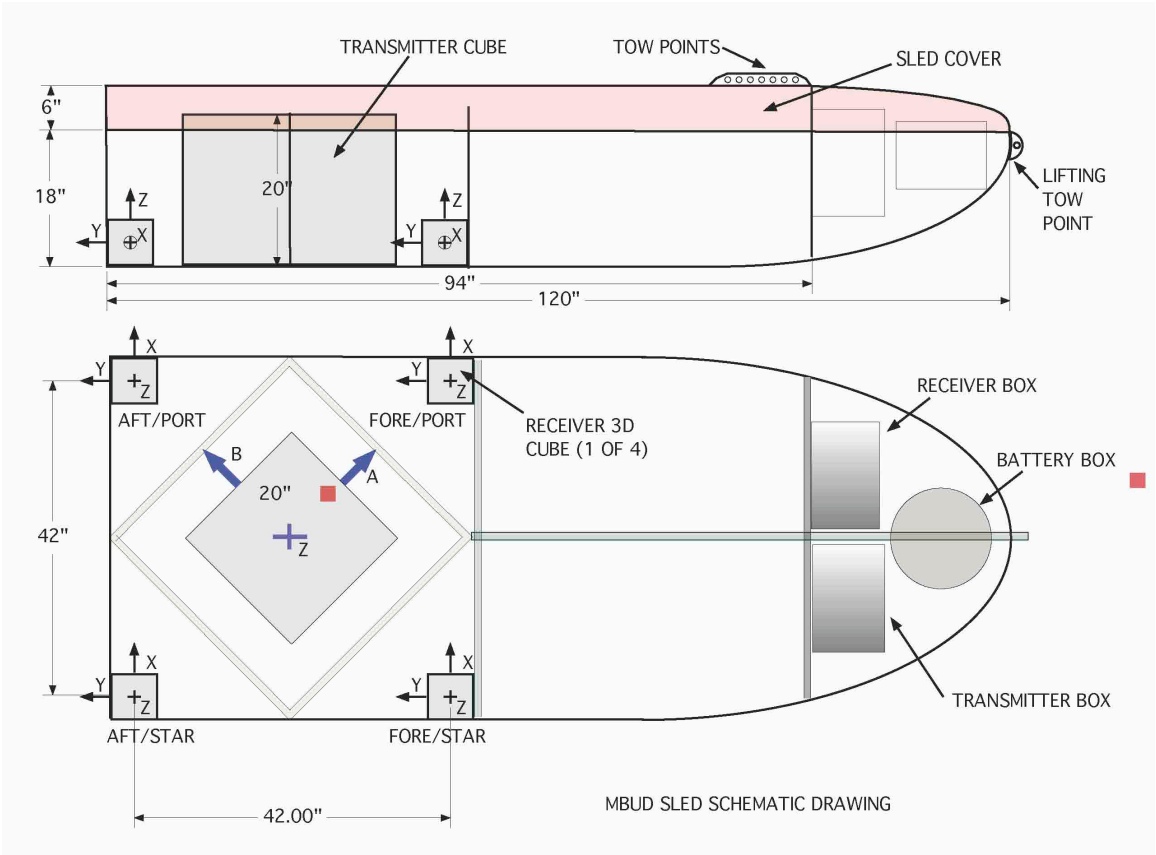

Figure 10. Design drawing of the MBUD sled.

This sled has a slightly upturned bow in elevation view to enable it to lift over obstacles on the bottom. The curvature of the bow was also designed to put the entire vessel just at the point where it would stay on the bottom at 1.5 knots but would lift off the bottom at higher speeds. The goal was to enable the vessel to lift off an object quickly that it hit on the bottom. The bow was also pointed in plan view to enable it to glance off any tall vertical objects on the bottom. The vessel is equipped with tow points on the top of the vessel near the bow and with an additional tow point on the bow itself. The tow cable is attached to the main tow points with a short cable designed to break if the vessel runs in two a large object. When this cord breaks towing is transferred to a second cable attached to the bow lifting point. With this connection the vessel is tilted up and rides over the object.

This design diagram shows the receiver box placed in the bow of the vessel: as noted above the receiver box was moved to the tow vessel in the final system.

A photo of the vessel without its cover showing the layout of the modules is shown in Figure 11 below.

Figure 11. Layout of modules in MBUD vessel

The sled with its cover attached is shown in Figure 12.

Figure 12. Enclosed MBUD vessel

Location and navigation of MBUD for marine tests

The original idea for locating the MBUD vessel during sea trials was to use a Sonardyne acoustic location system. The system entails a sonar source and receiver on the tow vessel and a transponder on the submerged towed vessel. The system has sufficient accuracy to locate the vessel to better than 30 cm at the depths and lengths of tow cable planned for preliminary MBUD testing.

A Sonardyne system was acquired on loan for evaluation. The first test was to place the transponder adjacent to the MBUD receivers to determine whether the pulsing of the acoustic system produced noise in the magnetic field sensors of MBUD. There was no noticeable interference.

A careful design exercise was undertaken to determine where on the tow vessel and on the MBUD sled the acoustic sensors would be placed. In the course of this exercise it was realized that while the MBUD sled could be very well located with respect to the tow vessel, its actual absolute location could only be determined with a very accurate knowledge of the pitch and yaw of the sonic source and receiver on the vessel. Further it was realized that although the correct location might actually be established, the ability to tow the sled to a predetermined location for seeded tests would be very difficult if not impossible to achieve. Such navigational criteria could probably only be met using an active control surfaces on the sled to position it over a desired location. This complexity was so far beyond the modest ambitions expressed in the proposal for Phase II that it was decided to drop the Sonardyne, or any equivalent system, from the tasks of Phase II. It was decided that should the system be shown to work well, test objects could be traversed using a diver to position it as it was towed on the bottom.

The MBUD marine tender

A catamaran vessel was constructed to carry the MBUD vessel on a trailer to the test site, launch it at a launching ramp and then tow it to the test position over a suitable depth of water. The trailer and catamaran structure are shown in the photos below illustrating this sequence.

Figure 13. MBUD in carrying/launching tender on transport trailer.

Figure 14. MBUD on launching ramp

Figure 15. MBUD under tow to test location.

Figure 16. MBUD being lowered to bottom.

The first tests were conducted in about 15 feet of water off the Richmond Marina in San Francisco Bay. The system was lowered to the bottom and measurements were made in the absence of a target to determine whether the noise level was degraded by system operation in seawater. The vessel was then towed along the bottom (Figure 17) again running without targets to determine the noise level while in motion.

Figure 17. Towing MBUD in 15' of water.

Marine tests of MBUD

Averaged values of the transients observed on selected channels, are shown in Figure 18. The dominant feature is the broad transient that is apparently inherent in BUD style systems. The origin of this transient is not understood. The small 'bump' in the transient at 800µsec after turnoff is believed to be due to a leakage current pulse in the SCR. It was present in an early version of the BUD system and disappeared when the SCRs were replaced by LGBTs. Since the final inversion for location and polarizability

is done on differences of the responses of separate receiver channels the bump, and the major transient itself, is much reduced in the differences (the bump appears to be very constant in time).

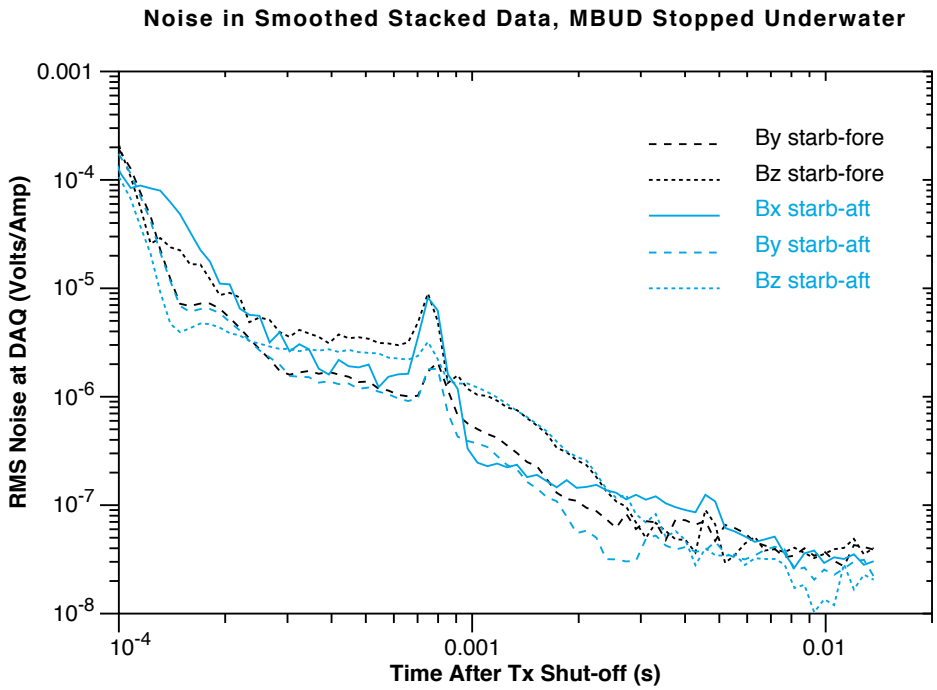

Figure 18. Sea trial noise levels on selected channels at rest on the bottom.

Noise levels during the towed tests, Figure 19, were contaminated by leakage in the acquisition module: the upper two channels in this plot were found to have been contaminated by moisture leakage; those channels with no leakage showed virtually the same noise as shown in the static test results of Figure 18.

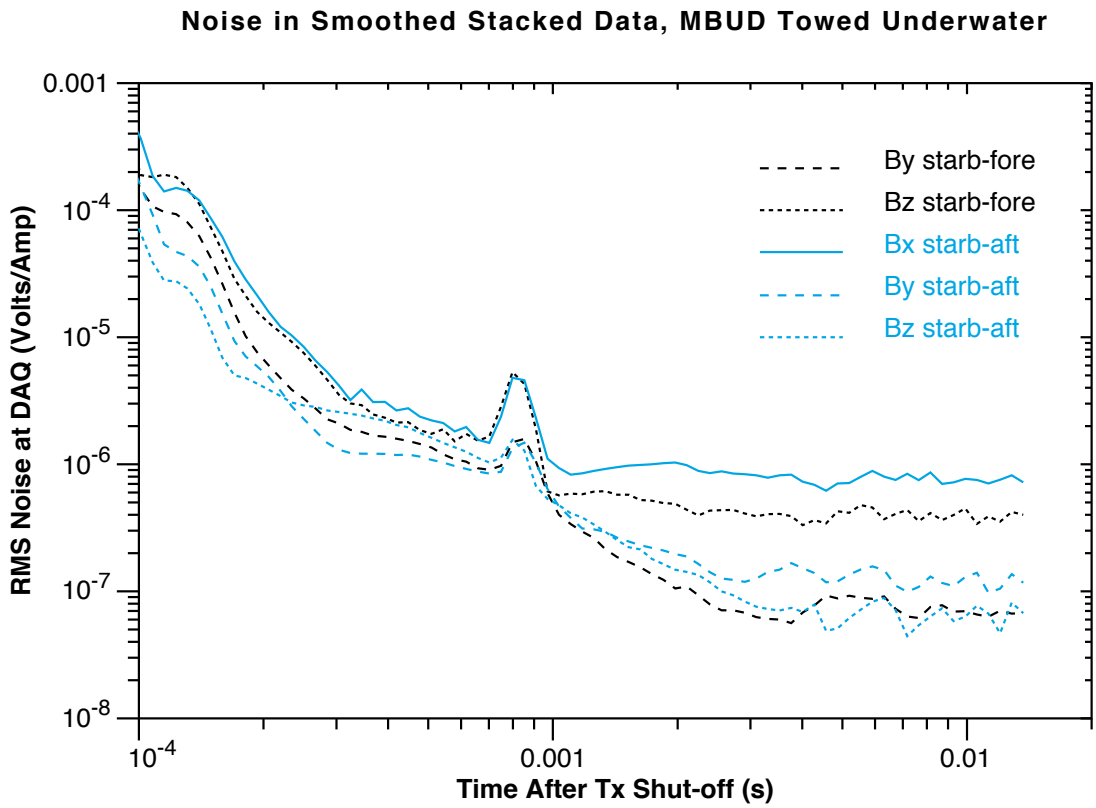

Figure 19. Sea trial noise levels on typical channels moving at 1.3 knots.

The results shown in Figures 18 and 19 were selected out of a great many trials in which most of the test results were unsuccessful apparently due to communication problems between the central microcomputer controller, the SCR triggers and the data acquisition module. When this whole system worked correctly the data seemed to be fine and the noise levels were good. Although very late in the planned schedule, it was decided to rebuild the circuits for inter module communication and synchronization and move the data acquisition module to the tow vessel as described above in the section: **Data acquisition system.**

A second set of tests were conducted in August 2014 using the new electronics and control system. The target was a 105 mm UXO shown in Figure 20.

Figure 20. A 105mm UXO.

The polarizabilities of this UXO obtained on land, with the vessel raised above ground and the UXO placed in a vertical position beneath it are shown in Figure 21.

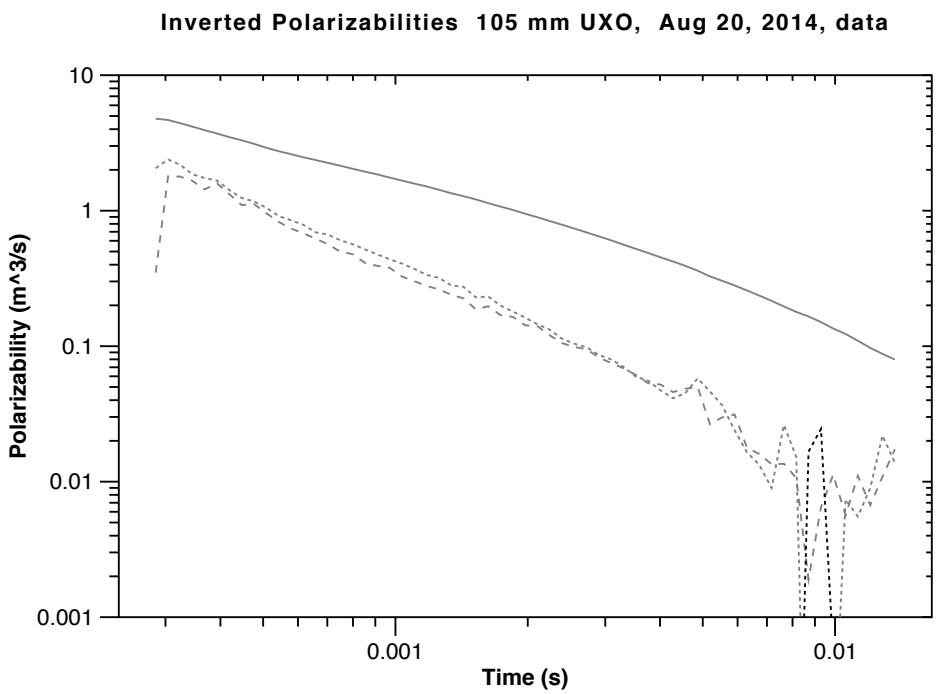

Figure 21. Inverted polarizabilities for vertically oriented 105mm UXO in air.

The depth estimate was within a few cm of the actual depth and the polarizabilities are compatible with past results with the BUD system over the same target.

A site within the Richmond marina with a water depth of 5.2 meters was selected for the trials. The vessel was lowered to the bottom and sets of data were taken without the UXO. The UXO was then implanted vertically in the bottom mud by a diver who simply dug a hole about a meter deep with a small shovel. The UXO was then pushed nose first into the mud at the bottom of the hole until its tail was a meter below the bottom. The MBUD vessel was then dragged into position over the UXO.

Despite repeated attempts, the marine tests yielded very poor data. Problems with timing of the control signals to the SCRs resulted in reduced averaging sequences and offsets of the recorded transients from the transmitter current shut-off. Transients suitable for differencing were finally selected visually to create the before and after data set after placing the UXO in the bottom mud. Presumably other malfunctions also occurred when it was submerged. The before and after transients were differenced and inverted to yield the polarizabilities of Figure 22.

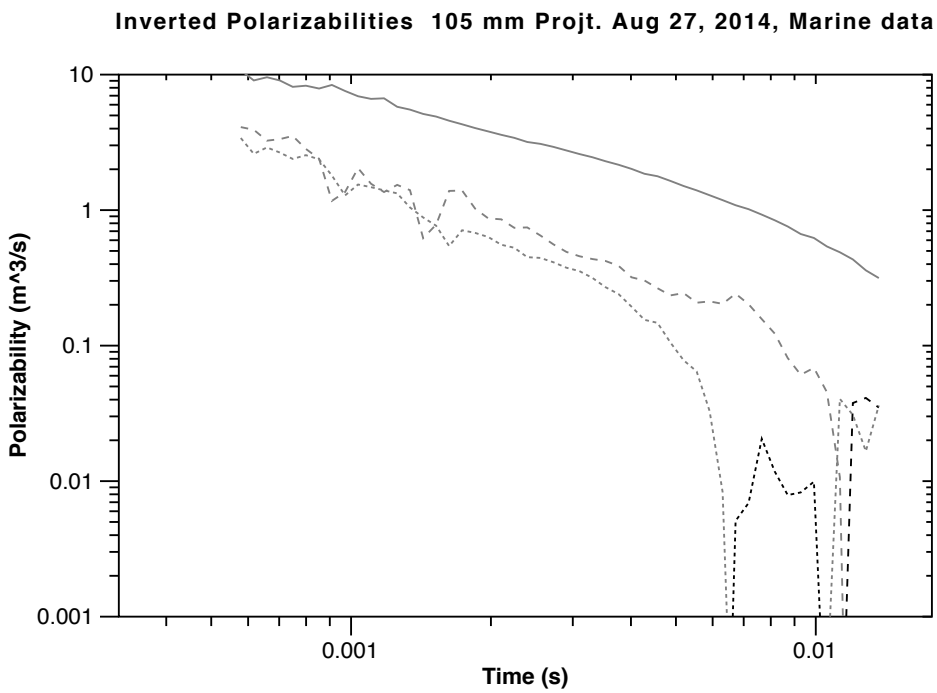

Figure 22. Inverted polarizabilities for a vertically oriented 105mm UXO, 1.0m beneath the sea bottom in 6m of water.

The recovery of the principle long axis polarizability and the two nearly identical minor axes polarizabilies appears to be correct for this UXO but the amplitudes of the polarizabilities are a factor of about 8 too large. The problem lies in the estimates of depth and inclination. The inversion process first uses the data from the multiple receivers to locate the target and determine its depth and orientation. The depth estimated from the data is greater than the actual depth and the inclination is estimated to be 45° rather than vertical. Using these estimates of depth and polarization the inversion process next estimates the magnetic fields at the target and then estimates the magnetic moments that the target must have to produce the observed amplitudes. Consequently if the depth estimate is too deep and the target is at an angle the moments needed to yield the observed fields must be larger

than those observed. The critical step in the process is accurately locating the object and this is where the highest quality data is required. Inversion for polarizability is very robust and involves a lot of data smoothing so the polarizability curve shapes and separations are not as sensitive to data quality.

The cause, or perhaps multiple causes, of this poor data quality is not completely understood. The fundamental sensitivities of the MBUD transmitter-receiver configuration was demonstrated with the first system in the simple static tests before that system leaked. In reconfiguring that system, locating the data acquisition module on the surface, the cabling, control pulse timing and pulser-acquisition system synchronization was also changed. The intent of these changes was to make the data acquisition more reliable and more robust. The land tests of the new system were very promising; the system functioned consistently in repeat tests, the data quality was high and the depth, orientation, and polarizability estimates for the UXO target were excellent. We also checked the data quality at the test site, before and after immersion and in both cases, the data quality was good. It was only when the MBUD system was placed on the sea floor at the test site that the data quality went down. We repeated the measurements on land with excellent results. It is unfortunate that the marine testing of the new acquisition system occurred so late in the project that there is neither time nor funding to launch a major debugging operation to determine the source of the poor data quality in the submerged vessel. The most likely cause of the poor data quality is an unknown noise source within the system or an external noise source.

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