

Detection & Classification Performance Report

UltraTEM Marine Towed System for Detection and
Characterization of Buried Ordnance

ESTCP Project MR19-5073

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14. ABSTRACT The objective of the project "UltraTEM Marine towed system for detection and characterization of buried ordnance" is to design and demonstrate a vessel-towed single-pass marine dynamic classification system for wide-area assessment and full coverage surveys. This will be achieved by modifying and integrating Gap Explosive Ordnance Detection's (GapEOD) and Black Tusk Geophysics' (BTG) existing multi-component multi-sensor UltraTEM package and associated software into Tetra Tech's (Tt) towed electromagnetic array (TEMA) platform, and then demonstrate its capabilities over a series of blind targets at controlled site.					
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1.0 INTRODUCTION

1.1 BACKGROUND

The objective of the project “UltraTEM Marine towed system for detection and characterization of buried ordnance” is to design and demonstrate a vessel-towed single-pass marine dynamic classification system for wide-area assessment and full coverage surveys. This will be achieved by modifying and integrating Gap Explosive Ordnance Detection’s (GapEOD) and Black Tusk Geophysics’ (BTG) existing multi-component multi-sensor UltraTEM package and associated software into Tetra Tech’s (Tt) towed electromagnetic array (TEMA) platform, and then demonstrate its capabilities over a series of blind targets at controlled site.

Previous versions of this sensor technology have been optimized for European dredging sites, where interest is focused on larger and deeper targets. For DoD munitions response sites, the coil configuration and deployment platform both need to be optimized for smaller, shallower (<1 m burial depth) targets of interest (TOIs). Dynamic classification of smaller TOIs, as well as consistent differentiation between TOI and clutter, requires data with high signal-to-noise ratio (SNR) and multiple transmitter excitation directions.

The purpose of this document is to describe a feasible proposed design of the UltraTEM system mounted on the TEMA platform and to report on the expected detection and classification performance of the system.

1.2 GapEOD UltraTEM HARDWARE

The UltraTEM system, a multi-component multi-sensor system that uses time-domain electromagnetic induction (EMI) to detect and characterize buried metal, can be deployed for both terrestrial and marine applications. The system has proven its unique capabilities in European-based production surveys for large area as well as deep large MEC detection, detection of ground-engaging tools in mine stockpiles, and clearance of harbors before dredging. The UltraTEM system is nominally comprised of the following four components:

1. A high-current transmitter connected to multiple transmitter loops mounted to the detection system;
2. Multiple three-component receiver sensor cubes comprised of three orthogonal 15cm coils with an effective footprint area of 4 square meters;
3. An UltraTEM data acquisition system (DAQ) running proprietary BTField software. Multiple DAQs can be integrated into BTField, enabling the use of multiple receiver sensor cubes; and
4. A position and attitude system for determining the precise location and orientation of the entire array.

The UltraTEM has a number of unique characteristics including: (1) large transmitter coils and high transmitter dipole moment (e.g., 300 Amp turns for the marine UltraTEM); (2) custom configurability with multiple transmitter loops and sensor cubes to address specific applications and environments; (3) extremely rugged and reliable electronics with precision time

synchronization; and (4) integration with BTField software, which can be easily custom configured with new transmitter receiver geometries and used for near real-time processing and interpretation of the collected data.

1.3 TETRA TECH TEMA

The TEMA currently houses three 1m x 0.5m combined transmitter and receiver sensor coils that are arranged to cover a 3m swath. These will be replaced with the UltraTEM system. The TEMA's submersible electronics and telemetry module, with a fiber optic data link, allows for the use of advanced instrumentation, and enables effective operation of MEC surveys at depths exceeding 100m.

The TEMA is capable of controlled flight at very short standoff distances with a positional accuracy that enables reliable target relocation and investigation. Towfish positioning is accomplished via ultra-short baseline (USBL), a GPS-aided inertial platform that measures position, heading, roll, pitch, and heave, as well as the angle and distance to the transponder, so it can independently determine the towfish position and attitude.

1.4 BLACK TUSK GEOPHYSICS SOFTWARE

In this project, data will be processed by BTG using the DAGCAP-accredited UXOLab software package. Developing UXOLab in the Matlab environment has meant that advancements made through SERDP-funded projects are readily incorporated into the software where they can be rigorously tested. The software is purpose built and optimized for UXO classification.

BTField combines data collection and post-processing capabilities into a single software package. BTField has collected data from a variety of terrestrial and marine EM platforms ranging from a terrestrial cart sensor with a single transmitter and four receiver cubes to a large marine sled platform with five transmitters and twenty-eight receiver cubes. BTField includes capabilities for real time gridding, processing, and inversion during data acquisition, which may be used to reduce the delay between mapping and dive operations, if required.

1.5 FEASIBLE UltraTEM designs

Three-way communication between the project team members provided a better understanding of the weight, size and power constraints on the system as well as any expected performance trade-offs. The parties exchanged CAD drawings of their respective systems (the TEMA system from Tt and several candidate transmitter/receiver layouts and models of the transmitter, receiver and power supply enclosures from GapEOD). Through a number of emails and video conferences the project team determined optimal positions for the transmitter and receiver electronics as well as constraints on the maximum size and weight of the full system.

In selecting candidate designs (Figure 1) to assess we were able to leverage previous research into layouts for the terrestrial one-pass classification UltraTEM system (called the NATA for North American Towed Array). That array used four overlapping vertical axis transmitters (i.e. that lie flat) that primarily provide vertical and across track excitation and one horizontal axis transmitters (i.e. that sits on its end) that primarily provides along track excitation. Due to the

requirement to operate at standoffs of 0.5 to 1.5 m above the sea-bottom the transmitters for this system need to be larger than those used with the NATA system (1.8 m x 1.8 m compared to 1 m by 1 m) and we tested layouts with both two and three of these vertical-axis transmitters (compared to four with the NATA). A horizontal axis transmitter would create a lot of drag and potentially create issues with launch and recovery of the TEMA. To provide along track excitation we instead modeled an offset vertical axis transmitter that extends the entire width of the TEMA system.

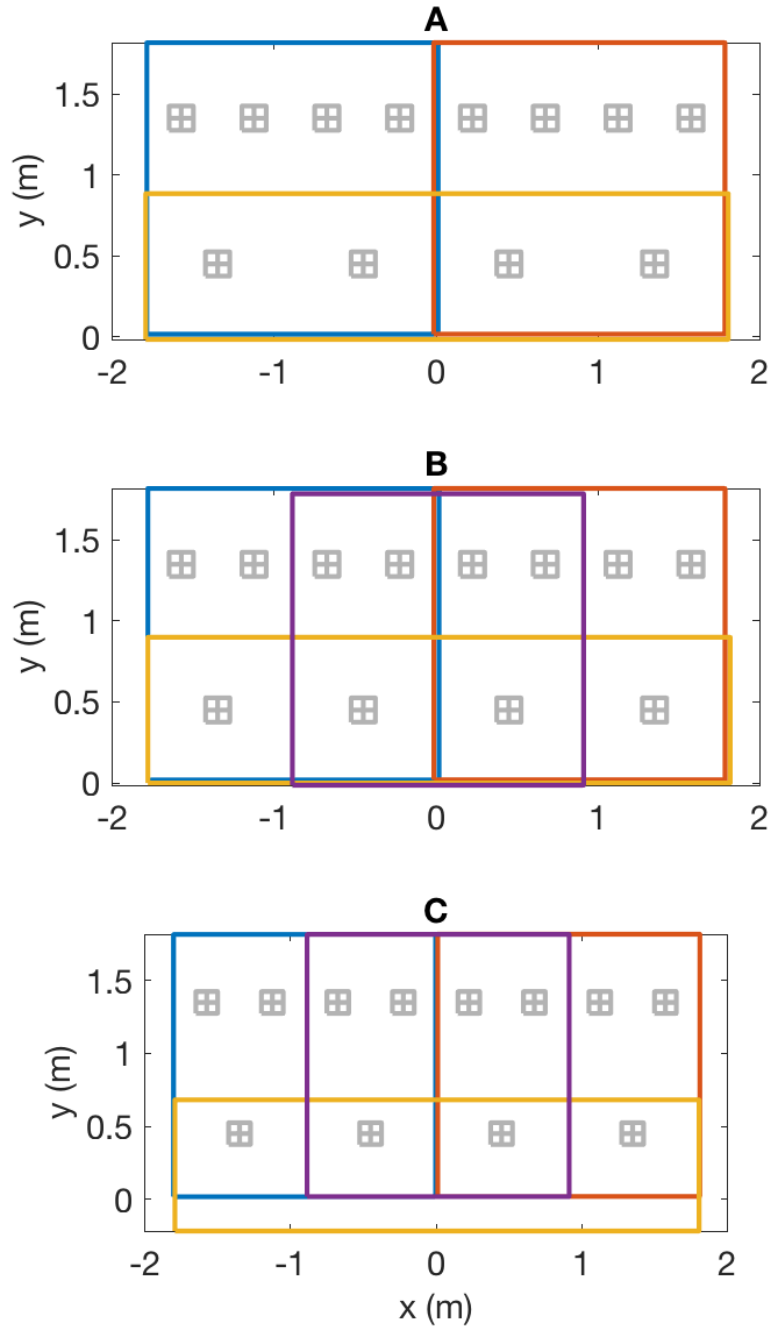


Figure 1. Candidate array designs for UltraTEM marine systems to be deployed on the TEMA platform. Solid colored lines are transmitter loops (jittered for clarity), grey lines are receiver sensors.

2.0 SENSOR OPTIMIZATION

We considered two performance characteristics when comparing the different transmitter & receiver layouts: one focussed on classification ability and the other on detection ability.

2.1 METHOD FOR ASSESSING PERFORMANCE

To optimize electromagnetic (EM) sensor design for marine detection and classification of UXO, we use a linearized analysis to characterize the uncertainty in recovered polarizabilities. At a given target offset (\mathbf{r}) from the center of an array, we calculate the covariance of the polarizability tensor (\mathbf{m}) as

$$\text{cov}(\mathbf{m}) = (\mathbf{Q}(\mathbf{r})^T \mathbf{W}_d^T \mathbf{W}_d \mathbf{Q}(\mathbf{r}))^{-1}, \quad (1)$$

where $\mathbf{Q}(\mathbf{r})$ is the forward modelling matrix that maps between the EM data at a single time channel and the model. The model contains the unique elements of the symmetric polarizability tensor

$$\mathbf{m} = [m_{xx} \ m_{xy} \ m_{xz} \ m_{yy} \ m_{yz} \ m_{zz}]^T. \quad (2)$$

We consider a spherical target with unit polarizabilities aligned with the geographic reference frame, so that

$$\mathbf{m} = [1 \ 0 \ 0 \ 1 \ 0 \ 1]^T \quad (3)$$

The diagonal weighting matrix \mathbf{W}_d contains the inverse standard deviations of the data. The data standard deviations (σ) are sensor and site specific. For these simulations we model them as

$$\sigma(d_i) = \text{percent}|d_i| + \text{floor} \quad (4)$$

with *percent*=0.05, and *floor* set equal to the 80th percentile of the predicted data. This is not intended to represent actual sensor noise statistics, but to allow for comparison of the relative merits of array designs. A high *floor* parameter effectively masks out lower amplitude data from the uncertainty calculation, placing more emphasis on measurements where there is strong coupling between target and array.

Uncertainty in estimated target location for a given array design can also be obtained by replacing $\mathbf{Q}(\mathbf{r})$ in equation 1 by the Jacobian matrix $\mathbf{J}(\mathbf{r})$ with elements

$$J_{ij} = \frac{\partial d_i}{\partial r_j}. \quad (5)$$

2.2 CLASSIFICATION PERFORMANCE OF CANDIDATE DESIGNS

We first consider the classification performance of the three candidate array designs. Figure 2 shows estimated standard deviations in the principal polarizabilities as a function of target location for array Design A. This system has 12 receiver cubes, two 1.8 m x 1.8 m square transmitters arranged side by side, and an additional 3.6 m x 0.9 m transmitter spanning the array swath. The leading edge of the wide transmitter provides along track illumination of targets within the array footprint at shallow depths. However, we note an increase in the cross-track uncertainty near the centers of the square transmitters at the 0.75 m offset, where the fields generated by these loops are largely vertical.

This weakness can be addressed by introducing a third square loop at the center of array Design B (Figure 3). The sides of this center loop provide cross-track illumination such that the cross-track polarizabilities become well constrained when the target is within the array footprint.

An additional reduction in along-track uncertainty can be achieved by shifting the wide transmitter back by 20 cm for Design C (Figure 4). This reduces along-track uncertainty at depth by maximizing the along-track illumination at a point that is closer to the receivers.

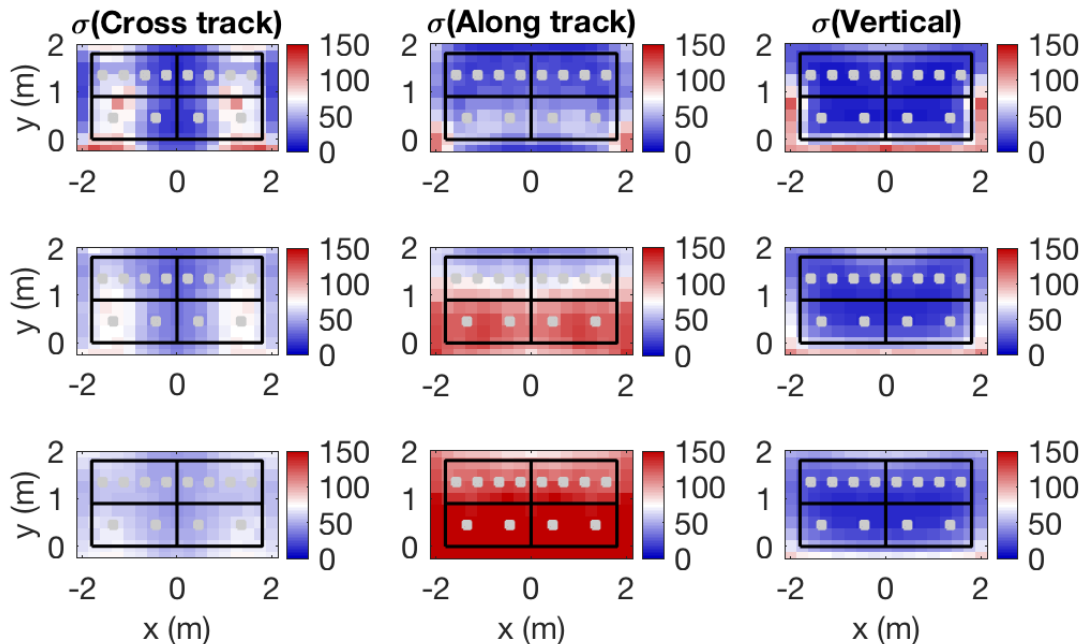


Figure 2. Percent standard deviation in principal polarizabilities for a target at 0.75 m (top row), 1.5 m (middle row) and 2.25 m (bottom row) below array Design A. Black and grey lines indicate transmitters and receivers, respectively.

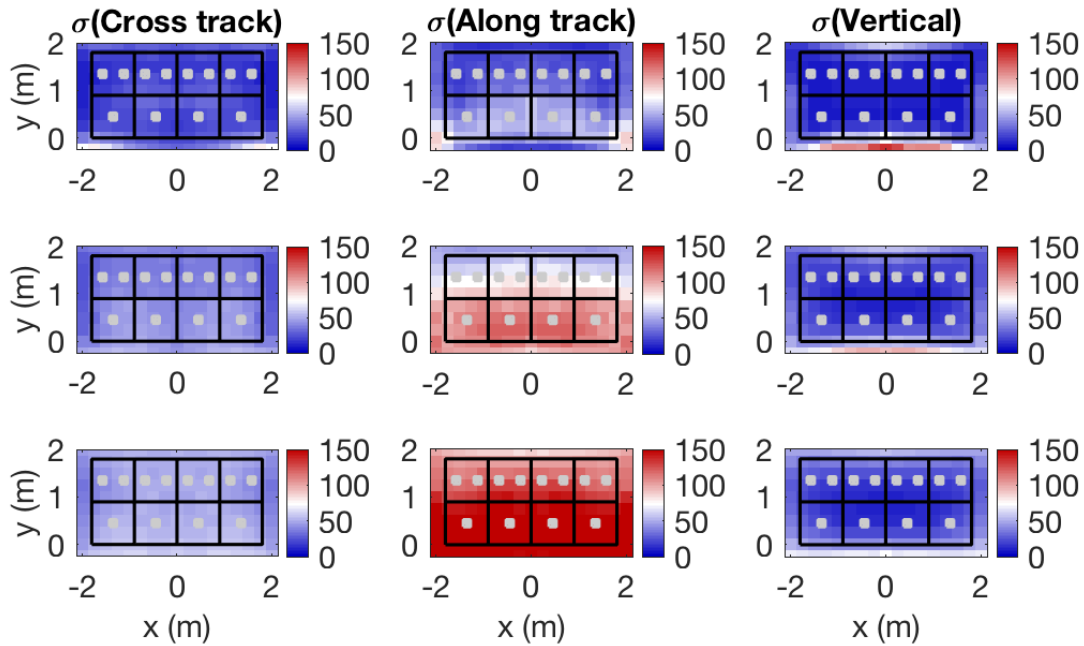


Figure 3. Percent standard deviation in principal polarizabilities (as in Figure 2) for Design B.

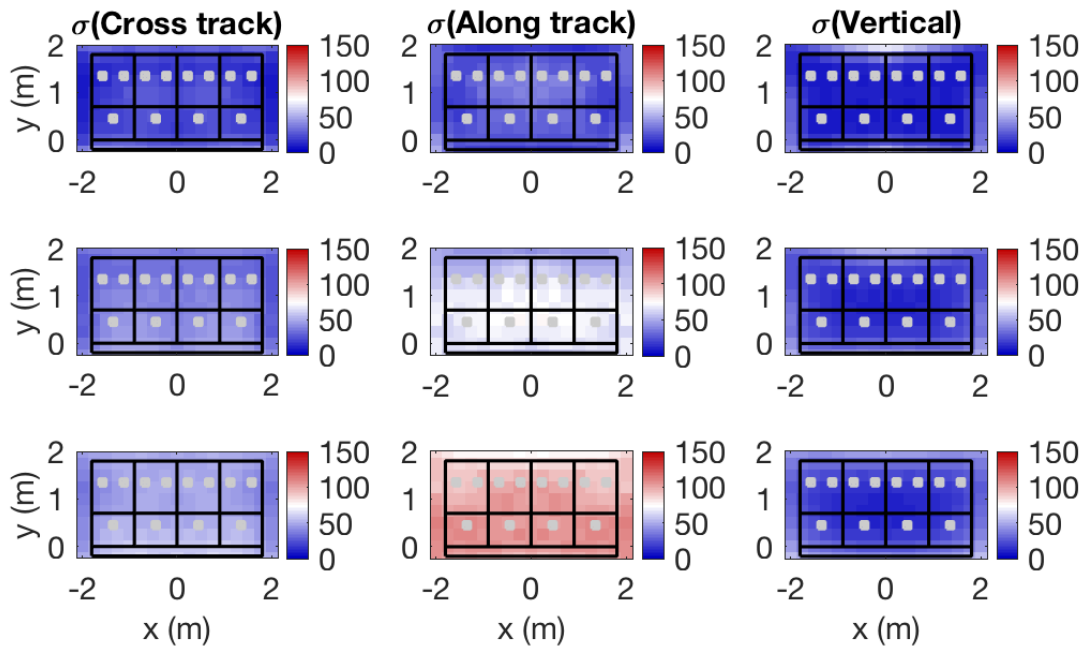


Figure 4. Percent standard deviation in principal polarizabilities (as in Figure 2) for Design C.

2.3 DETECTION PERFORMANCE OF CANDIDATE DESIGNS

We further investigate the detection and classification capabilities of our preferred array design (Design C), by modeling the responses of selected targets in the DoD ordnance library. Figure 5 shows the dependence of signal amplitude (in units of nT/s/A) at 0.235 ms on cross-track target location and orientation for a 105 mm projectile (DoD library item 105mm Projectile, M1, 105mm x 475mm) at 1.5 m depth below the array. For this modeling we used the same library scaled established for the UltraTEM North America Towed Array (NATA) system.

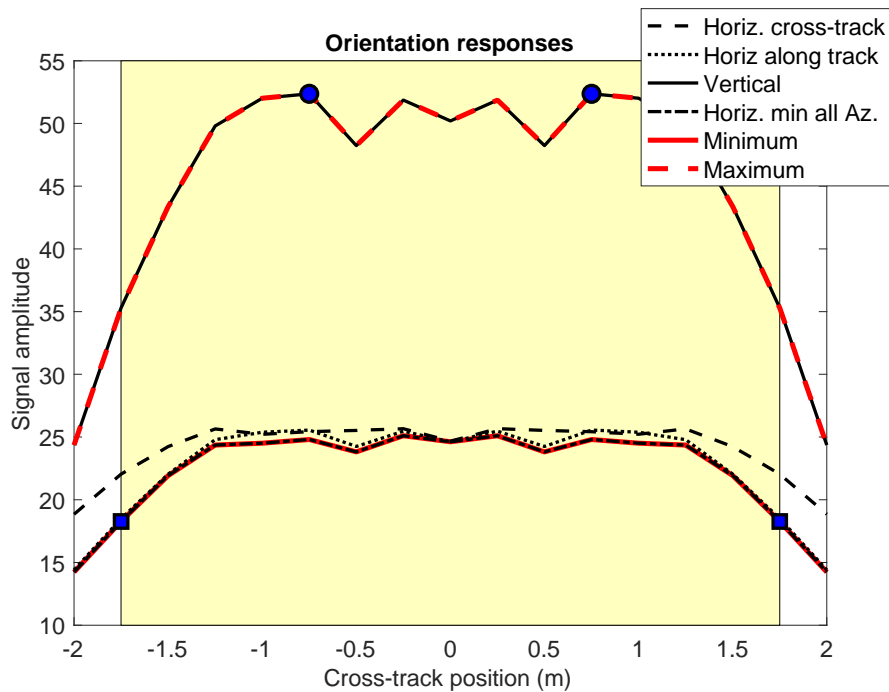


Figure 5. Orientation responses as a function of target cross-track position for a 105 mm projectile at 1.5 m depth below array Design C. Each profile shows the maximum amplitude response (over all receivers) when the array passes over the target in the specified orientation and cross-track position. We consider 4 target orientations relative to the array: horizontal cross track, horizontal along track, vertical, and horizontal “minimum azimuth.” The last case considers horizontal targets at all azimuths between cross and along track azimuths and identifies the azimuth producing minimal response for a given cross-track position. Blue squares indicate the minimum response within the array swath (indicated by yellow shaded area) and define the worst-case detection threshold, assuming a line spacing equal to the array swath. Blue circles indicate the best-case detection threshold within the array swath.

The worst-case detection threshold in this example occurs when this target is at the edge of the array and in a horizontal, along-track orientation. This will be true for most TOI, though it is possible that a target with secondary polarizabilities that are small relative to the primary polarizability can produce weak coupling when oriented cross-track and can thereby produce a minimum within the array swath.

The best-case detection threshold occurs for a vertically-oriented target within the array swath. This will be true for all ferrous, prolate (rod-like) TOI, which have a primary polarizability that is larger than the secondary polarizabilities.

Consistent with the uncertainty analysis presented above, the along-track target response is usually lower in amplitude than the cross-track response. This is because the dimensions of the TEMA design configuration allow for stronger target illumination in the cross-track direction. Note, however, that the minimum response within the array does not always coincide with the cross-track orientation. This is a consequence of the relative positioning of transmitters and receivers within the array: displacing a receiver away from the axes of symmetry of a transmitter results in minimal coupling between target and receiver at target orientations that are intermediate to the cross-track and along-track orientations.

Figure 6 shows the worst- and best-case response curves (detection thresholds as a function of depth) for the same target as in Figure 5. Using noise estimates from comparable UltraTEM marine data we calculate maximum depths of detection at the points where the response curves equal $N=5$ times the noise standard deviation at this time channel. This is a common rule of thumb for ensuring that SNR will be sufficient for target detection for all noise realizations. For the worst- and best-case scenarios shown in Figure 5, the maximum detection depths are 2.8 m and 3.3 m below the array, respectively.

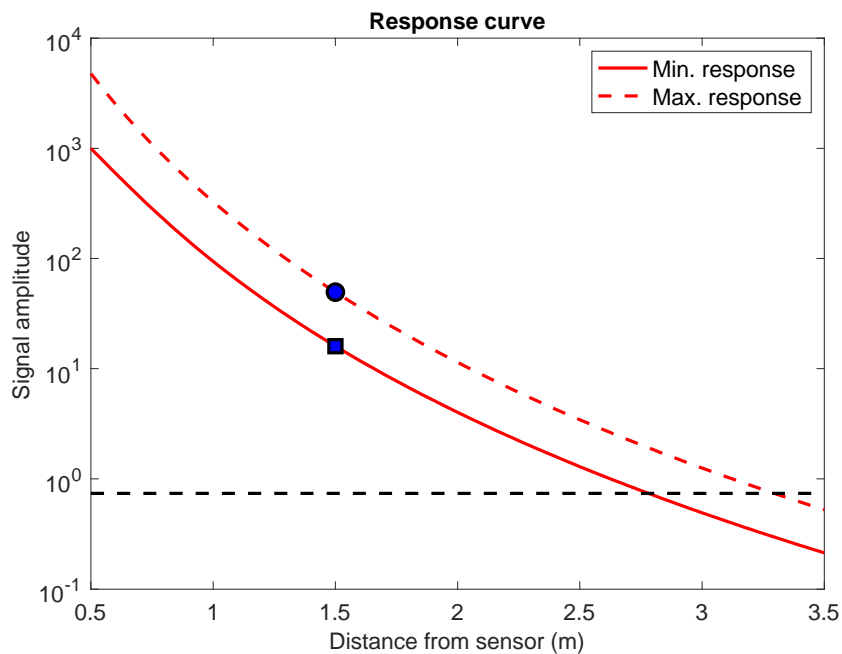


Figure 6. Response curve (signal amplitude as a function of depth below sensor) at 0.235 ms for 105 mm projectile below array Design C. Solid and dashed red lines are the worst- and best-case response curves within the array swath, respectively. Blue markers show thresholds at 1.5 m below the sensor, corresponding to the cases shown in Figure 5. Dashed black line indicates 5 times the estimated noise standard deviation at this time channel. Worst- and best-case response curves intersect this noise level at 2.8 m and 3.3m, respectively. This defines the worst- and best-case detection depths for this item

Figure 7 shows polarizabilities and worst- and best-case detection depths for the 105 mm projectile along with two other selected TOI in the DoD library (60mm Mortar, M720 HE, 60mm x 375mm; 81 mm Mortar, M821, 81mm x 423mm). Physical target diameter does not

necessarily correlate with detection depth: the 81 mm projectile has a deeper best-case detection depth than this particular 105 mm projectile because its primary polarizability at 0.235 ms is larger than that of the 105 mm projectile.

Note that there are other 105 mm projectiles in the DoD library with longer lengths and larger primary and secondary polarizabilities than the item used for this analysis. Thus, the detection depth for the 105 mm projectile is likely to be underestimated.

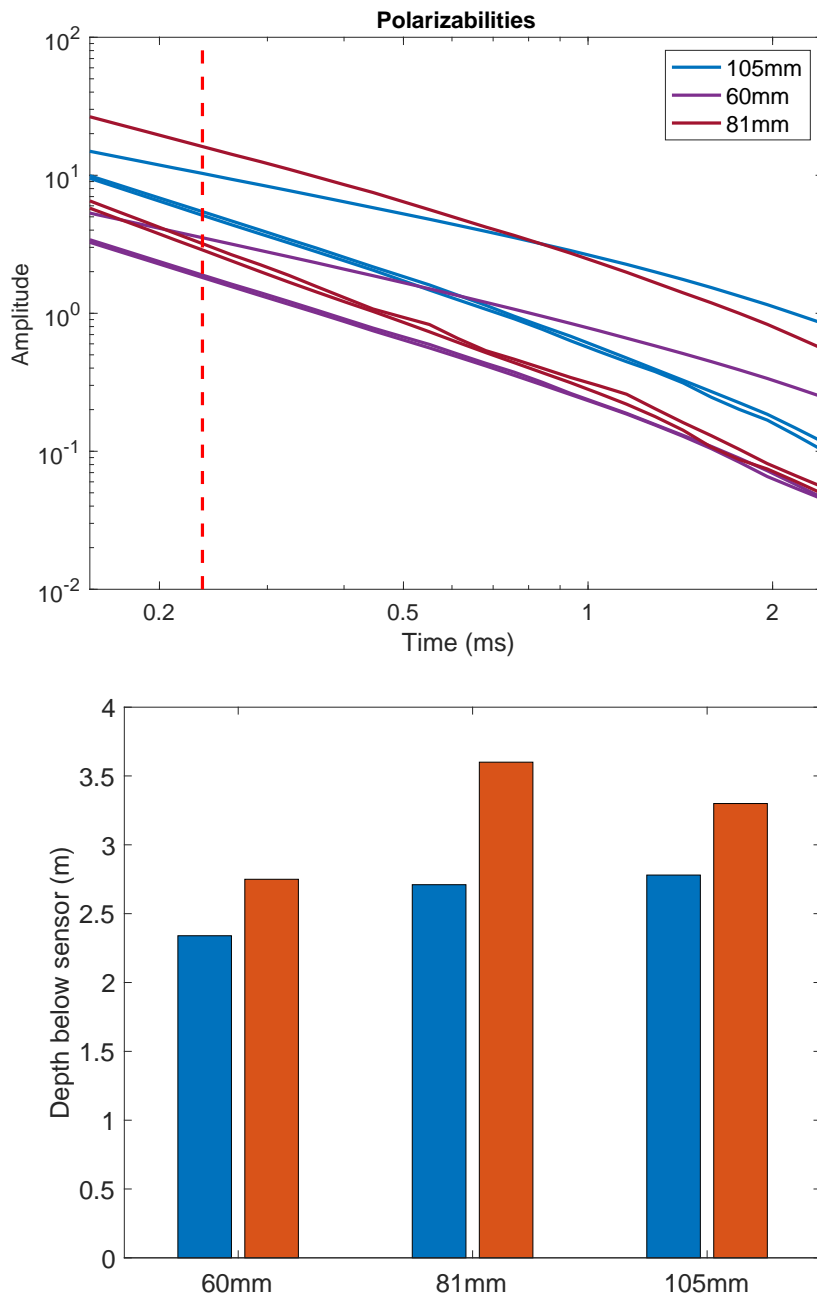


Figure 7. Top: DoD library polarizabilities for selected items. Vertical dashed line indicates 0.235 ms time channel used for modelling. Bottom: worst-case (blue) and best-case (red) detection depths.

While detection can be achieved based on a single time channel, target classification requires sufficient SNR over multiple time channels such that inversion can constrain estimated polarizabilities and obtain an acceptable match to the library. We therefore define the “classification depth” as the mean detection depth for a target, averaged over all time channels. Figure 8 shows worst case classification depths for the three targets considered previously; there is a slight reduction relative to the detection depths due to reduced SNR at late times.

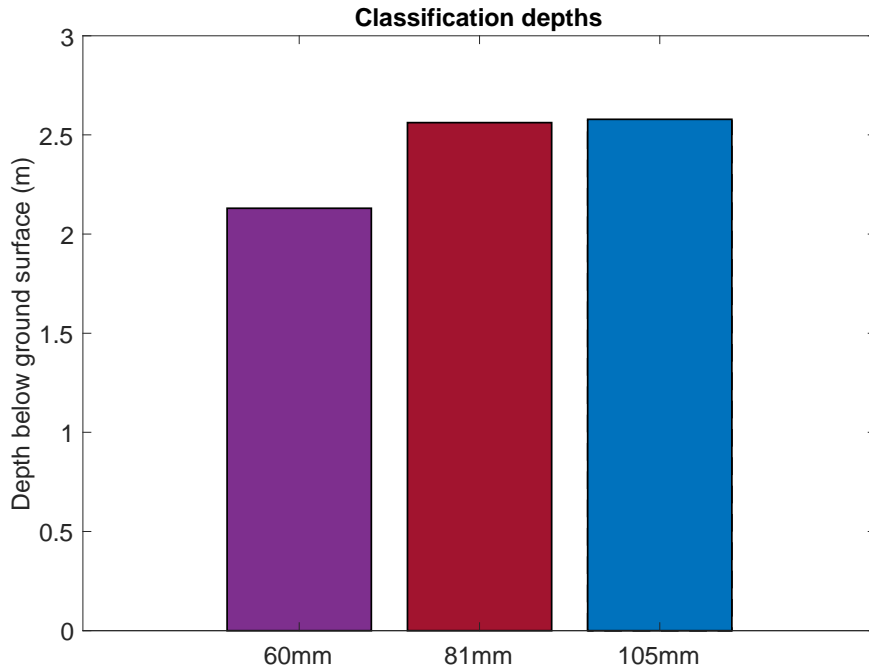


Figure 8. Worst-case classification depths (2.1 2.52 and 2.53 m respectively).

3.0 PROPOSED SYSTEM DESIGN

3.1 SENSOR LAYOUT ON THE TEMA SYSTEM

In Figure 9 we show a perspective view of the best-performing UltraTEM system installed on the TEMA platform. We anticipate that the electronics enclosures (see next section) will be installed on the front of the array with a minimum standoff distance of 1.5 m from any receiver. An engineering drawing of the transmitter & receiver layout is included as Figure 11.

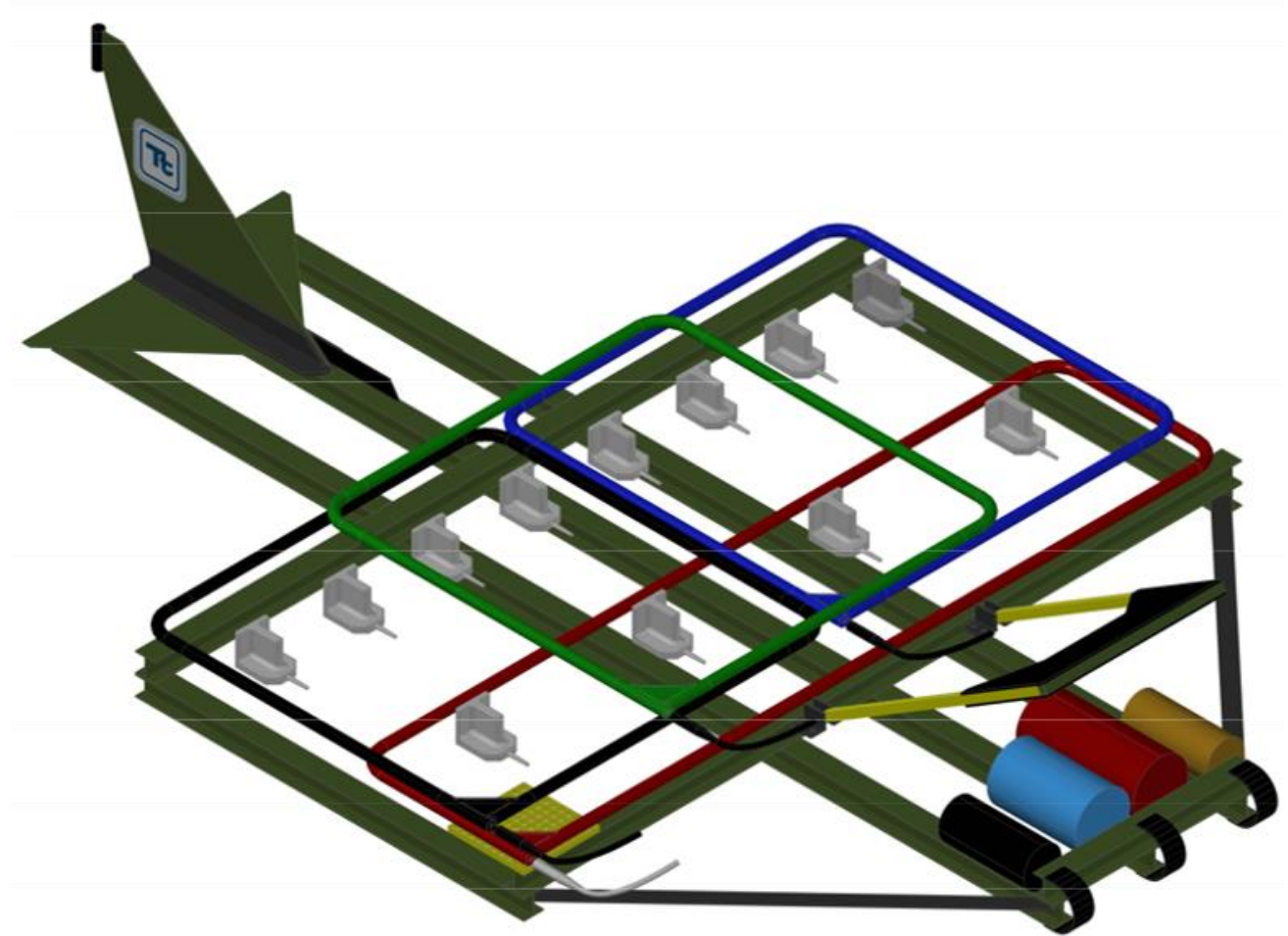


Figure 9. Perspective view of the best performing UltraTEM system attached to the TEMA platform with the positions of electronics bottles shown on the front of the array.

3.2 ELECTRONICS ENCLOSURES

GapEOD have completed construction of a twelve-receiver five-transmitter marine UltraTEM that will be used with the TEMA system (Figure 10). Only four of the five transmitter modules will be required for the TEMA system so one transmitter module will act as a redundant spare. The twelve-receiver system including enclosure and twelve UltraTEM T-Cubes have been assembled and tested. The five-transmitter system including enclosure has been assembled and tested, but the four underwater transmitters have not yet been fabricated (we will wait for Program Office approval of this report before commencing construction). An enclosure with a separate power-supply was also assembled and has been tested. Finally, a fourth enclosure with a Lord Microstrain 3DM-GX5-25 inertial motion unit and an Applied Physics 533 flux-gate magnetometer is being assembled so that the attitude of the UltraTEM system can be accurately measured.

4.0 SUMMARY

To optimize sensor design for marine detection and classification of UXO, we used a linearized analysis to characterize the uncertainty in recovered polarizabilities. In selecting candidate designs to assess we were heavily influenced by the layout of the terrestrial one-pass classification UltraTEM system. That array used four overlapping vertical axis transmitters (i.e. that lie flat) that primarily provide vertical and across track excitation and one horizontal axis transmitters (i.e. that sits on its end) that primarily provides along track excitation. Due to the requirement to operate at standoffs of 0.5 to 1.5 m above the sea-bottom the transmitters for this system needed to be larger than those used with the NATA system (1.8 m x 1.8 m compared to 1 m by 1 m) and we opted to use three instead of four. A horizontal axis transmitter would create a lot of drag and potentially create issues with launch and recovery of the TEMA. To provide along track excitation we instead used an offset vertical axis transmitter that extends the entire width of the TEMA system. The selected layout outperformed other physically feasible designs when assessed with the linearised uncertainty analysis and also from a detection standpoint (when assessed using BTG's Detection Modeller software).

Pending ESTCP approval of this report, the design phase of the project is now complete. The project team is now ready to start terrestrial testing of the system. We plan to mock-up the TEMA layout and perform a number of land-based tests to both verify correct operation of the system and to collect test data over UXO and surrogate items (such as small, medium and large ISO items). The system will then be installed on the TEMA platform and wet-shakedown tests will be performed in the Seattle area.



Figure 10. UltraTEM enclosures (from left to right they are power supply, transmitter & receiver)

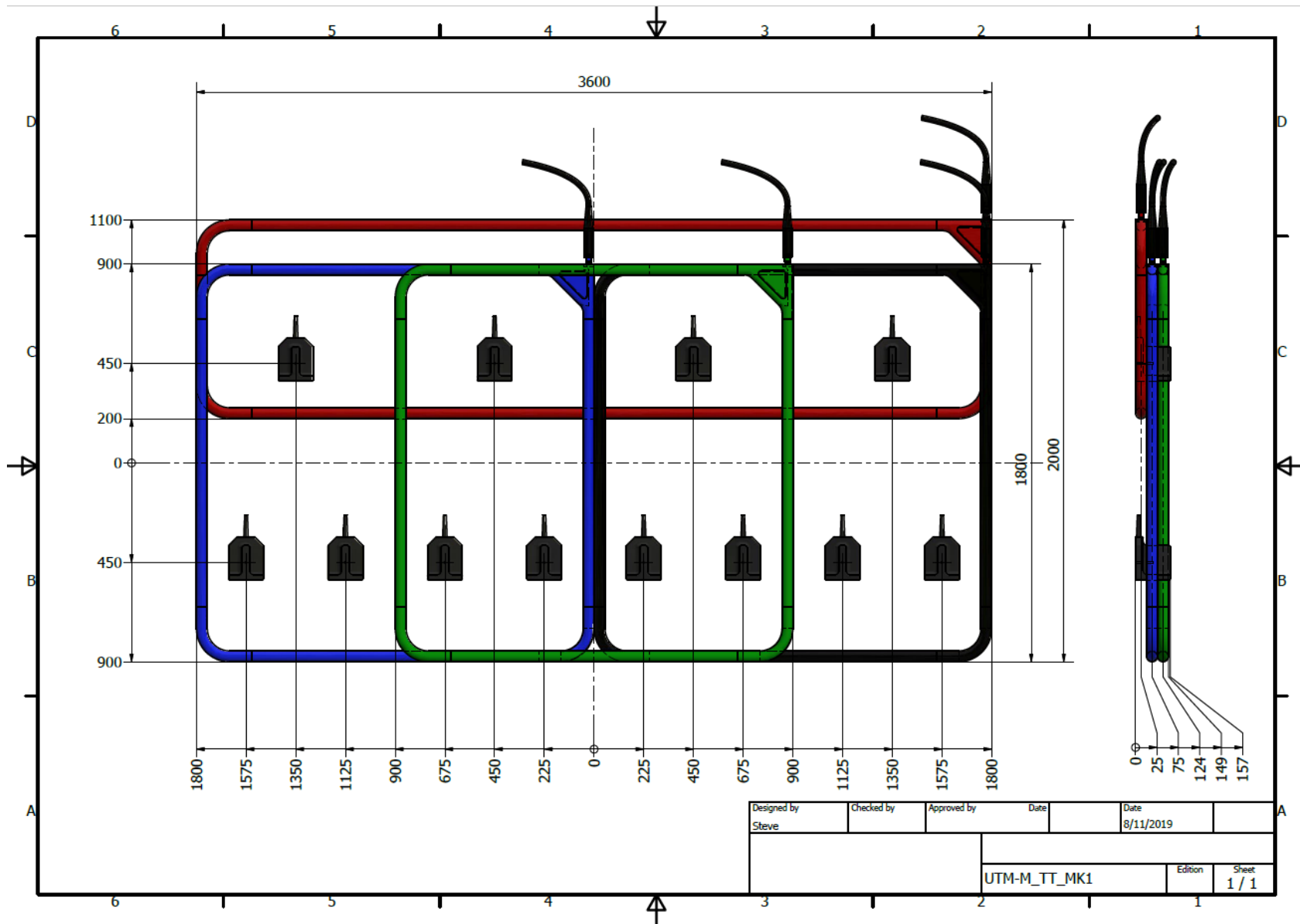


Figure 11. Proposed transmitter & receiver layout.