FINAL REPORT

A Preliminary Design Study of a Re-Deployable Underwater Test Bed

Requirements for and Development of Test Beds for Demonstration Sites

SERDP Project MR-2736

MAY 2019

Nagi Khadr
Criag Murray
Parsons Government Services, Inc.

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
31/05/2019

2. REPORT TYPE
SERDP Final Report

3. DATES COVERED *(From - To)*
3/10/2017 - 9/30/2019

4. TITLE AND SUBTITLE
A Preliminary Design Study of a Re-Deployable Underwater Test Bed: Requirements for and Development of Test Beds for Demonstration Sites

5a. CONTRACT NUMBER
17-C-0007

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Nagi Khadr
Criag Murray

5d. PROJECT NUMBER
MR-2736

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Parsons Government Services, Inc.
2 Vista Ave.
Lynchburg, VA 24503

8. PERFORMING ORGANIZATION REPORT NUMBER
MR-2736

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Strategic Environmental Research and Development Program (SERDP)
4800 Mark Center Drive, Suite 16F16
Alexandria, VA 22350-3605

10. SPONSOR/MONITOR'S ACRONYM(S)
SERDP

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
MR-2736

12. DISTRIBUTION/AVAILABILITY STATEMENT
DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This preliminary study focused on test beds capable of providing reliable platforms for model validation, in situ demonstrations and performance intercomparisons. This study explored the use of special re-deployable materials that ensures a consistent predefined, yet flexible, item emplacement process.

15. SUBJECT TERMS
Re-Deployable Underwater Test Bed, Aberdeen Proving Ground, GPS, synthetic aperture sonar

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UNCLASS	UNCLASS	UNCLASS	UNCLASS	28	Nagi Khadr
					19b. TELEPHONE NUMBER *(Include area code)* 303-501-2393

TABLE OF CONTENTS

1.0 ABSTRACT 1-1

2.0 OBJECTIVES 2-1

3.0 BACKGROUND 3-1

4.0 MATERIALS AND METHODS 4-1

5.0 RESULTS AND DISCUSSION 5-1

6.0 CONCLUSIONS AND IMPLICATION FOR FUTURE RESEARCH/ IMPLEMENTATION 6-1

7.0 LITERATURE CITED: 7-1

FIGURES

FIGURE 1 - THE CONCEPTUAL DESIGN FOR THE GU SHOWING A PVC-BASED TWO-BY-TWO SQUARE CELL GRID WITH A CELL DIMENSION OF 6-M OR 20' 4-5

FIGURE 2 - GU DESIGN SHOWING 6-METER PVC SECTIONS 5-2

FIGURE 3 – CUSTOM GRID JOINTS 5-3

FIGURE 4 – REMOVABLE PANEL EXAMPLE 5-4

FIGURE 5 – PINGER TAGS 5-5

TABLES

TABLE 1 RE-DEPLYABLE UNDERWATER TEST BED PRICE ESTIMATE – 25 GRID UNITS 5-7

TABLE 2 FIVE TOP POTENTIAL TEST BED SITES 5-8

ACRONYMS AND ABBREVIATIONS

AoA	angle of arrival
APG	Aberdeen Proving Ground
ATS	advanced telemetry systems
CDMA	code-division multiple access
GPS	global positioning system
GPS PPS	Common clock
GU	Grid unit
ID	identification
INS	Inertial navigation system
JPG	Jefferson Proving Grounds
LBL	long baseline
MINS	Mare Island Naval Shipyard
PIC	pulse interval coding
PVC	poly-vinyl chloride
SAS	synthetic aperture sonar
SBL	short base line
SDL	submersible datalogger
SYNAPS	Synthetic Aperture Positioning System
TOI	target-of-interest
TOAD	time of arrival differencing
UMAP	Formerly ALPS (asynchronous Logger Position System)
USBL	ultra-short baseline
UXO	unexploded ordnance
VDS	validation of detection systems
YPG	Yuma Proving Ground

1.0 ABSTRACT

Objective: This preliminary study focused on test beds capable of providing reliable platforms for model validation, in situ demonstrations and performance intercomparisons. This study explored the use of special re-deployable materials that ensures a consistent predefined, yet flexible, item emplacement process.

Technical Approach: The approach to the preliminary design consisted of: (1) conducting an analysis to determine item distribution scenarios that will apply to all sensor modalities and systems of interest over a variety of conditions; (2) fully elaborating on and investigating the feasibility of implementing a re-deployable item emplacement process that can be used for a range of different test bed scenarios. The main conceptual idea relies on deploying re-useable materials that are lightweight, can be set up on the water surface, submerged then outfitted with an adaptable mesh fabric containing a known spatial distribution of uniquely identifiable acoustic pinger tags; and (3) researching site possibilities for installing test beds that will apply to the largest possible variety of conditions to all sensor modalities and systems of interest.

Results: Underwater standardized test sites with scenarios similar to the calibration lanes, blind grid and open area found on the terrestrial Standardized Test Sites at Aberdeen Proving Ground (APG) and Yuma Proving Ground (YPG) are what is envisioned for an underwater test site.

The basic concept of the re-deployable underwater test bed consisted of a lightweight grid framework that can be efficiently assembled on the water surface before being submerged and guided to the bottom. This grid unit of four 6m X 6m cells can either be a standalone structure or add to an existing grid network. The goal would be to deploy the grid unit from a small boat or skiff in one trip with two people. The re-deployable underwater test bed platform will be placed on the water bottom and can accommodate pingers with known unique IDs at regular intervals in two dimensions. The pingers identify potential locations for which to emplace prescribed items in a given configuration either proud on the surface or buried at a given depth. The pingers allow divers armed with underwater receivers to efficiently navigate from one desired item emplacement location to the next based on a pre-planned and thought-out seeding strategy.

After a rigorous ranking process, five potential sites were identified based on identifying the following: current land ownership and existing local/on-site infrastructure; the availability of boat ramps and/or marinas in the vicinity; and the proximity of each identified boat ramp/marina to each of the depth column areas.

Benefits: This preliminary study is one of several undertaken in an attempt to clarify the best course of action to take when designing an underwater test site. If the proposed re-deployable item emplacement process is shown to be both feasible and cost-effective, this will pave the way towards establishing an underwater test site with test beds that are more complex than just simple grids and would rival the success that the terrestrial Standardized UXO Technology Demonstration Sites have had in evaluating and comparing emerging and existing technologies. Other benefits come from steps (1) and (3) of the technical approach in determining item distribution scenarios, and a ranked list of MR sites that could potentially host the desired test bed scenarios.

2.0 Objectives

The proposed objective is to conduct a preliminary design study on a re-deployable underwater test bed that will accommodate data collection by different sensor modalities and systems over carefully emplaced test items. Although not entirely re-deployable in the strict sense of the word, the idea is that the item emplacement aspect of the test bed makes use of special re-deployable materials that ensures a consistent predefined, yet flexible, emplacement process.

The approach to the preliminary design consisted of:

(1) conducting an analysis to determine item distribution scenarios that will apply to all sensor modalities and systems of interest over a variety of conditions;

(2) fully elaborating on and investigating the feasibility of implementing a re-deployable item emplacement process that can be used for a range of different test bed scenarios. The main conceptual idea relies on deploying re-useable materials that are lightweight, can be set up on the water surface, submerged then outfitted with an adaptable mesh fabric containing a known spatial distribution of uniquely identifiable acoustic pinger tags. Using handheld tunable devices, divers can navigate from one potential emplacement spot to another on a pre-emplacement reconnaissance mission and/or a predefined item emplacement mission. The addition of an array of fixed hydrophones integrated with a GPS reference can provide geographical locations to the tags; and

(3) researching site possibilities for installing test beds that will apply to the largest possible variety of conditions to all sensor modalities and systems of interest. This final step included methodically rank MR sites based on the diversity of desired test bed scenarios that can be accommodated throughout the year, also taking site accessibility and security into account.

3.0 Background

A number of MR SERDP- and ESTCP-sponsored underwater sensor detection and classification systems involving different modalities – e.g. magnetic, electromagnetic and acoustic – are approaching the stage of development where in situ demonstrations are recommended. Data collected over known items with reliable ground truth can be of great assistance in the final development phase of both sensors and algorithms. With a distribution of items emplaced under conditions that apply to all modalities and systems, blind comparative testing can also be performed.

Apart from some project-specific test beds that were mainly formed to validate certain sensor systems under very particular conditions, there have been several attempts at establishing more generalized test beds that could demonstrate competing systems, both commercial and military – e.g. an unexploded ordnance (UXO) test range at Barking Sands, Kauai; a validation of detection systems (VDS) test program at Mare Island Naval Shipyard (MINS); and, a freshwater test pond facility at Naval Surface Warfare Center - Panama City (NSWCPC), to name a few. Both Kauai and Mare Island used the terrestrial Jefferson Proving Grounds (JPG) UXO Advanced Technology Demonstration Program as a template, especially when it came to assessing demonstrator performance. The NSWCPC test pond facility is different in that it provides a much more controlled environment offering more of a laboratory setting by which to test and compare systems.

While Kauai offered depths ranging from 1 – 50 meters with generally low turbidity, it suffered from high magnetic clutter, frequent intense wave action resulting in large amounts of sediment transport, and a generally poor emplacement process that was typical of the period (i.e. a plumb line to the surface + DGPS). Mare Island, by comparison, offered a relatively good emplacement process that was facilitated by the eight-foot tidal influence (allowing the site to be walked on during low tide) but suffered from very shallow depths (< 3 meters) that could only be accessed for demonstration purposes during high tide. The shallow water depth, thus, essentially excluded acoustic sensors from the Mare Island demonstration since the proximity of the top and bottom surfaces provide for high levels of reverberation through acoustic multi-pathing. The reverberation process is the dominant contributor of acoustic clutter in very shallow areas. Processes contributing to the reverberation include scattering from suspended bubbles or roughened surfaces caused by surface and bottom-specific phenomena.

As the Kauai and Mare Island examples above show, it is not enough to have an item emplacement process that provides for accurate item ground truth – i.e. type description; location; orientation; and, depth. Equally crucial is accurate time dependent ground truth of the surrounding environment – i.e. sediment type description; bathymetry; salinity, temperature, turbidity and velocity profiles in the water column; surface waves description and/or measurement; and, characterization of any natural and man- made clutter – taken before, during and after experiments or demonstrations. This is particularly important for the modalities that require such information as input parameters when processing the data –acoustics, optics and higher frequency electromagnetics. In this way, a much more informed evaluation of the technologies can take place when the complete ground truth is available.

During the 2011 SERDP/ESTCP Symposium, a side meeting and roundtable discussion on underwater test beds was held with the objective of defining the needs of SERDP and ESTCP projects focused on underwater sensor detection and classification systems. The consensus from the meeting was that test beds similar to the land-based UXO test beds at Aberdeen

Proving Ground (APG) and Yuma Proving Ground (YPG) were needed and that these would serve two essential functions:

1. Allow data to be collected over known items with reliable ground truth to aid in the final stages of both SERDP sensor system and algorithm development projects; and
2. Provide standardized demonstration sites for ESTCP sensor system projects to allow for blind comparative testing to be performed.

In addition, these underwater test beds would need to accommodate acoustic, optical, magnetic, and electromagnetic detection and classification technologies over sufficiently large areas and across a range of water depths and environmental conditions.

Conclusions that emerged during the discussion were that:

1. The identification of marine sites needed to be a priority, and that this should include addressing general issues associated with obtaining any necessary permits for the sites;
2. A mobile, re-deployable, test bed concept would be preferable and likely more cost effective than the development of permanent single or multiple test beds, and that its deployment and maintenance would need to be undertaken by an independent third-party team; and
3. A technique that would remove the labor-intensive diver from the item burial and recovery process would also be preferable.

Since the 2011 meeting, SERDP has called for proposals on the development of test bed concepts. A second side meeting on underwater test beds was held during the 2017 SERDP/ESTCP Symposium to revisit and update the issue of test bed requirements in light of both the more recent advances occurring in SERDP and ESTCP sensor system development projects and the newly awarded projects dedicated to the topic of test beds. To create context for the ensuing discussion, the meeting opened with a presentation summarizing the outcome of the 2011 meeting followed by presentations covering the two newly awarded SERDP test bed projects – MR-2735 and MR-2736.

SERDP project MR-2735 directly addresses the first conclusion that emerged from the 2011 meeting – identifying a suitable marine site. Sequim Bay is proposed as the test site based, among other things, on the types of bottom compositions found that are representative of underwater munitions sites known to exist. Other attractive features of the site are that it is relatively protected and is located near a federal marine sciences laboratory that can support operations.

MR-2736 focuses on addressing a conclusion that emerged from the 2011 meeting – a re-deployable test bed concept, but one that would still involve the permanent emplacement of the test items. This concept envisions a re-deployable tool that aids in the design planning and test item emplacement stages of each test bed implementation, with many different implementations expected to take place across a candidate site to satisfy as many of the desired requirements that came out of the 2011 meeting as possible. With a modular grid-based design, the re-deployable tool offers a platform that is easily adaptable to differing levels of areal designs in a variety of environments, all the while providing for a means to simply maintain the appropriate minimum spacing between test items.

The discussion during the 2017 meeting focused on the needs of active SERDP and ESTCP projects, in addition to visions of what an ideal test bed/site should look like. Although no consensus was reached, participants suggested that an initial test bed strategy may be to implement a simple test bed configuration, preferably re-deployable, that would be available sooner rather than later and would be helpful to many, but to strive for an extensive permanent test site similar to APG and YPG that would meet all if not most of the requirements that came out of the 2011 meeting. A theme that gathered some momentum during the discussion was to implement a very long straight line of test items as a start. Also voiced was a reaffirmed preference for the removal of the labor-intensive diver from the item burial and recovery process.

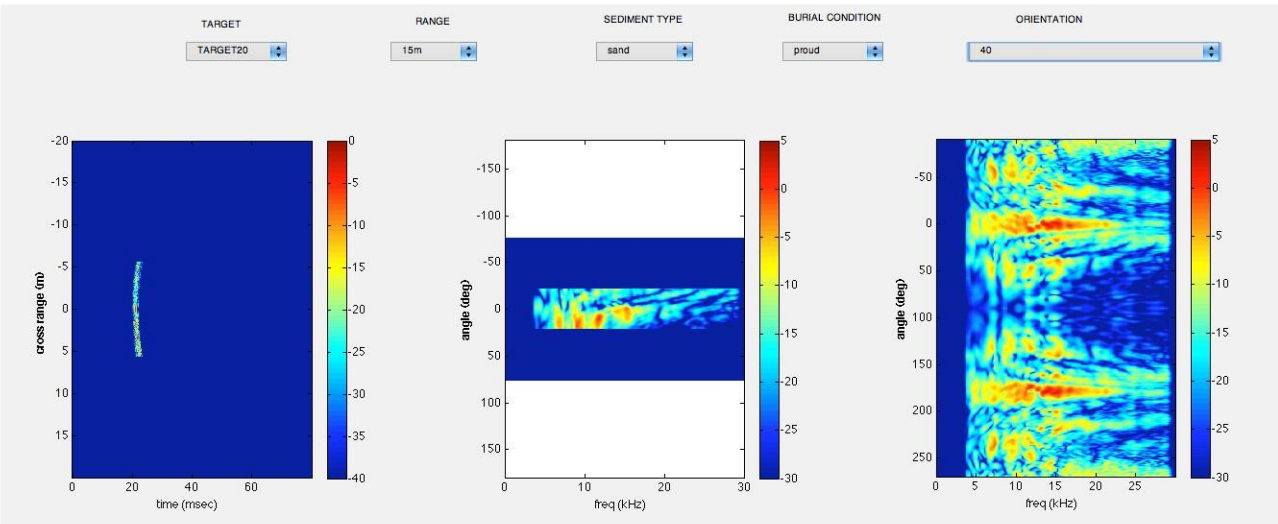
4.0 Materials and Methods

The proposed approach to the preliminary design of an underwater test site is to:

1. Conduct an analysis to determine item distribution scenarios that will apply to all sensor modalities and systems of interest over a variety of conditions.
2. Fully elaborate on and investigate the feasibility of implementing a re-deployable item emplacement process; and
3. Research site possibilities for installing test beds that will apply to the largest possible variety of conditions to all sensor modalities and systems of interest.

Item Distribution Scenarios

As an example of the richness of the acoustic response that is currently available from lower frequency Synthetic Aperture Sonar (SAS) data collected during TREX13 under SERDP MR-2231, the figure below shows plots of the calibrated cross range/time scattering data (leftmost panel) and the angle/frequency "acoustic color" template (center panel) for an aluminum UXO replica placed in an oceanic environment proud on a sand sediment at a range of 15 m and oriented at an angle of 40°. The plot in the right panel is the full angle acoustic color plot, incorporating response data collected from the same item at nine different orientations, and includes the structural resonances and shape content that together provides the basis for classifying items. During TREX13, data from a total of 27 items – spanning various simple shapes to UXO targets – and placed proud, partially buried or fully buried in sand, were collected at various range distances 5-40 m in the frequency band 3-30 kHz at nine different orientations with the source and receiver at an altitude of 3.8 m. Subsequent data collection at BAYEX14, also under SERDP MR-2231, took place in a brackish bay environment with a mud layer over sand sediment and included also using a higher frequency band of 100-200 kHz. The TREX13 data has been processed and released to the public.



After reviewing various item distribution scenarios in an actionable test plan; calibration lanes, a blind grid and an open area were suggested scenarios. The calibration lanes, with publicly-revealed item ground truth, would provide an avenue for sensor and algorithm development and validation; while the blind grid and open areas, with concealed item ground truth, would offer a means to comparatively evaluate the performance of sensor systems. The three scenarios are summarized by specifying the intended layout area and distribution methodology; the total number of items to be emplaced; and the item type distribution, including the depth/degree of burial and orientation distribution for each item type.

The calibration lanes are summarized as an 80-m by 100-m area consisting of eight lanes separated by 10-m, with each lane containing ten equally-spaced items of the same type and also separated by 10-m. In this case, the 10-m separation distances in both dimensions would be derived by consulting the compiled catalog of item responses and basing these on the maximum spatial extent necessary to prevent any signal overlap from occurring given the chosen item types, including depth and orientation distributions. The total number of items would be eighty, with the eight different item types either being specified precisely (e.g. an 81-mm mortar) or categorized into precisely specified groups (e.g. small, medium and large Target-of-Interest (TOI) and clutter groups, with the large clutter group, for example, being specified as either a 55-gallon drum, a scuba tank or a rock within a range of acceptable dimensions). Finally, each item type would also have their depth/degree of burial and orientation distributions specified, e.g. two different orientations for each of five degrees of burial – proud, partially buried, completely buried (very shallow, shallow and deeper) and all fully defined – with horizontal and inclined downwards by sixty degrees along-the-lane orientations, except for the proud case where inclination might be substituted by counter-clockwise azimuth about the along-the-lane line.

The purpose of the blind grid is to evaluate the detection and classification ability of the sensor system independent of absolute location uncertainty. This is done by placing the items at the center of randomly chosen cells within a well-defined grid where the cell size and number of cells determine the extent of the grid and where the absolute location of all the grid nodes are publicly available. In this case, the total number of cells and the cell size are to a large extent controlled by the desired performance metrics, with additional help gathered by consulting the compiled catalog of item responses. Thus, if the probability of detecting small, medium and large TOI each as a function of depth are desired as performance metrics, a minimum reasonable number of items in each TOI category across a spectrum of depths will be required to achieve acceptable levels of confidence while being economically viable. In addition, since the "proud on the sediment" case would likely be the only depth that applies to all sensor systems, a heavier emphasis might apply to this special case.

A minimum reasonable number for each TOI category is 100 and that the cell size is 10-m by 10-m. Based on this information, the blind grid might be summarized as a 300-m by 300-m area with a total of 900 cells: 300 of which contain the three categories of TOI; 300 of which contain small, medium and large clutter; and 300 of which remain untouched. A methodology would describe in detail the random assignment of the cells with the TOI and clutter items, including the distribution of items across depths and orientations. In this case, the depth/degree of burial distribution for each category might be specified as 25 proud; 15 partially buried; with the remaining 60 completely buried and uniformly distributed down to say 10 times the average of the two smallest orthogonal dimensions.

The open area, unlike the blind grid, will have the underlying grid structure hidden from public view with only the locations of boundary points demarcating a much larger area made public. The implementation plan, however, can be summarized in similar terms since the desired performance metrics will again control how many cells need to be populated and what size the cells need to be to prevent the possibility of signal overlap. While the spatial layout of the grid cells will now contain a statistical element by perhaps specifying a random spatial arrangement of sub-grids (each of which might consist of a random cell count and/or a random shape factor), the grid cells can be conceptually ordered, labeled and randomly assigned with items in the same manner as for the blind grid. Ultimately, the choice of the performance metrics will have to be weighed against the level of effort needed to emplace targets. Placement of 300 items in known locations and orientations could easily require several dive teams several weeks; more under zero visibility conditions, such as muddy environments. One can anticipate an evolutionary effort where the scenarios, performance metrics and number of targets will increase as proficiency increases over time.

Re-Deployable Item Emplacement Process

The proposed item emplacement process, as currently envisioned, entails physically laying out the test beds using the following re-deployable materials:

I. A lightweight grid framework that can be efficiently assembled – either in parts or in its entirety – roughly in situ either on the water surface before being submerged or at depth. Regardless, final arrangement will be carried out once on the bottom. While all grid nodes will be anchored temporarily, it is envisioned that detachable segments pre-outfitted with acoustic transmit tags at the grid corners defining the outer perimeter will be permanently anchored. The latter will take place just before the materials are recovered after item emplacement has been completed. Together with a permanently installed array of fixed hydrophones integrated with a GPS reference, the tags will be geographically located and, over time, very accurately determined.

II. Sections of durable mesh fabric that can be rolled out on the bottom and snapped securely into place on the nodes of the grid framework. Each section of fabric consists of a defined lattice of interconnected cells, each cell having the following essential qualities:
    i. A uniquely identifiable acoustic transmit tag outfitted at its center;
    ii. A size based on the largest footprint determined by the analysis conducted in the first step; and
    iii. An efficient means of temporarily removing itself entire from the fabric section in areas where obstacles exist.

With all fabric sections securely in place and obstacles protruding through gaps where fabric cells have been removed wherever necessary, an accounting of the remaining tag IDs offers a collection of spatial points upon which distributions of items forming the desired test bed scenario can be placed. In this way, the item configuration can be predefined before any emplacement occurs.

III. Handheld passive acoustic devices tunable to receive signals transmitted from any specific tag that can allow divers to navigate from one potential emplacement spot to another on a pre- emplacement reconnaissance mission and/or a predefined item emplacement mission. Crucial reconnaissance information would be whether desired burial depths can be achieved and, if not, whether any other location can accommodate the particular burial depth. With this reconnaissance, a predefined distribution can emerge before the final emplacement is actually implemented.

IV. An underwater positioning system that can locate the post-emplaced items to centimeter level accuracy. Redundancy measurements on the outer perimeter grid corners can be added to strengthen the confidence level of the location estimates. Where applicable, multiple points can be included on items to measure orientation and these can also be redundantly referenced using other tools and techniques.

V. Environmental ground truth stations that can be efficiently deployed before, during and after experiments or demonstrations. The exact sensor and layout needs will emerge from information gathered from the survey results discussed in the first step above.

While there are an abundance of commercial underwater positioning systems from a multitude of vendors ranging from standard ultra-short, short and long baseline (i.e. USBL, SBL and LBL, respectively) systems, all the way to customized hybrid systems that combine methodologies to provide more enhanced performance, we have identified a small number that will serve as a starting point for our evaluation effort. For the acoustic transmitter tags, mature technologies exist for tracking marine life from a number of manufacturers, including Lotek, Sonotronics and Advanced Telemetry Systems (ATS). In particular, Lotek's MAP acoustic product family (http://www.lotek.com/map-positioning-system.htm; http://www.lotek.com/acoustic-positioning-software.pdf) appears to provide all the hardware and software needs necessary to position the anchored grid tags. An array of at least four permanently anchored hydrophones integrated with GPS will be needed and while the time resolution for the 200 kHz system is 52 microseconds, or 8-cm in water, any sound speed variation, hydrophone movement and relative timing uncertainties will all conspire against achieving position estimates anywhere close to this. The saving grace is that the transmitter tags will also be anchored, thus allowing the averaging process over time to work in our favor. In addition to ID-only tags, Lotek also offers ID plus sensor (temperature, pressure/depth or motion data) tags and allows simultaneous monitoring and recording of these.

To locate the post-emplaced items to centimeter level accuracy, two systems have been identified as candidates to evaluate first: the GAPS system from iXBlue; and the Southstar system from Desert Star Systems LLC. The iXBlue GAPS solution (https://www.ixblue.com/products/4th-generation-gaps-usbl) appears to be the simpler system to deploy and is best for waters not deeper than 20-m. GAPS is an integrated underwater positioning solution which allows USBL underwater positioning to operate from any vessel, using a portable and pre-calibrated USBL head coupled with an inertial navigation system (INS) and GPS to maintain performance. The Southstar system (http://desertstar.com/product/southstar/) appears more complicated to deploy but is likely the better choice for deeper than 20-m waters. This LBL system relies on manually mounting an array of four stations on tripods around the floor of the area of concern that are radio linked to a surface control station with GPS.

The usage of the two independent positioning systems – the Lotek and iXBlue (or Desert Star) systems described above – provides for both efficiencies and location redundancy checks. The efficiencies come from the time saved from having to set up a high accuracy positioning system (which could be nontrivial, as in the case of the Southstar system) until the final stage when the actual emplaced items need to have their locations recorded. The location redundancy checks come from using both systems to measure a common subset of points, such as the permanently anchored grid points referred to earlier. An advantage of having the entire well-characterized grid framework set in place – at least until all the emplaced items have been located with the high accuracy positioning system – is that any number of additional grid points can also be located with the high accuracy positioning system. This allows rough accuracy bounds to be inferred using the geometrical constraints that the grid framework offers in conjunction with other available data, such as bathymetry. One possible idea would be to also collect the locations of the grid nodes surrounding each emplaced item (i.e. four points for a square-celled grid), at a minimum for all those in seemingly flat areas. With enough such grid node location samples collected and existing biases removed (e.g. slopes based on bathymetry data and grid center locations based on a suitable geometrically-constrained optimization), reasonable first order accuracy bounds should emerge that, combined with longer term monitoring of the permanently anchored grid points, can potentially tighten over time.

The original conceptual design for the GU was a PVC-based two-by-two square cell grid with a cell dimension of 6-m or 20' (Figure 1). Each cell area would accommodate a clip-on section with four removable square mesh fabric panels, each panel with dimension of 3-m (10') and containing a mesh pocket at the center to hold a uniquely identifiable pinger. The material for a GU should be manageable to deploy from a small boat or skiff with two people and 2 – 4 divers in the water.

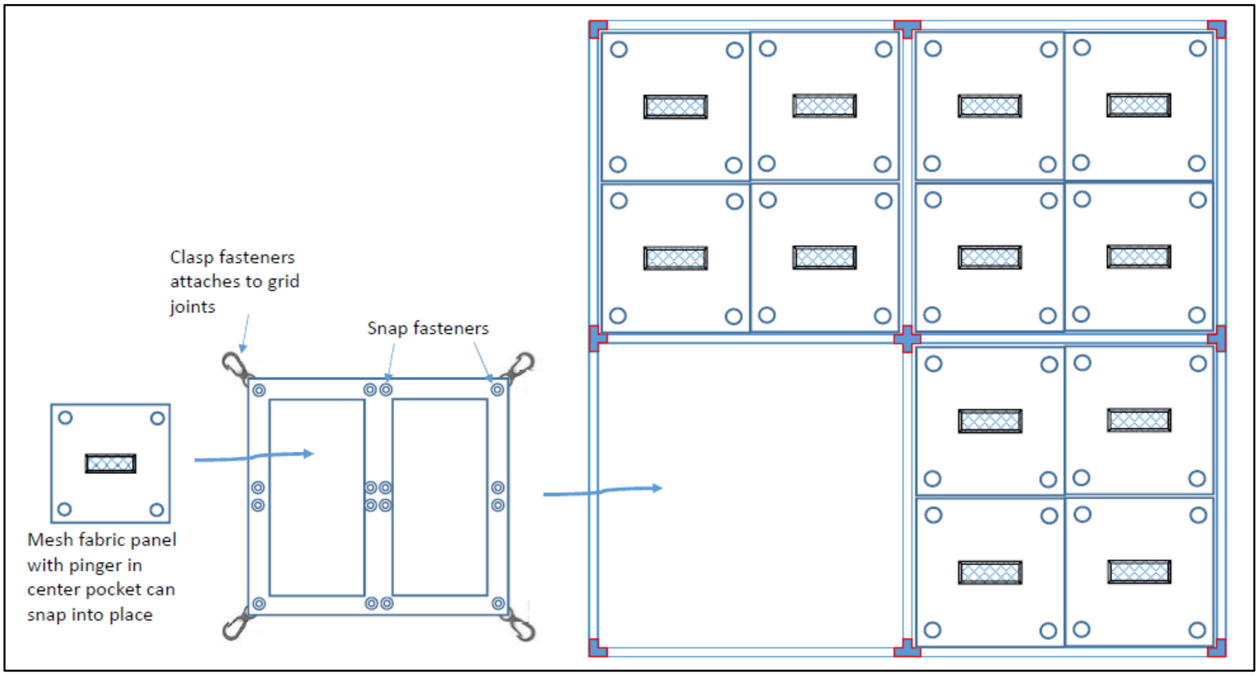


Figure 1 - The conceptual design for the GU showing a PVC-based two-by-two square cell grid with a cell dimension of 6-m or 20'.

Since test bed scenarios may well extend over areas easily exceeding tens of acres, a modular approach to the grid platform design seems to be the most practical. This means a unit platform structure, which we call the grid unit (GU), will form the basic building block of the re-deployable underwater test bed. The GUs can either be deployed to cover one continuous area or a series of non-contiguous areas depending on the desired test bed seeding scenario. Based on the ultimate material costs, a minimum number of these GUs will be deployed at any one time before they are recovered for later reuse.

Possible Sites

The goal of this last step was to identify potential sites where test beds can be installed to accommodate the largest possible variety of conditions to all sensor modalities and systems of interest. This involved not only examining the physical conditions in the vicinity of a geographical location, but also the changes that can occur over time. The sites should also be, or have the potential to be:

a. Securable, so that equipment such as GPS and/or monitoring instruments, can be left unattended for extended periods of time
b. Easily accessible for mobilization of sensor systems to the site

A methodical approach starting with the exhaustive Munitions Response Site (MRS) online inventory available on the DoD Environmental, Safety and Occupational Health Network and Information Exchange (DENIX) website, installations on the coastal waters of the Atlantic Ocean, the Gulf of Mexico and the Great Lakes was identified. Amongst these, potential test bed sites were evaluated for ease of access to a variety of aquatic conditions and water depths. Using a scoring process based on the availability of nearby acreage within specified depth ranges – including variations in water conditions from salinity, sediment type and current strength, to mention a few – the sites can be ranked to allow focus on about a dozen of the best options.

Ranking process:

1. First stage:
    a. Look at all water depths within 10-km radius of installation shore
    b. Place a 1 in the depth column (< 10’, 10’-30’, 30’-60’, >60’ of either salt, brackish or fresh water) wherever a ~3-km x 100-m (0.1-km) rectangular area can be placed
2. Second stage:
    a. Focus on top 20 sites with the largest column totals from 1.b above
    b. Identify from property map (pdf), aerial photos (google earth), etc.:
        a. Current ownership and existing local/on-site infrastructure
        b. Any obvious military bases or fed/state/local facilities on the water nearby?
        c. Boat ramps and/or marinas in vicinity (note number of these & add placemarks for each to the kmz file, with an ID for each)
        d. For each identified boat ramp/marina, determine distance to each of the depth column areas used in the first stage ranking process
    c. For distances between each boat ramp/marina to depth column area, examine NOAA chart more closely and note any notable features/restricted areas in or along path to each depth range area. Include any regulation details noted;
3. Third stage:
        a. Tidal information;
        b. Any available water temperature current information.
    b. Any available sediment type information for each site
    c. Seasonal variations

Among the top contenders are sites on the Outer Banks of North Carolina where areas of water depths in the 10-30 feet range and 30-60 feet range exist in the Atlantic Ocean in close proximity to the shoreline, and even shallower water ~10 feet also exists nearby in the more sheltered sounds. Other top contenders are sites on the panhandle and Gulf of Mexico side of Florida where bays, lagoons and the Gulf of Mexico provide for an array of depth and aquatic condition choices.

Among the top contenders identified during the evaluation of locations in MR-2736 are sites on the Outer Banks of North Carolina where areas of water depths in the 10-30 feet range and 30-60 feet range exist in the Atlantic Ocean in close proximity to the shoreline, and even shallower water ~10 feet also exists nearby in the more sheltered sounds. Other top contenders are sites on the panhandle and Gulf of Mexico side of Florida where bays, lagoons and the Gulf of Mexico provide for an array of depth and aquatic condition choices. Water depths of up to 120 feet could be considered, but we recommend utilizing water depths up to 60 feet during the first phase of establishing an underwater geophysical standardized test site.

Once a test site is selected, stakeholders will be identified, and their interest and support will be discussed along with any potential environmental permits or requirements that may be needed. Stakeholders are anticipated to include the landowners of the test site location, ESTCP, Department of Defense, and state and local government representatives.

Several technical project planning meetings will be required with the identified stakeholders to discuss the overall project goals and requirements, site specific requirements, and achieve consensus for moving forward to establish the test bed at the proposed location. This will include obtaining a commitment for the site location from the appropriate stakeholders. During this process the testing authority for control of the test bed will be identified.

5.0 Results and Discussion

The preliminary design study evaluated ways to accommodate platforms for model validation, *in situ* demonstrations and performance inter-comparisons. After reviewing various item distribution scenarios in an actionable test plan; calibration lanes, a blind grid and an open area were the suggested scenarios.

- The *calibration lanes*, with publicly-revealed item ground truth, provided a platform for sensor and algorithm development and validation.
- The *blind grid* and *open area*, with concealed item ground truth, offered a means to comparatively evaluate the performance of sensor systems.
    - The *blind grid* served to evaluate the detection and classification ability of the sensor system independent of positioning by placing the items at the center of randomly chosen cells within a well-defined grid where the cell size and number of cells determine the extent of the grid and where the absolute location of all the grid nodes are publicly available.
    - The *open area* had an underlying grid structure hidden from public view with only the locations of boundary points demarcating a much larger area made public.

The response and discrimination stage metrics utilized to evaluate and compare system performance at the APG and YPG terrestrial sites provided a good place to start when evaluating the detection and classification performance of underwater systems. Ultimately, the specific choices of metrics as it relates to munitions type/size were weighed against the level of effort needed to emplace items in the required numbers to provide meaningful metrics.

Current or former military underwater ranges/installations were researched to identify potential candidates that could accommodate test bed scenarios in a variety of aquatic environments for as many sensor system modalities as possible. This involved not only examining the physical conditions in the vicinity of a geographical location, but also the changes that can occur over time. A methodical approach of ranking the sites was pursued.

The end goal of the re-deployable underwater test bed is a platform that is placed on the water bottom and that can accommodate pingers with known unique IDs at regular intervals in two dimensions. The pingers identify potential locations for which to emplace prescribed items in a given configuration either proud on the surface or buried at a given depth. The pingers allow divers armed with underwater receivers to efficiently navigate from one desired item emplacement location to the next based on a pre-planned and thought-out seeding strategy.

The basic concept of the re-deployable underwater test bed consisted of a lightweight grid framework that can be efficiently assembled on the water surface before being submerged and guided to the bottom. This ***grid unit*** (Figure 2) of four 6m X 6m cells can either be a standalone structure or add to an existing grid network. The goal would be to deploy the grid unit from a small boat or skiff in one trip with two people.

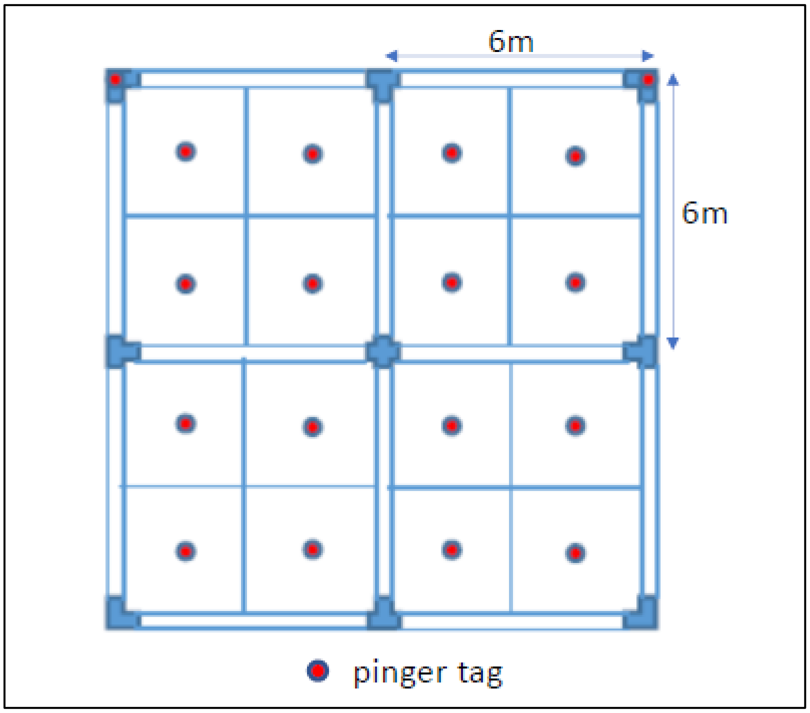


Figure 2 - GU design showing 6-meter PVC Sections

The current implementation looks to use two smaller diameter 3m (10ft) PVC sections coupled together to form the grid cell sides. To ensure buoyancy, attachable floats will be used. In addition, custom work will be required for the grid joints to allow clasp fasteners to latch on and, for the ell joint specifically, to allow anchoring and break away of the pinger tags. Three options have been explored for joints including an ell, tee & cross (shown in Figure 3); each joint is capable of allowing one, two and four clasp fasteners, to latch on. If the ell joint is used alone it will provide the ability to anchor in sediment, hold a ping tag; and allow the grid structure to break-away leaving behind the anchored pinger tag.

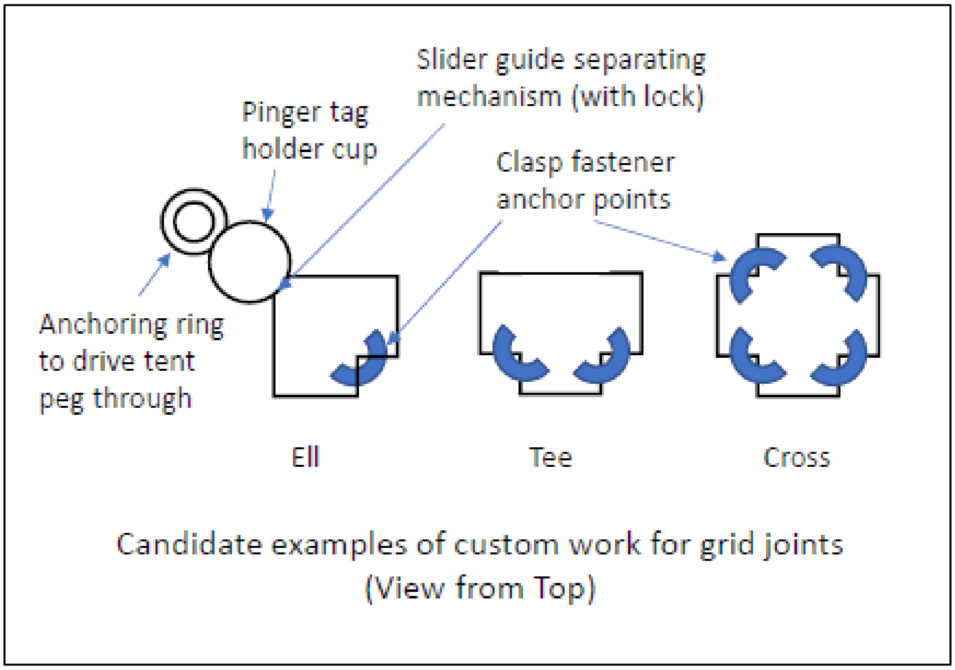


Figure 3 – Custom Grid Joints

Fabric sections that can easily be secured onto the grid unit with four 3m square mesh panels will need to be tailored to allow (i) placement of a unique ID pinger tag at each panel center, and (ii) an efficient means to remove panels whenever obstacles exist on the bottom (Figure 4).

The grid corners will initially be anchored temporarily on the bottom, with permanent anchoring of the tags taking place just before the materials are recovered after item emplacement has been completed. Together with an array of hydrophones integrated with a GPS reference, the perimeter tags will be geographically located and, over time, very accurately determined.

With all sections in place on the grid unit and obstacles protruding through gaps where panels have been removed, an accounting of the remaining panel tag IDs offers a collection of spatial points upon which distributions of items forming the desired test bed scenario can be placed. In this way, the item configuration can be predefined before any emplacement occurs.

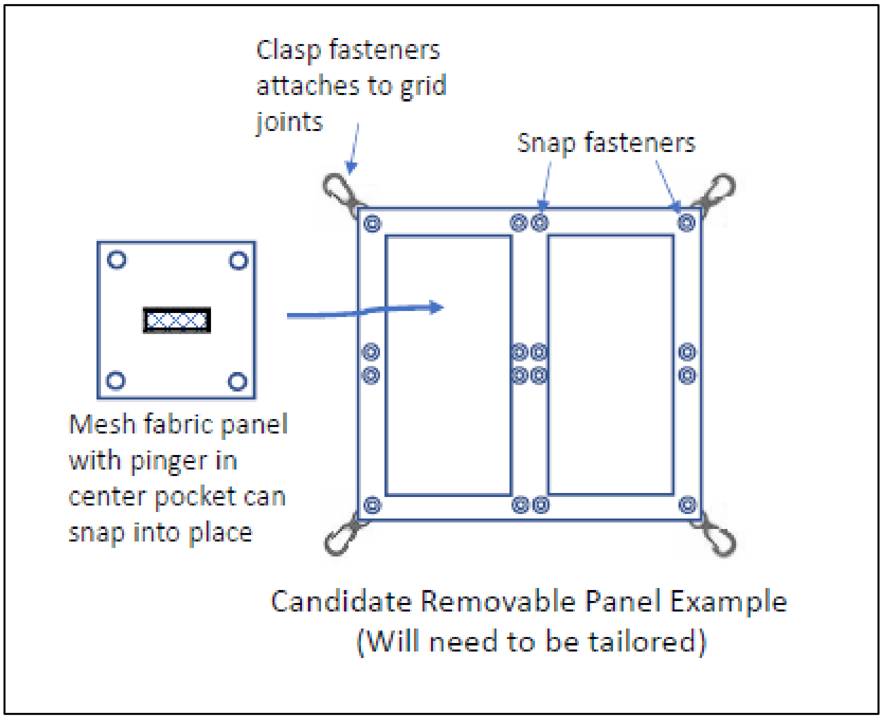


Figure 4 – Removable Panel Example

Handheld passive acoustic devices tunable to receive signals transmitted from any specific grid cell/panel tag will allow divers to navigate from one potential emplacement spot to another on a pre-emplacement reconnaissance mission and/or a predefined item emplacement mission. Crucial reconnaissance information would be whether desired burial depths can be achieved and, if not, whether any other location can accommodate the particular burial depth. With this reconnaissance, a predefined item distribution can emerge before the final emplacement is implemented.

Pinger tags are most often used to track fish and come in many different sizes and shapes but are commonly cylindrical (see Figure 5). They are typically composed of a piezoceramic transducer, drive/timing electronics, and a battery power source. An AC voltage is generated and impressed across two metalization layers which creates stress in the material causing the transducer to transmit a ping. Most tag manufacturers – e.g. Lotek, Sonotronics, Vemco – focus their use on tracking fish. In addition to ID-only tags, ID/sensor tags are also offered where sensor data such as temperature, pressure/depth and motion are also transmitted.

Two types of tags will be needed to perform separate functions:

1. Grid corner or perimeter pingers, for positioning (i.e. defining the overall grid perimeter geographic locations)

    - Lotek is the only source to offer a complete package – hydrophones, receiver/processor units *and* positioning software

2. Grid cell or panel pingers, for tracking by divers (i.e. for reconnaissance and/or item emplacement)

    - Sonotronics is only source to offer underwater diver receiver units

Source: http://www.lotek.com/m-series-coded-acoustic-transmitters.htm

Lotek's MAP-Series
76 or 200 kHz Acoustic TXs
> 80,000 Unique IDs

Figure 5 – Pinger Tags

There are key differences in the way the IDs are coded for Lotek's MAP-Series pingers vs. Sonotronics' pingers – Code-Division Multiple Access (CDMA) vs. Pulse Interval Coding (PIC), respectively. Unlike PIC, CDMA does not require time sharing of the acoustic channel and is therefore much more robust against code collision and noise interference.

Grid Corner Pingers:

Grid Corner Pingers will be used to define geographic locations of the overall grid perimeter. Lotek's Acoustic Positioning Software Suite offers three different solution paths to obtaining TX positions based on trilateration and multilateration, or time of arrival differencing (ToAD):

1. BioMAP – This assumes an array of moored hardwired hydrophones with submersible datalogger (SDL) receivers time synchronized to a common clock (GPS PPS);

2. UMAP, *formerly ALPS (Asynchronous Logger Positioning System)* – This removes the hardwired requirement but assumes the SDLs have been synchronized prior to deployment. Correcting for receiver clock drifts can then take place during postprocessing;

3. SYNAPS (Synthetic Aperture Positioning System) – This uses a vessel based real-time receiver configured for up to two hydrophones capable of instantly detecting the presence and relative direction of TXs. Estimates of TX locations can then take place during postprocessing by combining GPS tagged detection records collected along a trajectory to create a synthetic aperture array equivalent to an array of hydrophones fixed at the GPS positions associated with the individual signal detections. Also available with the sensor option for including temperature and pressure/depth data

Good TX position requires a minimum of 4 hydrophones based on multilateration. BioMAP works with a minimum of 2 hydrophones and can be useful for tracking with Angle of Arrival (AoA) positioning. UMAP requires a minimum of 3 hydrophones

Grid Cell Pingers:

Grid Cell Pingers will be used to guide divers along a planned visitation path (for reconnaissance and/or item emplacement).

Sonotronics' UDR would provide a better chance of tracking and localizing pingers separated by 3 meters, especially in a high population scenario, if:

1. Flat transducers are employed – this transmits in one direction with limited range (at 69kHz); and
2. Neoprene is put around the hydrophone to provide better directionality

Deployment Details

Diver assisted grid placement on bottom will require a grid anchoring method, which will include tent pegs to secure the Ell joints. Tent pegs should be installed in a way that does not damage the acoustic tag or grid structure.

If obstacles exist on the water bottom, necessary panels should be removed to allow for obstacles to protrude through and allow the grid structure to lie flat on the bottom (*assumes scale of bottom variation >> 40'*). Pinger tag IDs on the removed panels will then be noted and removed from the list of possible item emplacement location cells.

Diver-assisted item emplacement

UDR will be used to follow a planned visitation path for driver-assisted item emplacement. Pre-emplacement reconnaissance operations will be performed to aid in the following situations:

1. If in the deployment stage of the grid several panels were removed with no or unclear documentation as to reason for removal and a large number of gaps appear in a localized area, it would be helpful to the analyst to get more information before finalizing the layout of items in that area;
2. If a number of large items need to be buried deep in the sediment, it might be useful to send divers ahead of time to the pre-designated ID locations to determine emplacement feasibility (and possibly alternative ID locations, if not feasible)

An item emplacement directive will be followed as described below:

1. Day 1 – Visit the following 20 IDs and emplace the corresponding items (as per labels or markings) proud on the surface; acquire GPS for each emplaced item (using RTK GPS + INS + USBL system, such as the iXBlue GAPS system)
2. Day2 – Visit the following 10 IDs and bury large ISOs 1-ft deep in the sediment; acquire GPS for each emplaced item

Table 1 presents cost estimates for the re-deployable underwater test bed basic concept.

Table 1
Re-Deployable Underwater Test Bed Price Estimate – 25 Grid Units

Material	Details	Cost
PVC	25 x 40 = 1000 10’ sections	$6,600
Floatation devices	25 x 16/GU = 400	$5/device => $2,000
Custom made fittings	25 /grid unit, or 625	$5/fitting => $3,125
Custom tailoring of the mesh fabric panels	400 (25 x 16)	$250 / 10’ x 10’ panel => $100,000
Sonotronics UDR + 400 (25 x 16) pingers		$83,500
IXBlue GAPS system	Including 3 transponders	$280,000
Hardware	25 Gus & GPS system	$350,000
Ground truth equipment		$50,000
	Total	**$875,225**

Possible Sites

Potential sites where test beds can be installed to accommodate the largest possible variety of conditions to all sensor modalities and systems of interest were examined based on physical conditions in the vicinity of a geographical location, but also the changes that can occur over time.

Table 2 presents the five top potential test bed site contenders. The first stage of the ranking process narrowed the field of potential sites to 22 sites. The second stage ranking process on these sites was mainly based on identifying the following: current land ownership and existing local/on-site infrastructure; the availability of boat ramps and/or marinas in the vicinity; and the proximity of each identified boat ramp/marina to each of the depth column areas used in the first stage ranking process. In this second stage, private land ownership, lack of infrastructure and lack of easy or reasonable access to the available depth column areas were used to eliminate candidates and allowed us to narrow the field further to the five top contenders.

In addition, for each of the five top contenders as potential test bed sites, information was compiled on the following: restricted areas, including environmentally protected areas; tidal information; water temperature; water currents; sediment type; and other potentially useful information, such as planned coastal restoration projects, predicted sea level trends, etc. An evaluation of the best means to condense, present and document this information is currently being undertaken.

Table 2
Five Top Potential Test Bed Sites

Installation Name	DOD Component	Seawater				Brackish Water				Freshwater				Total	Marina Distance Rank (1-Low Priority, 4-High Priority, 0 Not Useable)	Tide Station Used	Mean Range of Tide (ft)	Great Diurnal Range (ft)	Property Owner	Local Infrastructure	Local Boat Ramps / Marinas (#)	Notable Features / Restricted Areas
		Extended Acreage at Depth Range																				
		< 10'	10'-30'	30'-60'	> 60'	< 10'	10'-30'	30'-60'	> 60'	< 10'	10'-30'	30'-60'	> 60'									
EGLIN AFB	AIR FORCE	1	1	1	1	1	1	1						7	4	Destin, East Pass	0.59	0.61	Department of Defense	Eglin AFB, Hurlburt Field AFB, John Beasley Park (local)	9	Intracoastal Waterway near Brackish locations (see Coast Guard local notice to mariners).
FORT CLINCH	FUDS	1	1	1		1	1	1			1			7	2	Fernandina Beach FL	6.02	6.56	State of Florida	Fort Clinch State Park, Cumberland Island National Park, Naval Submarine Base (Kings Bay, GA)	3	Regulated navigation area (165.732) near/at seawater and brackish locations. Intracoastal waterway near brackish locations (see Coast Guard local notice to mariners).
FORT MANSFIELD	FUDS		1	1	1	1	1	1	1					7	2	Watch Hill Point	2.58	3.00	Town of Westerly (Conservation Area)	Barn Island Wildlife Management Area. New London Submarine Base (far)	6	Restricted area (165.100) at Brackish (10'-60') locations.
NSA PANAMA CITY / PANAMA CITY HARBOR DEF / TYNDALL AFB	NAVY	1	1	1	1	1	1	1						7	1	Panama City	1.25	1.34	Department of Defense	Current Navy Installation, Tyndall AFB, City owned marinas (Panama City)	8	Seawater locations NW of channel: restricted area 334.763. Calculated distances are based on locations SE of channel (unrestricted areas). Brackish location (30'-60') restricted area 334.761.
PASSAGE KEY AIR / FORT DADE	FUDS	1	1	1		1	1	1						6	3	Port Manatee	1.54	2.18	Department of the Interior	Passage Key National Wildlife Refuge, Egmont Key National Wildlife Refuge, MacDill AFB (>10km from site)	2	Channel near Brackish (30'-60') location.

6.0 Conclusions and Implication for Future Research/Implementation

Conclusions

The end goal of the re-deployable underwater test bed is a platform that is placed on the water bottom and that can accommodate pingers with known unique IDs at regular intervals in two dimensions. The pingers identify potential locations for which to emplace prescribed items in a given configuration either proud on the surface or buried at a given depth. The pingers allow divers armed with underwater receivers to efficiently navigate from one desired item emplacement location to the next based on a pre-planned and thought-out seeding strategy. The proposed re-deployable item emplacement process is shown to be feasible and cost effective.

Implications for Future Research/Implementation

Increased TX position accuracy can be obtained by:

- Adding hydrophones to the array and solving the least squares for the overdetermined system
- Improving the individual signal timings (calibration)
- Averaging over longer times
- Finding an array configuration that minimizes the error of the estimate of the position (proper coverage)
- Improving hydrophone position estimates
- Enhancing the sound speed estimates
- Reducing noise/interference (increasing detection reliability)

Two hydrophone array configuration options should be considered:

1. Array of N permanently-moored wireless (i.e. asynchronous) hydrophones surrounding the overall grid area and spaced ~100 meters apart

Advantages:	Disadvantages:
• All tags properly covered	• Potentially high capital cost for large areas
• Regular continuous updates, to include data (e.g. T & P/depth)	• Potentially large uncertainties in hydrophone locations
	• Postprocessing required to correct for clock drifts

2. Array of 5 hydrophones attached in a cross configuration to a platform structure that can be moved and moored wherever needed or towed behind a vessel

Advantages:	Disadvantages:
• Hydrophone location uncertainties minimized	• Movement required to obtain proper coverage
• Flexible enhanced coverage options	• Regular continuous updates of local TXs only
	• Less averaging per TX over time
	• If used in towed mode, custom postprocessing needed

Currently, the UDR displays the ID of the pinger that is being detected at the time.

Firmware modifications will be needed in order to:

1. Input a specific pinger ID for tracking
2. load a list of specific pinger IDs to sequentially track

Of note: UDR can detect pings from the Lotek 76kHz TXs, but cannot decode

Implicit in the usefulness of this re-deployable test bed is the accurate accounting and distribution of pinger tag IDs. This will require careful preparation and oversight so that desired tag IDs get deployed in the correct arrangement order.

7.0 Literature Cited:

[1] Appendix D, "SERDP Workshop on Acoustic Detection and Classification of Munitions in the Underwater Environment", FINAL REPORT, April 2018.

[2] Tomich et al, "Preliminary Design Study for Munitions Response Underwater Test Site", SERDP Final Report, MR-2735, February 2018