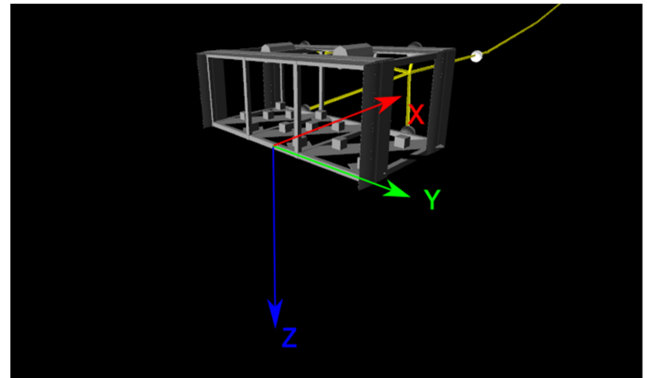
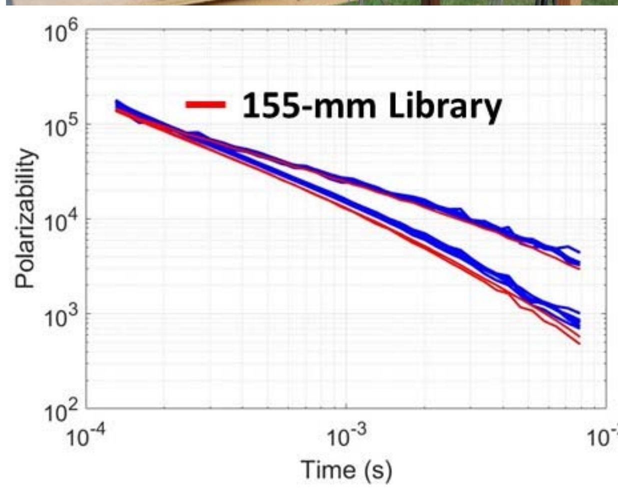
Underwater Dynamic Classification Technology

MR-201614
Jonathan Miller
White River Technologies
In-Progress Review Meeting
2/21/17

ESTCP

MR-201614: Underwater Dynamic Classification Technology





Performers: White River Technologies (WRT), Dynamic Systems Analysis (DSA), Woods Hole Oceanographic Institute (WHOI)

Technology Focus

- *Dynamic classification methods applied to marine towed surveys*

Demonstration Site

- *Modeling, simulation, and experimental proof-of-concept*

Demonstration Objectives

- *Electromagnetic modeling to verify sensor design*
- *Hydrodynamic simulation to evaluate operational requirements*
- *Experimental data collection to confirm model results*

Project Progress and Results

- *Concept feasibility study completed*
- *Draft Final Report submitted*

Implementation Outlook

- *Follow-on concept development effort proposed*

Social Media Content

- ***Electromagnetic methods for marine UXO detection and classification at SAGEEP 2018:*** *White River Technologies will participate in the Non-Acoustic Methods for Marine MEC session at the upcoming SAGEEP Meeting in Nashville (https://enengs.memberclicks.net/sageep-2018-program). This session will present state-of-the-art sensor concepts for the marine UXO application.*

Project Team

- **Jonathan Miller** (WRT)
- **Fridon Shubitidze** (WRT)
- **Greg Schultz (**WRT)
- **Andrew Baron** and **Dean Steinke** (DSA) – Hydrodynamic modeling and simulation
- **Hendrik Muller** (WHOI) – Marine electromagnetic modeling

Problem Statement

The marine UXO problem:

- Access to UXO is difficult; requires diver or ROV; targets obscured by marine growth or sediment
- Survey positioning quality significantly degraded underwater; limited availability of GPS methods
- Reacquisition is challenging due to access limitations compounded by positioning constraints

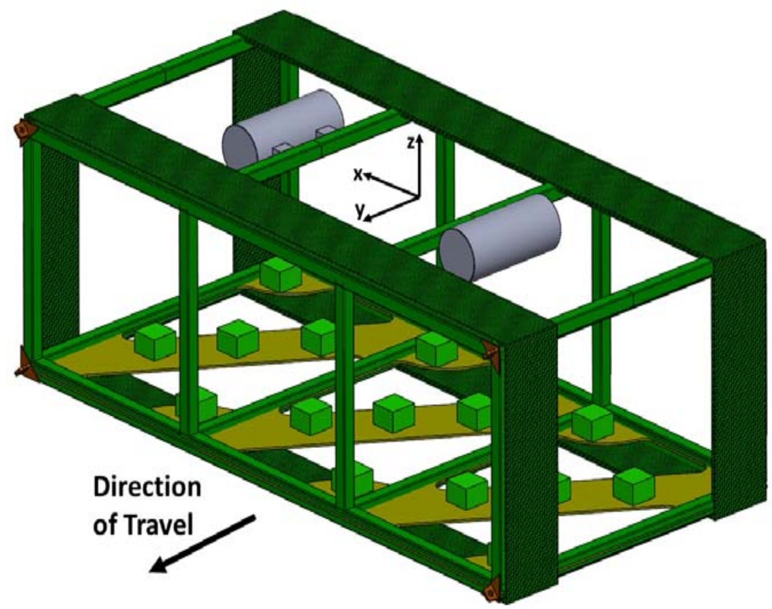
Current approaches:

- Advanced EMI very effective for land-based classification, but deployment underwater limited by increased standoff and positioning constraints
- Acoustic sensors provide increased standoff capability, but challenged by buried or obscured targets

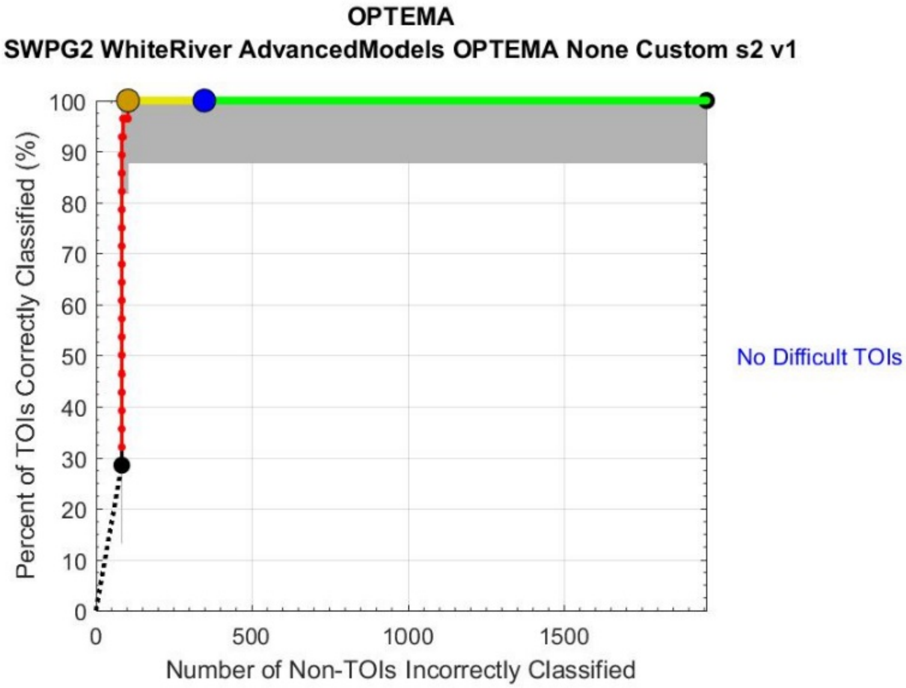
Technical Objectives

Identify the key design features of an effective underwater dynamic classification EMI sensor:

- Demonstrate a sensor form factor modified for operating at increased standoff for underwater towed operation
- Verify that dynamic classification methods used on land will be applicable to the underwater environment
- Demonstrate the hydrodynamic feasibility of towing the modified sensor form factor and identify operating requirements specific to this sensor



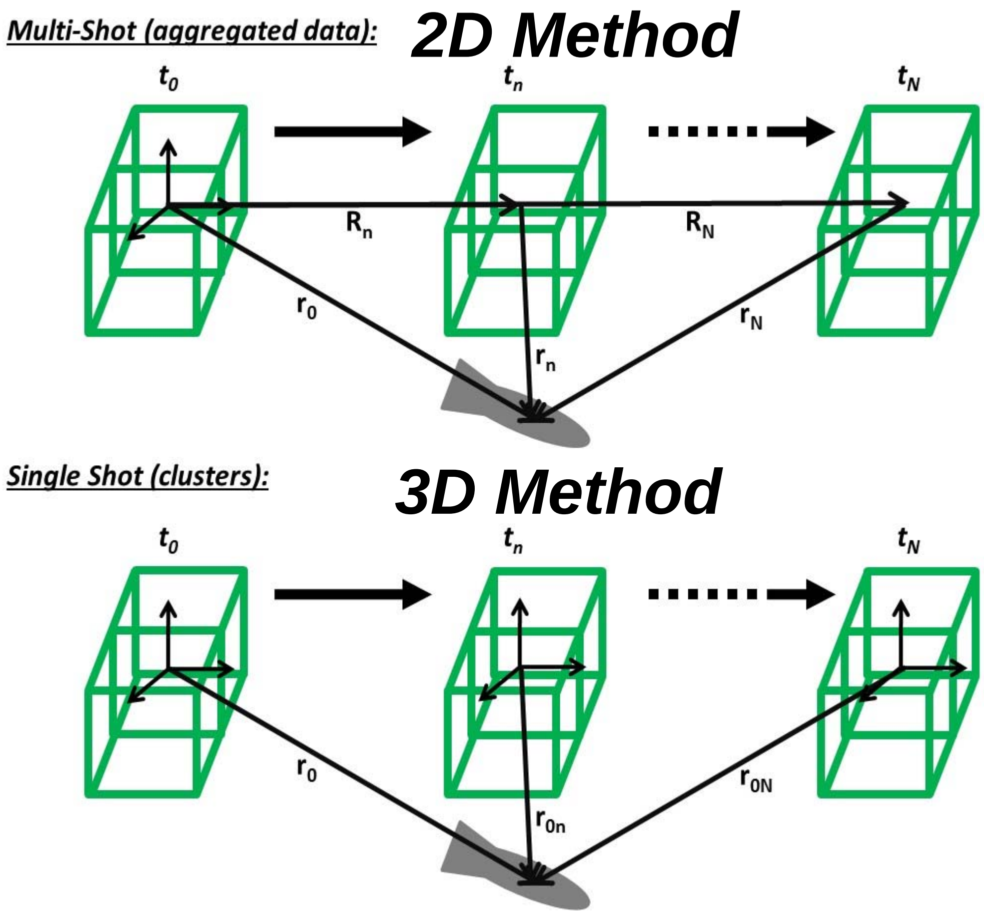
Background: Dynamic Classification



Dynamic classification methods based on those demonstrated successfully under MR201225, benefits for underwater include:

- One pass classification means no cued reacquisition
- Methods are particularly tolerant of positioning errors

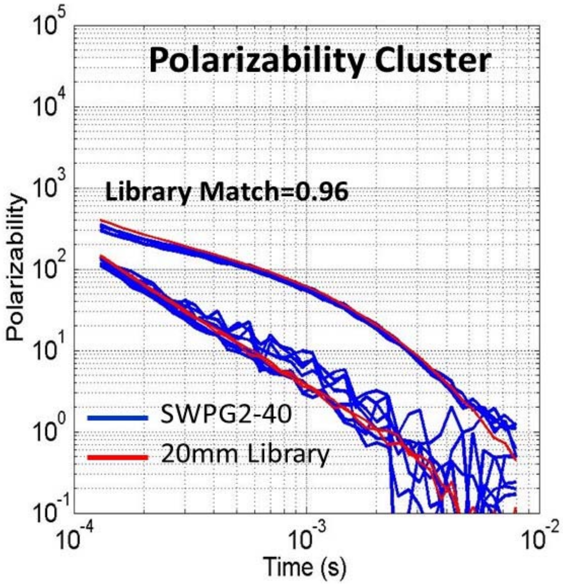
Classification Approach: 2D vs. 3D

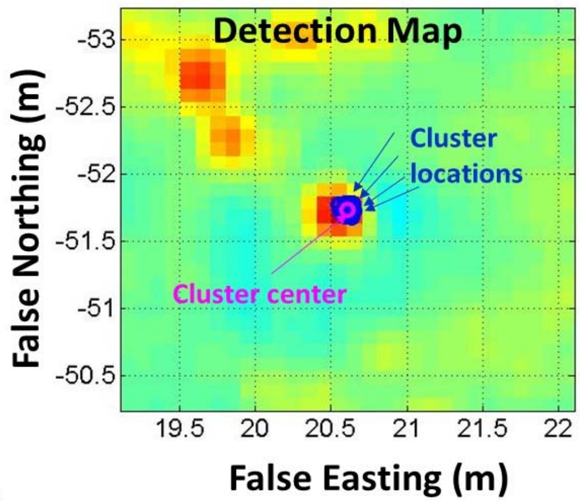


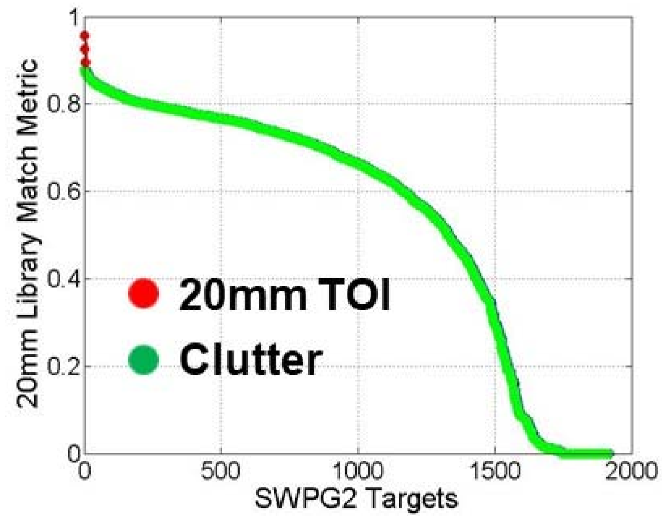
Position error tolerance: Single Shot

- Each sensor position provides complete data for inversion of polarizabilities
- Polarizability "clusters" obtained from multiple sensor locations
- No need to accurately track relative position vectors, $\mathbf{R_n}$
- May be useful for underwater towed operation where towpoint surge could reduce accuracy of relative position tracking over short distances

Polarizability Cluster: Classification Decision







Dynamic classification decision flow:

- Library match performed on polarizability cluster
- Average of cluster locations (cluster center) provides location estimate
- Targets ranked based on library match value

Technical Approach

Sensor design study comprises three tasks:

- **Electromagnetic modeling and simulation** – evaluate EMI sensor classification performance in the simulation environment; test out principles of dynamic classification for the underwater environment
- **Electromagnetic experimentation** – verify simulation results; use scaled-down mockup version of the towed sensor configuration
- **Hydrodynamic modeling and simulation** – evaluate operational performance in the simulation environment; identify requirements for towed array operation

Electromagnetic Modeling and Simulation

$$[f_x \;\; f_y \;\; f_z] \;=\; [L1 \;\; L2 \;\; L3] \begin{bmatrix} T11 & T12 & T13 \\ T21 & T22 & T23 \\ T31 & T32 & T33 \end{bmatrix}$$

Forward Model Output — **Target Library Polarizabilities** — **Target Location, Orientation, and Tx Field Projection**

$$[d_x \;\; dy \;\; d_z] = [f_x \;\; f_y \;\; f_z] + [\sigma_x N_1 \;\; \sigma_y N_2 \;\; \sigma_z N_3]$$

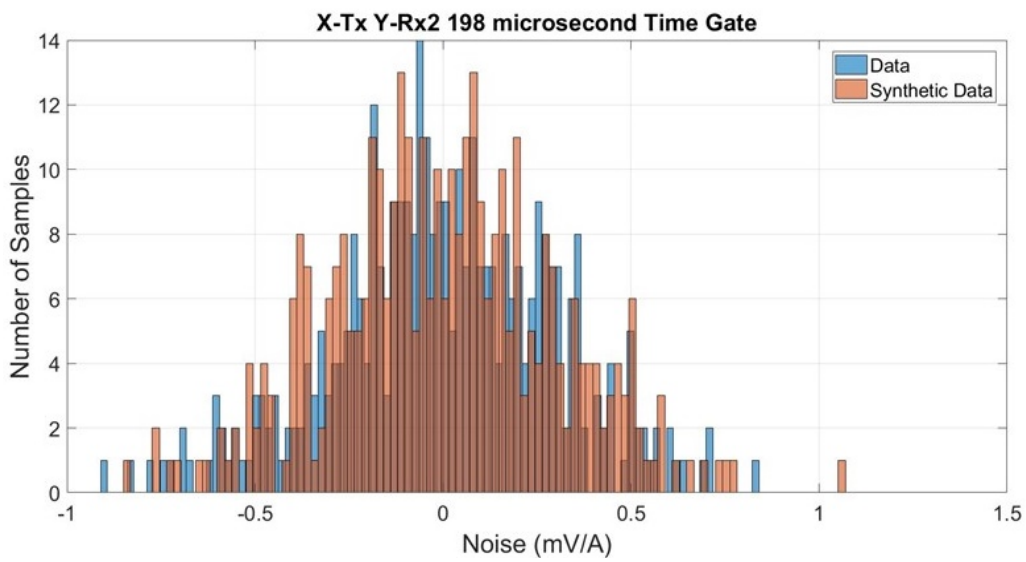
Synthetic Data (x, y, z) — **Forward Model Output** — **Normal Distribution Noise Scaled by Channel Specific Noise Standard Deviation**

To Constrain L2:

$L2*T21 >> \sigma_x$
$L2*T22 >> \sigma_y$
$L2*T23 >> \sigma_z$

Electromagnetic design simulator:

- Generates synthetic data using EMI classification forward model developed for specific sensor configuration
- Synthetic noise characteristics replicate those of actual survey data



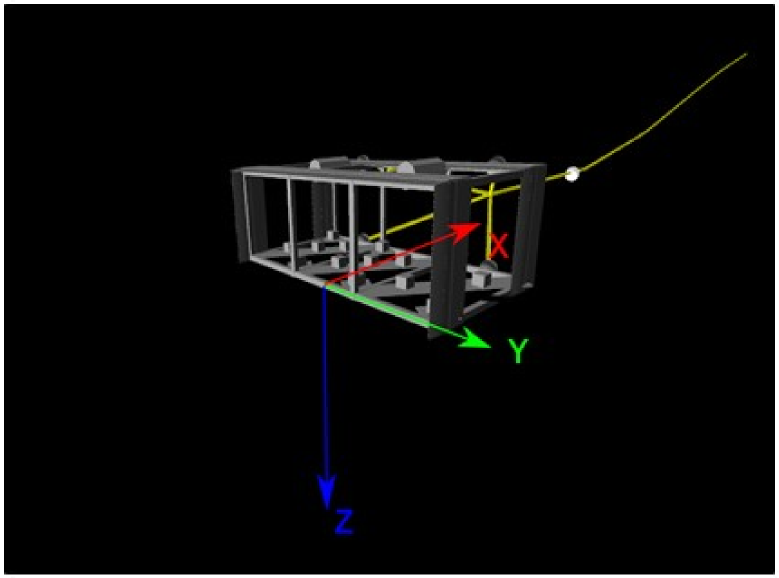
Electromagnetic Experimentation

2/3-Scale Mockup:

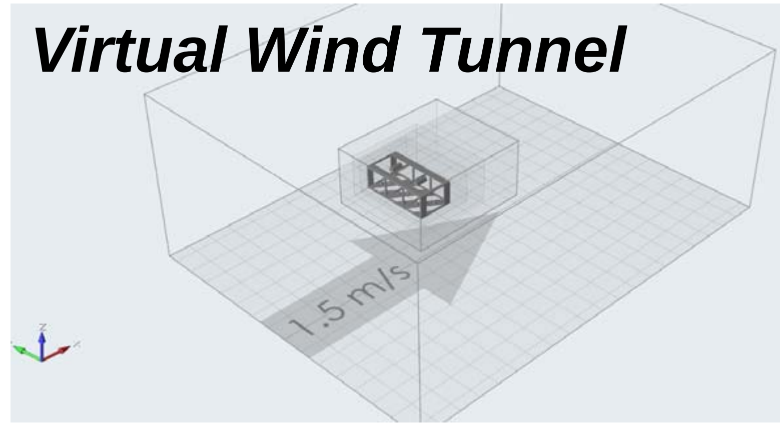
- Replicates configuration of full-scale concept
- Used to verify that model accurately predicts classification performance
- Driven by OPTEMA electronics
- Tested in both static and dynamic modes

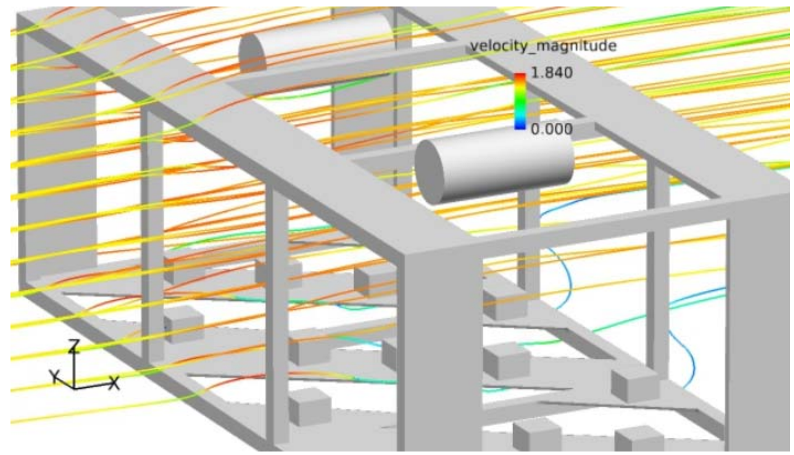
Hydrodynamic Modeling and Simulation

ProteusDS



Virtual Wind Tunnel

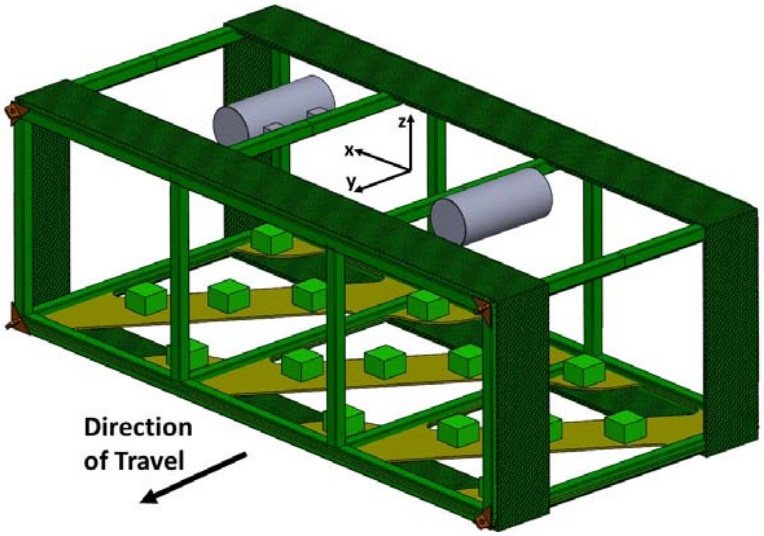


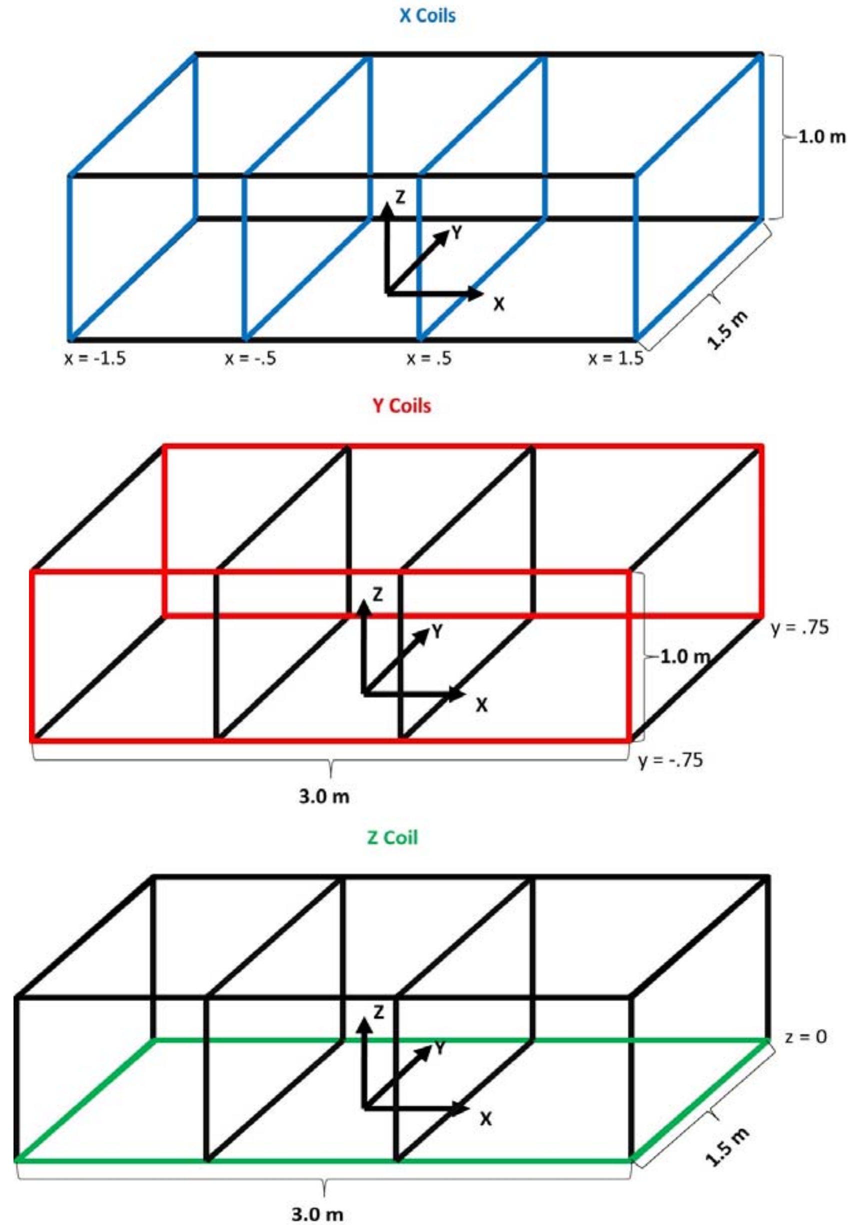


DSA ProteusDS Simulation Environment:

- Identifies forces acting on towed body
- Finite element model determines towed body response to load cases
- Accounts for mass distribution and buoyancy (volume of components)
- Drag analysis accounts for hydrodynamic shielding through Virtual Wind Tunnel (VWT) simulations

Electromagnetic Simulation: Sensor Design

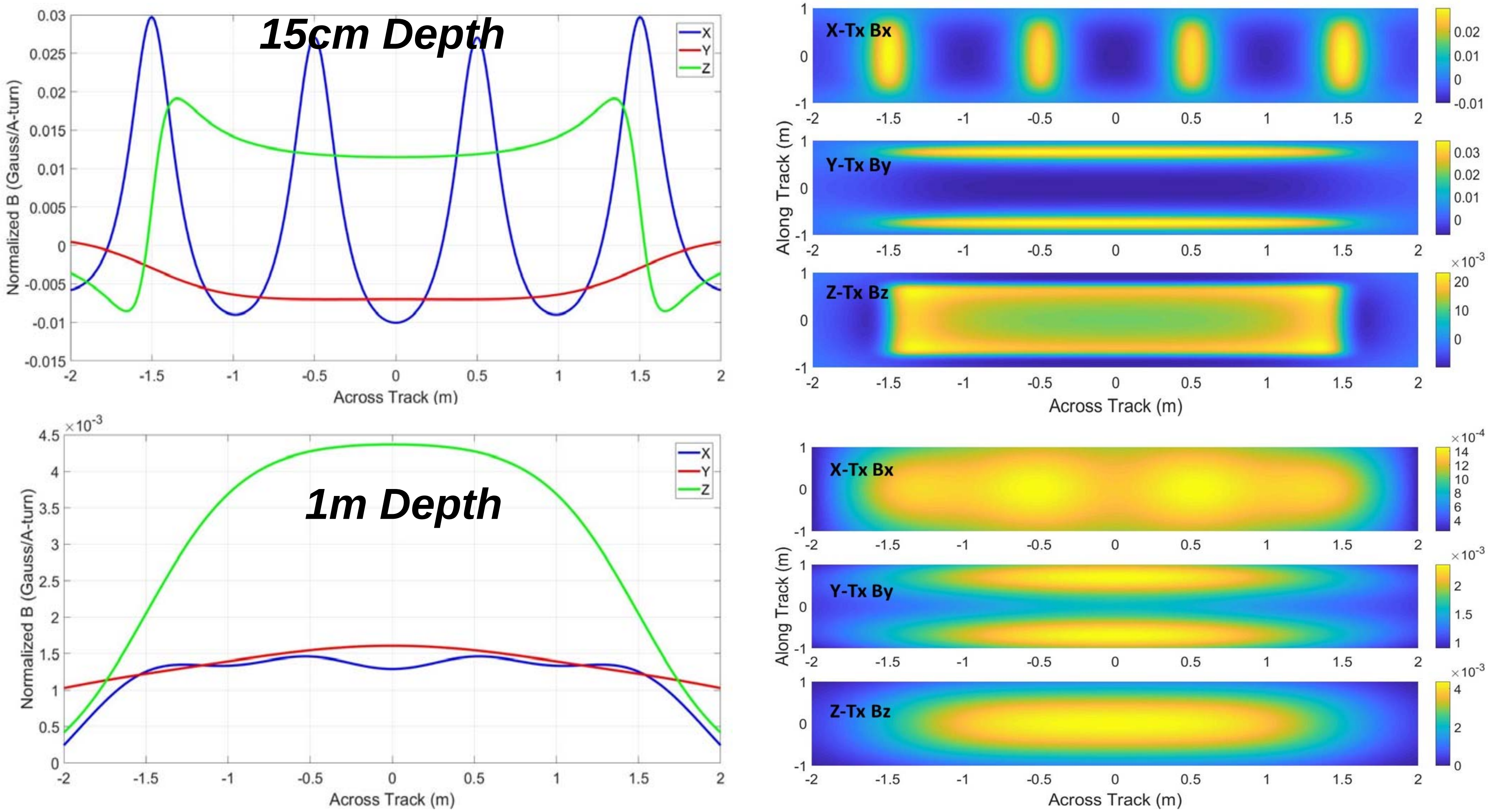




Full "3D" Configuration:

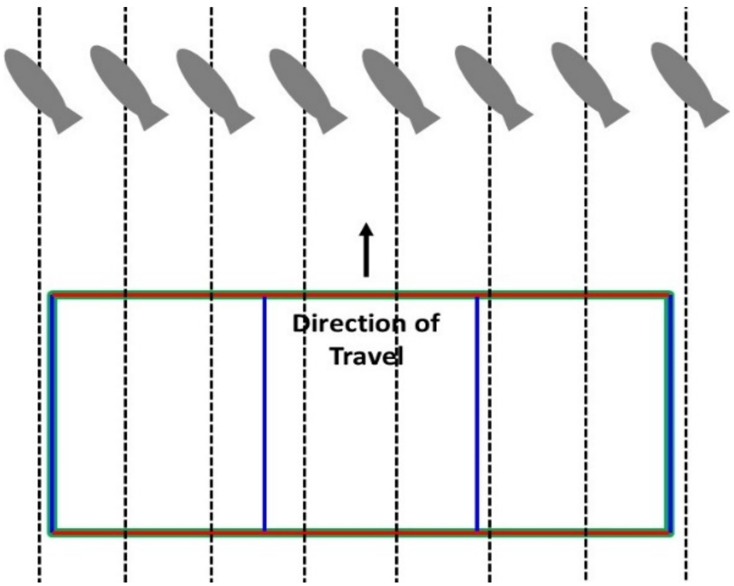
- Enables single shot approach
- Optimized for increased standoff range
- Extended for towed survey swath of 3m
- Incorporated in design simulation forward model

Electromagnetic Simulation: Tx Field



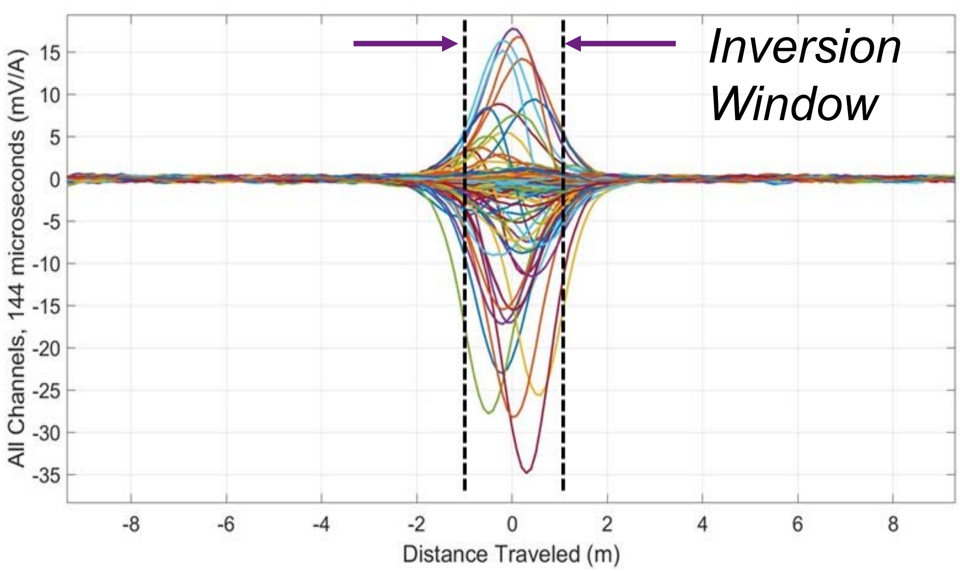
- Optimized for uniform field distribution at ranges >1 meter

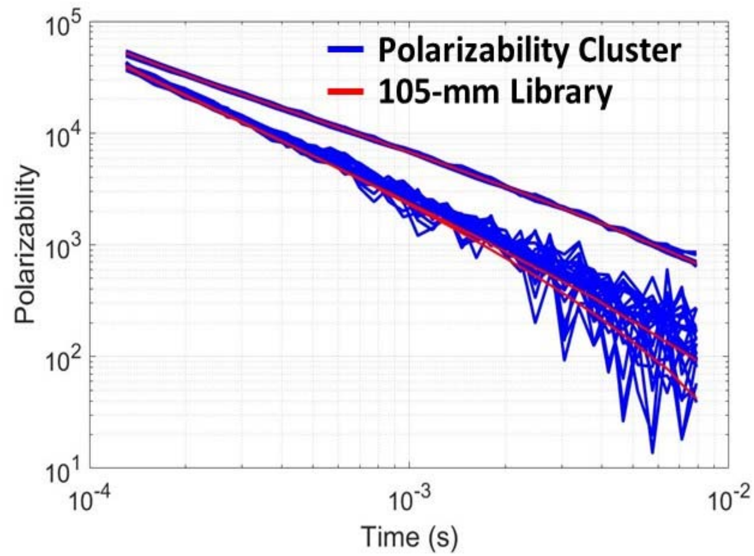
Electromagnetic Simulation: Dynamic Encounters



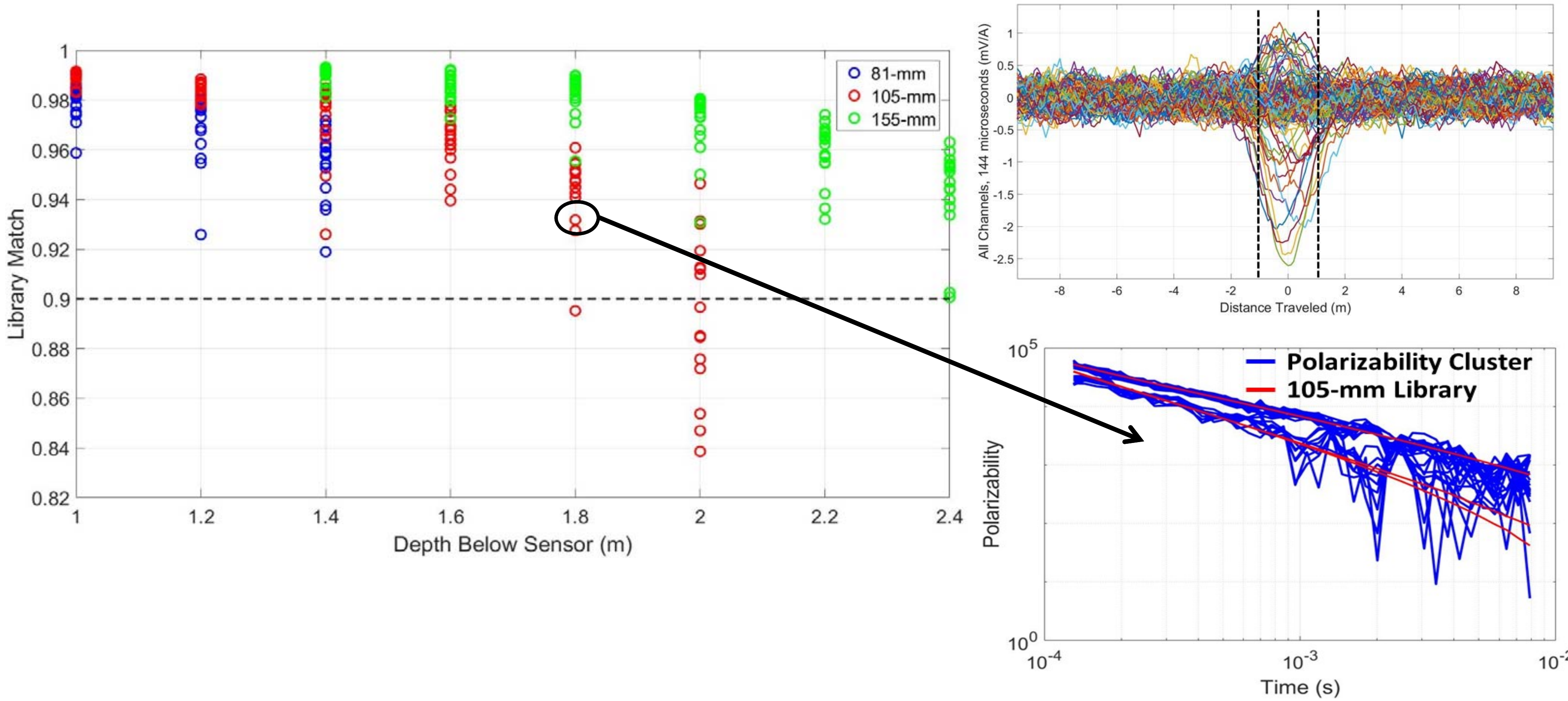
250 Dynamic Simulations:

- 20m lines (+/-10m from target)
- Across track offsets +/-1.6m
- Standoff ranges 1m – 2.4m
- TOI included 81mm – 155mm
- Dynamic noise added from OPTEMA survey data



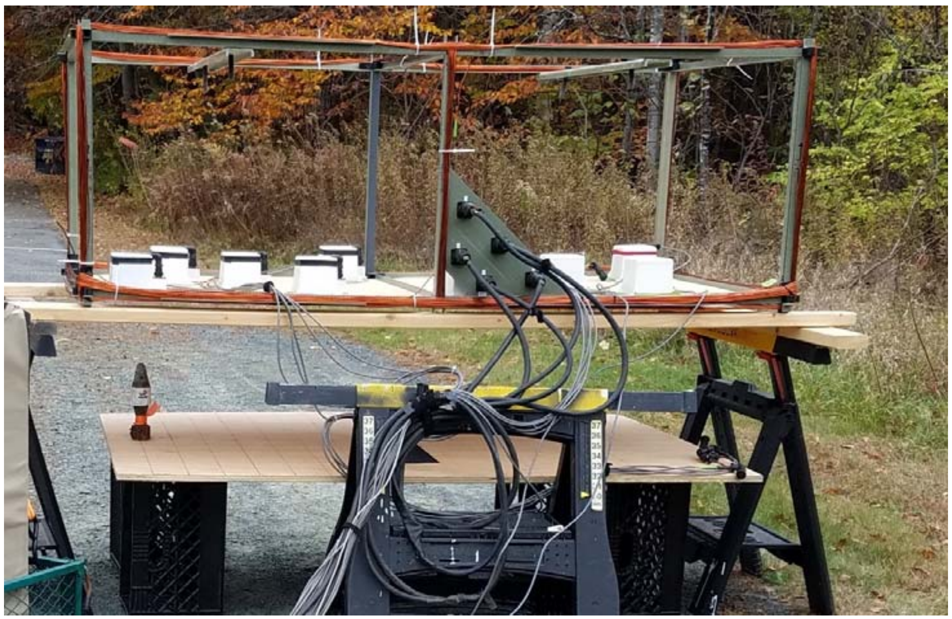


Electromagnetic Simulation: Dynamic Encounters

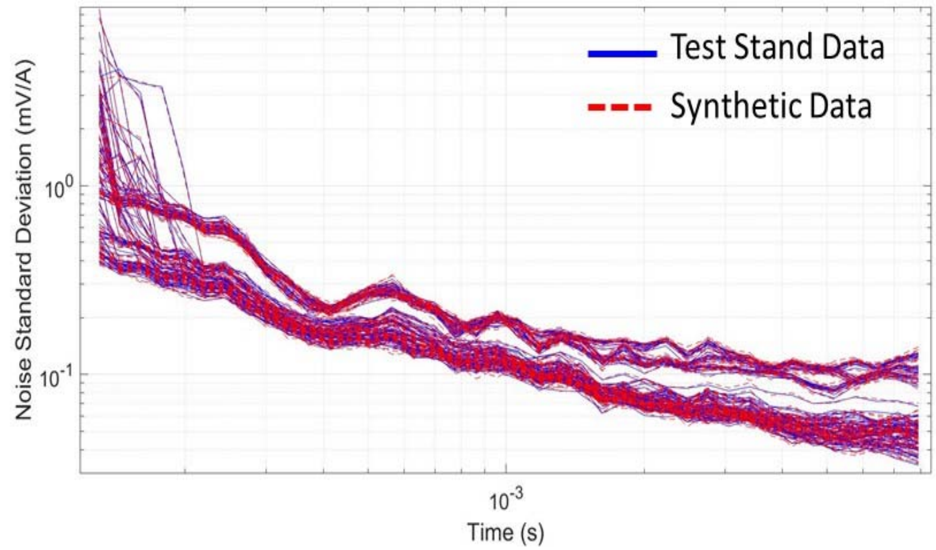


- Library match value of 0.9 used for classification quality threshold
- 81mm – 1.4m; 105mm – 1.8m; 155mm – 2.4m reliable classification depths
- Transmitter effective power = 200 A-turns

Electromagnetic Experiment: Grid Measurements

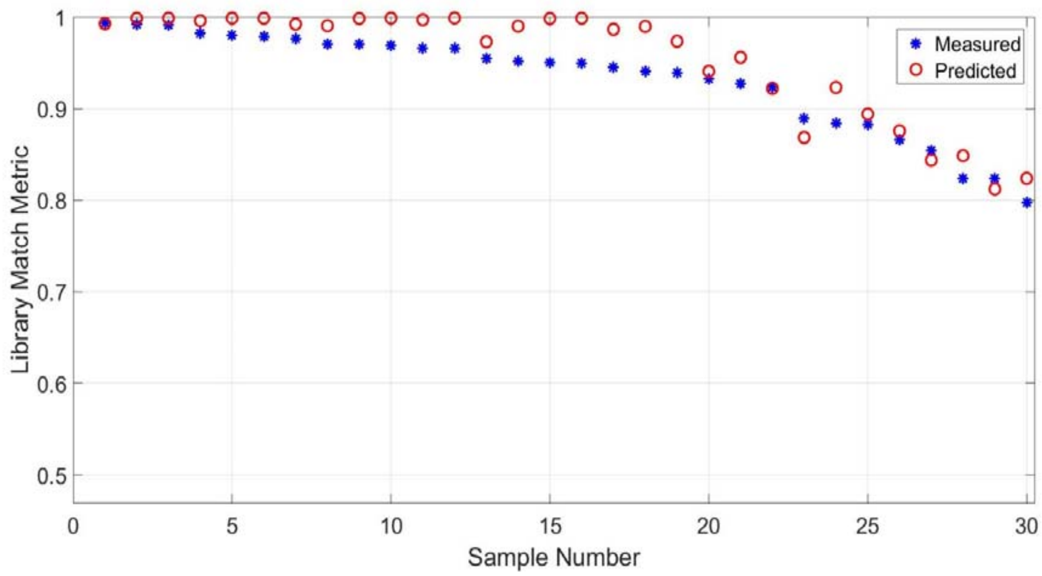


Noise Standard Deviation for 90 Data Channels



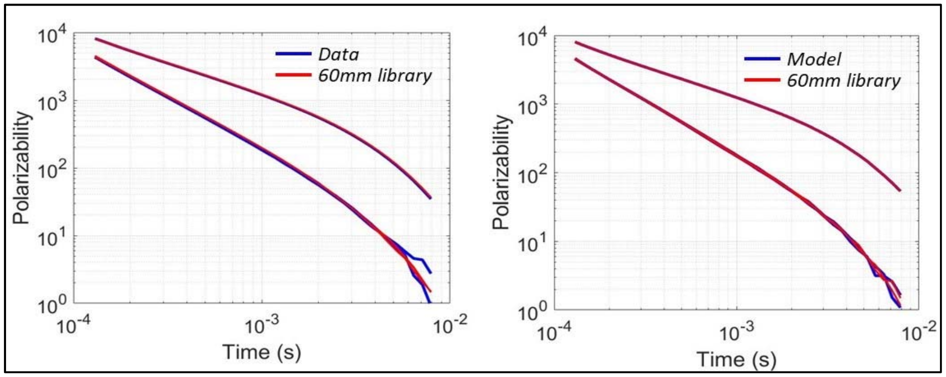
- Static grid measurements collected to compare model predictions with actual inversion results
- Sensor noise captured and added to simulation

Electromagnetic Experiment: Model Verification

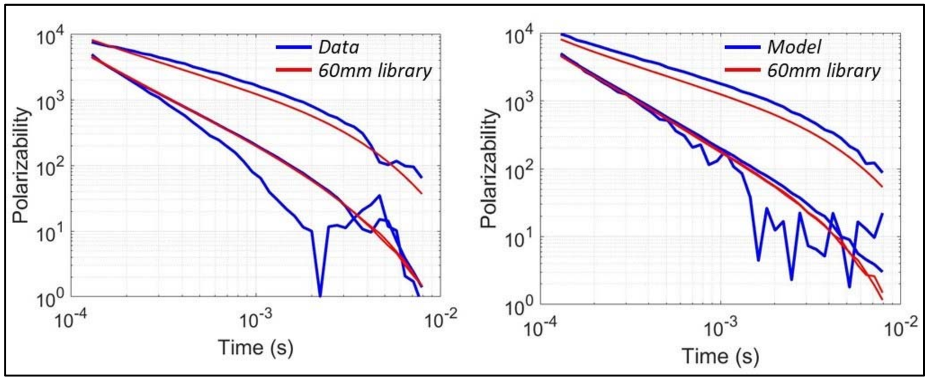


- 30 grid measurements
- Includes well constrained and poorly constrained grid locations
- Predicted match within 5% of observed match

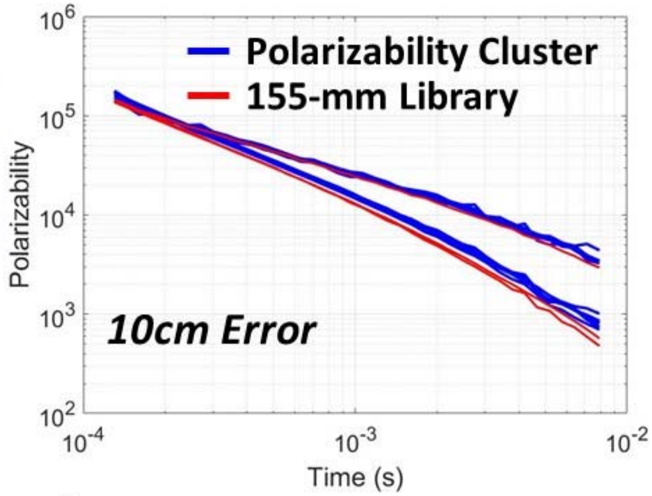
Constrained

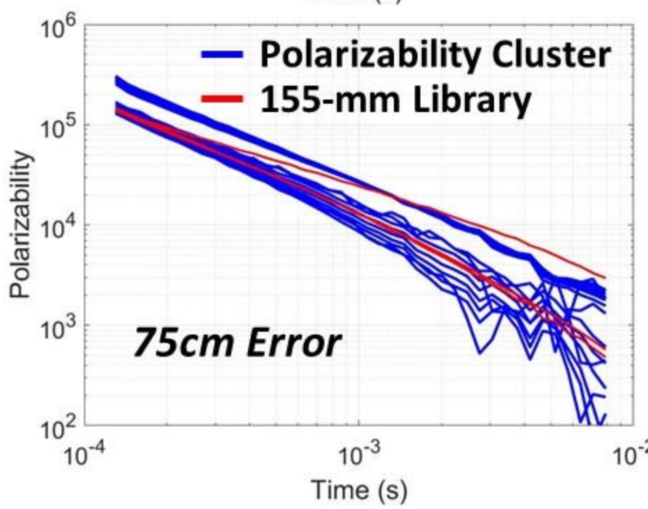


Poorly Constrained



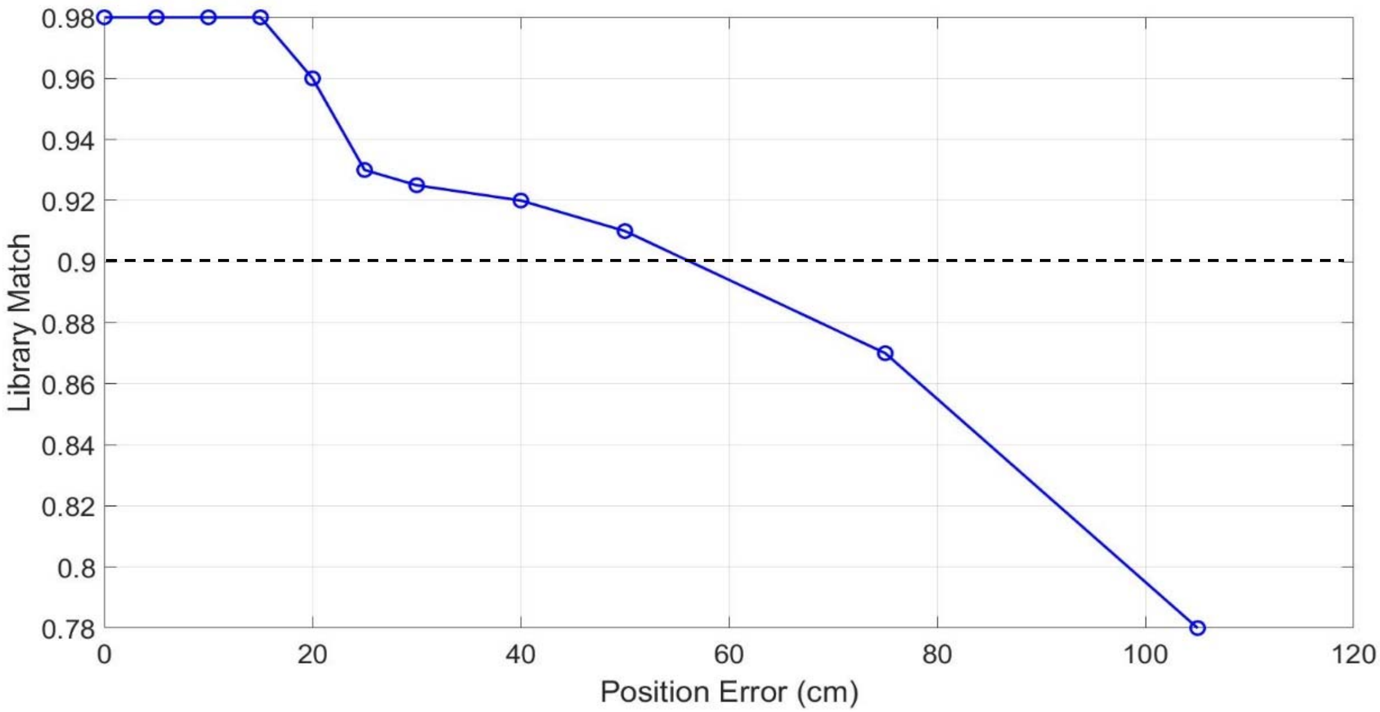
Electromagnetic Experiment: Error Simulation





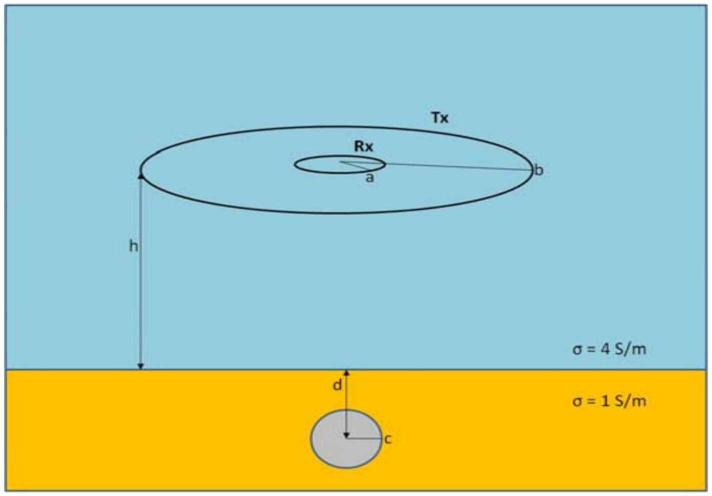
- Acquired dynamic data over 155mm using constant tow speed
- Added sample-to-sample position error in post-processing
- Evaluated single shot tolerance to relative position error between samples

Electromagnetic Experiment: Error Simulation



- No change in classification quality for up to 15cm error
- Quality match value (0.9 or higher) maintained to 50cm error

Electromagnetic Analysis: Background Correction



RX radius a [m]	0.05
Standoff h [m]	2.0
Depth of Sphere d [m]	0
Diameter of Sphere c [m]	0.125
Variables:	
TX radius b [m]	0.5, 1.0, 1.5, 2.0, 2.5

1. Variable Tx Size

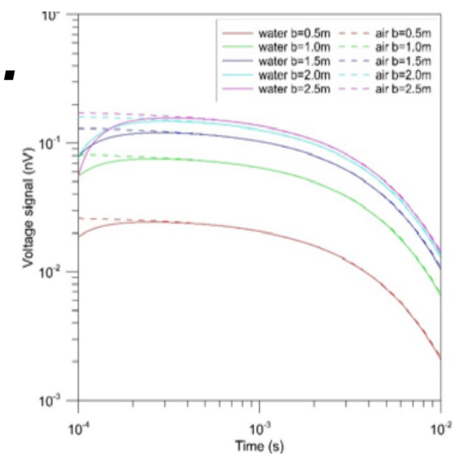
RX radius a [m]	0.05
TX radius b [m]	1.5
Depth of Sphere d [m]	0
Diameter of Sphere c [m]	0.125
Variables:	
Standoff h [m]	0.5, 1.0, 1.5, 2.0, 2.5, 3.0

2. Variable Standoff

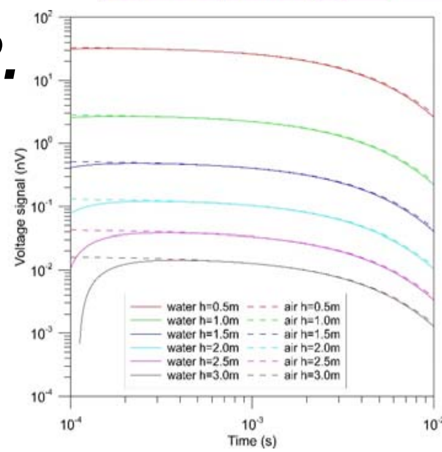
RX radius a [m]	0.05
TX radius b [m]	1.5
Standoff h [m]	1.0
Diameter of Sphere c [m]	0.125
Variables:	
Depth of Sphere d [m]	0.25, 0.50, 0.75

3. Variable Target Depth

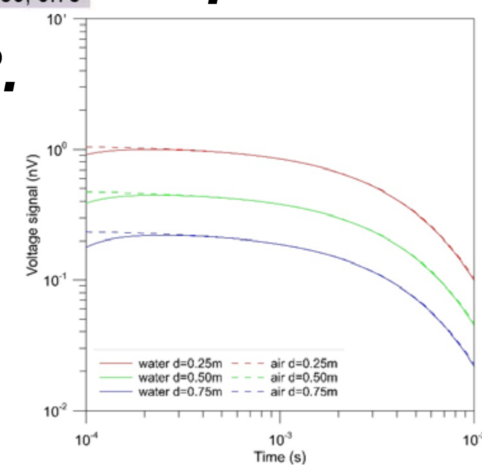
1.



2.

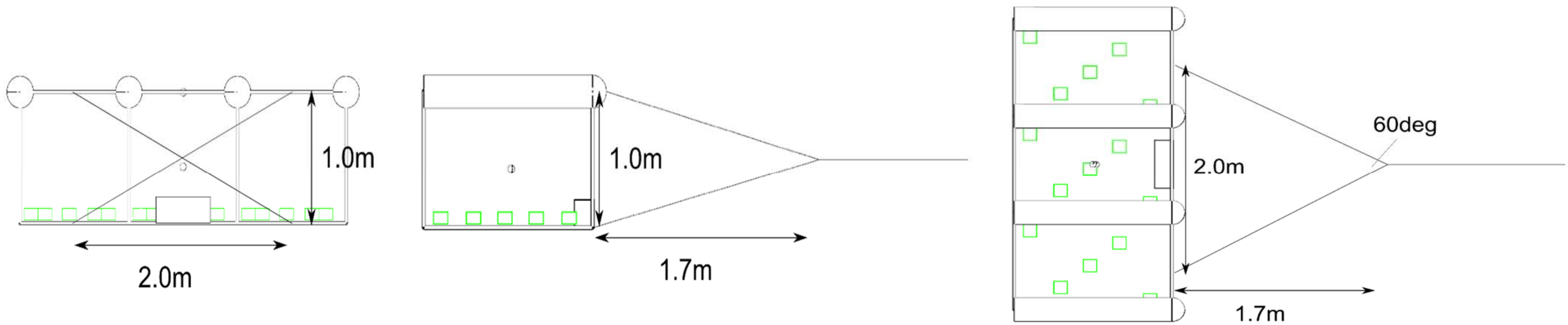


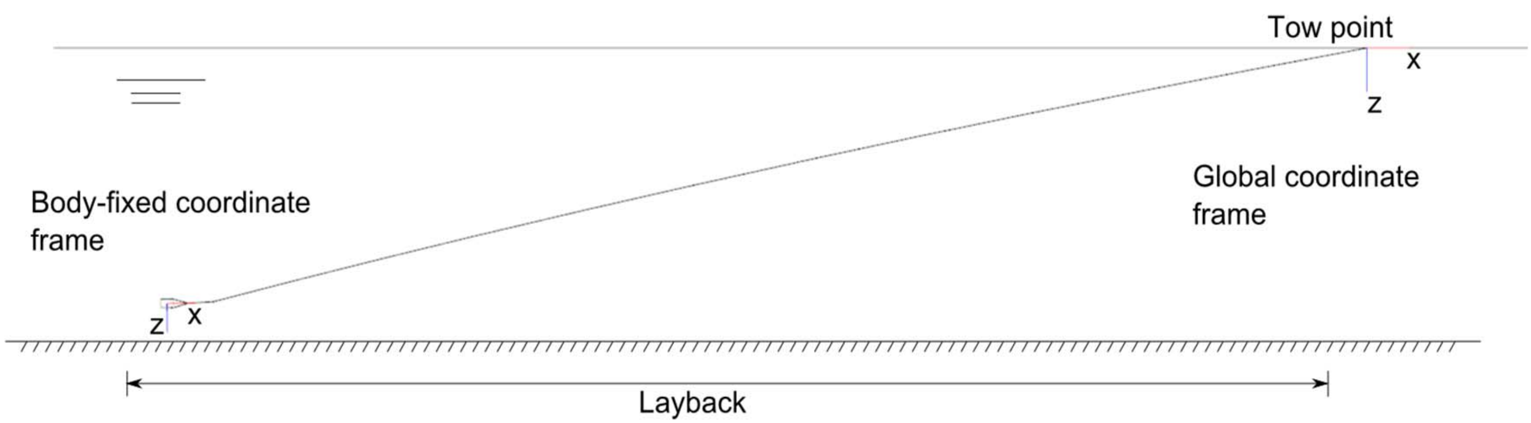
3.



- Compare In-Air to In-Water – Background:
  - » $\boldsymbol{R_T}^{air}(t_n) \approx \boldsymbol{R_T}^{sea}(t_n) - \boldsymbol{R_B}^{sea}(t_n)$
- No significant background interaction >300-400 microseconds

Hydrodynamic Model: Design





- Four point tow bridle designed for yaw and pitch stability
- 6 DOF rigid body model that calculates loads and buoyancy force
- Depth determined by towline angle and layback
- Towline angle determined by drag and clump weight

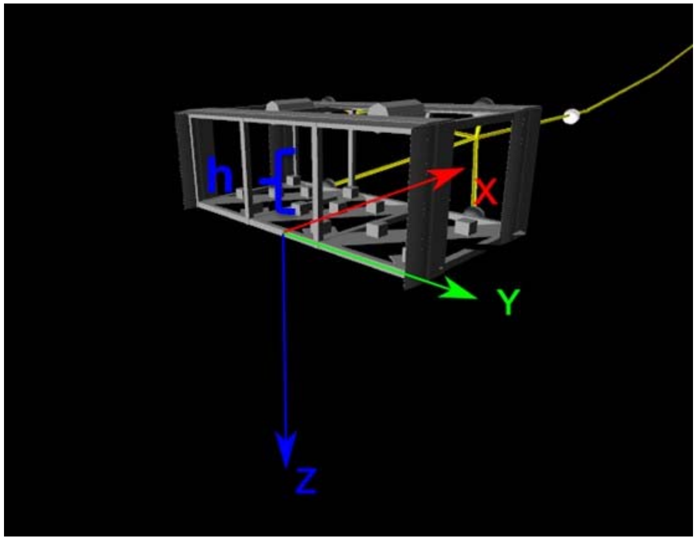
Hydrodynamic Model: Operating Parameters

- Towed EMI sensor body width: 3m
- Tow speeds: Operate in 3-4 knots
- Tow altitude: The towed sensor is to maintain a height above seabed of 1m (2m maximum)
- Water depth: Operate in depths of 10-30m
- Wave conditions: Operate in Sea state 3, H = 1.25m, T=5 second

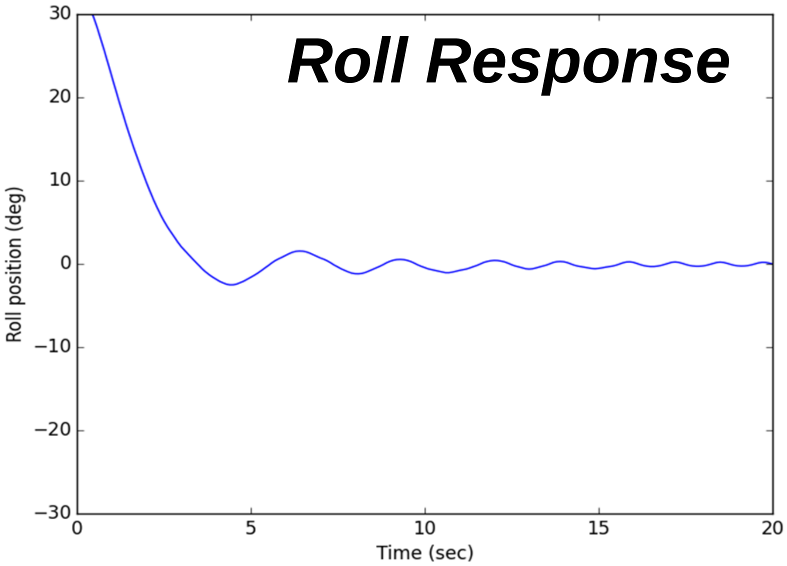
Hydrodynamic Simulation: Test Cases

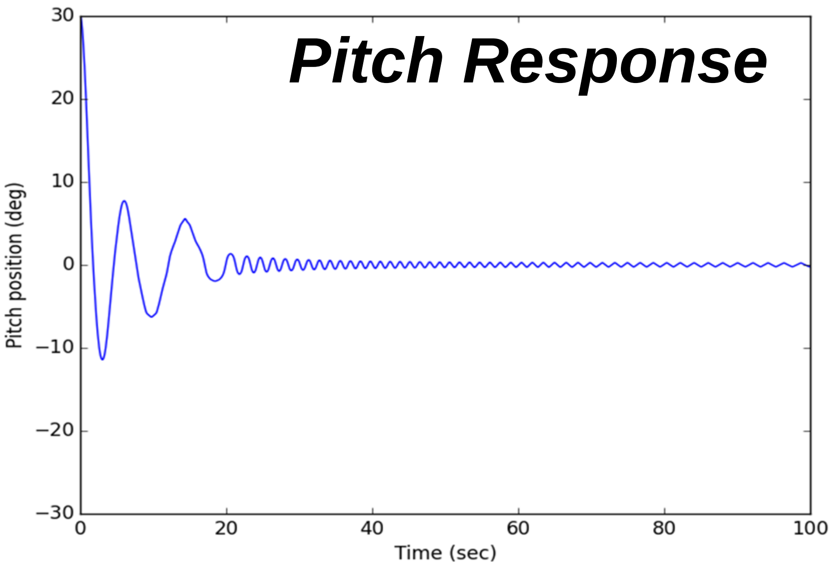
Category	Sub-Category	test	Test Number	Comments
Stability Load Cases				
	Towed EMI sensor righting moment			Array only, no towline. Initial roll/pitch offset.
		Roll	S-01	
		Pitch	S-02	
	Transient response			Towline present, yaw/heave offset.
		Sway	S-03	
		Heave (falling)	S-04	
		Heave (rising)	S-05	
	Wave response			Wave test cases, both wave encounter frequencies.
		Sea state 3 - opposing	S-06	Height: 1.25m Period: 5.0sec
		Sea state 3 - with	S-07	Height: 1.25m Period: 5.0sec
	Cross current			Platform stability and sway position in 0.5 m/s and 1 m/s cross current
		0.5 m/s	S-08	
		1 m/s	S-09	
Control Load Cases				
	Winch response			Determine towed EMI sensor heave response to winch control
		1.0 m/s tow speed, 25kg clump weight	C-01	
		1.0 m/s tow speed, 50kg clump weight	C-02	
		1.0 m/s tow speed, 75kg clump weight	C-03	
		1.5 m/s tow speed, 25kg clump weight	C-04	
		1.5 m/s tow speed, 50kg clump weight	C-05	
		1.5 m/s tow speed, 75kg clump weight	C-06	
		2.0 m/s tow speed, 25kg clump weight	C-07	
		2.0 m/s tow speed, 50kg clump weight	C-08	
		2.0 m/s tow speed, 75kg clump weight	C-09	
Operating Load Cases				
	Operating configurations			Determine loads and layback on the system during normal towing operations
		Tow speed 1 knot	O-1	
		Tow speed 2 knot	O-2	
		Tow speed 3 knot	O-3	
		Tow speed 4 knot	O-4	
	Turning			Determine array stability when turning
		Turning - 1	O-5	
	Start/stop			Determine towed EMI sensor reaction on start up or sudden stop
		Sudden stop	O-6	
		Start up	O-7	

Hydrodynamic Simulation: Stability

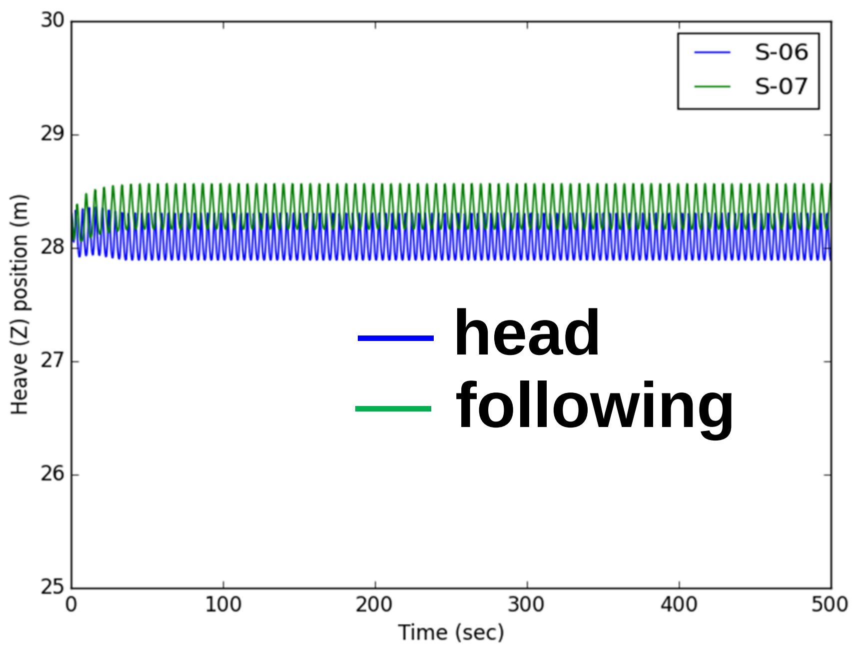


- Stability aided by increased metacentric height (h) for 3D configuration
- Increases righting moment and improves roll and pitch stability
- Roll and pitch stability tested for 30 degree perturbation; settles to within 5 degrees of neutral within 3 seconds (roll) and 20 seconds (pitch)





Hydrodynamic Simulation: Heave Response

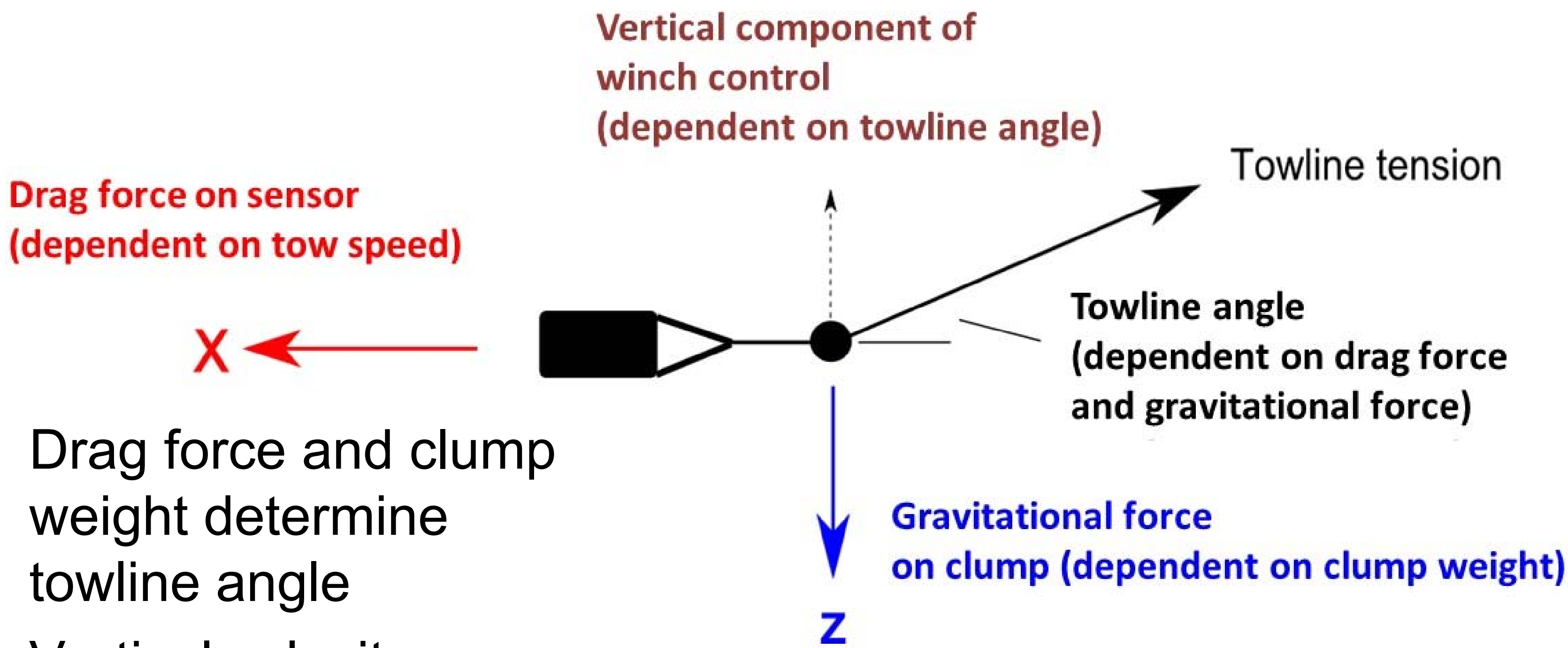


- Sensor heave response evaluated for tow point heave and surge encountered in Sea State 3 conditions (head and following seas)
- Maximum heave variability is +/-15cm for 1.25m wave height
- Indicates stability for maintaining seafloor standoff

Towline Tension

Load case:	Mean tension - Bottom (kN):	Max tension – Bottom (kN):	Mean tension - Top (kN):	Max tension - Top (kN):
S-06	2.32	4.98	2.44	5.20
S-07	2.26	4.09	2.37	4.28

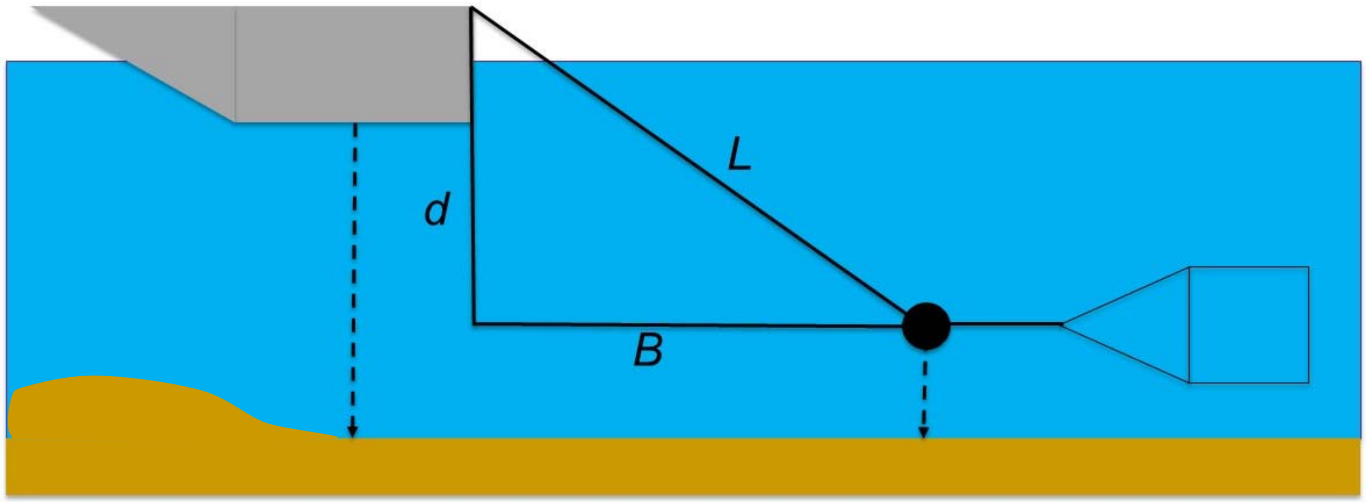
Hydrodynamic Simulation: Depth Control



- Drag force and clump weight determine towline angle
- Vertical velocity (responsiveness) is a function of the vertical component of winch pay-in velocity
- Responds to up to 10% seafloor incline

Test number:	Tow speed (m/s):	Clump weight (kg):	Vertical (heave) velocity (m/s):
C-01	1.0	25	4.3×10^{-2}
C-02	1.0	50	7.1×10^{-2}
C-03	1.0	75	9.6×10^{-2}
C-04	1.5	25	3.2×10^{-2}
C-05	1.5	50	4.3×10^{-2}
C-06	1.5	75	5.4×10^{-2}
C-07	2.0	25	2.2×10^{-2}
C-08	2.0	50	3.2×10^{-2}
C-09	2.0	75	4.2×10^{-2}

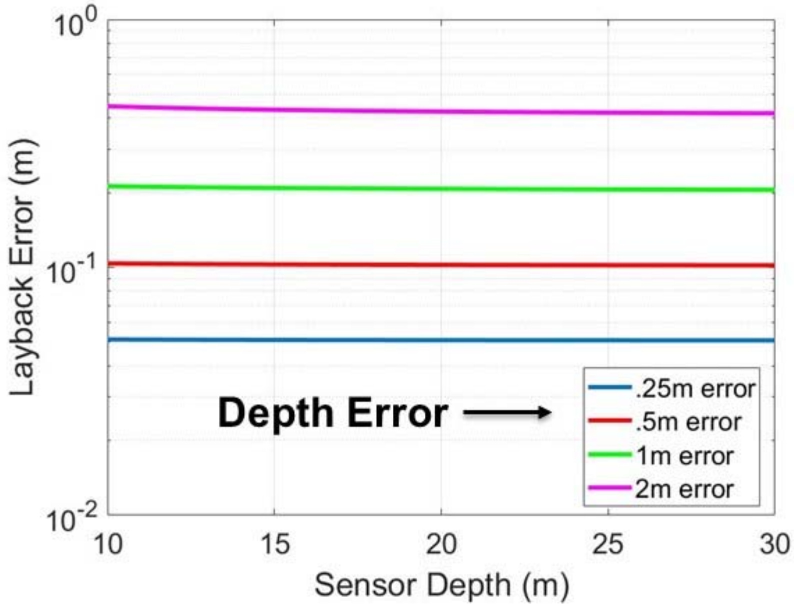
Hydrodynamic Simulation: Sensor Position Error



- Layback position (B) calculated from measurements of line length pay-out (L) and depth (d);
- Depth taken as difference between vessel altitude and sensor altitude measurements
- Main source of position error is depth measurement (d) resulting from surface variability

Hydrodynamic Simulation: Target Position Error

Sensor Location Error



Target Location Error

OPTEMA Target Location Error	SWPG TOI		
	Mean Error (cm)	Standard Deviation (cm)	Maximum Error (cm)
Northing/Easting	5.5	2.4	11.8
Depth	3.3	4.6	14.0

- Layback estimation error tolerant of depth measurement error; 2m depth error produces <0.5m layback position error (at 3 knot tow speed)
- Target relative location determined from inversion, typically <0.15m
- Total target position (global) error combines sensor location error and target location error

Summary

- Reliable classification depth for 200 A-turn system expected: 81mm – 1.4m; 105mm – 1.8m; 155mm – 2.4m
- Classification approach tolerant to relative position error: 15cm error (sample-to-sample) without degradation of classification quality
- Land-based dynamic processing applicable to underwater environment; may require some adjustment for background removal in time gates <300-400 μs
- Metacentric height for 3D frame provides inherent hydrodynamic stability in pitch, roll
- Standoff stability expected: +/-15cm worst case operating conditions (Sea State 3)
- Standoff adjustment responsive to 10 degree incline; quicker response may require heavier clump or slower tow speed
- Total target position error expected: <0.5m; includes sensor location error and target location error

Technology Transfer

- ***Underwater Dynamic Classification Technology*** to be presented at the Non-Acoustic Marine UXO session at the March 2018 SAGEEP meeting in Nashville

BACKUP MATERIAL

Performance Objective	Metric	Data Required	Success Criteria
EMI-Based Classification Performance Objectives			
Model Accuracy	Model prediction of classification performance	• Model predictions and test stand data corresponding to relevant 3D EMI sensor configuration	Model-based library match predictions consistent with library matches recovered from test stand data
Effective EMI Sensor Configuration	Library match metric	• Synthetic data corresponding to towed sensor configuration encounters with targets at standoffs >1 meter	Library match >0.9 for polarizabilities corresponding to TOI >1 meter from sensor bottom
Effective Underwater Dynamic Classification	Library match metric	• Test stand data with positional error added to simulate underwater positioning constraints	Library match >0.9 for polarizabilities corresponding to data with added positional errors
Effective Processing Methods for the Underwater Environment	Background response	• Simulation of seawater, sensor, and target interactions	Demonstration of effective background removal technique for underwater environment

Performance Objective	Metric	Data Required	Success Criteria
Hydrodynamic Performance Objectives			
Orientation stability	Roll and pitch righting response to perturbation	• Simulation of pitch and roll angles after initial offset condition	Settles to within +/- 5 degree pitch and roll after initial perturbation
Position stability	Heave and sway transient response to perturbation	• Simulation of heave and sway offset after initial offset condition	Settles to within 0.5m (lateral) and 0.15m (vertical) of neutral position after initial perturbation
Standoff stability	Heave offset during worst-case operating conditions	• Simulation of heave motion in Sea State 3	Maintains seafloor standoff within +/-15 cm variability
Depth control responsiveness	Vertical velocity as a function of winch pay-in	• Simulation of vertical velocity in response to winch pay-in	Responsive to seafloor slope of up to 10% incline
Operating load feasibility	Towline tension	• Simulation of towline tension under typical start, stop, and steady state conditions	Ensure operating loads are within specification limits for standard towline and winch components
Effective target location tracking	Target localization error	• Estimates of cumulative sensor and target location error	Overall target location error <0.5 meter

Pitch angle (deg):	VWT Drag area (m^2):	ProteusDS frontal area (m^2):	ProteusDS Surge direction drag coefficient:
0	1.439	1.640	0.87
45	4.732	Not calculated	N/A
90	5.242	6.113	0.85