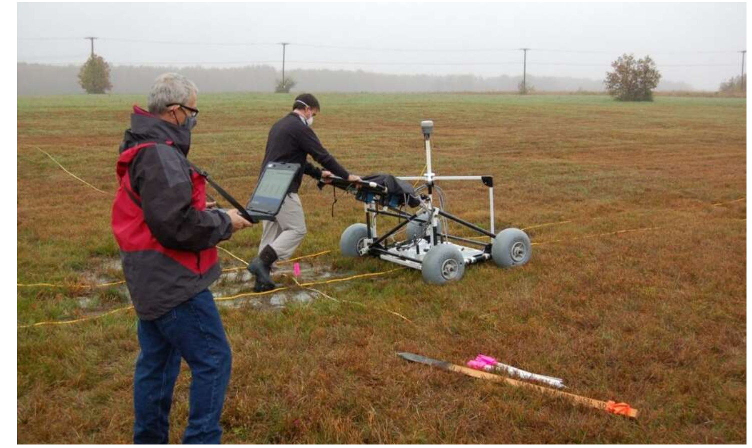
EMI Detection and Classification of Underwater Munitions:

Sequim Bay Demonstration

Lin-Ping Song
Stephen D. Billings
Leonard R. Pasion
David Sinex
Laurens Beran

SAGEEP 2nd Munitions Response Meeting.
New Orleans, LA.
April 2-6, 2023

Terrestrial vs Marine EMI classification

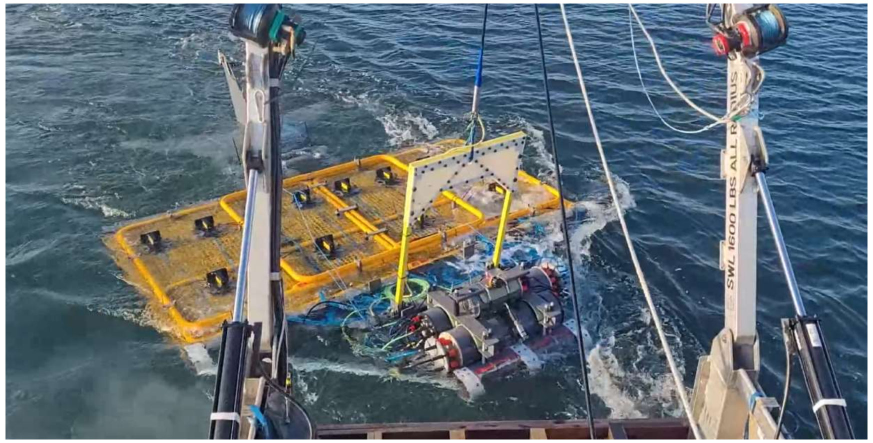


Physical Model	Dipole model effective for classification
Background Signals	Low background levels Some challenges in magnetic geology
Instrument Positioning	Dynamic: RTK-GPS, SLAM, RTS Cued: Static and fixed geometry
Target Signal Strength	Close proximity to targets: High SNR

Black Tusk GEOPHYSICS GapEOD Explosive Ordnance Detection SERDP DOD • EPA • DOE

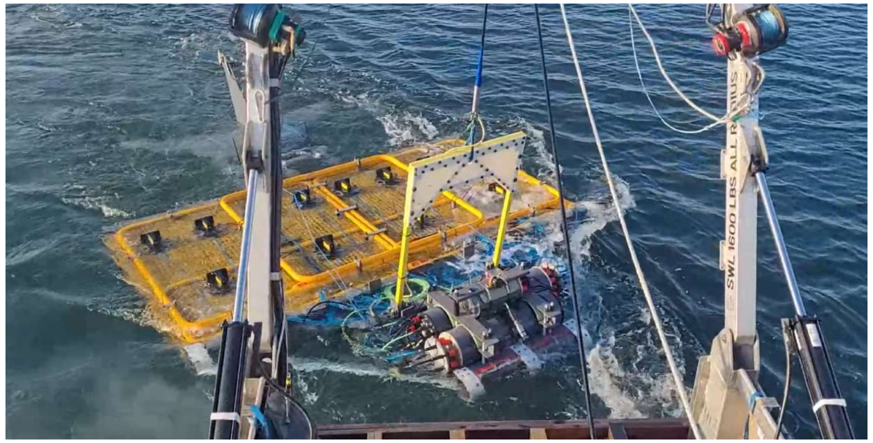
Terrestrial vs Marine EMI classification

Physical Model	Potential interaction effects between object and sea-water (early time)
Background Signals	Varies with water depth and temperature, sensor height, sediment composition
Instrument Positioning	Dynamic: Underwater positioning is much less accurate Cued: Logistical challenges
Target Signal Strength	Offset to the sea-bottom: Low SNR



Outline

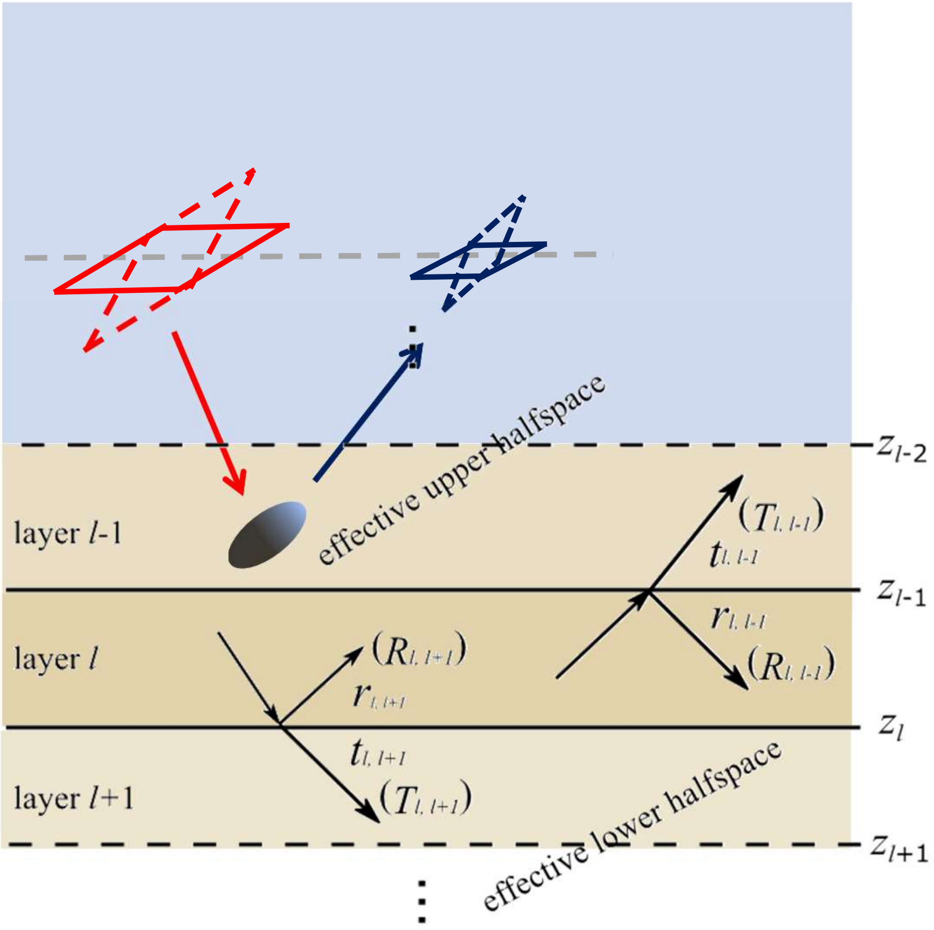
- Modeling & characterizing EMI response in a marine setting
  - Integral equation (IE) to compute conductive layered background and target responses
  - Conductive background response removal
  - Validation of magnetic dipole model
- Mitigating sensor positional uncertainties
  - Independent model location inversion (IMLI)
- Enhancing target detectability
  - TEM synthetic aperture (SA) method
- Results of Sequim Bay



Black Tusk GEOPHYSICS   GapEOD Explosive Ordnance Detection   SERDP DOD • EPA • DOE

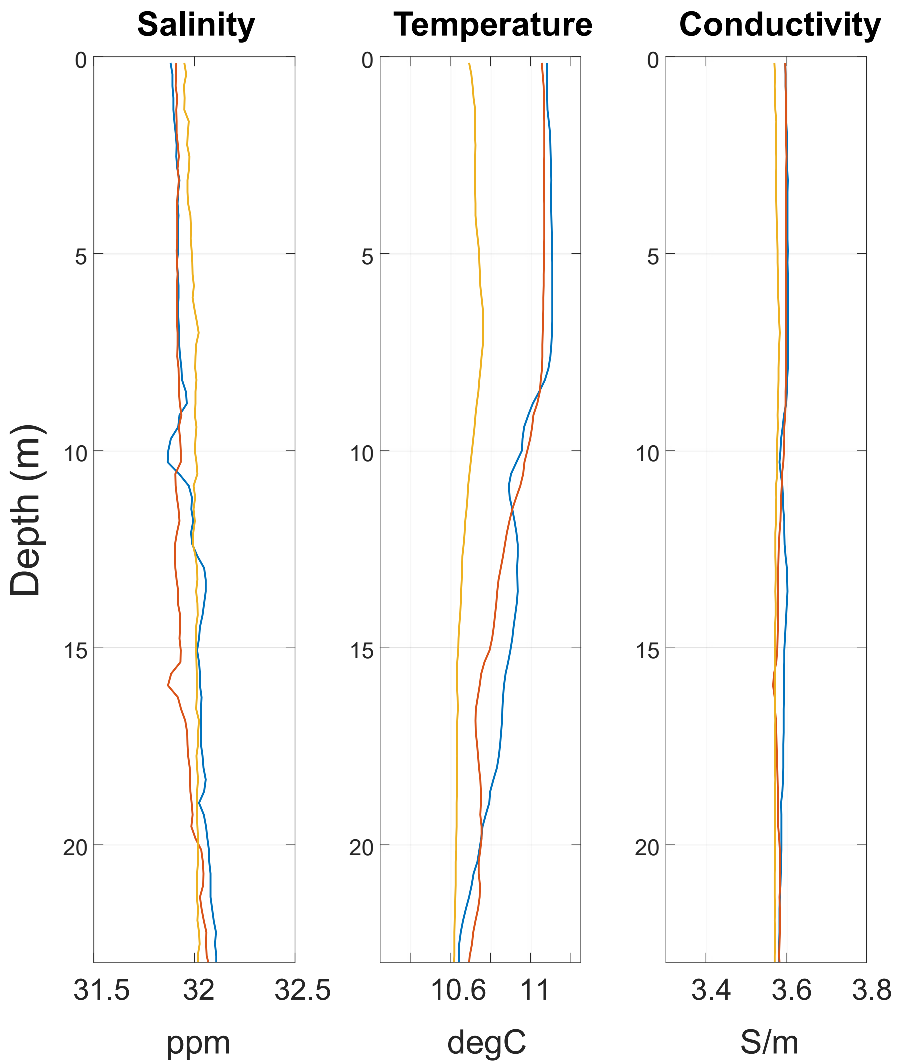
Modeling & Characterizing EMI Response in a Marine Setting

- Developed an integral equation technique that computes the EMI response for an arbitrarily oriented sensor in a multi-layered medium
- Technique also used to calculate scattering response of an elongated target in a layered medium
- *Implementation:* apply appropriate source and field decomposition and defining generalized reflection and transmission coefficients at interfaces (Recursive Propagation)

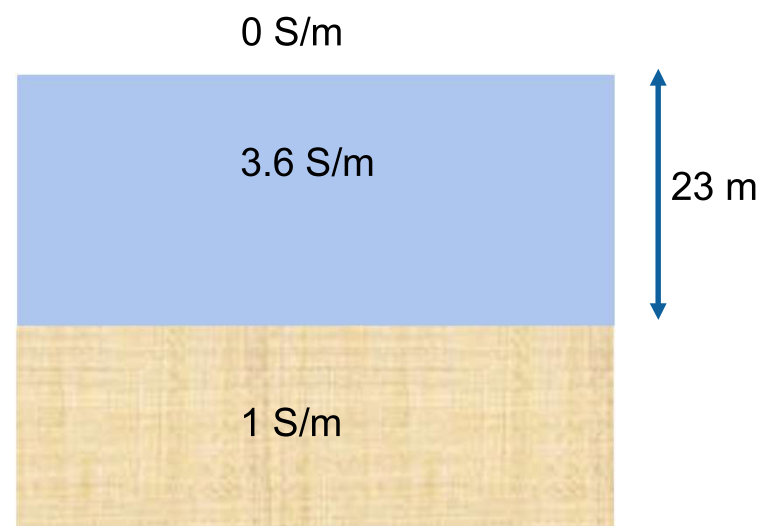


Estimating EMI Background Responses

CTD Cast Data



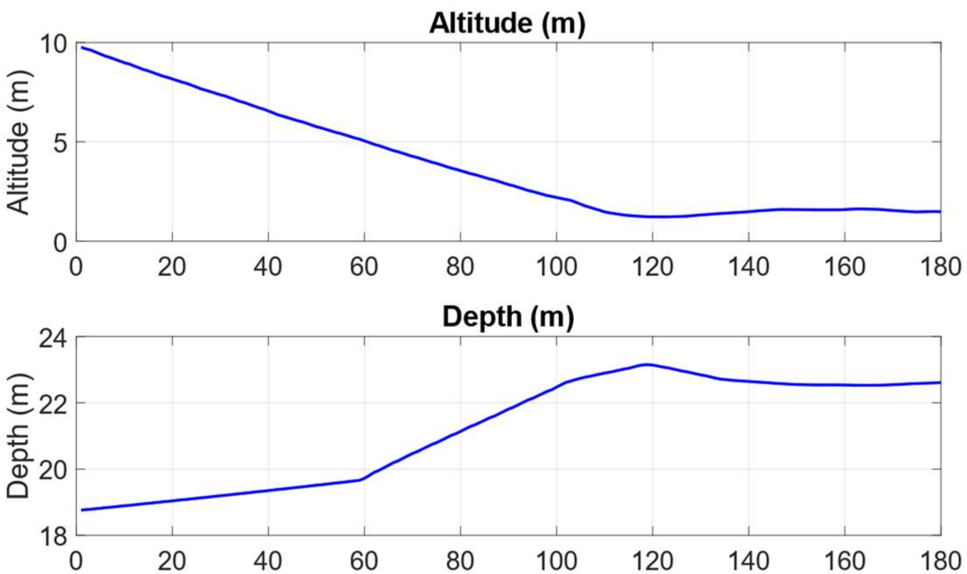
- 2021 data acquisition at Sequim Bay
- A 3-layer model is constructed assuming homogenous sea-water and sea-bed conductivity



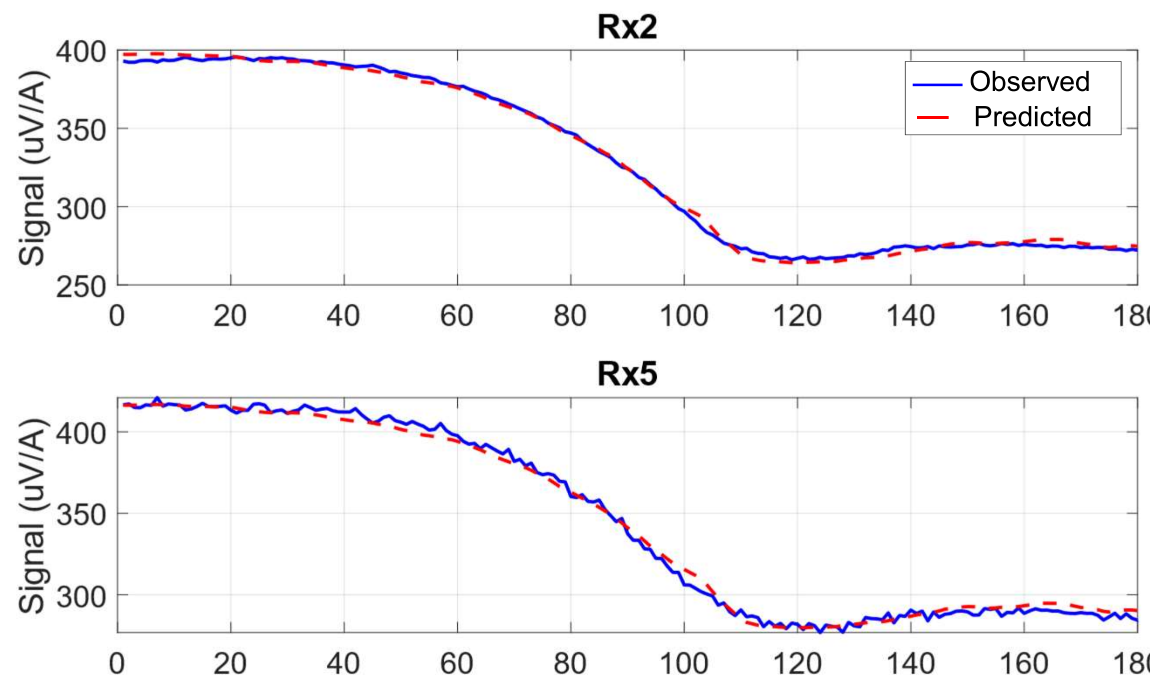
3-layer model

Estimating EMI Background Responses

Modelling Inputs



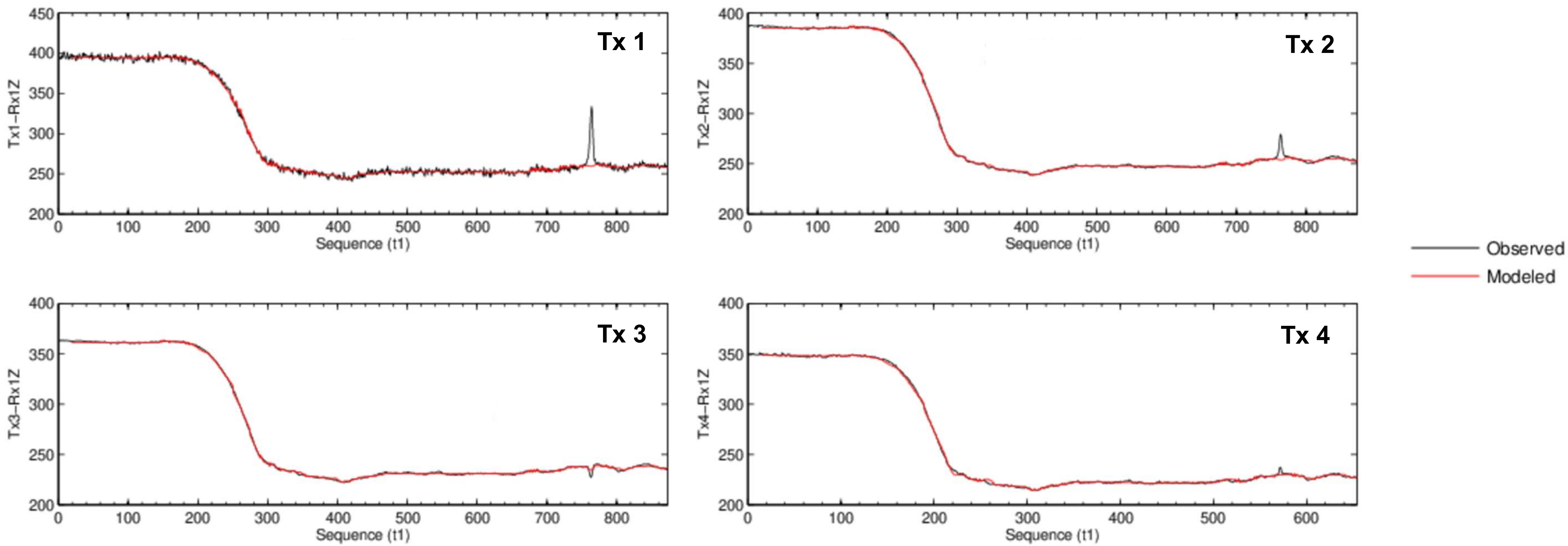
Predicted Response



Black Tusk GEOPHYSICS
GapEOD Explosive Ordnance Detection
SERDP DOD • EPA • DOE

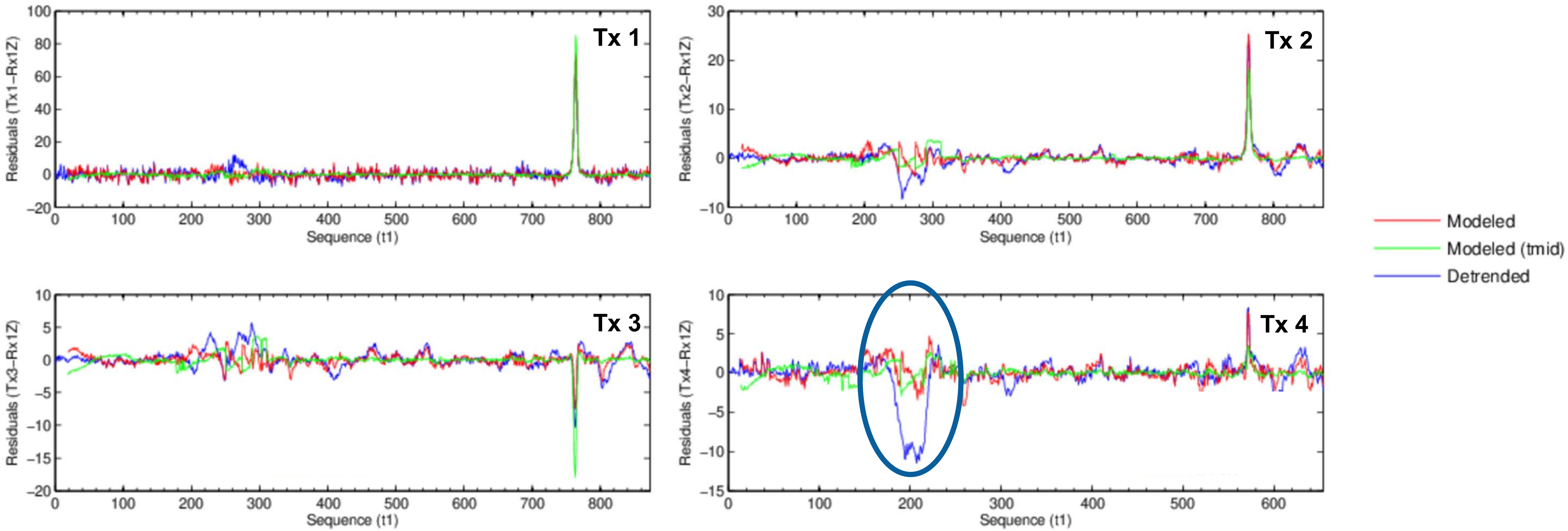
Background signal removal using IE modelling

- Line 3, Rx1, Z-comp
- time = 0.19ms



Background signal removal using IE modelling

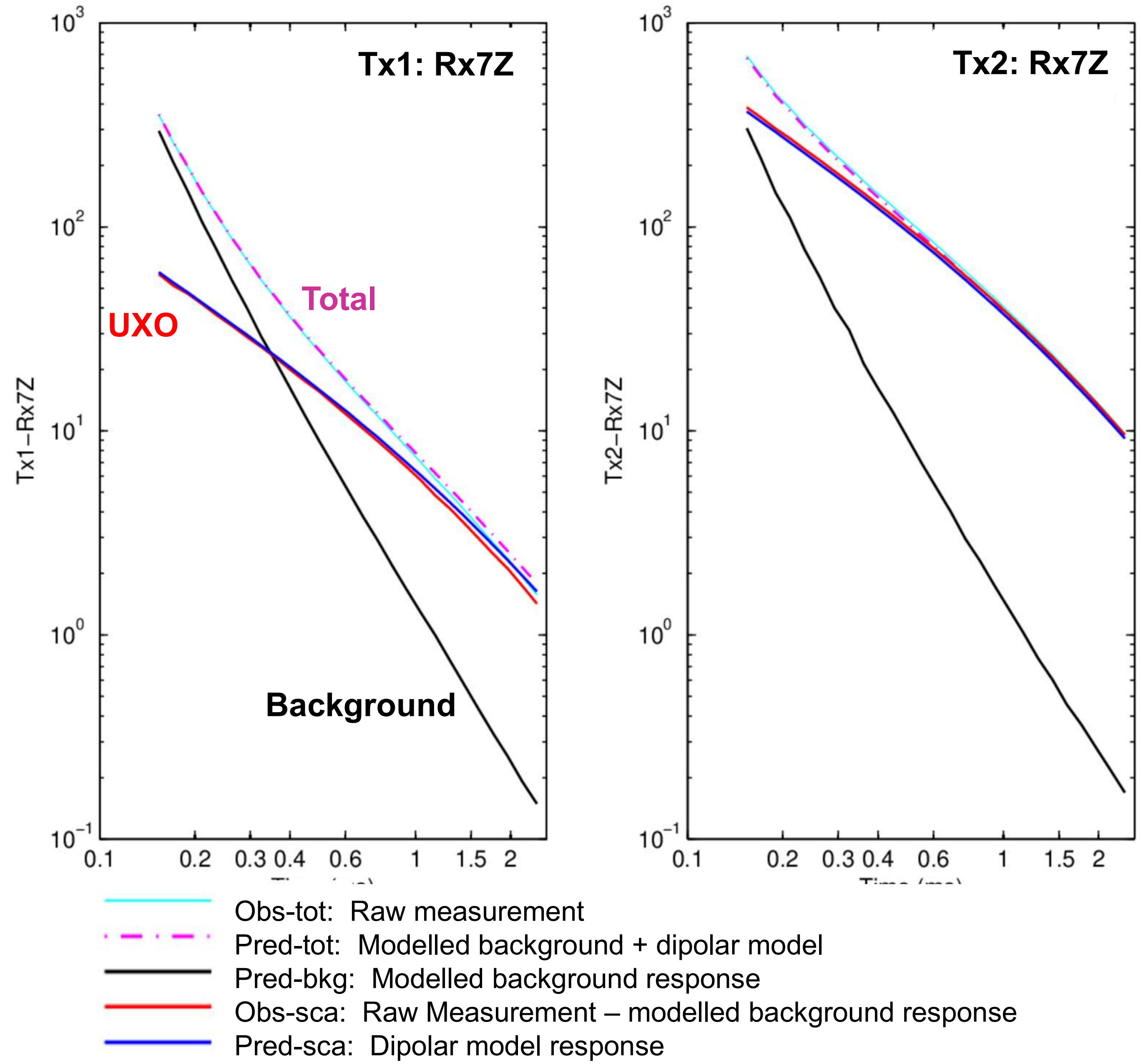
- Rapid changes in background signal due to variations in sensor altitude and attitude can be more effectively removed using modelling instead of detrend filtering.



Modelling scattered responses

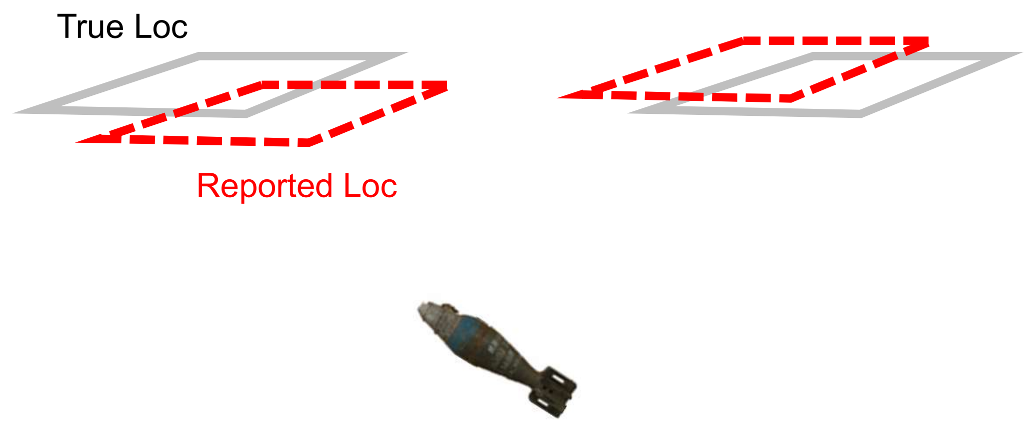
- Integral equation modelling used to study scattered responses in a conductive medium – e.g., spheroids in a layered medium
- Interaction effects are very subtle if they are present
- Theoretically after approximately 0.1 ms the UW response well approximated as a superposition of dipolar target response and a conductive background response

- *Right: Layered modelling compared to UltraTEMA measurements at Sequim Bay*



Mitigating sensor positional uncertainty

- Relative positional errors between adjacent survey lines can lead to an erroneous inversion and subsequent misinterpretation



Two methods developed:

JETSP: Joint Estimation of target and Survey/sensing Parameters

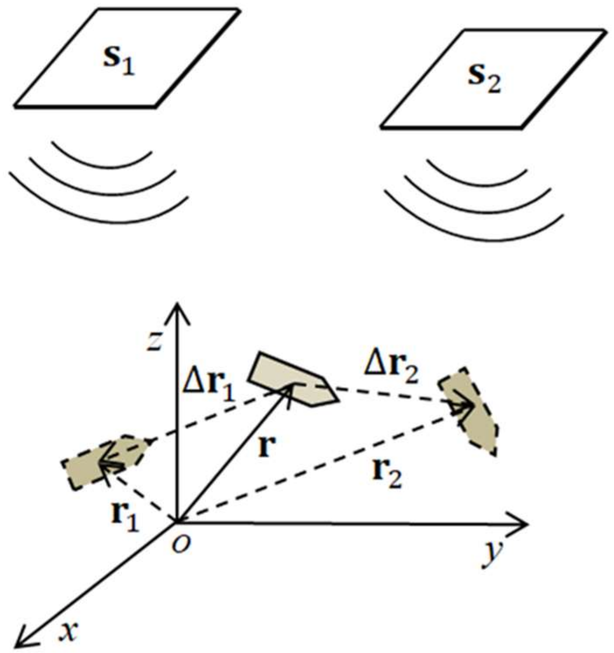
Explicitly account for sensor positioning errors as unknown perturbations that are to be solved

IMLI: Independent Model Location Inversion

Introduce intermediate steps where each line (or shot location) has an independent model location and orientation, while solving for common polarizabilities for a target.

Mitigating sensor positional uncertainty: IMLI

- Break the full dataset into subregions and allow the position and orientation of the item in each subregion to differ
- The principal axis polarizabilities $\boldsymbol{\beta}(t)$ are shared across the regions



Solve standard problem first

Minimize the function

$$\left\| \boldsymbol{d}_{RT}(\boldsymbol{x}, t) - \boldsymbol{s}_{RT}\left(\boldsymbol{x}, \boldsymbol{\beta}(t), \boldsymbol{\theta}, \boldsymbol{x}_{\beta}\right) \right\|$$

by solving for

$$\boldsymbol{\beta}(t), \boldsymbol{\theta}, \boldsymbol{x}_{\beta}$$

IMLI method

Break region into N subregions: $\boldsymbol{x}_n, \boldsymbol{d}_n$

Minimize the function

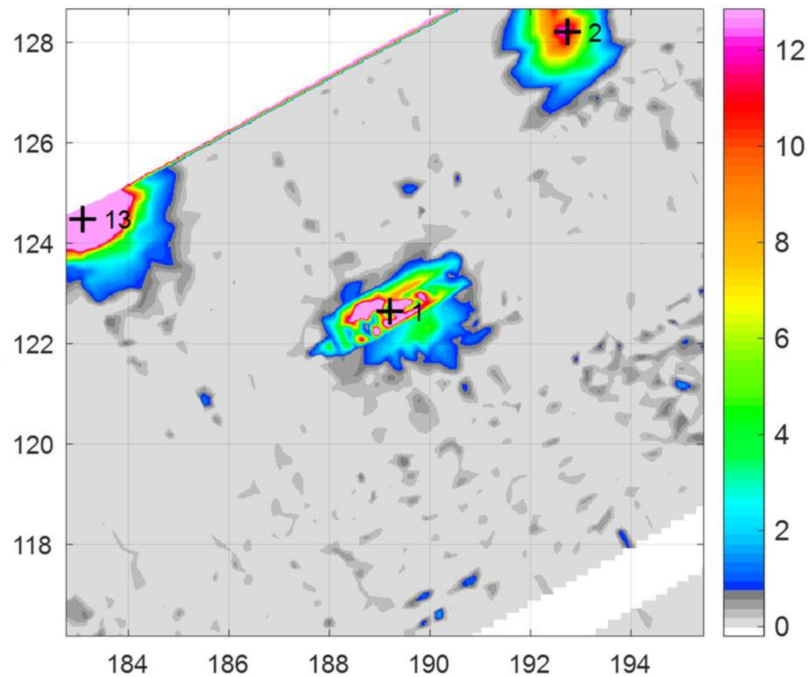
$$\sum_n \left\| \boldsymbol{d}_n(\boldsymbol{x}_n, t) - \boldsymbol{s}_{RT}\left(\boldsymbol{x}_n, \boldsymbol{\beta}(t), \boldsymbol{\theta}_n, \boldsymbol{x}_{\beta n}\right) \right\|$$

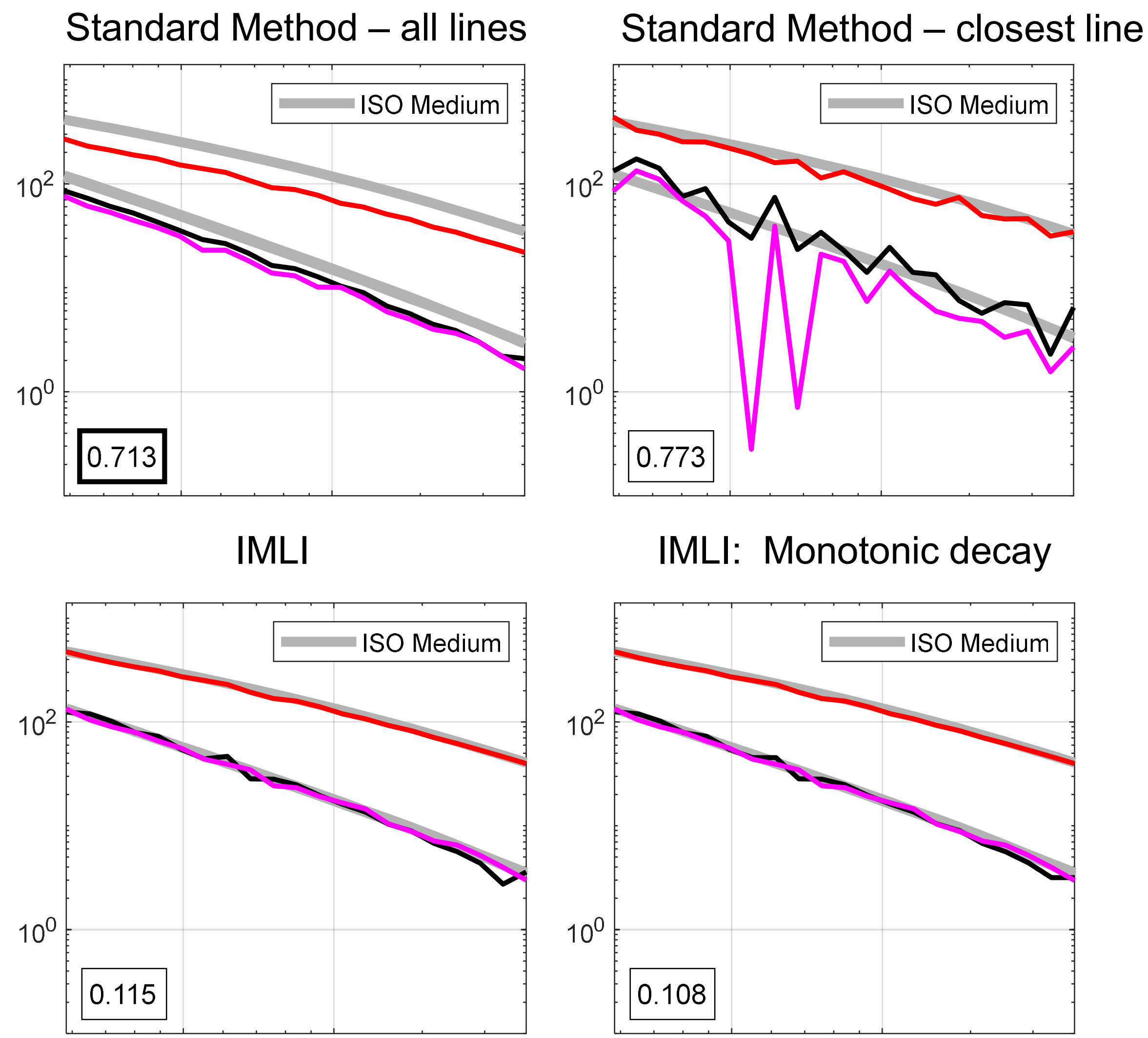
by solving for

$$\boldsymbol{\beta}(t), \boldsymbol{\theta}_n, \boldsymbol{x}_{\beta n}$$

Mitigating sensor positional uncertainty: IMLI

- Medium ISO in Calibration lane
- Data fit for standard is 0.86
- Data fit for IMLI is 0.95



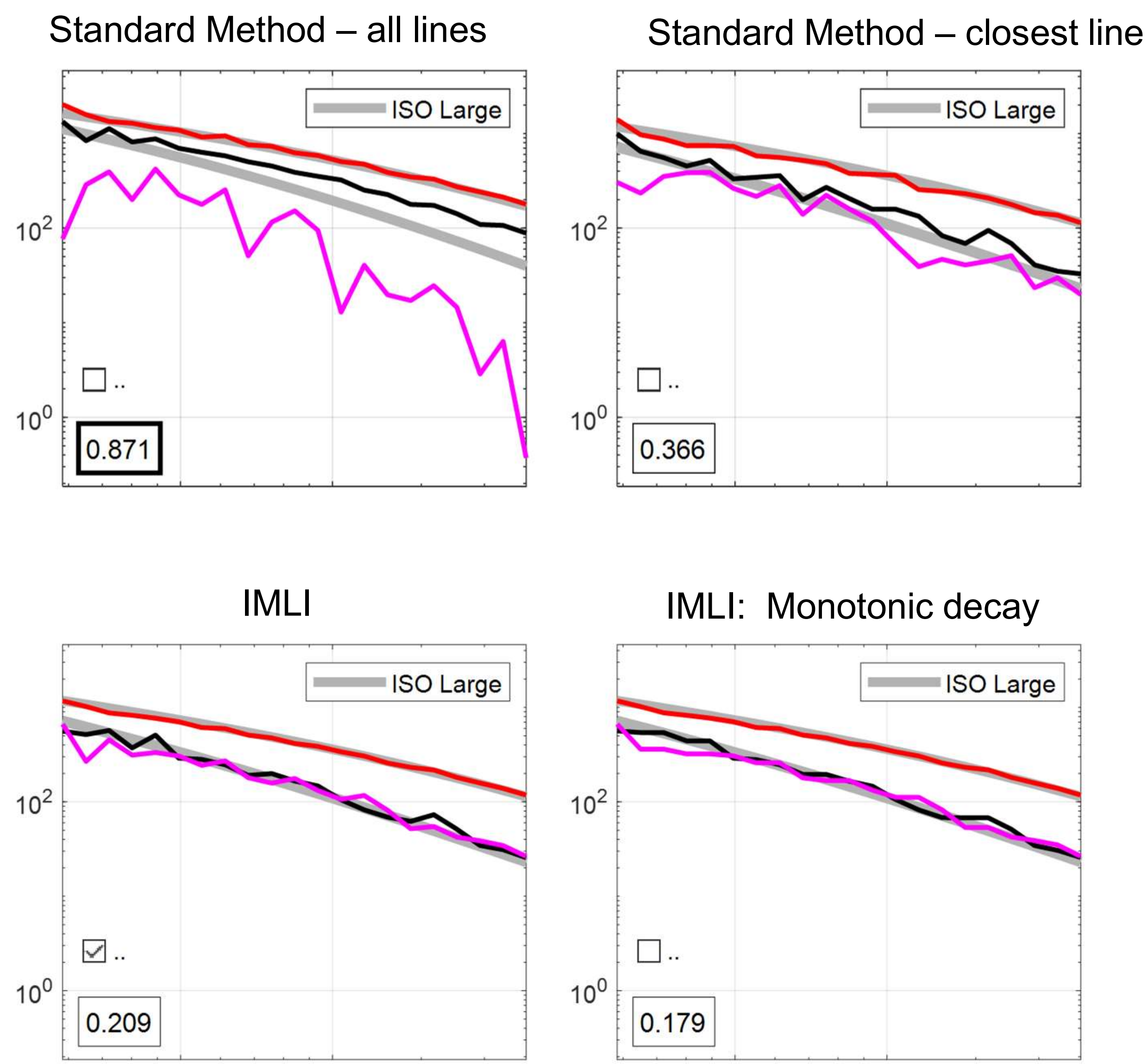


Black Tusk GEOPHYSICS GapEOD Explosive Ordnance Detection SERDP DOD • EPA • DOE

Mitigating sensor positional uncertainty: IMLI

- Large ISO in Calibration lane
- Increased standoff: 1.75m

- Error in relative positioning results in inability to recover all polarizabilities accurately.
- Using only the closest line does recover the polarizabilities, but are “noisy”
- Best fit to Large ISO pols occur when using all lines and accounting for positioning errors.



Black Tusk GEOPHYSICS GapEOD Explosive Ordnance Detection SERDP DOD • EPA • DOE

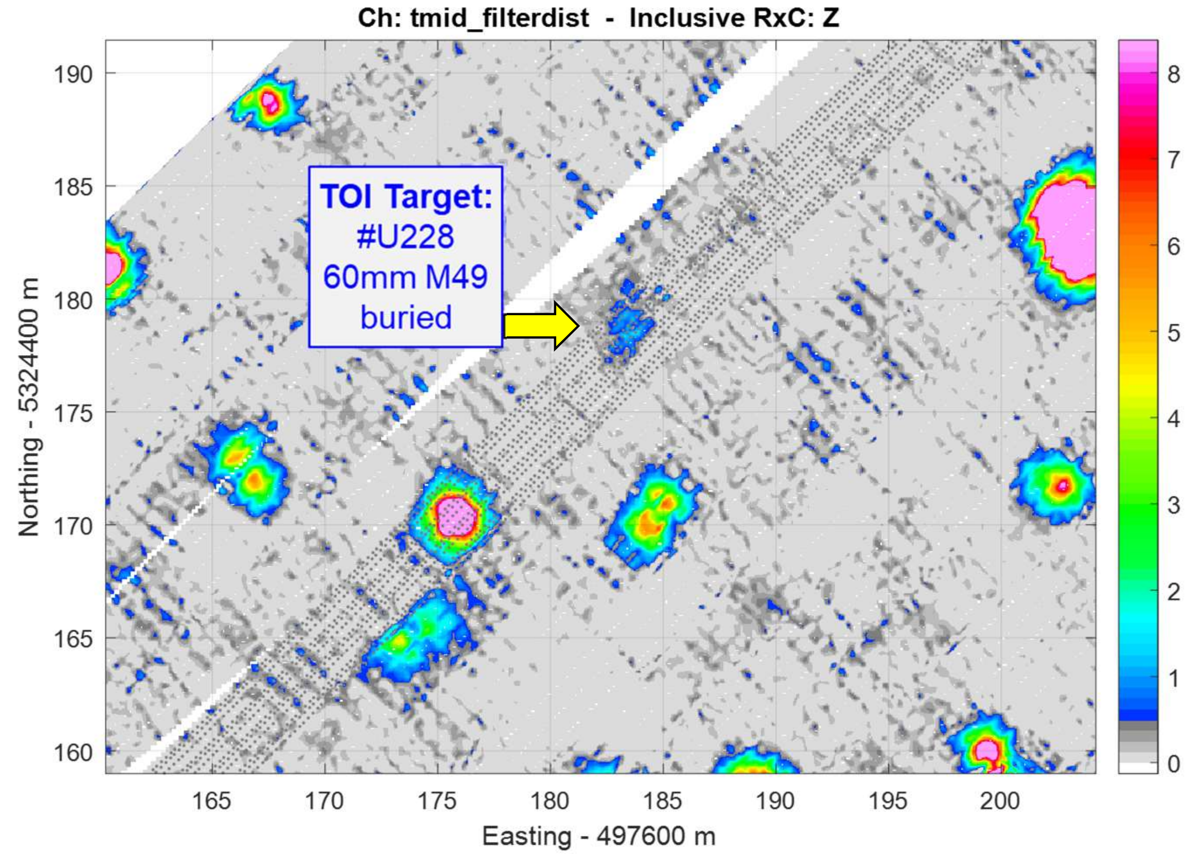
Enhancing Target Detectability

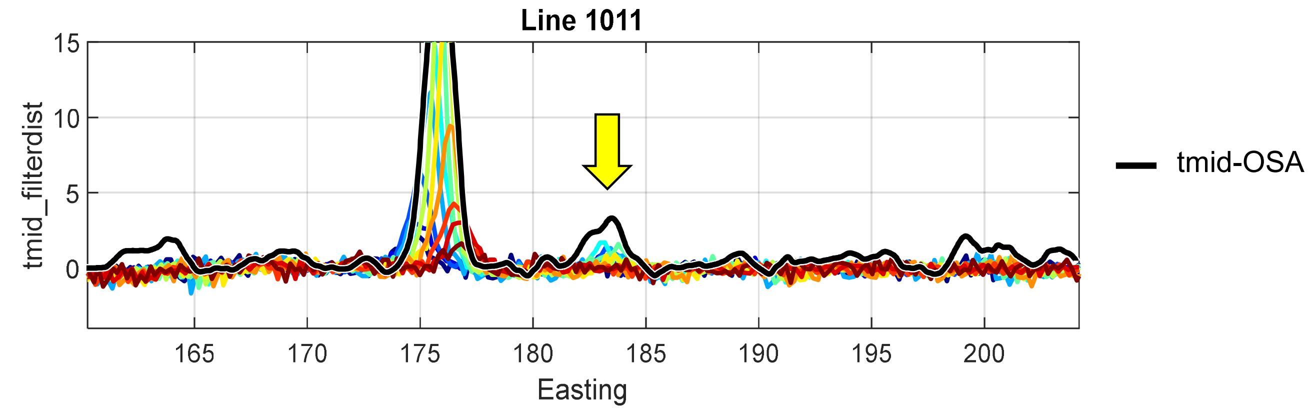
- Exploring Synthetic Aperture (SA) type methods for improving detection performance
- By reciprocity principle, SA can be applied as synthetic transmitting or receiving
- Determine optimal weights to improve signal

$$\boxed{d_{\xi i,SA}(t)} = \sum_{l=1}^{L} w_{\psi,l}\, d_{\xi\psi,il}(t) = \mathbf{B}_{\xi}^{\mathrm{T}}(\mathbf{r},\mathbf{r}_i)P(t)\boxed{\mathbf{T}_{\psi,SA}}$$

$$\mathbf{T}_{\psi,SA} = \sum_{l=1}^{L} w_{\psi,l}\, \mathbf{T}_{\psi}(\mathbf{r},\mathbf{r}_l)$$

- Continuing to investigate different approaches and weighting schemes to further boost SNR.

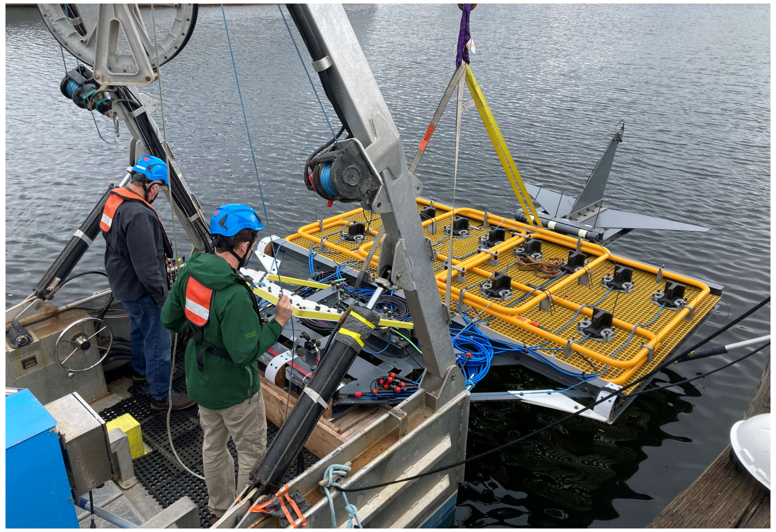


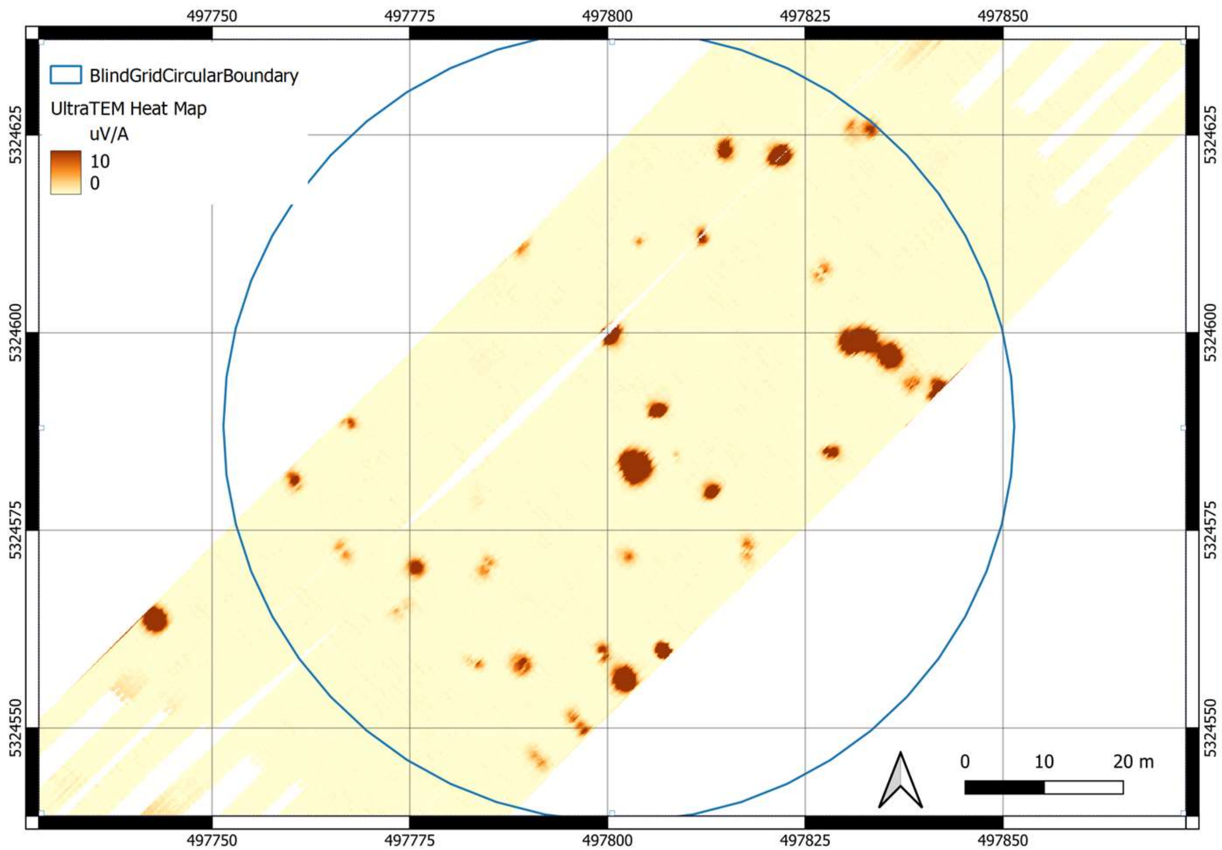


Black Tusk GEOPHYSICS
GapEOD Explosive Ordnance Detection
SERDP DOD • EPA • DOE

2021 Sequim Bay Test

- Initial testing
- By matching three recovered polarizabilities against the ordnance (UltraTEM) library.
- 27 objects were classified as being most likely to be a UXO
- 10 objects were classified as being most likely to be clutter.

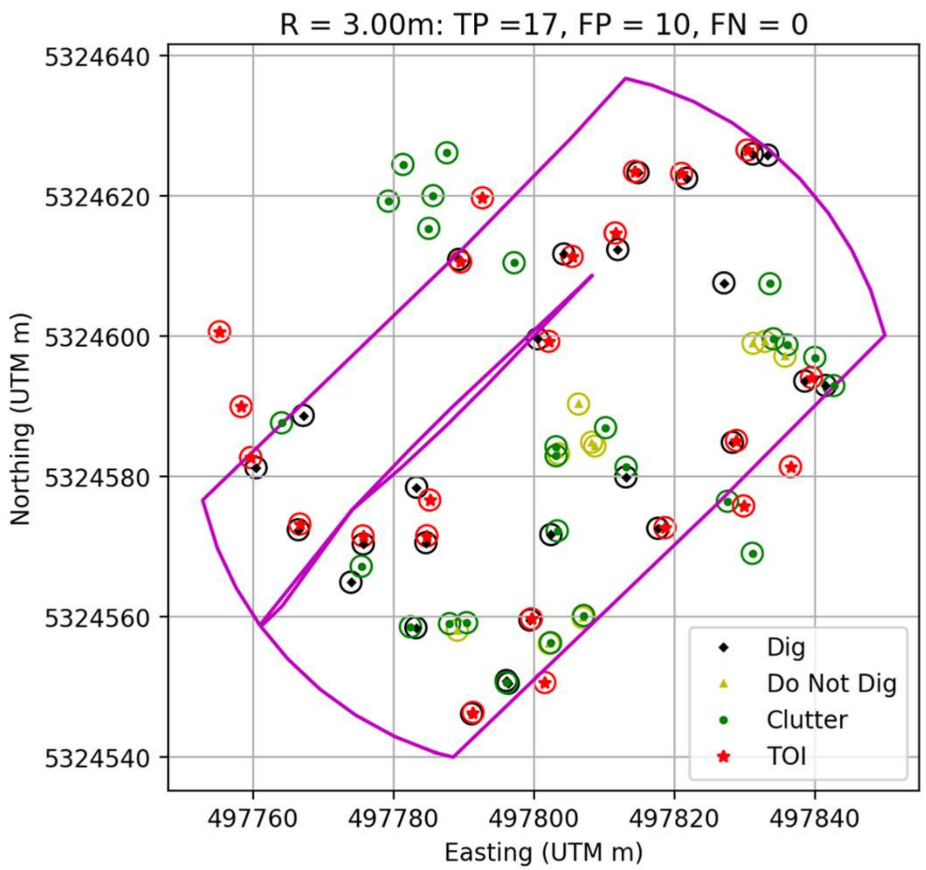


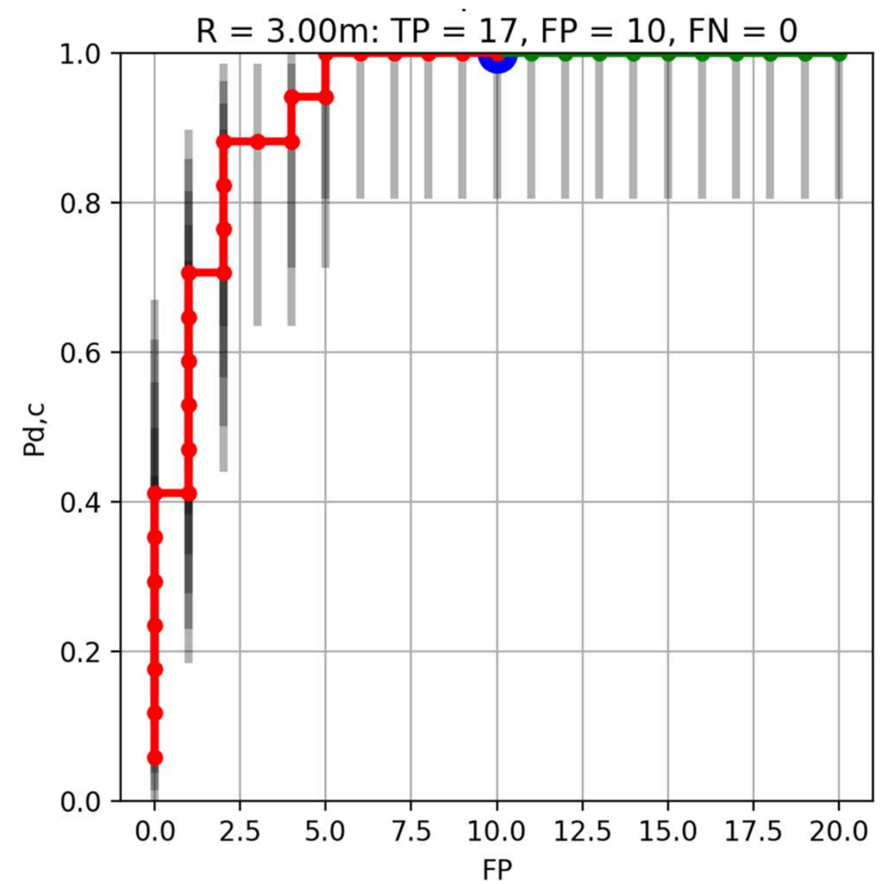


Black Tusk GEOPHYSICS
GapEOD Explosive Ordnance Detection
SERDP DOD • EPA • DOE

2021 Sequim Bay Blind-Grid results

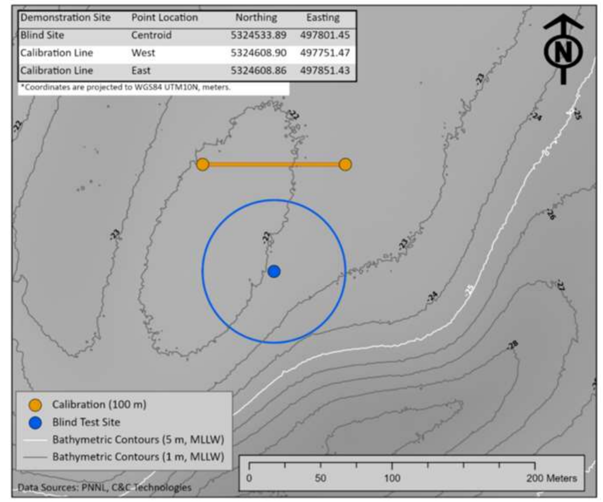
18	Clutter
1	155m Howitzer M107
3	105mm M60
1	105mm HEAT
4	81mm M821 finned
6	81mm M889A1
2	60mm M49

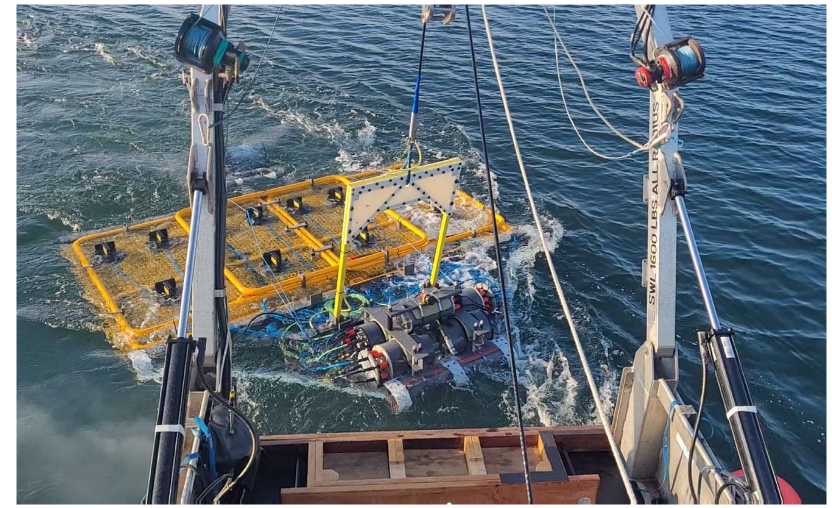




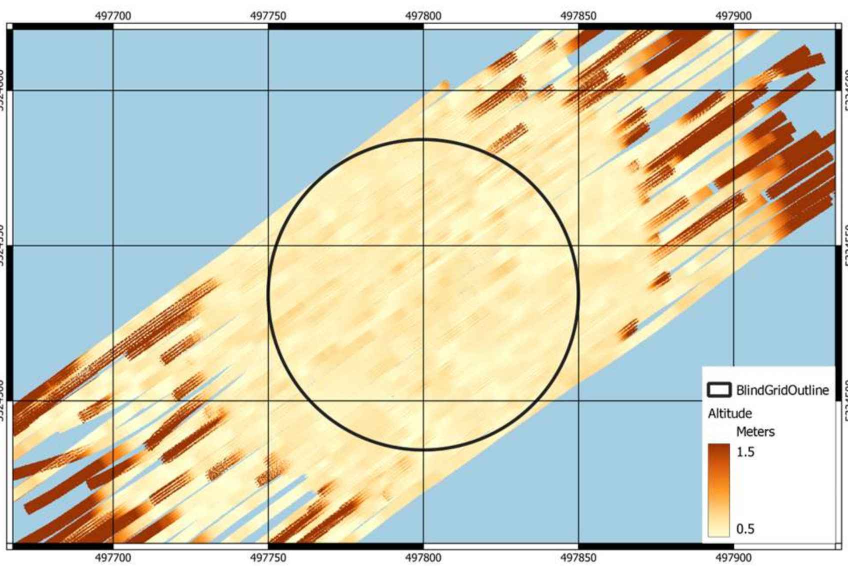
Sequim Bay 2022 Demonstration

- Three data sets acquired

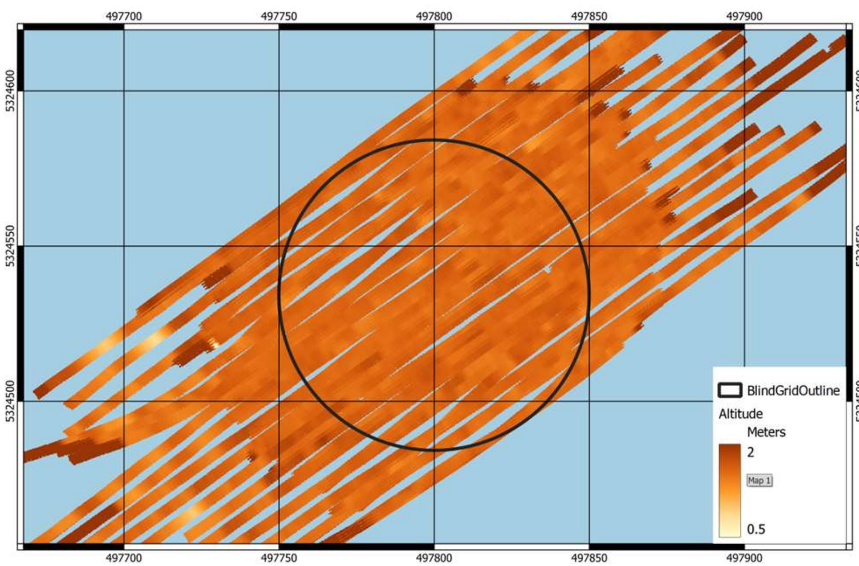




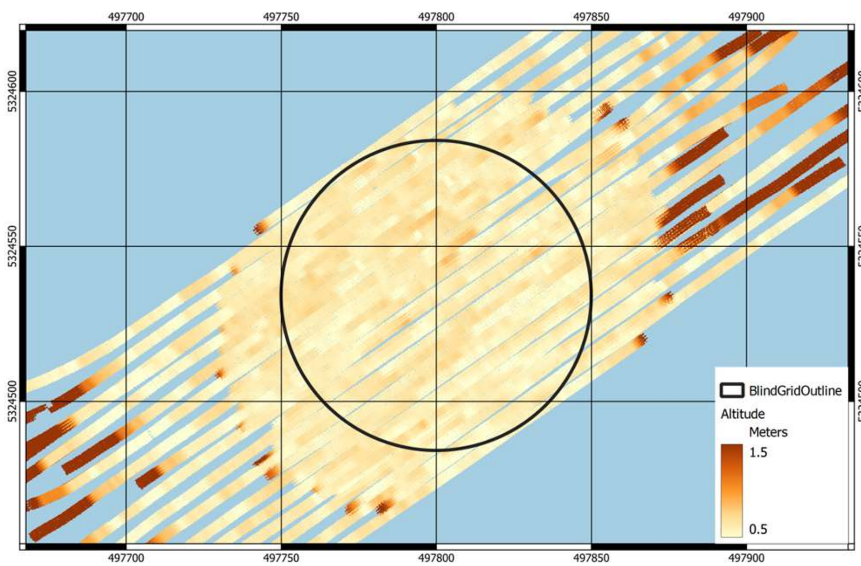
90 Hz base-frequency
lowest achievable altitude



90 Hz base-frequency
1.5 m survey altitude

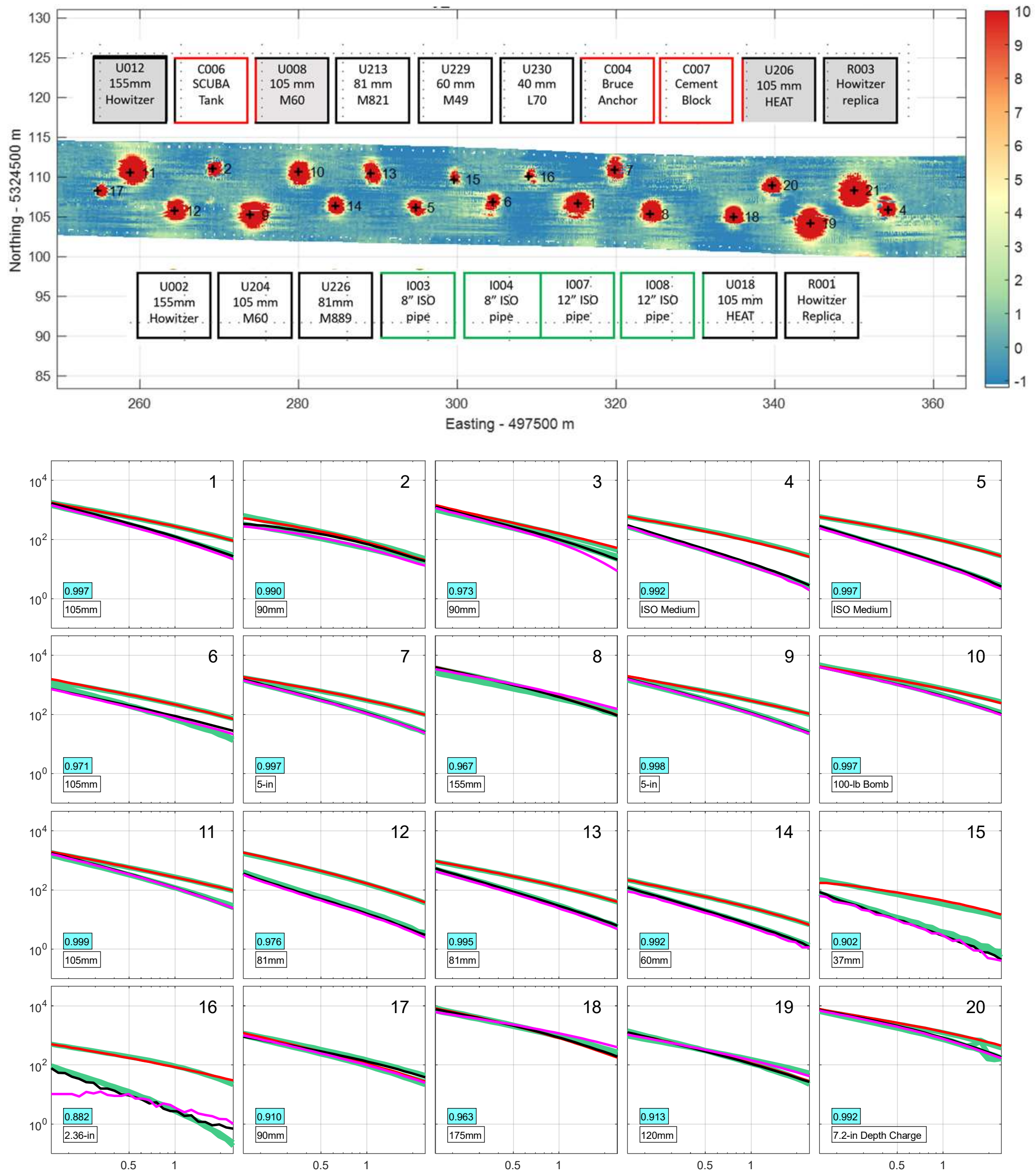


30 Hz base-frequency
lowest achievable altitude

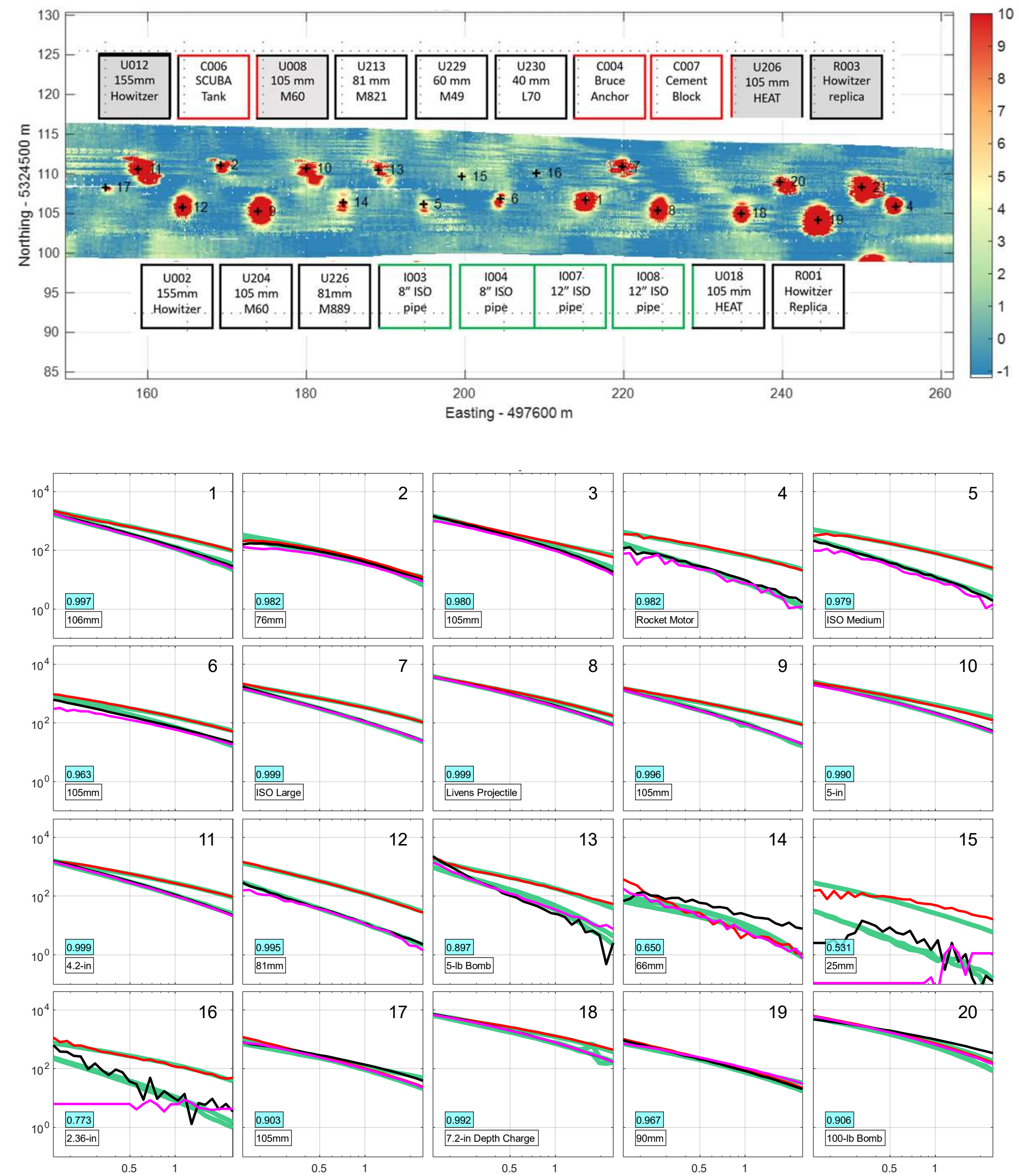


Sequim Bay 2022: Calibration Lane

0.5 to 0.75 m altitude



1 to 1.25 m altitude



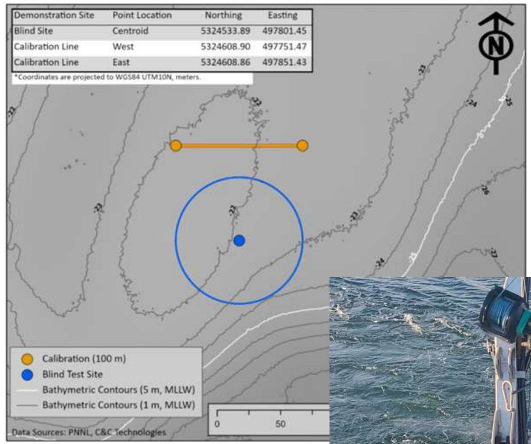
1	Large ISO
2	Scuba Tank
3	East Anchor point
4	Medium ISO
5	Medium ISO
6	Bruce Anchor
7	Large ISO
8	155mm Howitzer
9	105mm M60
10	155mm Howitzer
11	105mm M60
12	81mm M821
13	81mm M821
14	60mm M49
15	40mm L70
16	West Anchor
17	105mm HEAT
18	Howitzer Replica
19	105mm HEAT
20	Howitzer Replica

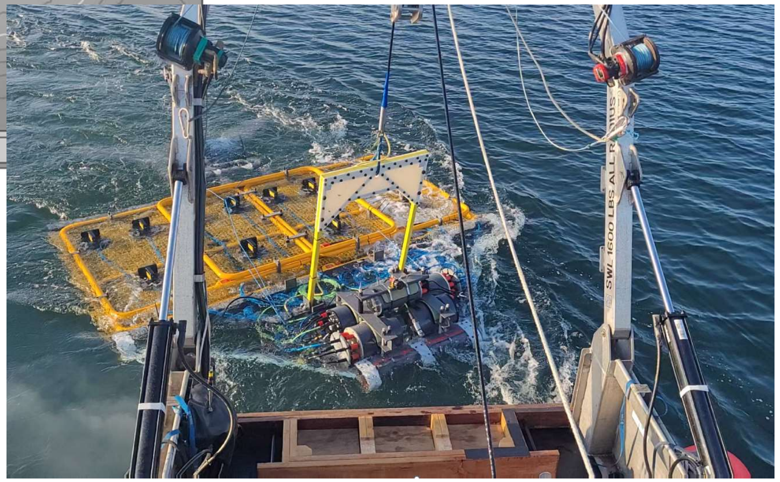
Sequim Bay 2022 Demonstration

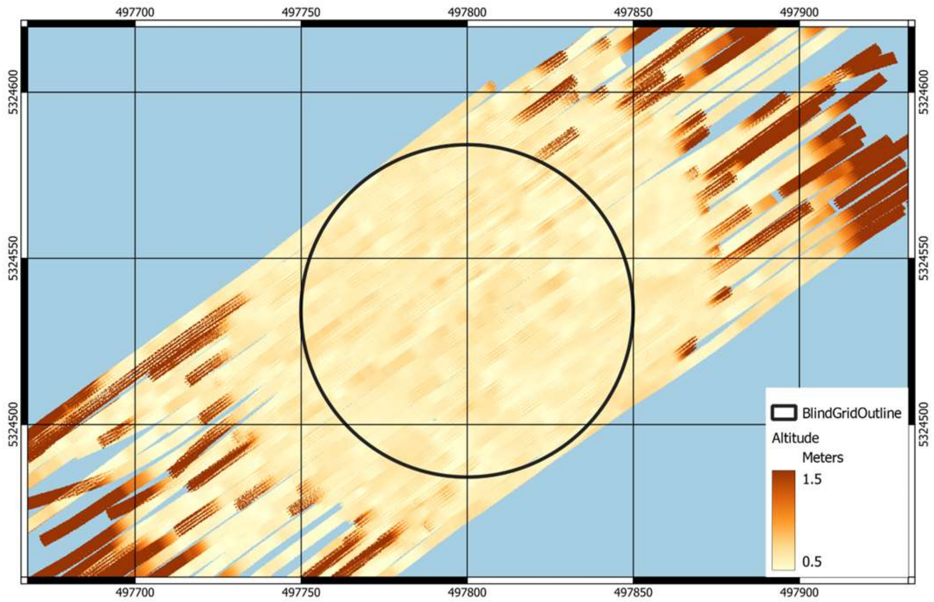
Only results from the 90 Hz base-frequency, lowest achievable altitude diglist has been scored.

From Program Office:

- At the demonstrator stop dig point, UltraTEMA successfully detected and classified all TOI with 5 false alarms.
- Use of the optimum stop dig point would have resulted in only 2 false alarms at the Pd,c = 100% point on the ROC curve.
- Geolocation differences between PNNL ground truth and UltraTEMA positions were significantly larger than in 2021, with a 3.5 m halo required for best performance.



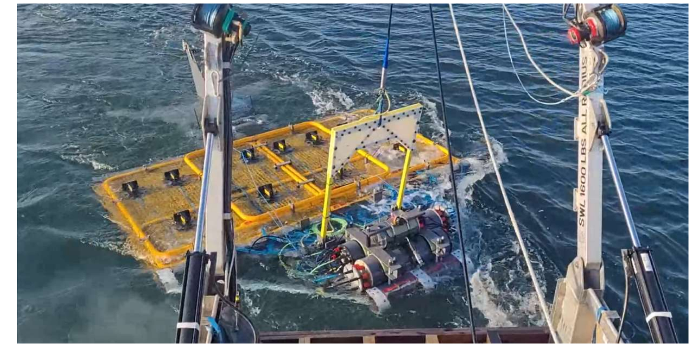


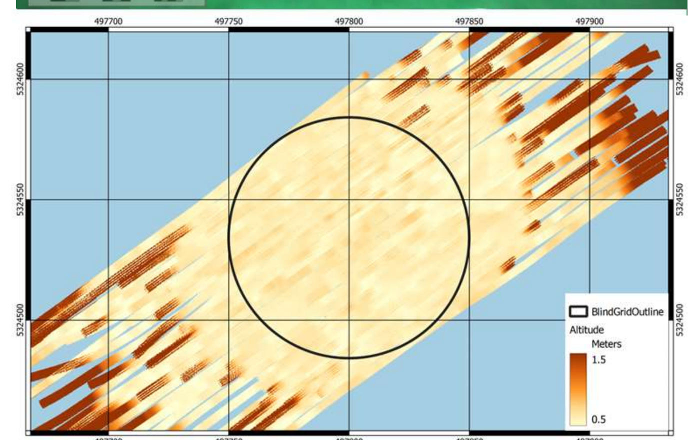


Black Tusk GEOPHYSICS
GapEOD Explosive Ordnance Detection
SERDP DOD • EPA • DOE

Summary

- Developed a full IE technique to compute the TEM response for an arbitrarily oriented sensor in a multi-layered medium.
  - Conductive background responses are correlated with survey parameters, can obscure or distort target responses, and can be removed via modeling the UW environment as multiple layers.
  - The impacts of the conductive sea-water on the scattered fields from a buried metallic object are negligible within the time range of interest. Terrestrial EMI modeling techniques and methods can be utilized for marine detection and characterization.
- Developed an inversion methods to account for the errors in sensor positioning.
- Developing methods that can enhance target responses
- Results at Sequim Bay showed that marine EMI sensing has considerable potential to be deployed as a practical and effective AGC tool.





Black Tusk GEOPHYSICS GapEOD Explosive Ordnance Detection SERDP DOD • EPA • DOE