



Quantitative Assessment of LiDAR Technology for Detecting, Localizing, and Characterizing Underwater Munitions in Shallow Waters

Project Number: MR22-3257

Principal Investigator: Jeffrey P. Thayer

PI's Organization: University of Colorado Boulder (UCB)

Final Debrief

DATE: August 14, 2025

Project Team



Team	Responsibilities
Prof. Jeff Thayer (UCB, Team Lead)	Principal investigator led the research, advised and mentored a PhD student and two Masters students, transferred outcomes to the commercial entity.
Mr. Kevin Sacca (UCB)	Aerospace PhD student responsible for topobathy LiDAR system simulation, underwater calibration targets, MTF application, and data analysis.
Ms. Alexandra Wise (OSS)	Aerospace Masters student responsible for LiDAR assessment evaluation using uncertainty quantification modeling (now PI of ESTCP project at Orion Space Solutions/ArcField)
Ms. Maya Greenstein (UCB)	Aerospace Masters student performed lab experiments and theory on scanning mirror pointing solution.
Mr. Bryce Garby (UCB / OSS)	Lead LiDAR Engineer and subcontract lead. He coordinated the processing and data handling of the raw point cloud data collected by EDGE and provided guidance on system-specific details and post-processing approaches. (Now an aerospace PhD student in Prof. Thayer's lab)

Bottom Line Up Front

- What technology or methodology is being evaluated during this demonstration?
 - Assessing quantitatively the 3D topographic/bathymetric LiDAR mapping of shallow water scenes for proud munition detection, localization, and classification.
- What's been going well?
 - Quantitative assessment schemes of LiDAR performance have been advanced providing assessments and solutions to improve operations and observations.
 - LiDAR system performance modelling has been advanced to assess factors that can impact the detection, localization, and classification of proud munitions – including water surface and water turbidity effects

Bottom Line Up Front

- What's not working?
 - Object detection and classification solutions have been hindered by the limited level of information content from observations.
 - Machine learning approaches have yet to be employed due to the need to expend more effort on improving concept of operations, system capabilities, and system/scene modeling.
- What support do you need?
 - Orion Space Solutions needs to improve their measurement capabilities – R&D unit in development
 - Applying machine learning approaches to the 3D LiDAR point cloud for classification solutions are just beginning and will require future effort.

SERDP Current Project (MR22-3257)

Technical Objective

- To investigate methods that **quantitatively** assess the MR capabilities of drone-based LiDAR technologies for shallow-water applications
- To transition research for operational purposes

Technical Objective: 3D Point Cloud Imaging

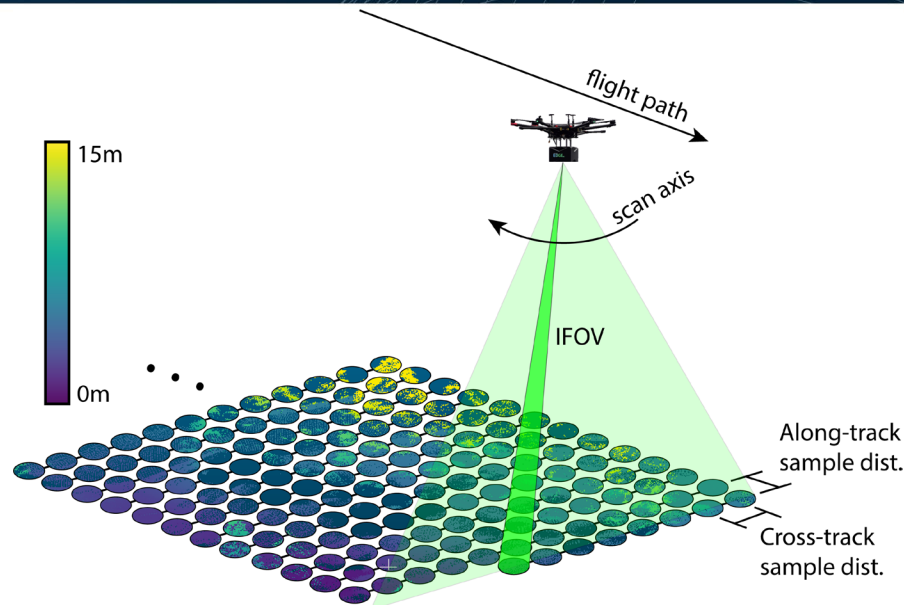
Concept of Operations

- Drone Platform: motion, attitude, altitude
- Conditions: sea state, turbidity, bottom reflectance

LiDAR Sampling Scheme

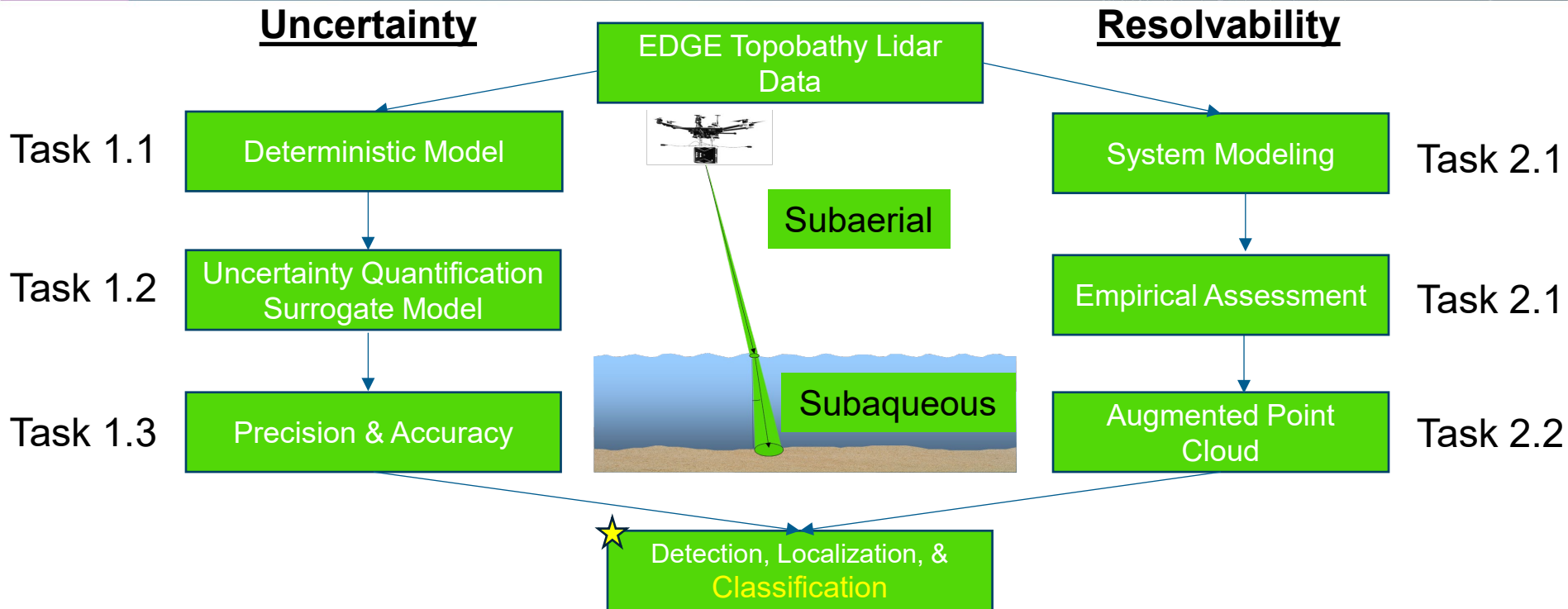
- System specifics
- Drone flight plan

Effective IFOV / Beam Spot Area	Along-track Sampling	Cross-track Sampling
- Beam divergence - Mirror angle - Scattering media	- Drone velocity - Drone pitch	- Mirror rate - Laser rate



For LiDAR images, height is the contrasting signal

Technical Approach: **Tasks Completed**



Results: Summary

New methods and analysis schemes have been developed to assess topobathy LiDAR technology for shallow-water MR response.

- First development of an Uncertainty Quantification (UQ) model for topobathy lidar with the capability to error assess every point within the point cloud
- First underwater calibration targets and empirical quantification of LiDAR performance
- First application of modulation transfer function to LiDAR point clouds to quantitatively assess resolution and contrast performance
- Complete end-to-end system performance modeling enabling observing system simulated experiments (OSSEs).

Results: Uncertainty Quantification

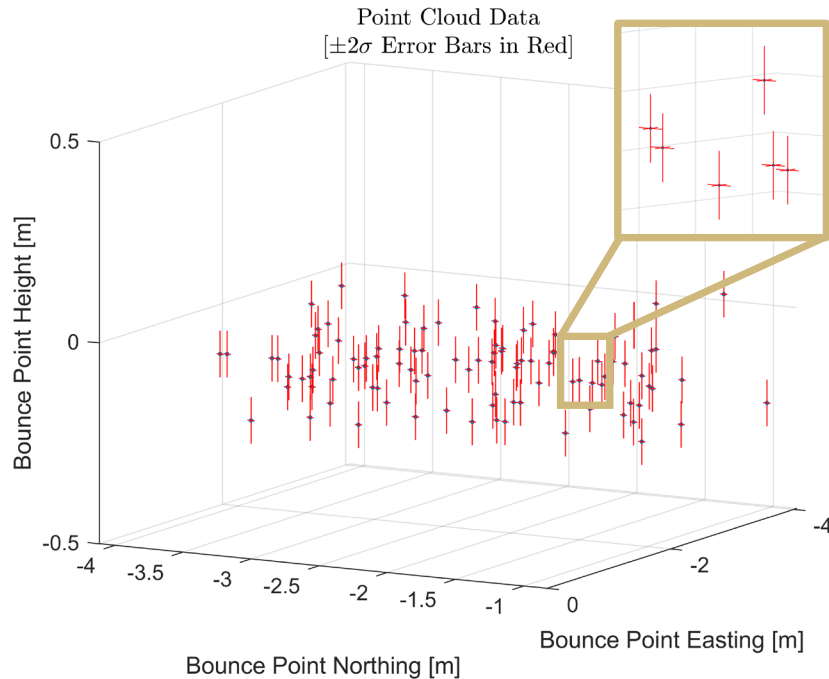
Uncertainty

Completed the Codebase for the Uncertainty Quantification (UQ)
model of LiDAR point clouds

- Global Sensitivity Analysis – System design / CONOPS
- Lidar Data Point Processing
 - Shot by Shot Error Ellipsoids*
 - Shot by Shot Analysis of Causes of Uncertainty*
 - Intrinsic LiDAR Calibration (e.g., Bore-sighting)

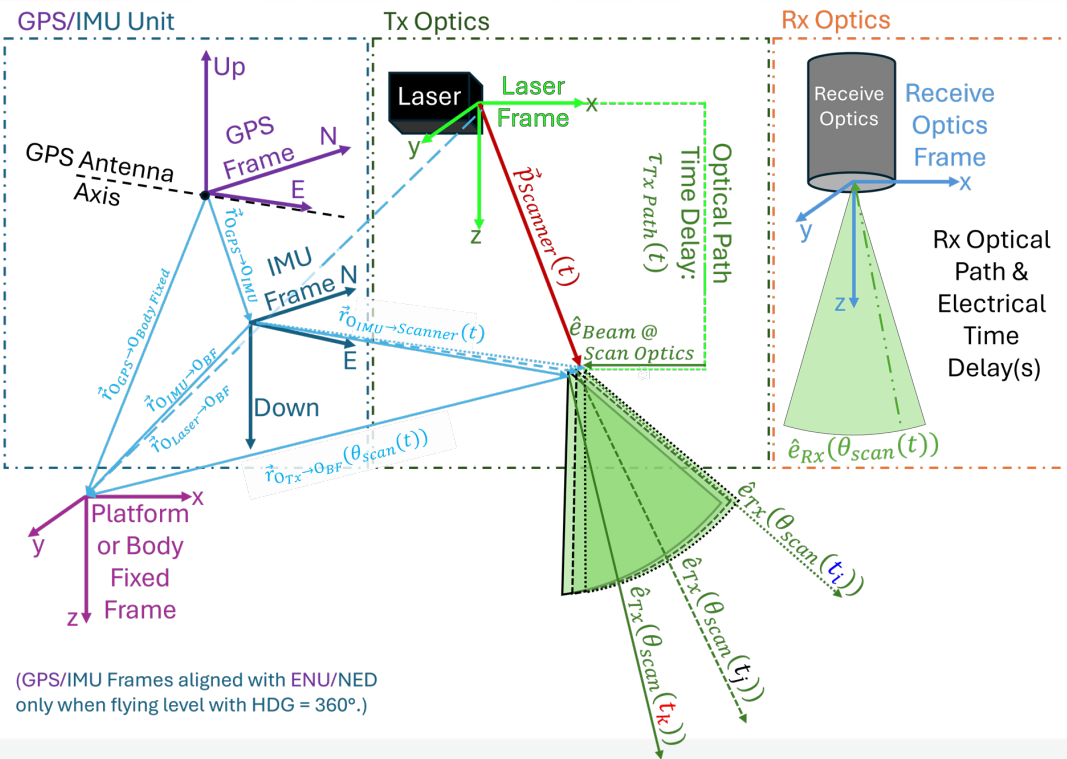
*Additional Context Layers for Classification Methods

gPCE Uncertainty Quantification Model



- gPCE shown to be
 - Computationally efficient
 - High-fidelity
 - Minimal a priori assumptions
- Completed sub-aqueous gPCE implementation for simultaneous calculation of
 - Quantities of interest
 - e.g., geolocated photon bounce point location
 - Point-wise full-system uncertainty quantification

UQ Requirements on System Specifications



- UQ analysis demonstrated the need for more complete description and measurement of LiDAR system specs:

- Improve boresighting
- Improve pointing solution
- Improve scanning mechanism
- Improve x, y, z registration of detected laser shots

- Incorporated in Next Generation System

Results: Empirical and Theoretical Assessment

Resolvability

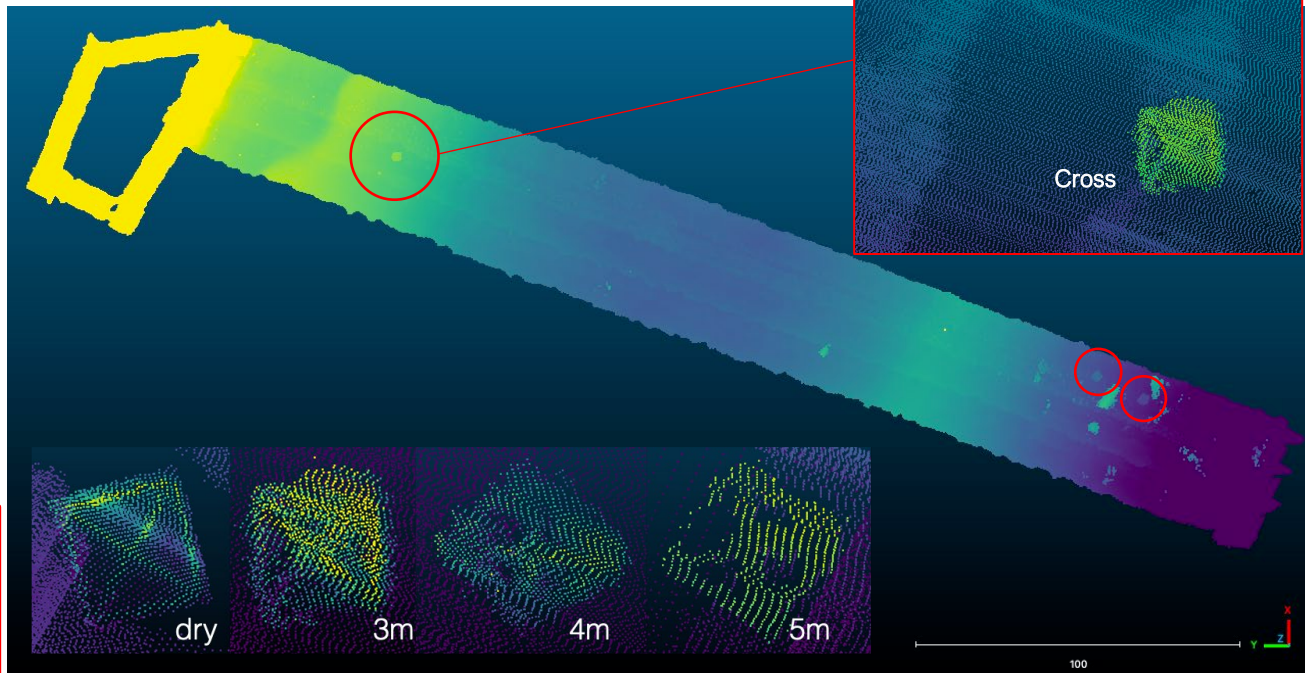
Completed empirical assessment methodologies and system modeling

- Developed calibration targets for underwater deployment
- Defined and applied modulation transfer function (MTF) analysis to LiDAR 3D point clouds
 - Empirically determined resolution
 - Modeled contributing factors impacting resolution
- Modeled System End-to-End
 - Introduced realistic water surface structure
 - Introduced effects of turbidity on system performance
 - Evaluated sampling strategies
 - Quantified overall resolution performance (subaerial and subaqueous)

Bathymetric Point Cloud of Calibration Targets

Calibration Target Analysis

- All calibration targets deployed at Panama City were detected on land and underwater
- Used targets to investigate point density distribution and resolution properties



Corner-cube
retroreflector



Retroreflective Line

MTF Analysis

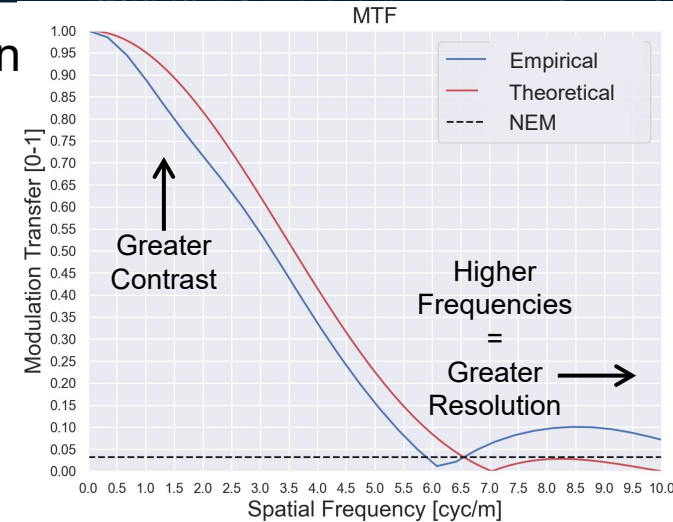
Empirical and Theoretical MTFs

- **Empirical** MTF analysis reveals true effective resolution

- Water surface and column produce a dynamic MTF
- Submerged calibration targets serves as point/line targets for MTF analysis

- **Theoretical** LiDAR MTF can be modeled to find expected resolutions:

- Sampling
 - Scanning (Laser/mirror rates, beam spread)
 - ConOps (Flight speed, altitude)
- Noise/Uncertainty
 - MTF is evaluated at the Noise-Equivalent Modulation (NEM) threshold



Kevin W. Sacca, Jeffrey P. Thayer. Empirical Quantification of Topobathymetric LiDAR System Resolution using Modulation Transfer Function. ESS Open Archive . March 19, 2025 DOI: 10.22541/essoar.173204180.08904483/v2.

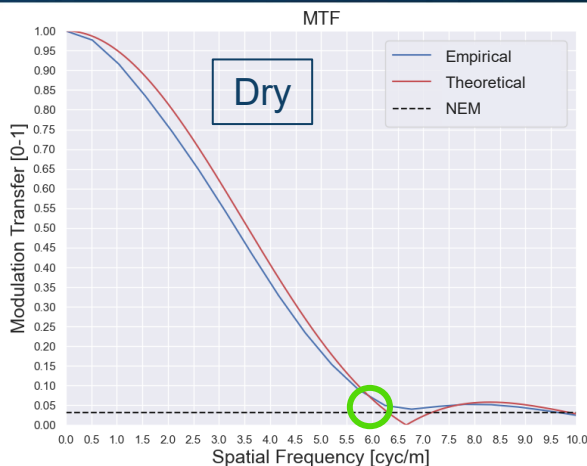
Panama City, FL Campaign MTF Analysis



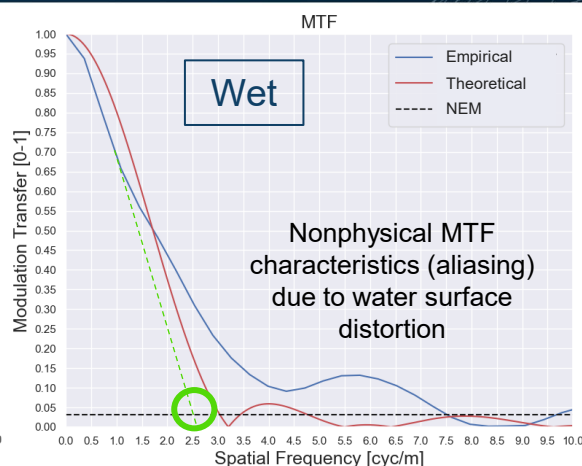
75 mm clutter object

IVS Object: Multi-Swath Pt Cloud

Colored by height



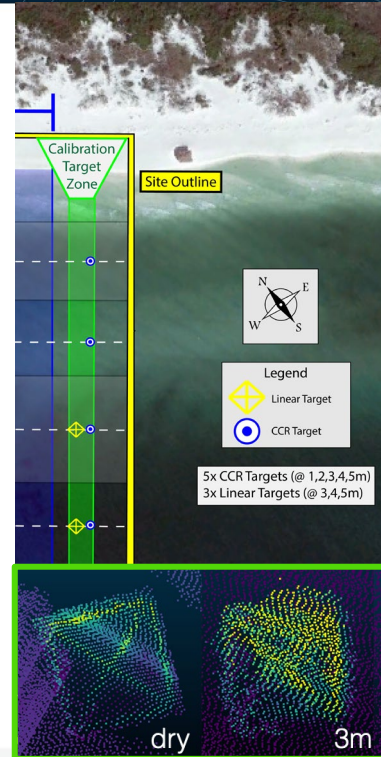
Dry cutoff resolution $\approx 80\text{mm}$



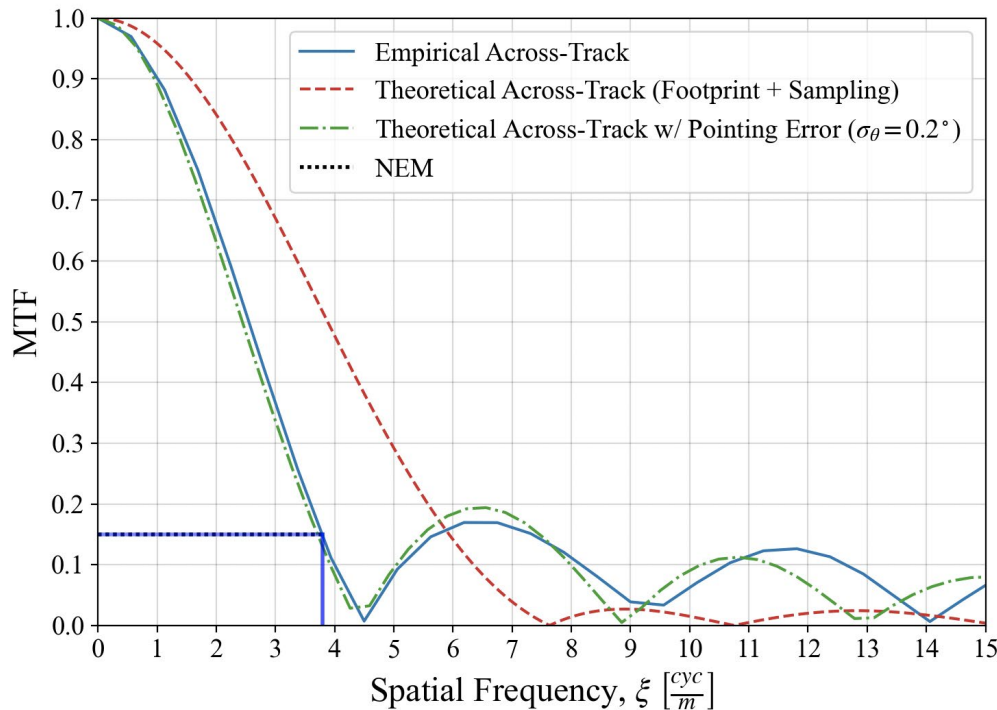
Wet cutoff resolution $\approx 200\text{mm}^*$

Retroreflector MTFs represent
best-case detectability, **worst-case** resolutions

Multi-swath MTF analysis indicates many munition targets are not resolvable, due in part by the varying sampling between swaths



Results: Empirical / Theoretical MTF Analysis



Empirical / Theoretical MTF analysis of dry calibration line target reveals instrument pointing error of **0.2 degrees (@20 m altitude = 40 mm uncertainty)**

Resolution

$$d = \frac{1}{2f} [m]$$

$$f = 5 \text{ then } d = 100\text{mm}$$

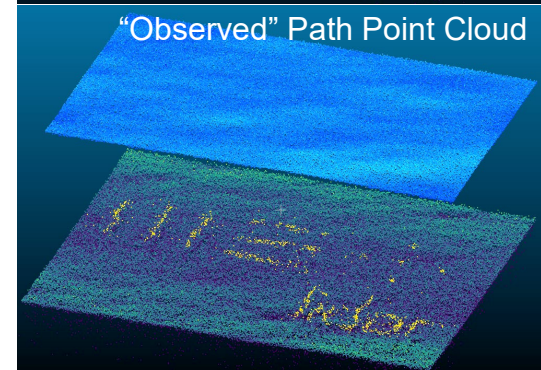
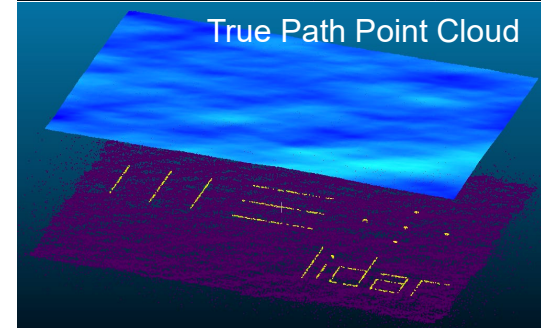
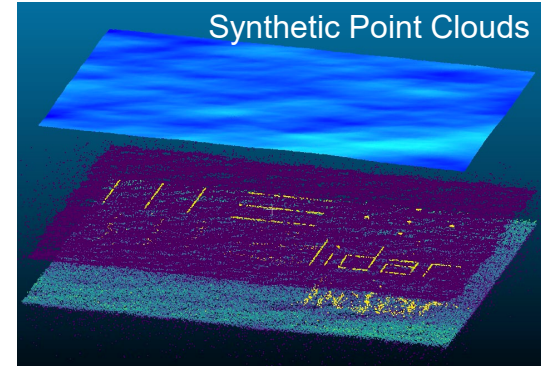
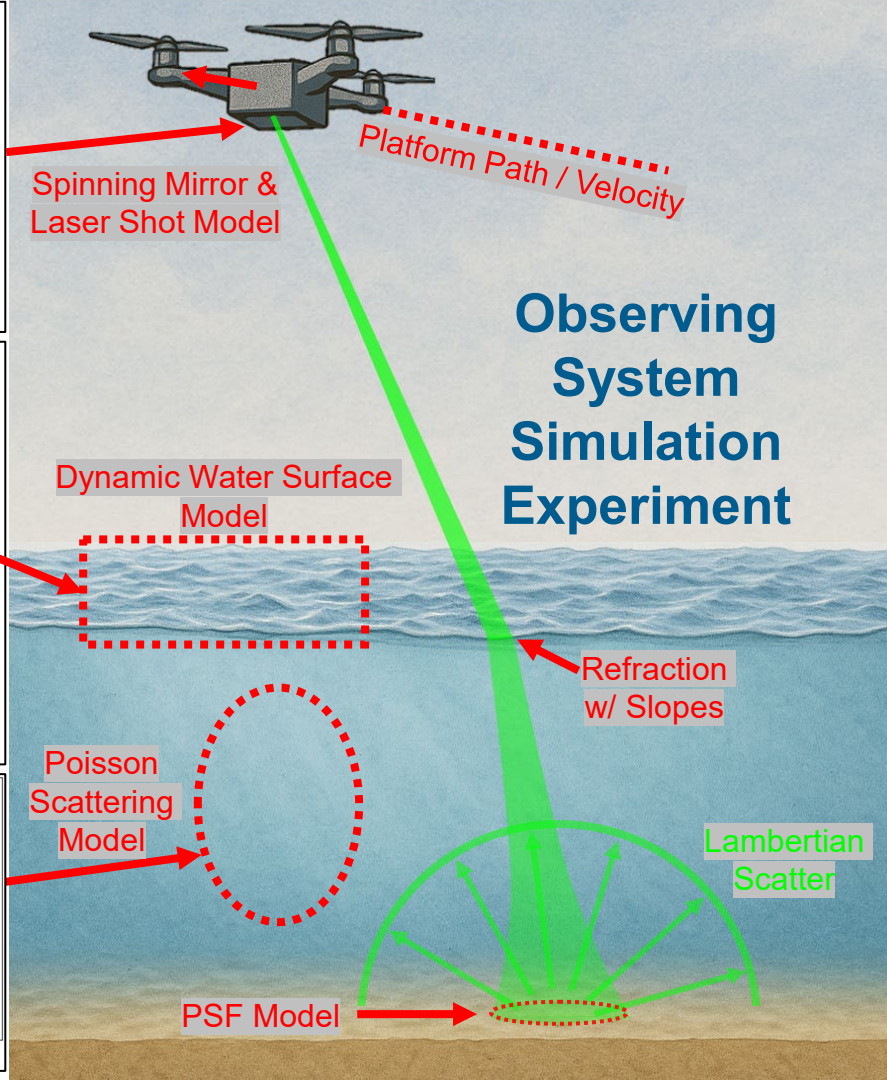
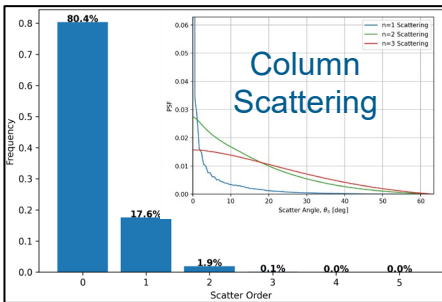
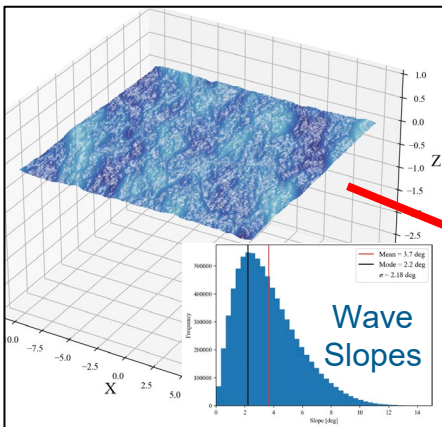
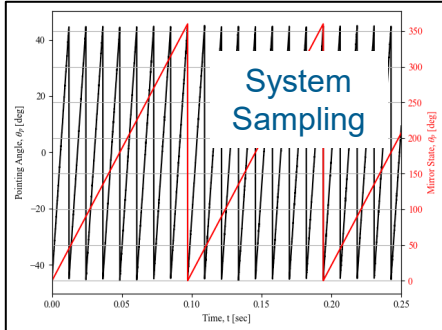
Methods – Instrument Parameters

Differences between 'Base' instrument design and 'Improved' instrument (@15m AGL)

Parameter	Base	Improved
Points per scan	88	293
Mirror pointing error	0.25 deg	0.01 deg
Across-track sampling at 15m	90 mm	27 mm
Spot diameter at 15m	64 mm	15 mm
Beam divergence ($1/e^2$)	4.2 mrad	1 mrad
Point Density (points/m ² /swath)	350	1371

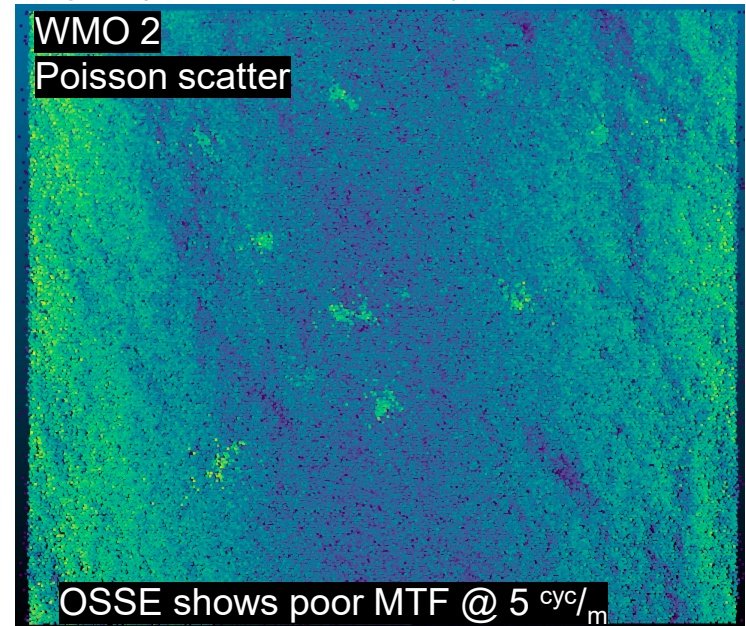
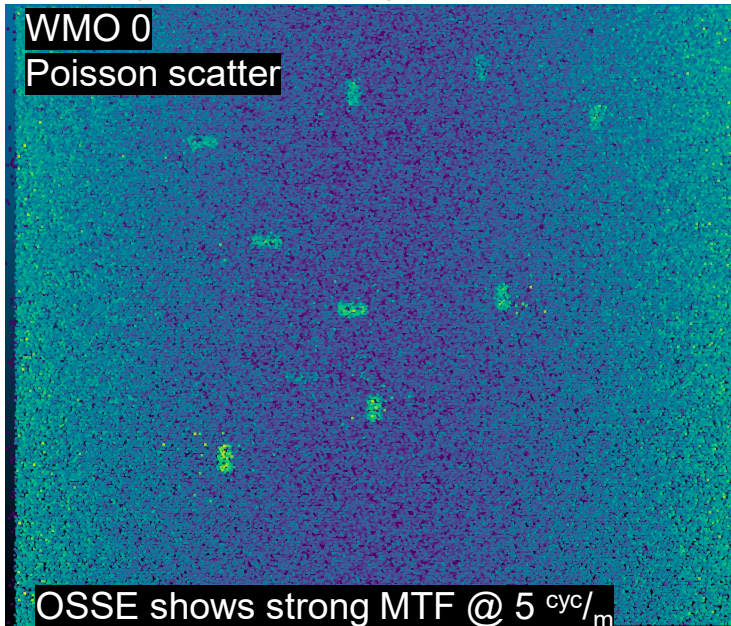
Improved instrument designed to sample 4 points across 100mm targets within a single swath

System Performance Modeling



Results – Detectability vs Resolvability

Synthetic data from OSSEs can illustrate detectability vs. resolvability
(5-meter depth | 100 mm x 400 mm Lambertian targets | 100%-10% proud)



Methods – OSSE Configuration Parameters

Base and Improved Instrument Parameters:

- Wavelength
- Laser fire rate
- Pulse energy
- Pulse width
- Pulse shape
- Beam divergence
- Mirror spin rate
- Mirror facets
- Pointing error
- Receiver time error
- Receiver dead time

CONOPS Parameters:

- Altitude
- Velocity
- Path of motion
- Roll, Pitch, Yaw

Target Parameters:

- Position / Depth
- Shape
- Reflectivity
- Quantity

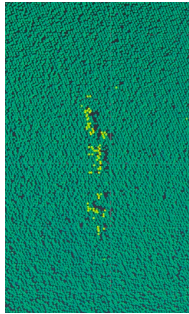
Environmental Parameters:

- Water surface sea state
- Water surface reflectivity
- Index of refraction
- Water Type
 - Turbidity (a & b coeffs)
 - Scattering phase function
- Order-of-scattering model
- Water depth
- Seafloor reflectivity

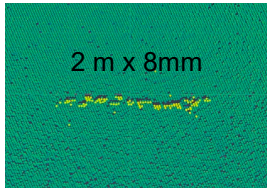
Methods – OSSE Test Matrix

Generates simulated measurements of MTF calibration line targets

Evaluate impacts on effective resolution for each parameter



Across-track MTF
of submerged
target point cloud



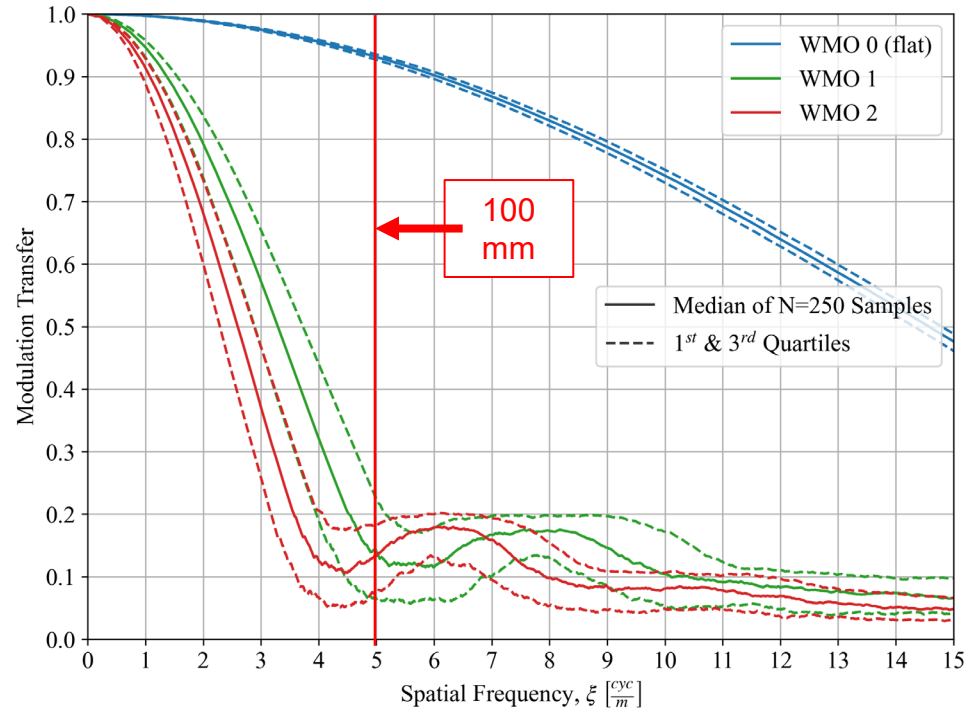
Along-track MTF
of submerged
target point cloud

Water Surface State ^(a)	Water Type: Scattering Phase Function & Extinction Coefficients ^(b)	Scatter Order ^(c)	MTF Target Depth	Instrument Design
WMO 0 (flat)	Filtered Seawater $a = 0.085 \text{ [1/m]}$ $b = 0.008 \text{ [1/m]}$	Poisson distribution ($N_{\max}=10$)	1m	Base
WMO 1 (calm) 0 to 0.1 m	Clear Water $a = 0.114 \text{ [1/m]}$ $b = 0.037 \text{ [1/m]}$	Zero-scatter	3m	Improved
WMO 2 (smooth) 0.1 to 0.5 m	Coastal Ocean $a = 0.179 \text{ [1/m]}$ $b = 0.219 \text{ [1/m]}$	1 st order (single-scatter)	5m	
	Turbid Harbor $a = 0.366 \text{ [1/m]}$ $b = 1.824 \text{ [1/m]}$	2 nd order		

Results – OSSE: Change in Water Surface

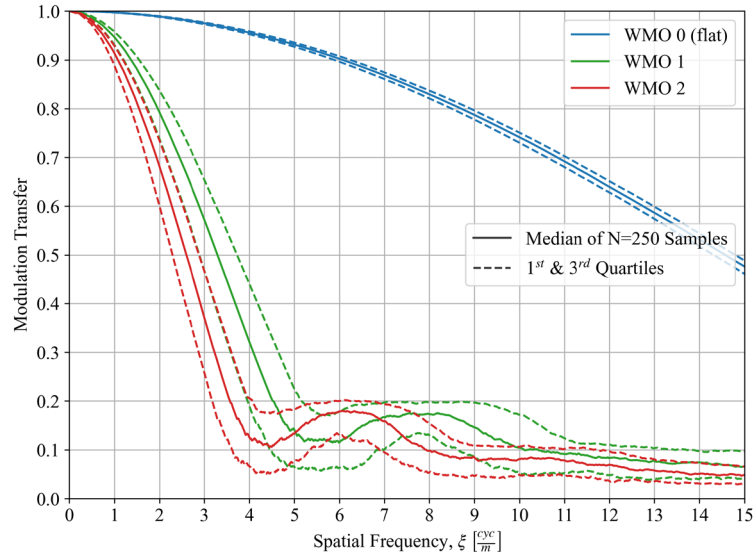
Free Parameter	OSSE
Sea State	✓
Turbidity	Clear
Scatter Order	0
Depth	3m
Instrument	Improved

Water surface distortions > WMO 1 are strongly impacting resolvability of 100mm targets



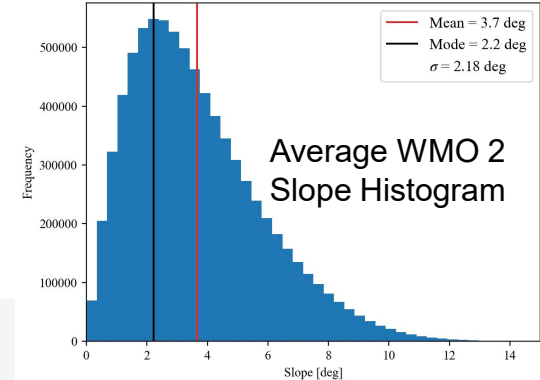
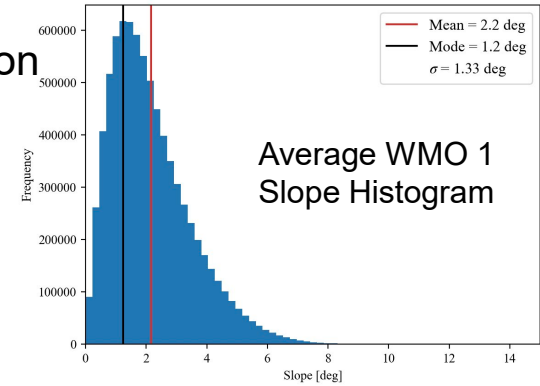
Results – OSSE: Change in Water Surface

This work revealed that WMO sea state classes are too coarsely defined to use them to describe impact to LiDAR bathymetric resolution



Standard deviation of water surface slopes were used to quantify the dynamic range of possible beam spreading/steering

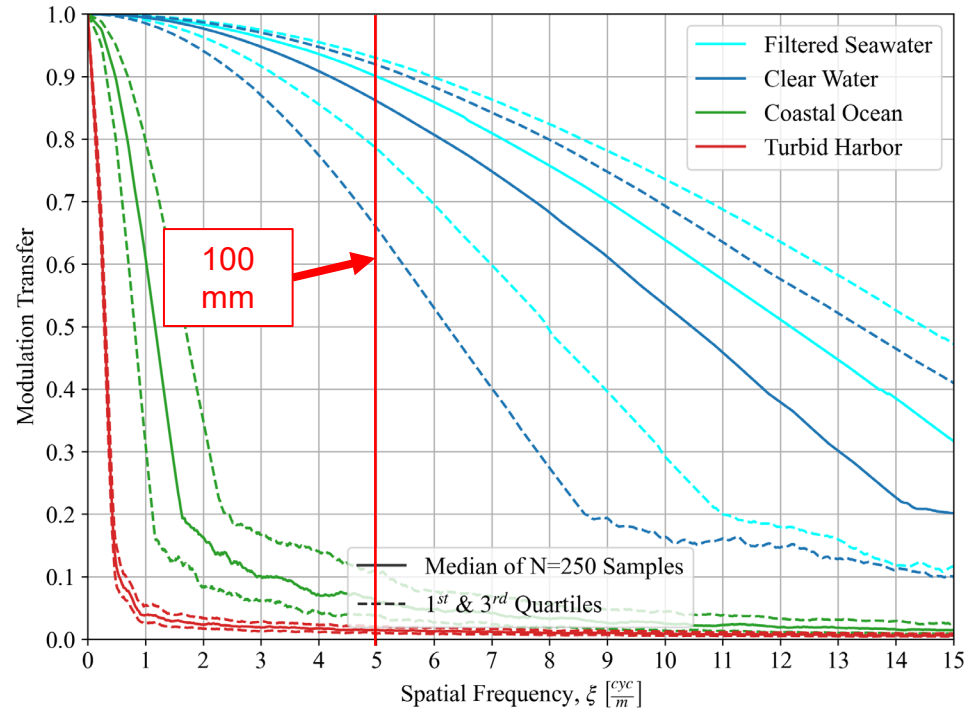
- Model with OSSE, or
- Measure with buoys or other instruments



Results – OSSE: Change in Turbidity

Free Parameter	OSSE
Sea State	WMO 0
Turbidity	✓
Scatter Order	Poisson
Depth	3m
Instrument	Improved

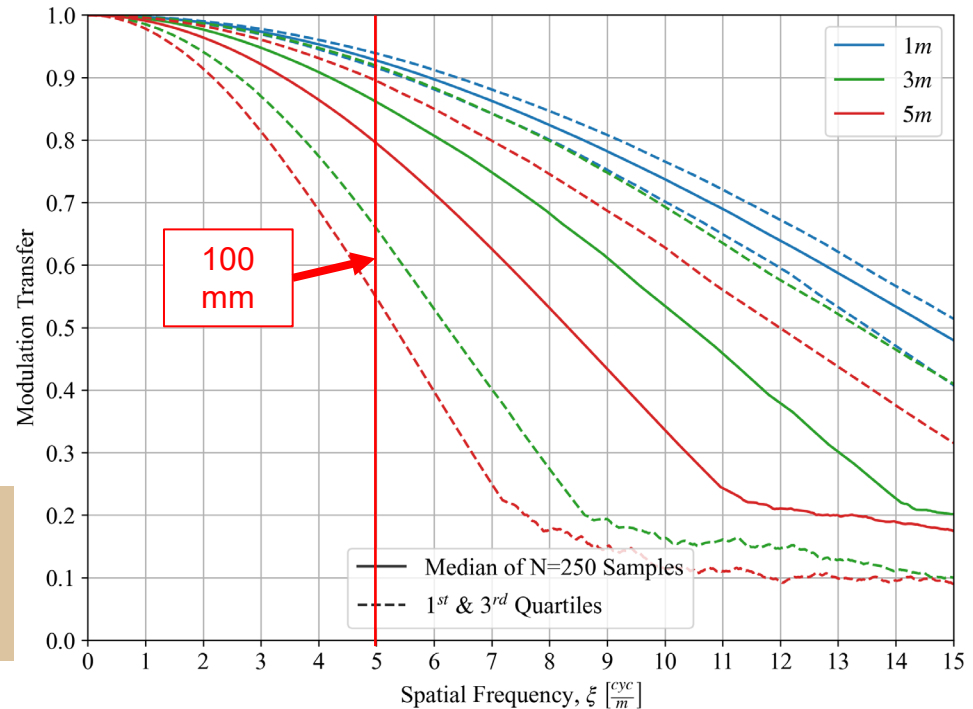
Turbidity levels between 'clear' and 'coastal' may allow for resolution of 100mm targets



Results – OSSE: Change in Depth

Free Parameter	OSSE
Sea State	WMO 0
Turbidity	Clear
Scatter Order	Poisson
Depth	✓
Instrument	Improved

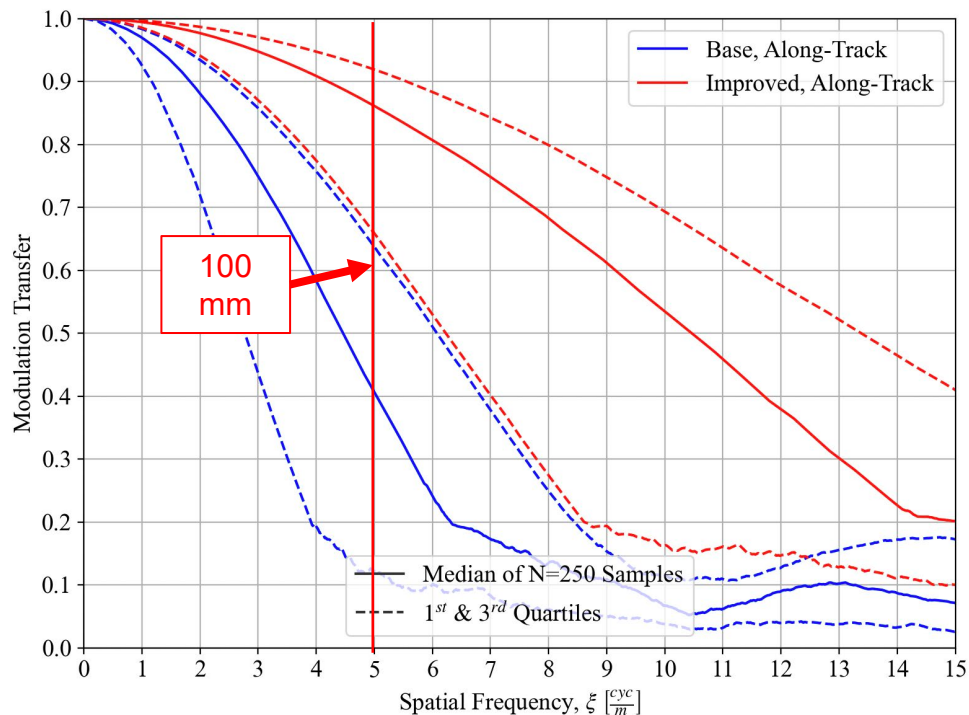
In favorable conditions, depth is not a major factor affecting resolvability of 100mm targets



Results – OSSE: Change in System Sampling

Free Parameter	OSSE
Sea State	WMO 0
Turbidity	Clear
Scatter Order	Poisson
Depth	3m
Instrument	✓

Improved system design produces effective sampling with high likelihood of resolving 100 mm targets



Go / No-Go Decisions

Results: Go / No-Go decisions

- Assessment tools were applied to Panama City campaign resulting in required revisions recommended to the OSS LiDAR team. Failure to meet these system specifications will not meet resolution and detection capabilities required to resolve 100 mm targets (or less) resulting in a **No-Go** decision.
- Environmental factors create conditions that can degrade the measurement capabilities leading to a **No-Go** decision
 - Water surface state (>WMO 1 conditions → water slopes > 1-degree standard deviation)
 - Water column particulates:
 - 'Coastal' water type or $b_{\max} > 0.1 \text{ [m}^{-1}\text{]}$
 - empirically NTU > 7

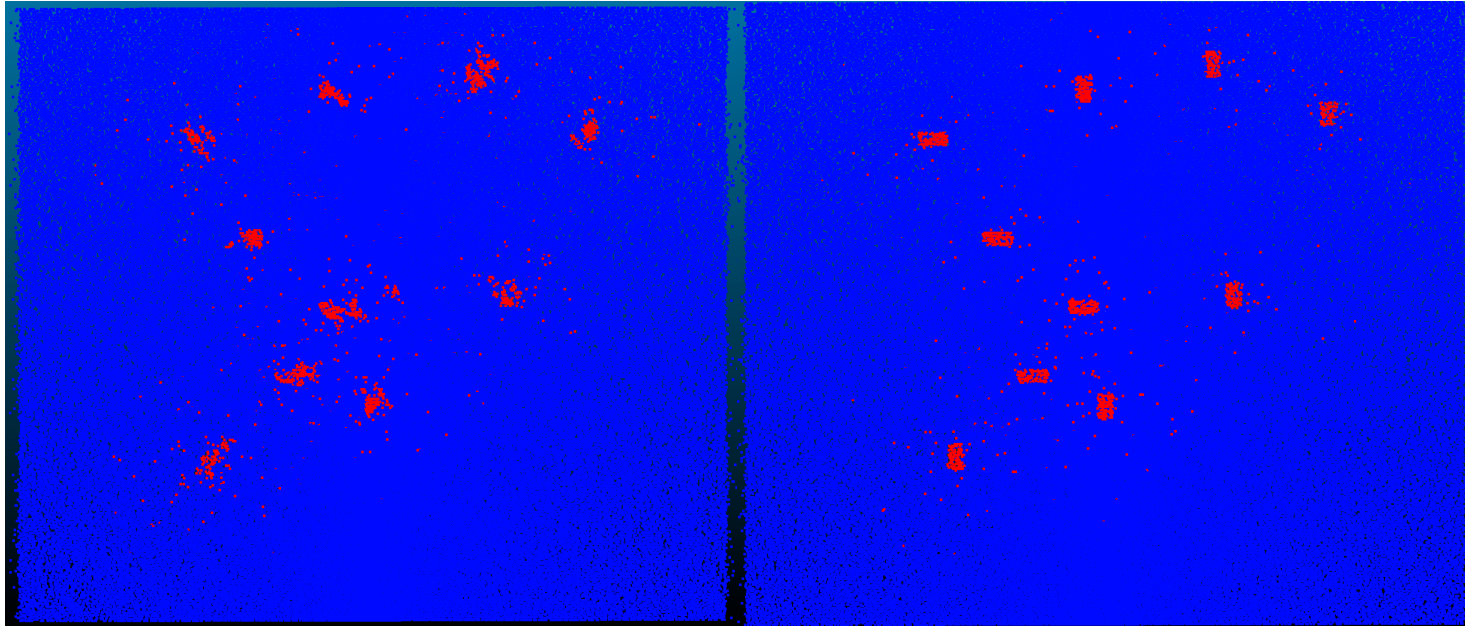
Future Developments

- Assist in empirically evaluating improved OSS Lidar system data (HI Campaign)
- Publish results from OSSEs
- Pursue further system advancements for MR applications
- Standardize definition of inherent optical properties that are measurable or derivable by user
- Improve classification methodologies

Classification – OSSE

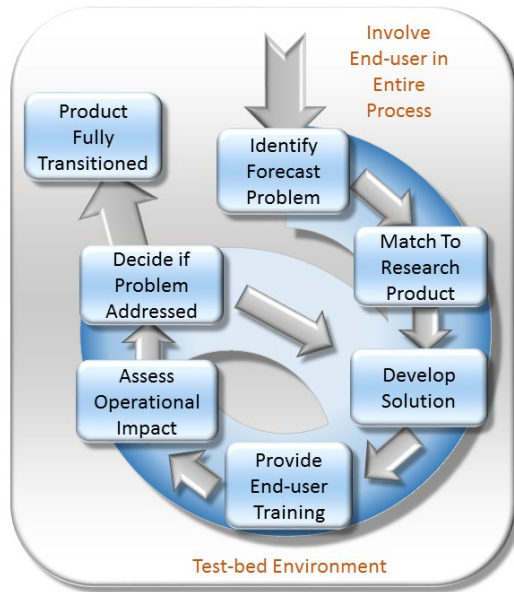
Recommend using OSSEs to validate unsupervised classification ML methods

- Synthetic data is inherently pre-labeled / classified



Technology Transfer

Research to Operations to Research (R2O2R)



- Provide Post Operational Assessment
 - Use underwater calibration line targets for MTF Analysis
- Transition CU SERDP research to OSS drone-based topobathy system and operations
 - Employ UQ methodologies and MTF analysis tools
 - Advance LiDAR system technique for MR applications
- Perform OSSEs for specific sites to inform users of expectations
 - Evaluate impact of water conditions
 - Balance areal coverage with resolution requirements

Technology Transfer: EPA and State Regulators

- Drone-based topobathy LiDAR shows promise as a MR technology for detecting, localizing, and classifying proud munitions in water depths of 5 meters or less.
- Current technology provides 3D point clouds with a nominal sampling of 4 points per 100 mm.
- EPA and state regulators should consider the technology requires:
 - Drone operations
 - Laser operations
 - Surveyed or relative ground control points and deployment of underwater control points in areas of interest
 - Geolocation sources either from local base station or a nearby NOAA continuously operating reference station (CORS) network (within a few kilometers)

Technology Transfer: Remedial Program Managers

- Remedial PMs can expect:
 - A 3D point cloud of seafloor and proud underwater objects from 0-5 meters depth with four points per 100 mm sampling.
 - Object geolocation identification with <1-meter accuracy (often better, depends on sea state)
 - LiDAR data processing for detection and classification assessment by trained operator
- Remedial program managers should consider the following when applying this technology with specific site characterization:
 - Atmospheric conditions
 - Sea state conditions
 - Water clarity
 - Clutter density
 - Areal coverage

Technology Transfer: Researchers

- Technology Transfer to Researchers:
 - End-to-end system simulation to evaluate drone and LiDAR specification variables, and environmental conditions for assessing underwater mapping performance
 - Sensitivity analysis of error sources for point geolocation and boresighting solutions
 - Underwater calibration targets for empirical evaluation of system performance (MTF Analysis)
- Researchers should pursue:
 - Machine learning techniques for improved classification schemes from acquired point cloud informed by simulated data
 - Water surface characterization techniques to improve the refraction correction effects on retrieved point cloud (co-aligned camera system, IR laser tracer)
 - Standardized water optical properties relevant to LiDAR systems and determinable by users
 - System improvements in laser transmitter characteristics such as increase pulse energy, decrease beam divergence, diversified wavelengths, increased pulse repetition rate, and detection schemes.

Backup slides

MR22-3257: Quantitative Assessment of LiDAR Technology for Detecting, Localizing, and Characterizing Underwater Munitions in Shallow Waters

Performers: University of Colorado / Orion Space Solutions (formerly LiTeWave Technologies, Inc.)

Technology Focus: Investigate methods, both empirical and theoretical, to **quantitatively** assess a topobathy UAS LiDAR technology for detection, localization, and classification of submerged targets of interest.

Research Objectives

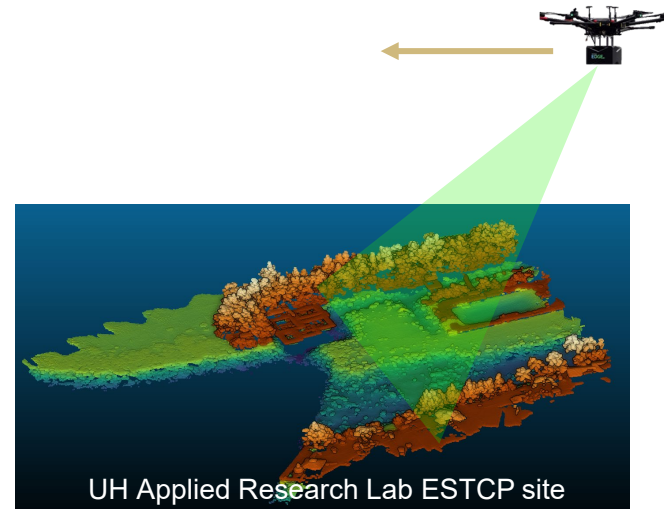
- Assess 3D LiDAR point clouds for MR applications in shallow waters (< 5 m)
- Determine position accuracy, resolution, and uncertainties in the system relevant to munition detection and classification including water effects

Project Progress and Results

- Surrogate uncertainty quantification model developed for sensitivity analysis
- Calibration targets established for empirically estimating resolution
- End-to-end System modeling to enable observing system simulation experiments (OSSEs) and recommend operational conditions

Technology Transition

- Enhance ESTCP field capabilities for MR remediation
- Foster new commercial LiDAR capabilities for DoD/ DOE applications
- Benefit user community with observing system simulations



Plain Language Summary

- What problem are you addressing?

Detection, classification, and localization of proud unexploded ordnance (UXOs) in shallow waters of 0-5 meters depth.

- What are you trying to achieve and how are you doing it?

Develop quantitative assessment and analysis tools to evaluate and advance a drone-based, scanning, topographic-bathymetric LiDAR technology for detecting and classifying munitions in depths less than five meters.

Technical objectives are met by employing uncertainty quantification methods, developing calibration targets, advancing resolution analysis, and constructing observing system simulation experiments.

Plain Language Summary

- What are the expected outcomes and how is it advancing existing knowledge?

Successfully develop analysis tools to quantitatively determine appropriate LiDAR system requirements and environmental conditions for applying technology to munitions remedial action in shallow waters.

- What's the most impactful thing that's happened since the last time you presented your work to us?

An end-to-end model of the sensing system and sampled scene, that includes water surface and water column effects, to determine the impact of environmental conditions on Lidar resolution and object classification.

- Why is this important?

Defines resolution limits for detecting and classifying submerged proud objects.

Informs system performance and improvements for better success in munition detection, classification, and localization deployments.

Impact to DoD Mission

- How is your project advancing DoD capabilities?

Informing DoD users of the system requirements and environmental conditions necessary for effective application of the technology to detect, classify, and localize proud underwater munitions in shallow waters from above the water surface.

Publications

- Sacca, K. W., & Thayer, J. P. (2025). Empirical quantification of topobathymetric lidar system resolution using modulation transfer function. *Earth and Space Science*, 12, e2024EA004098. <https://doi.org/10.1029/2024EA004098>.
- Greenstein, M. (2024), A Comprehensive Analysis of Polygon Mirror Scanning for a UAV Based Bathymetric LiDAR, Master of Science Thesis, Ann and H.J. Smead Aerospace Engineering Sciences Department, University of Colorado at Boulder.
- Sacca, K. W., J. P. Thayer, G. Thompson, B. Garby, M. S. Greenstein, and A. K. Wise (2023), Water column compensation using submersible calibration targets for 3D LiDAR bathymetry, AGU Fall 2023 conference, San Francisco, Dec 11-15, 2023, poster presentation B31F-2169.
- Wise, A. K., K. W. Sacca, and J. P. Thayer (2023), LiDAR point-cloud uncertainty quantification for earth science using generalized polynomial chaos expansion, AGU Fall 2023 conference, San Francisco, Dec 11-15, 2023, poster presentation EP13F-1842.

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- Thayer, J. P. (2023), UAS-based Lidar System for Shallow Water Munitions Response, DoD Energy & Environment Innovation Symposium, Washington DC, Nov 28 – Dec 1, 2023, oral.
- Thayer, J. P., K. W. Sacca, A. K. Wise, and G. Thompson (2023), Quantitative assessment of LiDAR technology for detection, localization, and classification of underwater munitions in shallow waters, DoD Energy & Environment Innovation Symposium, Washington DC, Nov 28 – Dec 1, 2023, poster presentation.
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Publications

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- Thayer, J.P., Sacca, K.W., Wise, A. K., and Thompson, G. (2022), Quantitative assessment of LiDAR technology for detecting, localizing, and characterizing, underwater munitions in shallow waters, SERDP/ESTCP Symposium, Nov 29 – Dec 2, 2022.
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- Wise, A.K., Sacca, K.W., and Thayer, J.P. (2022), LiDAR Uncertainty Quantification for Topo-Bathymetric Earth Science using Generalized Polynomial Chaos Expansion, American Geophysical Union Fall Meeting, Dec. 2022.

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- Sacca, K.W., and Thayer, J.P. (2023), Water column compensation using submersible calibration targets for 3D LiDAR bathymetry, IGARSS, Pasadena, CA July 2023.
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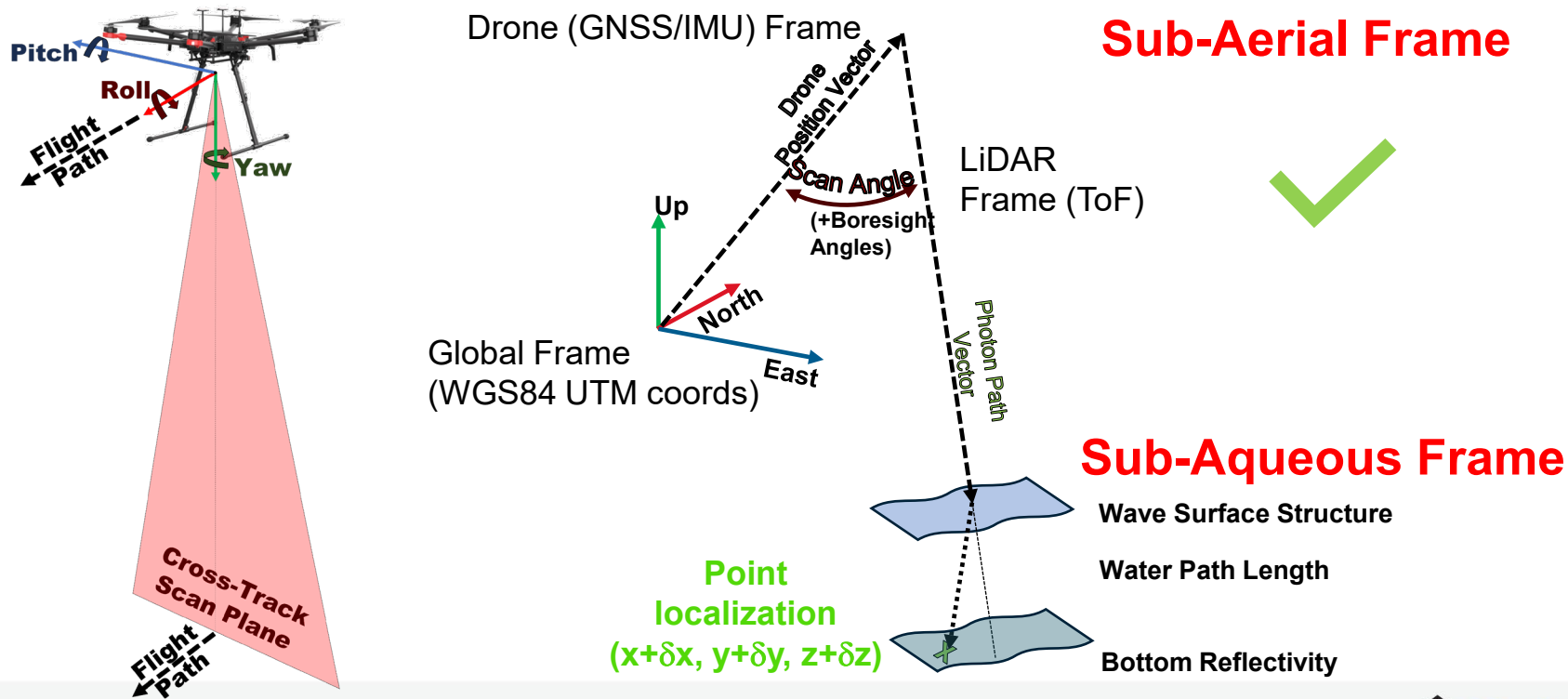
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Acronym List

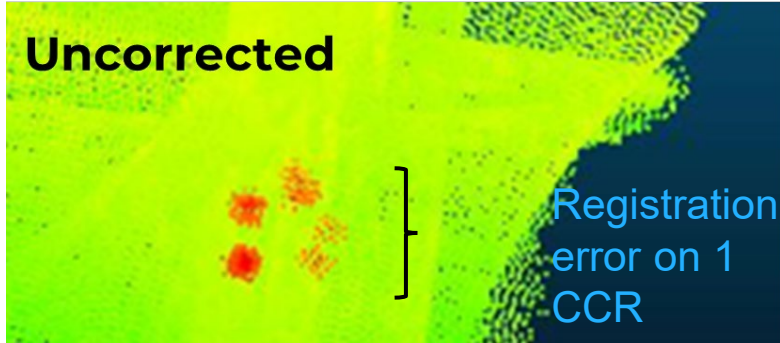
CCR – Corner Cube Reflector
CONOPS – Concept of Operations
CU – University of Colorado
DoD – Department of Defense
gPCE – generalized Polynomial Chaos Expansion
GPS – Global Positioning System
IFOV – Instantaneous Field Of View
IMU – Inertial Measurement Unit
IR – Infrared
LiDAR – Light Detection and Ranging
MTF – Modulation Transfer Function
MR – Munitions Response

NEM – Noise-Equivalent Modulation
NTU – Nephelometer Turbidity Units
OSS – Orion Space Solutions
OSSE – Observing System Simulation Experiments
PSF – Point Spread Function
SERDP – Strategic Environmental Research and Development Program
TOI – Targets of Interest
UAS – Unmanned Aerial System
UQ – Uncertainty Quantification
VLOS – Visible Line Of Sight
WMO – World Meteorological Organization
UXO – Underwater Unexploded Ordnance

Localization: Point Uncertainty Quantification

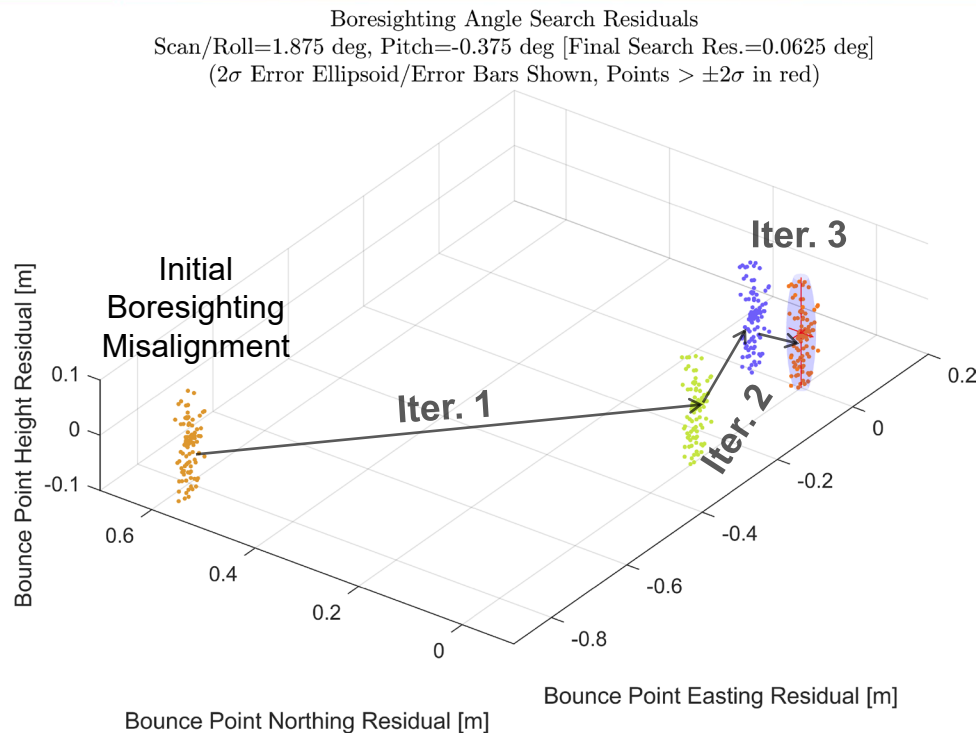


gPCE UQ: Boresighting



- Boresighting correction for measurement co-registration remains difficult & manual
- Measurements of ground control points of known position can assist
- gPCE can be used to automate modeling and solve for boresighting angles

gPCE UQ: Automatic Boresight Correction

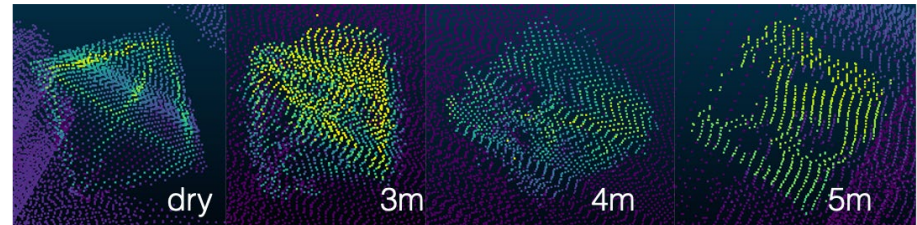


- gPCE UQ allows direct modeling of boresight angle bias on target location
- Determination of minimum error boresight correction angles can be done using either:
 - Control points with known locations (implemented)
 - Multiple overflights of the same object

Topobathy LiDAR Calibration Targets

- Empirically evaluated MTF using compact point / line source targets
 - In 3D point clouds, **height** differences provide **contrast** to resolve features
 - **Retroreflector targets** provide best case detectability under water

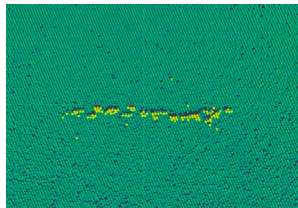
- Submerged MTF targets **quantify the point spread function** due to random water surface and column effects



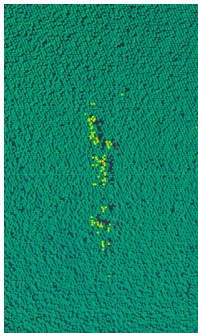
3D bathymetric point clouds from Panama City campaign

Methods - MTF

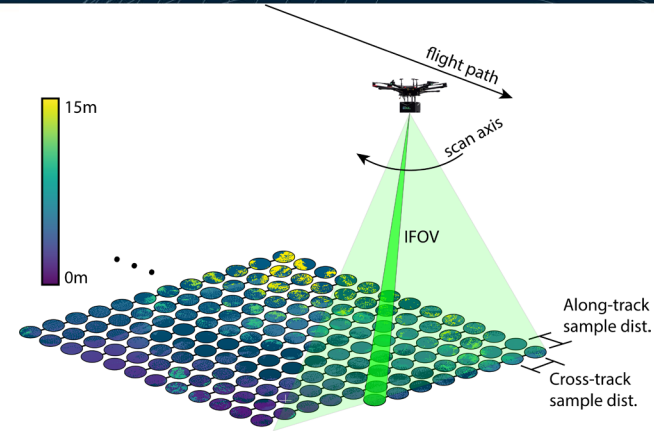
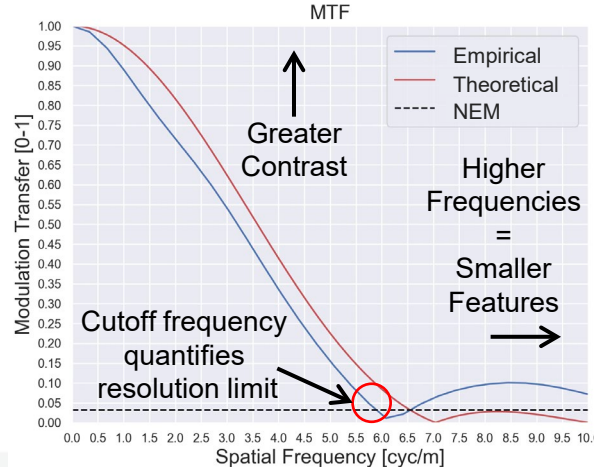
- MTF can be measured via point spread function
- Long retroreflective line targets are ideal compact targets for bathymetry



Along-track MTF target point cloud



Across-track MTF target point cloud



- Must have overlapping samples to employ MTF analysis
- Greater point densities improve PSF fits, thereby improving accuracy of MTFs

Mid-Project Assessment Recommendations

- Improve concept of operations (ConOps)
- Improve point distribution and # of viewing angles on scene/targets
- Reduce noise in vertical dimension
- Improve pointing solution
- Improve boresighting correction
- Reduce projected laser spot size
- Improve understanding of sea state effects

Specifications

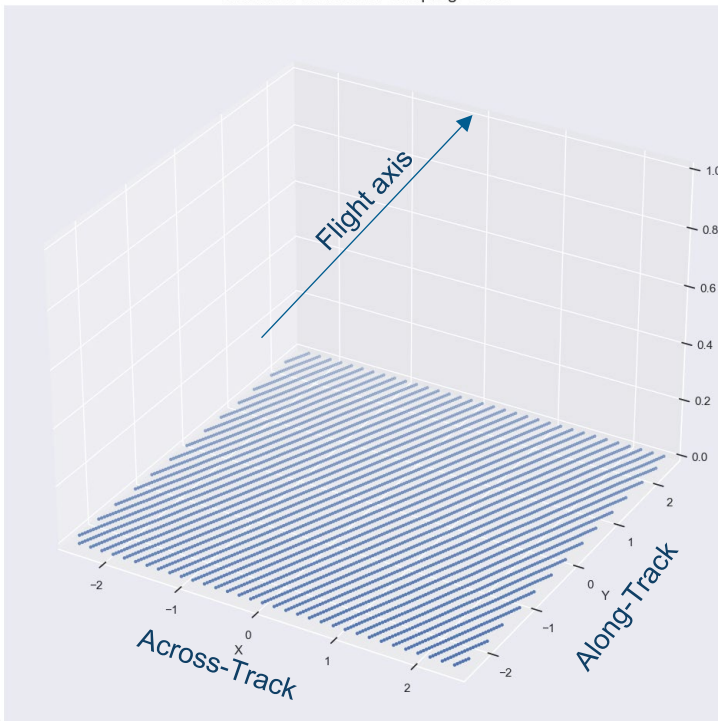
- **Fly lower and slower to improve along-track ground resolution.**
 - Maintain a steady flight speed of 2.0 m/s at 15.0 meters above ground level with 50% side lap of consecutive swaths. At 15.0 meters above ground level and with a 30-degree scan range through nadir, the projected swath width is 7.5 meters. This provides 40 scans per one meter of travel and along-track sampling of 27 mm.
- **Increase beam collimation to project a smaller ground spot.**
 - Reduce laser beam divergence exiting the unit to < 1.0 mrad to produce a ~15 mm diameter ground spot at 15-meter flight altitude.
 - Consider flying lower to reduce spot size and increase sample resolution
- **Increase laser shots within scan range to improve across-track ground resolution.**
 - At the recommended flight speed and altitude, design scan in the across-track direction to have an effective across-track sampling of 19 mm at ground level (25 mm at 3 m depth) ensuring four samples across a 100mm diameter target.

Specifications

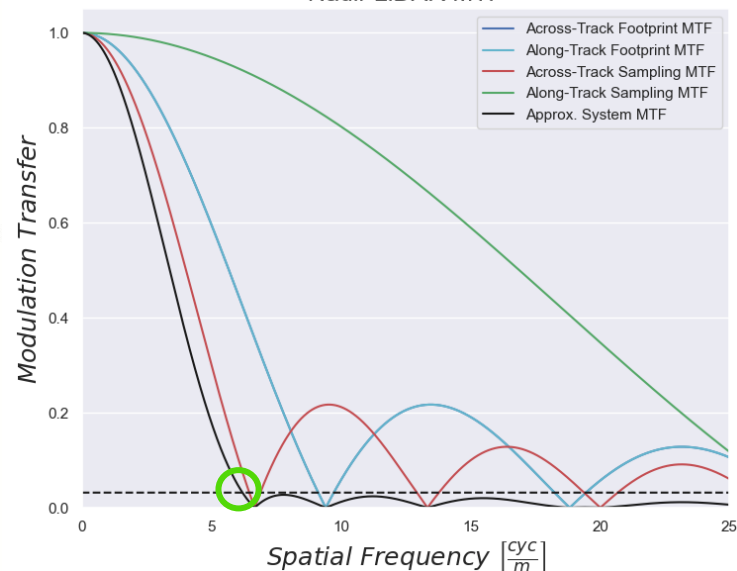
- **Improve pointing and boresighting solution to better define spot location on the ground.**
 - Pointing and boresighting solution should achieve an uncertainty better than 0.05 degrees in post processing to reduce image blur. At 15.0 meters altitude, 0.05 degrees of uncertainty translates to approx. 7.5 mm.
- **Reduce uncertainty in estimating the vertical dimension (Z) in the point cloud.**
 - Standard deviations < 30 mm in the vertical dimension are necessary to improve contrast between seafloor and proud targets. This would effectively reduce noise allowing for finer resolutions to be achieved.

MTF to Inform Instrument and ConOps Design

Simulated Instrument Sampling - Base



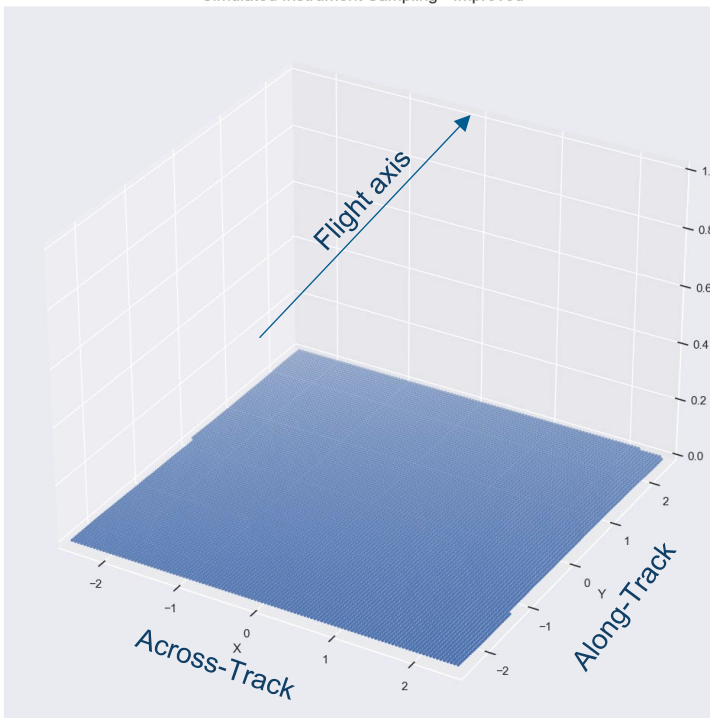
Nadir LiDAR MTF



Dry cutoff @ 80mm

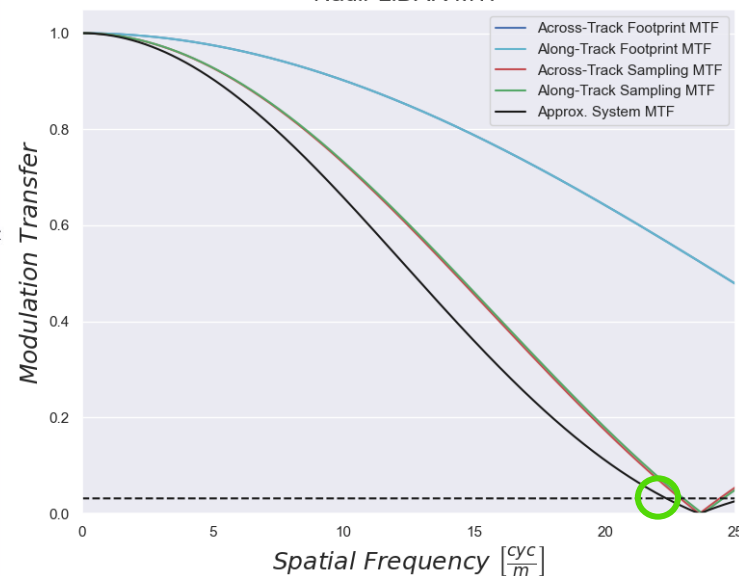
MTF to Inform Instrument and ConOps Design

Simulated Instrument Sampling - Improved



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Nadir LiDAR MTF



Water surface introduces another MTF component to the overall system MTF

Dry cutoff @ 23mm

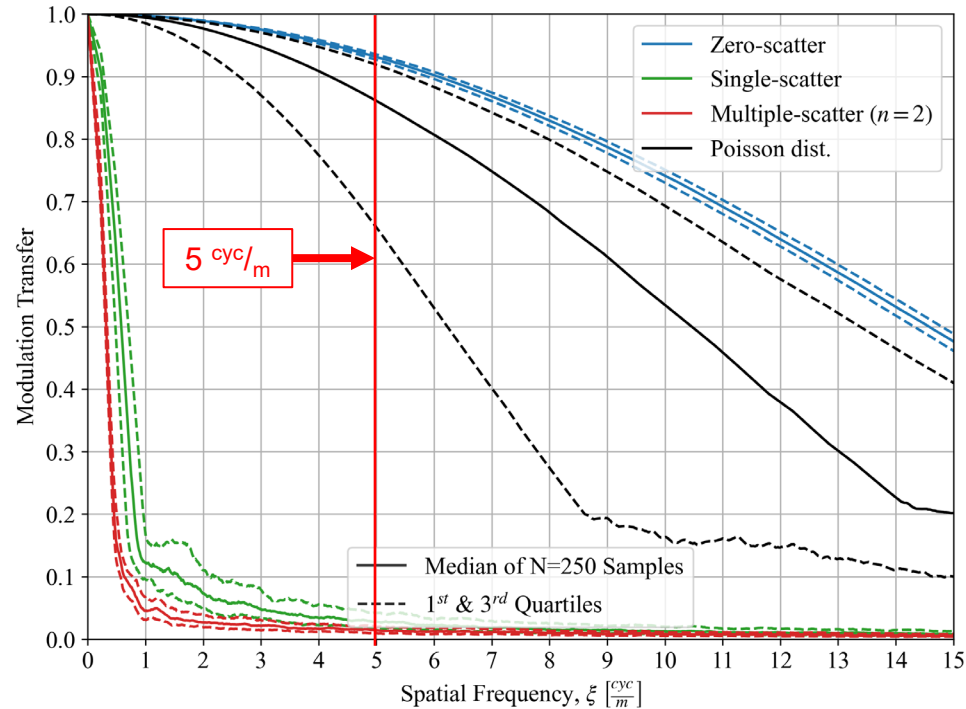
Results – OSSE: Change in Scatter Order

OSSE fixed parameters:

- WMO 0 (flat) water surface
- “Clear” water ($a=0.114 \text{ [m}^{-1}\text{]}$, $b=0.037 \text{ [m}^{-1}\text{]}$)
- Depth = 3m
- “Improved” instrument
- Zero-scatter and Poisson demonstrate high resolvability at 5 cyc/m (100mm targets)
- Single- and multiple-scattering do not

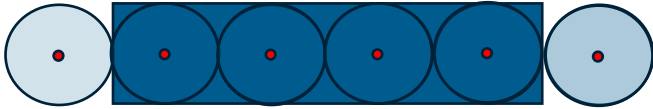
Free Parameter	
Sea State	
Turbidity	
Scatter Order	✓
Depth	
Instrument	

Poisson distribution is most-realistic for natural waters, result shows high resolvability of 100mm targets



Point Sampling Across Targets

Spot size and sample distance are equal (25 mm) = 4pts across 100 mm object



Spot size twice the sample distance (50 mm) = 5 pts across 100 mm object

Spot size broadens the actual target effectively degrading resolution even though point density is increased

