Comparing LiDAR and Acoustic Bathymetry Using TPU and the CUBE Algorithm

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- Fugro Pelagos collected data with the SHOALS-1000T bathymetric LiDAR system for NOAA's Office of Coast Survey.

- Objectives:
  - Study the Total Propagated Uncertainty (TPU) for the SHOALS-1000T system.
  - Examination target detection capabilities.

Overview

- Previous bathymetric LiDAR target and accuracy analysis:
  - Idealized control multibeam dataset (absolute reference)
  - All error attributed to LiDAR dataset
  - Subjective analysis
- If uncertainty is known, use tools such as CUBE
  - Derive TPU Model for Bathymetric LiDAR depths
  - Build CUBE surfaces
  - Compare how each datasets describe the same seafloor and targets

Survey Parameters

Shilshole Bay, Puget Sound

2005 – Manufactured Targets placed on seafloor

2005 - Reson 8101Multibeam acquired

2007 – SHOALS-1000T Hydrographic LiDAR acquired

- August 27 to 29, 2007
- Bathymetric LiDAR data
- Digital Aerial Photography
- GPS Ground Control and tide gauge data
- From MHW to 20m Water Depth
- 20% overlap

Survey Area

arget ID	

x1x1m 7 40 15.25N 22 23 23.10W 2.5

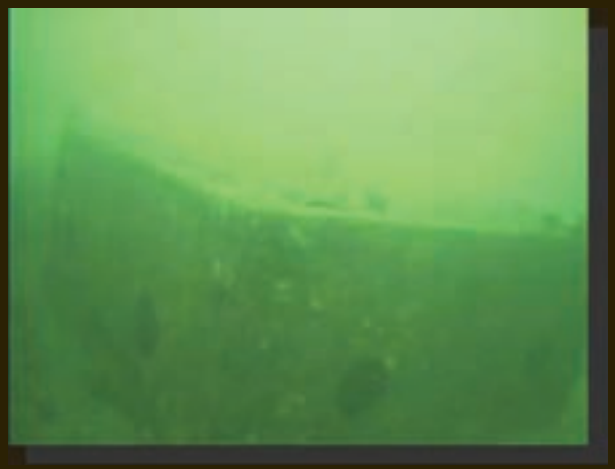
Seafloor Targets

2005

2m x 2m x 2m Target

2m x 2m x 1m Target

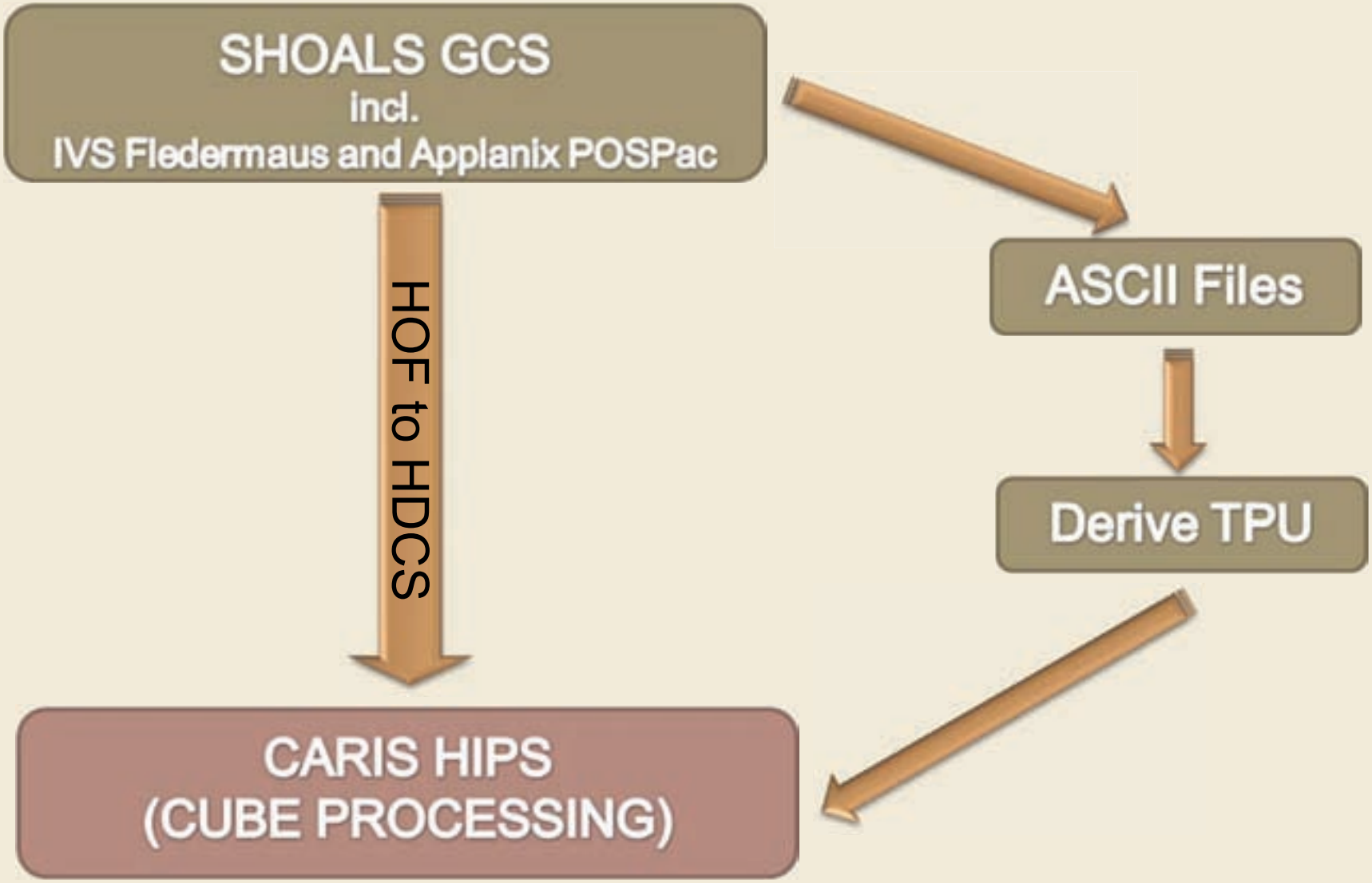
2007



Survey acquisition variables

- Spot Spacing (2x2m, 3x3m, 4x4m, 5x5m)
- Flight Altitudes (300m, 400m)
- Line Directions (Same or opposing)
- Times of Day (Day, Night)
- Coverage (100%, 200%, 300%, 400%, 500%)

General LiDAR Processing Flow



- **TPU**
  - the sum of all random and systematic uncertainties in the measurement process, including the uncertainty contribution of all sensors embedded in the SHOALS-1000T

- **Analytical TPU**
  - determine each sensor uncertainty a priori
  - may not be possible for LiDAR system
    - complex physical interaction of laser pulse with sea surface, sea water and seafloor.

Need an Alternative Method

Depth Variance as Proxy for Analytical TPU

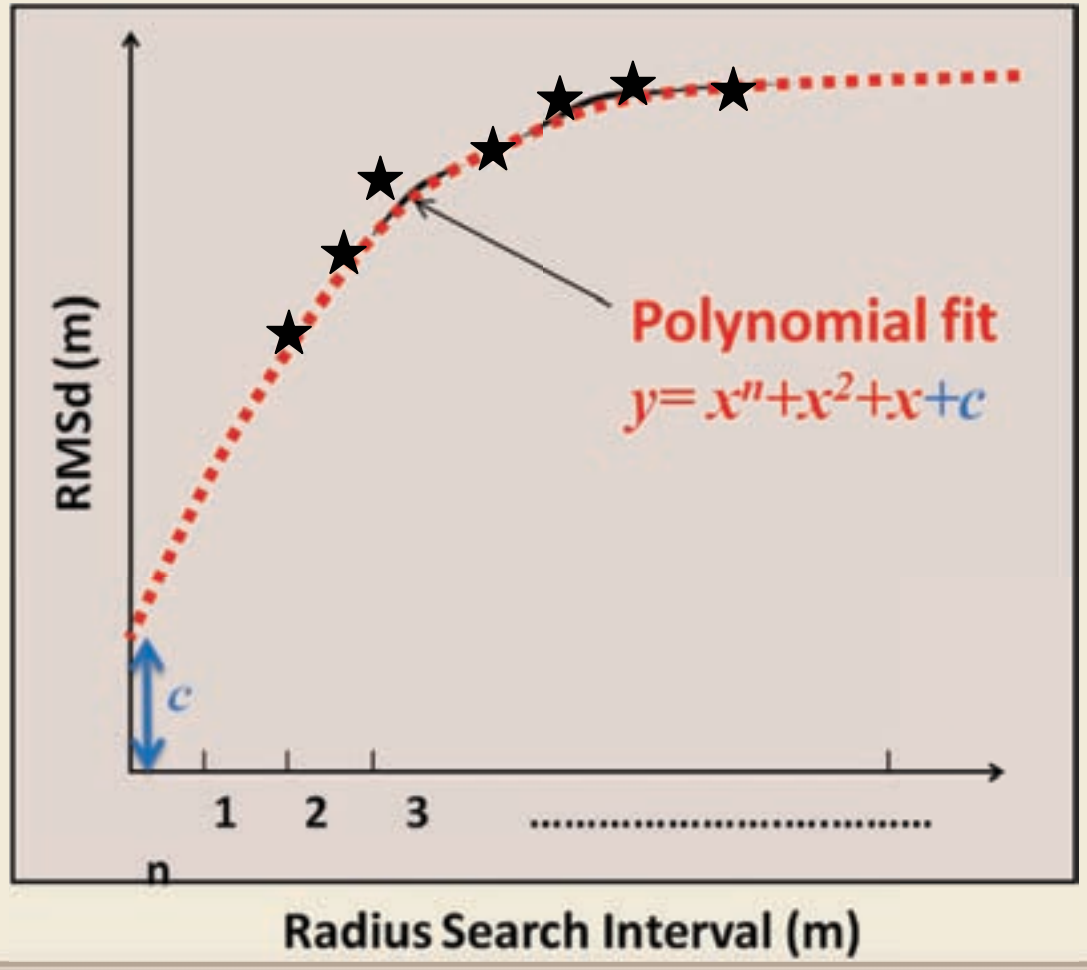
- Determination of depth variance

- LiDAR bottom detection dependent on depth
  - Analysis carried out on depth ranges split in 2m increments (1-3m, 2-4m, …….., 14-16m, 15-17m)

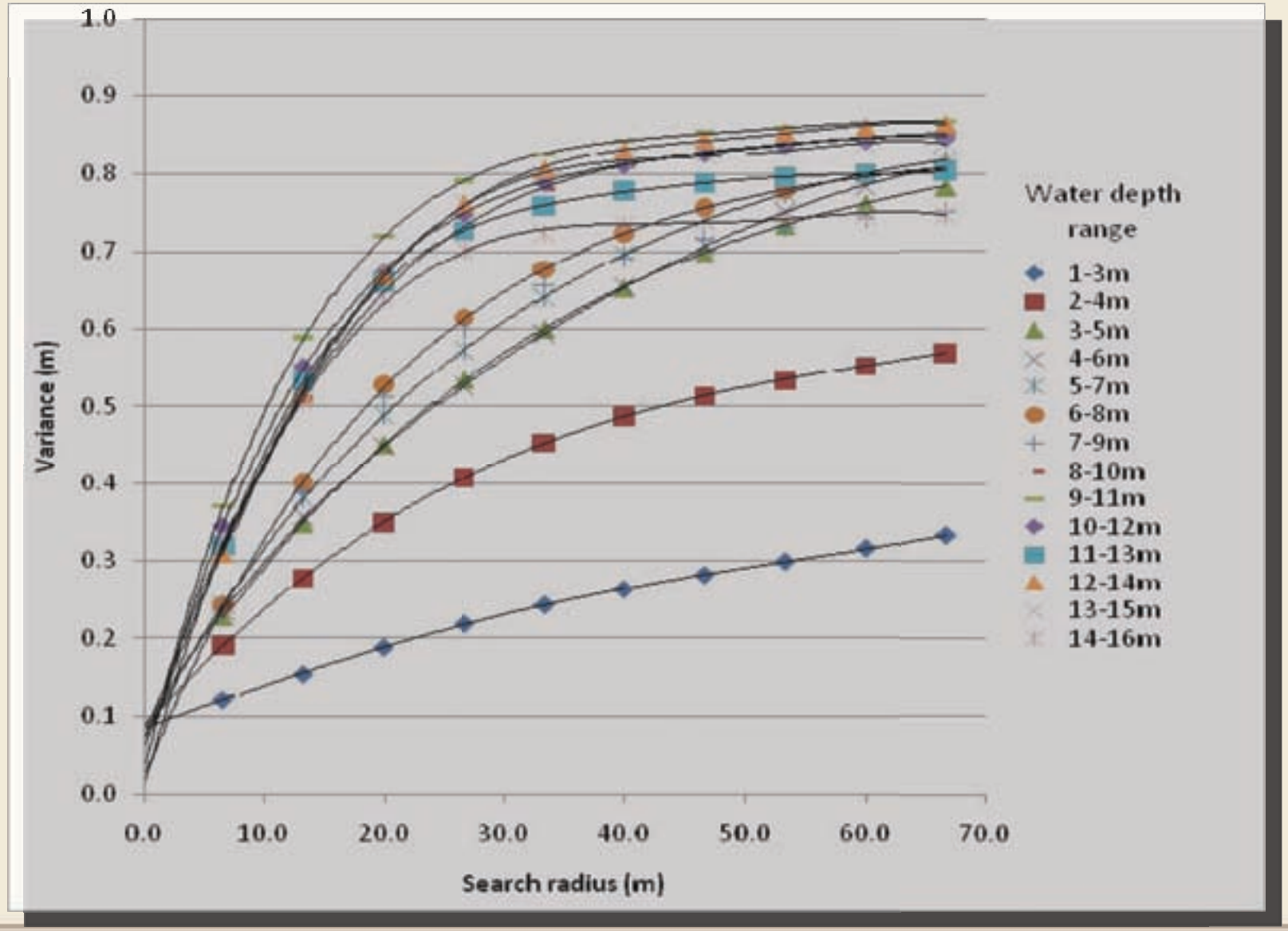
- For each Range:
  - Variance estimated as a function of horizontal search radius
  - Variance is expected to grow as the radius increases

Variogram for Determining Node Variance

- Variance at node is determined by constant *c* in polynomial equation

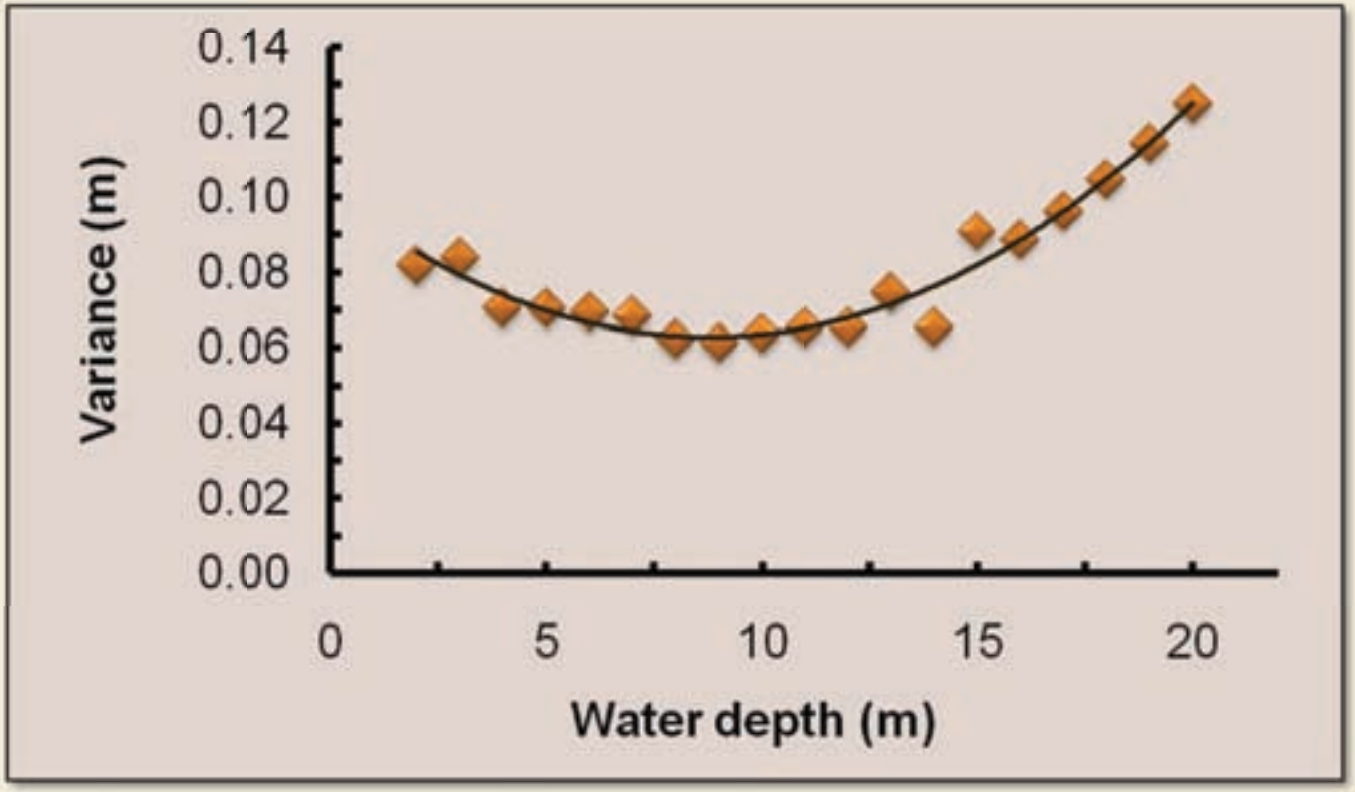


Variance Function for Each Depth Interval



Variance as a Function of Water Depth

- Fluctuates between 0.07 to 0.09m to 15m Water Depth
- Grows to 0.125m at 20m Water Depth



- Calculated Variance represents:
  - Total seafloor variance σ^2_T
    - Sensor variance (incl. Tides)
    - Seafloor (slope and roughness)

$$\sigma^2_m = \sqrt{[(\sigma^2_T)^2 - (\sigma^2_S)^2]}$$

σ^2_m = Sensor variance

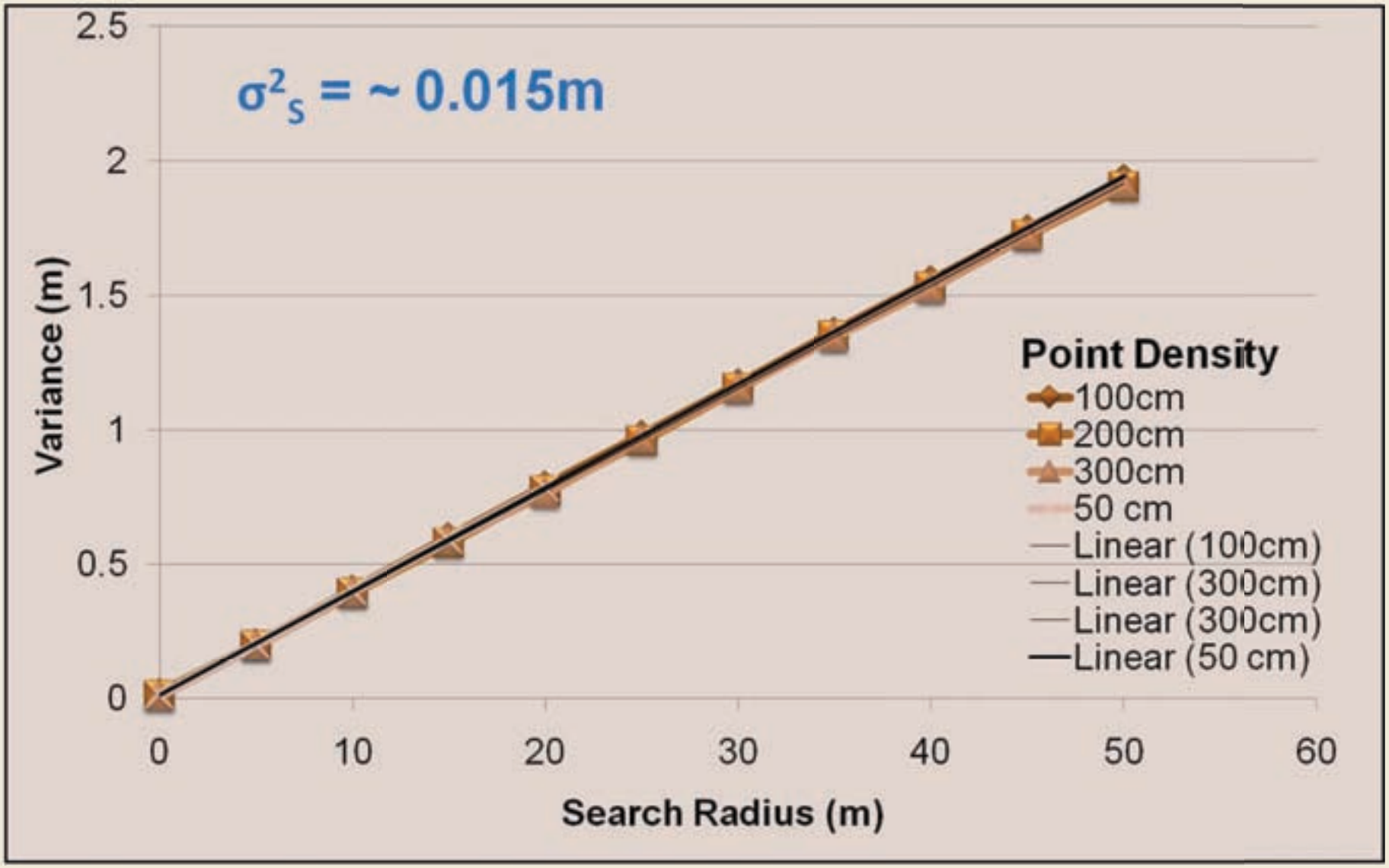
σ^2_T = Total Variance

σ^2_S = Seafloor Variance

Removal of Seafloor Variance

- Morphology Trend Observed in Multibeam
  - Slope gradient
  - Amplitude & frequency of general bottom roughness
- Used to Create a Synthetic Surface
- Calculate Node Variance for Synthetic Surface
  - Different point densities
  - Account for any sub-sampling effects

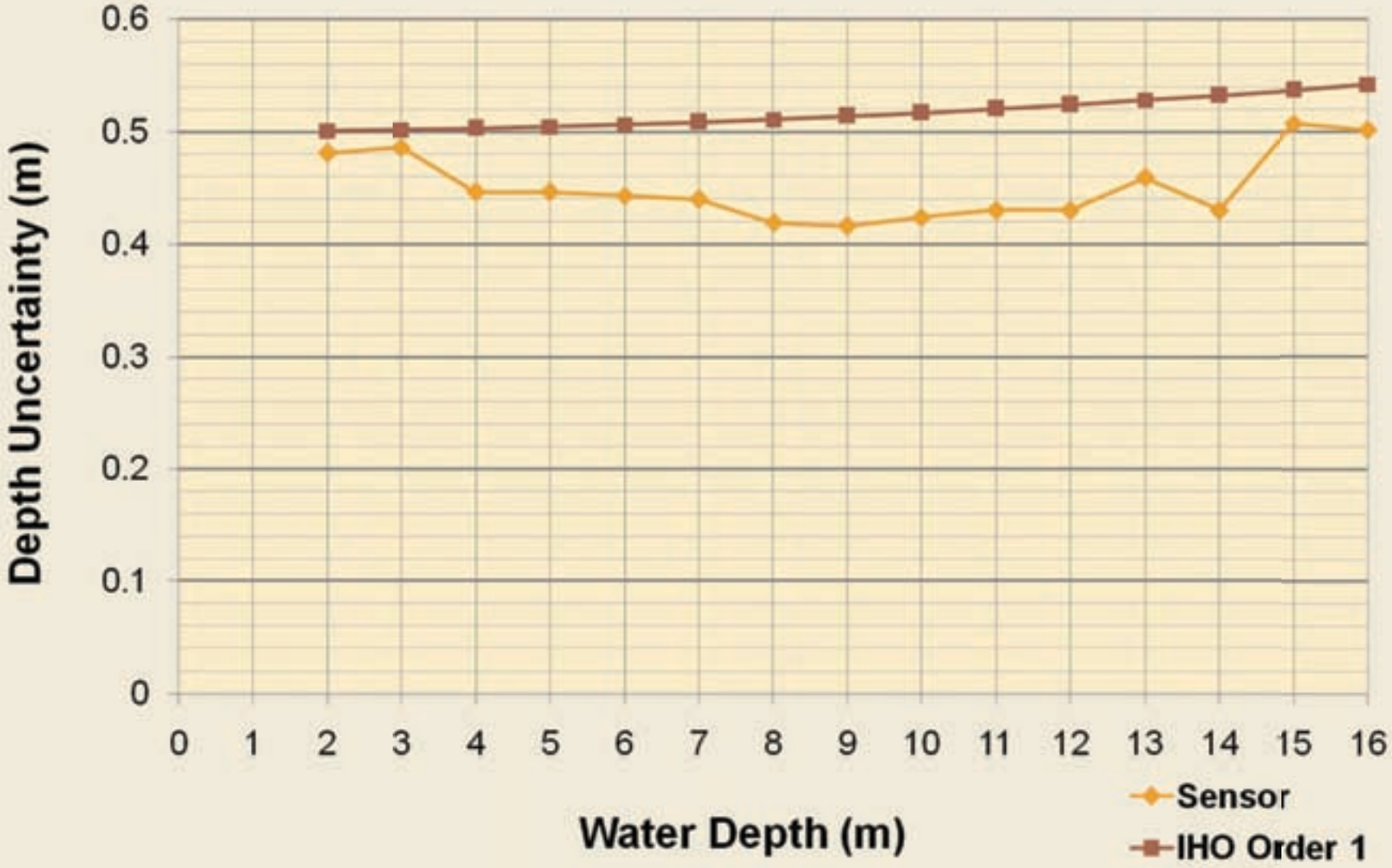
Variance of Synthetic Seafloor at Varying Point Density



Final Sensor Variance & TPU Compared to IHO Order 1

Depth (m)	Total Variance	Sensor Variance	Sensor StDev (TPU)	Sensor 2-StDev	IHO Order 1 (2-StDev)
2	0.083	0.058	0.240	0.481	0.501
3	0.085	0.059	0.243	0.486	0.502
4	0.072	0.050	0.223	0.446	0.503
5	0.072	0.050	0.223	0.446	0.504
6	0.071	0.049	0.222	0.443	0.506
7	0.070	0.048	0.220	0.440	0.508
8	0.064	0.044	0.210	0.419	0.511
9	0.063	0.043	0.208	0.416	0.514
10	0.065	0.045	0.212	0.424	0.517
11	0.067	0.046	0.215	0.430	0.520
12	0.067	0.046	0.215	0.430	0.524
13	0.076	0.053	0.230	0.459	0.528
14	0.067	0.046	0.215	0.430	0.532
15	0.092	0.064	0.253	0.507	0.537
16	0.090	0.063	0.250	0.501	0.542

Sensor Uncertainty v IHO Order 1

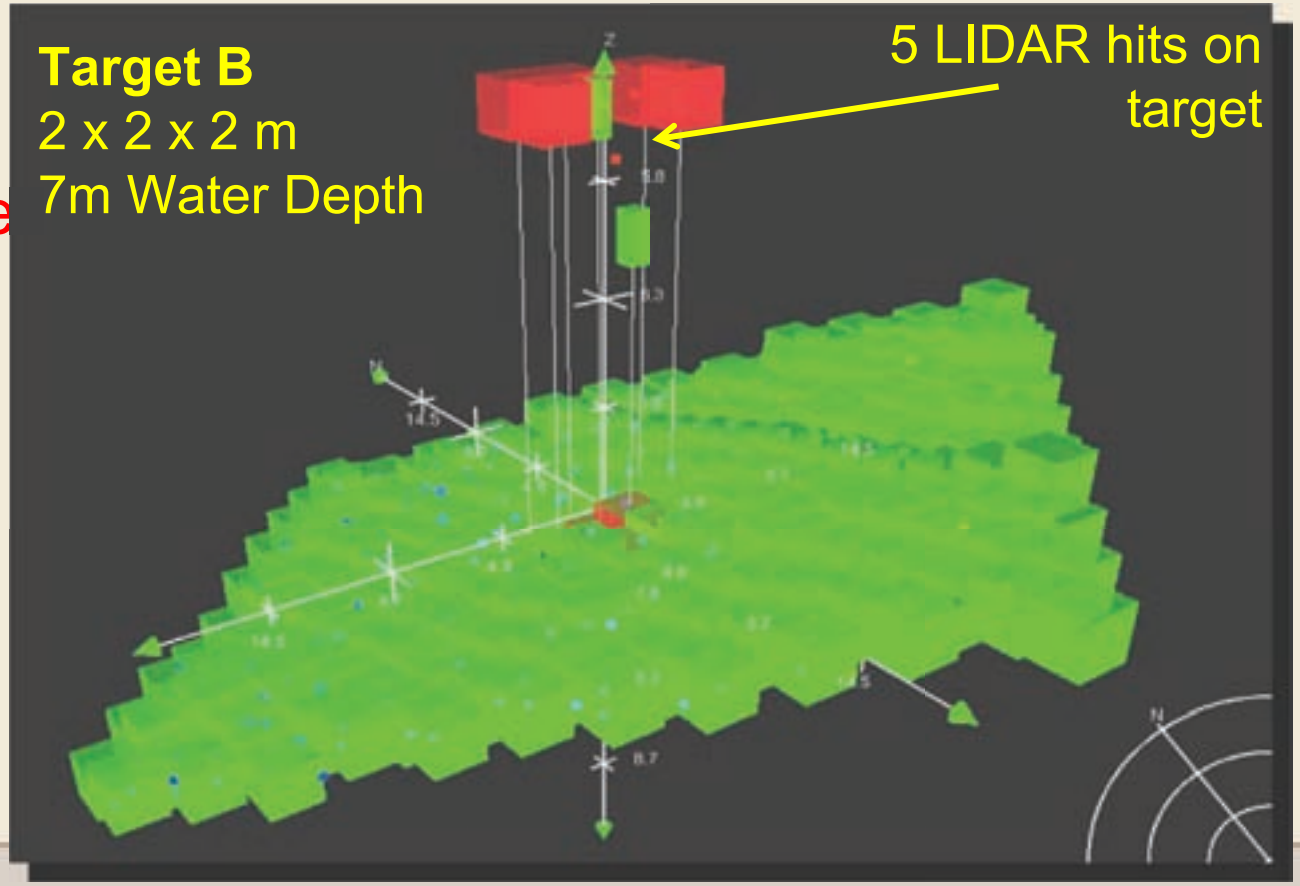


Notes on TPU Derivation Method

- TPU is valid for the water conditions at the time of survey
- Bathymetric LiDAR Uncertainty will vary depending on:
  - Local water column conditions
  - Seafloor reflectance
  - However, model can be applied to different locations with similar environmental conditions
- One TPU model does not fit all
  - Shilshole Bay model can be used in SE Alaska but not necessarily in Florida.

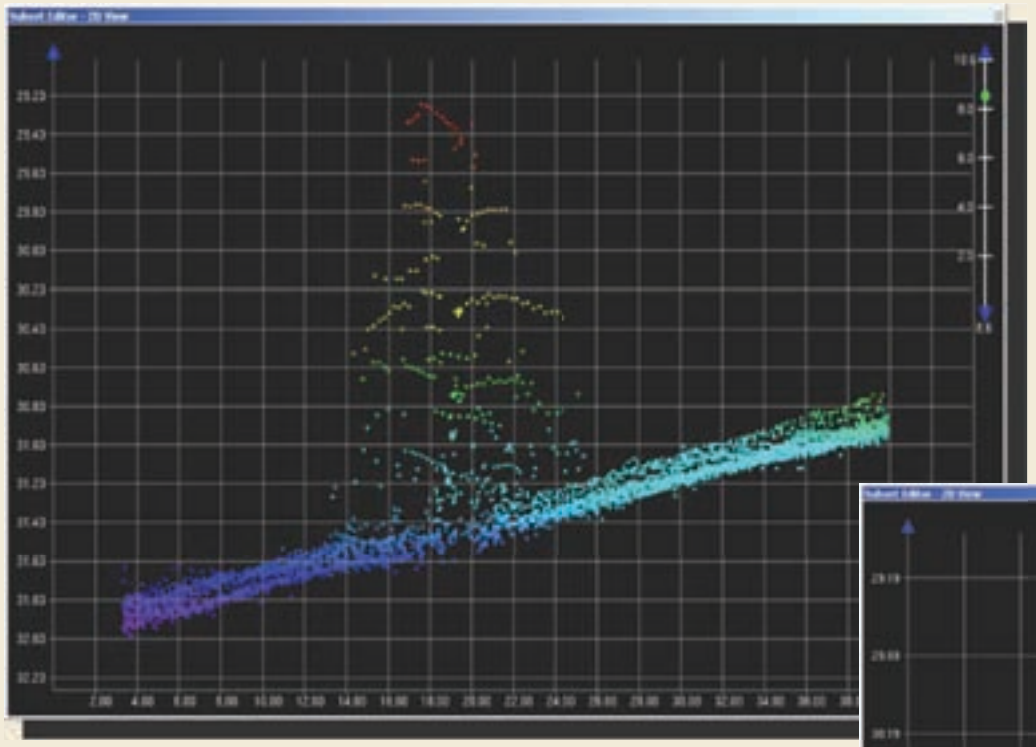
- Combined Uncertainty and Bathymetry Estimator (CUBE)
  - algorithm developed at the University of New Hampshire (Calder and Mayer, 2001) to validate soundings based on the understanding of uncertainty.
  - transforms randomly spaced data points to regularly spaced grid of depth estimates
  - For each grid node:
    - Depth
    - Uncertainty (from TPU)
    - Number of hypotheses
    - Hypothesis strength
  - Designed to aid in processing of dense multibeam datasets

- CUBE surface with LiDAR data
  - 3x3m, 400% coverage
  - Likely hypothesis in green: relatively weak
  - Alternate hypothesis in re

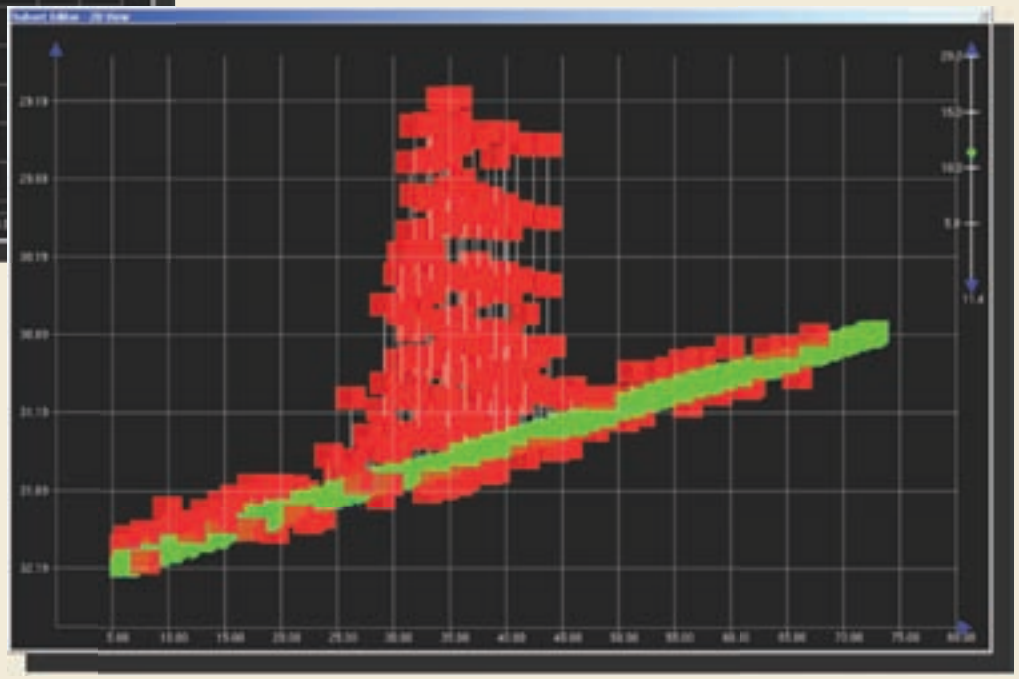


CUBE with LiDAR Datasets

- CUBE selected a correct primary hypothesis
  - Relatively sparseness of LiDAR data, likely candidates
- However hypothesis over targets usually weak
  - They can still be filtered out in automatic editing for final surface creation
- Fine-tuned CUBE parameters still required
  - Provide stronger primary hypothesis on targets



Multibeam Data Over Target B



CUBE Hypotheses

CUBE with Mutlibeam

- LiDAR data have few chances as primary hypothesis when compared to multibeam datasets of comparable uncertainty.

- Refinement of CUBE parameters is required for multibeam processing as well.

- Until then, fair comparison between the two datasets remains elusive

Conclusions

- TPU can be estimated for LiDAR depth intervals through **variance node analysis**
- Analysis can be performed over a small control area in water conditions very similar to the actual main survey area, and therefore could be calculated on a **project-by-project**, or **area-by-area** basis.
- This methodology for calculating TPU should be further refined and automated with the use of formal kriging techniques.
- At the time of writing, CUBE has not been successfully used to compare the LiDAR and multibeam datasets. However the authors feel that with further effort, particularly in choosing suitable CUBE parameters for hypothesis selection, this can be accomplished.

Thank you