Modeling uncertainty in lidar-derived NOAA shoreline

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JALBTCX 2010
Mobile, AL

NOAA / NGS CMP:

- Mandate: provide accurate, consistent, up-to-date National Shoreline
- Depicted on NOAA nautical charts
  - Treated as legal shoreline by many US agencies
- Other uses:
  - Coastal management
  - Coastal science
    - Understanding and responding to threats of climate change

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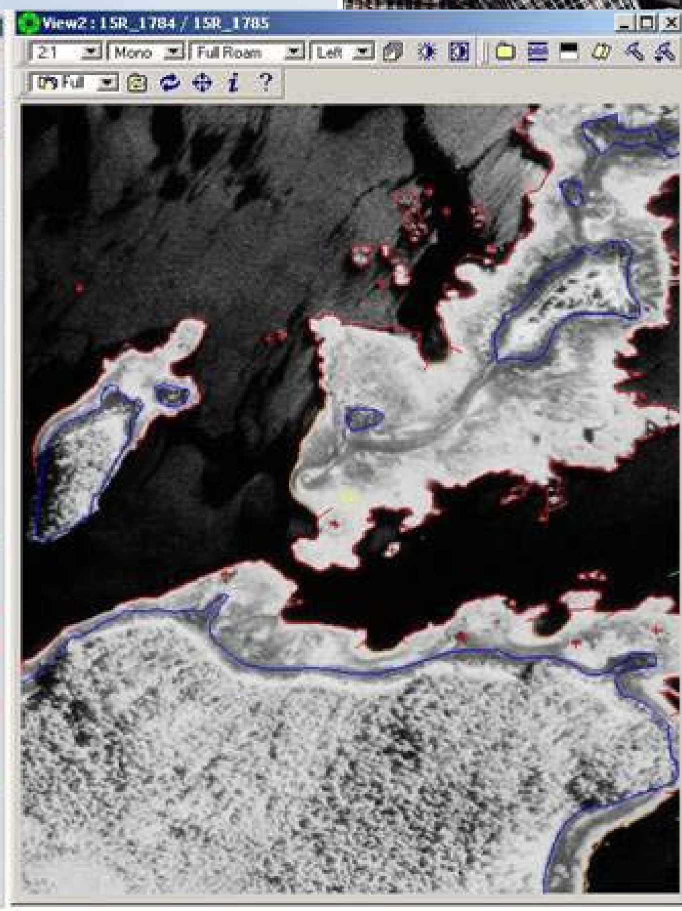
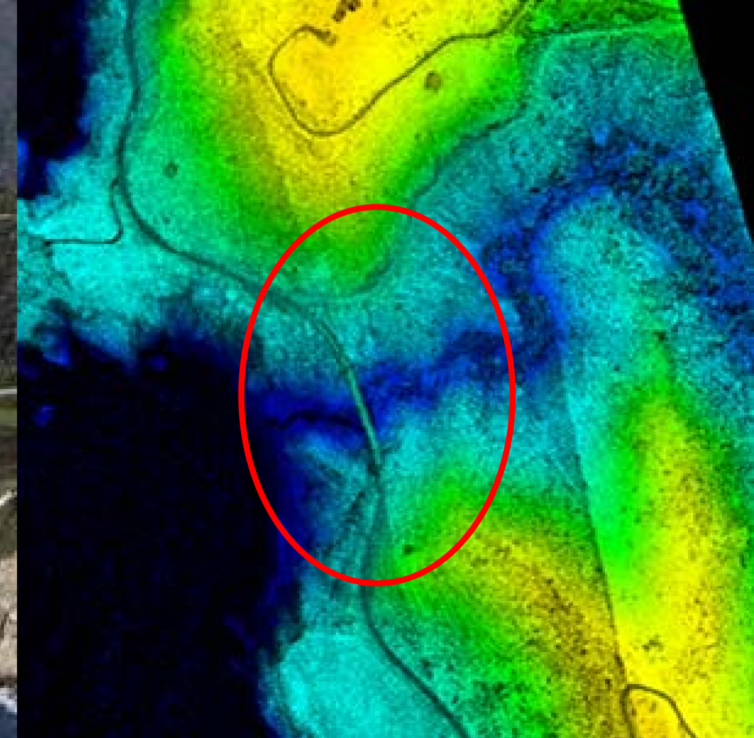
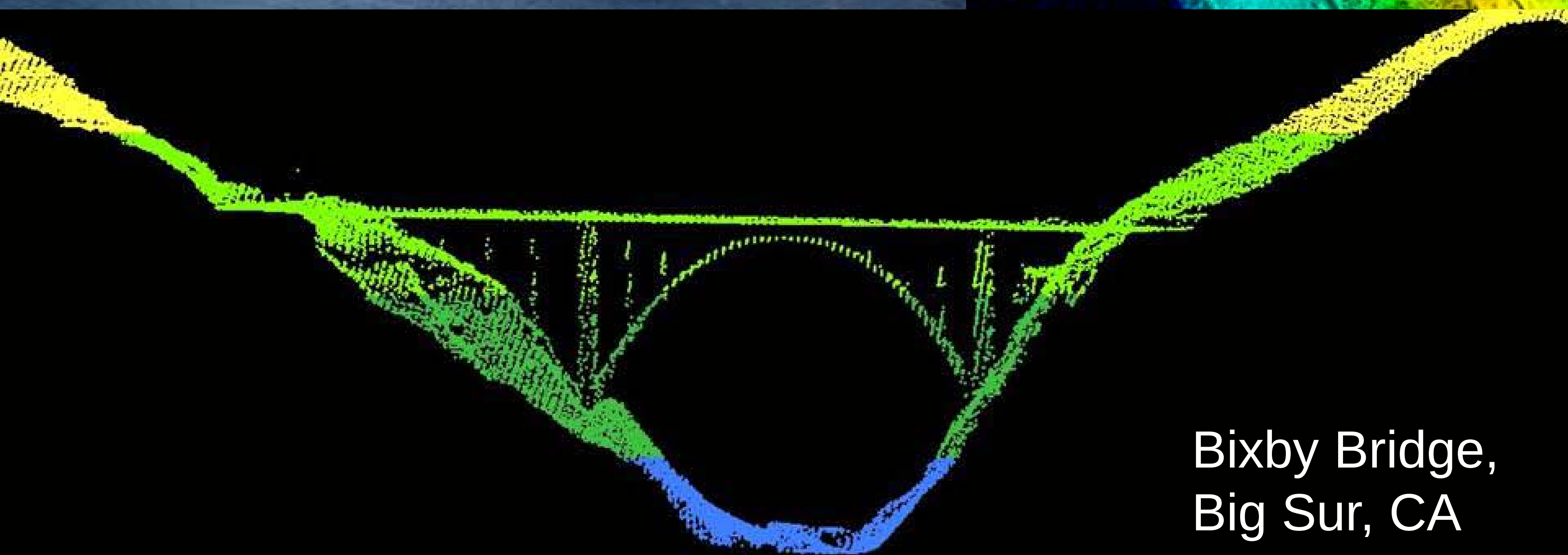
Conventional Method of Shoreline Mapping:

Stereo compilation from tide-coordinated aerial imagery



Lidar Shoreline Acquisition





Bixby Bridge,
Big Sur, CA

Benefits of Lidar-Derived Shoreline

- Provides consistent, non-interpreted shoreline
  - Minimizes variability and subjectivity
- Tide-coordination requirements are not as stringent as with photogrammetric methods
- Can (*theoretically*) enable multiple tidally-based shorelines (e.g., MHW & MLLW) to be derived from a single dataset
  - But typically very difficult in practice!

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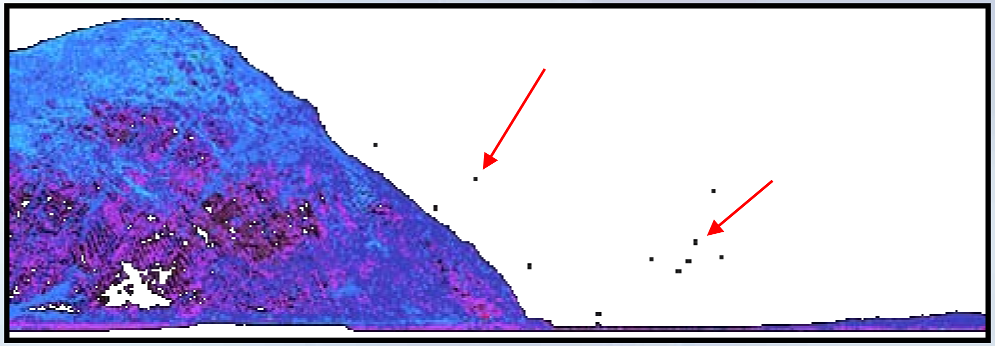
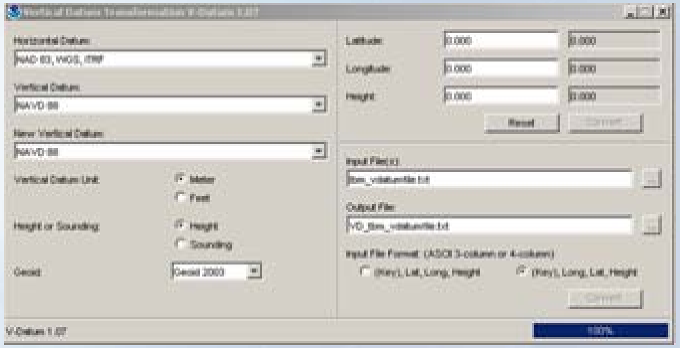
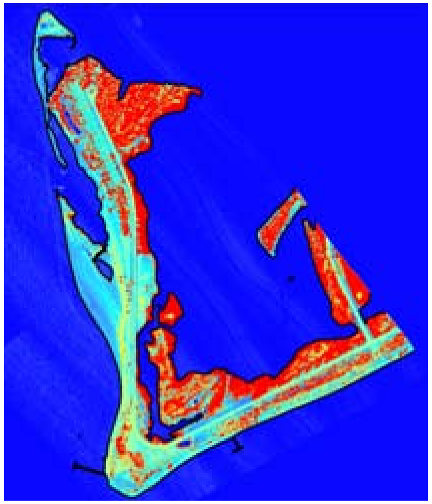
Lidar Shoreline Extraction

Edit Lidar Point Cloud



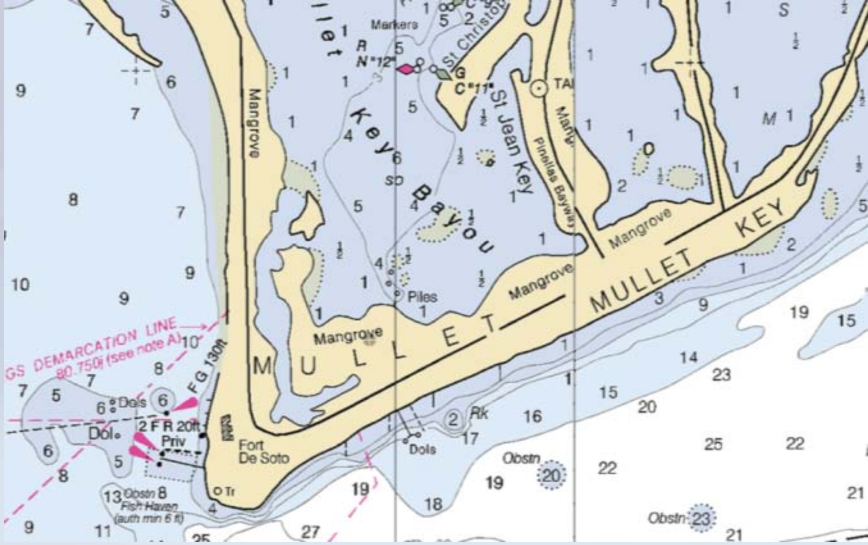


VDatum



Contour Shoreline from DEM

Editing, Attribution, and QA/QC



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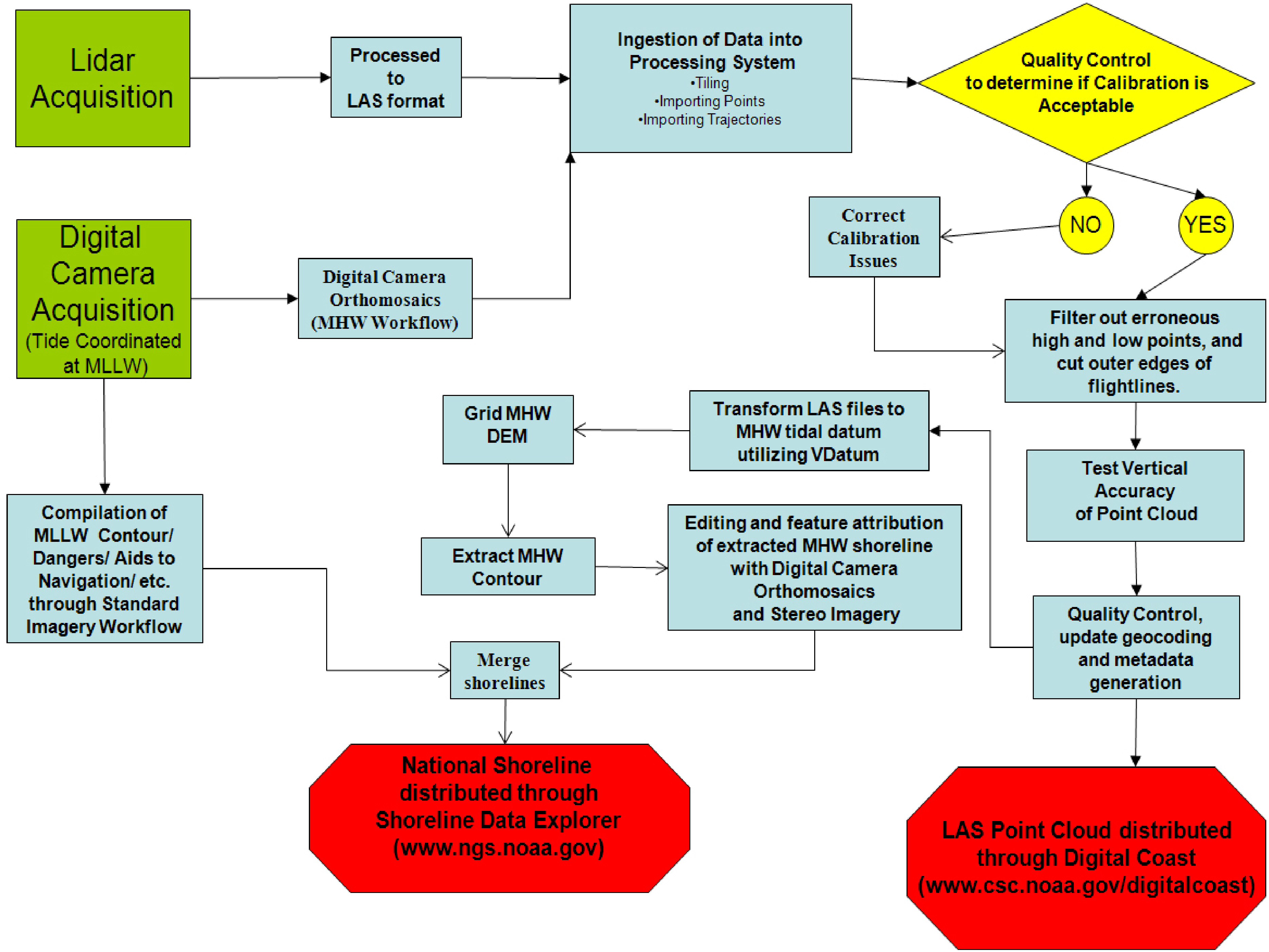

Lidar Acquisition
Processed to LAS format
Ingestion of Data into Processing System
•Tiling
•Importing Points
•Importing Trajectories
Quality Control to determine if Calibration is Acceptable
NO
YES
Correct Calibration Issues
Digital Camera Acquisition (Tide Coordinated at MLLW)
Digital Camera Orthomosaics (MHW Workflow)
Filter out erroneous high and low points, and cut outer edges of flightlines.
Grid MHW DEM
Transform LAS files to MHW tidal datum utilizing VDatum
Test Vertical Accuracy of Point Cloud
Compilation of MLLW Contour/ Dangers/ Aids to Navigation/ etc. through Standard Imagery Workflow
Extract MHW Contour
Editing and feature attribution of extracted MHW shoreline with Digital Camera Orthomosaics and Stereo Imagery
Quality Control, update geocoding and metadata generation
Merge shorelines
National Shoreline distributed through Shoreline Data Explorer (www.ngs.noaa.gov)
LAS Point Cloud distributed through Digital Coast (www.csc.noaa.gov/digitalcoast)

Lidar-Derived Shoreline Uncertainty Analysis

- Why do we need uncertainty analysis?
  - Produce accuracy metdata
  - Needed to satisfy the requirements of IHO S-44
  - Inform internal policy decisions
    - Where and when to collect lidar
    - Acquisition and processing guidelines/SOPs
    - Evaluating methods of achieving future improvements in efficiency and/or accuracy
  - Enable uncertainty analysis in downstream products
    - E.g., shoreline change rate estimates
    - Since coastal science is increasingly being used to inform policy makers, it is our responsibility, as mapping scientists, to provide good uncertainty analyses in a readily-understandable manner!

IHO S-44

- **IHO (2008)** ***S-44: Standards for Hydrographic Surveys***, **5th Ed**.: "A statistical method, combining all uncertainty sources, for determining positioning uncertainty should be adopted…The position of…the coastline and topographical features should be determined such that the horizontal uncertainty [THU] meets the requirements specified."

IHO S-44

TABLE 1
Minimum Standards for Hydrographic Surveys
(To be read in conjunction with the full text set out in this document.)

Reference	Order	Special	1a	1b	2
Chapter 1	**Description of areas.**	Areas where under-keel clearance is critical	Areas shallower than 100 metres where under-keel clearance is less critical but *features* of concern to surface shipping may exist.	Areas shallower than 100 metres where under-keel clearance is not considered to be an issue for the type of surface shipping expected to transit the area.	Areas generally deeper than 100 metres where a general description of the sea floor is considered adequate.
Chapter 2	**Maximum allowable THU 95% *Confidence level***	2 metres	5 metres + 5% of depth	5 metres + 5% of depth	20 metres + 10% of depth
Para 3.2 and note 1	**Maximum allowable TVU 95% *Confidence level***	a = 0.25 metre b = 0.0075	a = 0.5 metre b = 0.013	a = 0.5 metre b = 0.013	a = 1.0 metre b = 0.023
Glossary and note 2	***Full Sea floor Search***	Required	Required	Not required	Not required
Para 2.1 Para 3.4 Para 3.5 and note 3	***Feature Detection***	Cubic *features* > 1 metre	Cubic *features* > 2 metres, in depths up to 40 metres; 10% of depth beyond 40 metres	Not Applicable	Not Applicable
Para 3.6 and note 4	**Recommended maximum Line Spacing**	Not defined as *full sea floor search* is required	Not defined as *full sea floor search* is required	3 x average depth or 25 metres, whichever is greater For bathymetric lidar a spot spacing of 5 x 5 metres	4 x average depth
Chapter 2 and note 5	**Positioning of fixed aids to navigation and topography significant to navigation. (95% *Confidence level*)**	2 metres	2 metres	2 metres	5 metres
Chapter 2 and note 5	**Positioning of the Coastline and topography less significant to navigation (95% *Confidence level*)**	10 metres	20 metres	20 metres	20 metres
Chapter 2 and note 5	**Mean position of floating aids to navigation (95% *Confidence level*)**	10 metres	10 metres	10 metres	20 metres

Methods

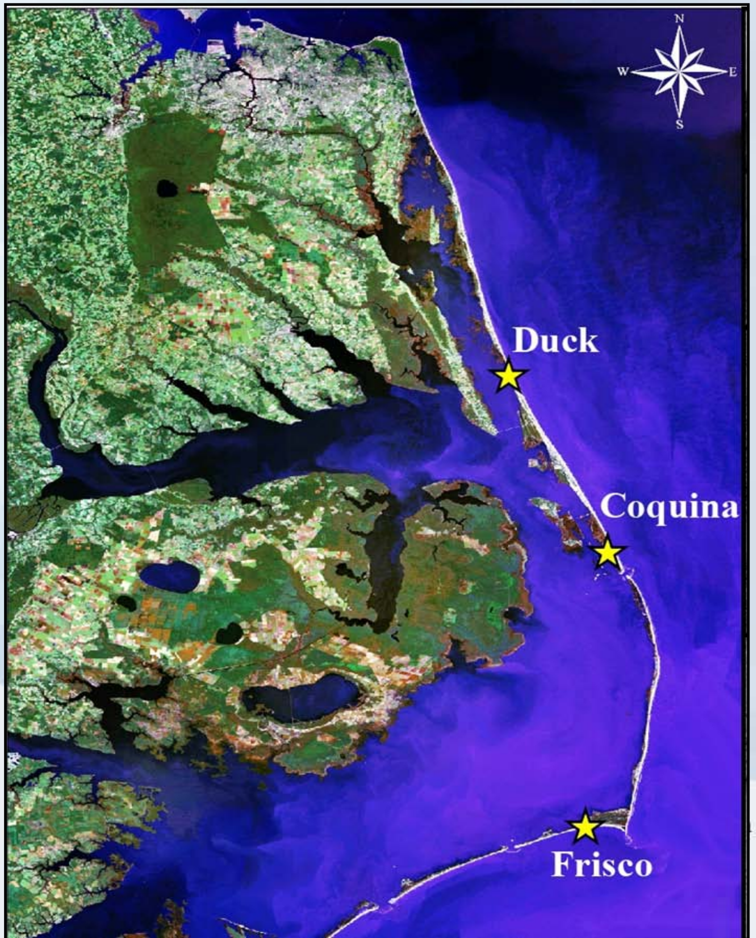
We propose and investigate two methods to approach this difficulty:

1. **Empirical Approach**: field survey provides reliable estimates of uncertainty based on observations tied to TBMs and NSRS with high-precision integrated GPS and laser-level system.
2. **Stochastic Approach**: Monte Carlo simulation of the product construction process that allows us to estimate the plausible variation of the observed product shoreline, given what we know about the observations that are used to derive it.

Study site: NC Outer Banks

Airborne Survey: Spring, 2008:

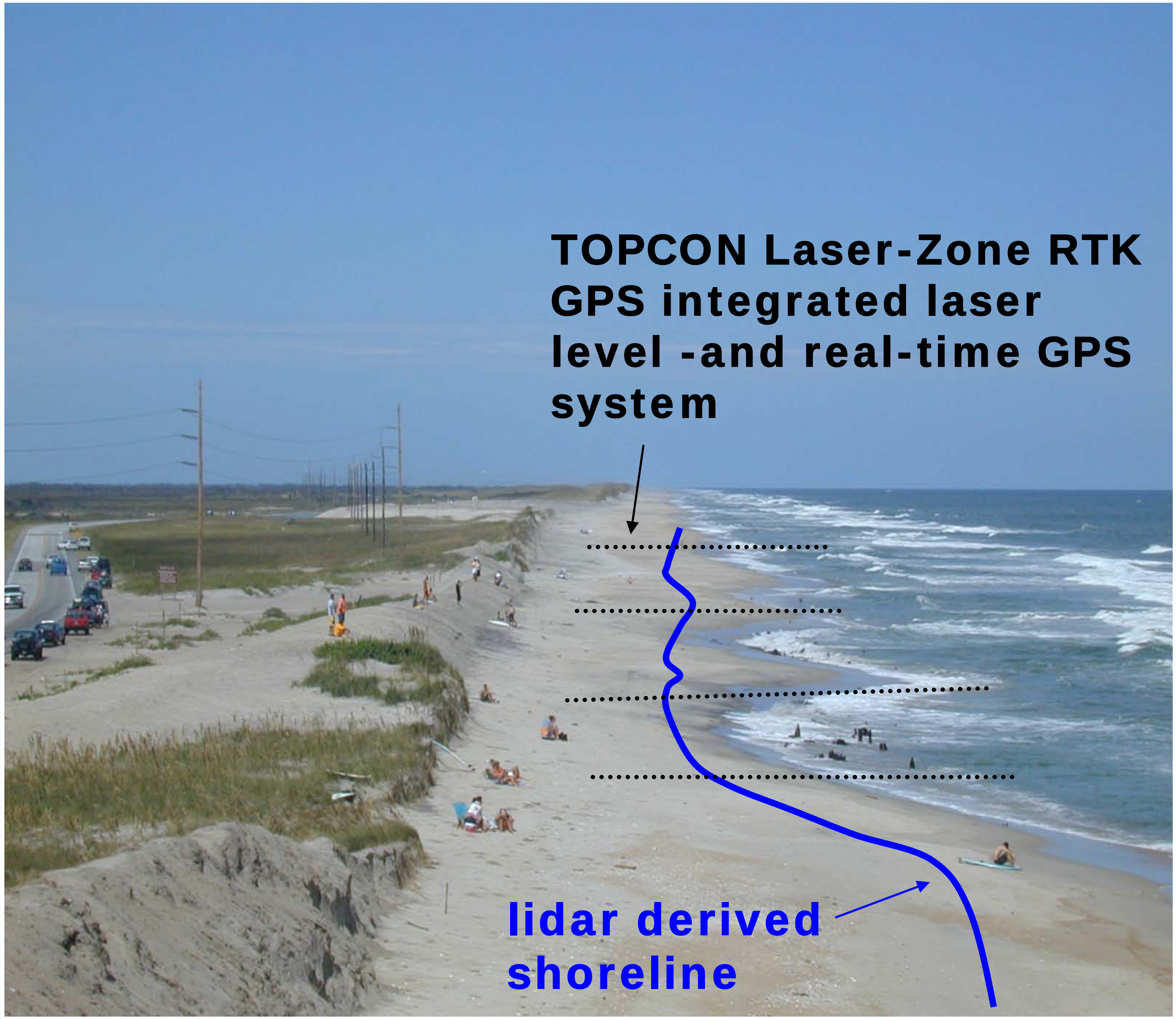
- **Optech ALTM 3100**
- **Applanix DSS DualCAM**



Lidar – derived MHW shorelines

- Duck: 5° slope
- Coquinta: 2° slope
- Frisco: 2° slope

Field-Survey: Shoreline Transects



Field Survey

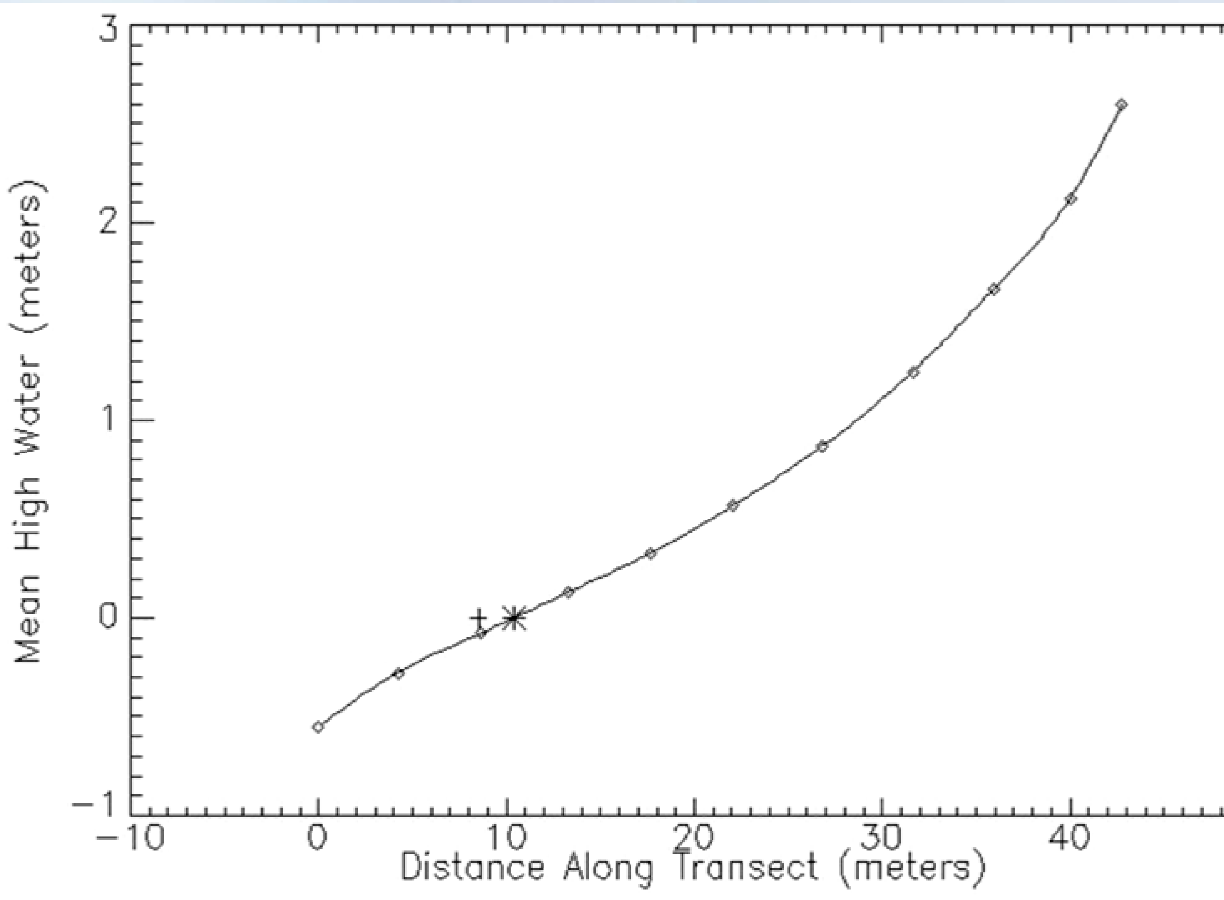
Shoreline Transects:

- **Instrument:** Topcon Laser-Zone integrated laser level and real-time GPS systems
- **Spacing:** ~10m spacing between transects, ~5 m spacing of points along each transect
- **Horizontal Positioning:** NAD 83 (CORS96) coordinates computed from RTK GPS component of system
- **Vertical:** Direct tidal datum tie by running levels from NOAA tide stations

Accuracy Site	Tide Station	Vertical Benchmark ID	Number of Transects
Duck	8651370	FW0686	20
Coquina	8652587	EX0141	12
Frisco	8654400	EX0249	25

Extracting ground-truth MHW points from transects

- Transect: 2D cross-section of beach profile
- Transect elevations directly tied to tidal datum
- Interpolate to find MHW zero-crossing point
  - If transect points are kept close (~5m), interpolation method has negligible effect



Empirically-determined shoreline positional accuracy, based on ILL-GPS ground truth

	Frisco		Coquina		Duck	
	cubic spline	linear	cubic spline	linear	cubic spline	linear
$RMSE_{HOR}$	3.59	3.63	2.18	2.16	0.53	0.56
Mean distance between lidar-derived MHW and Topcon-measured transects	3.55	3.58	2.12	2.10	0.45	0.50
Std. Deviation of distance between lidar-derived MHW and Topcon-measured transects	0.56	0.58	0.54	0.54	0.29	0.27
NSSDA $Accuracy_r$ (95% Confidence Level)	5.86	5.93	3.39	3.38	0.92	0.97

(All values in meters)

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Empirical results: examining differences between shoreline positional accuracies at 3 different sites

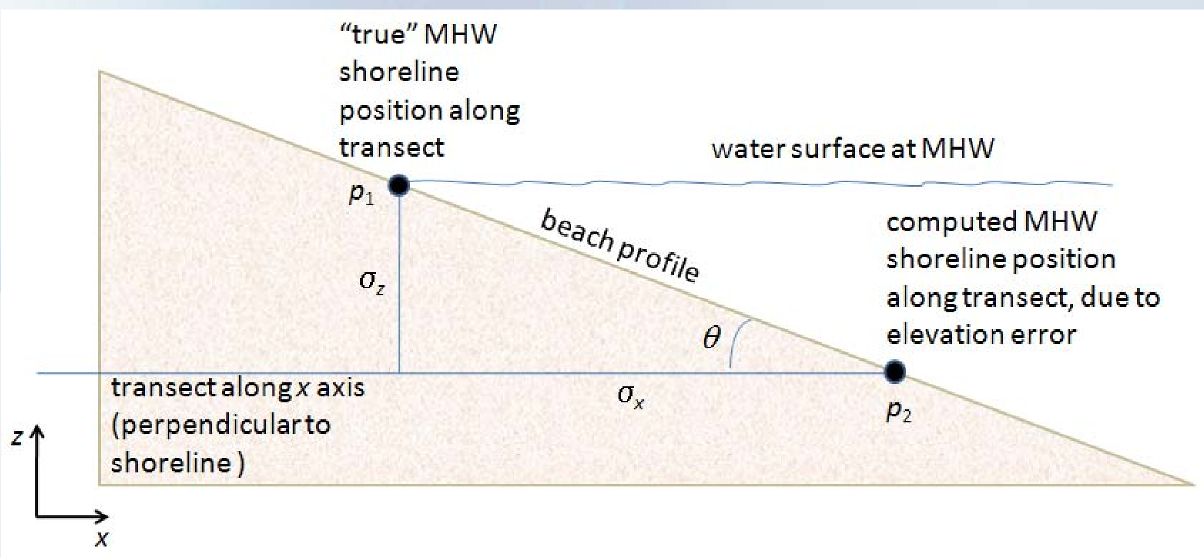
Differences appear to be primarily attributable to:

1. GPS baseline distance

	Frisco	Coquina	Duck
Duck Field Research Facility (NCDU)	108 km	46 km	~0

2. Beach slope

	Frisco	Coquina	Duck
Mean along MHW Line:	2.00^{o}	1.53^{o}	5.87^{o}
Mean for Entire Beach:	2.23^{o}	2.15^{o}	4.67^{o}



$$\Delta x = \frac{1}{tan\theta} \Delta z_{lidar\ bias}$$

Empirically-determined shoreline positional accuracy after removing lidar bias

	Frisco		Coquina		Duck	
	cubic spline	linear	cubic spline	linear	cubic spline	linear
$RMSE_{HOR}$	0.36	0.36	0.43	0.47	0.54	0.55
Mean distance between lidar-derived MHW and Topcon-measured transects	0.32	0.32	0.39	0.43	0.44	0.48
Std. Deviation of distance between lidar-derived MHW and Topcon-measured transects	0.16	0.17	0.17	0.19	0.32	0.28
NSSDA Accuracy (95% Circular Error)	0.60	0.63	0.74	0.81	0.93	0.93

Empirical Approach: Benefits

- Integrated laser-level-RTK GPS shown to work very well for this type of field accuracy assessment
- By running ILL-GPS transects from NOAA TBM, obtain ground truth that are (a) independent of, and (b) significantly higher accuracy than test data (lidar-derived shoreline)
- Computations can be done following Federal Geographic Data Committee’s National Standard for Spatial Data Accuracy (NSSDA) (FGDC, 1998)

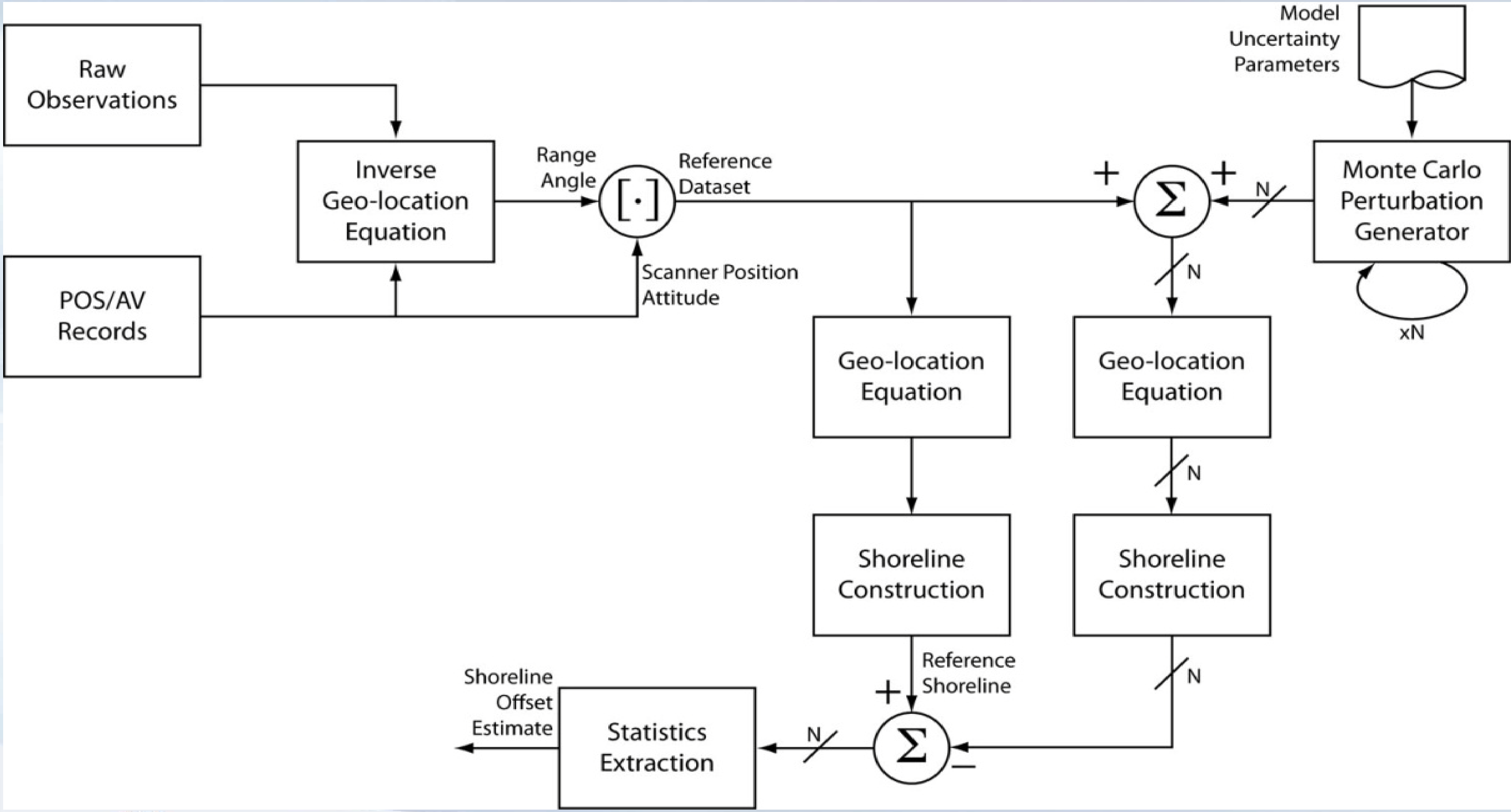
Stochastic Uncertainty Analysis: Motivation

- Empirical (field-survey-based) approach is infeasible for large-scale deployment
  - Not practical or cost effective to send field crew out to do extensive field survey for each and every shoreline project
- Satisfy IHO S-44 specs, which mandate that: "A statistical method, combining all *uncertainty sources, for determining positioning uncertainty should be adopted*"
- Perform sensitivity analysis
- Inform internal (NGS Coastal Mapping Board) decisions
  - Example: can we fly higher in certain areas and still meet specs?

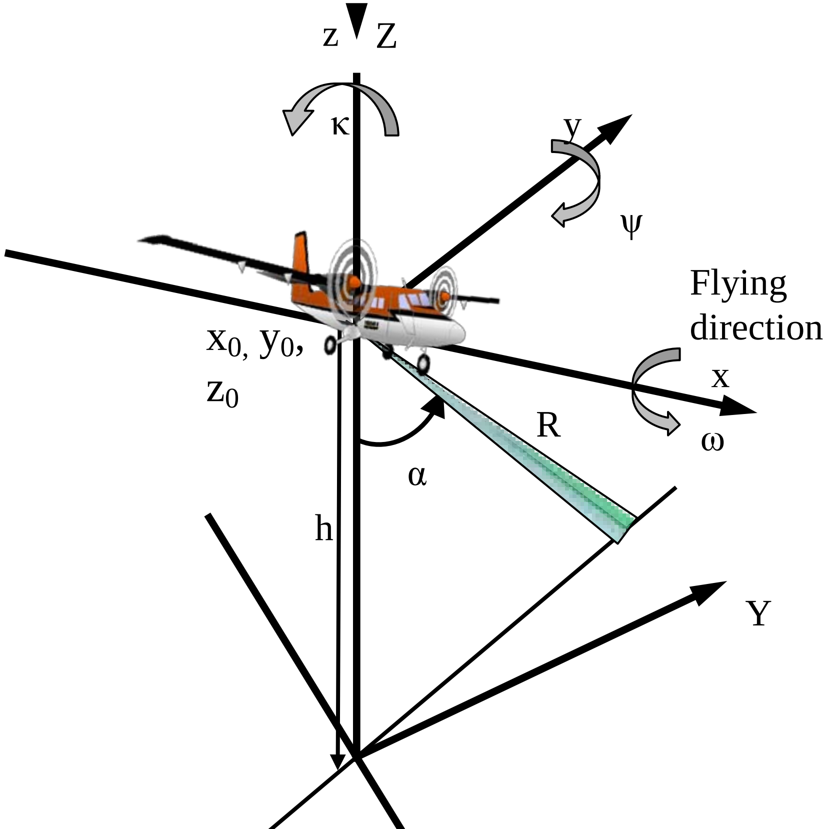
Overview of Stochastic Approach

- NGS production lidar shoreline mapping process (Slide 7) is complex: many steps, nonlinear & algorithmic in nature
  - Could construct uncertainty estimates for lidar point cloud, but difficult to propagate these into estimates of horizontal shoreline uncertainty
- When you can't practically use the textbook (analytical) approach to uncertainty propagation, Monte Carlo approach is commonly-used alternative
- 1) Model uncertainties in raw measurements, 2) perturb observed values to create a set of "plausible estimates," 3) propagate through full NGS lidar shoreline mapping workflow to create ensemble of shorelines, 4) compute distributions of orthogonal offsets about the reference shoreline, and 5) compute summary stats

Configuration of Monte Carlo Analysis Method



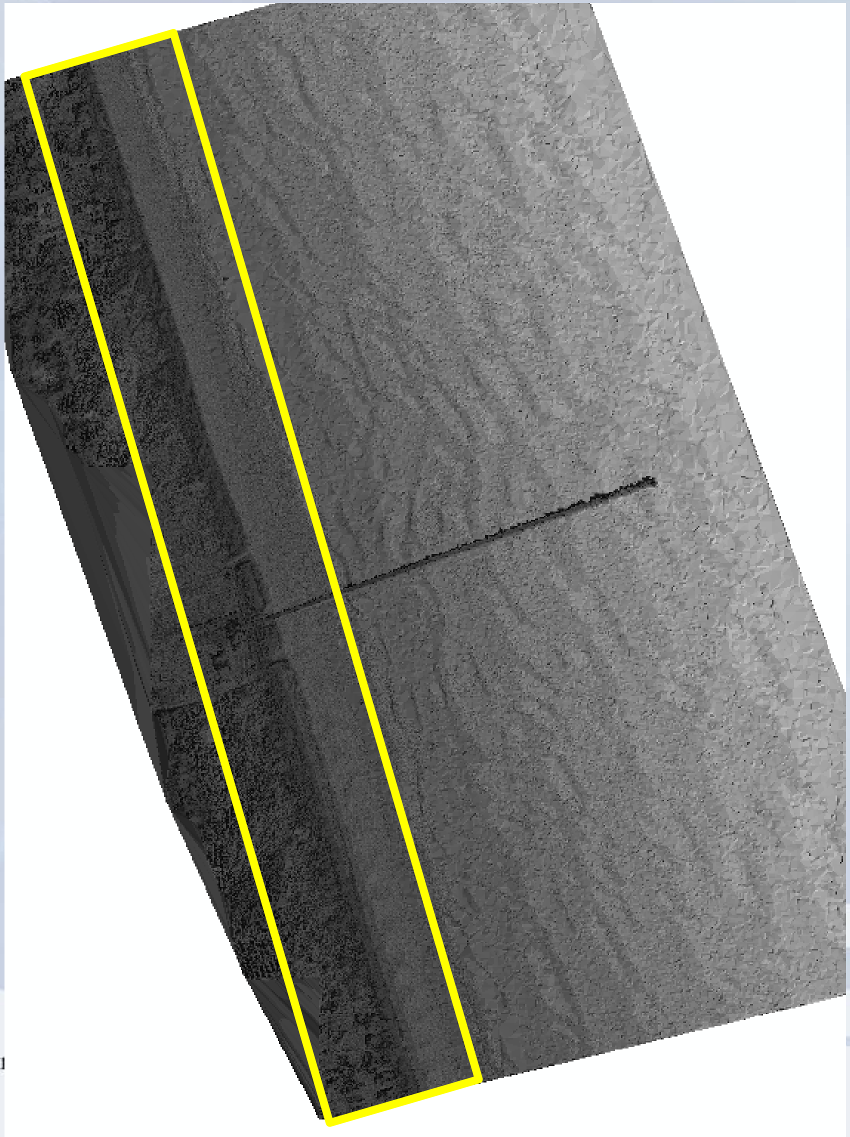
Uncertainty Parameters



Variable	Value	Units	Variable	Value	Units
(XYZ) Offsets	50	mm	Roll Measurement	0.003	deg.
Roll Offset	0.0006	deg.	Pitch Measurement	0.003	deg.
Pitch Offset	0.0006	deg.	Heading Measurement	0.004	deg.
Heading Offset	0.0012	deg.	Range Measurement	50	mm
GPS Absolute	80	mm	Angle Measurement	0.001	deg.
GPS Relative	10	mm	Refraction Angle	0.0011	deg.
			Latency Angle	0.005	deg.
			Torsion Coefficient	7.3614×10^{-5}	N/A

(All values are reported at one standard deviation)

Study Site
(Duck, NC)



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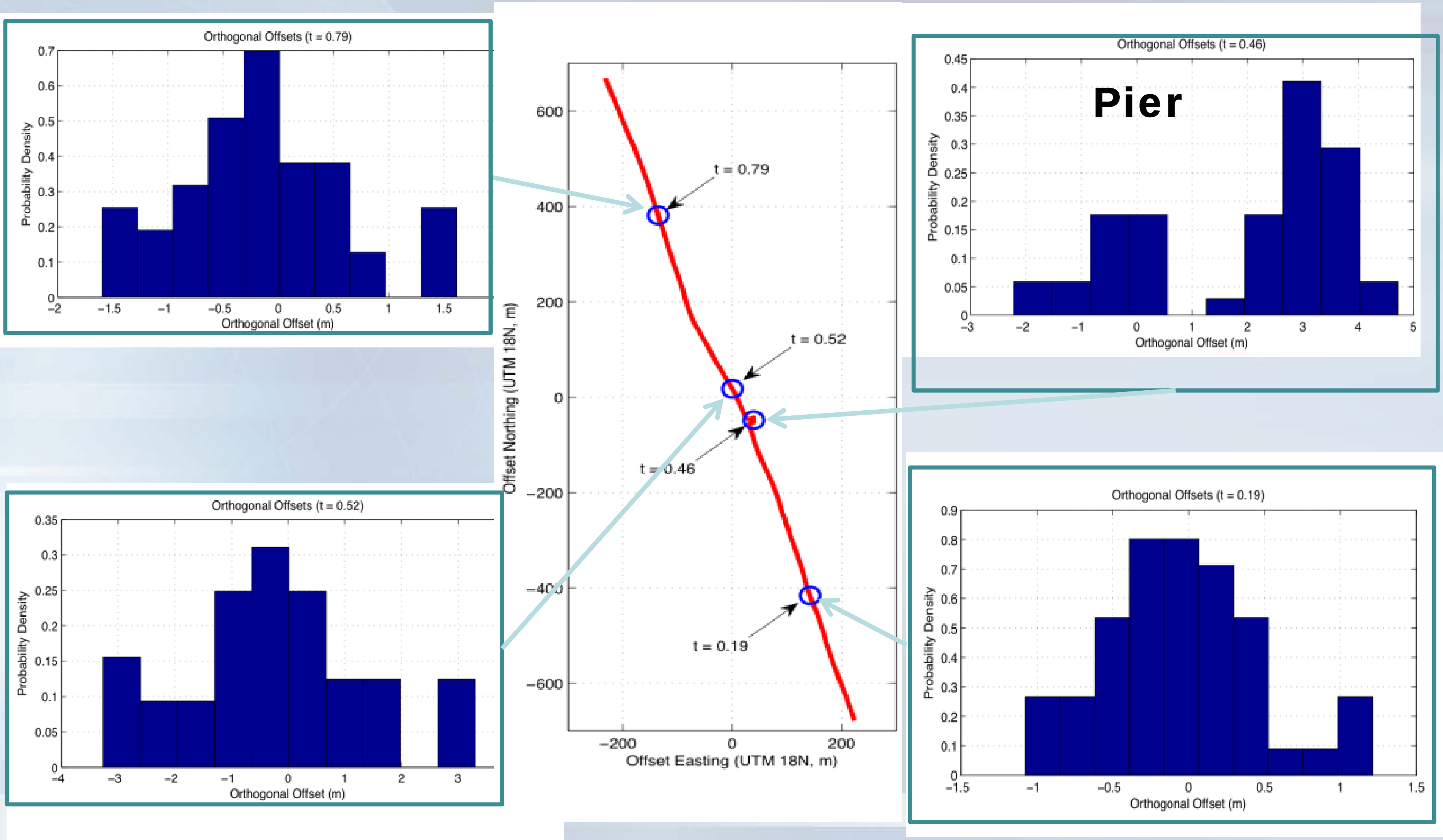
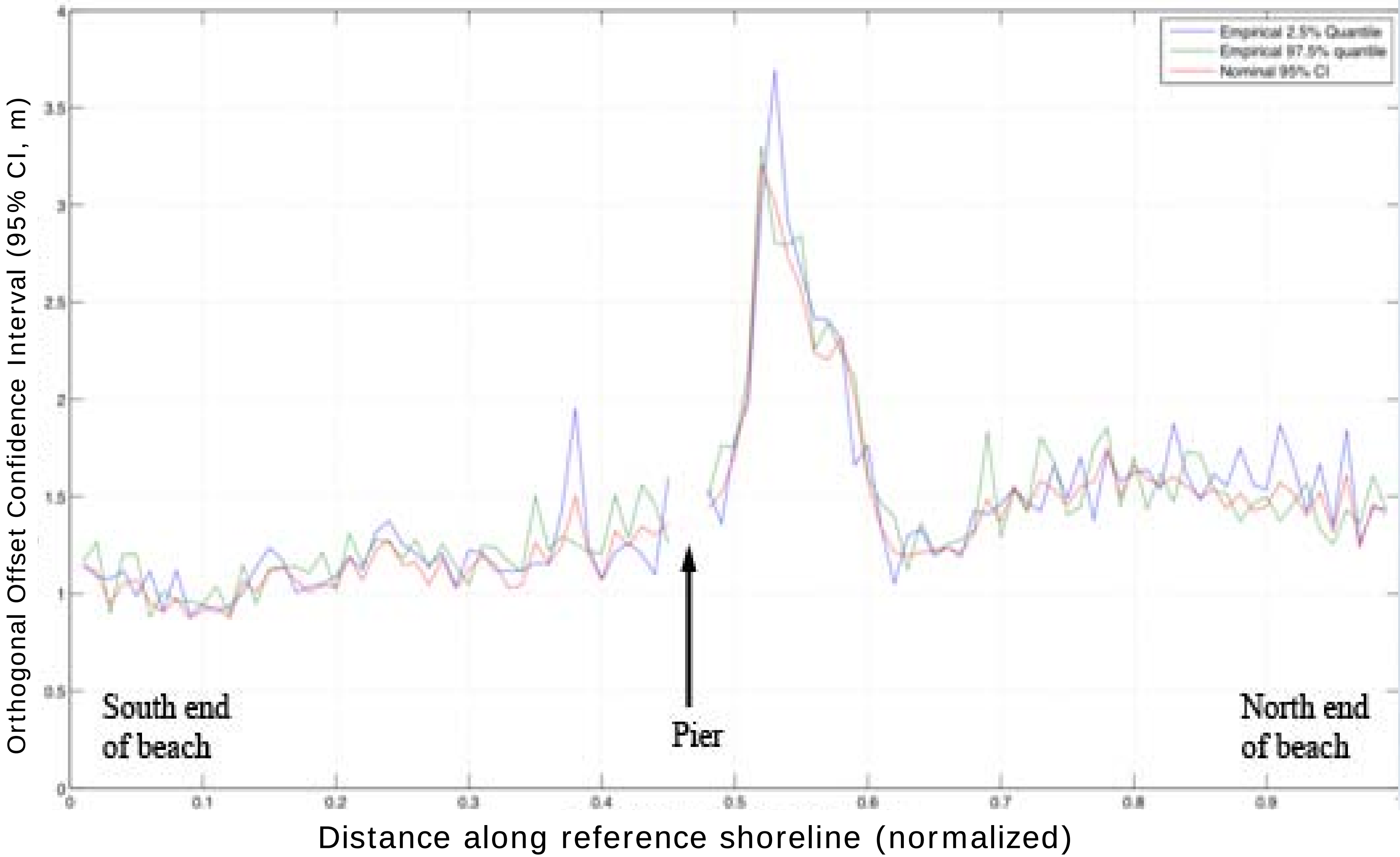
Distributions of offsets

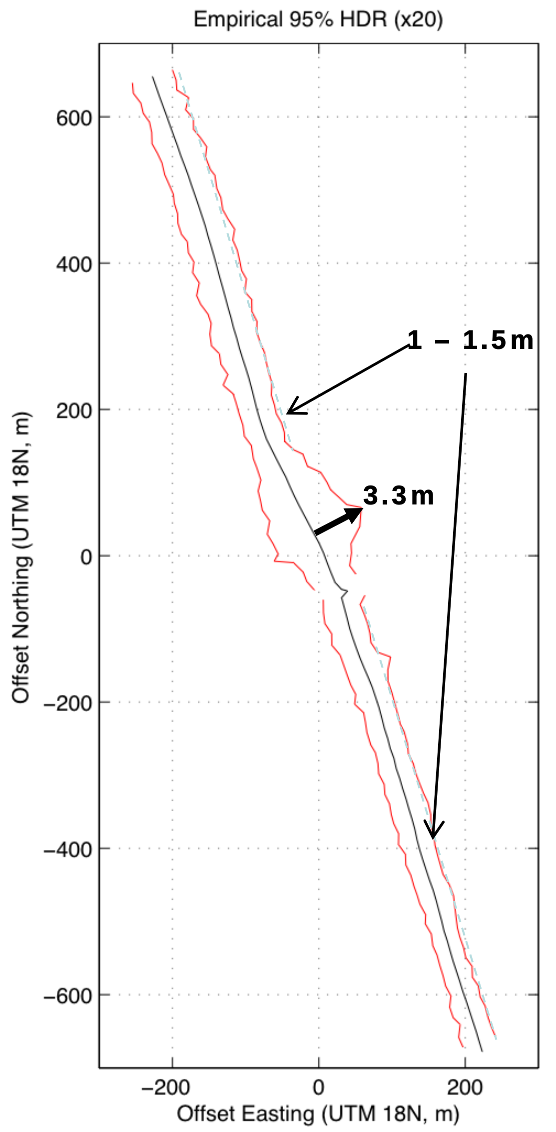


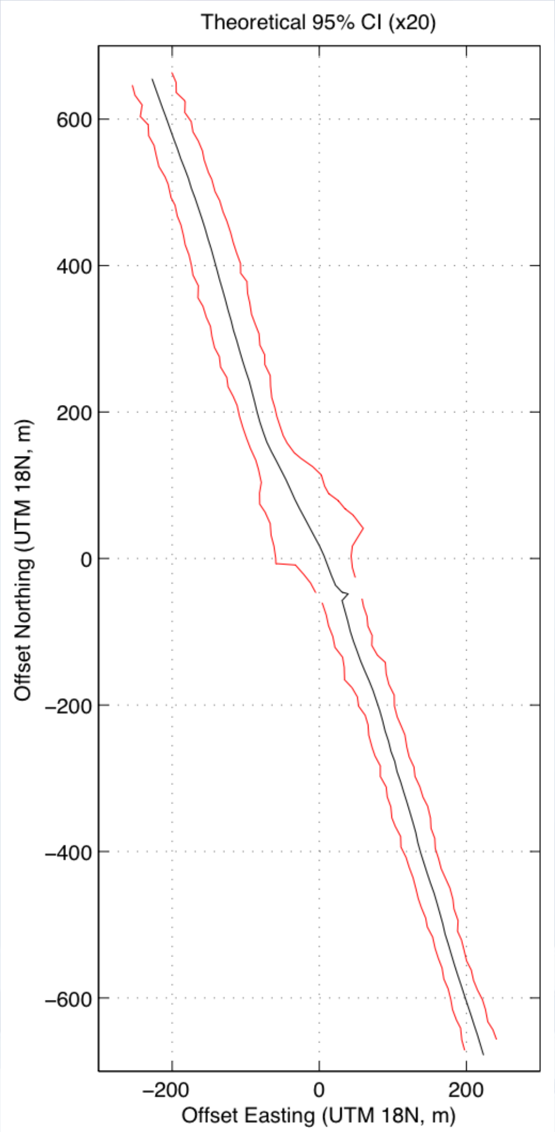
Horizontal uncertainty estimates



Stochastic model results

Reference shoreline outer 95% CI bounds as estimated using the Monte Carlo method





Empirical bounds computed from the data

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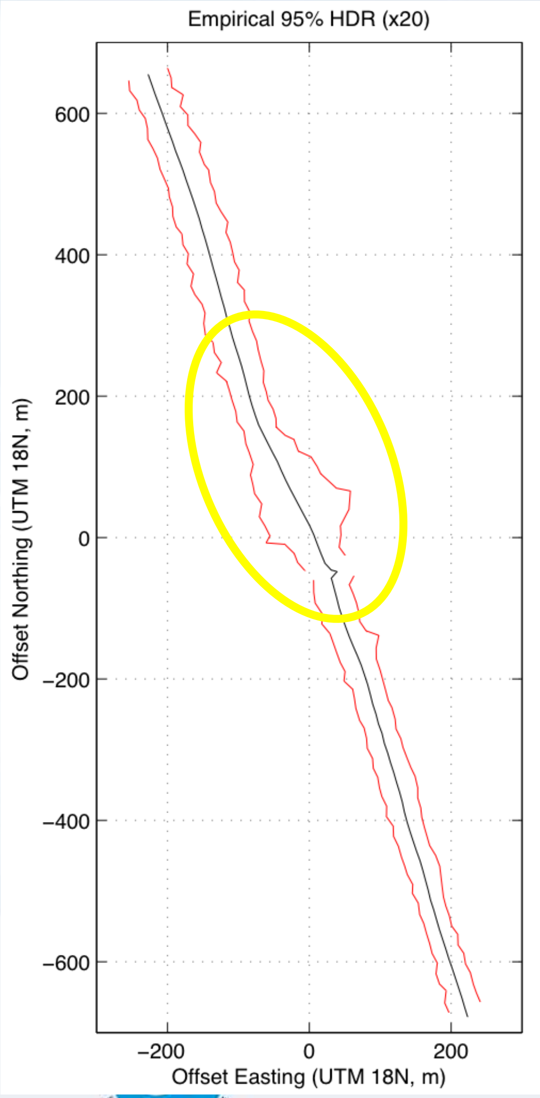
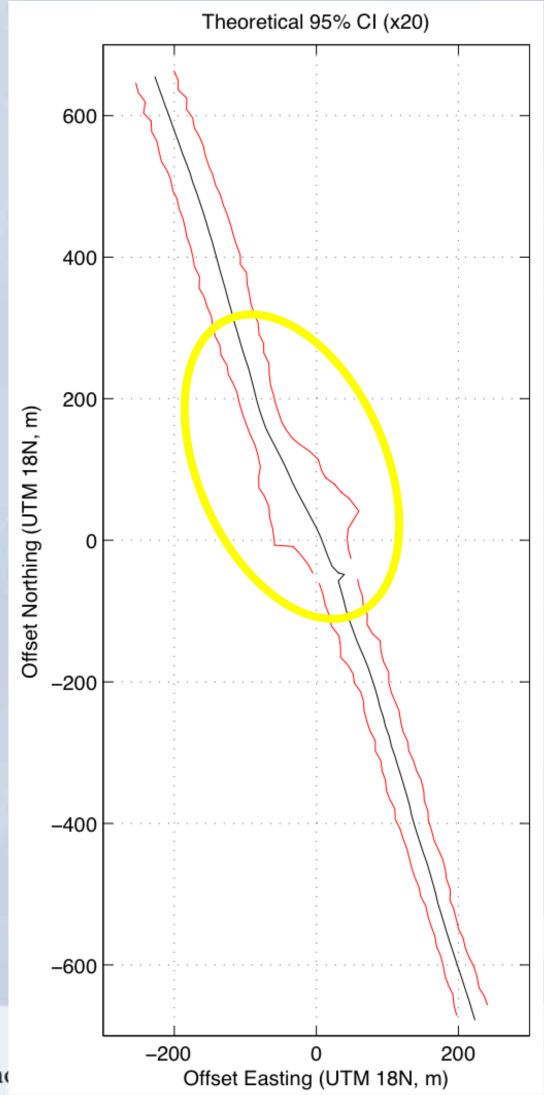
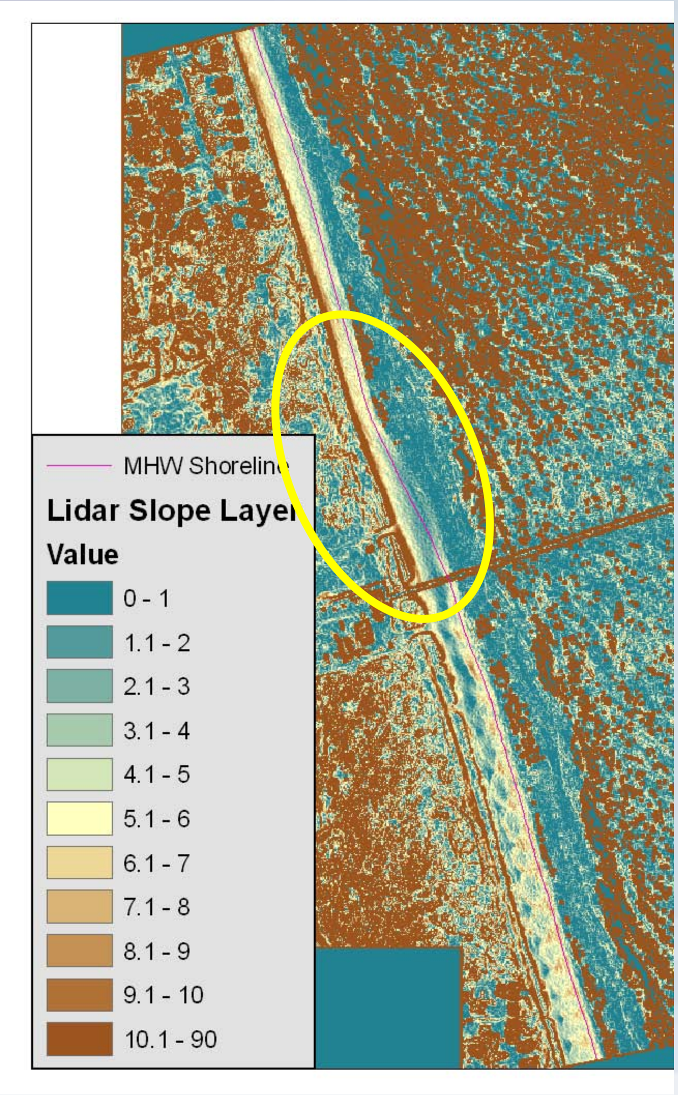
Correlation with beach slope







Stochastic Approach: Discussion

- Results are consistent with those determined through field campaign
  - Uncertainties on the order of 1.0-1.5 m through most of project area, with increases to 3.3 m (95%) in low-slope areas
  - Method is at least first-order accurate
  - Although algorithm isn't fed any *a priori* info about beach slope, we see strong correlation of output uncertainties with beach slope (as expected)
- Fidelity depends heavily on input uncertainty estimates for the raw measurements
- Not yet implemented in production, but we believe computational complexity will be acceptable

Conclusions and Future Work

- Good agreement between two approaches is encouraging
  - In the future, NGS may be able to utilize the Monte Carlo approach operationally to assess positional uncertainty in lidar derived shoreline, without having to rely on extensive field surveys
- Future work will focus on:
  - Assessing/refining component uncertainties
  - Testing in different areas
  - Tuning size of the ensemble
  - Making “production-ready” (including consideration of computational complexity, development of user-friendly interfaces, etc.)
  - Extending to photogrammetrically-derived shoreline