CHC-NSC 2018

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Victoria, B.C.
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Victoria, C.B.
26 au 29 mars 2018

Land and Sea Shaping the World
Terre et Mer Façonnant le Monde

Topographic-Bathymetric Lidar Total Propagated Uncertainty Modeling

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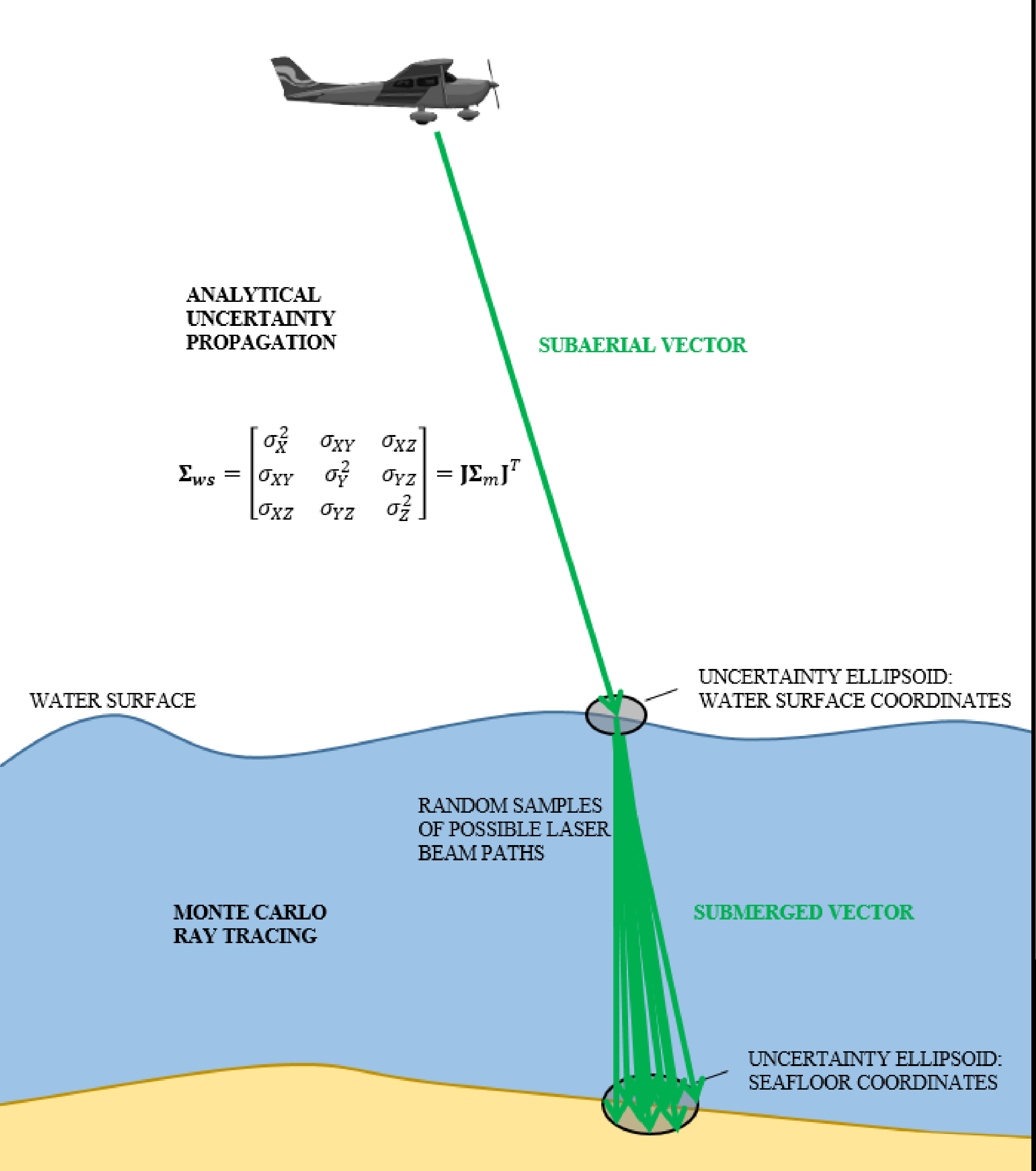
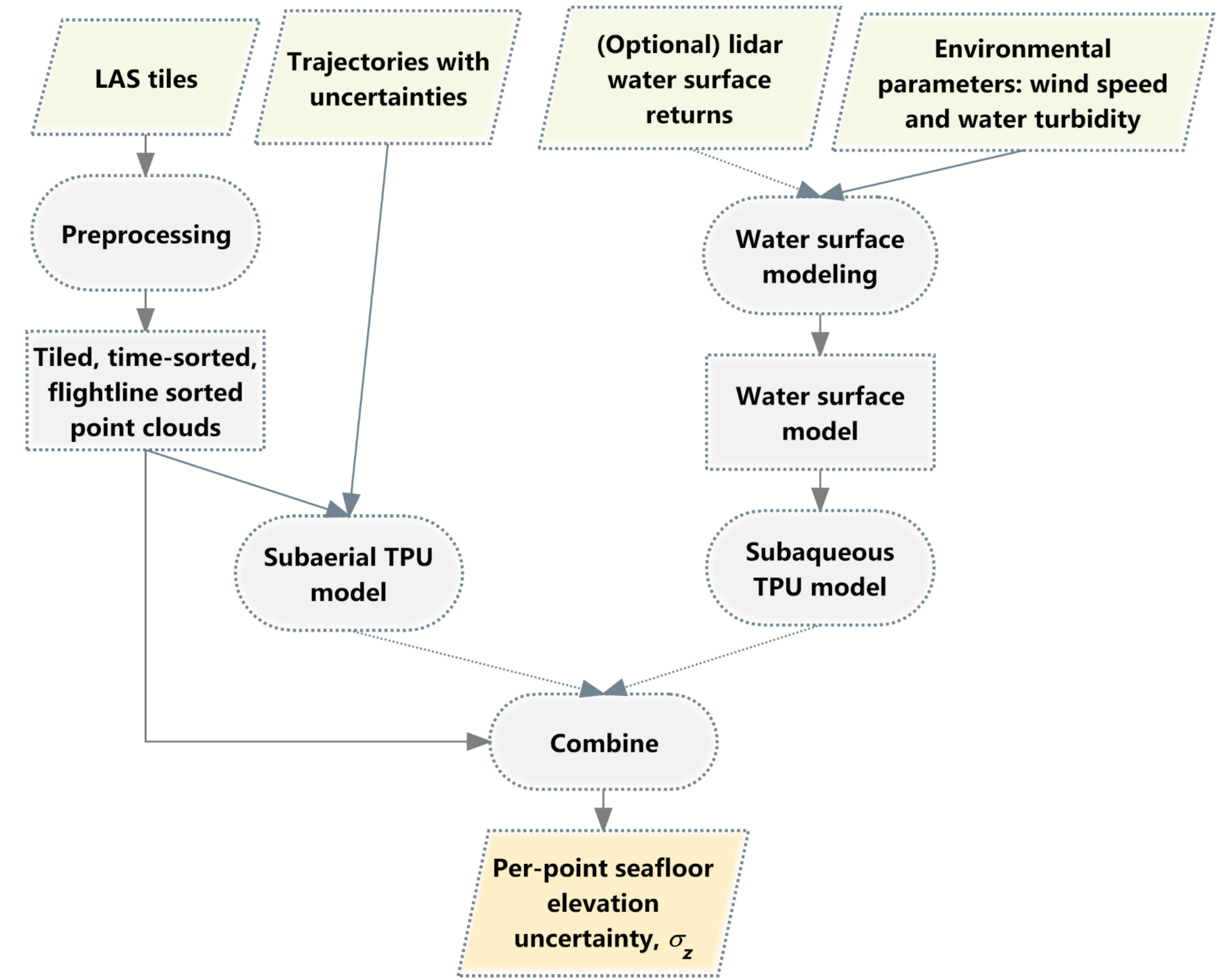
#chcnsc2018

Project Overview

- Motivation
  - NOAA/NGS and partners currently collecting topo-bathy lidar data for mapping the National Shoreline
  - Growing interest in also using the lidar bathymetry for nautical chart updates
  - IHO S-44 TPU requirement: must account for "*all contributing measurement uncertainties*" using a "*statistical method, combining all uncertainty sources, for determining positioning uncertainty…at the 95% confidence level*" (IHO, 2008).
- Goals:
  - Develop, test and deploy ***operational TPU software*** for topo-bathy lidar
  - Start with Riegl VQ-880-G, then extend to other systems operated by JALBTCX partner agencies

TPU Approach





Subaerial component: Laser geo-location equation

$$\begin{bmatrix} X_L \\ Y_L \\ Z_L \end{bmatrix} = \begin{bmatrix} X_T \\ Y_T \\ Z_T \end{bmatrix} + \mathbf{R}_b^m \mathbf{M}_{lb}^b \begin{bmatrix} 0 \\ 0 \\ -\rho \end{bmatrix}$$

$$\begin{bmatrix} X_L \\ Y_L \\ Z_L \end{bmatrix} = \begin{bmatrix} X_T - \rho(r_{11}m_{13} + r_{12}m_{23} + r_{13}m_{33}) \\ Y_T - \rho(r_{21}m_{13} + r_{22}m_{23} + r_{23}m_{33}) \\ Z_T - \rho(r_{31}m_{13} + r_{32}m_{23} + r_{33}m_{33}) \end{bmatrix} + \begin{bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{bmatrix}_{offset} = \begin{bmatrix} f_1^N \\ f_2^N \\ f_3^N \end{bmatrix}$$

$$\begin{bmatrix} X_L \\ Y_L \\ Z_L \end{bmatrix} = \begin{bmatrix} X_T \\ Y_T \\ Z_T \end{bmatrix} + \begin{bmatrix} \cos h & -\sin h & 0 \\ \sin h & \cos h & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos p & 0 & \sin p \\ 0 & 1 & 0 \\ -\sin p & 0 & \cos p \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos r & -\sin r \\ 0 & \sin r & \cos r \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha \\ 0 & \sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ -\rho \end{bmatrix}$$

$$J = \begin{bmatrix} \frac{\partial f_1^N}{\partial \alpha} & \frac{\partial f_1^N}{\partial \beta} & \frac{\partial f_1^N}{\partial r} & \frac{\partial f_1^N}{\partial p} & \frac{\partial f_1^N}{\partial h} & \frac{\partial f_1^N}{\partial x} & \frac{\partial f_1^N}{\partial y} & \frac{\partial f_1^N}{\partial z} & \frac{\partial f_1^N}{\partial \rho} \\ \frac{\partial f_2^N}{\partial \alpha} & \frac{\partial f_2^N}{\partial \beta} & \frac{\partial f_2^N}{\partial r} & \frac{\partial f_2^N}{\partial p} & \frac{\partial f_2^N}{\partial h} & \frac{\partial f_2^N}{\partial x} & \frac{\partial f_2^N}{\partial y} & \frac{\partial f_2^N}{\partial z} & \frac{\partial f_2^N}{\partial \rho} \\ \frac{\partial f_3^N}{\partial \alpha} & \frac{\partial f_3^N}{\partial \beta} & \frac{\partial f_3^N}{\partial r} & \frac{\partial f_3^N}{\partial p} & \frac{\partial f_3^N}{\partial h} & \frac{\partial f_3^N}{\partial x} & \frac{\partial f_3^N}{\partial y} & \frac{\partial f_3^N}{\partial z} & \frac{\partial f_3^N}{\partial \rho} \end{bmatrix}$$

M: DCM: laser scanner to body frame

R: DCM: body frame to local level frame

f: geo-location equation

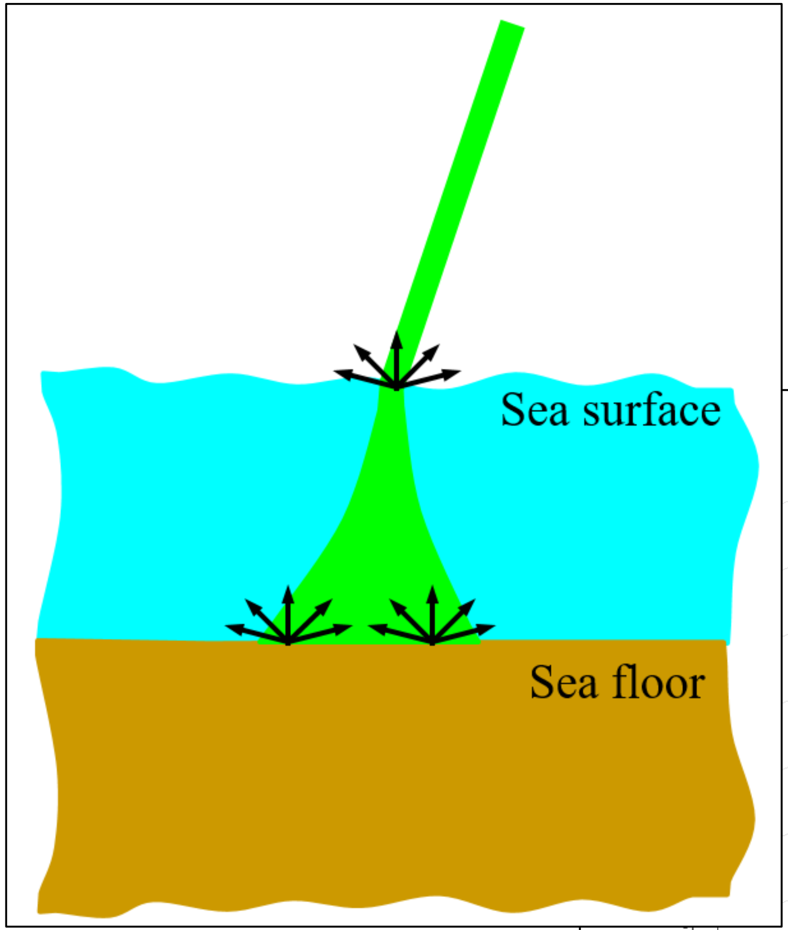
$$\Sigma = \begin{bmatrix} \sigma_X^2 & \sigma_{XY} & \sigma_{XZ} \\ \sigma_{XY} & \sigma_Y^2 & \sigma_{YZ} \\ \sigma_{XZ} & \sigma_{YZ} & \sigma_Z^2 \end{bmatrix} = J \begin{bmatrix} \sigma_\alpha & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \sigma_\rho \end{bmatrix} J^{\mathrm{T}}$$

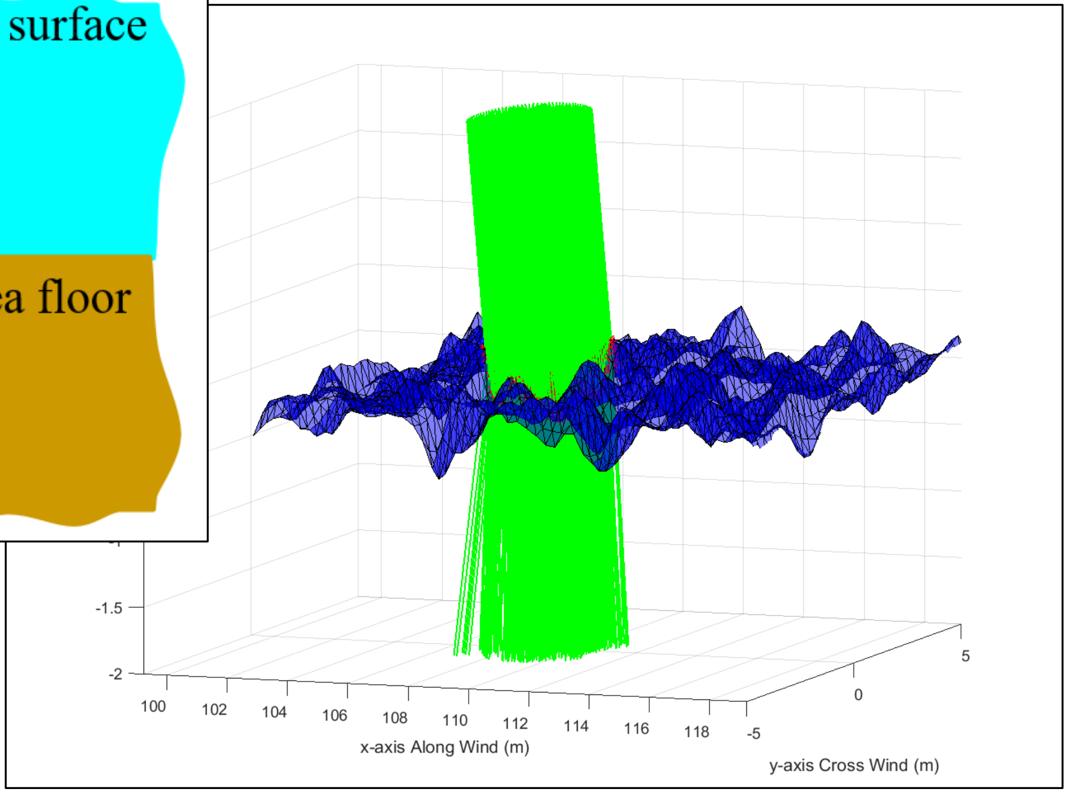
$\sigma_x, \sigma_y, \sigma_z, \sigma_r, \sigma_p, \sigma_h$: trajectory uncertainties: position and orientation (from SBETs)
$\sigma_\alpha, \sigma_\beta$: angular uncertainties of scanner (from specs and discussion with Riegl)
σ_ρ: range uncertainty (from specs)

Subaqueous component: Monte Carlo ray tracing

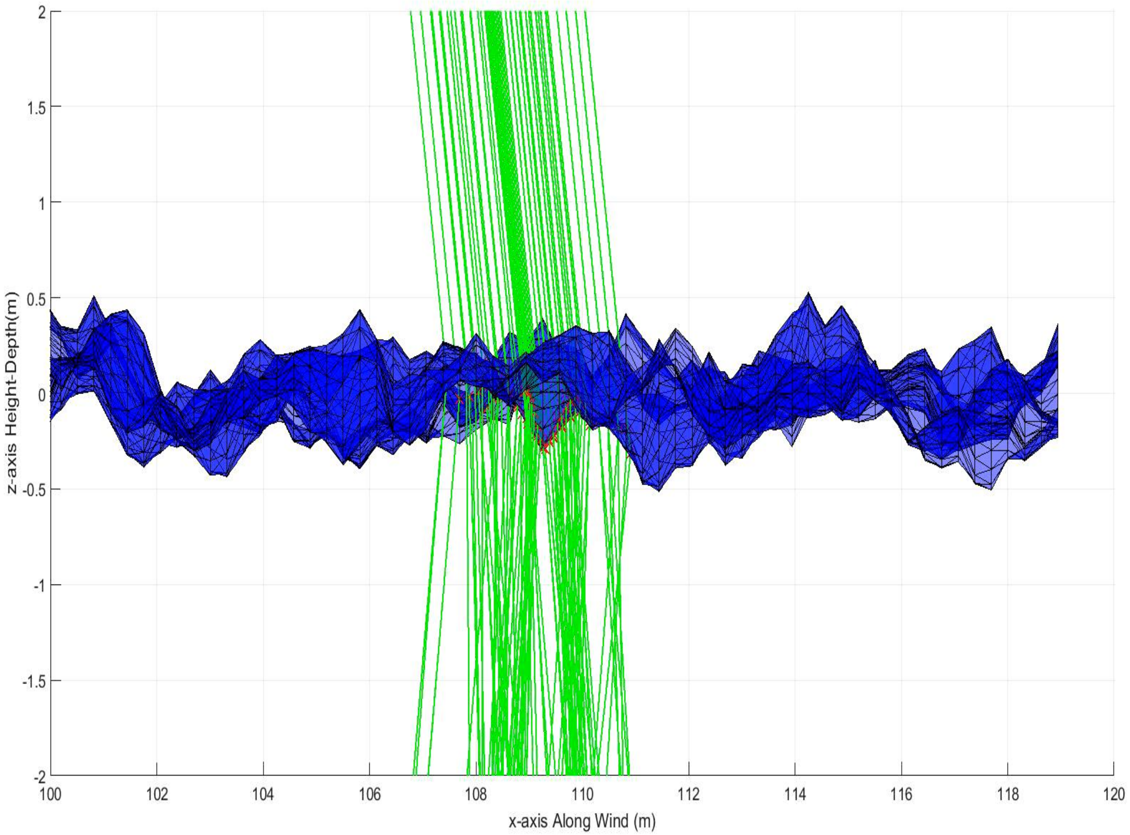
What happens to the laser beam as it travels through the environment?

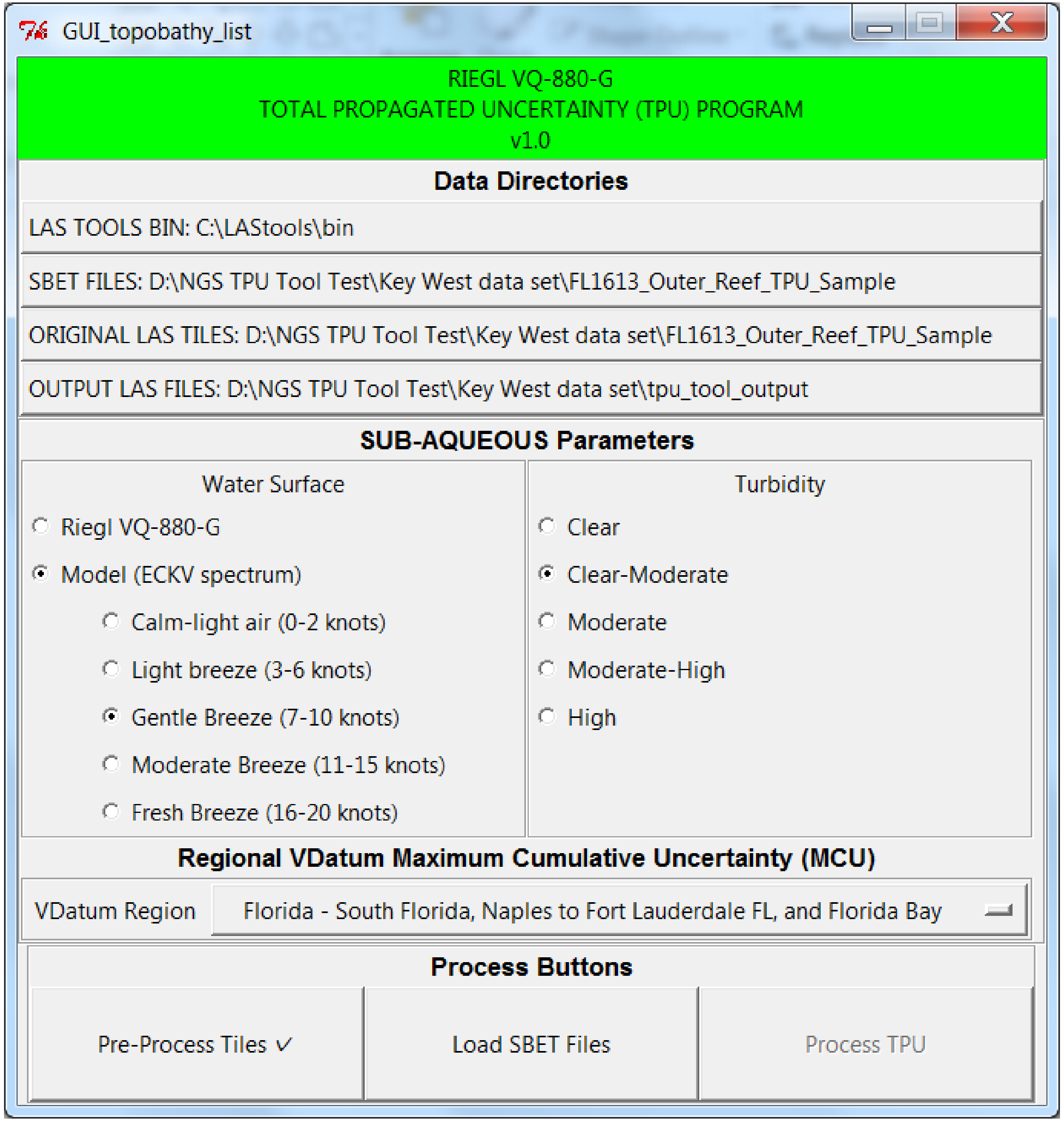
- **Complex interactions → Monte Carlo Ray tracing algorithm**
  - Water surface refraction
  - Scattering and absorption in water column
  - Laser beam geometry and energy change in water column
  - How do these factors impact seafloor uncertainty?

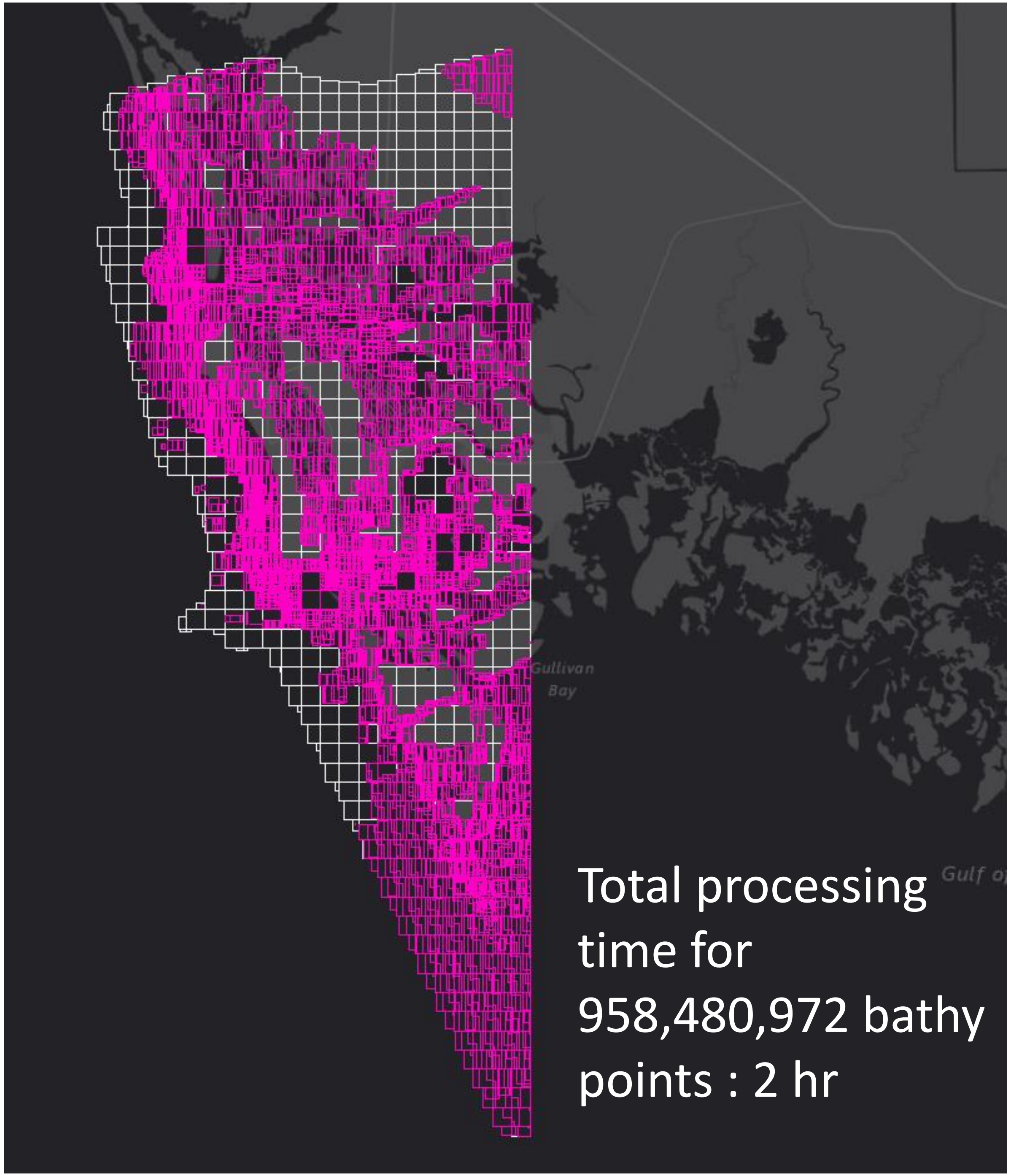




Movie: Wind speed 3 m/s
100 rays Δt =0.1 sec




GUI_topobathy_list
RIEGL VQ-880-G
TOTAL PROPAGATED UNCERTAINTY (TPU) PROGRAM
v1.0
Data Directories
LAS TOOLS BIN: C:\LAStools\bin
SBET FILES: D:\NGS TPU Tool Test\Key West data set\FL1613_Outer_Reef_TPU_Sample
ORIGINAL LAS TILES: D:\NGS TPU Tool Test\Key West data set\FL1613_Outer_Reef_TPU_Sample
OUTPUT LAS FILES: D:\NGS TPU Tool Test\Key West data set\tpu_tool_output
SUB-AQUEOUS Parameters
Water Surface
Riegl VQ-880-G
Model (ECKV spectrum)
Calm-light air (0-2 knots)
Light breeze (3-6 knots)
Gentle Breeze (7-10 knots)
Moderate Breeze (11-15 knots)
Fresh Breeze (16-20 knots)
Turbidity
Clear
Clear-Moderate
Moderate
Moderate-High
High
Regional VDatum Maximum Cumulative Uncertainty (MCU)
VDatum Region
Florida - South Florida, Naples to Fort Lauderdale FL, and Florida Bay
Process Buttons
Pre-Process Tiles ✓
Load SBET Files
Process TPU


Gullivan Bay
Total processing time for 958,480,972 bathy points : 2 hr

Outputs

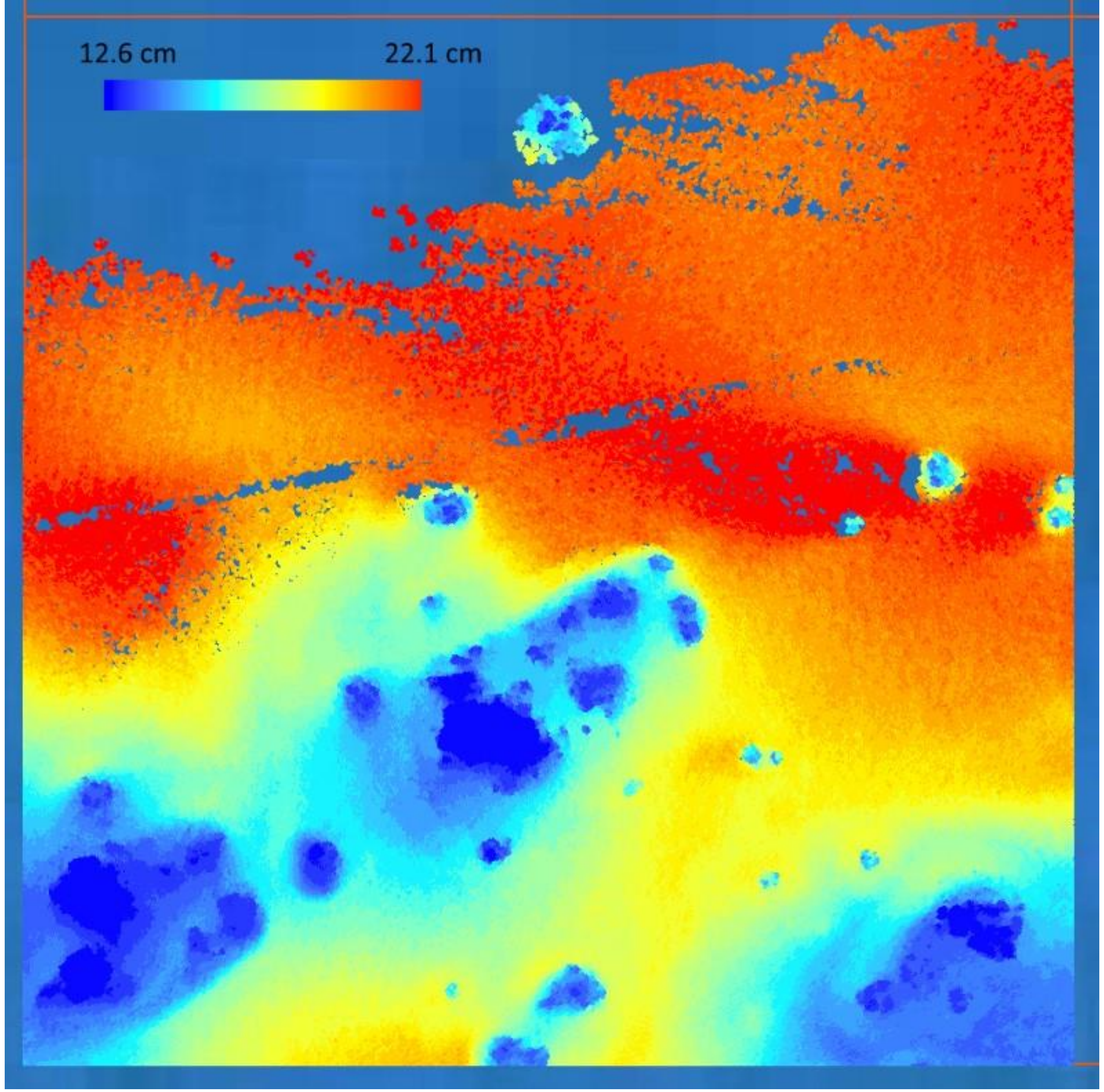
```
2016_413000e_2708500n TPU METADATA FILE

---------------------------------------------------
PARAMETERS
---------------------------------------------------
water surface       :  Model (ECKV spectrum)
wind                :  Light breeze (3-6 knots)
kd                  :  Clear
VDatum region       :  Florida - Apalachicola to Anclote Key
VDatum region MCU   :  0.102 (m)

---------------------------------------------------
TOTAL SIGMA Z TPU (METERS) SUMMARY
---------------------------------------------------
FILE ID     MIN         MAX         MEAN        STDDEV      COUNT
0           0.12694     0.19020     0.15310     0.01531     204983
1           0.12691     0.20547     0.15702     0.01978     567315
2           0.12624     0.21894     0.19762     0.00601     92338
3           0.12712     0.22121     0.16592     0.02391     390393
4           0.12713     0.21942     0.16005     0.02127     560137

---------------------------------------------------
FILE IDS (BATHY-ONLY FLIGHT-LINE FILES)
---------------------------------------------------
0 - I:/NGS_TPU/FL1613_Outer_Reef_TPU_Sample/las/OutputLas\2016_413000e_2708500n_SORTED_0000005.las
1 - I:/NGS_TPU/FL1613_Outer_Reef_TPU_Sample/las/OutputLas\2016_413000e_2708500n_SORTED_0000004.las
2 - I:/NGS_TPU/FL1613_Outer_Reef_TPU_Sample/las/OutputLas\2016_413000e_2708500n_SORTED_0000001.las
3 - I:/NGS_TPU/FL1613_Outer_Reef_TPU_Sample/las/OutputLas\2016_413000e_2708500n_SORTED_0000002.las
4 - I:/NGS_TPU/FL1613_Outer_Reef_TPU_Sample/las/OutputLas\2016_413000e_2708500n_SORTED_0000003.las
```

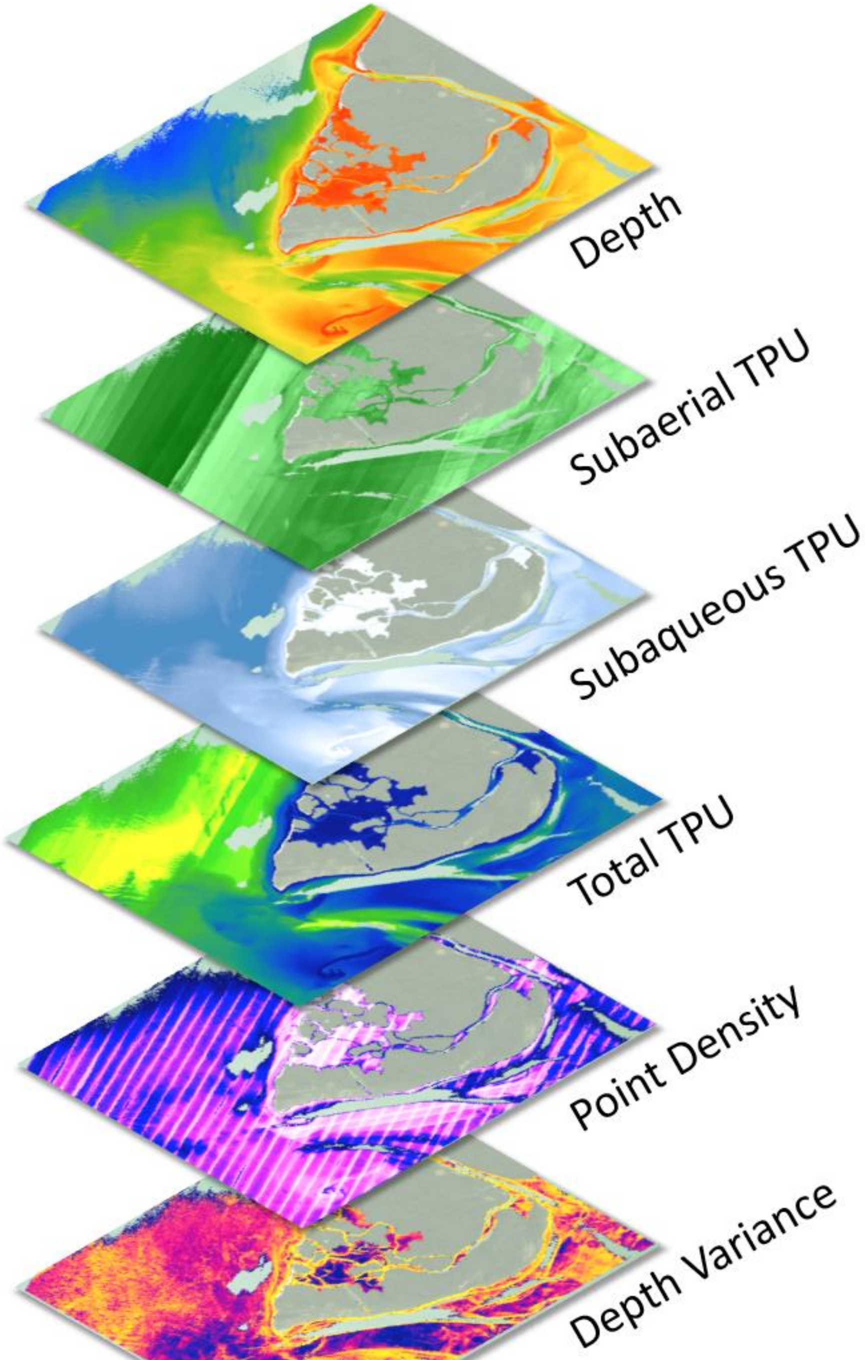
TPU Metadata File



Per-point TPU (displayed as uncertainty surface

Summary and next steps:

- Version 1.0 delivered to NOAA/NGS
  - Currently being evaluated for operational use
- Continuing to improve model by:
  - Accounting for additional component uncertainties
    - Boresight angle uncertainties
  - Improving how some component uncertainties are modeled
    - Range and scan angle uncertainties
- Extending to other bathy lidar systems
  - Leica Chiroptera II, EAARL-C, others, …
- Assessing outputs for a number of project sites to gain enhanced understanding of TPU and the environment



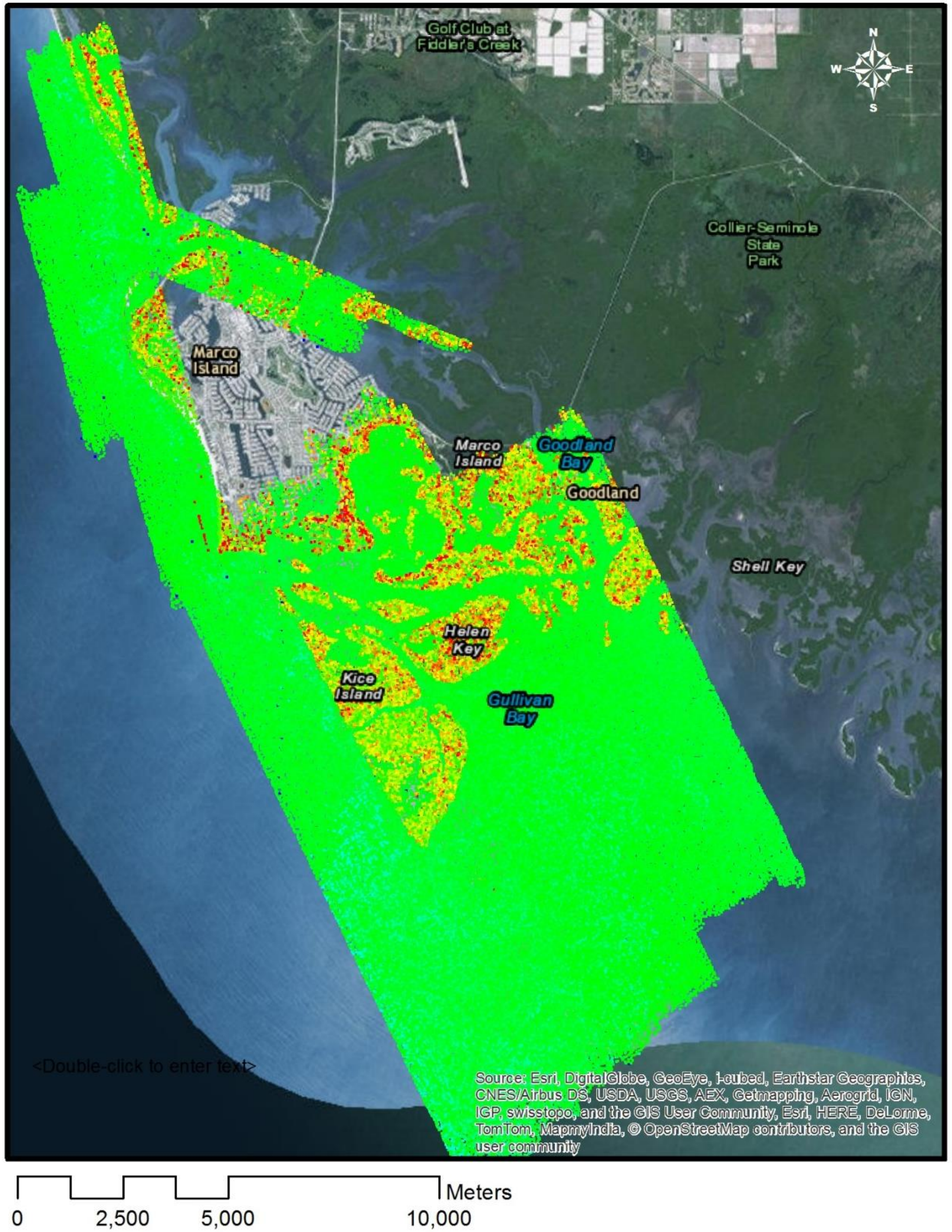
Acknowledgements

- Mike Aslaksen, NOAA NGS
- Brian Calder, Larry Mayer, and Andy Armstrong, UNH CCOM-JHC
- Minsu Kim, USGS

Backup Slides

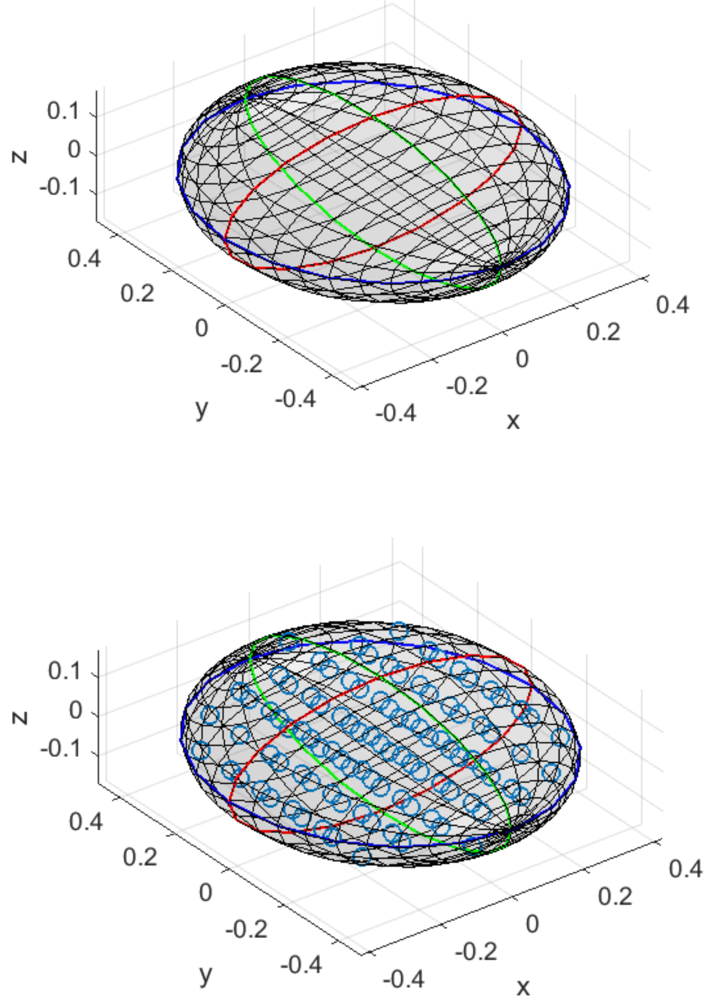
Initial study site

- Southwest Florida
  - Cape Romano/Marco Island/Gullivan Bay
  - > 150 km^2
- Flown by NOAA/NGS/RSD in May 2016 with Riegl VQ-880-G
- Data provided by NOAA
  - SBET ascii output with standard deviations: σ_X, σ_Y, σ_Z, σ_r, σ_p ,σ_h
  - Wind speed, direction and fetch
  - NOAA NCCOS (Stumpf, et al.) K_d grid product
  - LAS file with Riegl reflectance and pulse shape deviation in LAS ExtraBytes



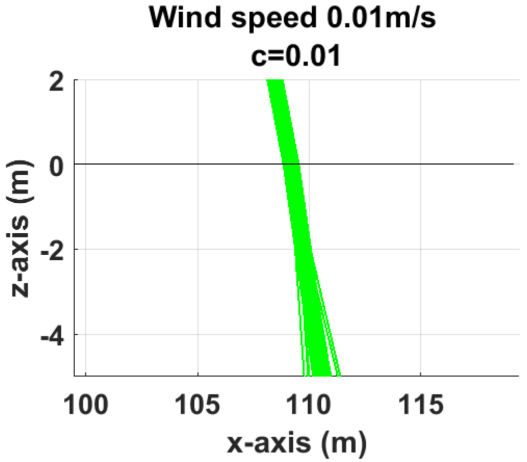
Combining subaerial and subaqueous uncertainties

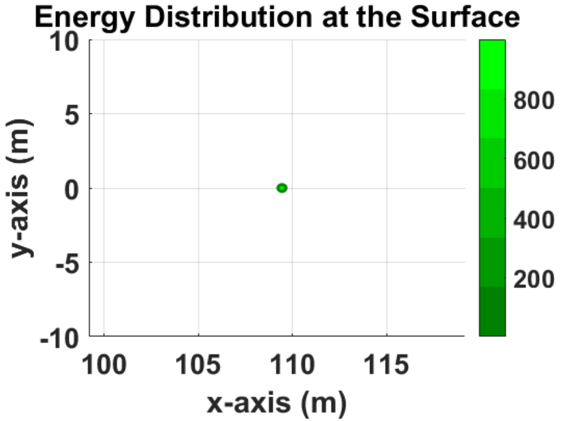
- Surface σ_x, σ_y and σ_z values are determined through geolocation equations
- Generate an uncertainty ellipsoid around a single laser point on the water surface.
- σ_x, σ_y and σ_z propagated to the seafloor through MC simulations

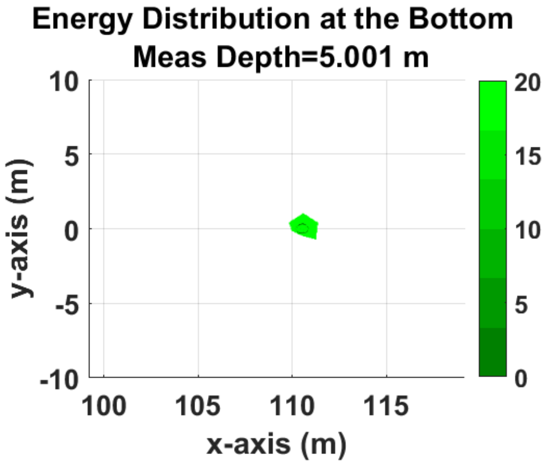


Uncertainty ellipsoids on water surface (top) and seafloor (bottom)

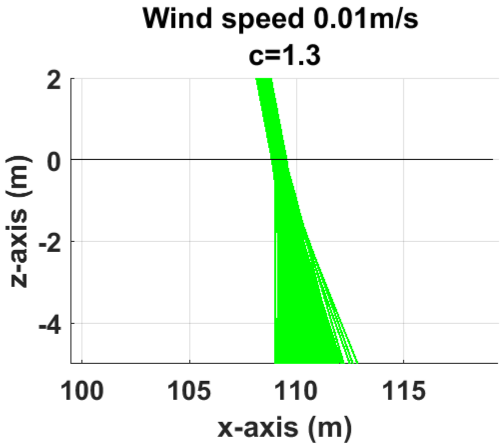
Effects of water turbidity:

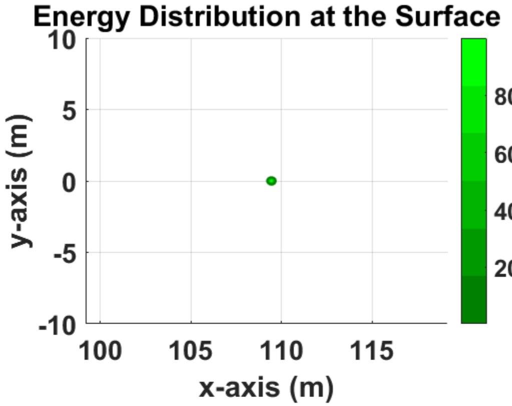


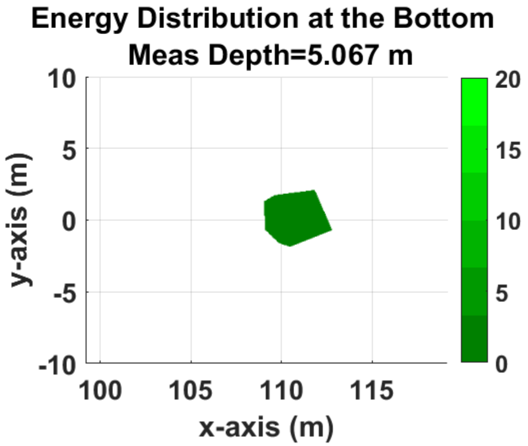




less turbid water







more turbid water

Key to reasonable runtime: polynomial fits of σ_Z (subaqueous) to input parameters!

- Determined that polynomial surface fits of σ_Z to water clarity, depth and wind speed (or Riegl water surface) provide good results
- Eliminates need to time-consuming Monte Carlo ray tracing each time user hits: “Compute TPU”
  - Just need to pre-compute and store polynomial coefficients