DUNEX Swash Data and Modeling

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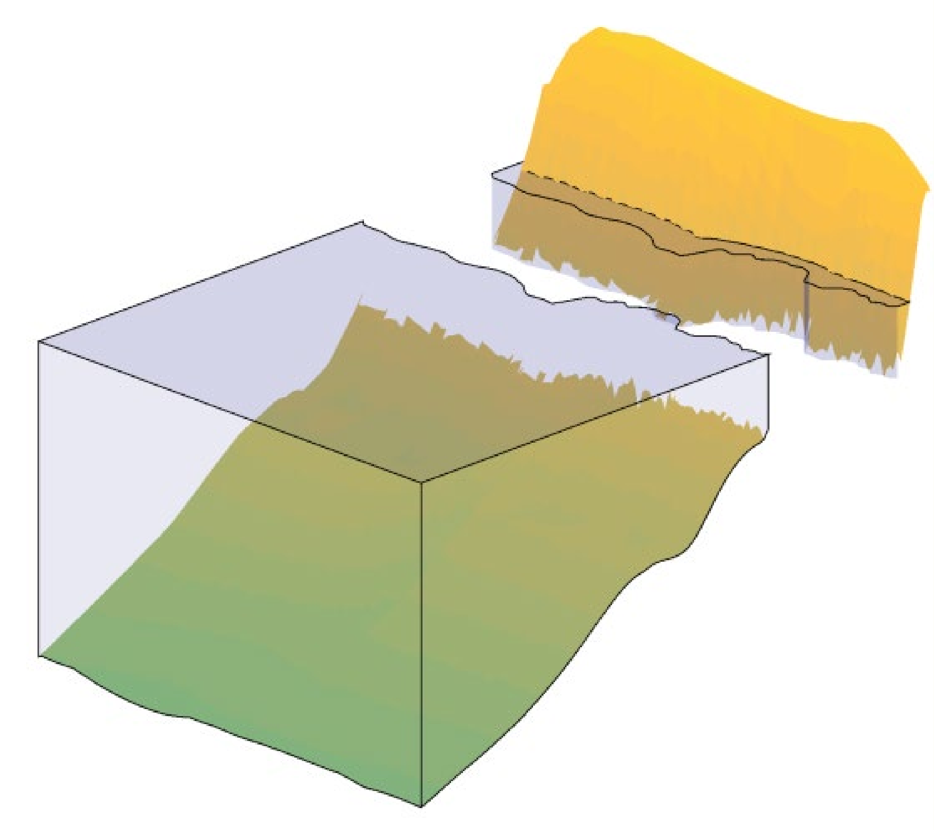
April 25, 2023

- Swash formulation and new justification
- 1D inter-model comparison
- 2D formulation challenges
- 2DH data

Swash Modeling



CMS SWASH Extension:

- Time-steady
- Wave and currents are combined
- Demarcation is at shoreline in absence of waves
- Hydrodynamics are one-way coupled, appropriate for simulations with low current at interface.
- Transport is two-way coupled
- Bed conservation is rigid
- Simplified propagation model
- Necessarily dependent on empirical data

Formulation

- Based on momentum eqn (As the energy eqn has lost meaning)
- All time-dependent term are lost (OK for thin film)

$$\frac{\partial}{\partial s}\left(\overline{U_s^2 h} + \frac{g}{2}\overline{h^2}\right) = -g\bar{h}\frac{\partial z_b}{\partial s} - c_f\overline{|U_s|U_s}$$

A far-reach here:

$$U \sim \sqrt{g\bar{h}} \qquad M \sim g\bar{h}^2 \sim gH_{rms}^2$$

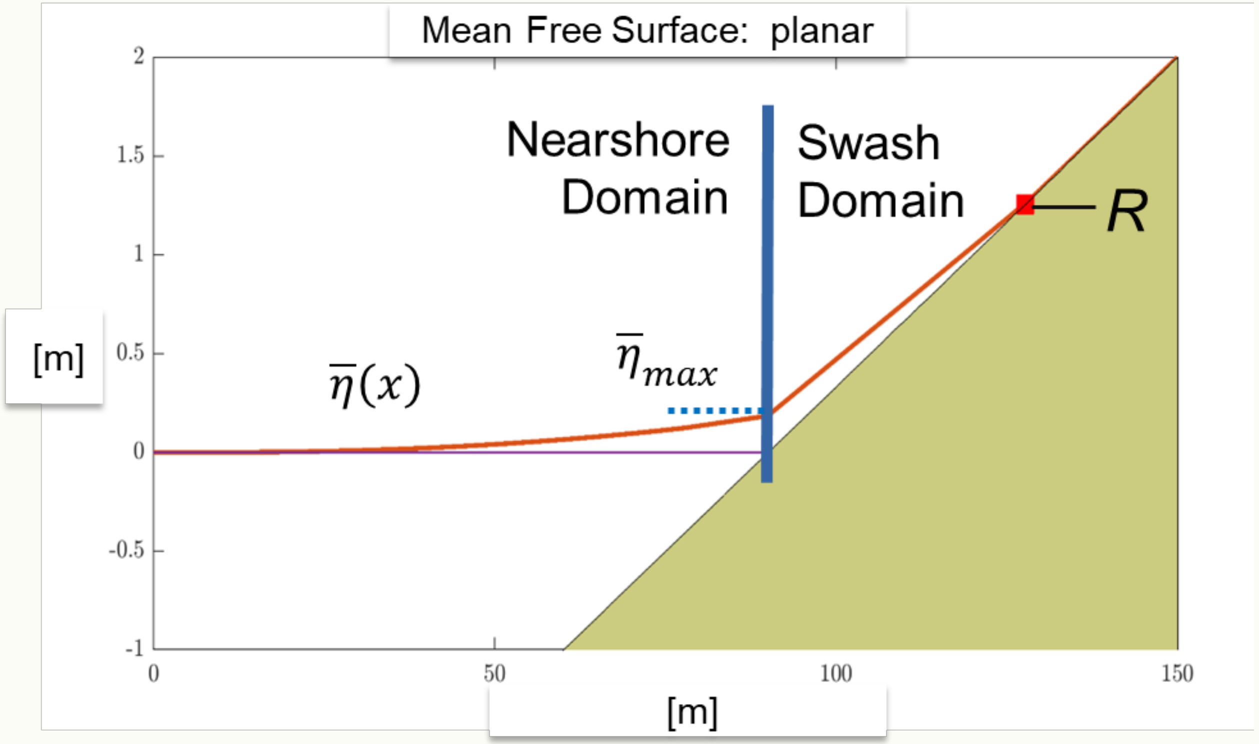
$$M = \overline{U_s^2 h} + \frac{g}{2}\overline{h^2}$$

$$M \simeq A_0 g\bar{h}^2 \qquad c_f' g\bar{h} \simeq c_f\overline{|U_s|U_s}$$

$$\frac{\partial}{\partial x}\left(M\cos\alpha\right) = -g\bar{h}\frac{\partial z_b}{\partial x} - c_f\overline{|U|U}\cos\alpha$$

New Domain partition

- Slope break of water line indicates differing physics
- Separate model domain, solve separately
  - Non-IG wave models predict *locally-identical* saturated wave height condition near the shoreline
  - Demarcation at a *constant depth* results in predictions of runup that are nearly constant



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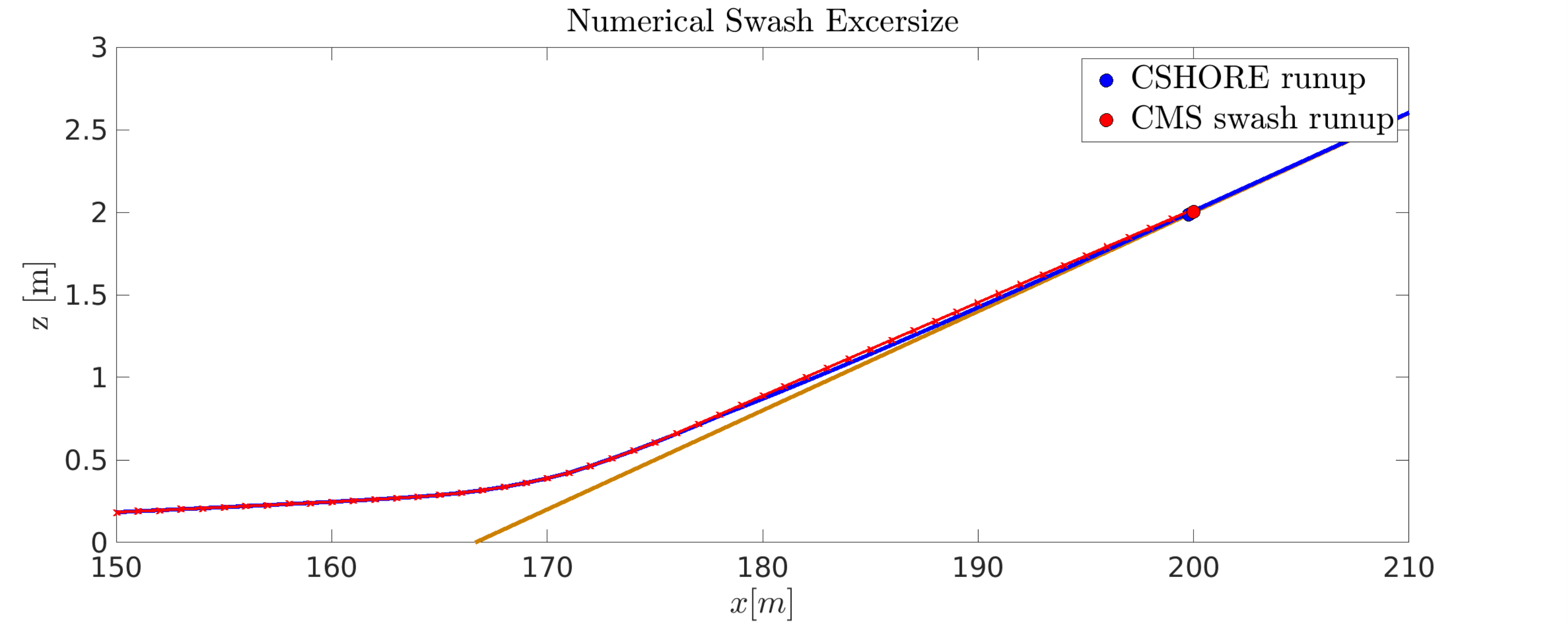
- Data (and intuition) indicate as $H_{mo}\uparrow$, $R_{2\%}\uparrow$ from both dynamic (oscillatory swash) and static (wave setup) components
  - NEW demarcation set to depth of max wave setup
  - Requires NEW simplified wave ray-tracing in CMS (trivial for steady 1D models)
  - Results in IG and setup components that are set proportional to *H* offshore

Swash Modeling

$$\frac{M_{i+i} - M_i}{\Delta x} = -g\overline{h_i}\frac{\partial z_b}{\partial x} - c_f' g\overline{h}$$

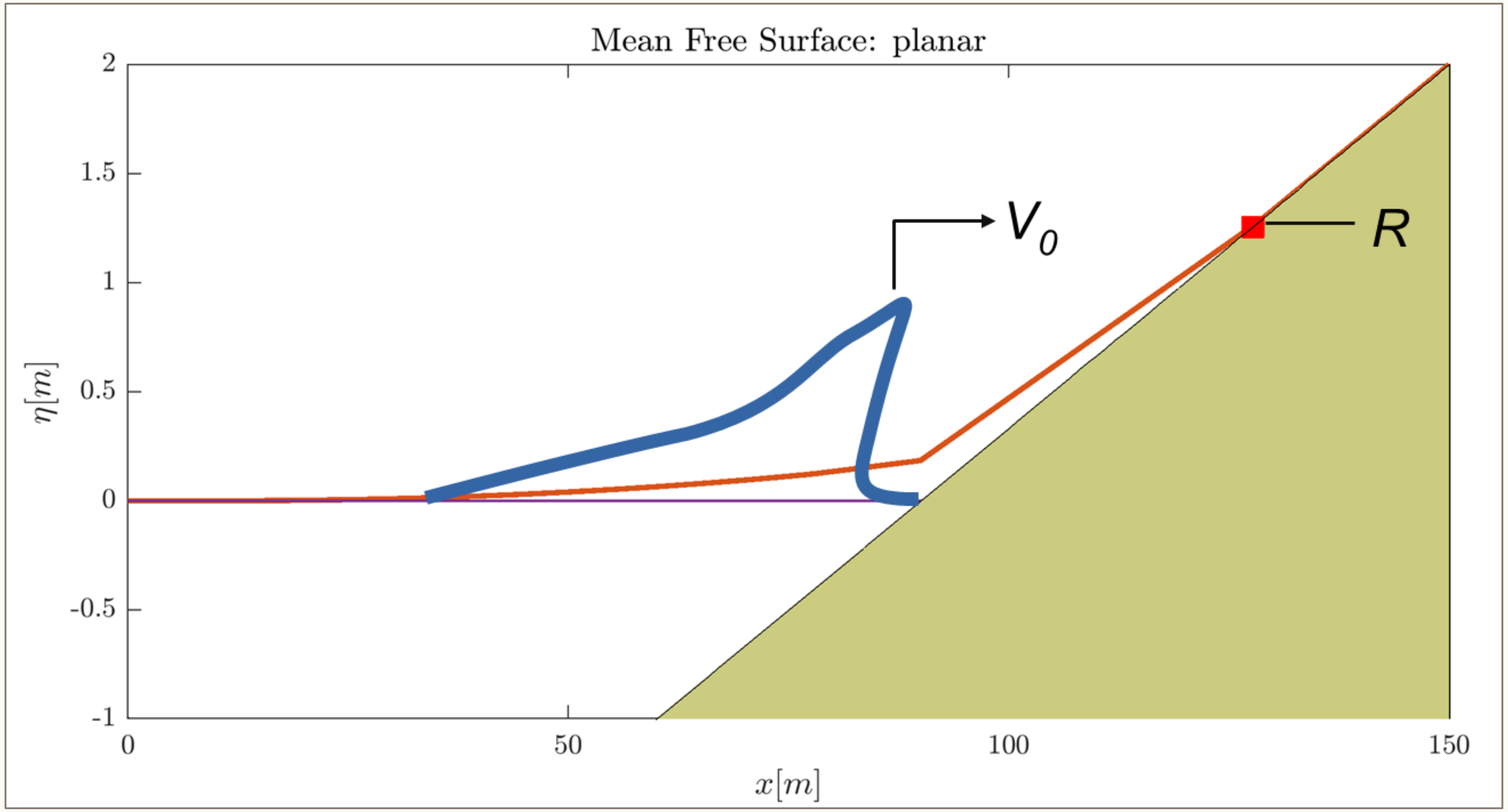
$$M \simeq A_0 g\overline{h}^2$$



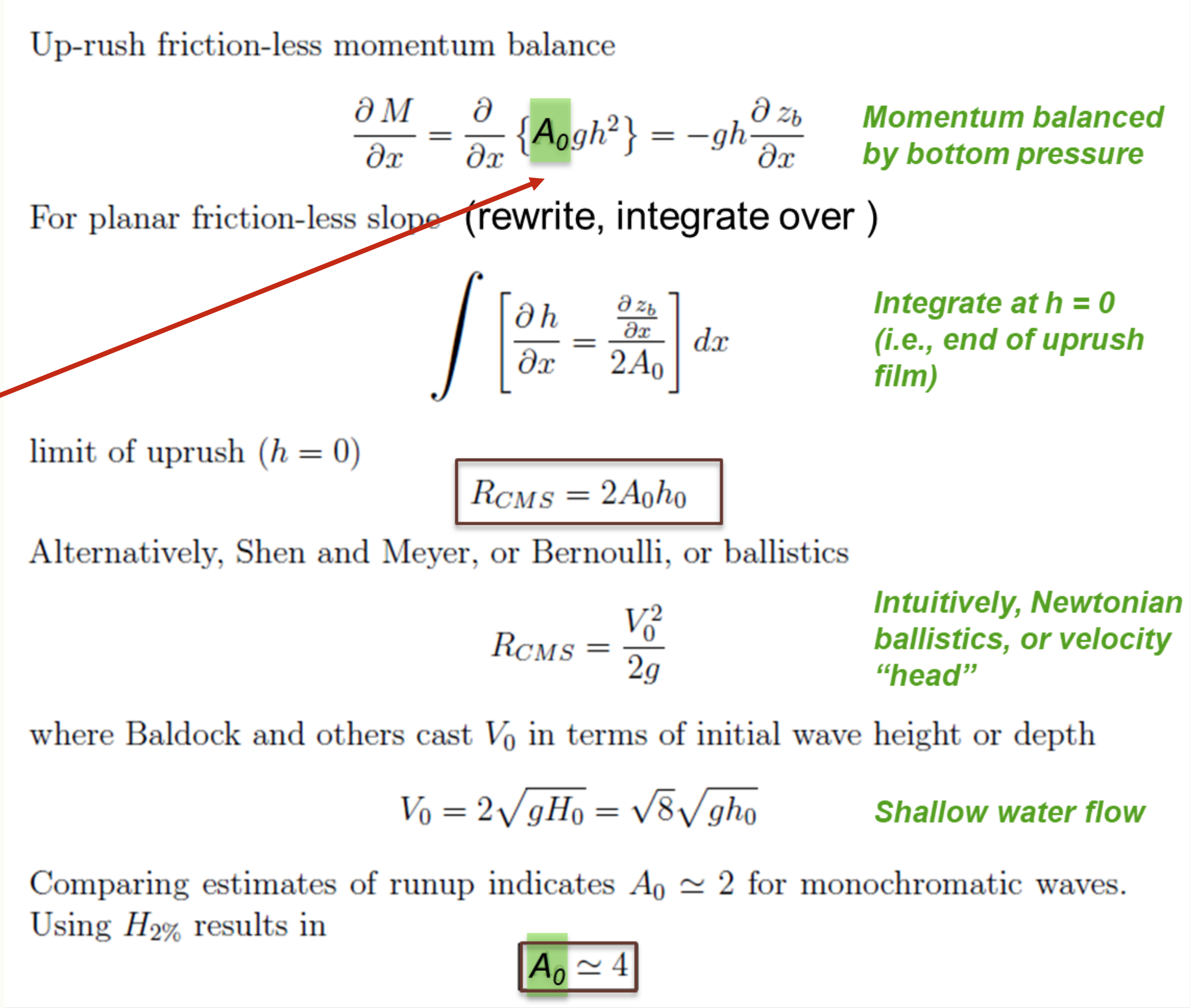
New Formulation Justification

Consider: Friction-less planar beach and monochromatic waves

Classic view of swash has a position at shoreline where bores collapse, generating fluid velocity V_0 and resulting in runup R



New Formulation Justification



Up-rush friction-less momentum balance

$$\frac{\partial M}{\partial x} = \frac{\partial}{\partial x}\{A_0 g h^2\} = -gh\frac{\partial z_b}{\partial x}$$

Momentum balanced by bottom pressure

For planar friction-less slope (rewrite, integrate over)

$$\int \left[\frac{\partial h}{\partial x} = \frac{\frac{\partial z_b}{\partial x}}{2A_0}\right] dx$$

Integrate at h = 0 (i.e., end of uprush film)

limit of uprush ($h = 0$)

$$\boxed{R_{CMS} = 2A_0 h_0}$$

Alternatively, Shen and Meyer, or Bernoulli, or ballistics

$$R_{CMS} = \frac{V_0^2}{2g}$$

Intuitively, Newtonian ballistics, or velocity "head"

where Baldock and others cast V_0 in terms of initial wave height or depth

$$V_0 = 2\sqrt{gH_0} = \sqrt{8}\sqrt{gh_0}$$

Shallow water flow

Comparing estimates of runup indicates $A_0 \simeq 2$ for monochromatic waves. Using $H_{2\%}$ results in

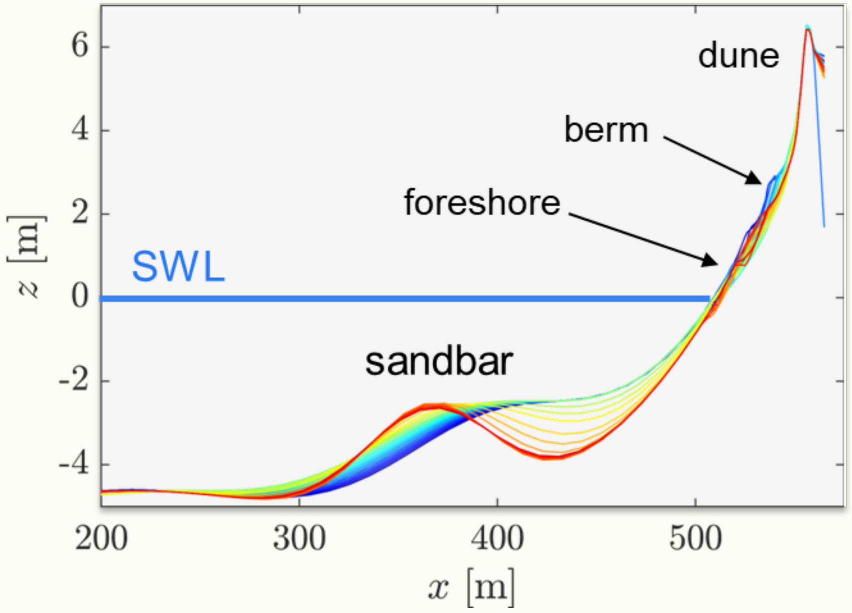
$$\boxed{A_0 \simeq 4}$$

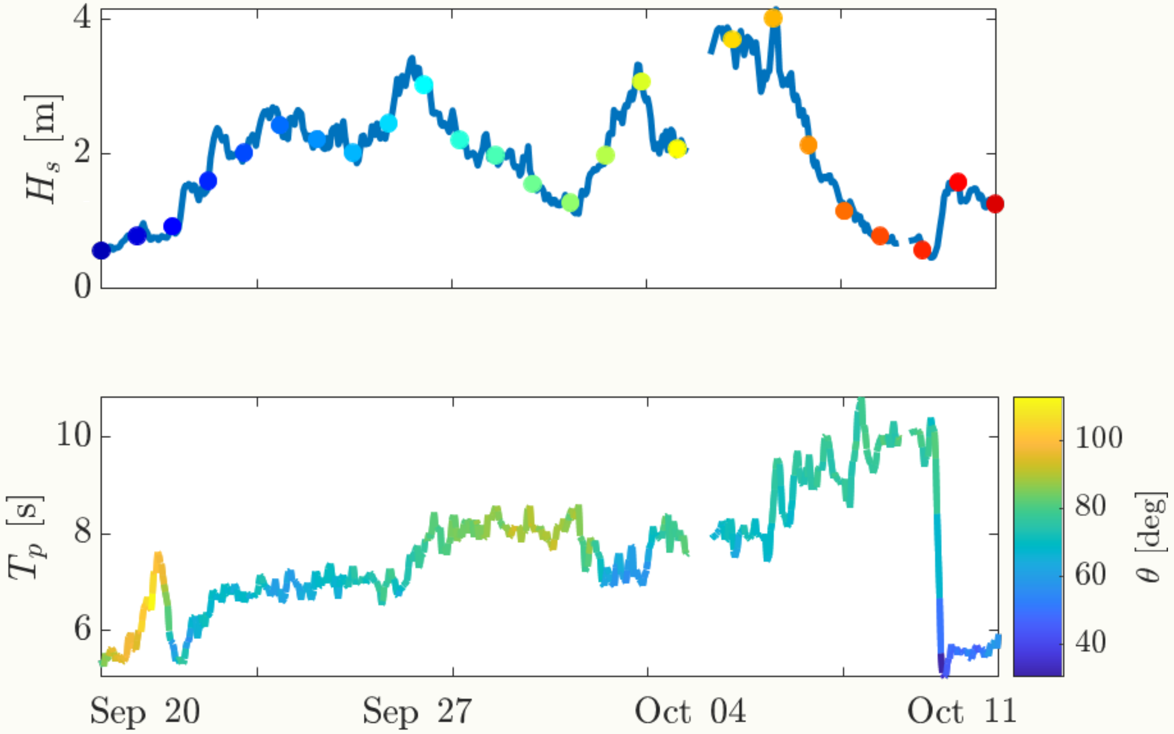
CMS Runup R_{CMS} requires single-parameter closure A_0

Closure A_0 varies for monochromatic H vs $H_{2\%}$

Model Comparison

- Validate swash-zone processes on wave-dominated coast (FRF, Duck, NC)
  - 2D case, comparison of surf zone velocity field collected via aerial optical imagery (*TD on Tues 4/25*)
  - ***1D case, comparison of wave runup statistics collected via continuous laser scanning (LiDAR)***
    - CMS/CSHORE and comparison models with range of complexity (algebraic to nonhydrostatic)
    - 533 “snapshots” of runup stats over 1.5 months

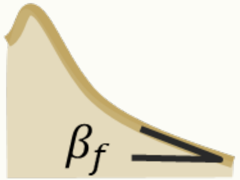




Model Comparison

- **Stockdon, et al. (2006) – least complex, mostly widely used Runup model**
  - Algebraic equation developed from observations at Duck FRF, West Coast, and abroad
  - Separate terms for different key physical processes, all dependent on Iribarren number (*Ib*)

$$R_{2\%} = 1.1\left\{\underbrace{0.35\beta_f(H_{mo}L_o)^{1/2}}_{\text{wave setup}} + \frac{1}{2}(H_{mo}\underbrace{L_o\left[0.563\beta_f^2\right.}_{\text{incident swash elevation}} \underbrace{\left.+ .004\right]^{1/2}}_{\text{infragravity (IG) swash elevation}}\right\}$$



$$Ib = \frac{tan(\beta_f)}{\sqrt{H_{mo}/L_o}}$$

H_{mo} = deep water wave height

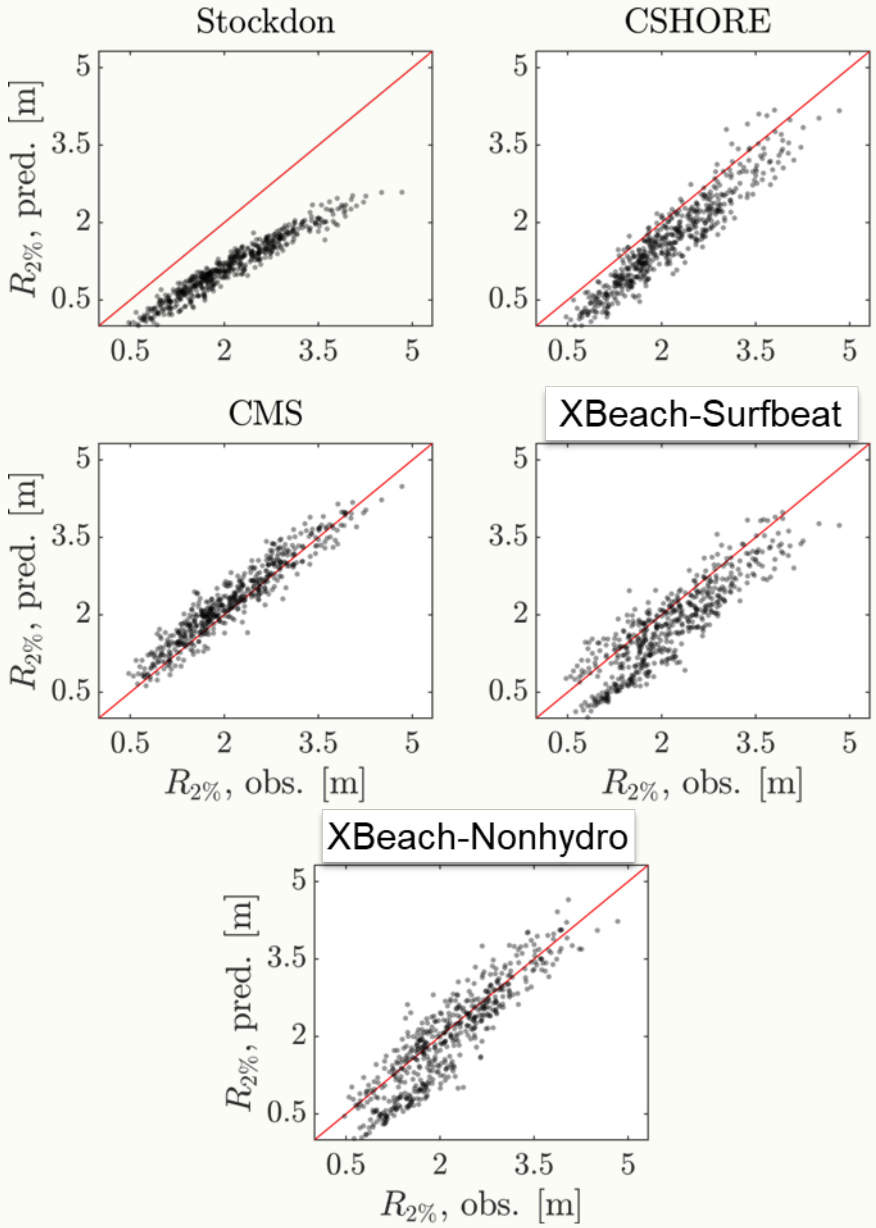
L_o = deep water wavelength

- **XBeach – more complex, two modes with distinctly different physics**
  - Surfbeat – phase averaged; swash routine forced with IG energy band and wave group envelope
  - Nonhydrostatic (most complex) – phase (wave-by-wave) resolving, similar to Boussinesq models, nonlinear frequency interactions, breaking, fully dispersive

Intermodel comparison

	Runtime	RMSE (m)	NRMSE (-)
Stockdon, et al. (2006)	0.18 s	1.01	0.89
CSHORE	25.0 s	0.55	0.34
CMS – new formulation	**4.1 min**	**0.29**	**0.13**
XBeach-Surfbeat	35.5 hr	0.53	0.30
XBeach-Nonhydrostatic	124.4 hr	0.45	0.23

- After model improvements, CMS had the lowest (N)RMSE
- East/West observations indicate closure parameter $\boldsymbol{A_0}$ does have some variation



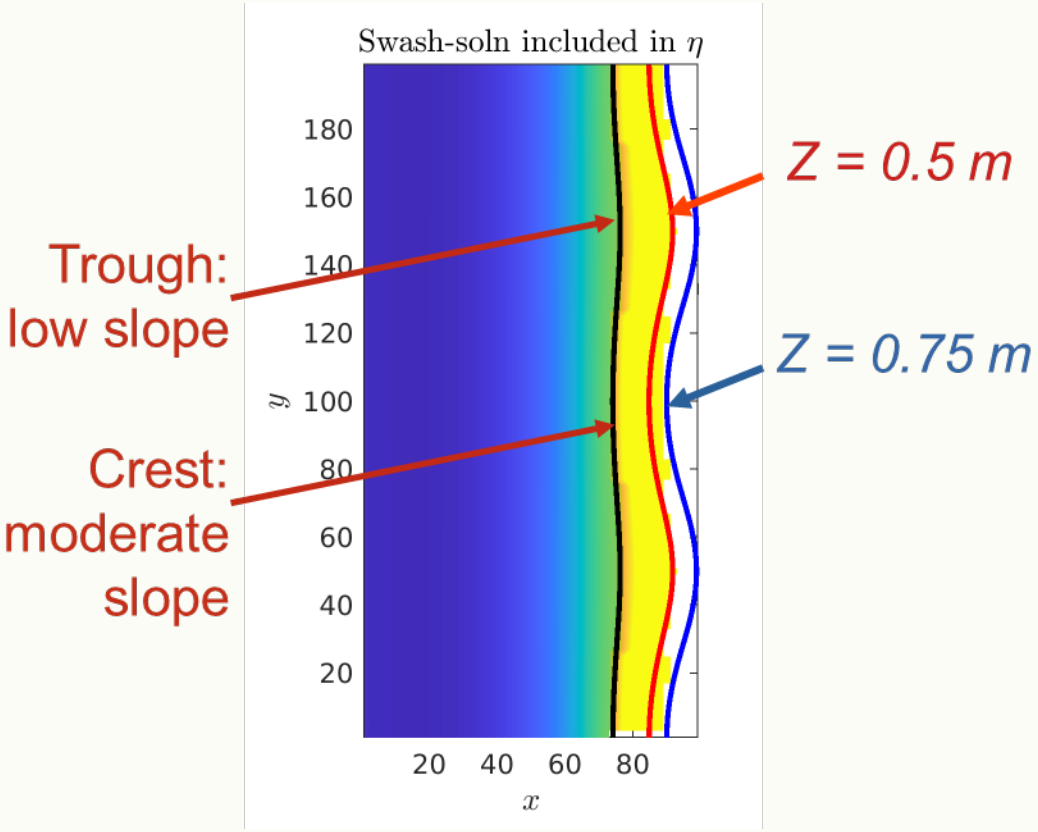
2DH Formulation

Analytical Surface

- Cuspate Beach
- L = 100m

Series of 1D longshore-uniform computations

- Demonstrates proper
- slope-dependence
- Doesn’t include realistic momentum veering



Trough: low slope

Crest: moderate slope

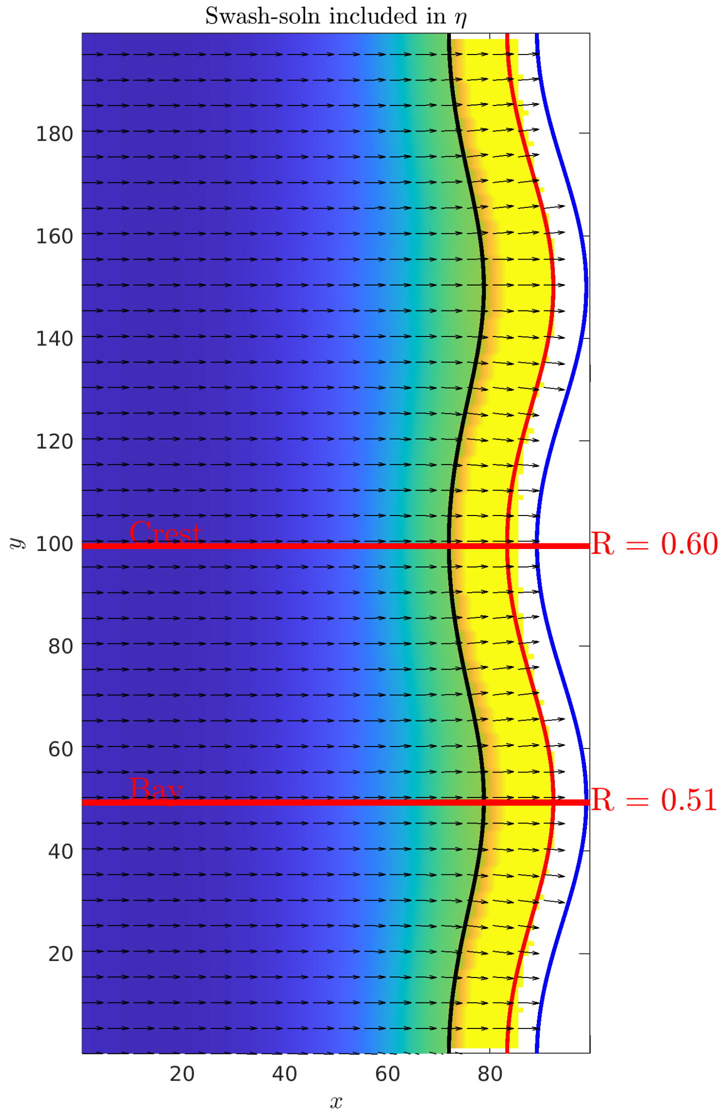
Z = 0.5 m

Z = 0.75 m

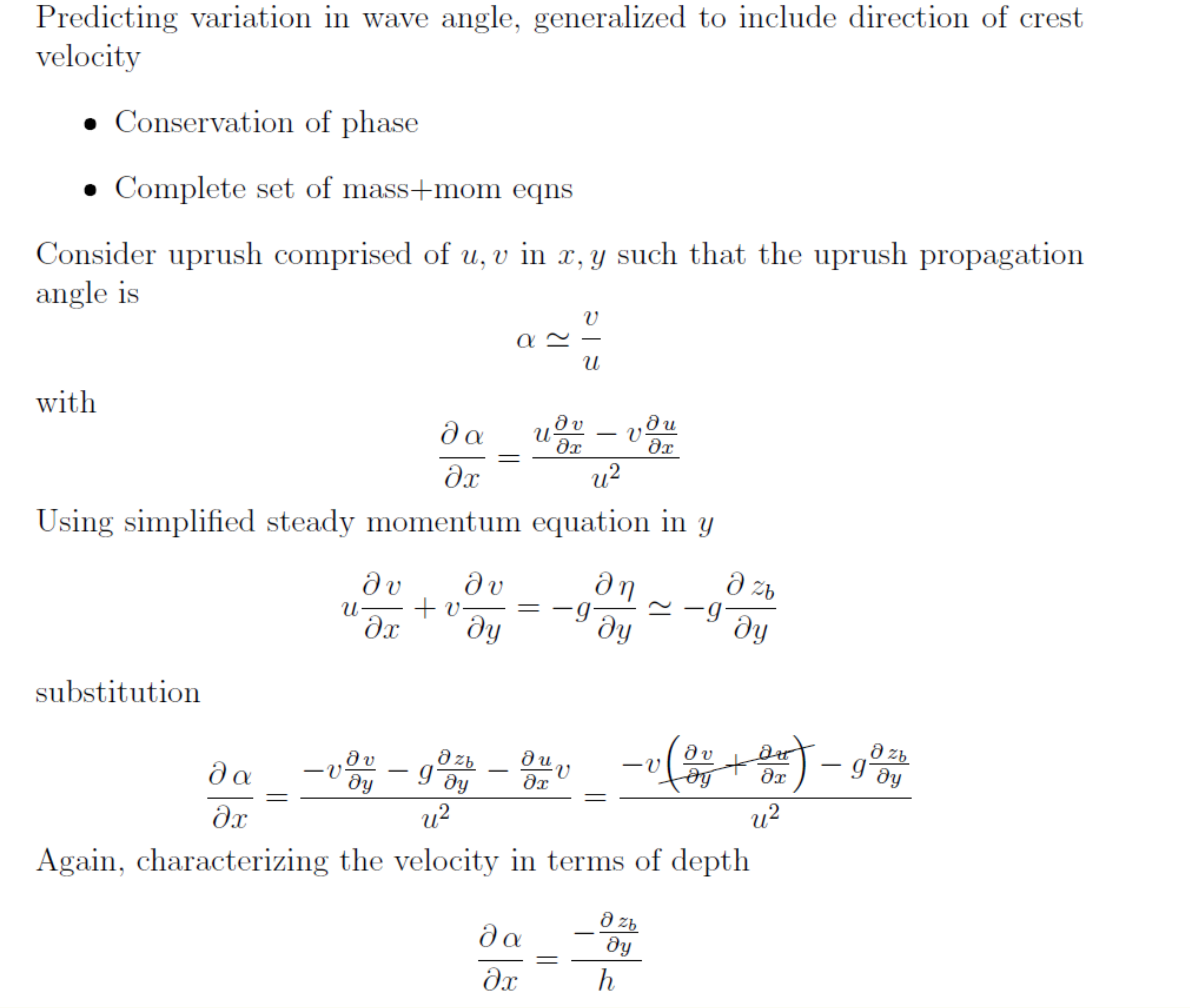
2DH Formulation

CMS-Wave and 2D swash

- Wave vector → crest velocity
- Swash vectors inherit angle
- Crest velocities SHOULD veer away from crest
- Require proper angle variation for sediment transport



2DH Formulation



Predicting variation in wave angle, generalized to include direction of crest velocity

- Conservation of phase
- Complete set of mass+mom eqns

Consider uprush comprised of u, v in x, y such that the uprush propagation angle is

$$\alpha \simeq \frac{v}{u}$$

with

$$\frac{\partial\,\alpha}{\partial x} = \frac{u\frac{\partial\,v}{\partial x} - v\frac{\partial\,u}{\partial x}}{u^2}$$

Using simplified steady momentum equation in y

$$u\frac{\partial\,v}{\partial x} + v\frac{\partial\,v}{\partial y} = -g\frac{\partial\,\eta}{\partial y} \simeq -g\frac{\partial\,z_b}{\partial y}$$

substitution

$$\frac{\partial\,\alpha}{\partial x} = \frac{-v\frac{\partial\,v}{\partial y} - g\frac{\partial\,z_b}{\partial y} - \frac{\partial\,u}{\partial x}v}{u^2} = \frac{-v\cancel{\left(\frac{\partial\,v}{\partial y} + \frac{\partial\,u}{\partial x}\right)} - g\frac{\partial\,z_b}{\partial y}}{u^2}$$

Again, characterizing the velocity in terms of depth

$$\frac{\partial\,\alpha}{\partial x} = \frac{-\frac{\partial\,z_b}{\partial y}}{h}$$

A general conservation statement

$$\begin{aligned} \frac{\partial\, LM}{\partial x} &= -Lgh\left\{\frac{\partial\, z_b}{\partial x} + c_f\right\} \\ \frac{\partial\, L}{\partial x}M + L\frac{\partial\, M}{\partial x} &= -Lgh\left\{\frac{\partial\, z_b}{\partial x} + c_f\right\} \end{aligned}$$

making use of

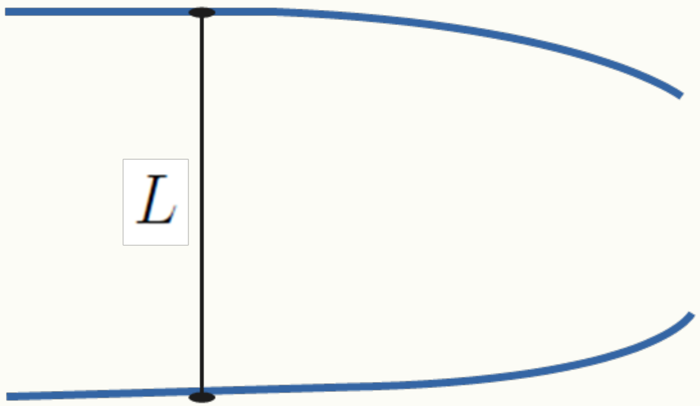
$$\frac{\partial\, L}{\partial x} = 2\Delta y\frac{\partial\, \alpha}{\partial y} \;\; ; \;\; L \simeq 2\Delta y$$

results in

$$\frac{\partial\, M}{\partial x} = -gh\left\{\frac{\partial\, z_b}{\partial x} + c_f\right\} - \frac{\partial\, \alpha}{\partial y}\frac{\Delta y}{\Delta x}M$$

or in h

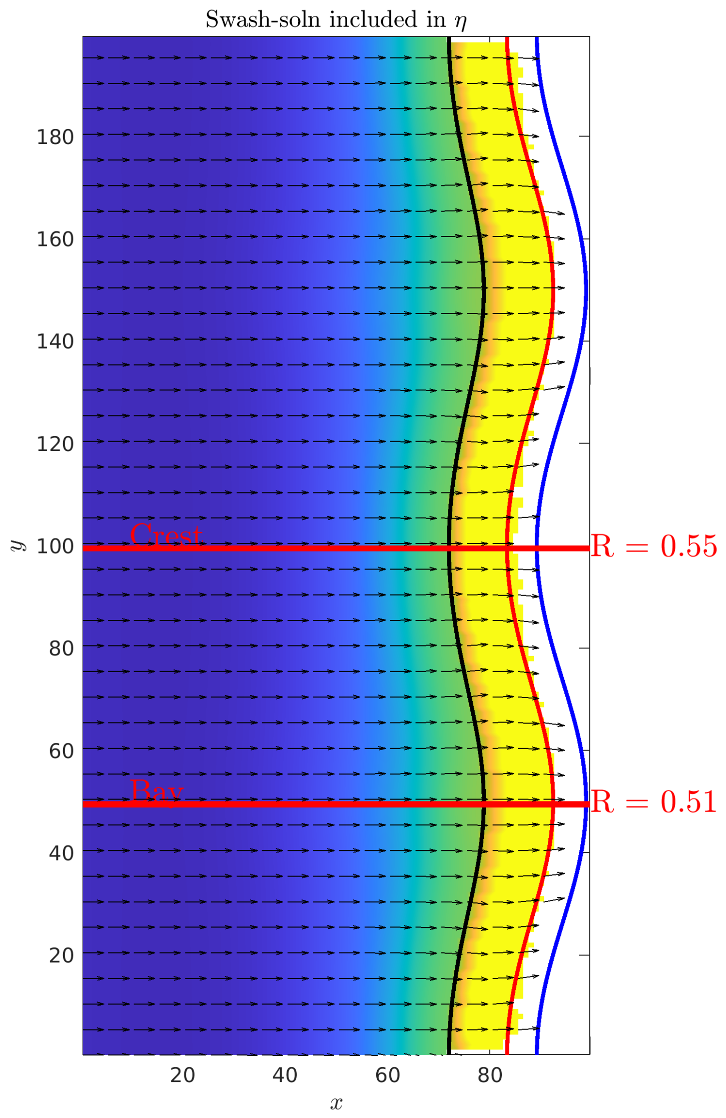
$$\frac{\partial\, h}{\partial x} = \frac{-\left\{\frac{\partial\, z_b}{\partial x} + c_f\right\}}{2A_0} - \frac{h}{2}\frac{\partial\, \alpha}{\partial y}\frac{\Delta y}{\Delta x}$$



Updated 2DH Formulation

<u>CMS-Wave and 2D swash</u>

- Now include veering and momentum focus/defocus
- Runup reduced at ridges
- Formulation now requires predictor-corrector scheme
- Localized nature of CMS presents a challenge
- Data is required to verify simple formulation



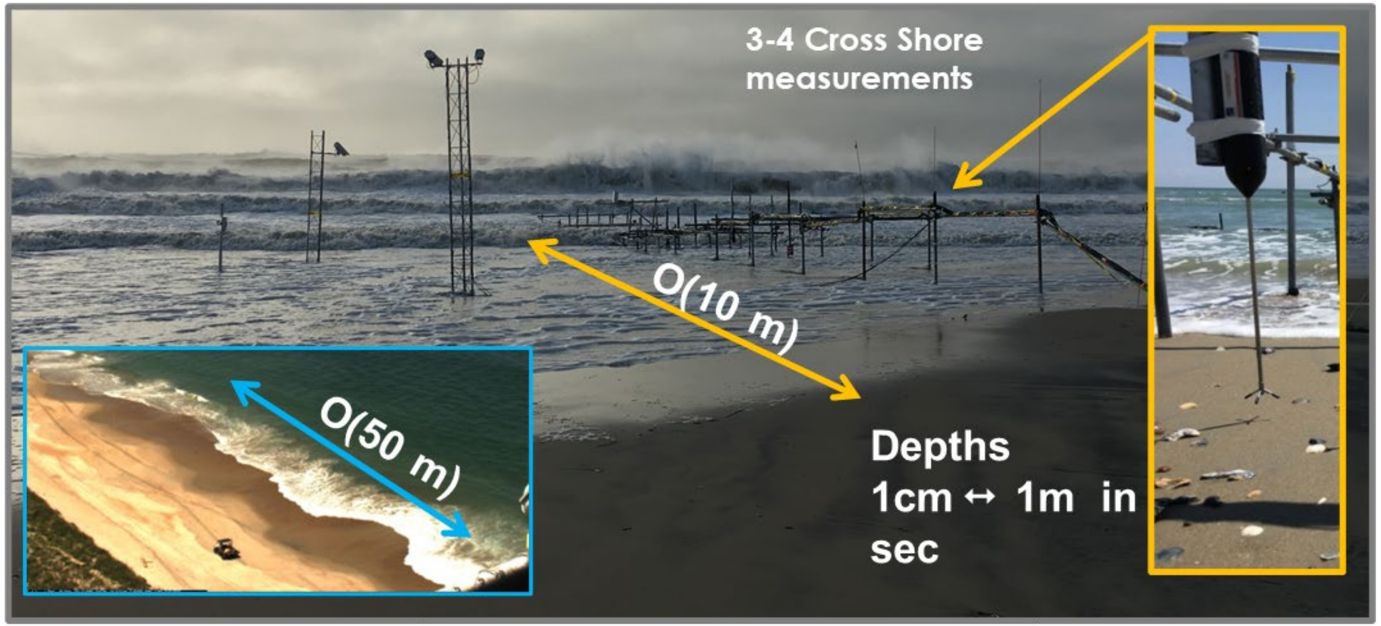
BACKGROUND

The Swash Zone

- Energetic + dynamic ocean/beach interface
- Flows critical for understanding + predicting
  - Cross/alongshore sediment transport
  - Runup
  - Shoreline evolution

In-situ Measurements Difficult + Laborious

- Rapidly changing environment
  - Water depths
  - Topography
  - Location/ Extent
- Bubble + Sediment laden flows
- Harsh Environment
  - Strong currents >2m/s
  - Shorebreak, bores



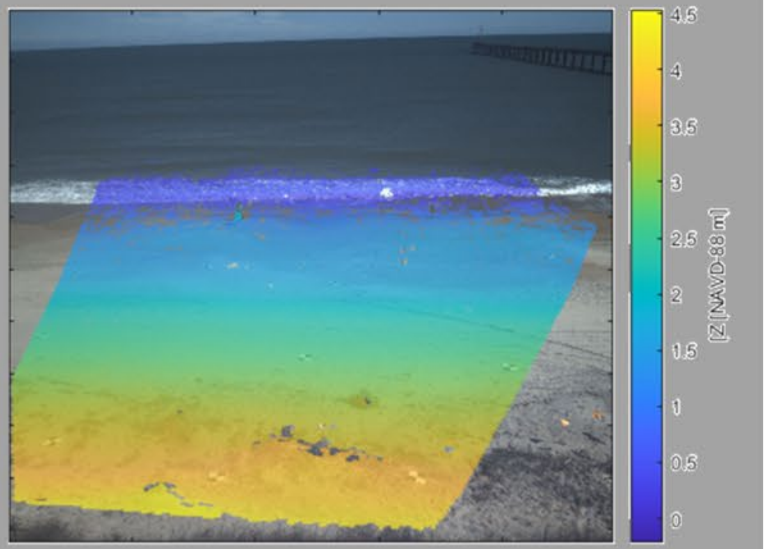
As a result, alongshore swash hydrodynamics have limited field measurements for model validation

APPROACH

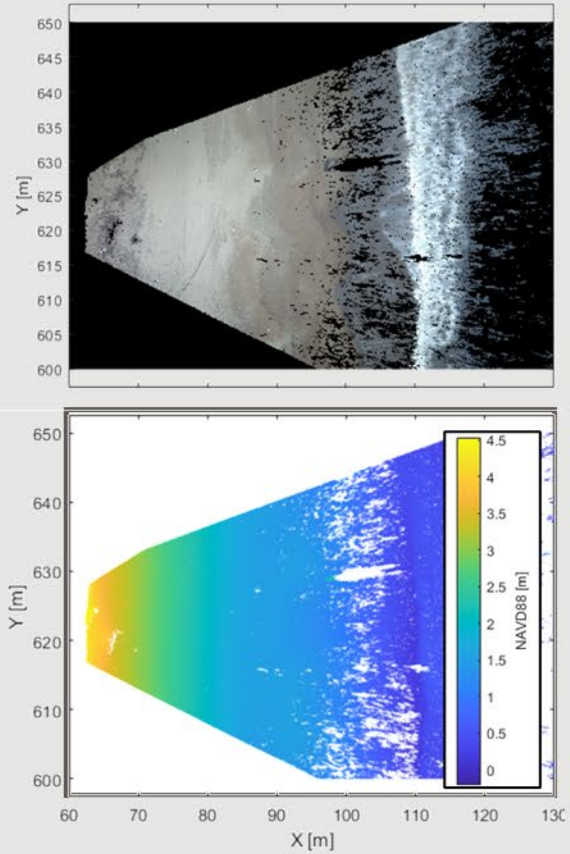
Stereophotogrammetry

Using overlapping + simultaneous imagery

to estimate depth field + absolute position/ elevation with GCPs

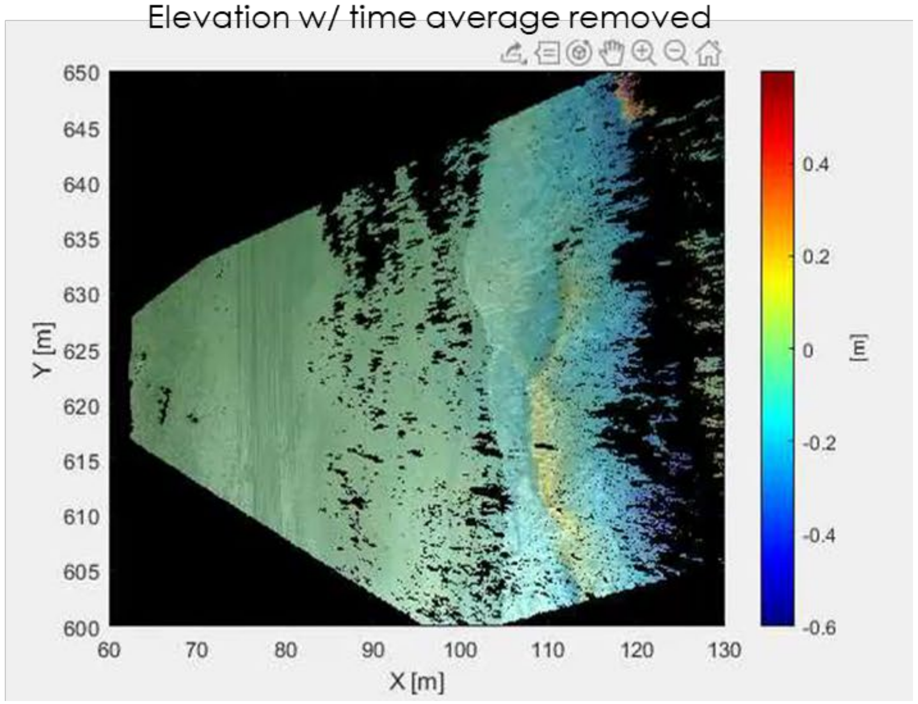


and provide accurate 3D point clouds of topography and water surface



2019 PILOT DEMONSTRATION

PARTICIPATED IN 2019 DURNING NEARSHORE EVENT EXPERIMENT (DUNEX) PILOT USACE ERDC-CHL FIELD RESEARCH FACILITY: DUCK,NC



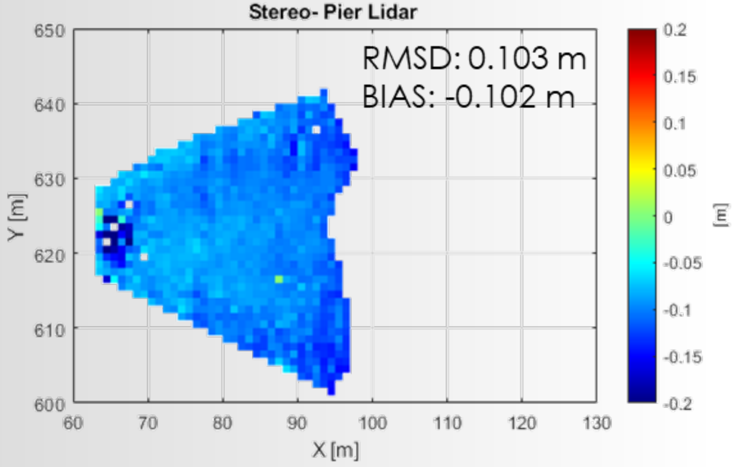
Collected 2Hz imagery 10 min every hour concurrent with in-situ pressure sensors

Stereo imagery processed with Agisoft Metashape Batch Processing (No Fixed GCPS)

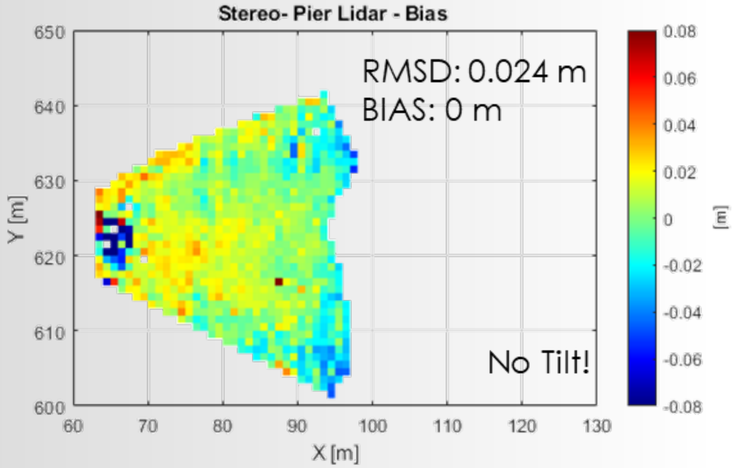
- 1200 Point Clouds Each hour @
  - 2Hz
  - 50 Alongshore extent
  - 70 m Cross-shore extent

2019 DEMONSTRATION

Stereo topography stable and had small constant bias (10 cm) and RMSE (3 cm) with terrestrial Lidar



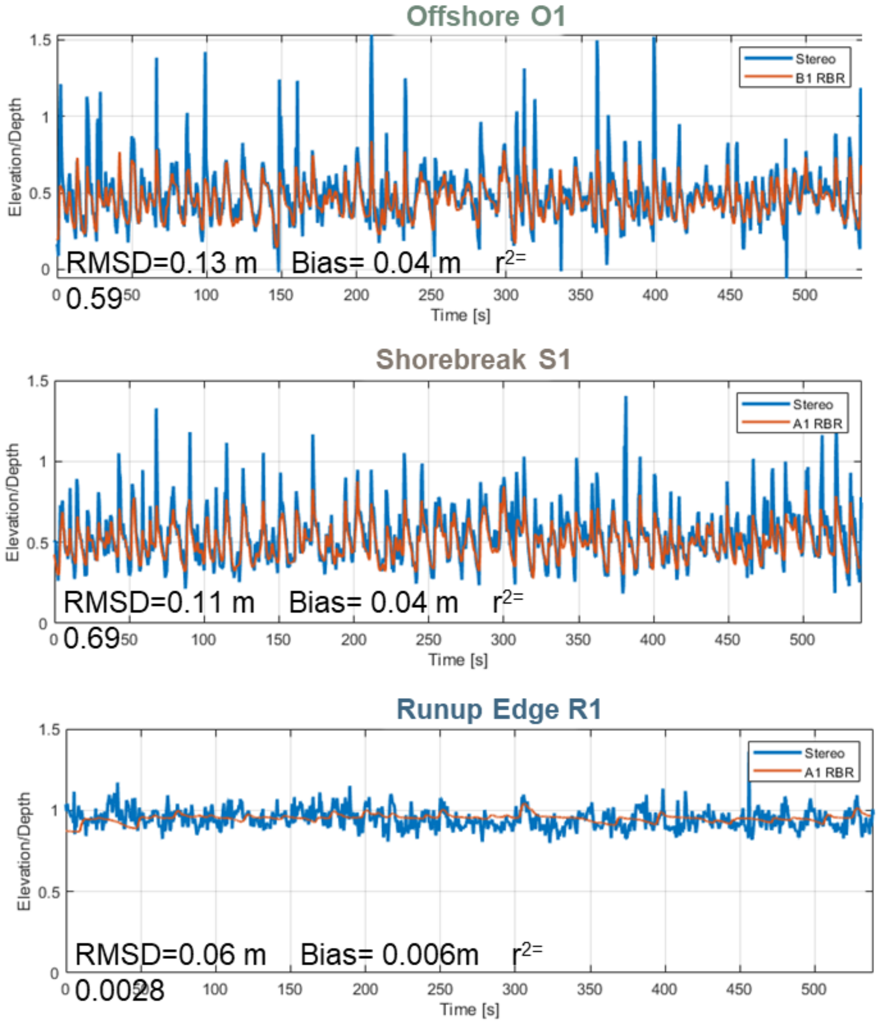
RMSD: 0.103 m
BIAS: -0.102 m



RMSD: 0.024 m
BIAS: 0 m

No Tilt!

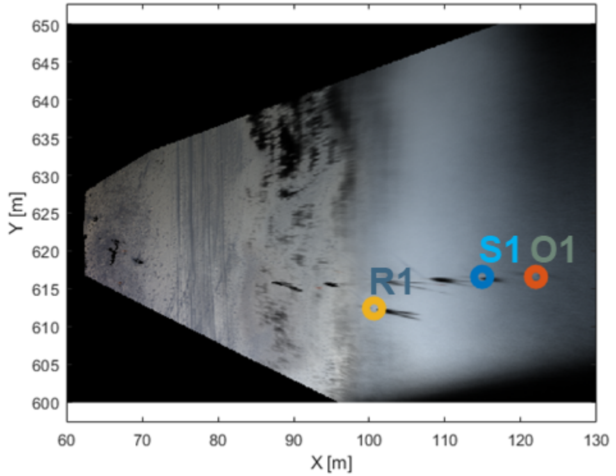
Absolute water level elevation and wave statistics had good correlation with in-situ pressure gauges (assuming hydrostatic pressure)

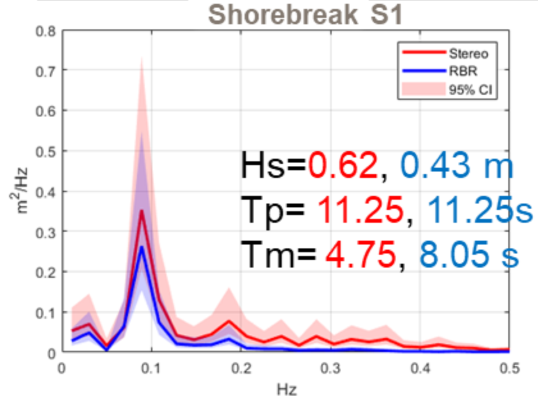


RMSD=0.13 m Bias= 0.04 m r^2= 0.59

RMSD=0.11 m Bias= 0.04 m r^2= 0.69

RMSD=0.06 m Bias= 0.006m r^2= 0.0028



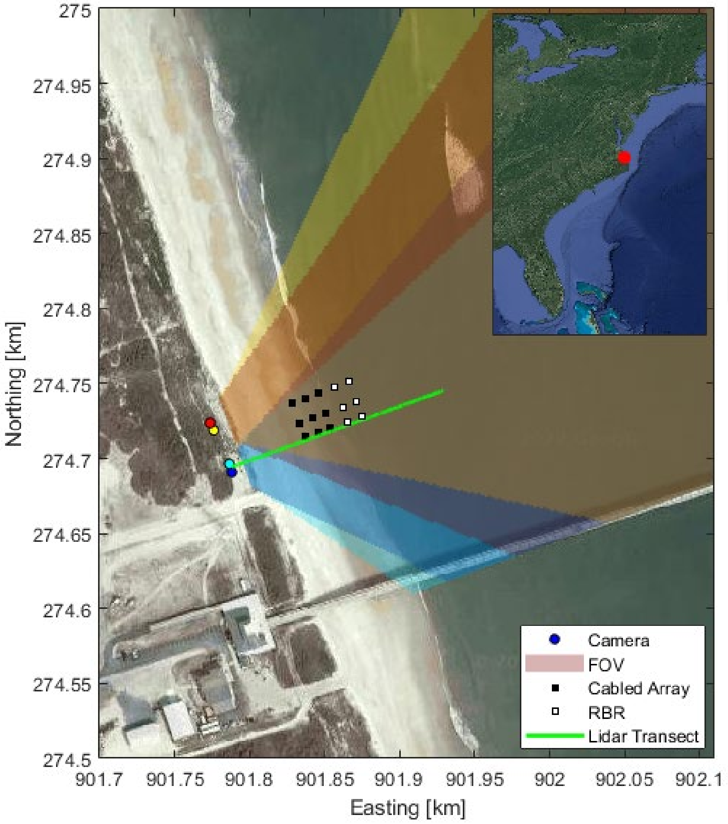


Hs=0.62, 0.43 m
Tp= 11.25, 11.25s
Tm= 4.75, 8.05 s

Upper Swash <5cm within stereo noise level

2021 EXPERIMENT

REPLICATED 2019 EFFORT AT LARGER SCALE FOR 2021 DUNEX




Two Stereo Camera Pairs


North Camera Views


South Camera Views

Remote Sensing

Two Towers 15m NAVD88, each with

- i2Rgus System
  - Two 12MP Cameras, 2Hz
  - GPS Triggered
  - 8mm Lens
  - 30 Min during daylight hours
- Reigel Z210ii 905nm Lidar (1 Tower)
  - Every hour 1 frame scan
  - Every hour 30 min linescan, 7Hz

In-situ

3x3 Cabled Analog Instrument Swash Array

- Spacing approx. 10-15m
- SBE-50 Pressure Sensor
- Nortek Vectrino
- Continuous recording @ 10Hz
- GPS Time synced


Cabled Array

Collected From September 2- November 5, 2021.

- Few Instances where all running simultaneously (Best late October)
  - Buried sensors, fogged cameras, etc
- Sensors adjusted every day

STEREOPROCESSING

Imagery

- 12 MP Image → 36 Mb
- 4 Cameras, 2Hz, 30 min

500 GB/Collect

136 TB over 2 months

Processor

- AMD Ryzen 9 5950X 16-Core Processor 3.40 GHz
- 128 RAM
- 2 NVIDIA GeForce RTX 380 w/ 74 GB Memory

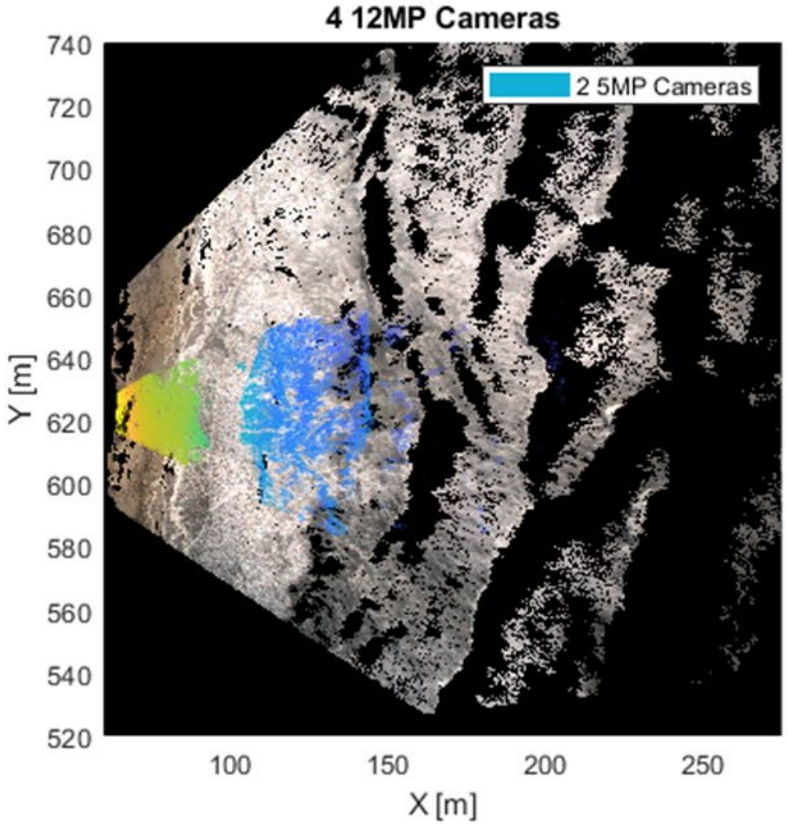
Elevation Output

- 3600 Metashape Point Clouds (PCs)
- Highest Accuracy/Depth Filter : 1 min/PC
- Each PC: 14Mil Pts, 240PPm^2, 0.4 Gb

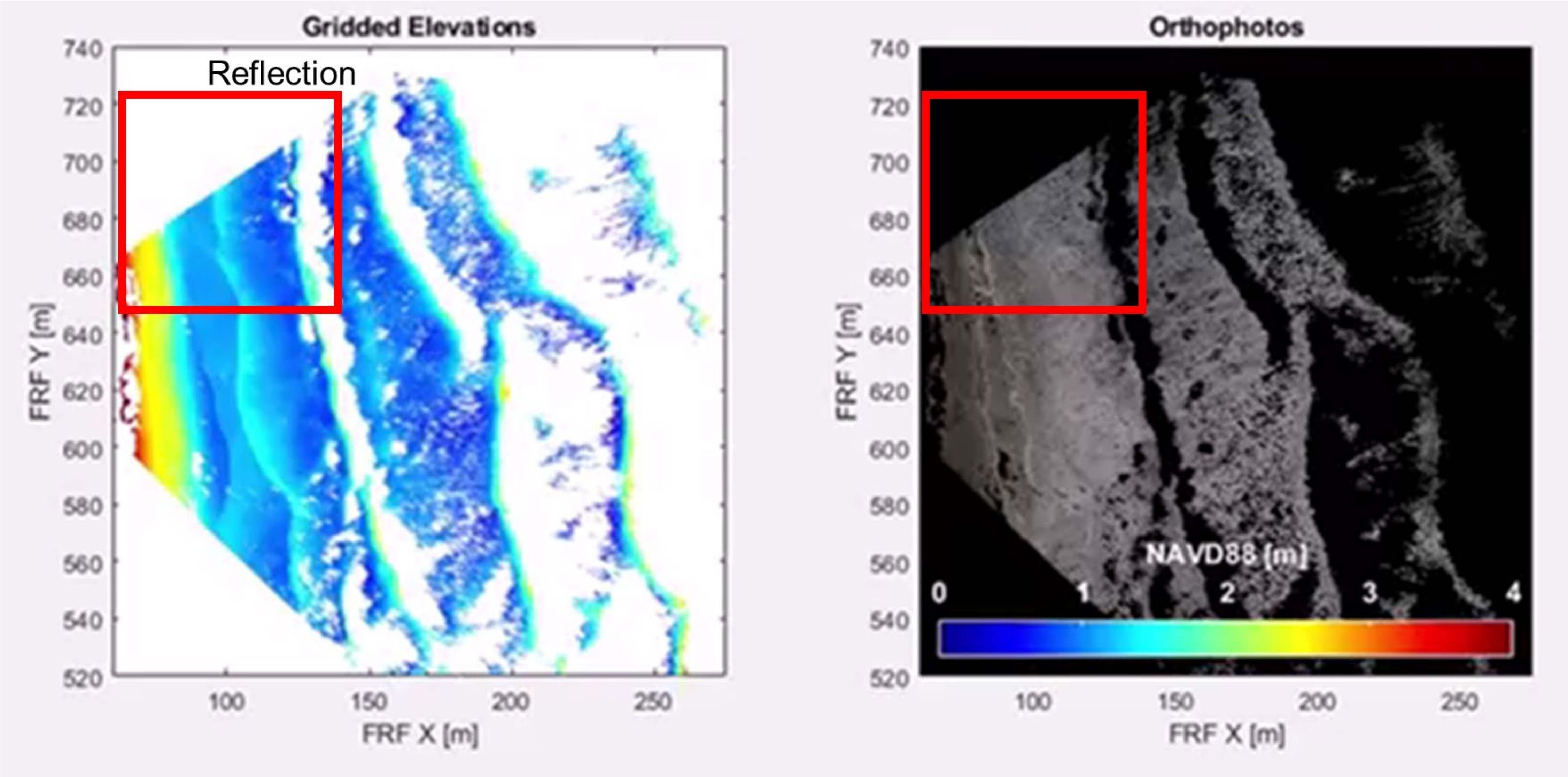
1.5 Tb/Collect (PCs)

0.7 Gb/Collect (20cm Grid)

60hrs/Collect



Example Data Products



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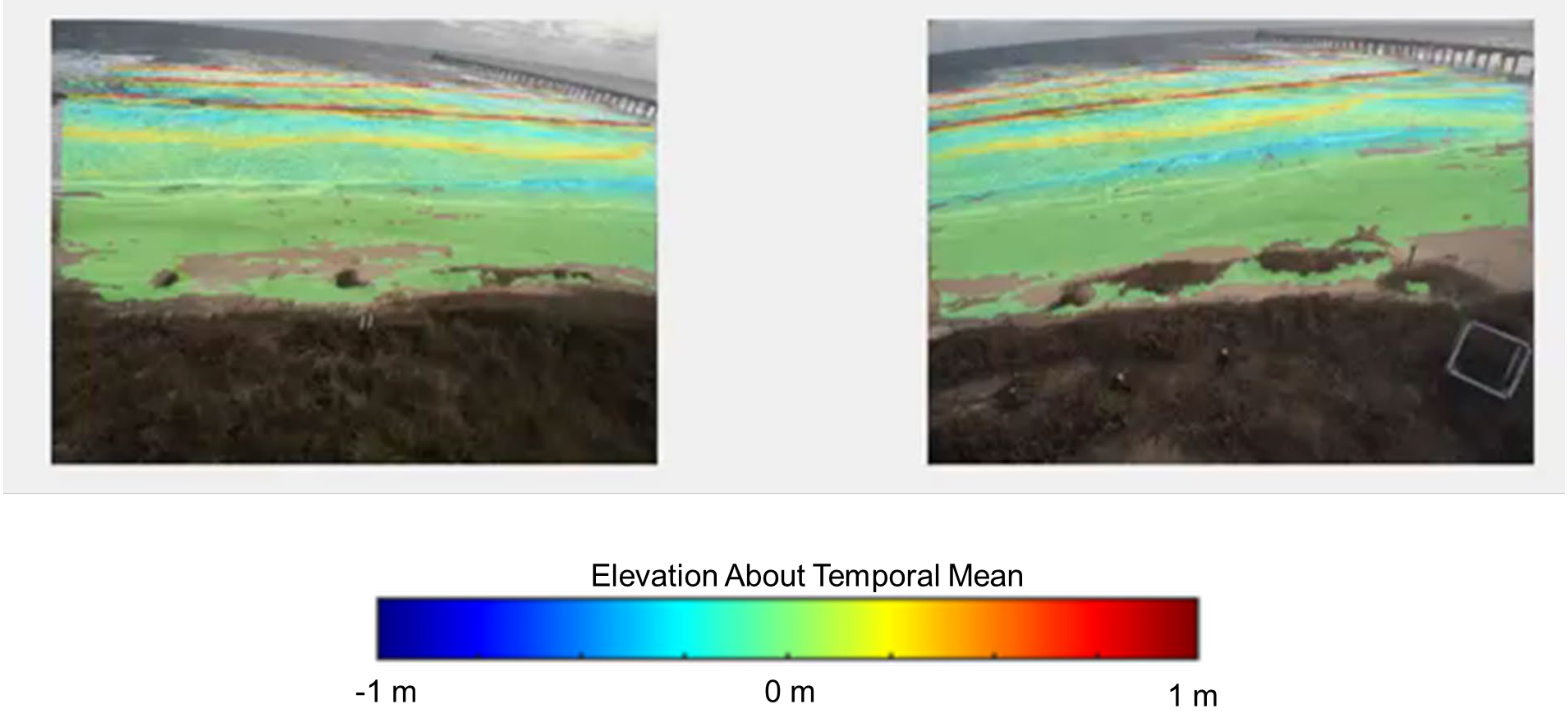


Ground Truth Comparisons

Conditions

November 5, 2021 1400-1430 GMT

Hs= 1.98 m

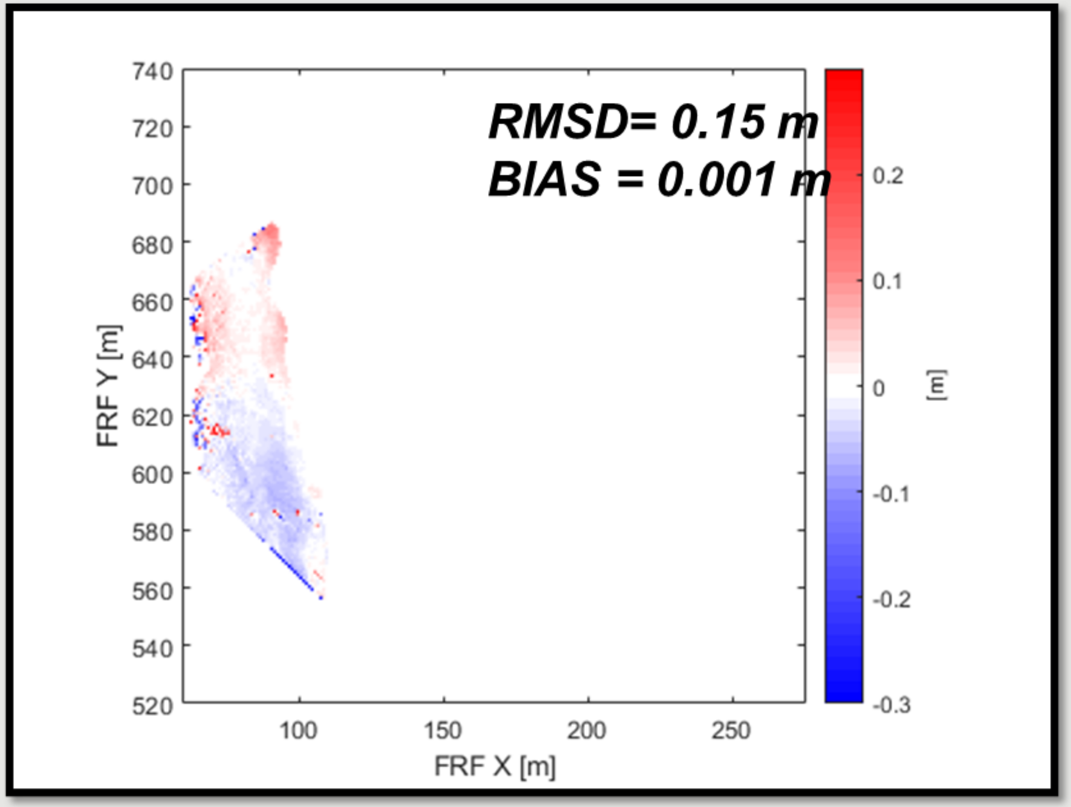
Tm=12.54 s

Tp=15.38 s

Water Level= 0.575 m (High Tide

Dp=102 deg (from SE)

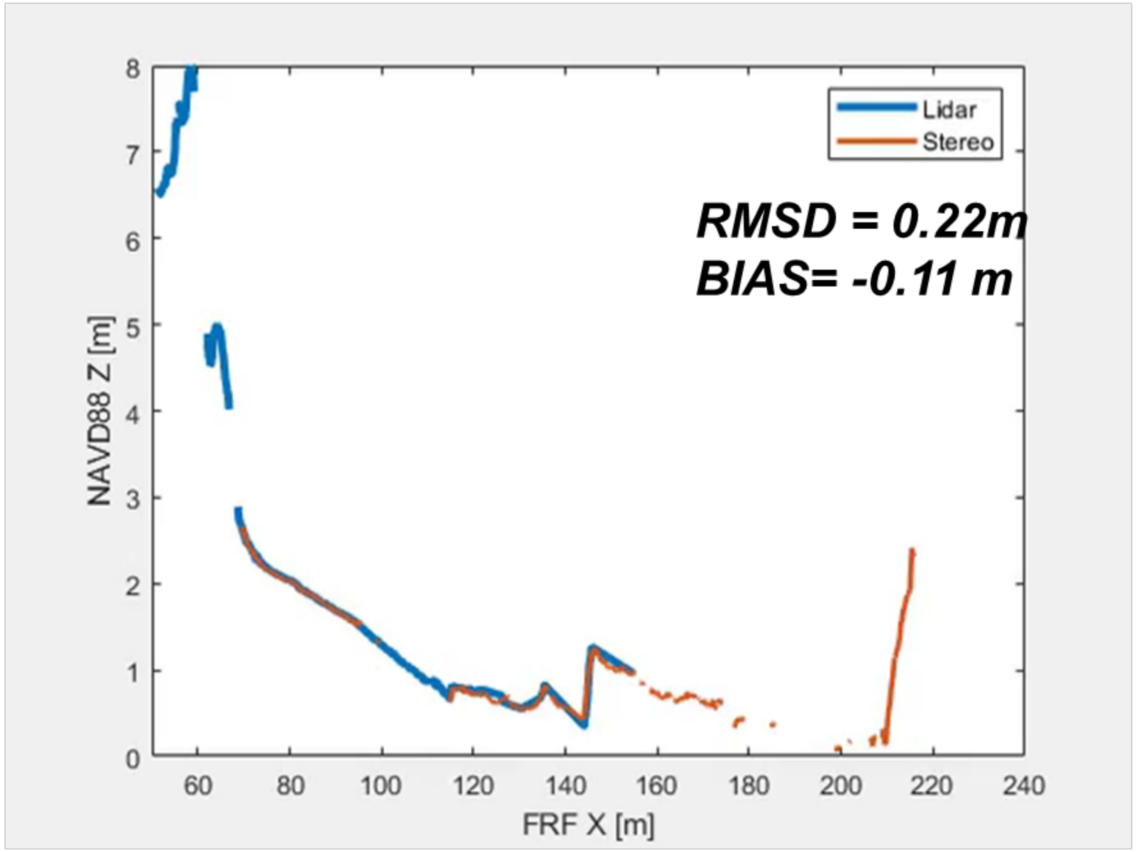
Lidar- Topography



RMSD= 0.15 m

BIAS = 0.001 m

Lidar- Water Surface



RMSD = 0.22m

BIAS= -0.11 m

Lidar Processing: O'Dea 2019

Velocity Comparisons

Conditions

November 5, 2021 1400-1430 GMT

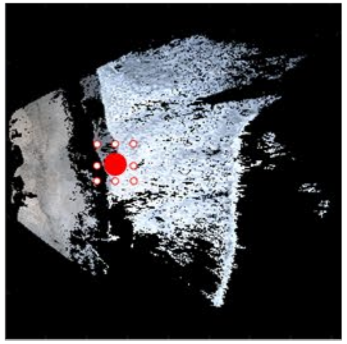
Hs= 1.98 m

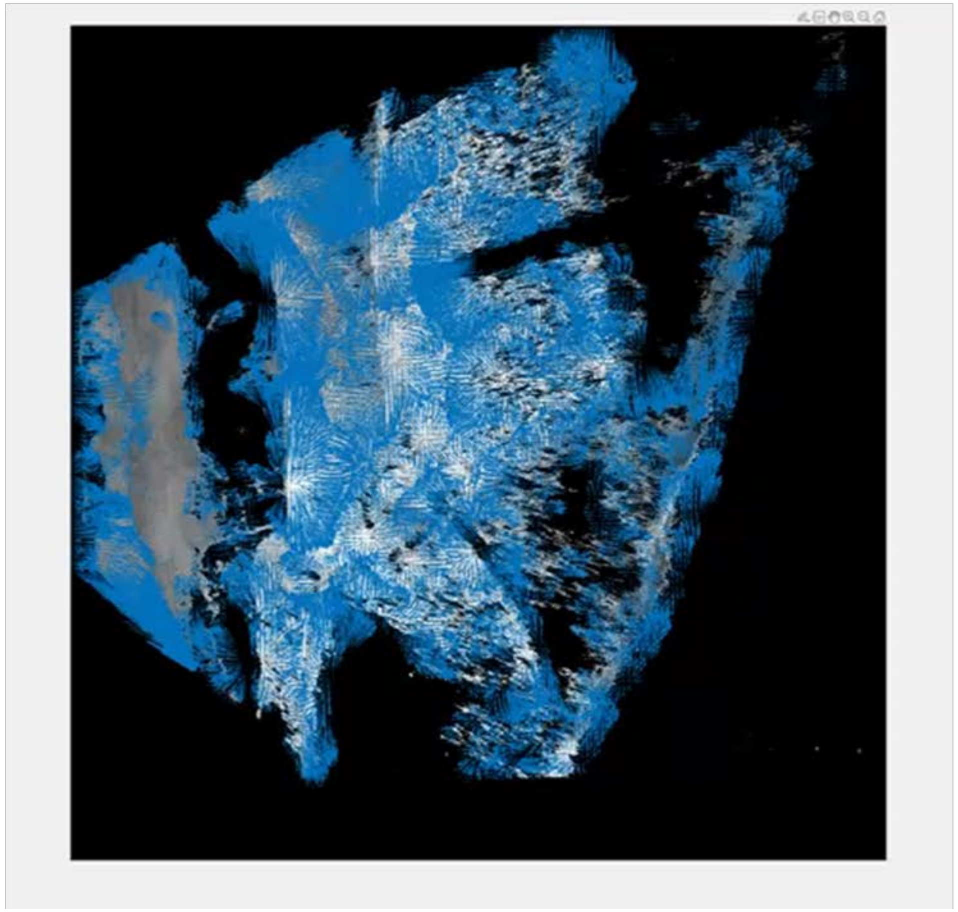
Tm=12.54 s

Tp=15.38 s

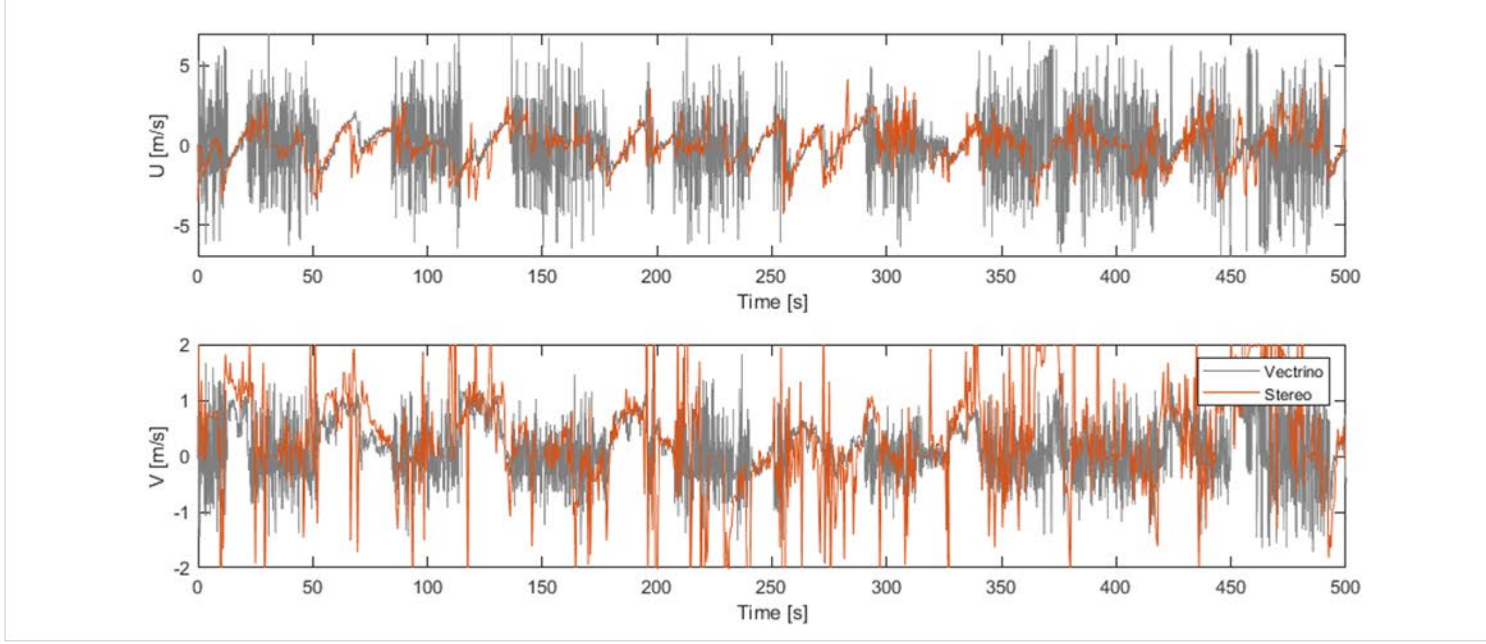
Water Level= 0.575 m (High Tide

Dp=102 deg (from SE)





Raw- Unfiltered Comparisons



MEASUREMENT OVERVIEW

- Stereophotogrammetry can be used in the field to provide point clouds in the field
  - 5-10cm Accuracy
  - 200m by 200m cross/alongshore extent
  - 240PPm^2
- Higher resolution Cameras help resolve less textured features
  - Non foamy water surface
  - Inter-swash/tidal area (still difficult)
- Oblique Imagery has difficulty observing backside of large waves
- Improved Orthorectification
  - Gridding/Rectification Needing Investigation
- 2D Velocity Field Estimates promising with OpticalFlow Techniques

AND

……..BETTER HAVE SOME HARD DRIVES!!!!!

FUTURE WORK + CONSIDERATIONS

- Significant Metrics for Comparison?
  - Runup
  - Significant wave height?
  - Peak Period?
  - Mean Water Level
  - Spatially varying?
  - Phase resolving or averaged?

- Accuracy of Phase Averaged Metrics
  - Improved Gridding/Rectification
  - Data Gaps?