Reconstruction of the Nearshore Surface Wave Field Via Assimilation of Remote Sensing Data

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Coastal & Ocean Engineering

Value & Availability of Phase-Resolved Wave Data

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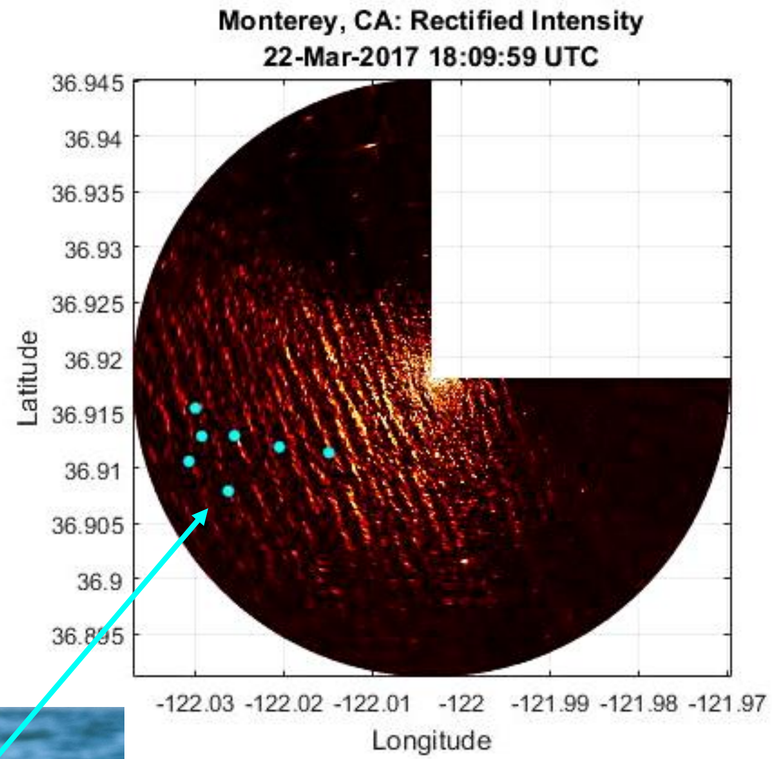
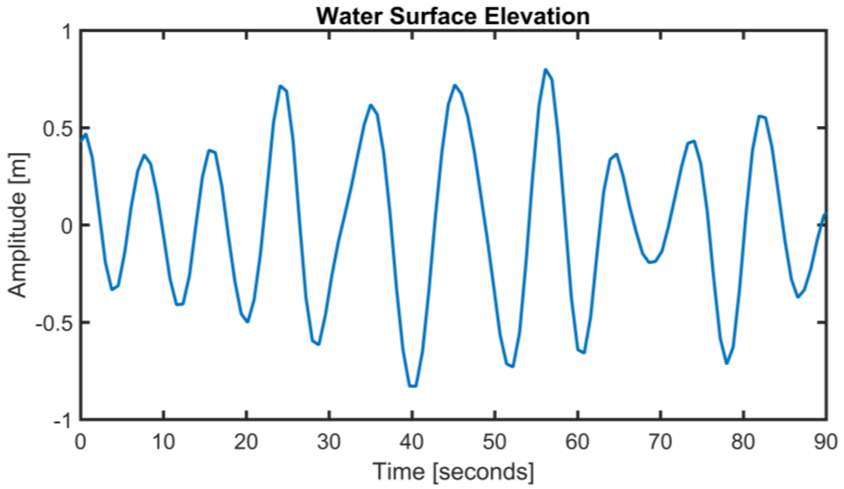
- Vast majority of available wave data is spectral
- Nearshore processes are often on the time and spatial scales of wave groups, not resolved by bulk statistics
- Wave profiling buoys provide in situ phase-resolved measurements at single locations in space
- Remote sensing can provide phase-resolved information over spatial scales of kilometers





Wave profiling buoy (Spoondrift)

Radar Imaging of Ocean Waves

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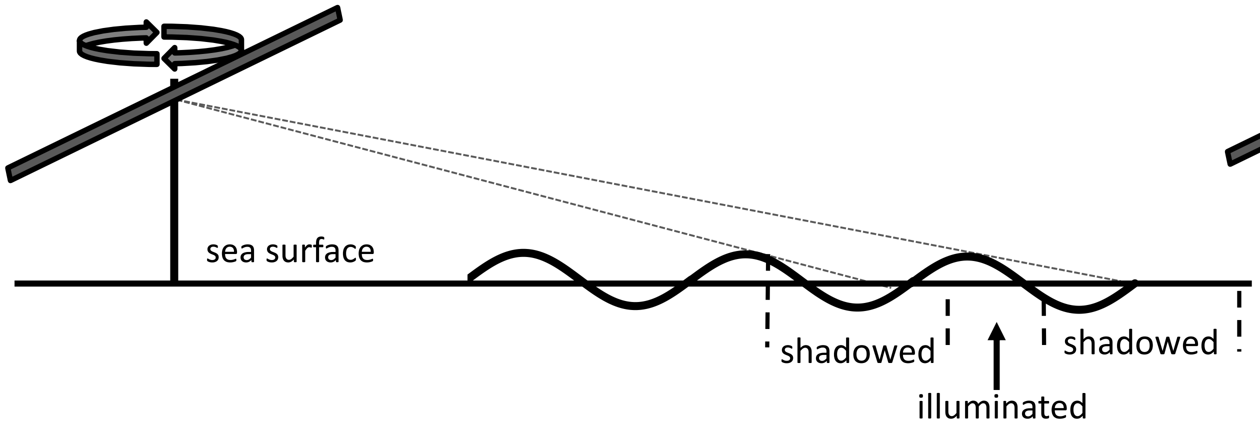

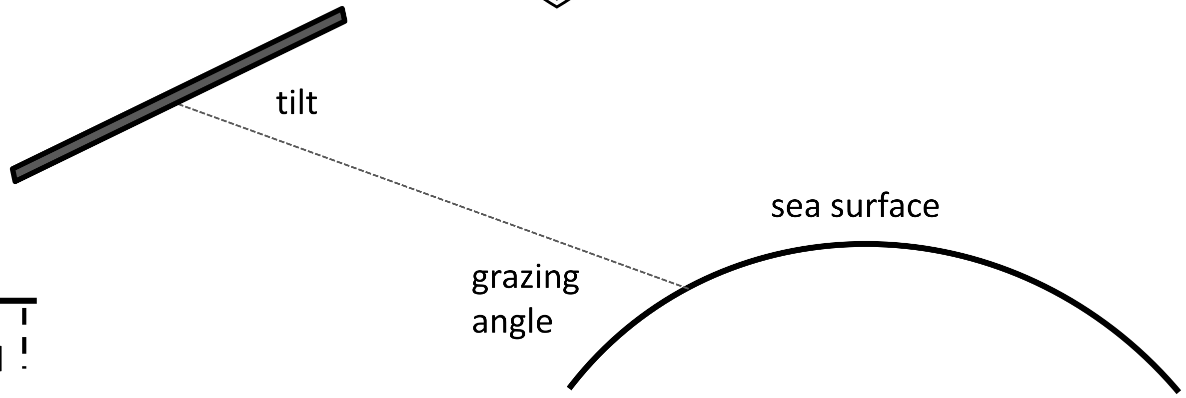

Platform-based
Radar Height up to 100m

Shore-based
Radar Height < 45 m

Vessel-based
Radar Height < 10 m

Background: Wave Estimation from Radar

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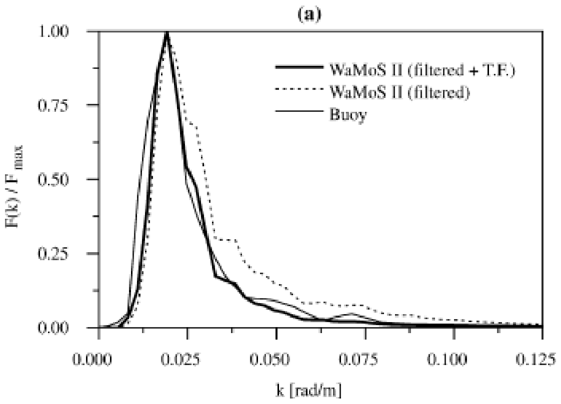
Bulk Wave Parameters (H_{sig}, T_p, θ_{mean})

3D-DFT Approaches

- Wave-like spectrum from radar using Modulation Transfer Function
- Hsig proportional to SNR
- Calibration to buoy required

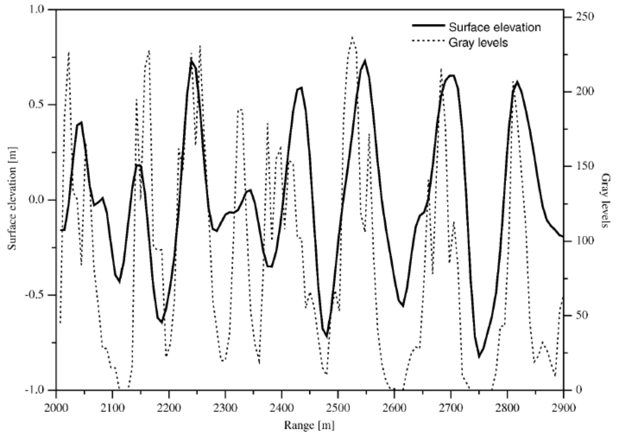


(Nieto Borge et al., 2004)

Texture-based Approaches

- Utilize radar imaging mechanisms (shadowing, surface tilt)
- Often calibration-free

Phase-Resolved Wave Parameters (η, θ)



3D-DFT + IFFT

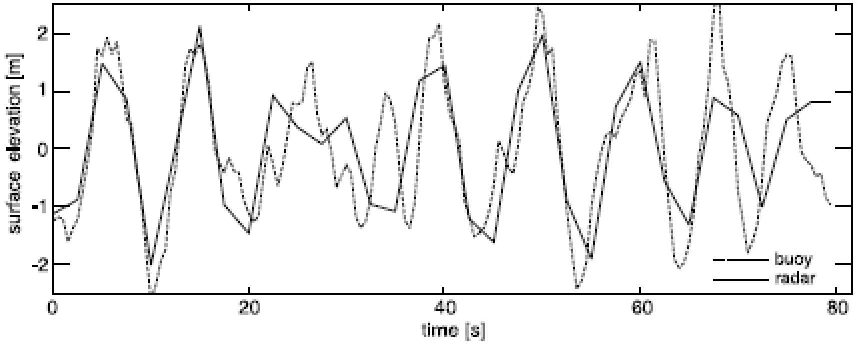
(Nieto Borge et al., 2004)

- MTF approach, with IFFT to phase-resolved
- Calibration to buoy required

Surface Tilt

(Dankert & Rosenthal, 2004)

- No calibration
- Radar must be sufficiently high



How will we get from backscatter intensity to water surface elevation?

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Radar transmits and receives backscatter intensity from sea surface.

↓

Radar imaging model extracts wave slope information from intensity.

↓

Adjoint assimilation model iterates solution to a physics-based wave model until modeled waves match observations of slope (cost function minimization).

↓

The result is a reconstruction of the surface wave field.

Imaging Model of Lyzenga & Walker

- Has not been field tested
- Applies only to un-shadowed regions of sea surface

Lyzenga & Walker (2015)
A Simple Model for Marine Radar Images of the Ocean Surface.
IEEE Geoscience and Remote Sensing Letters

Surface Elevation Reconstruction Algorithm

Adjoint Equations: *note similarity to Mild Slope Eqns*

$$\alpha_{t'} = -\nabla \cdot \left(CC_g \nabla \psi\right) + \left(\omega^2 - k^2 CC_g\right)\psi$$

$$\psi_{t'} = -\alpha + M\left(\eta_r - \eta_r^{obs}\right)_r$$

Haller, Simpson, Walker, Lynett, Pittman (2017)
Assimilation of Wave Imaging Radar Observations for Real-Time Wave-by-Wave Forecasting.
Final Report DOE-OSU-06789

USC

SRI International

Radar Intensity to Wave Slope

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Radar imaging model of Lyzenga & Walker:
(Lyzenga & Walker, 2015: IEEE GRSL)

$$\eta_r(r,\phi) = \frac{h}{r}\left[\frac{I(r,\phi)}{\langle I(r,\phi)\rangle} - 1\right]$$

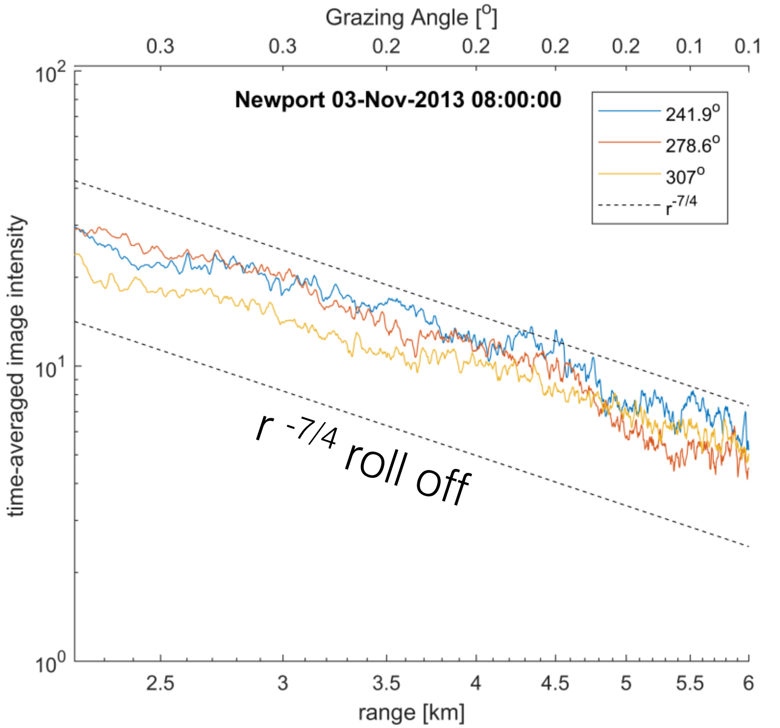
η_r	=	radial component of slope
h	=	radar height
r	=	range
I	=	Intensity
$\langle I \rangle$	=	ensemble averaged I

Intensity represented by Normalized Radar Cross Section (*Valenzuela, 1978*) and log-amplified power law

$$I(r,\phi) = C(\phi)e^{(-a/r)^2}r^{-3/4}[\eta_r + h/r]$$

Ensemble-avg. intensity found using geometric shadowing simplifications

$$\langle I(r,\phi)\rangle = C(\phi)e^{(-a/r)^2}h\,\boxed{r^{-7/4}}$$



Assumptions:

- small grazing angles
- antenna height is much larger than the surface elevation
- time-avg radar signal has a $r^{-7/4}$ roll off with range

Algorithm Verification: Synthetic Input

Does not require radar imaging model

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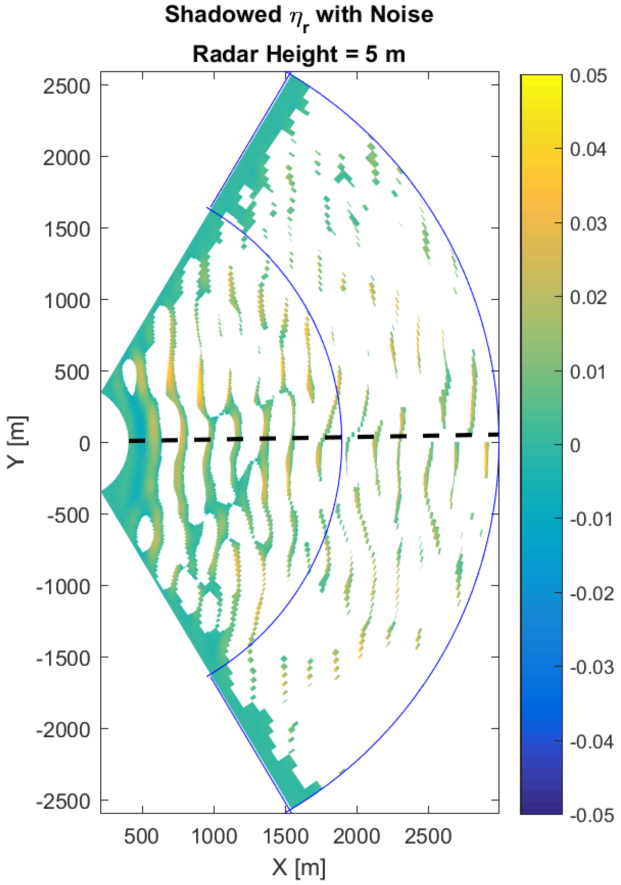
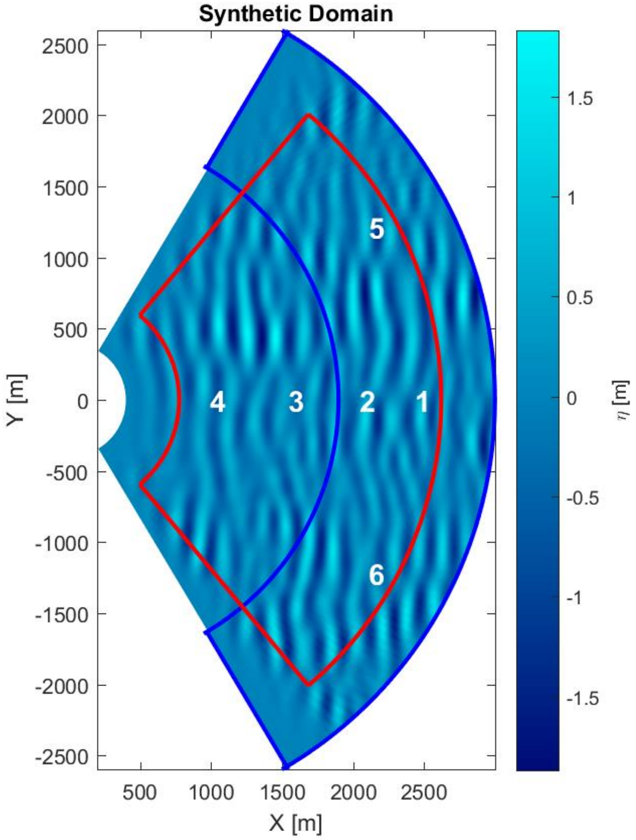
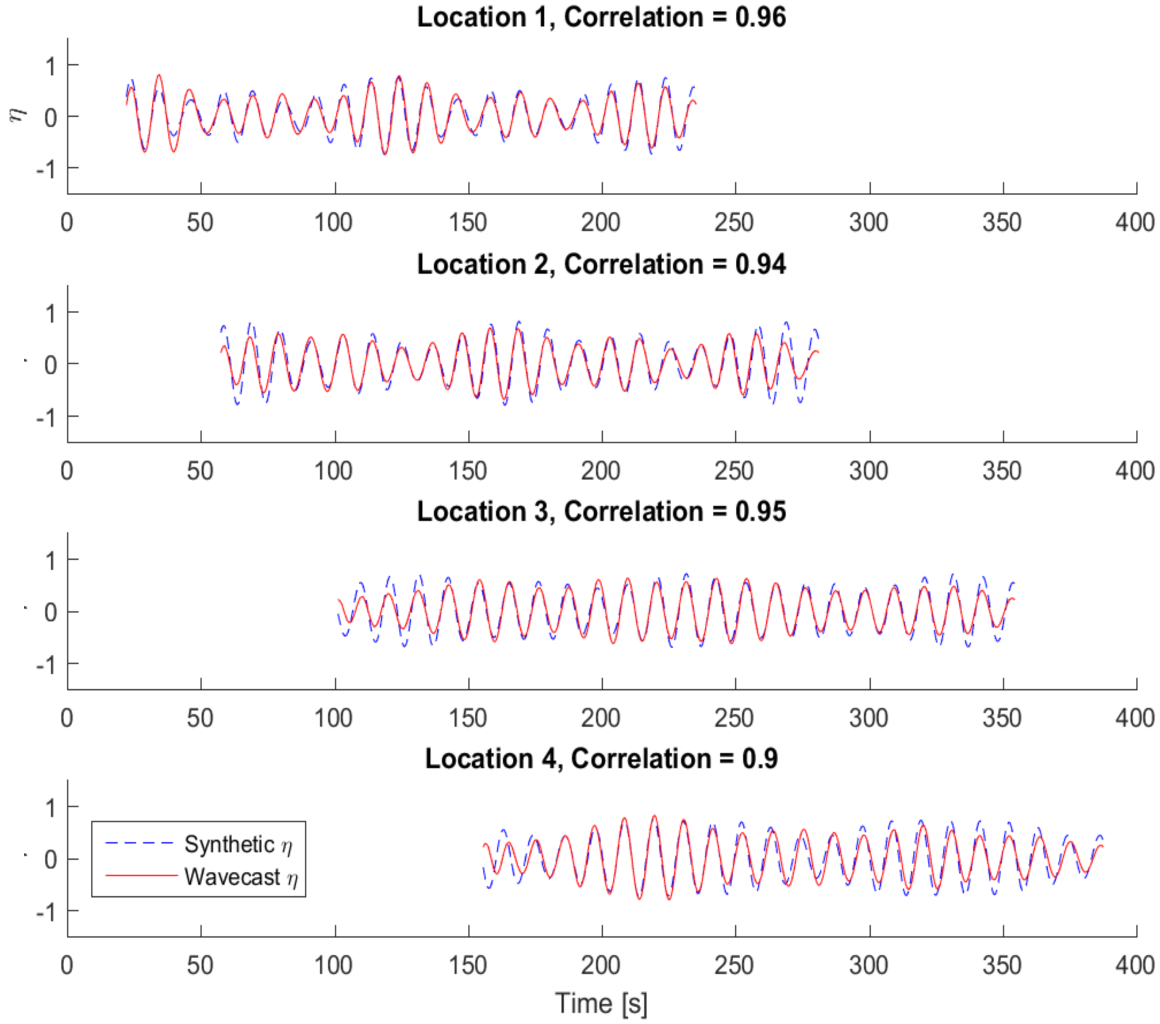
Assimilated Synthetic Radial Slope



Reconstructed Surface Elevations





Field Data Collection: Santa Cruz, CA

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Array of Spoondrift Buoys

Measurements:

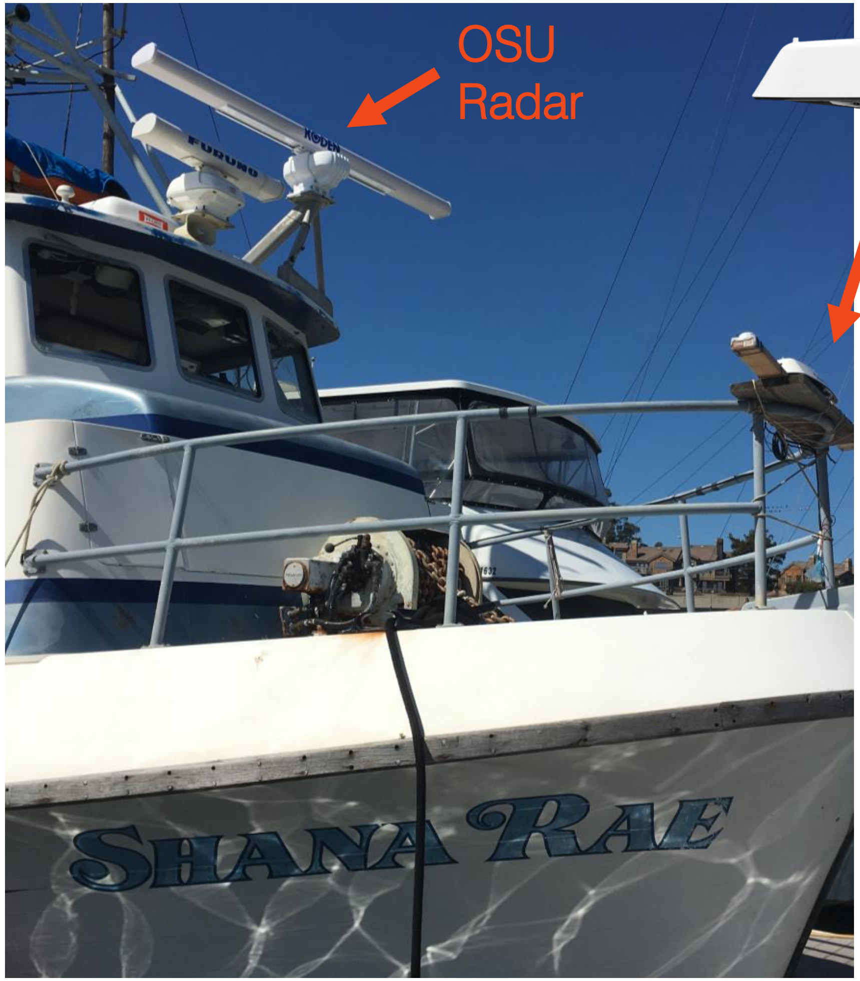
η, x, y

GPS lat, lon

Non-Stationary:

20m scope

Anchor drift



OSU Radar

GPS Compass

Measurements:

Heading (to 0.3°)

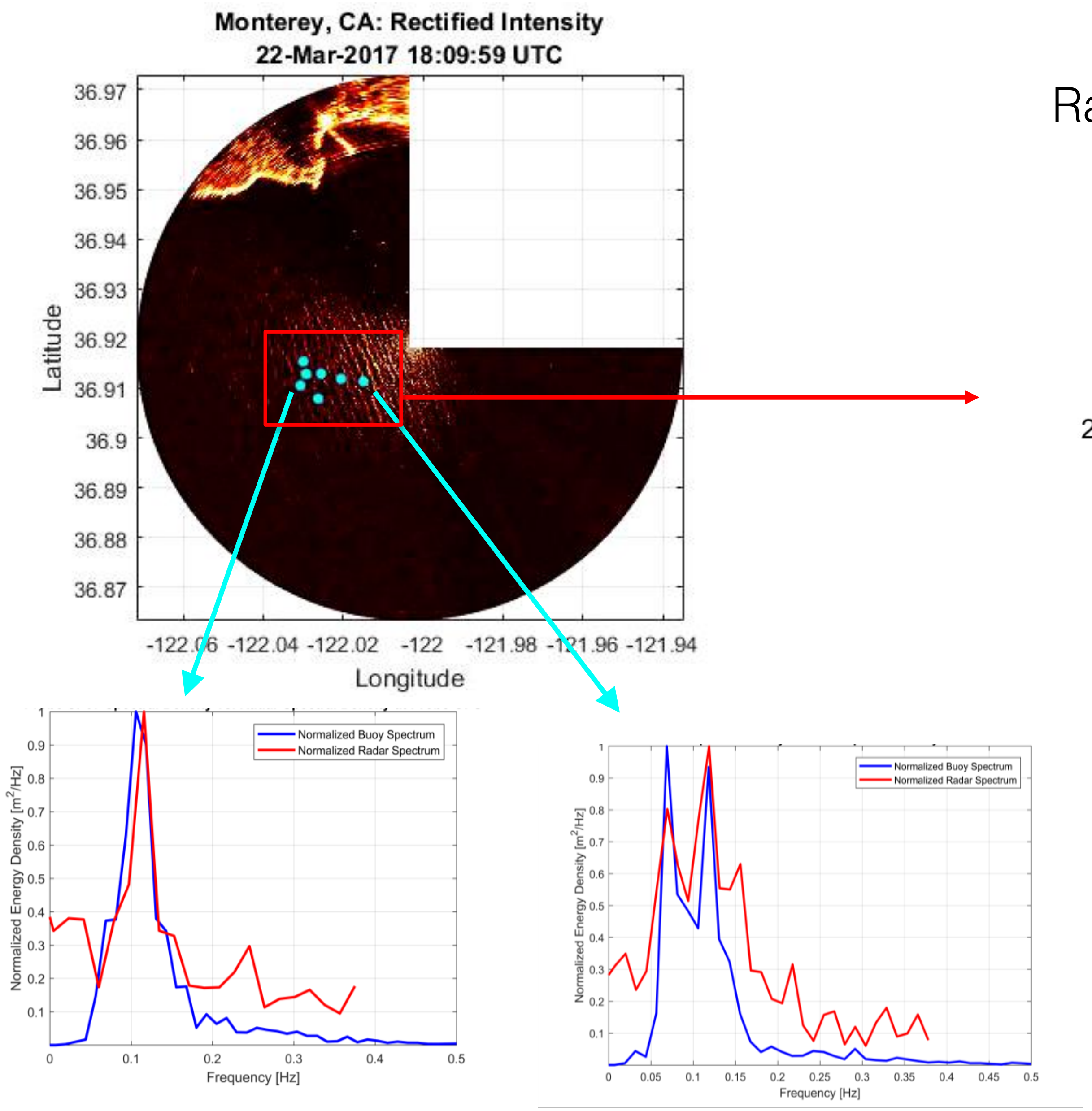
Lat, Lon (to 1.2m)

Non-Stationary:

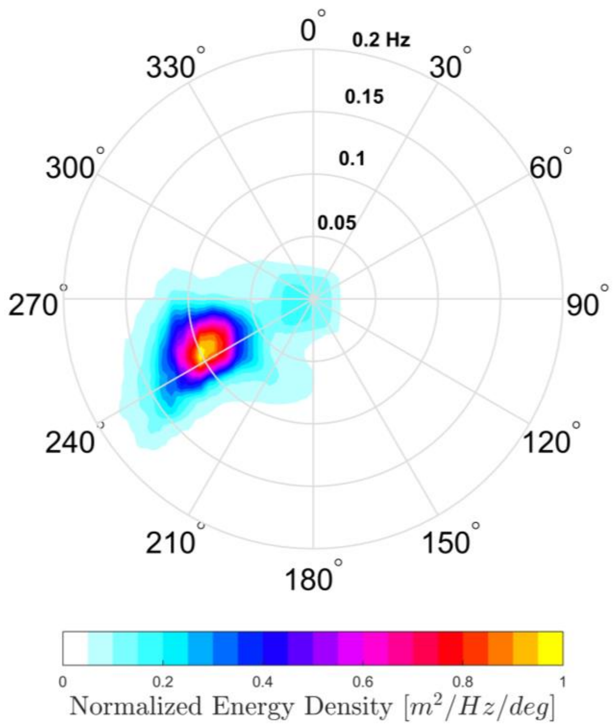
~1 km/hr current

Rotation and Heave on wave timescales

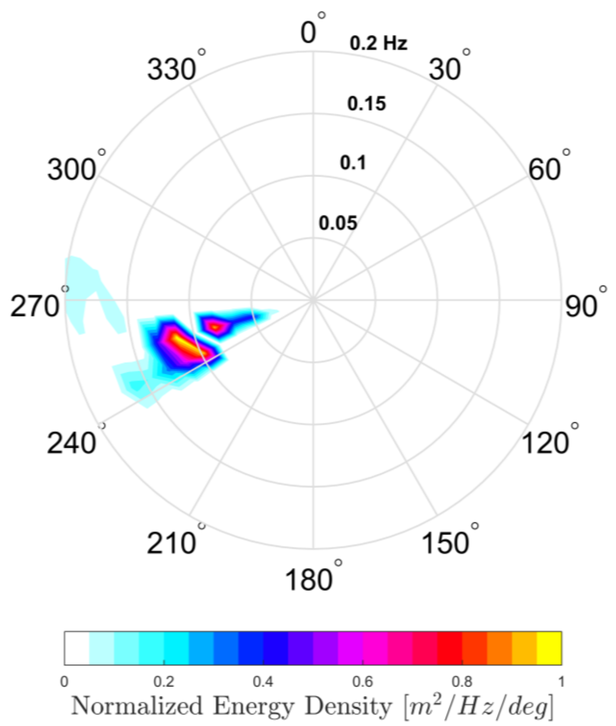
Rectified Radar Imagery



Radar Directional Spectrum



Buoy Directional Spectrum



Rectified Radar Imagery → Radial Slope

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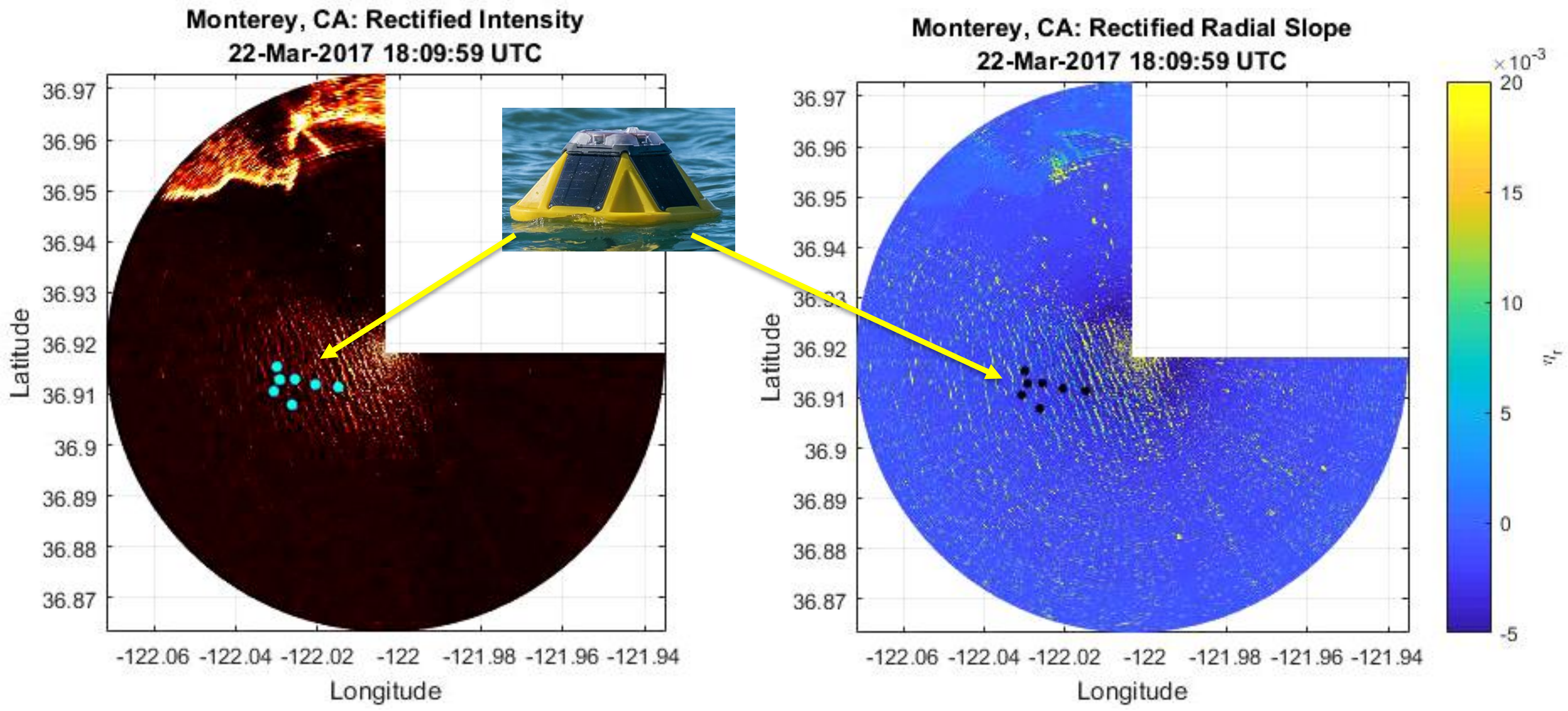


Phase-Resolved Slope Comparison

Convert buoy η to wave slope

Time derivative: $\eta_t = -\frac{H\sigma}{2}\sin(kx+\sigma t)$

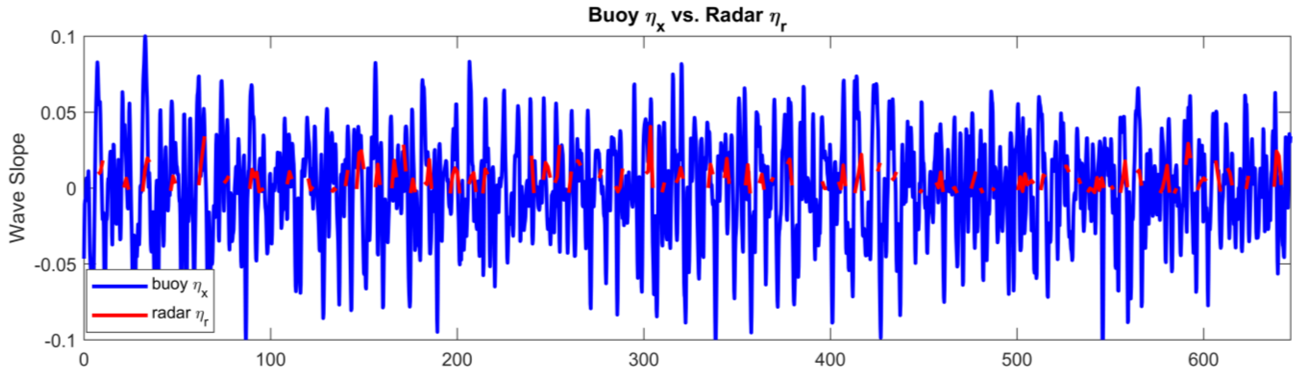
Spatial derivative: $\eta_x = -\frac{Hk}{2}\sin(kx+\sigma t)$

Relate slope to time derivative: $\eta_x = \frac{\eta_t k}{\sigma} = \boxed{\frac{\eta_t}{c}}$

T from peak frequency, L from dispersion relation: $c = \frac{L}{T}$

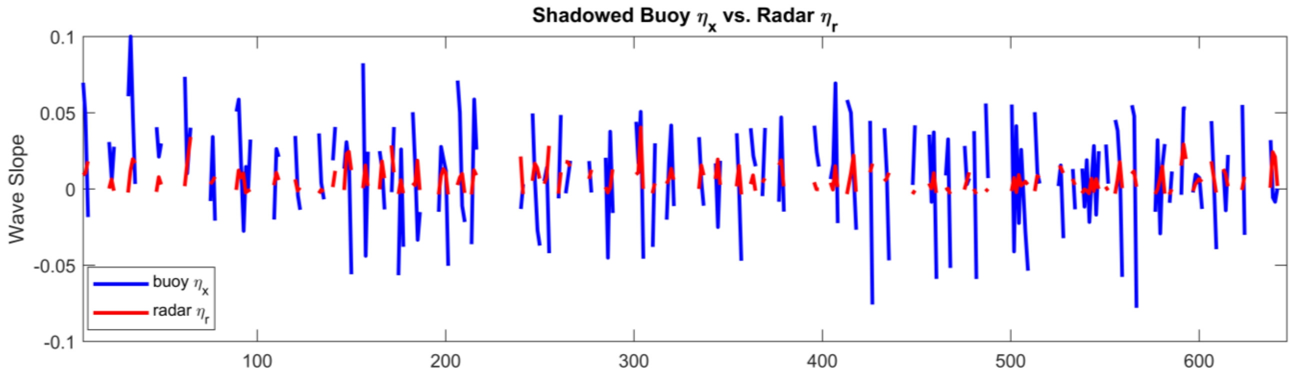
Convert Buoy η to Slope:

Buoy η_x and Radar η_r



Add Shadowing:

Shadowed Buoy η_x and Radar η_r



Lessons Learned from Shipboard Testing

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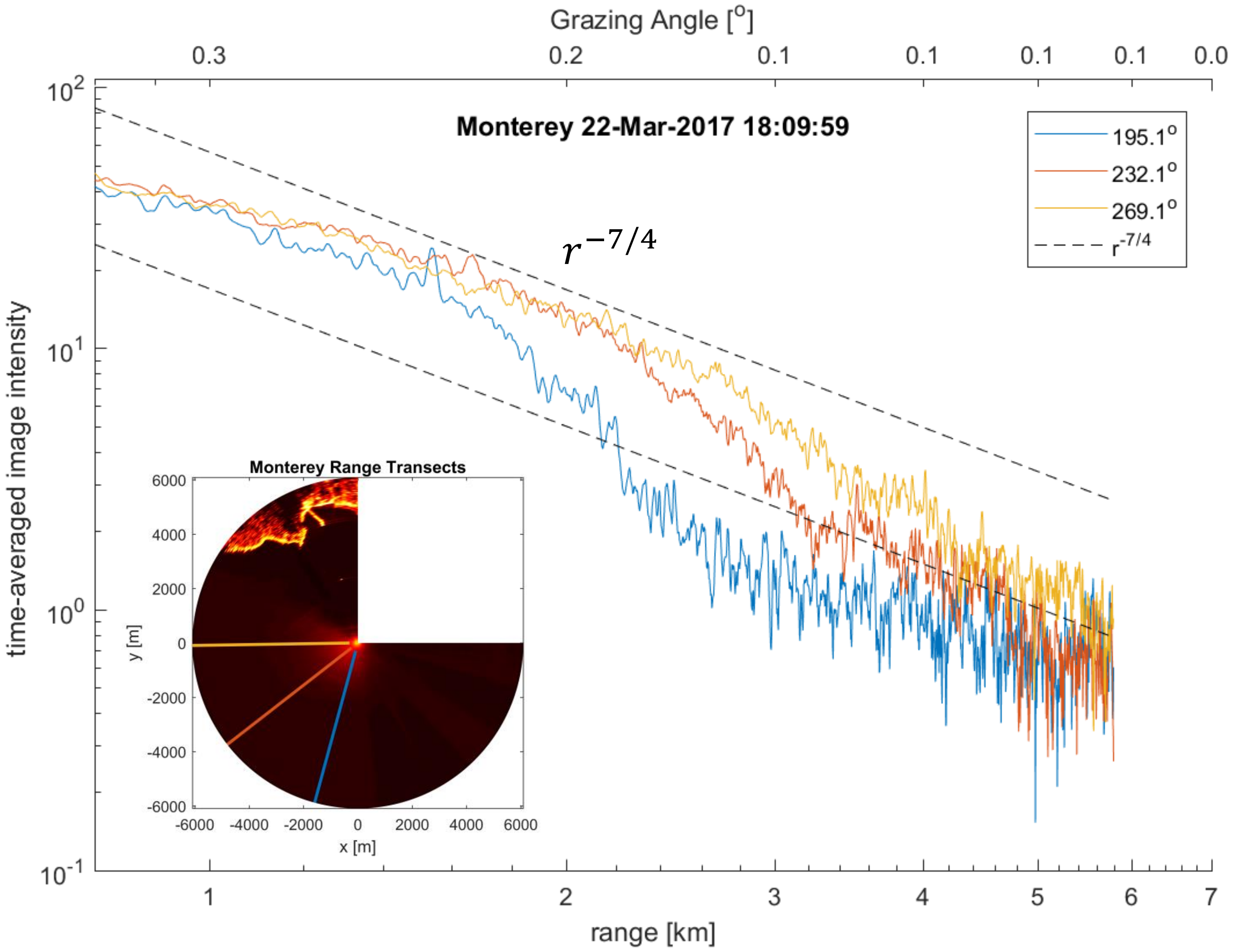
- Successful image rectification
- Radar imaging model gives underestimate (~1/3) of expected wave slope
- Intensity roll-off is inconsistent
- ***Radar height is highly-variable***

$$\eta_r(r,\phi) = \frac{h}{r}\left[\frac{I(r,\phi)}{\langle I(r,\phi)\rangle} - 1\right]$$



Shore-Based Radar: Inner Shelf DRI

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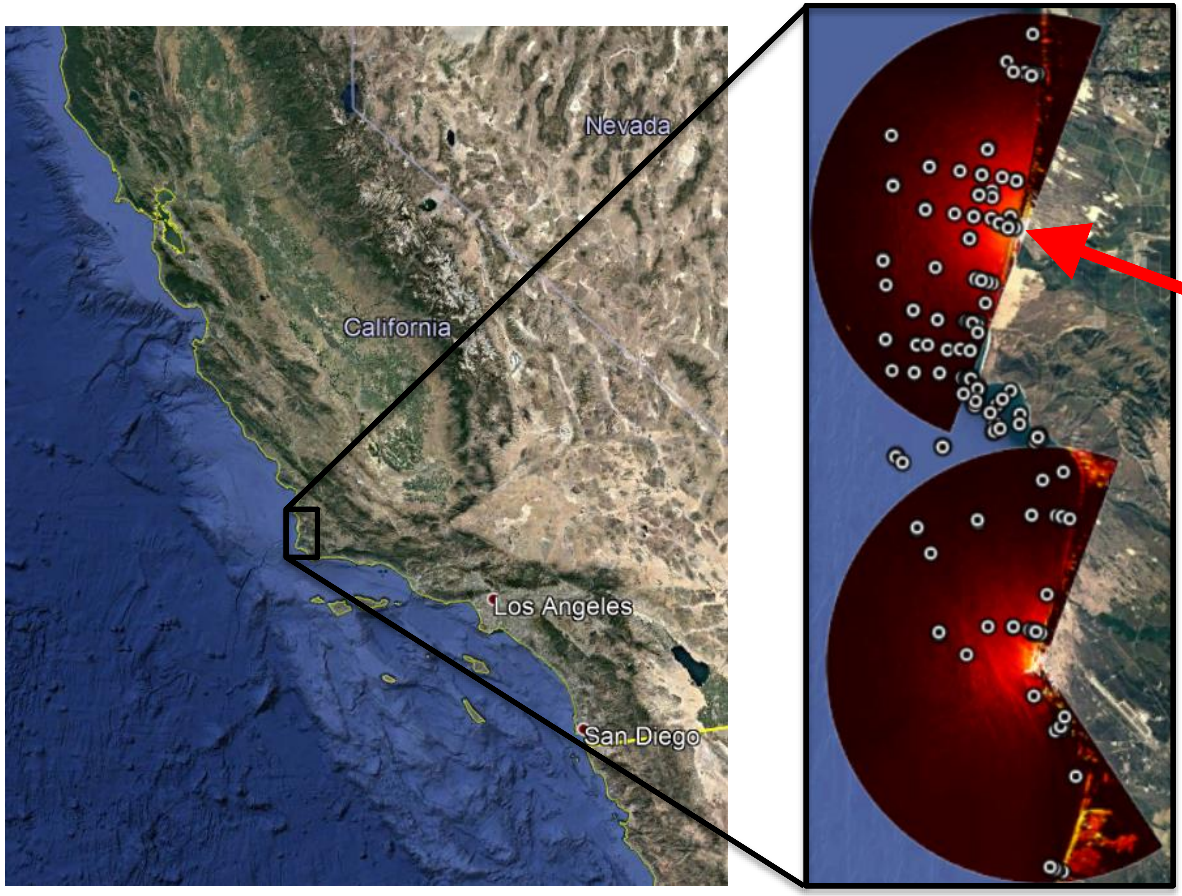

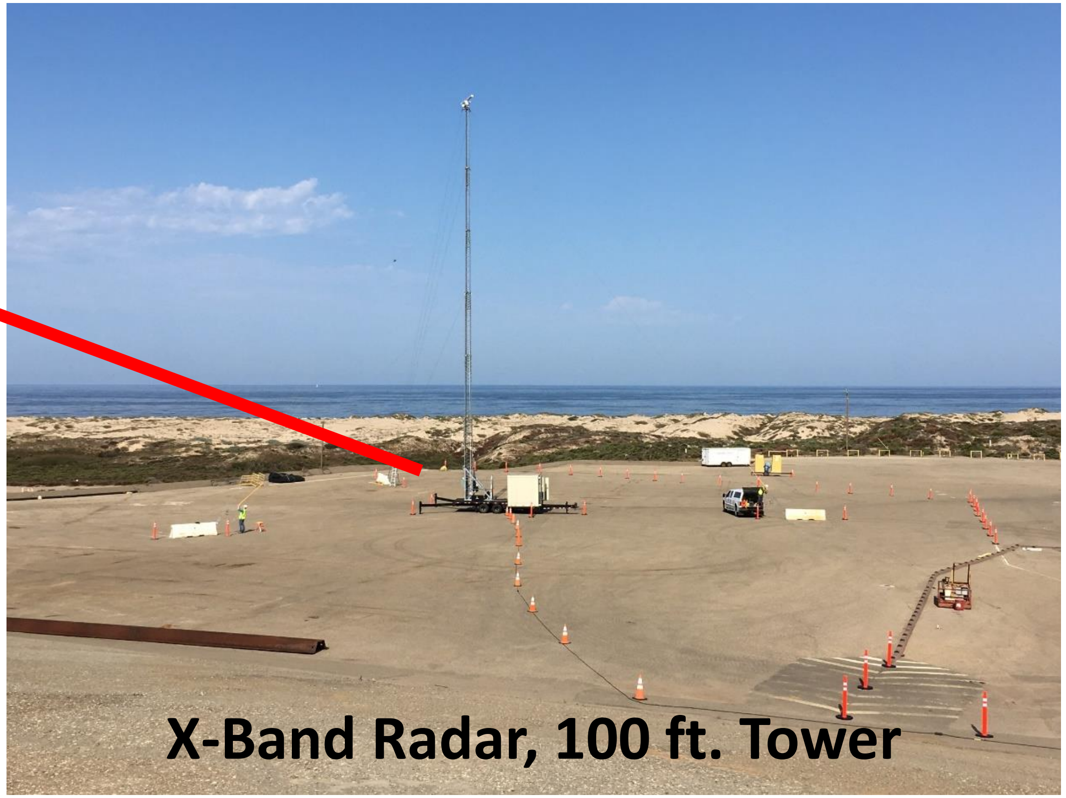

In situ Data Availability

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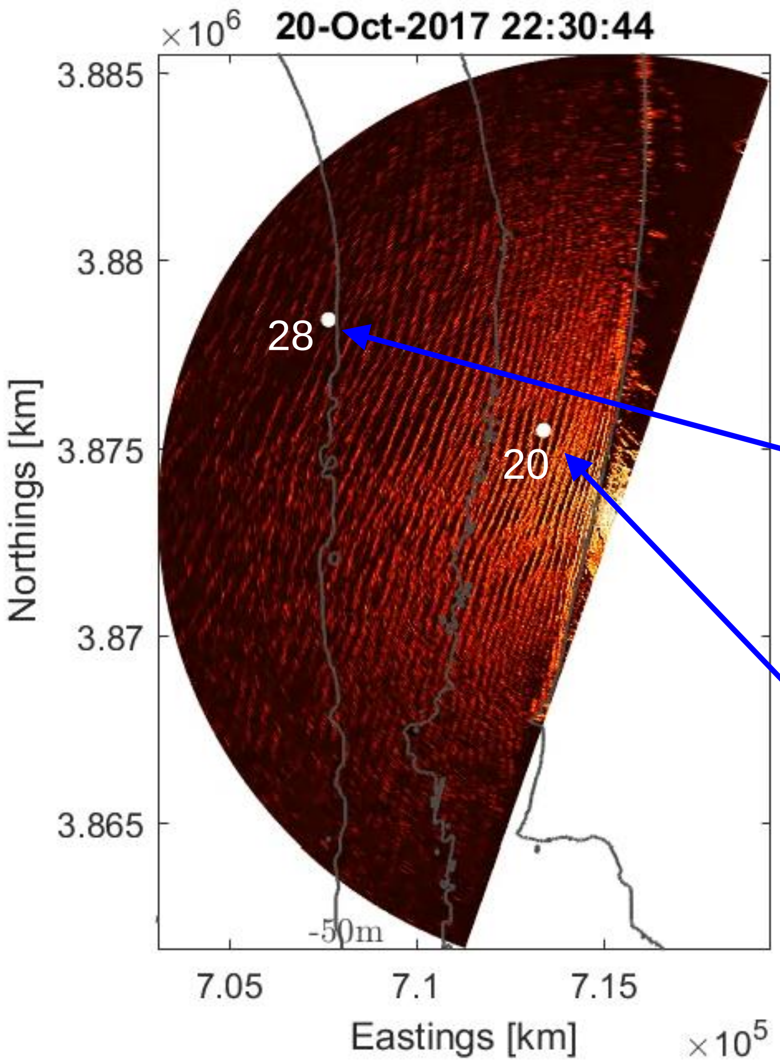
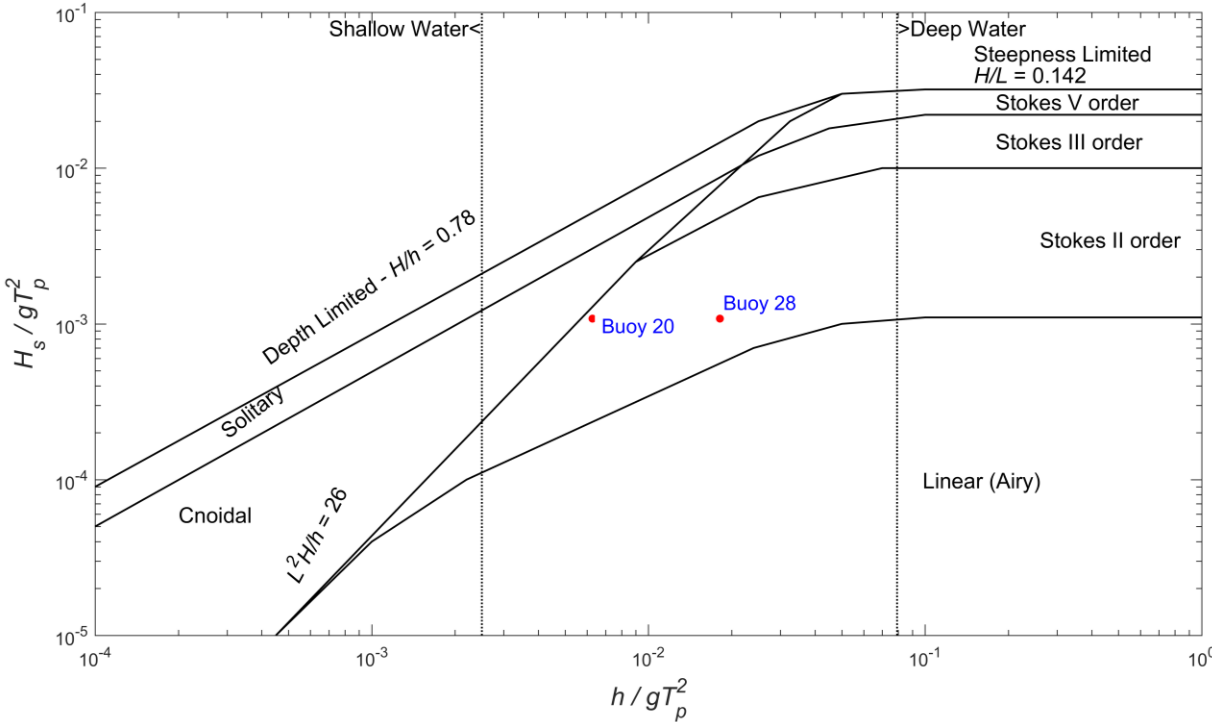


Buoy 28
h = 52m
Hs = 3.1m
Tp = 17.1 sec

Buoy 20
h = 18m
Hs = 3.1m
Tp = 17.1 sec

Linear applicability?



Applicability of Radar Imaging Model

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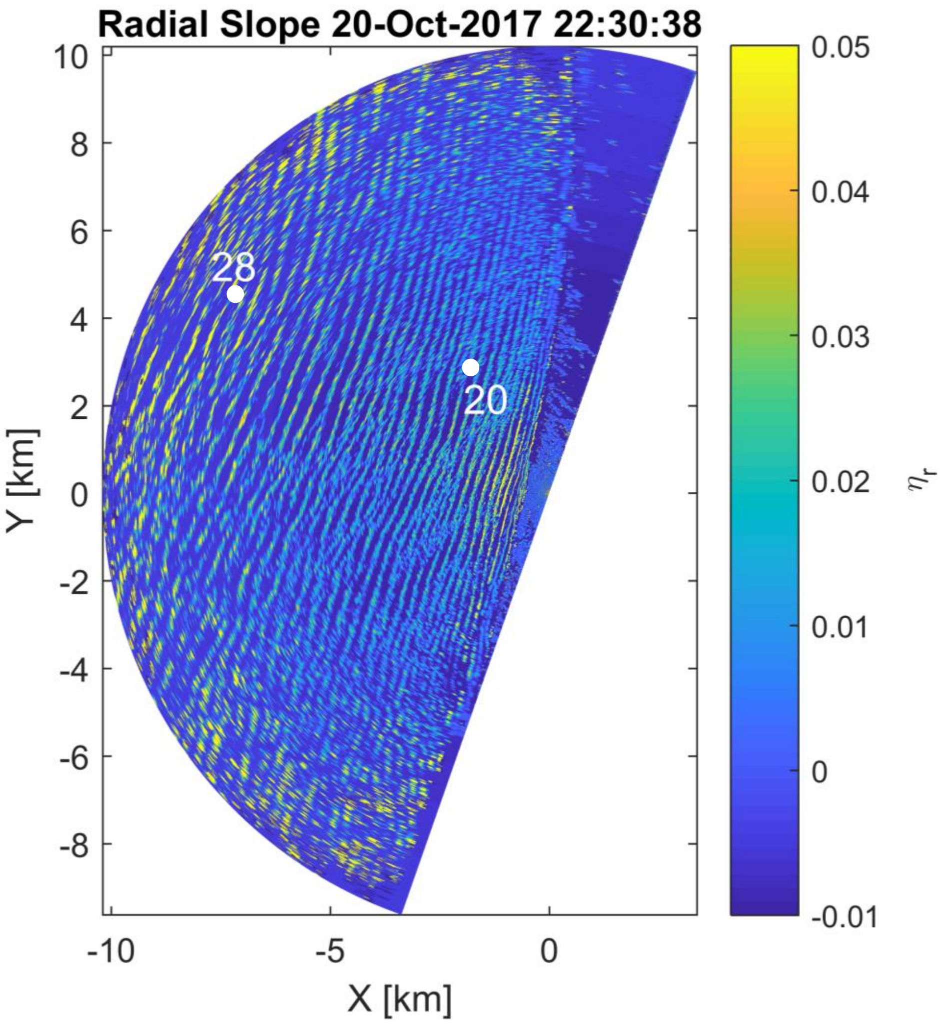


Convert Radar to Radial Slope

Radar imaging model

(Lyzenga & Walker, 2015: GRSL)

$$\eta_r(r,\phi) = \frac{h}{r}\left[\frac{I(r,\phi)}{\langle I(r,\phi)\rangle} - 1\right]$$

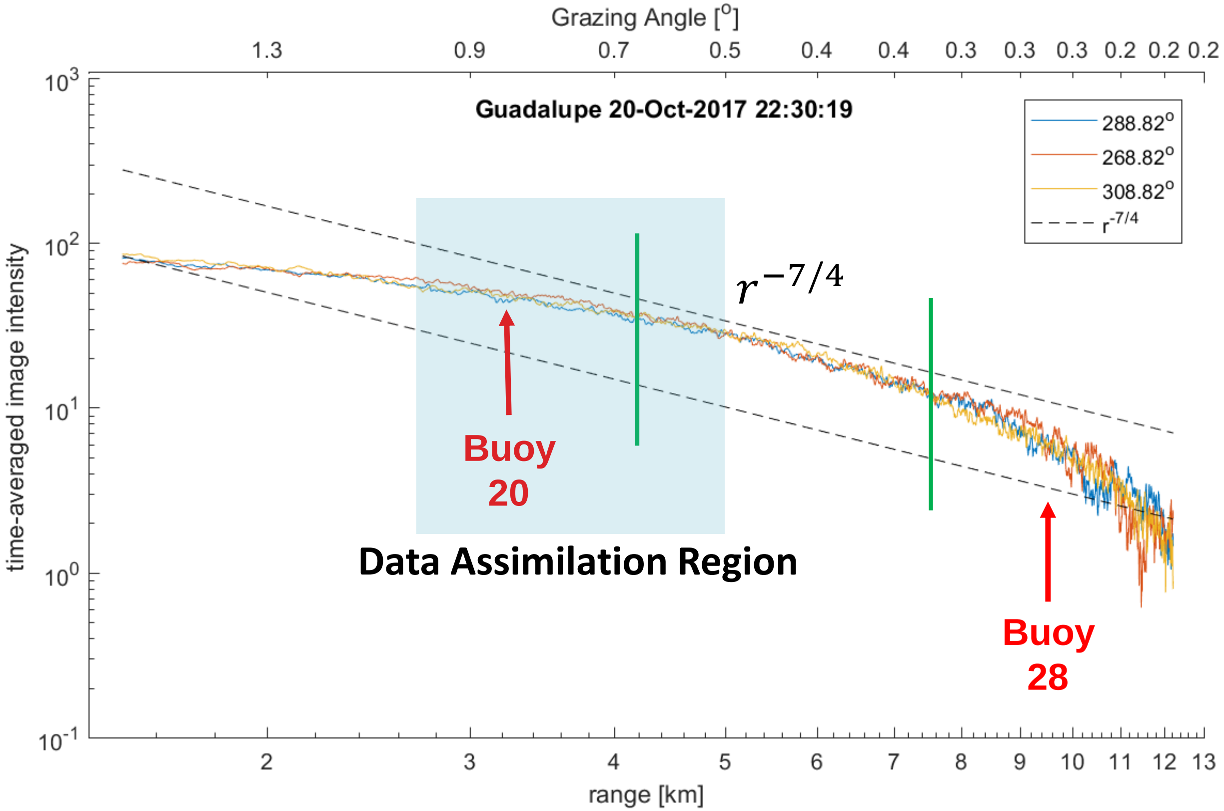
η_r = radial component of slope

h = radar height

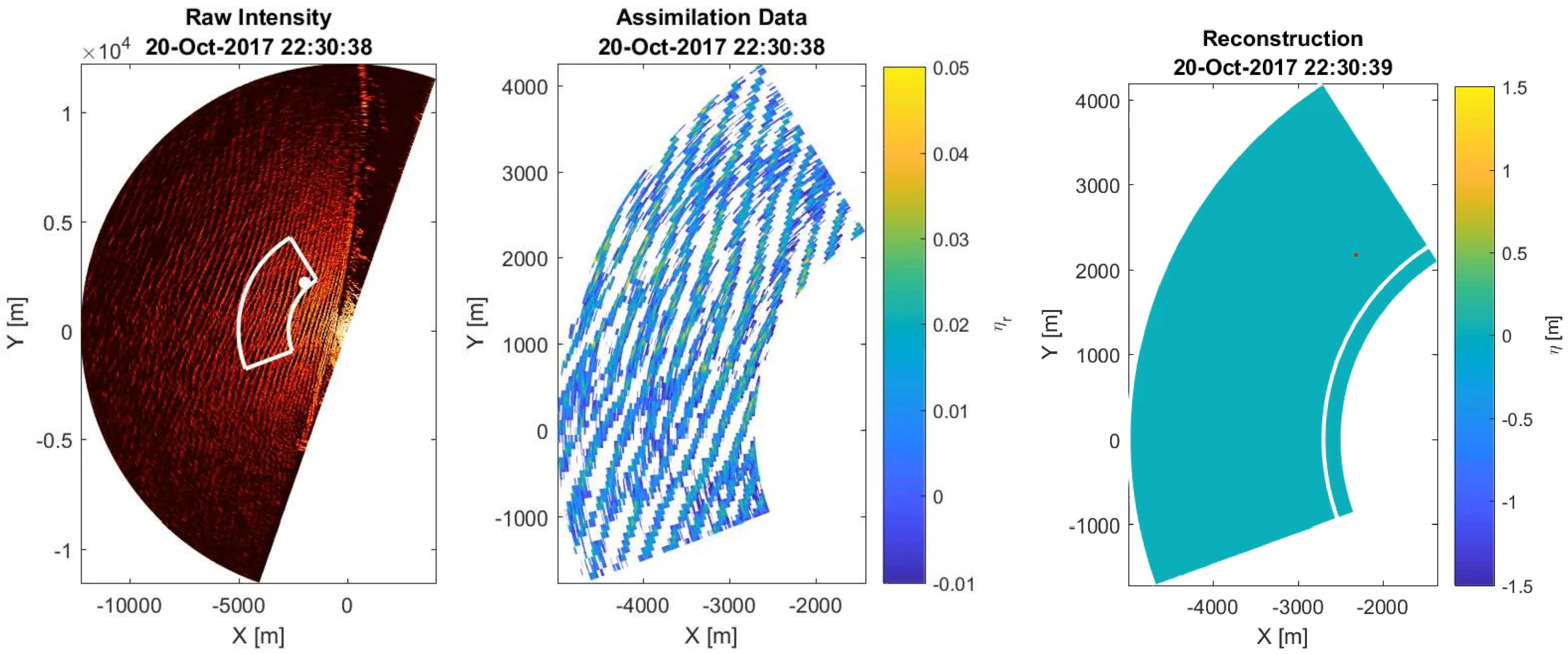
r = range

I = Intensity

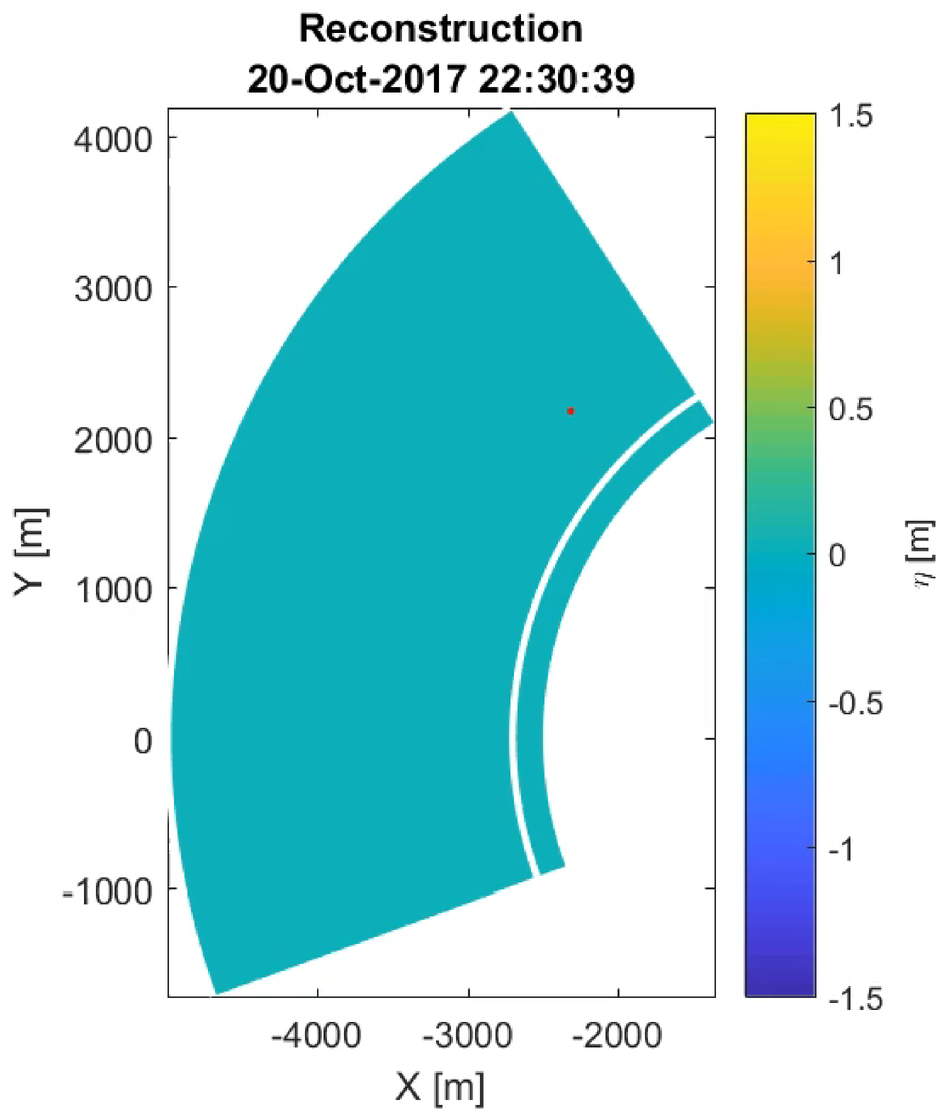
$\langle I \rangle$ = ensemble averaged I

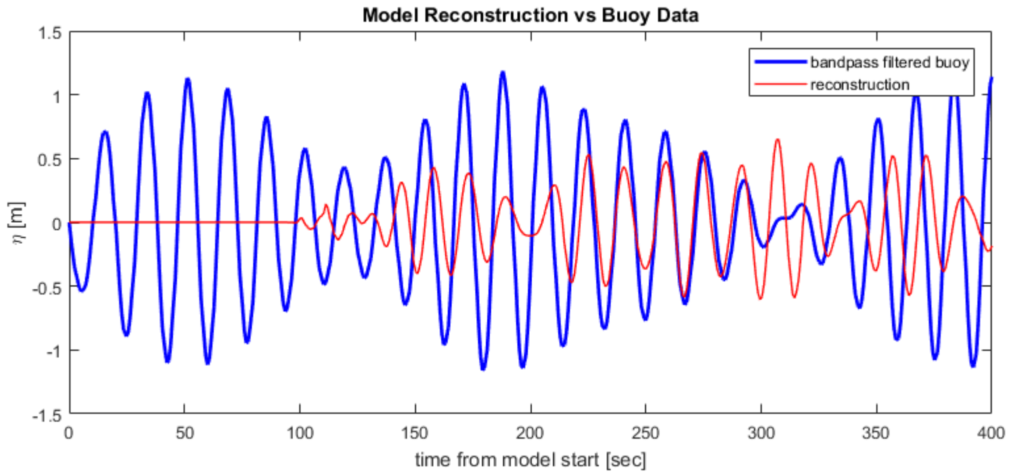


Surface Elevation Reconstruction

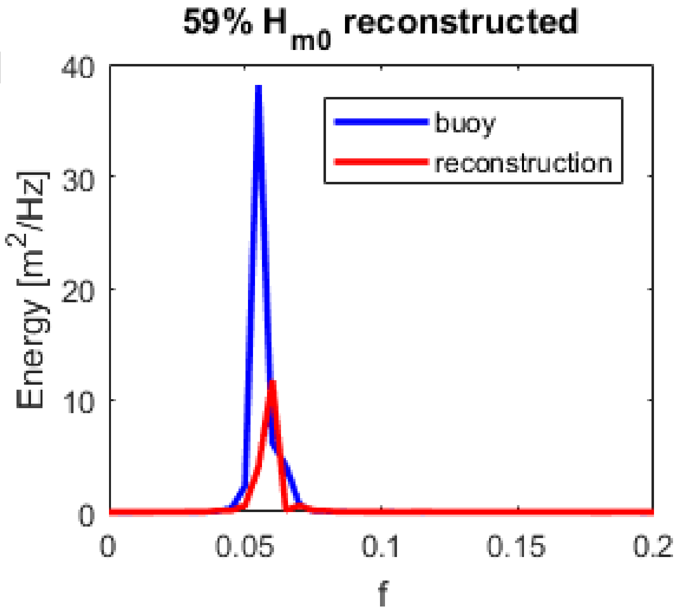


Surface Elevation Reconstruction





- Band-pass filter buoy around MSE solution frequency
- H_{m0} Buoy = 2.8 m
- H_{m0} Reconstructed = 1.7 m
- Solution subject to linear limitations
- Outside imaging model applicability



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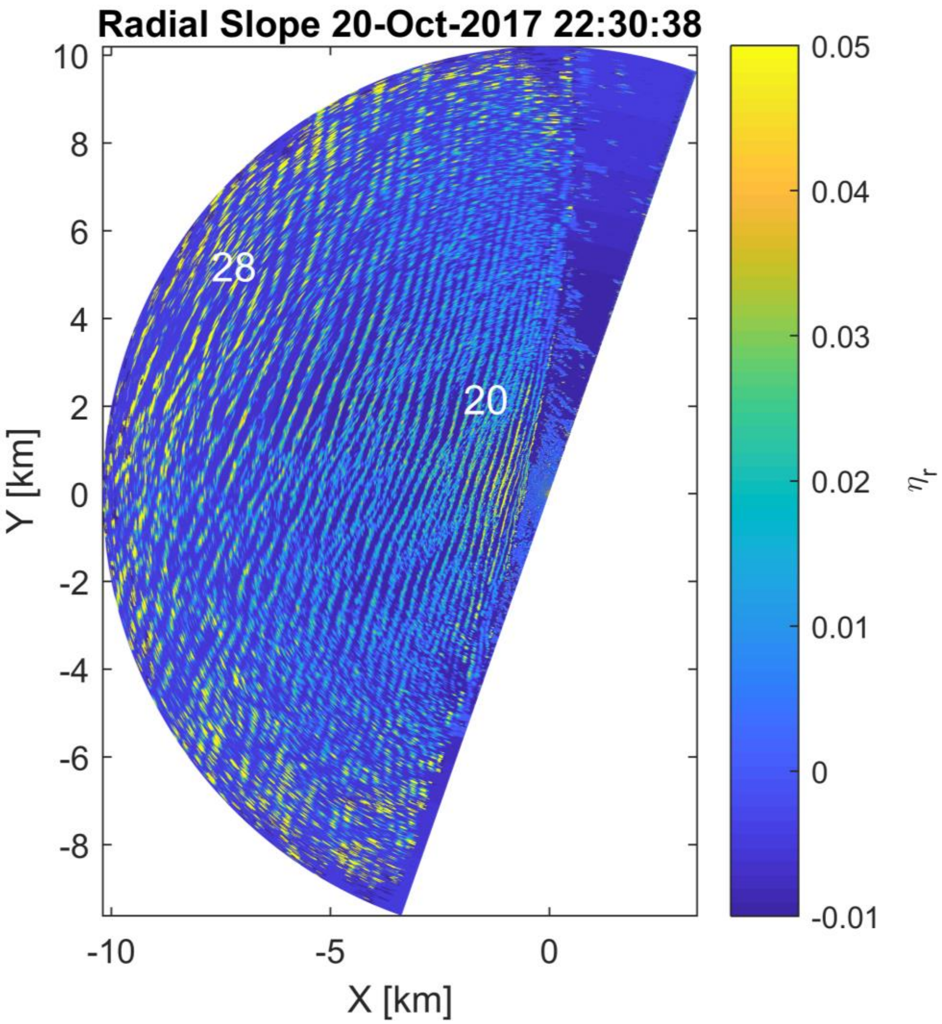

<u>Convert Radar to Radial Slope</u>

Radar imaging model

(Lyzenga & Walker, 2015: GRSL)

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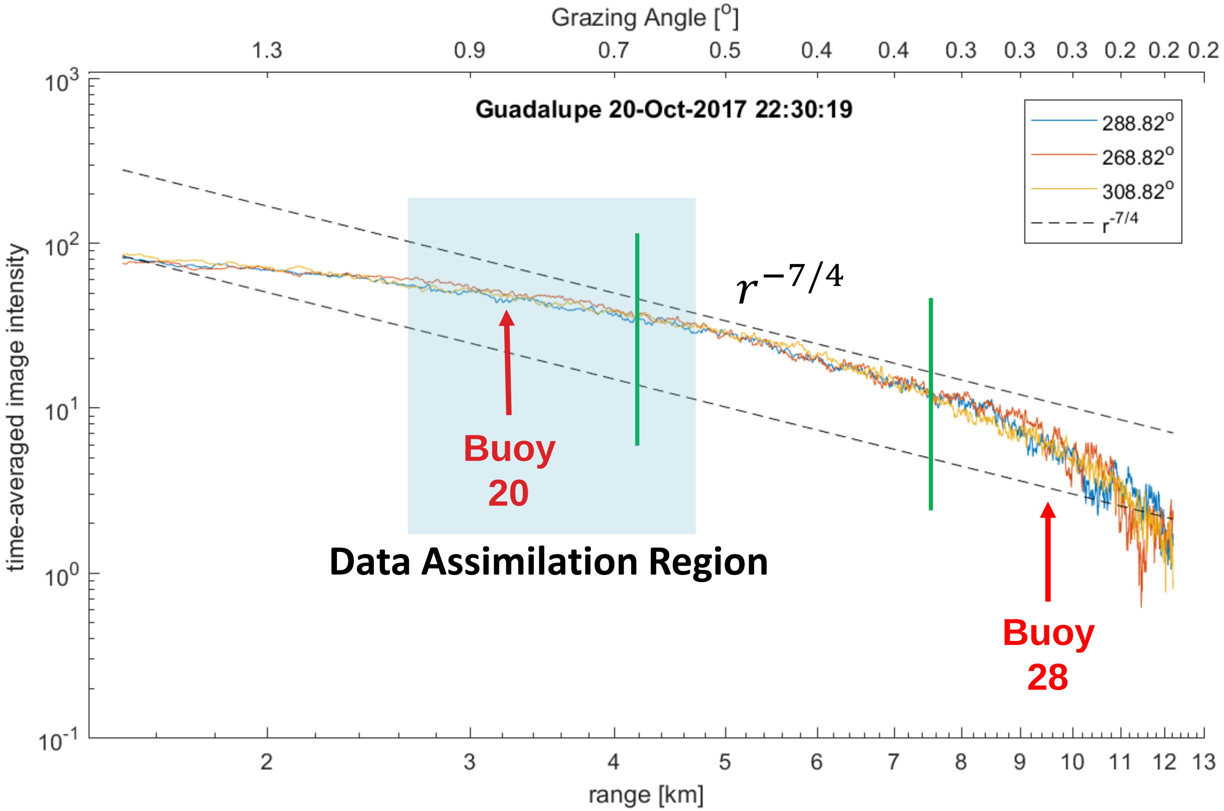

Surface Elevation Prediction

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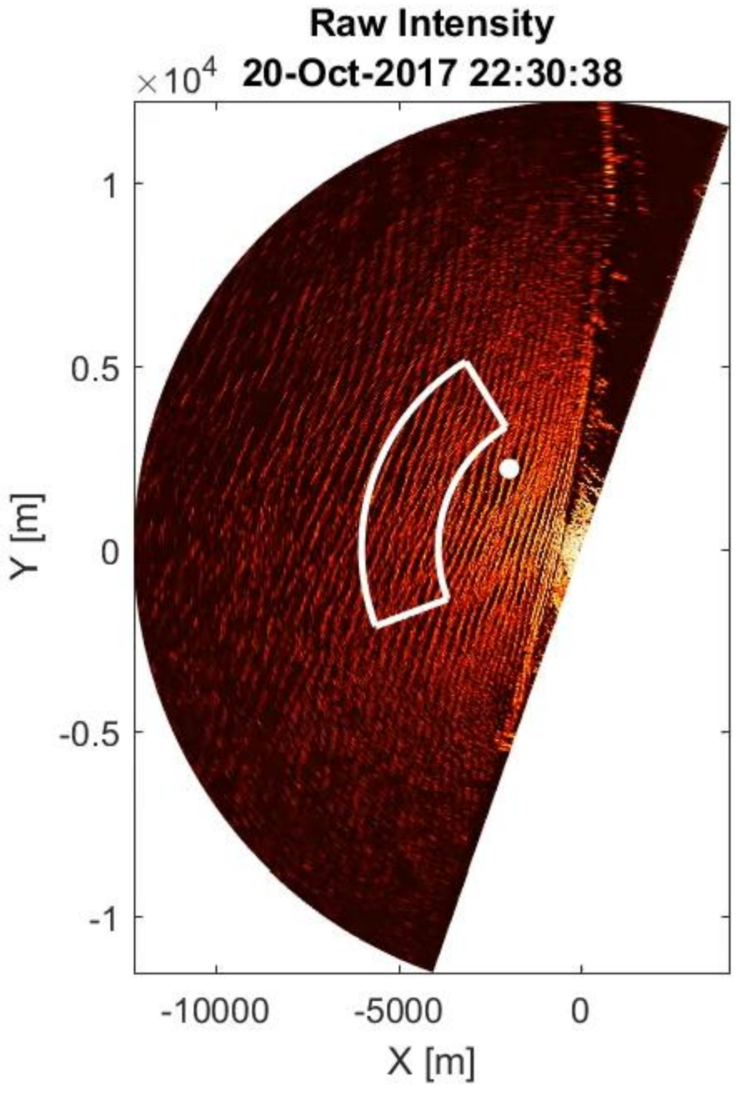

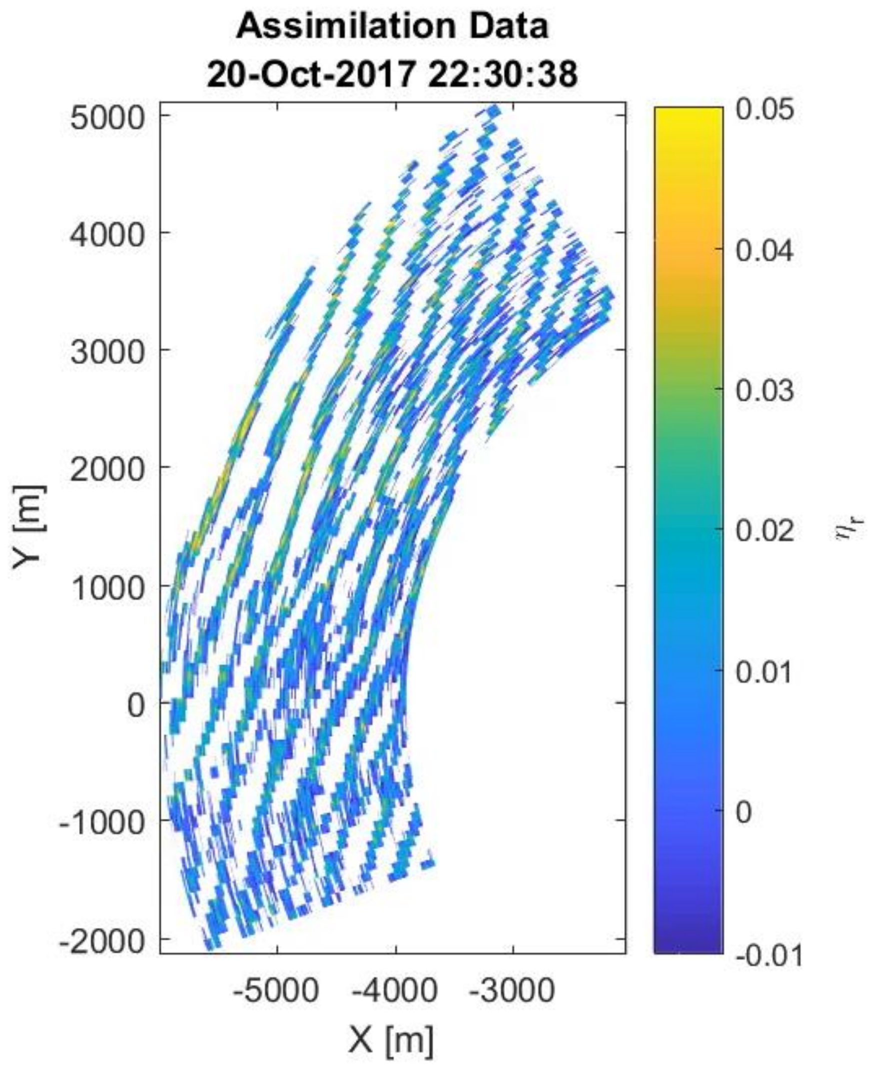

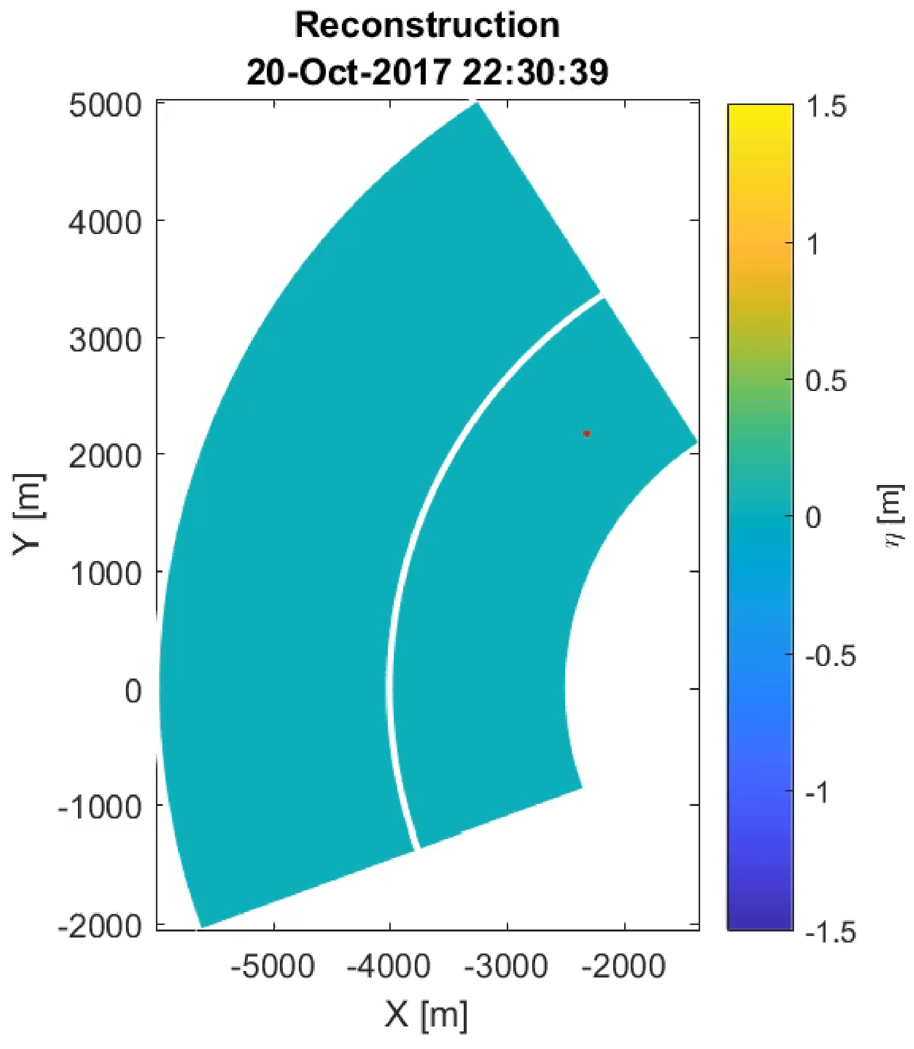

Surface Elevation Prediction

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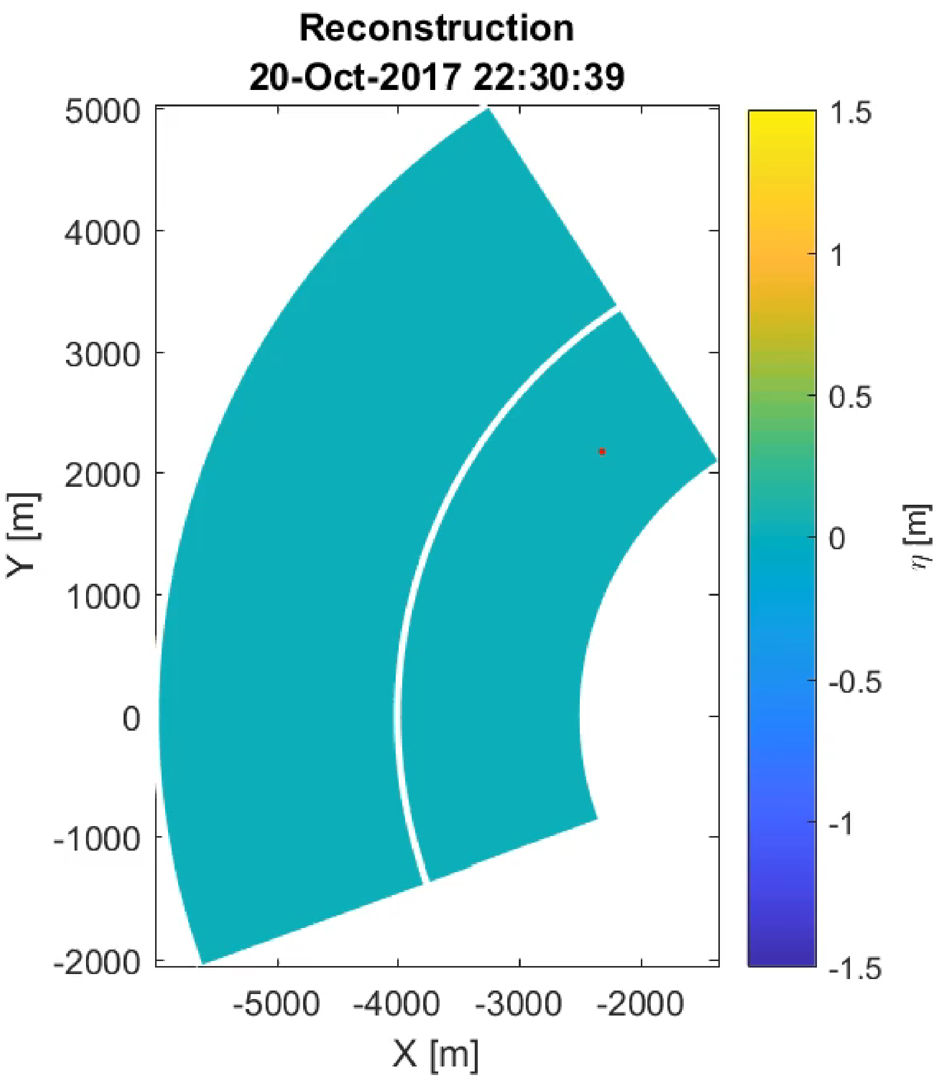
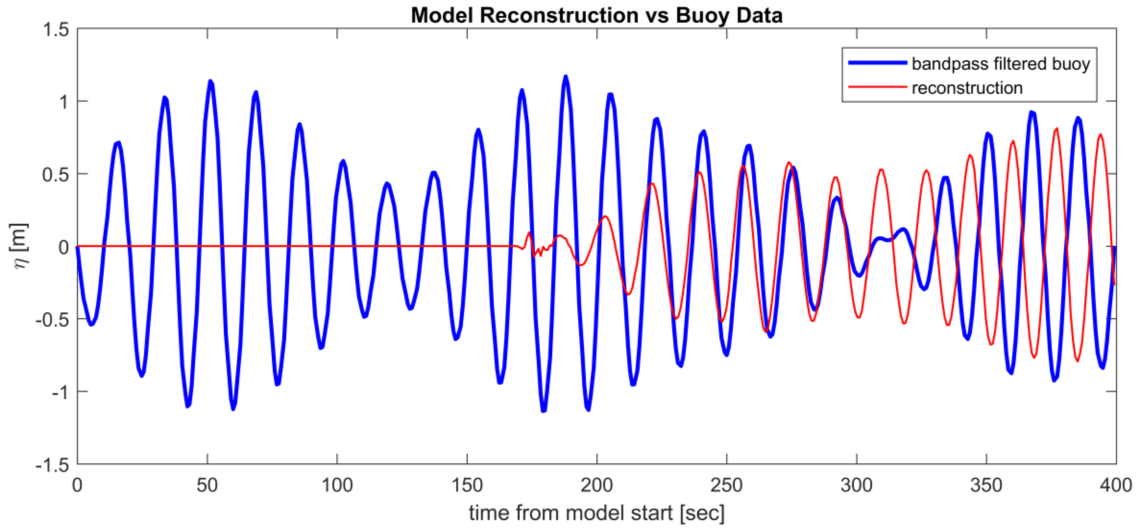
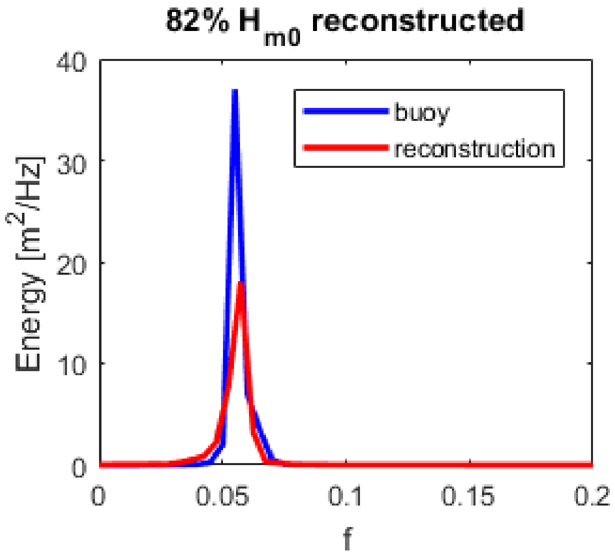




- Waves are "predicted"
- Band-pass filter buoy around MSE solution frequency
- H_{m0} Buoy = 2.8 m
- H_{m0} Reconstructed = 2.3 m
- Solution subject to linear limitations



Summary

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- Development of a novel surface elevation reconstruction method from radar imagery
- Successful synthetic validation using radar-like model inputs
- Vessel-based radar observations contain too much uncertainty for reconstruction at this time
  - Inconsistent intensity roll-off
  - Radar height too variable
- Shore-based radar showing promising results for phase-resolved reconstruction and prediction

Thank you!

Oregon State University
College of Engineering

Collaborations:

Dr. Patrick Lynett

USC

Dr. David Walker

SRI International

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SPOONDRIFT

integral consulting inc.

revision
Enabling Marine Renewables

Funding:

LINK FOUNDATION
EST. 1953

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