Spatiotemporal Modulation and Analysis of High-Resolution Backscatter and Doppler X-band Radar Measurements of Ocean Surface Waves in Low Sea States

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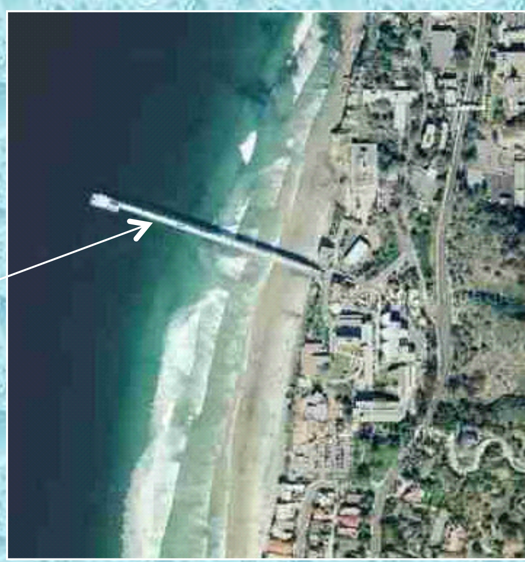
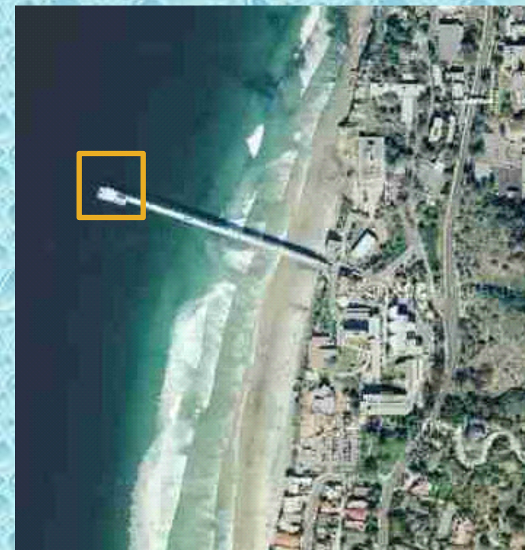
Overview

- Data description
- Modulation of Doppler and RCS in spatiotemporal domain
- Spatiotemporal analysis of Doppler

Scripps Pier



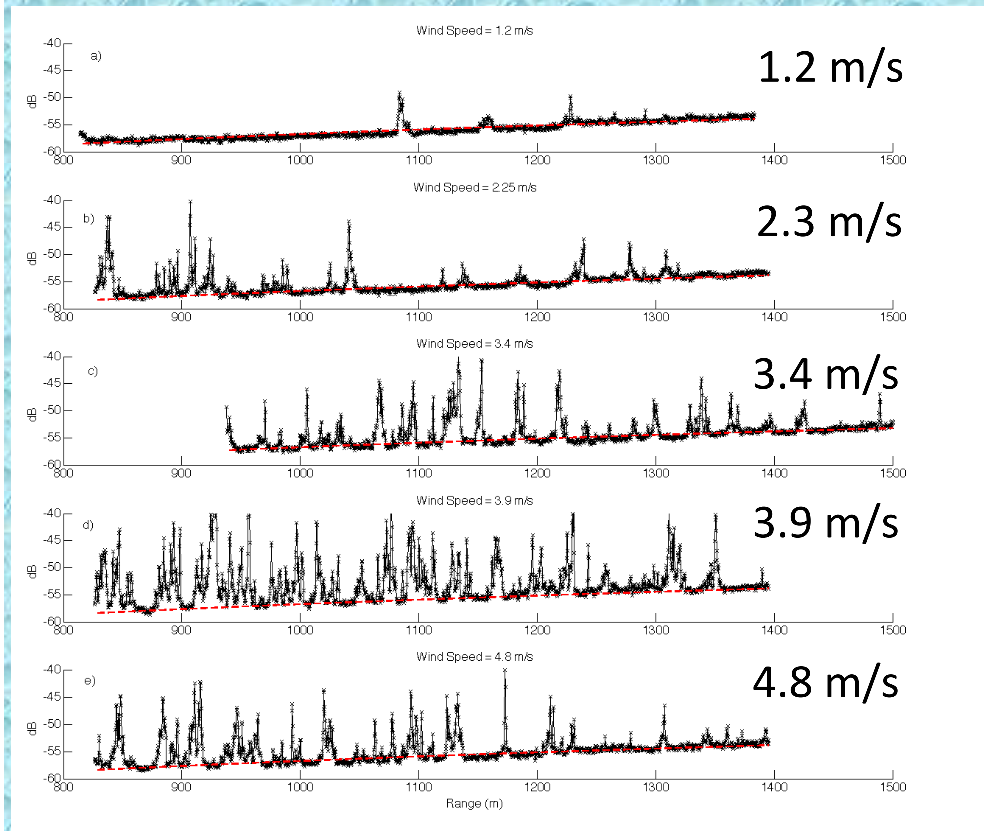
Radar System Overview

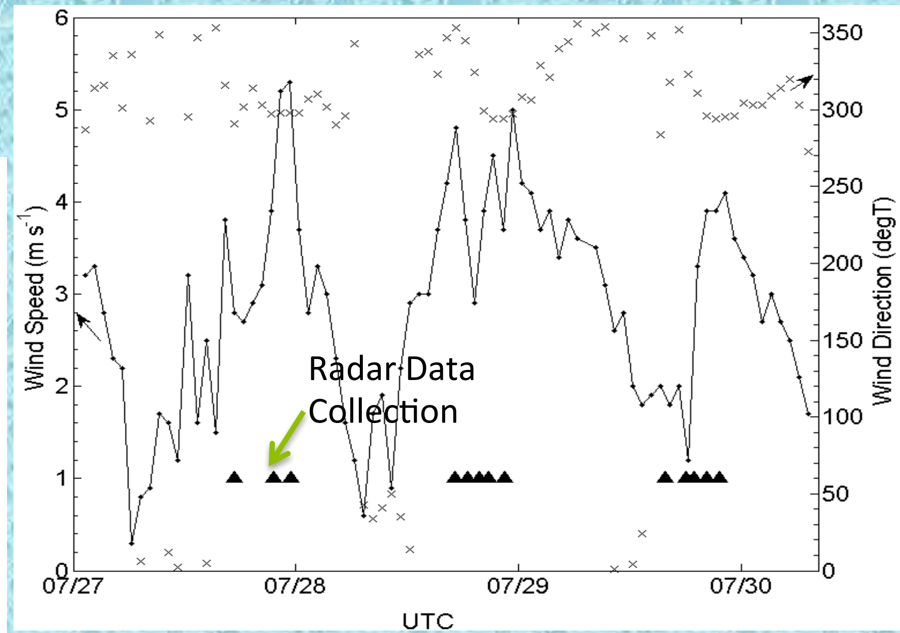


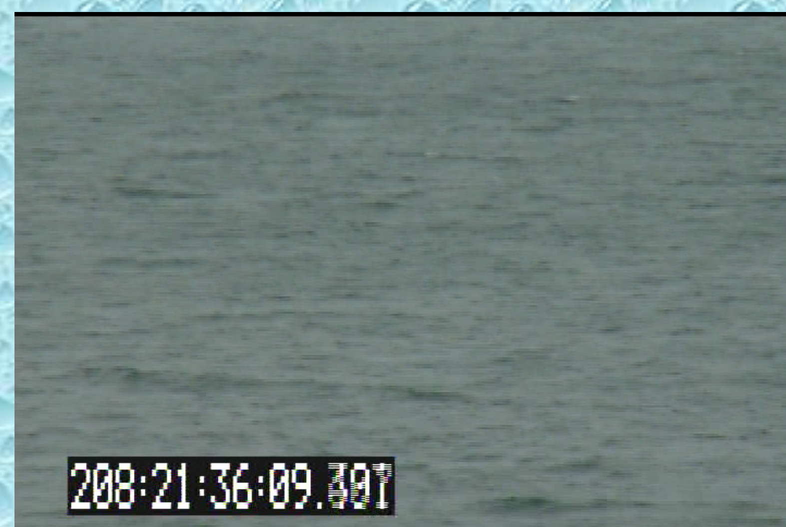
- Coherent
- X-band: f_c= 9.3 GHz and λ=3.2 cm
- VV and HH polarizations
- Spatial resolution: 30 cm (bandwidth 0.5 GHz)
- Temporal resolution: 0.0013 s (PRF 800 Hz)
- One-dimensional (non-rotating)

- Antenna height: ~14 m above MLLW
- Grazing angle: ~1 deg
- Range coverage: ~600 m
- Pencil beam: 1 deg in elevation & azimuth

Wave Environment





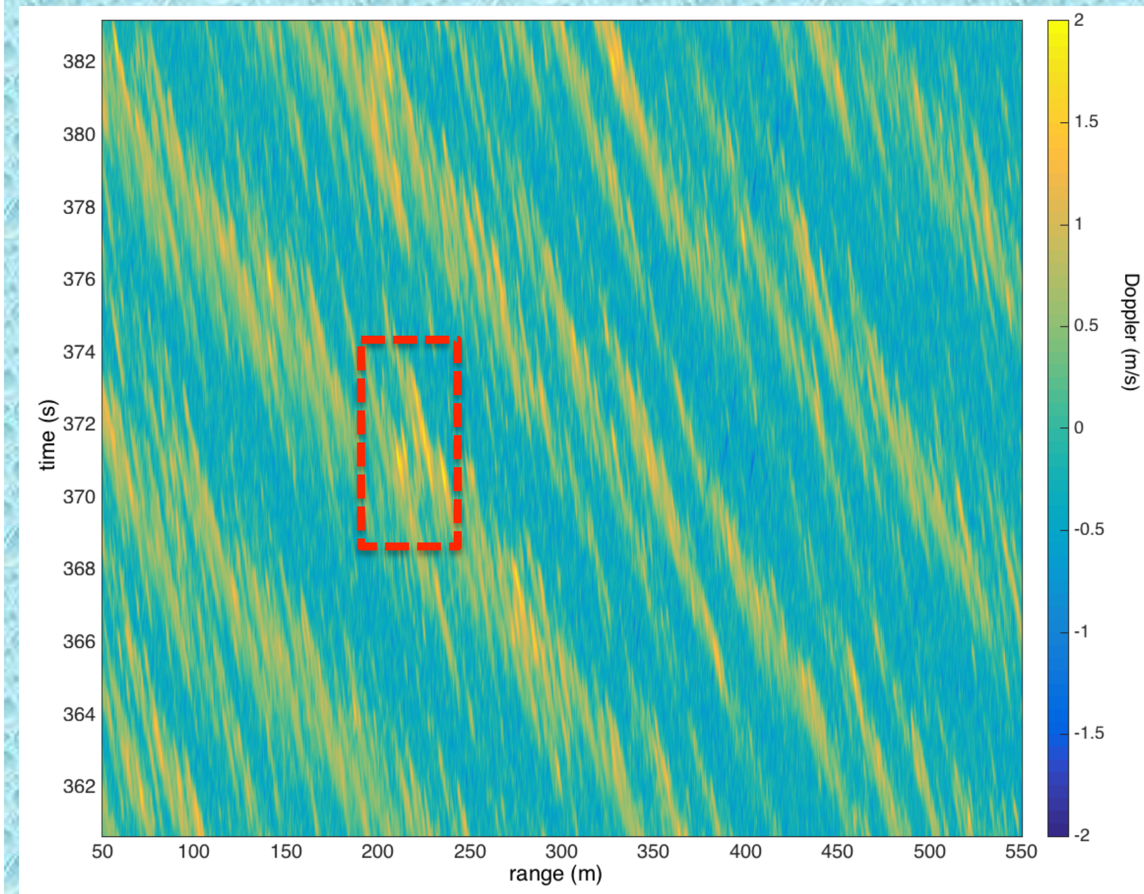


- Average water depth ~ 48 m

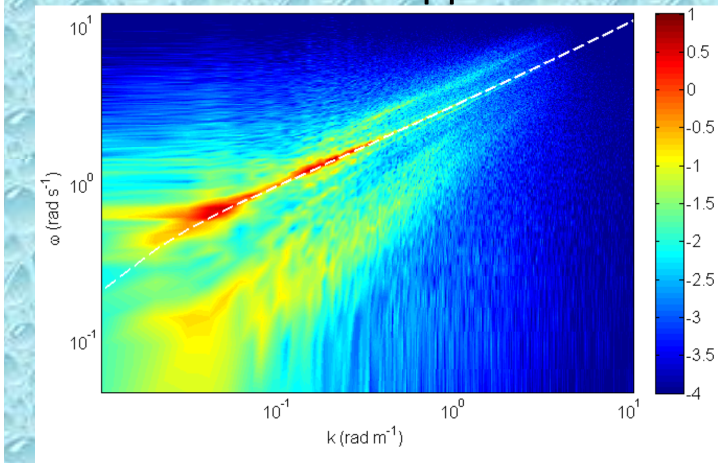
- Angle between peak wave direction and DREAM antenna azimuth mostly < 20 deg

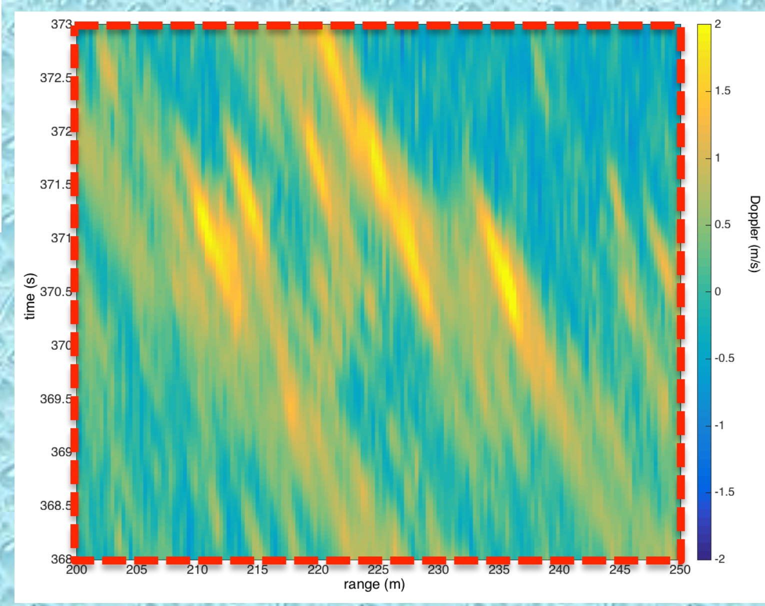
- Significant wave height ~0.6 m

Doppler Processing



Mean 2D PSD of Doppler Velocities

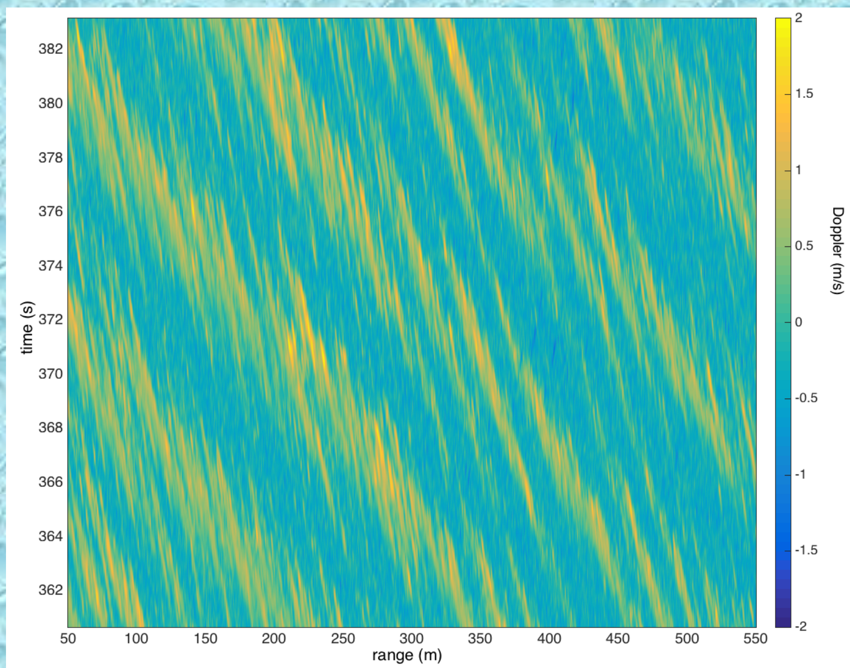


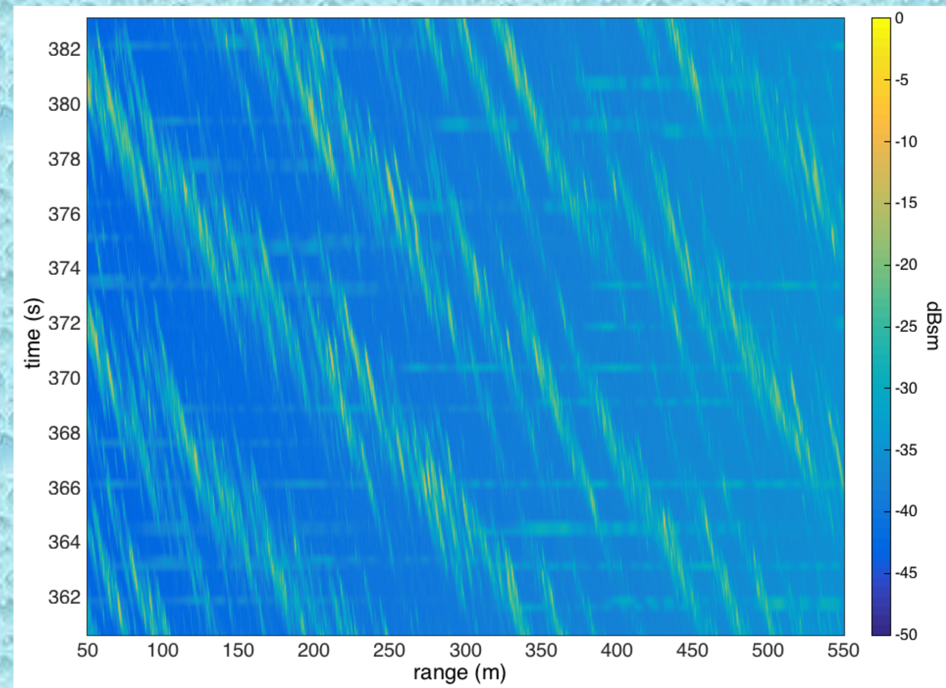


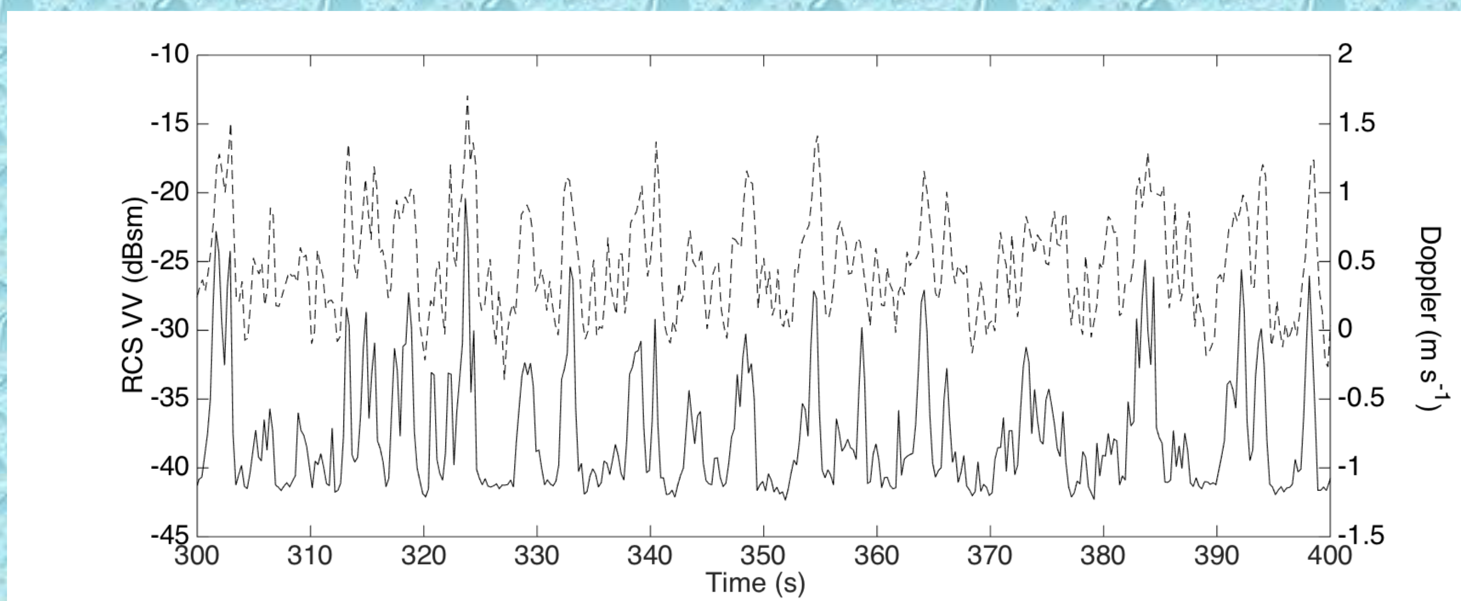
Pulse-Pair Processing

$$v_d = -\frac{\partial \phi(r,t)}{\partial t} \frac{1}{2k_r \cos\theta_g}$$

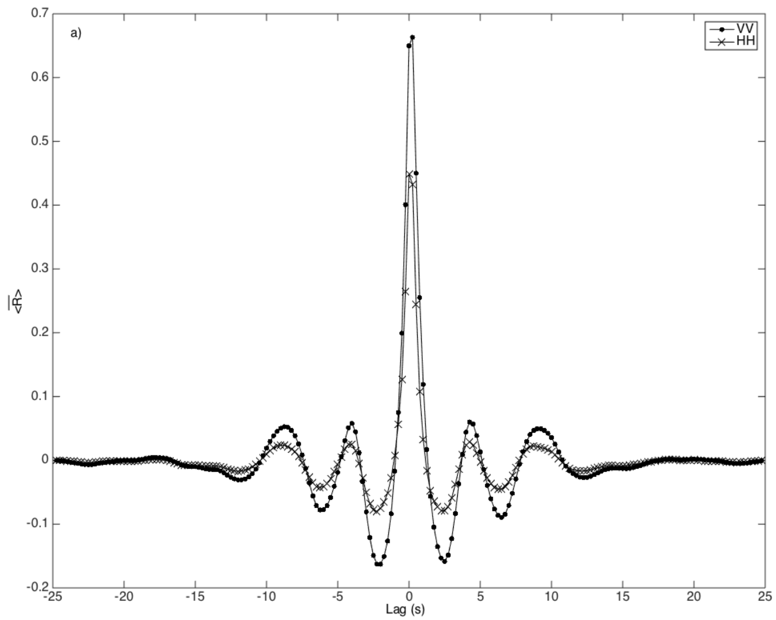
Signal Modulation in Spatiotemporal Domain

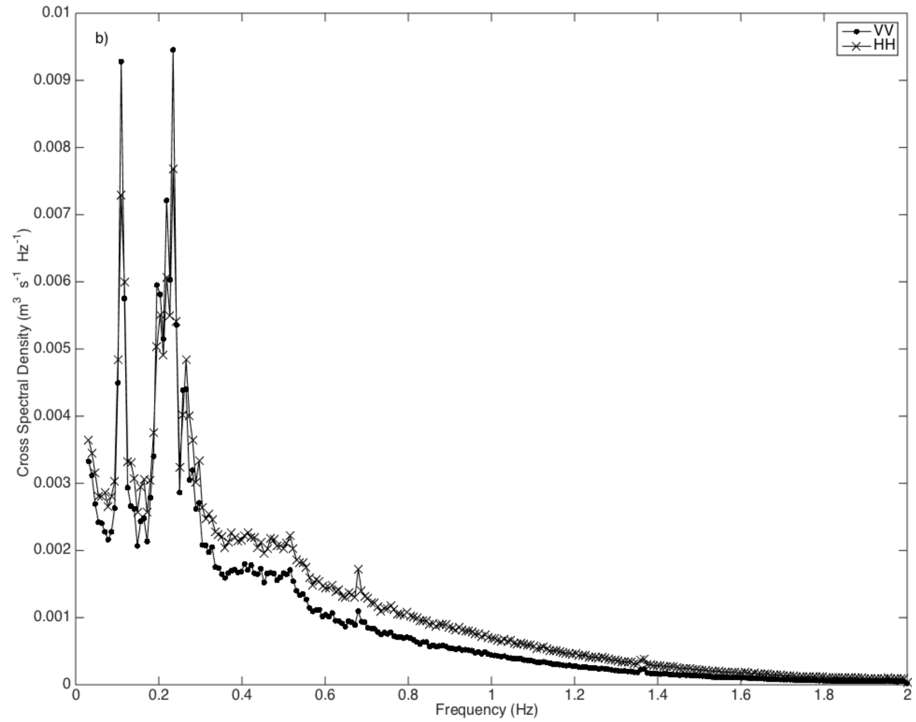






Signal Modulation in Spatiotemporal Domain

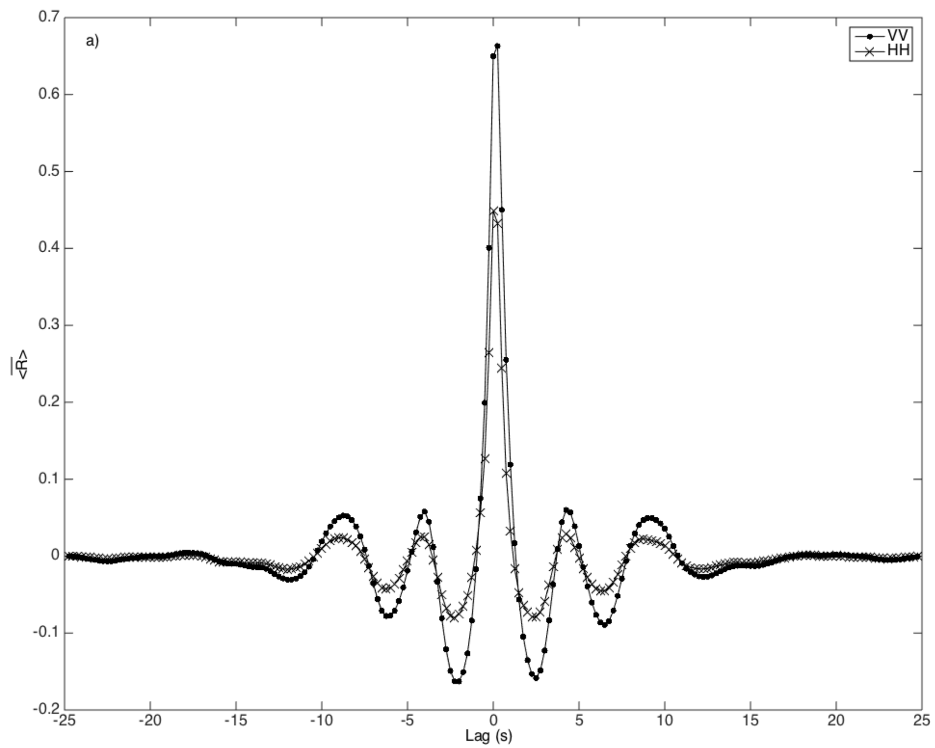


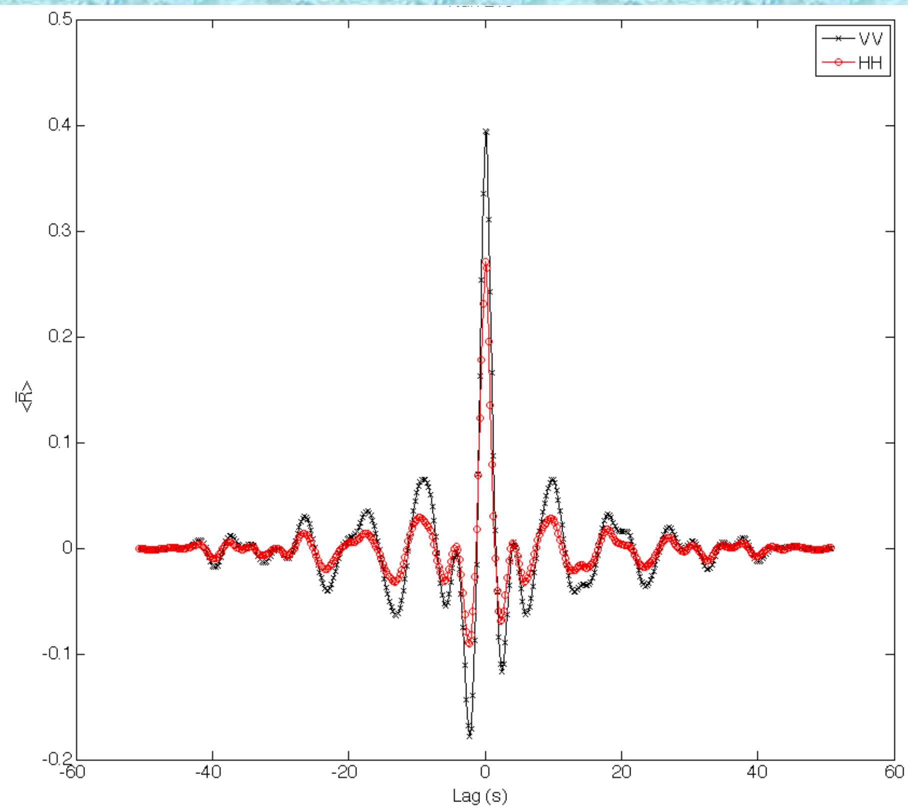


Correlation Function

Co-Spectra

Signal Modulation in Spatiotemporal Domain





No Dispersion Filtering

Dispersion Filtered

Signal Modulation in Spatiotemporal Domain

Johnson et al., 2009

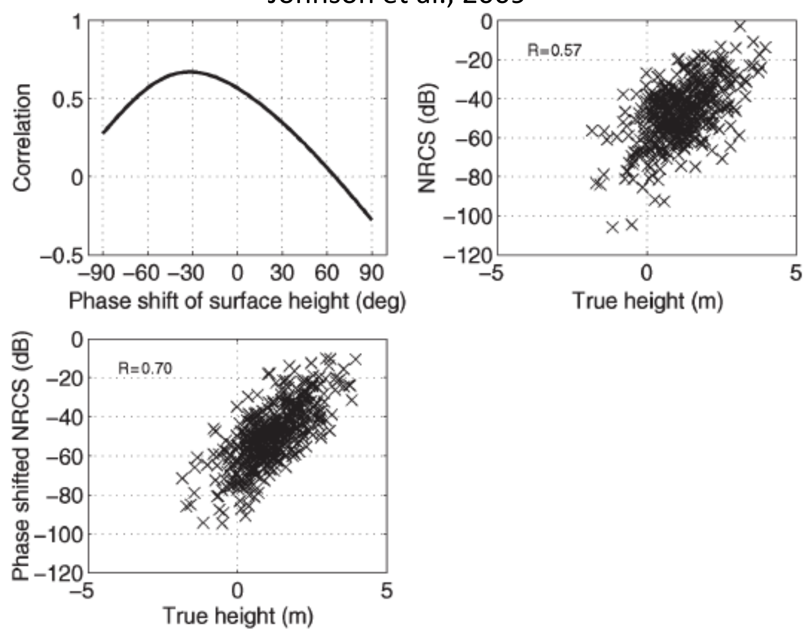


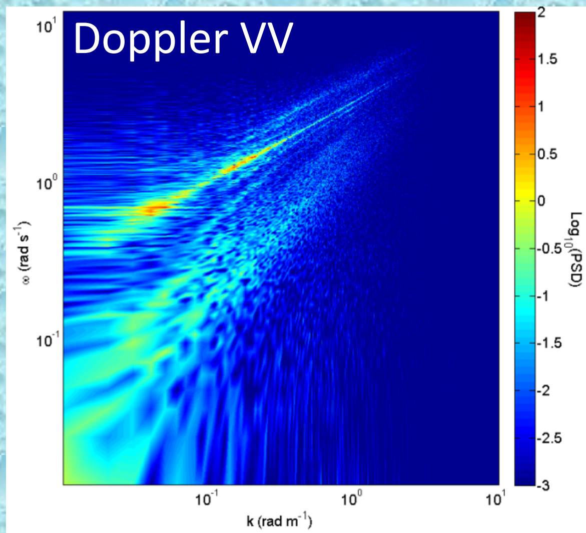
Fig. 3. Investigation of the impact of phase shifting the NRCS, in decibels, in correlation to surface height. (Top left) Correlation of NRCS, in decibels, with the surface height as a function of the phase shift of the surface height. (Top right) Original scatter plot of visible HH NRCS with the surface height. (Bottom left) Scatter plots of visible HH NRCS with surface height following phase-shifting operation.

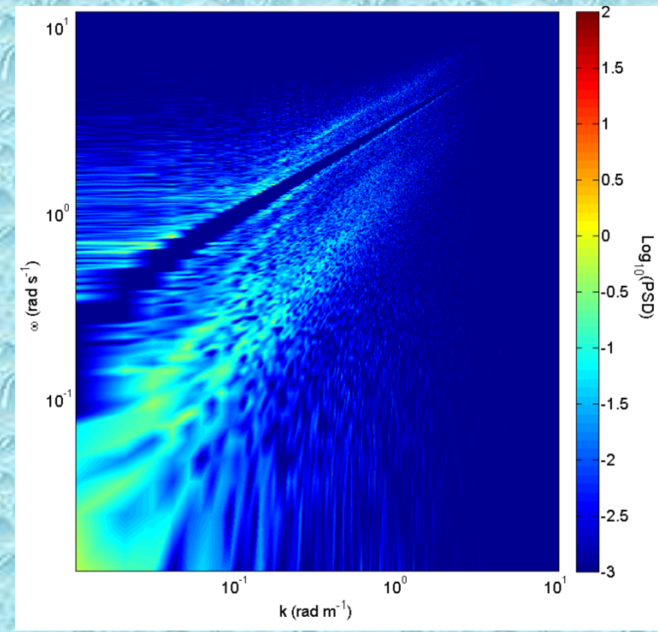
Run	VV	HH	lag VV (s)	lag HH (s)	Frequency Peak (Hz)
236	0.52	0.20	0	0	0.23
246	0.66	0.45	0.25	0	0.23, 0.11
250	0.65	0.45	0.25	0	0.21, 0.12
252	0.37	0.20	0.25	0.25	0.22
254	0.40	0.10	0	0	0.21
258	0.55	0.26	0.25	0.25	0.21
259	0.67	0.45	0.25	0.25	0.23
263	0.64	0.38	0.25	0.25	0.23
265	0.20	0.09	0.25	0.5	0.19
267	0.17	0.005	0	-0.25	none
268	0.33	0.11	0.25	0.25	0.20
269	0.64	0.39	0	0	0.19
272	0.60	0.39	0.25	0.25	0.20

Shift between maximum Doppler and maximum RCS typically in the range of 0 - 20 deg but was not observed to exceed 45 deg

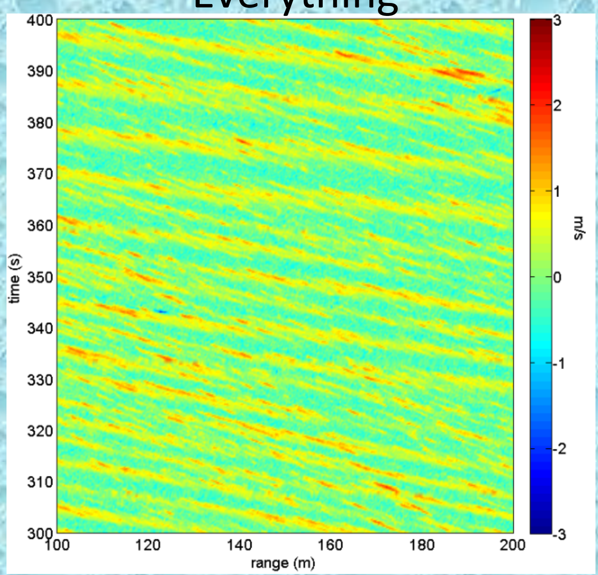
Suggests tilt modulation does not completely explain signal variance in spatiotemporal domain even in low sea states where shadowing effects are presumably small

Signal Analysis in Spatiotemporal Domain





Everything



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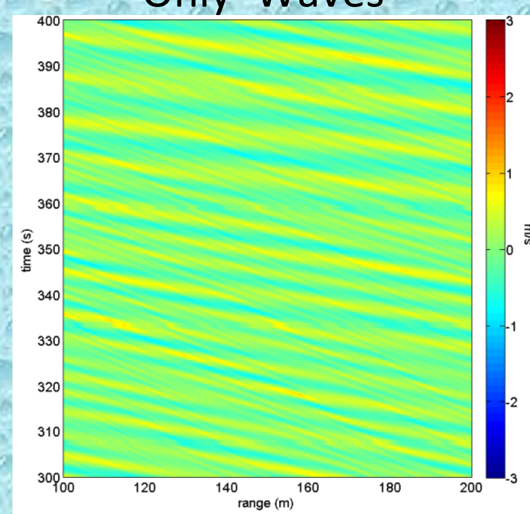
Only ‘Waves’



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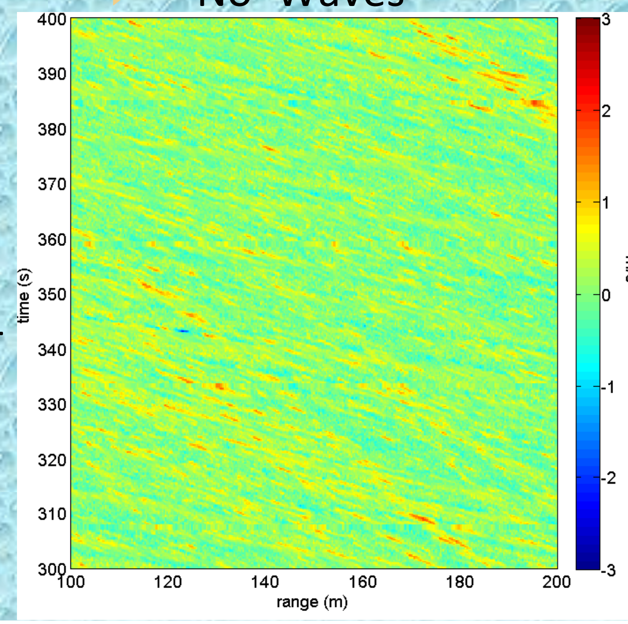
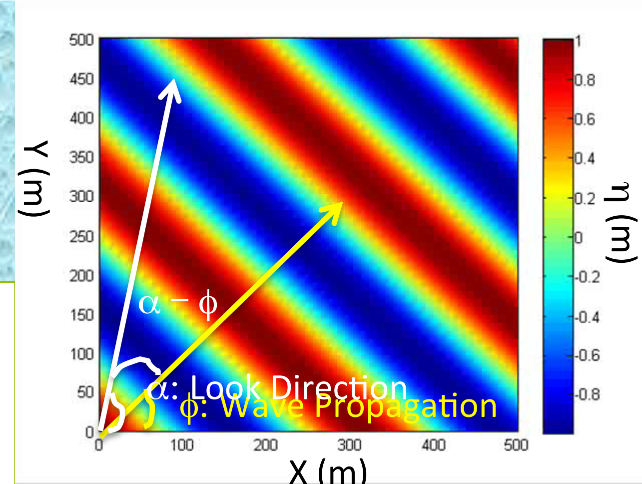
No ‘Waves’

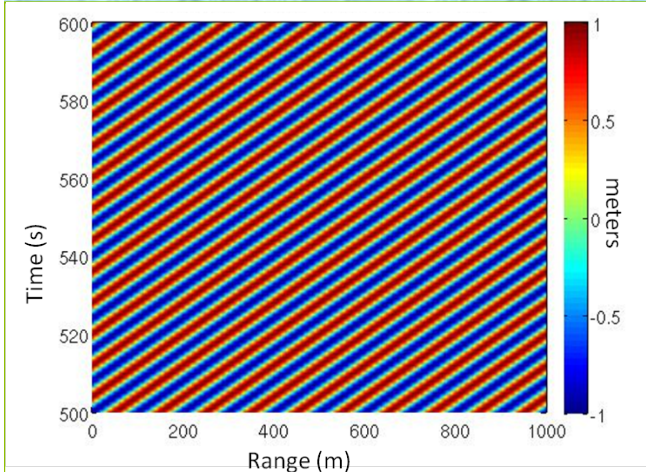


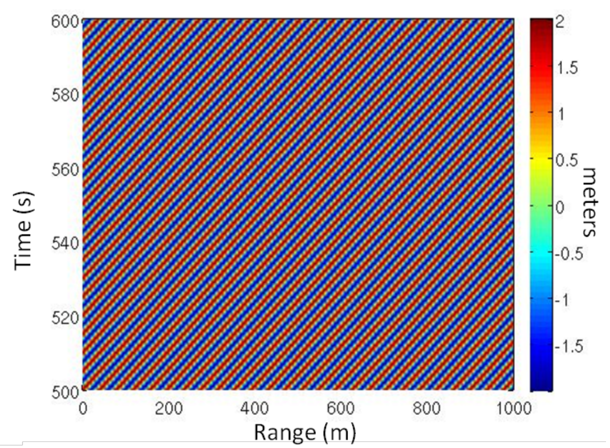
Simple Sinusoid

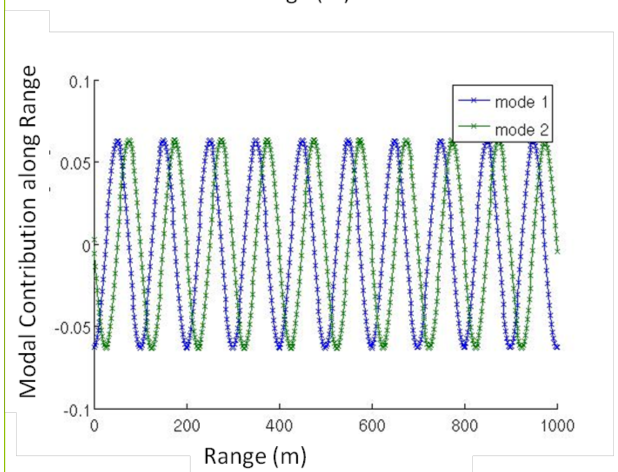


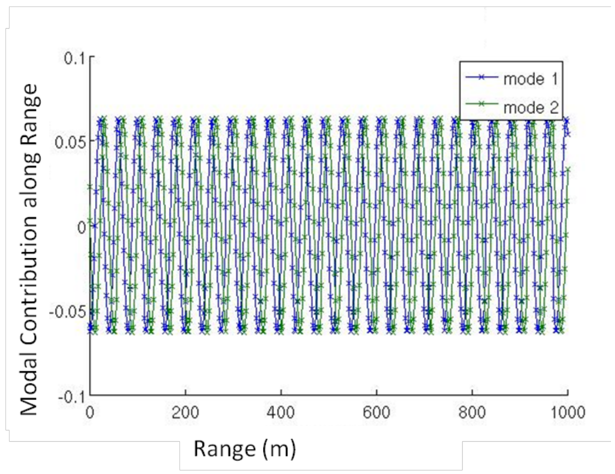
8 s period; 1 m amplitude

5 s period; 1 m amplitude









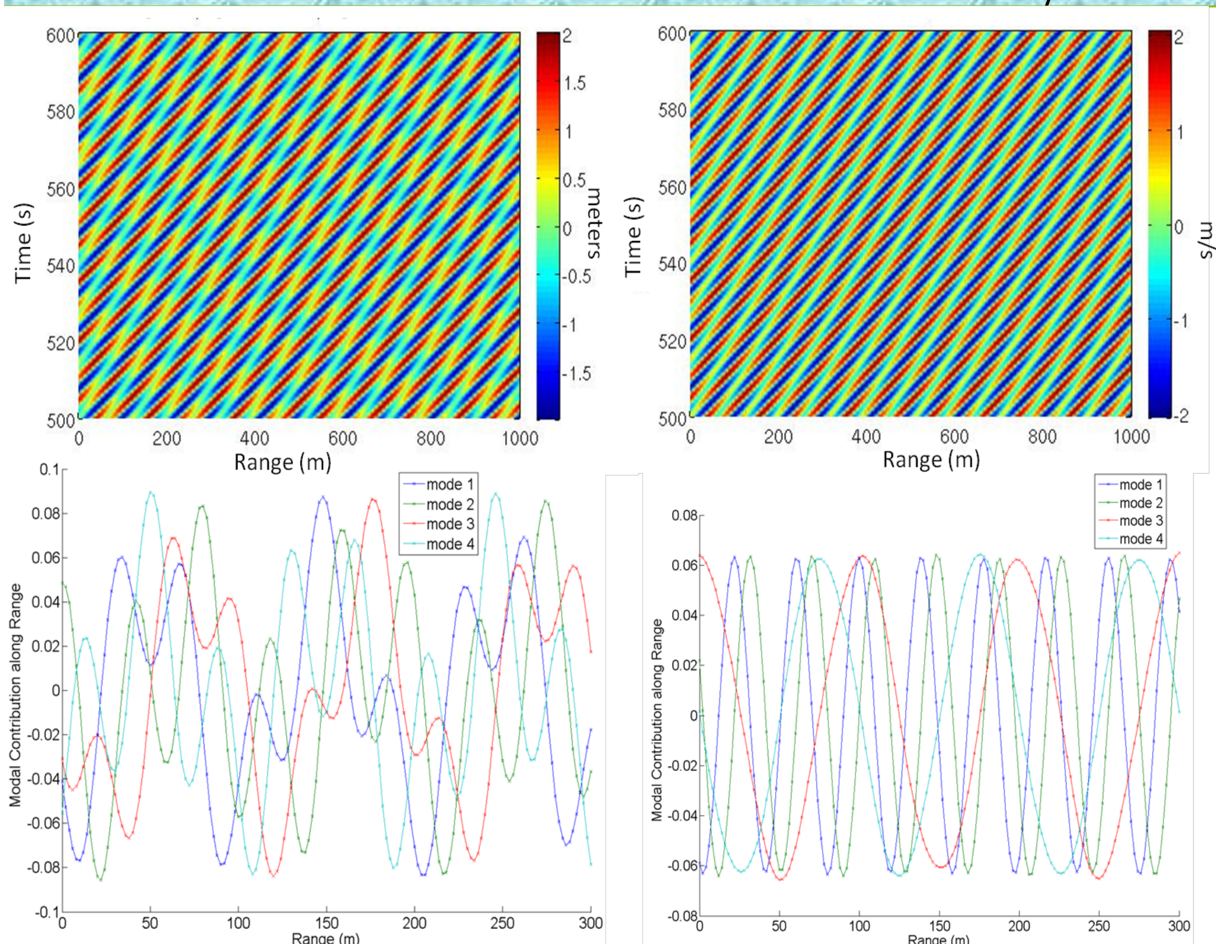
- Complex conjugate mode pair
- “Perceived” wavelength captured in mode: $\lambda/\cos(\alpha-\phi)$
- Orbital velocities show same trends

Linear Superposition

Two Waves
- 8 s period, 1 m amplitude
- 5 s period, 1 m amplitude
- Wave propagation and look direction are aligned

Sea surface elevation

Orbital velocity



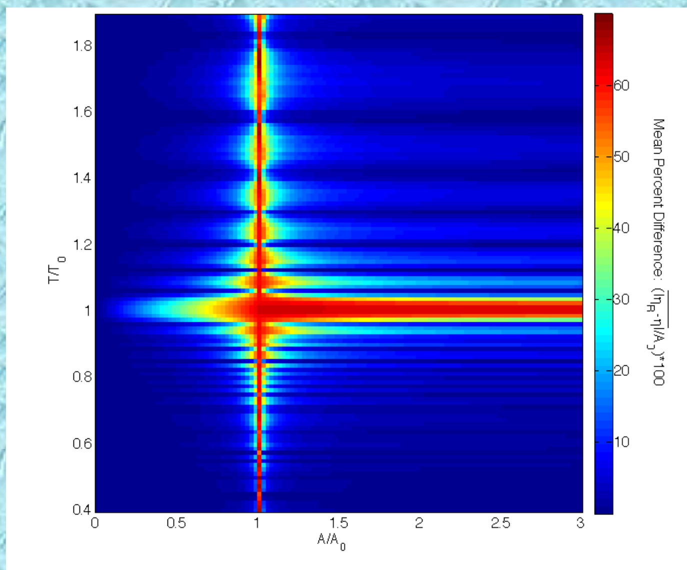
- Separation of wave systems requires frequency and amplitude diversity
  - 4 modes dominate for distinct periods but same amplitude (any direction)
  - 2 modes dominate for distinct amplitude but same period (any direction)
  - 4 wave-related modes for same direction, but distinct period and amplitudes
- Relatively insensitive to direction

Separation of Wave Systems

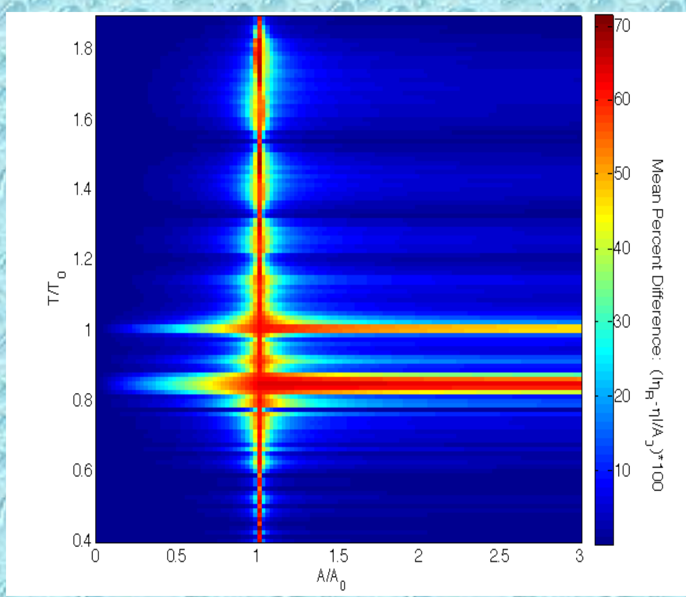
Percent accuracy on single wave reconstruction - separated based-on POD modes

Up-Wave

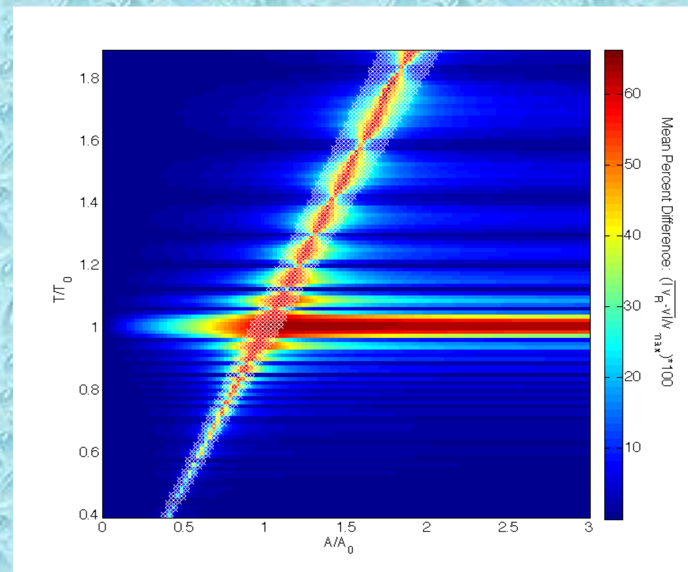
Wave Height



At an angle

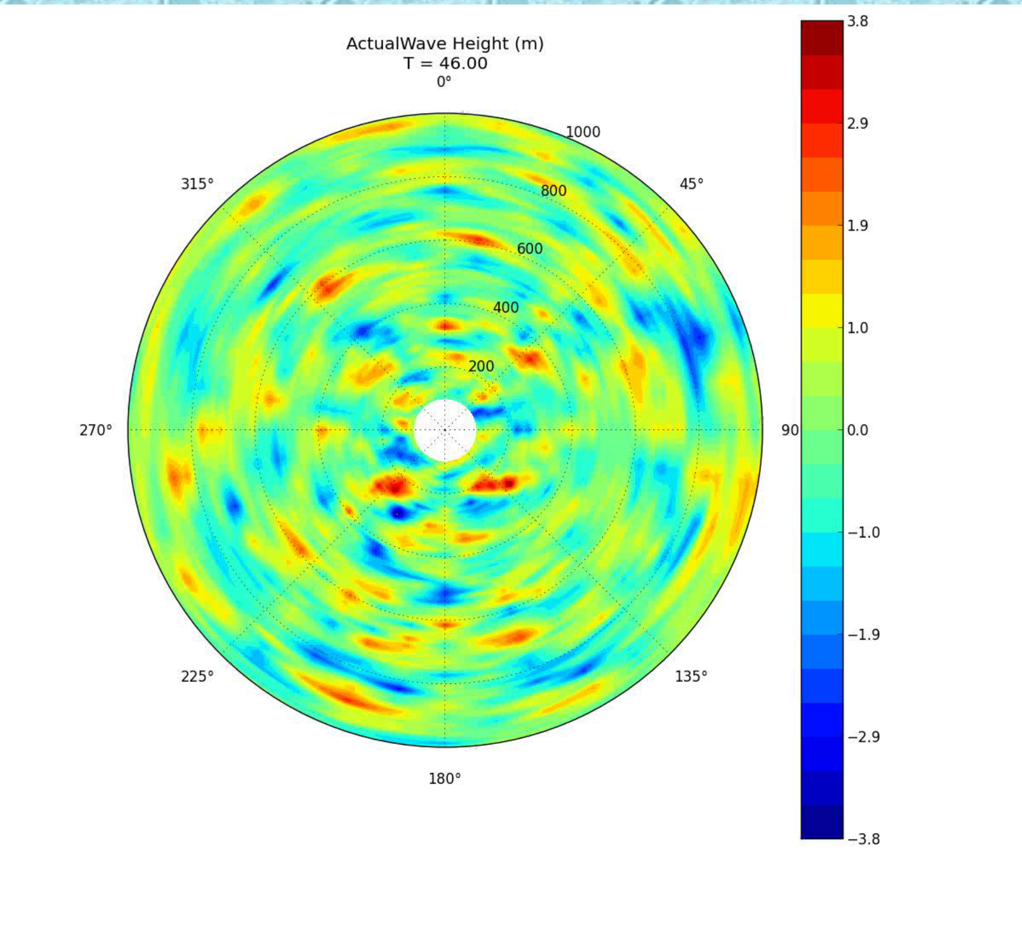


Orbital Velocities



- ~10% separation in amplitude and period needed to reduce errors below 30%
- Separation in period more critical, particularly if the wave being reconstructed has a smaller amplitude

Bretschneider Spectrum



Significant Wave Height: 3.7 m
Peak Period: 11.5 s
Spread Angle (μ): 80 deg

Incorporates directional and frequency bandwidth

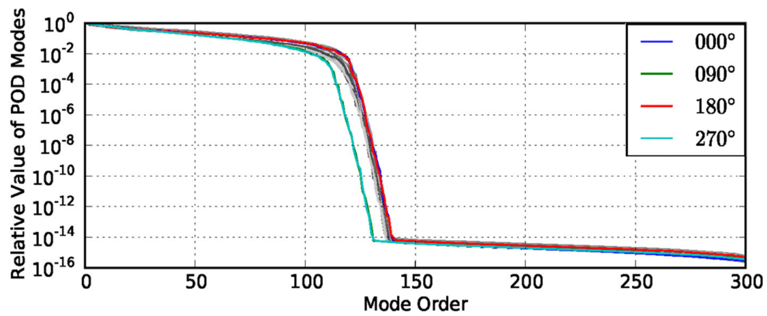
$$S_{BS}\left(f\right) = \frac{A}{f^5} e^{\left(-B/f^4\right)}$$

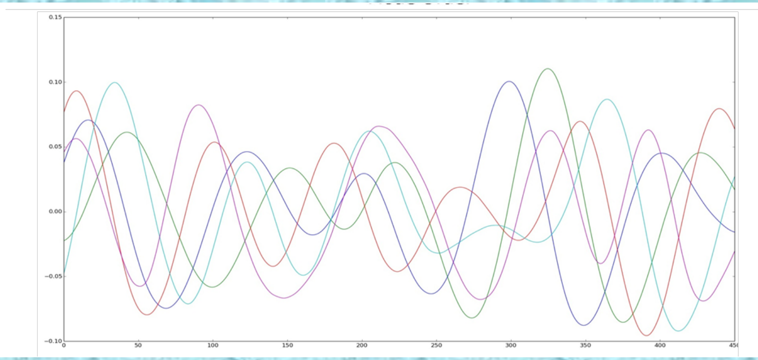
- 200 frequency components
- Cosine squared directional spreading

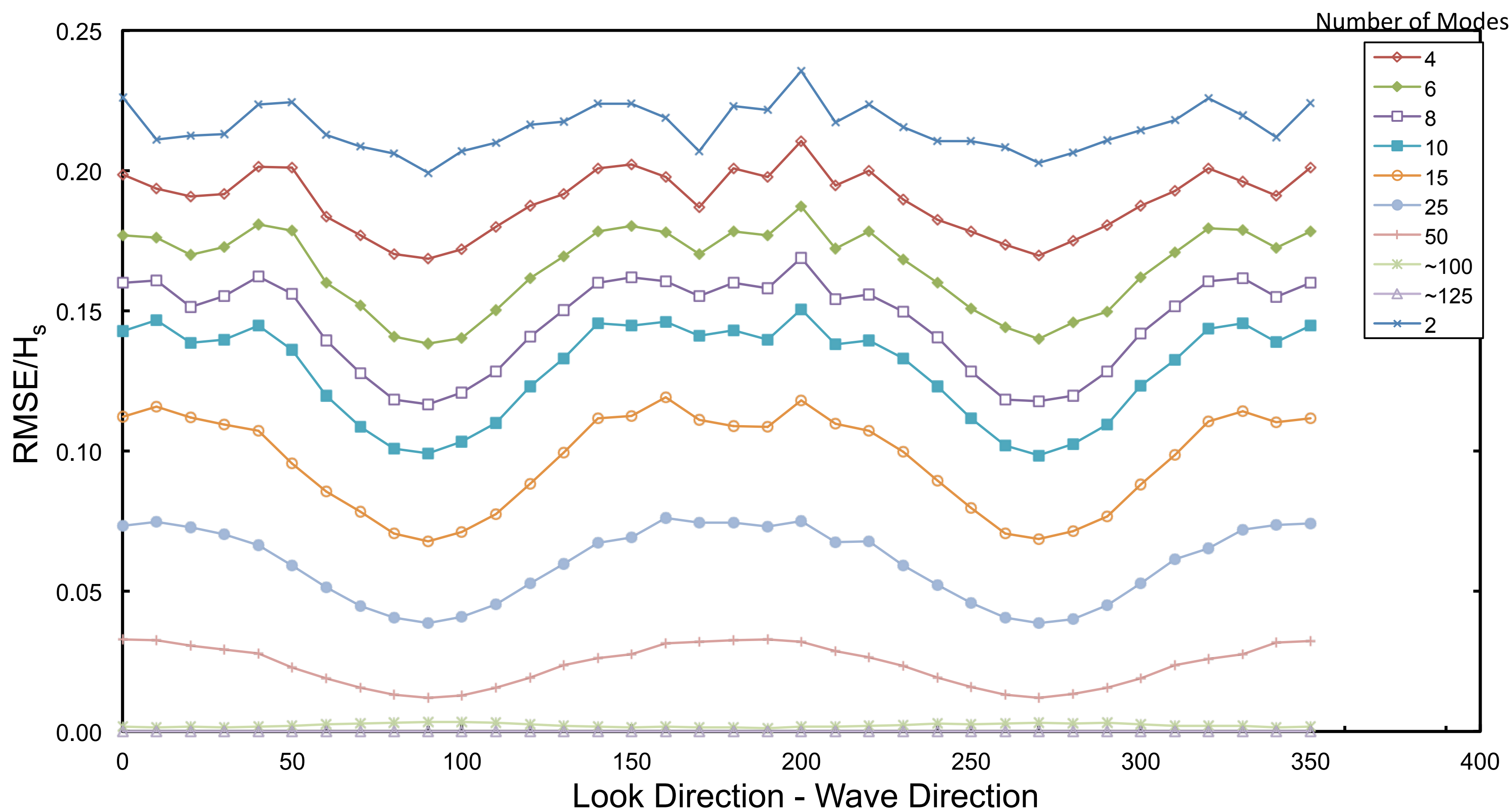
$$M(\mu) = \frac{2}{\pi}\cos^2 \mu$$

$$S(f,\mu) = S_{BS}\left(f\right) M(\mu)$$

Bretschneider Spectrum







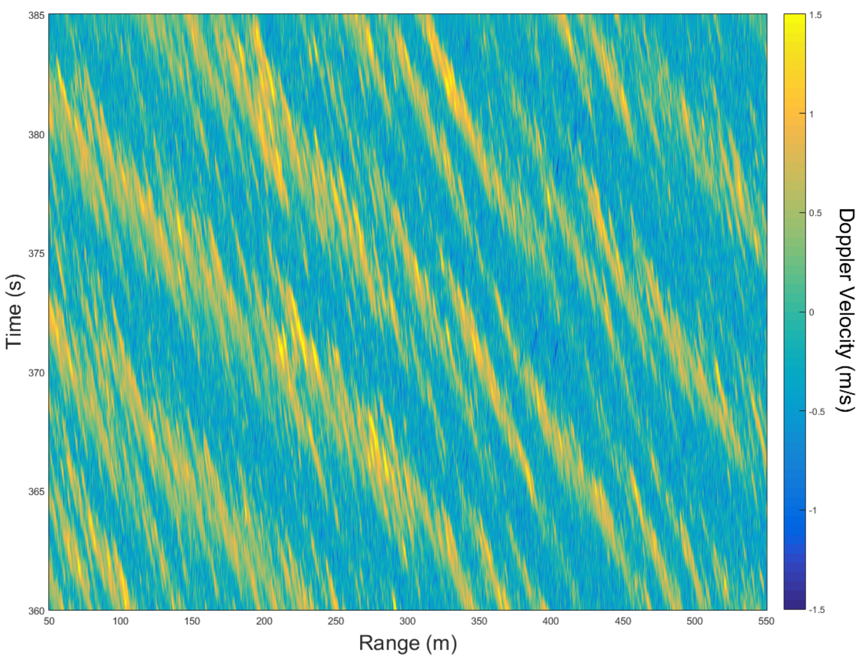
Signal Analysis in Spatiotemporal Domain

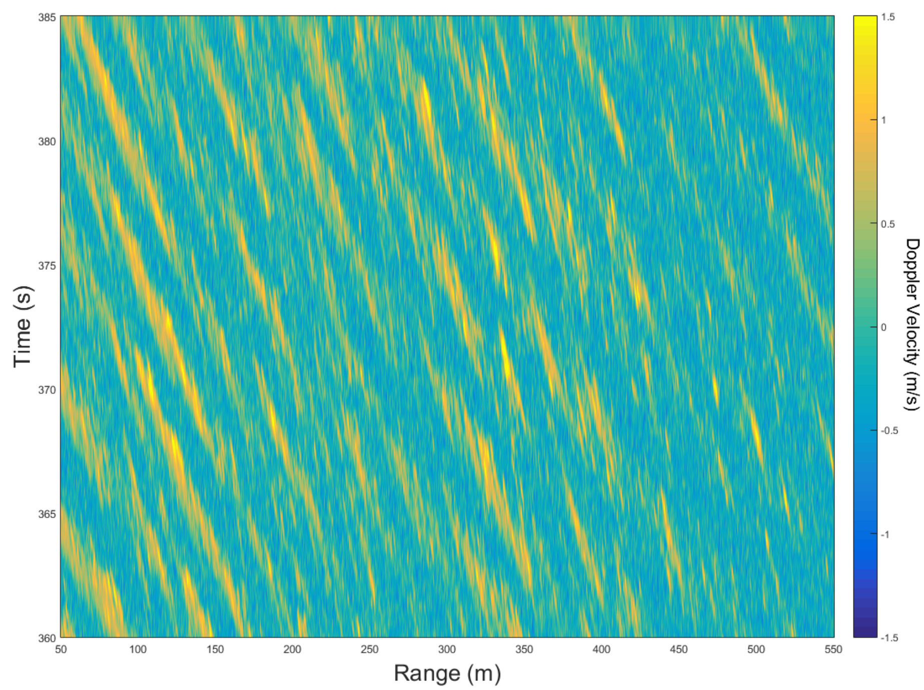
Swell and Wind Wave Case

- H_s = 0.60 m
- Peak Periods: 9 s and 4 s
- Wind Speed: 3.9 m/s
- Alignment: 12.6 deg offset from peak wave direction
- Grazing Angle: 1 deg

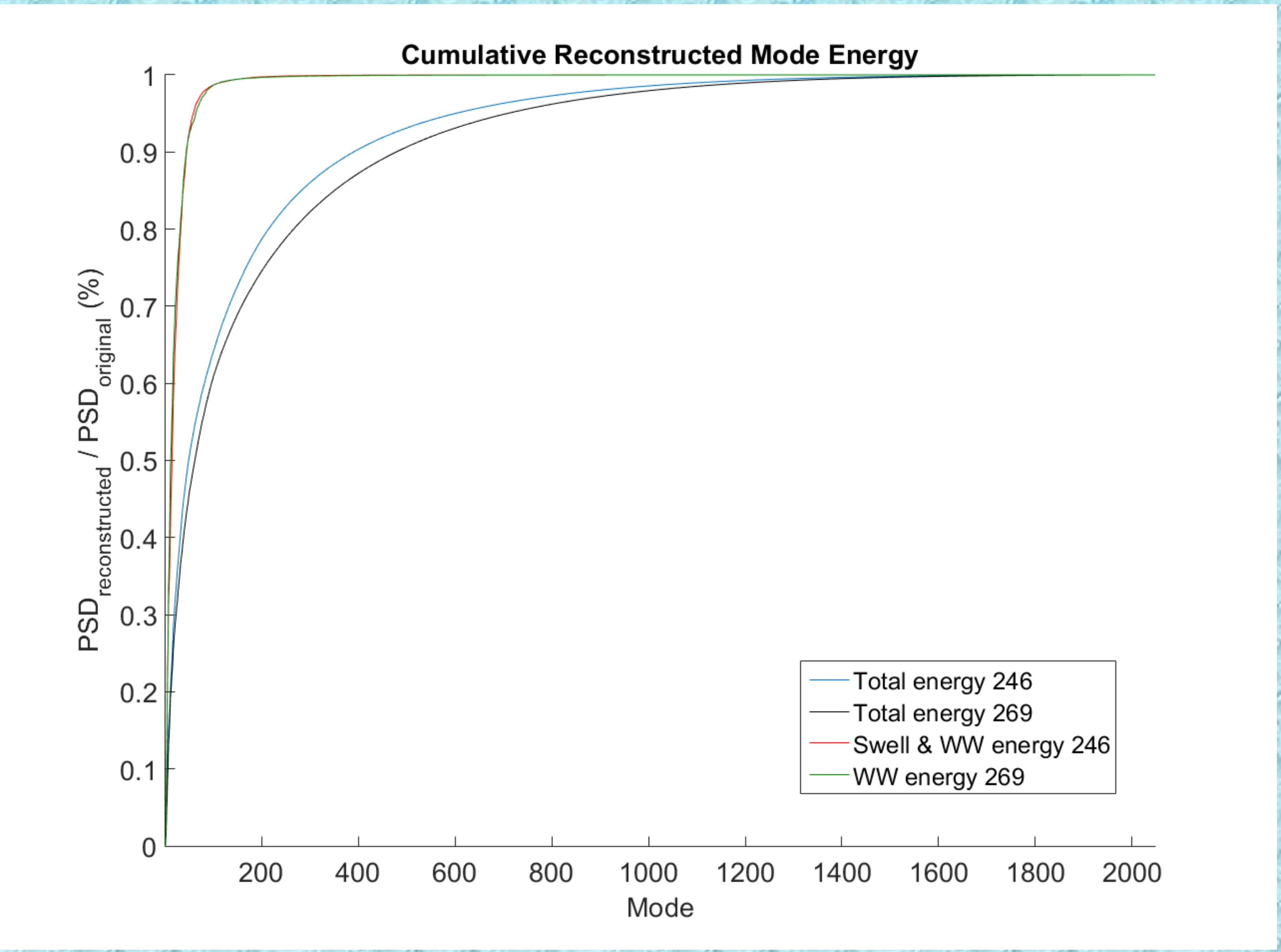
Wind Wave Case

- H_s = 0.62 m
- Peak Period: 5 s
- Wind Speed: 3.9 m/s
- Alignment: 4.5 deg offset from peak wave direction
- Grazing Angle: 1 deg





Signal Analysis in Spatiotemporal Domain

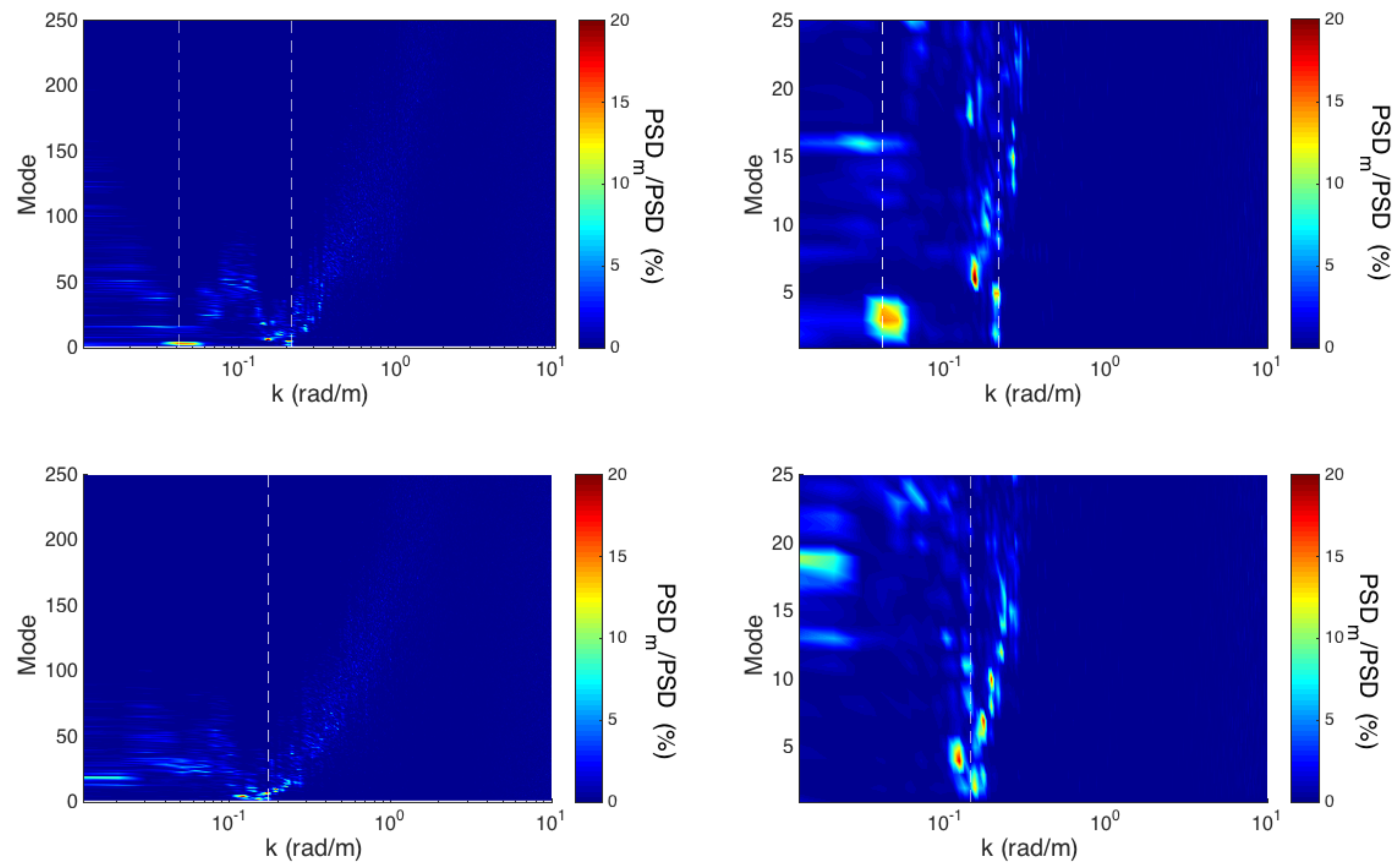


All energy in wave bands is reconstructed by 100 modes but adding in the high frequency content requires many more modes

Signal Analysis in Spatiotemporal Domain

Swell and Wind Wave Case

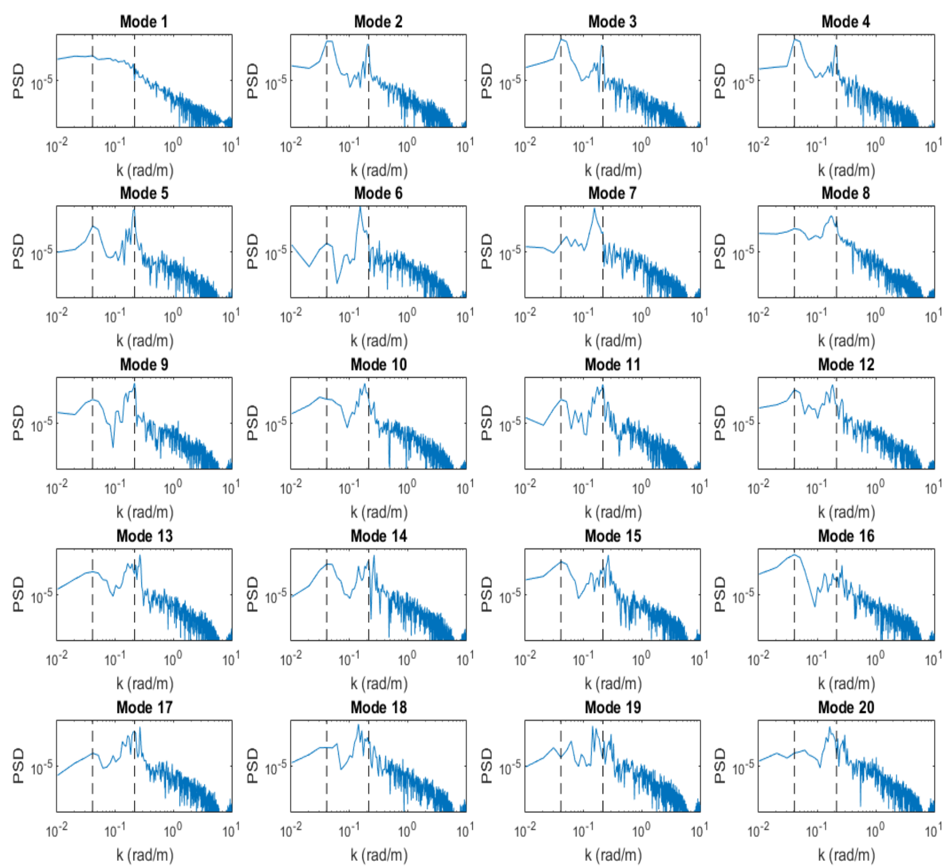
Wind Wave Case



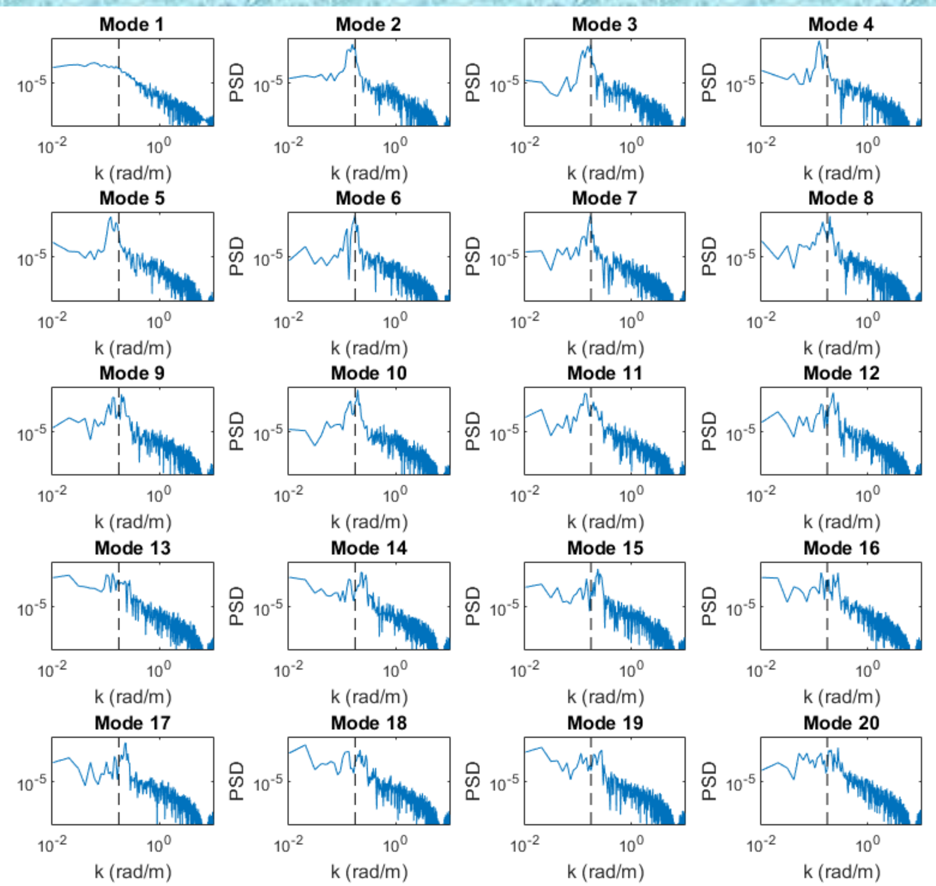
Most of the energy in peak wavenumber bands are in the lowest modes

Signal Analysis in Spatiotemporal Domain

Swell and Wind Wave Case



Wind Wave Case



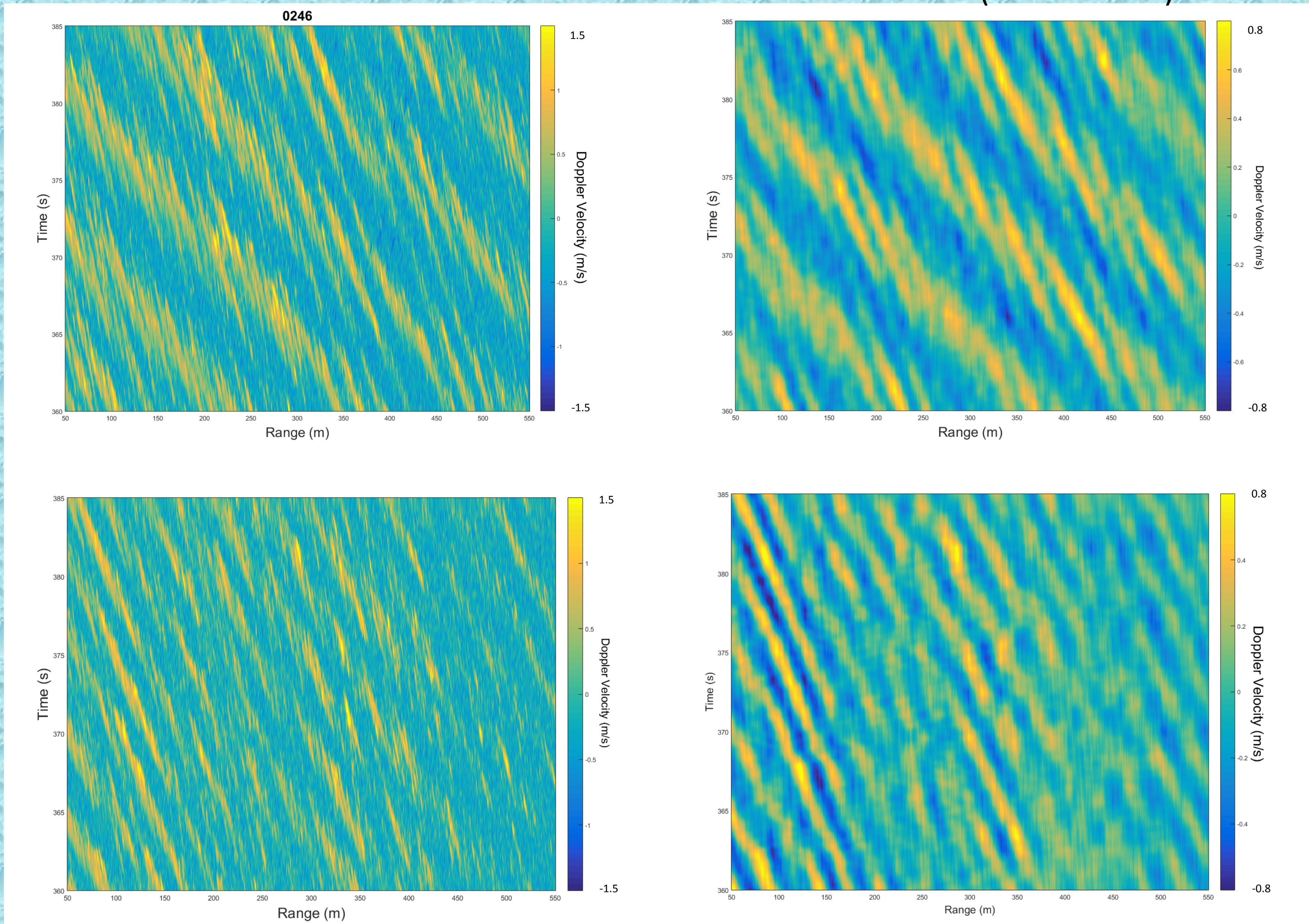
Largest variance surrounds wave frequencies

Signal Analysis in Spatiotemporal Domain

Original | Reconstructed (2-20 Modes)

Swell and Wind Wave Case

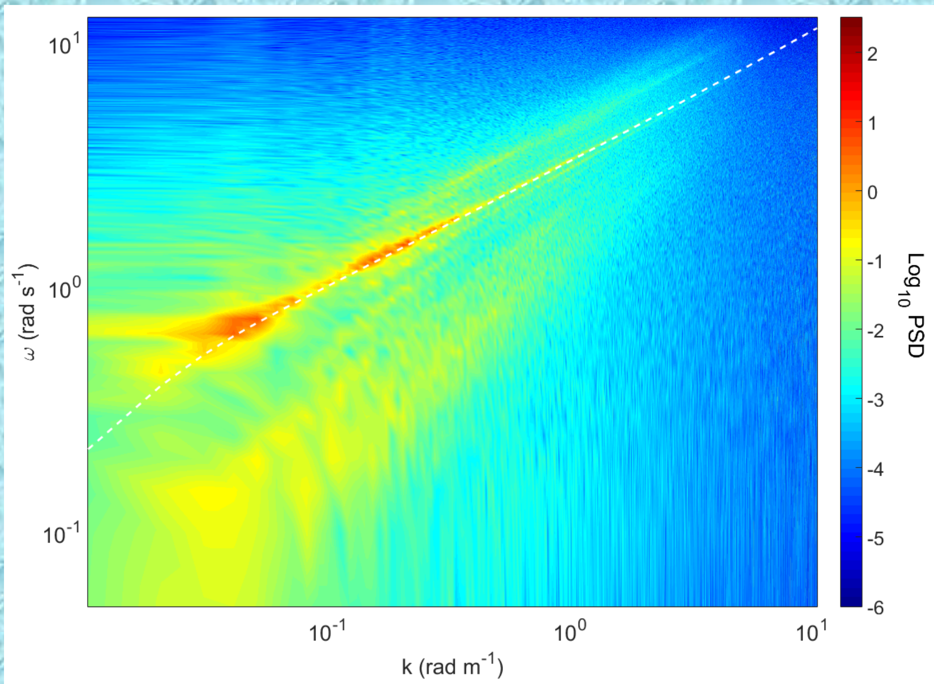
Wind Wave Case



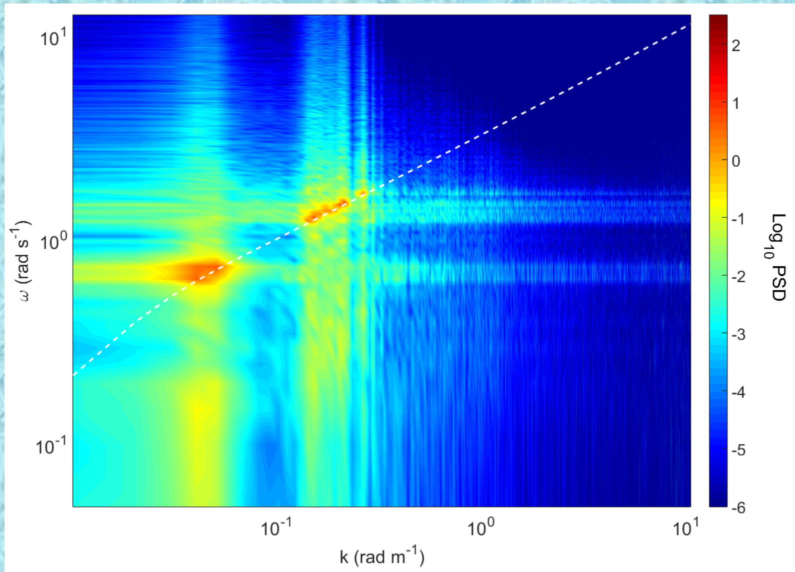
Signal Analysis in Spatiotemporal Domain

Swell and Wind Wave Case

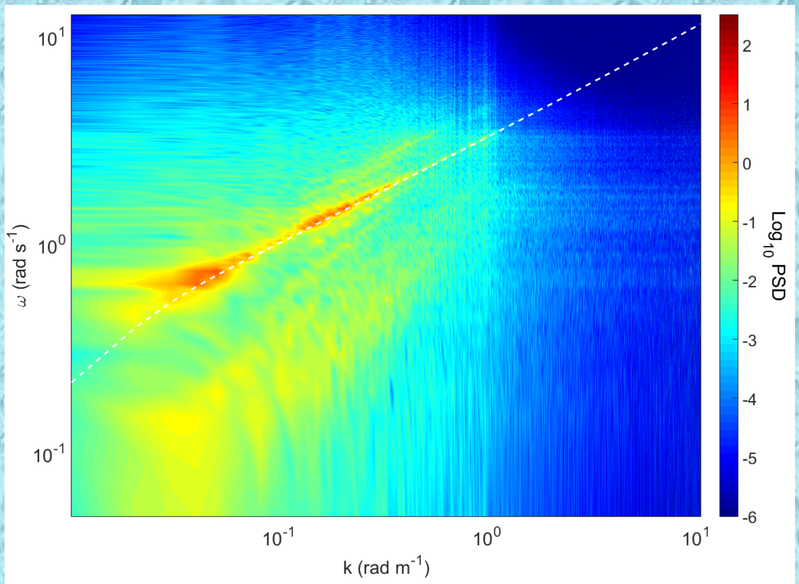
2D FFT of Original Data



2D FFT of 2-20 Mode Reconstruction



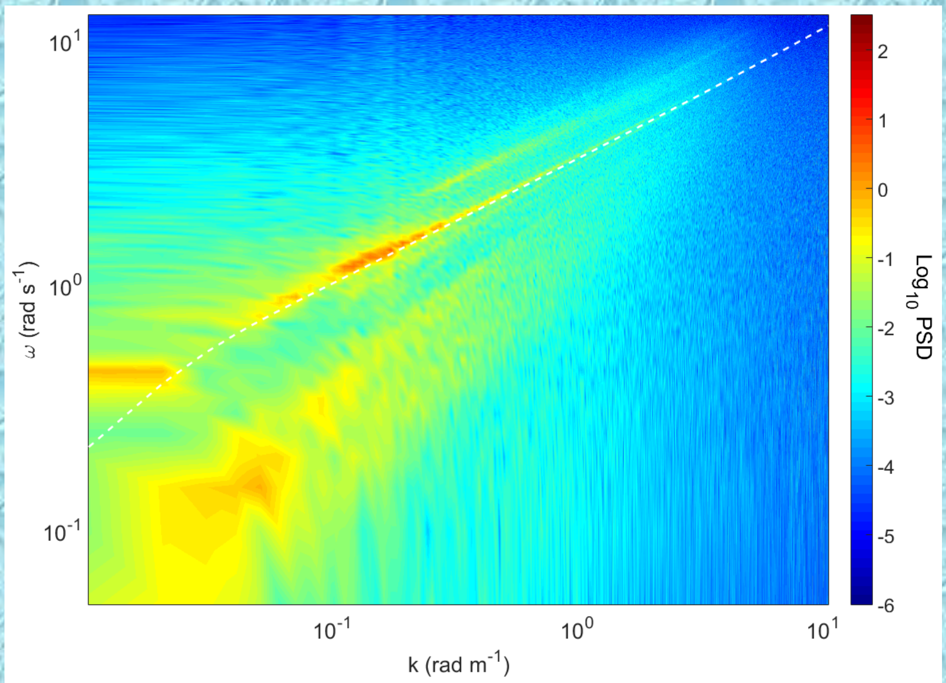
2D FFT of 2-100 Mode Reconstruction



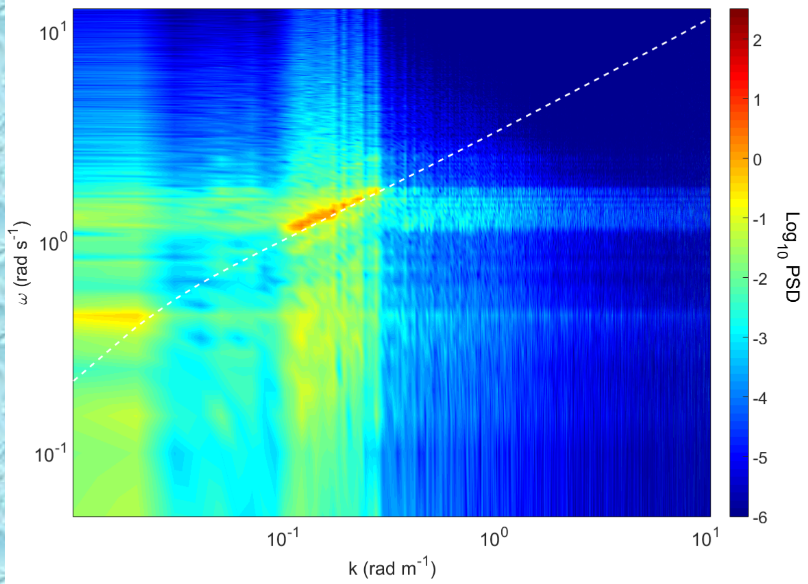
Signal Analysis in Spatiotemporal Domain

Wind Wave Case

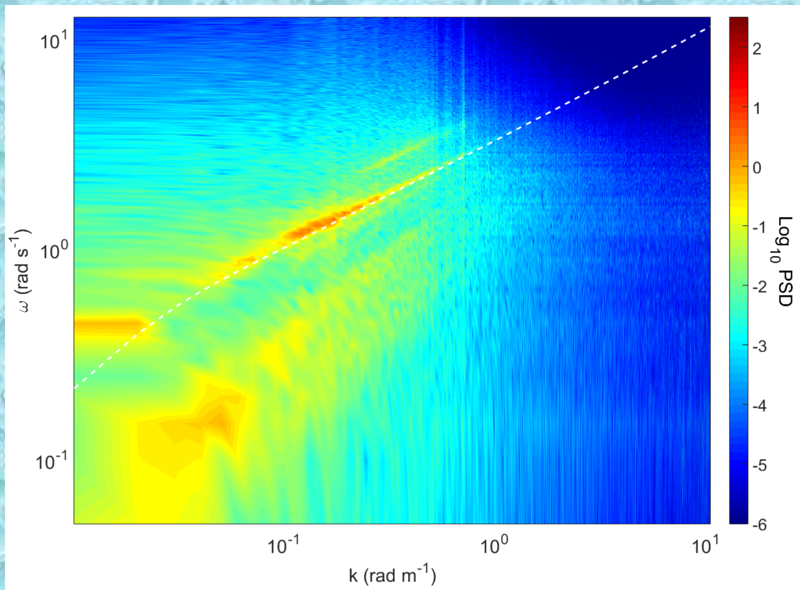
2D FFT of Original Data



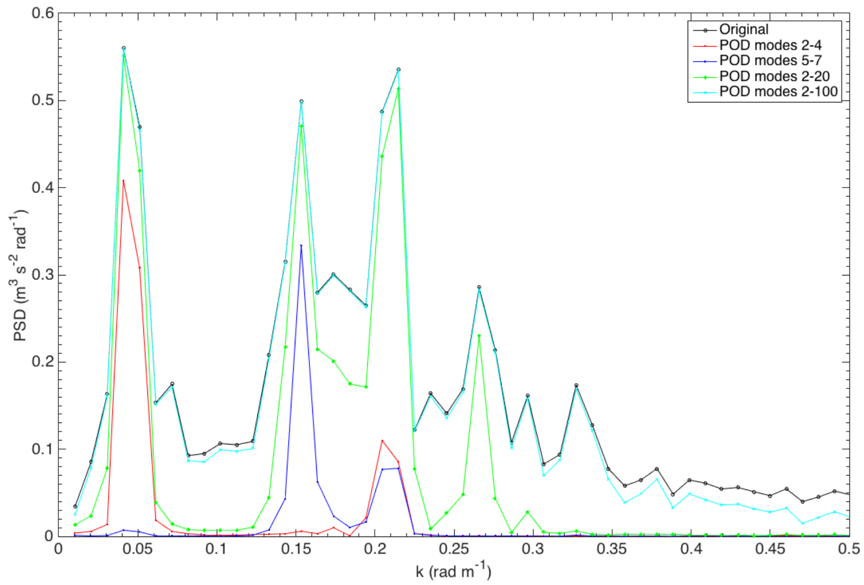
2D FFT of 2-20 Mode Reconstruction



2D FFT of 2-100 Mode Reconstruction



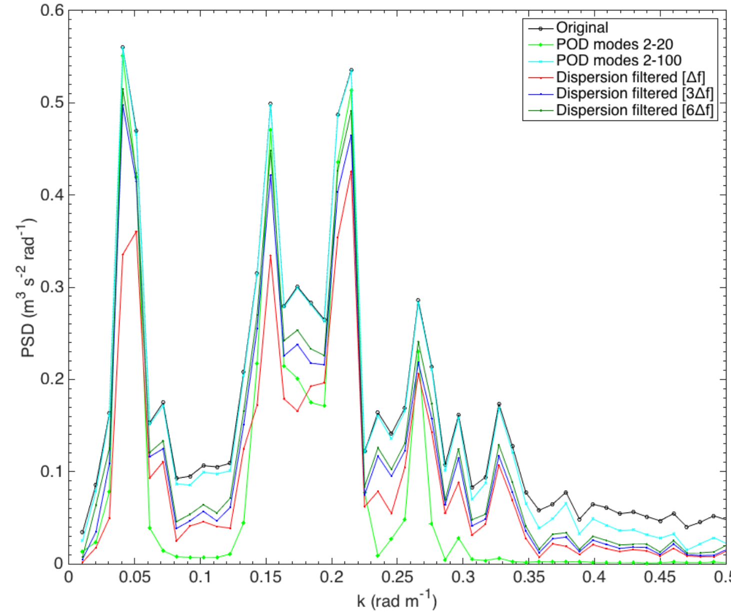
Signal Analysis in Spatiotemporal Domain



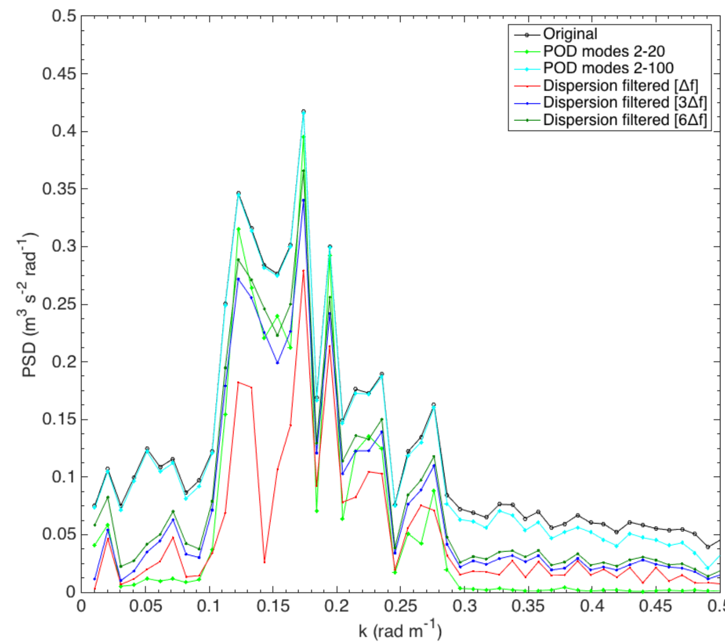
Certain modes capture more swell energy than wind sea energy

Comparison to dispersion curve filtering

Swell and Wind Wave Case



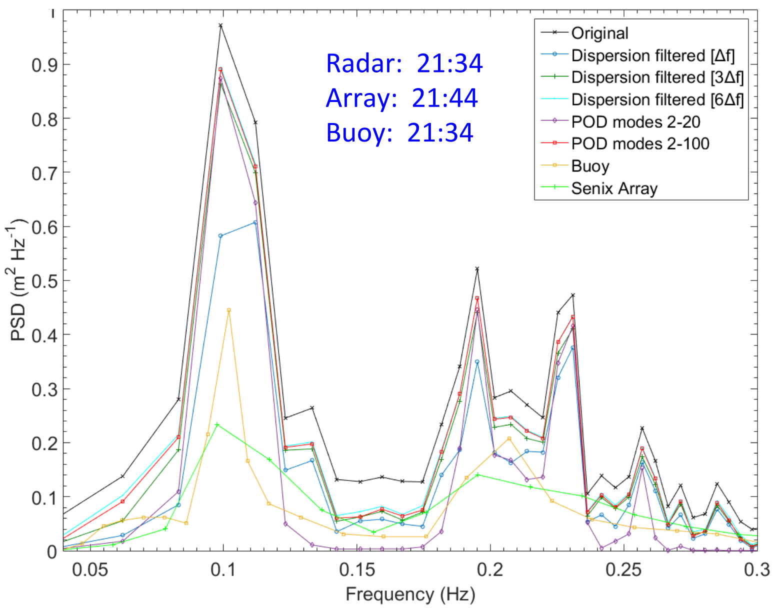
Wind Wave Case

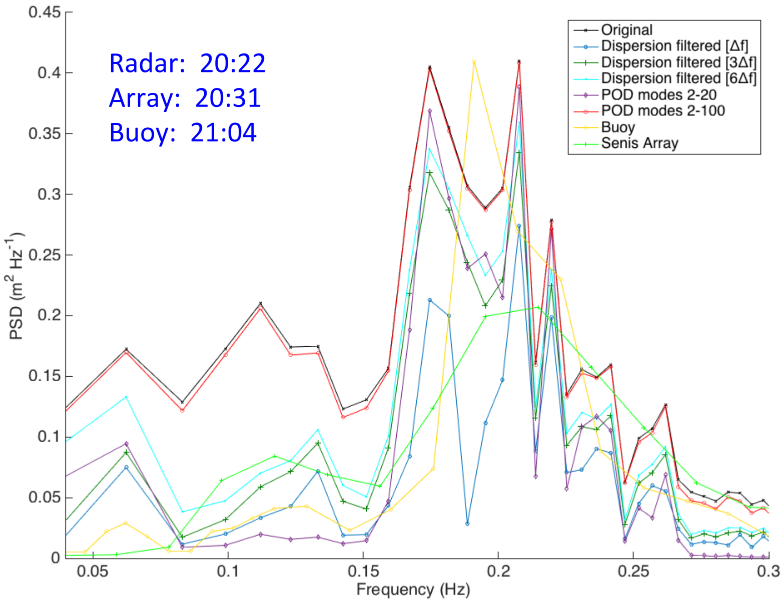


Signal Analysis in Spatiotemporal Domain

Swell and Wind Wave Case

Wind Wave Case





Need better ground truth to evaluate advantages/disadvantages of method

Summary

- High-resolution X-band VV radar measurements at SIO pier
- Modulation of Doppler and RCS signals in-phase – consistent with numerical results of Johnson et al., 2009
  - Suggests that maximum RCS occurs closer to wave crests than tilt modulation theory alone would predict
- Empirical decompositions could provide means to retain more non-linear features of the wave field in addition to sampling and data storage advantages
- Mode decompositions of simple wave fields demonstrate that modes can present physically meaningful content
- Preliminary results of application of method to SIO data
  - First 20 modes contain majority of energy in peak wavenumber/frequency bands – both on and off dispersion curve
  - Energy retained in these modes is greater than or equivalent to that retained via dispersion curve filtering in wave frequency bands
  - Results are encouraging for use of modes as a filter to isolate the wave signal