Applied Physical Sciences

Wave Sensing Radar and Wave Reconstruction

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Wave Sensing Requirements

Simple relations from linear wave theory:

Dispersion relation

$$gk = \omega^2$$

Wavelength in meters

$$\lambda \approx 1.56T^2$$

Phase speed in m/s

$$c_p \approx 1.56T$$

Group speed in m/s

$$c_g \approx 0.8T$$

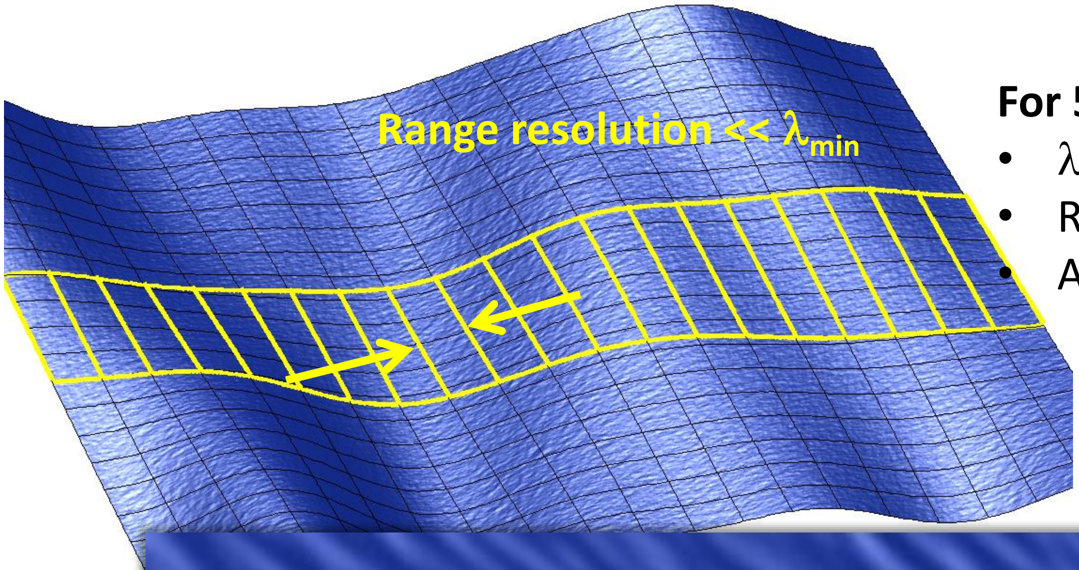
Period T (s)	Frequency (Hz)	Wavelength (m)	Group Speed (m/s)
4	0.250	25	3.2
6	0.170	56	4.8
8	0.125	100	6.4
10	0.100	156	8.0
12	0.083	225	9.6
14	0.071	305	11.2
16	0.063	399	12.8

Waves of interest (rows 6–16 s)

Group speed determines sensing range for forecasting

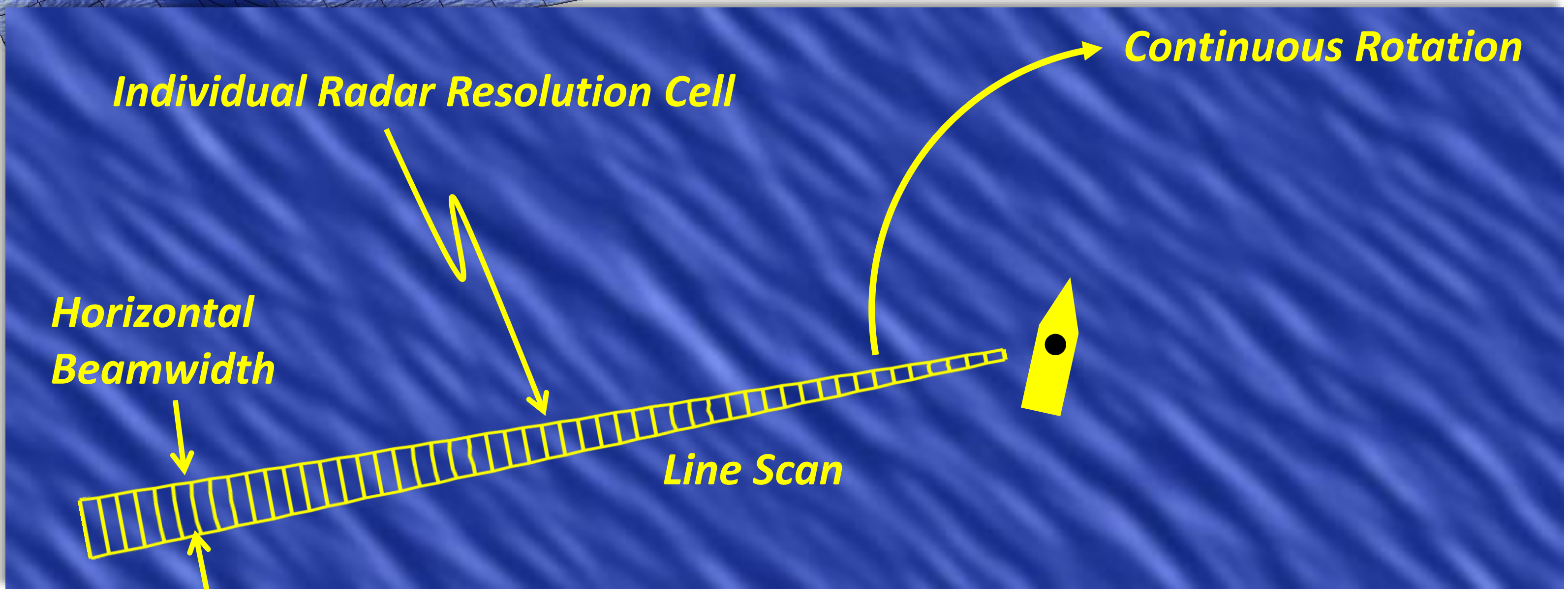
- Example: T_f = 300 s, C_g = 12.8 m/s: **R_{max} ~ 3840 m**

Resolution Requirements



For 5 s waves…

- λ = 40 m
- Range resolution < 20 m
- Azimuthal sweep interval < 2.5 s



Doppler Measurement Requirements

- $v_d = v_{orb} + n$
- How much error in the observation can be tolerated for accurate wave retrieval?
- Modeling and simulation of the APS wave retrieval process suggests that 0 dB "Doppler noise" can be tolerated:

$$\frac{std(v_{orb})}{std(n)} = 1$$

- As peak wave period increases, and significant wave height decreases – mean orbital velocity decreases
- Lowest expected rms orbital velocity is ~8 cm/s

RMS Orbital Velocity

$$SWH = 4\eta_{RMS}$$

$$V_{orb,RMS} \approx \omega_p \, \eta_{RMS}$$

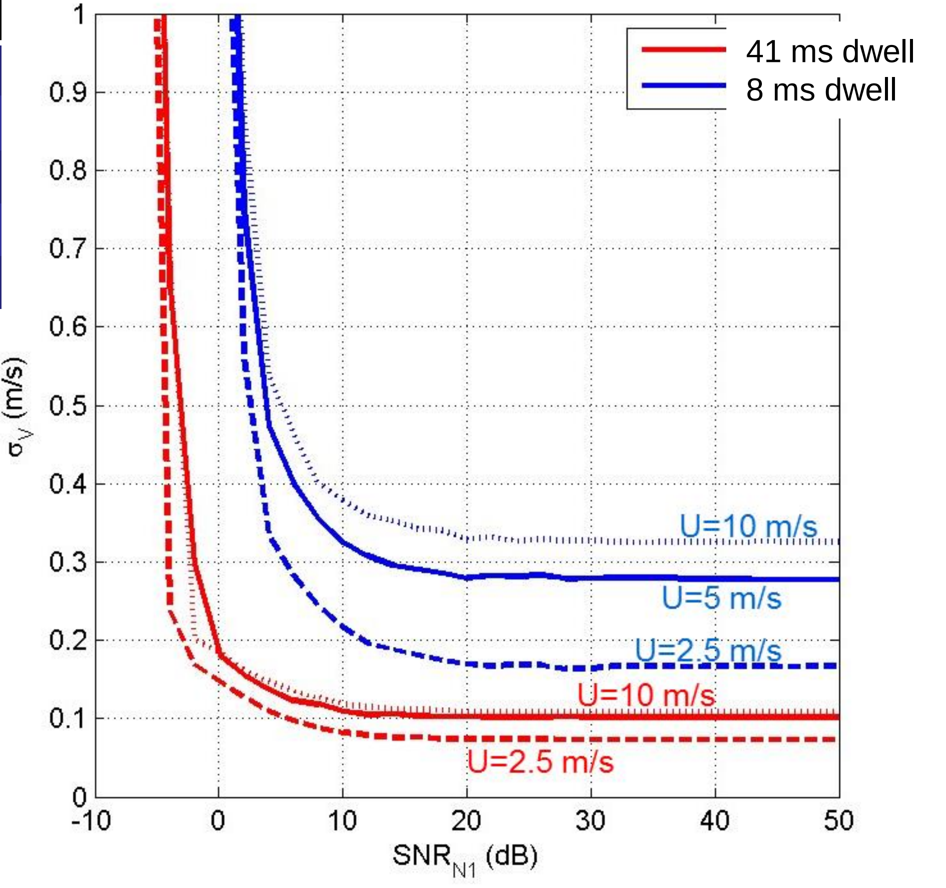
Peak Period	SWH (m)	η_{RMS} (cm)	$V_{orb,RMS}$ (cm/s)
6	0.5 (SS2)	12.5	13
6	1.0 (SS3)	25	26
6	2.0 (SS4)	50	50
8	0.5 (SS2)	12.5	10
8	1.0 (SS3)	25	20
8	2.0 (SS4)	50	40
10	0.5 (SS2)	12.5	8
20	1.0 (SS3)	12.5	8
20	2.0 (SS4)	25	16

Doppler Measurement Requirements

Rotation rate:	Slow	Fast
Observation Time (ms)	41	8
Range resolution (m)	7.5	11
τ_s (ms) (U = 2.5 m/s)	39	39
τ_s (ms) (U = 5 m/s)	22	20
τ_s (ms) (U = 10 m/s)	20	17

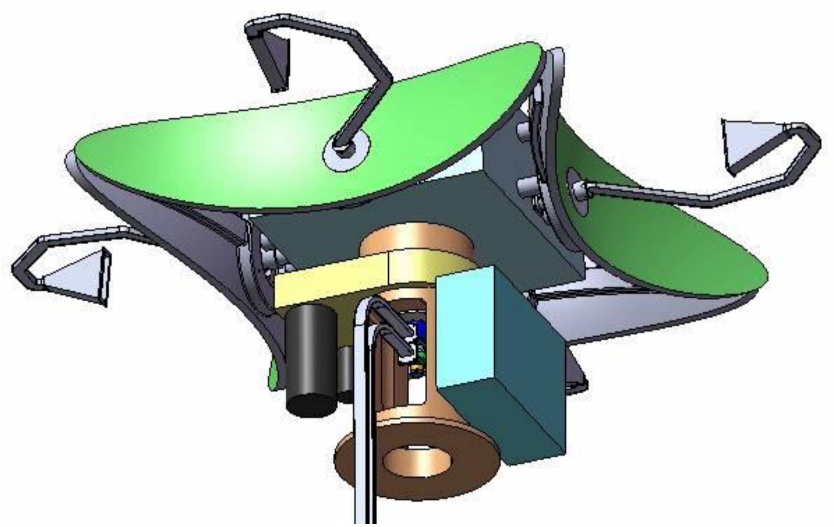
- Scanning the antenna slower (increasing dwell) reduces the Doppler variance in the measurement
- Yet to determine the impact of less measurements per second on wave retrieval accuracy

Doppler Variance vs SNR
for different dwell times and wind speeds



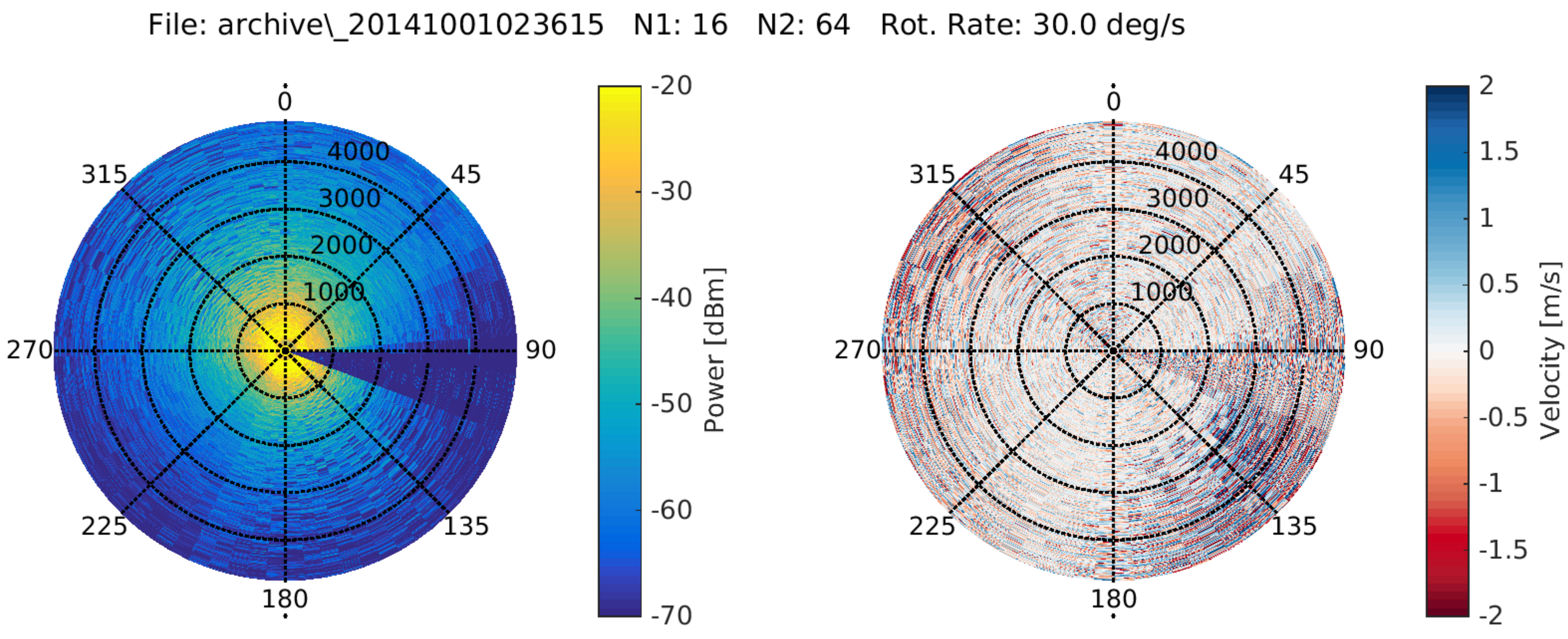
The Advanced Wave Sensing Radar (AWSR)

- Based on CORAR that was built by Bill Plant at APL-UW
- Solid state X-band transmitter
- Vertical polarization
- Fully-coherent radar
- Configurable center frequency
- Configurable pulse repetition frequency
- Pulse compression
- Variable rotation rate pedestal
- Four antennas to meet wave sampling requirements while scanning slowly
- Arbitrary directional blanking
- Measurement out to 5 km
- GPS time-stamped data
- Open data format



AWSR Specifications	
Frequency	9.2 – 9.4 GHz
Bandwidth	10 – 40 MHz
Tx Power	2 kW
Transmitter	SSPA
Antennas	4 – Vertical Pol.
Horizontal Beamwidth	2.5 deg.
Vertical Beamwidth	10 deg.
Switching Pattern	Variable
PRF	3.125 – 25 kHz
Rotation Rate	0 – 96 deg/s

Example Radar Data



Backscattered Power

Doppler Velocity

Doppler Measurement

- Radar (nominally) observes the radial component of orbital velocity

$$f_{D,n} = \mathrm{Re}\left(\sum_{m=1}^{M} D_{n,m} A_m \exp\left(i\left(\boldsymbol{x_n}\cdot\boldsymbol{k_m} - \omega_m t_n\right)\right)\right) + \left(\boldsymbol{u_c} - \boldsymbol{v}_{s,n}\right)\cdot\boldsymbol{e}_{look,n} + \text{noise}$$

Fluctuates in range, A_m is the modal amplitude

DC in range, slowly varying in azimuth

- $D_{n,m}$ ("D Function") accounts for factors such as measurement angle with respect to the waves
- Use a least-squares approach to solving for the complex modal coefficients (A_m)
- Reconstruct wave height at specified x, y, t

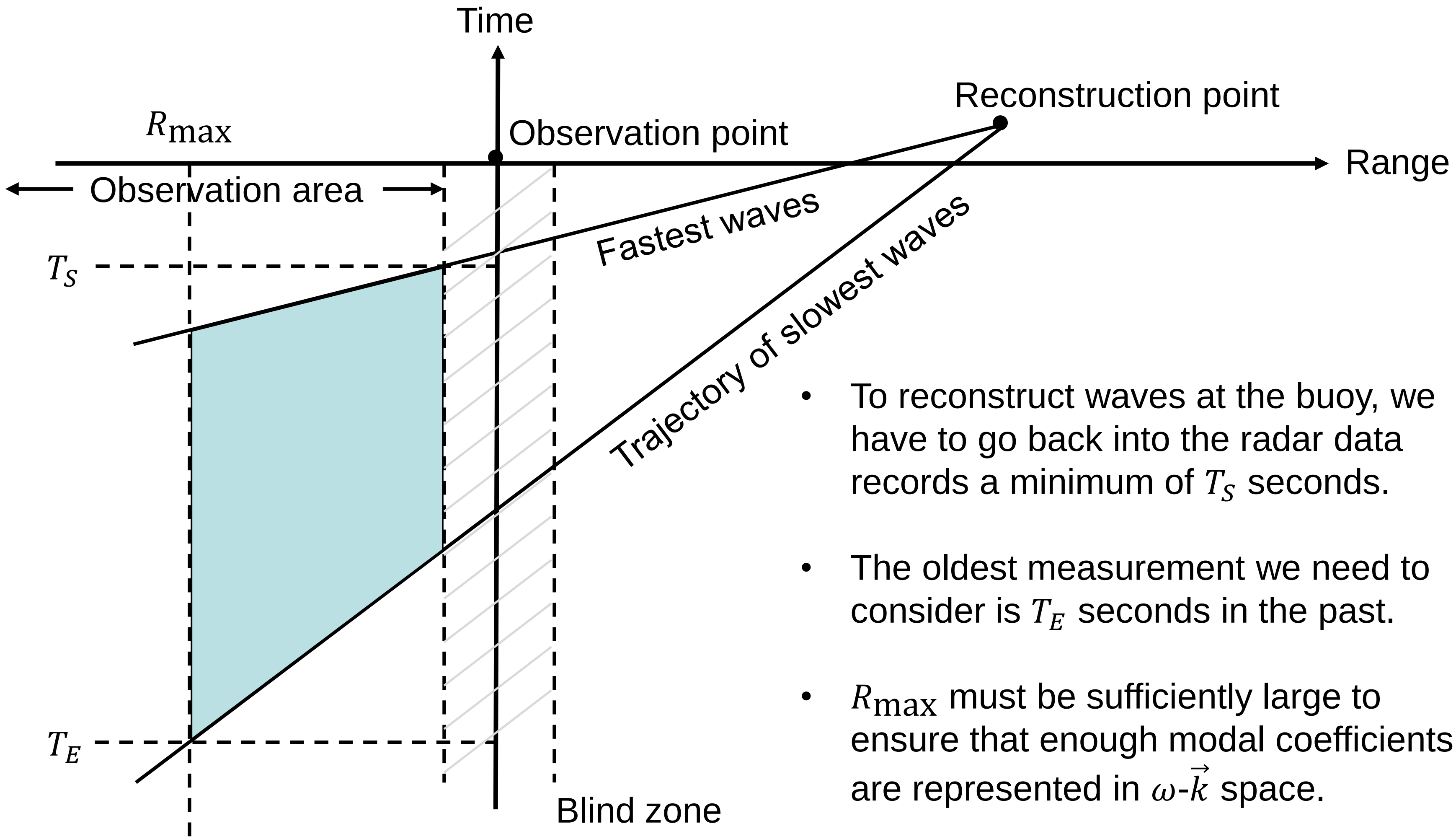
$$\eta(x, y, t) = \mathrm{Re}\left(\sum_{m=1}^{M} A_m \exp\left(i\left(k_{x,m}x + k_{y,m}y - \omega_m t\right)\right)\right)$$

Specified set of ω-β

Least squares solution

Synthesized wavefield

Extraction Region (in 1 Dimension)

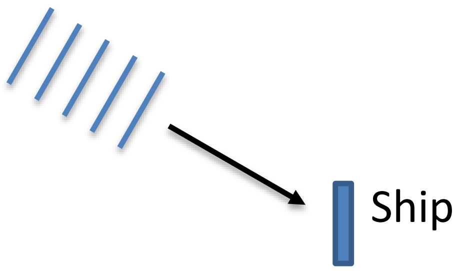


- To reconstruct waves at the buoy, we have to go back into the radar data records a minimum of T_S seconds.
- The oldest measurement we need to consider is T_E seconds in the past.
- $R_{\max}$ must be sufficiently large to ensure that enough modal coefficients are represented in ω-$\vec{k}$ space.
- If $R_{\max}$ is too large, low SNR data will be used in the reconstruction.

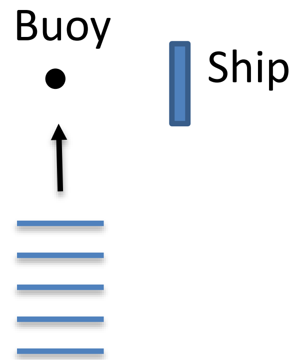
Buoy Measurement Reconstruction

- Buoy measurement reconstruction allows us to debug the wave retrieval algorithm
- The following conditions must be imposed when doing buoy measurement reconstruction:
  - » Waves propagating towards the buoy must be visible from the point of view of the radar – this can make buoy measurement reconstruction in bimodal seas difficult

Ship motion forecasting

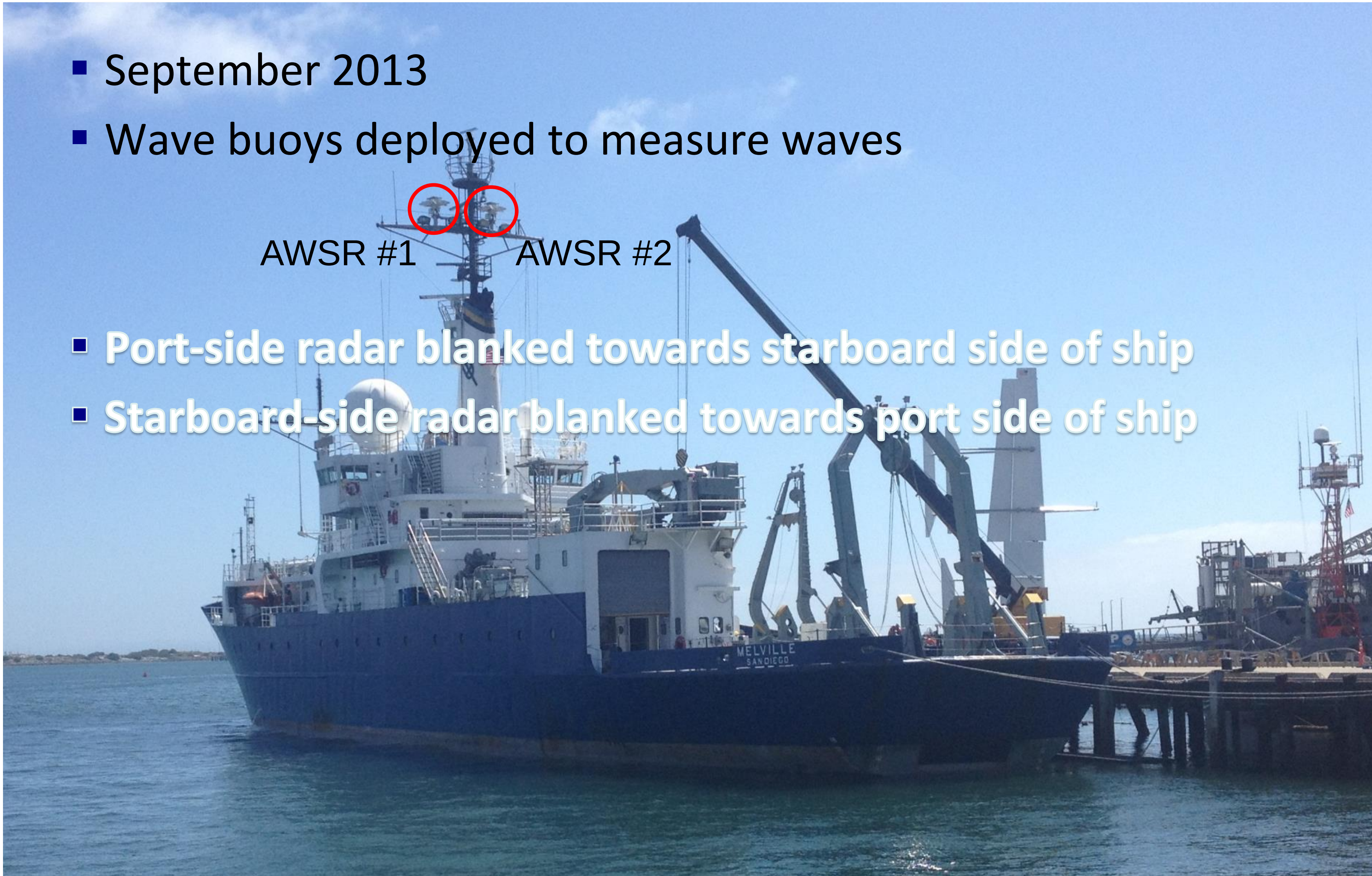


Buoy reconstruction



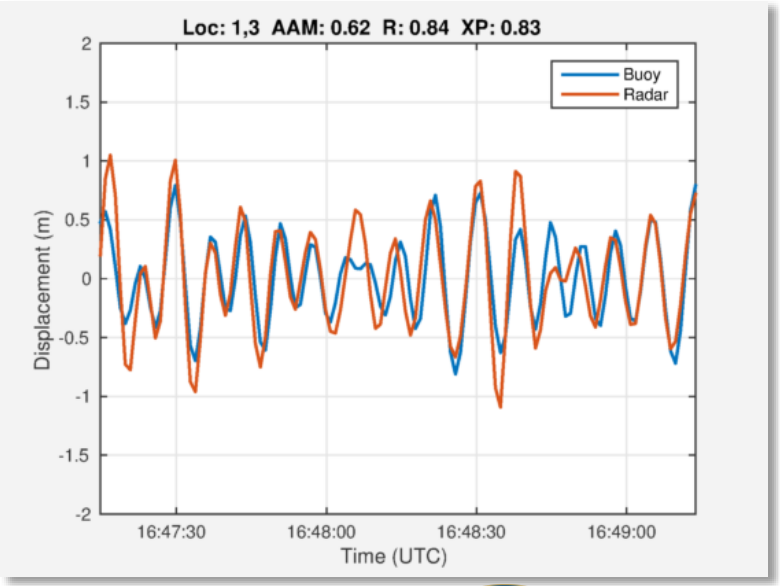
R/V Melville Test

- September 2013
- Wave buoys deployed to measure waves



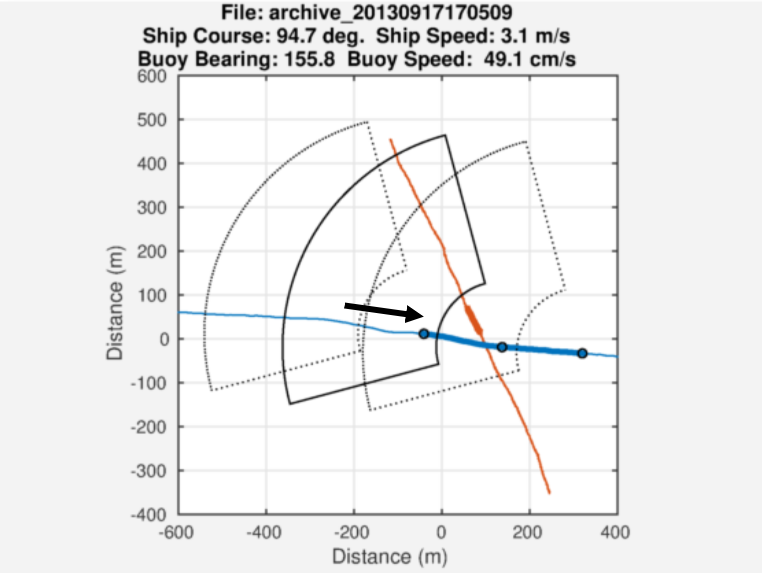
- Port-side radar blanked towards starboard side of ship
- Starboard-side radar blanked towards port side of ship

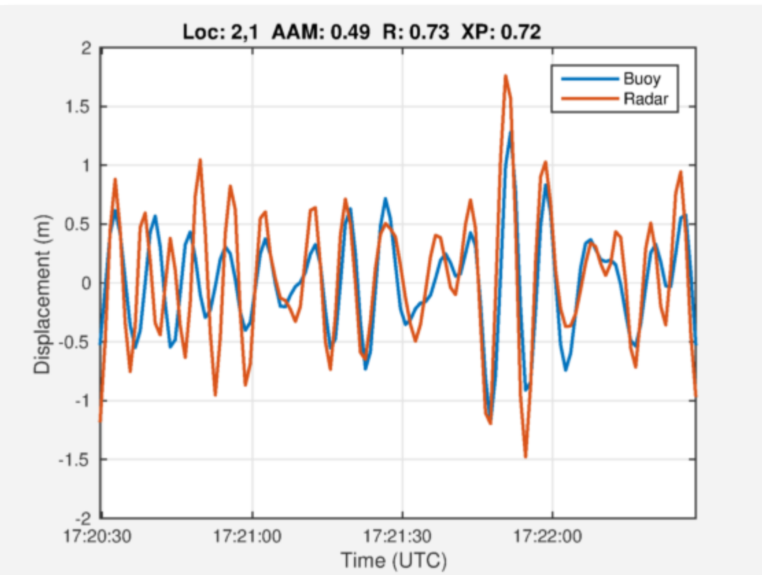
Melville 2013-09-17 Run 1



- In all cases, waves are from the north east, and the buoy was drifting south.
- Record length shown is 120 s.
- Buoy within, but on the edge of the extraction region until around half way through the record.
- Ship comes within 40 m of the buoy.

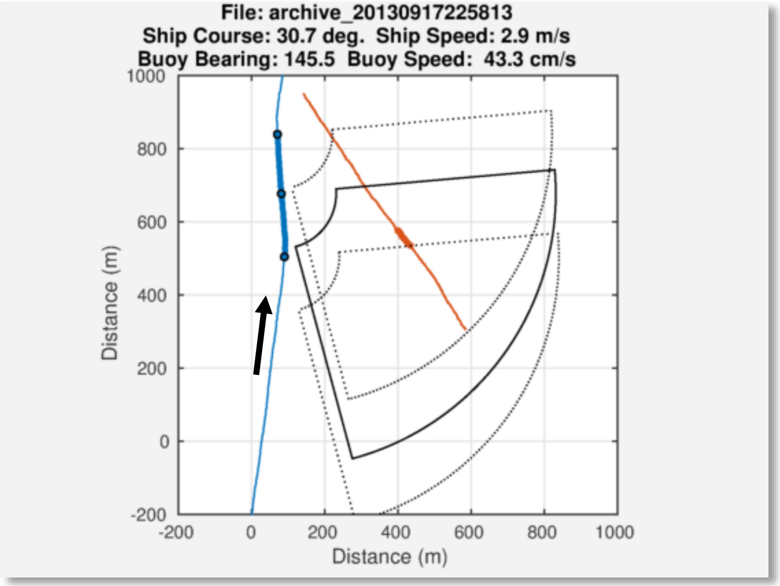
Melville 2013-09-17 Run 2

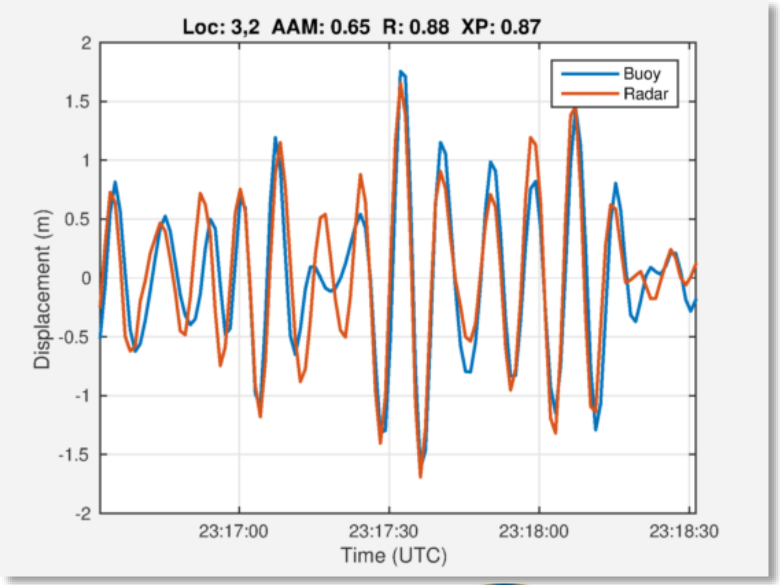




- Buoy well located for wave retrieval.
- In this case, buoy measurement reconstruction is very much like reconstruction of waves at the ship.
- Why aren't we getting better correlations?

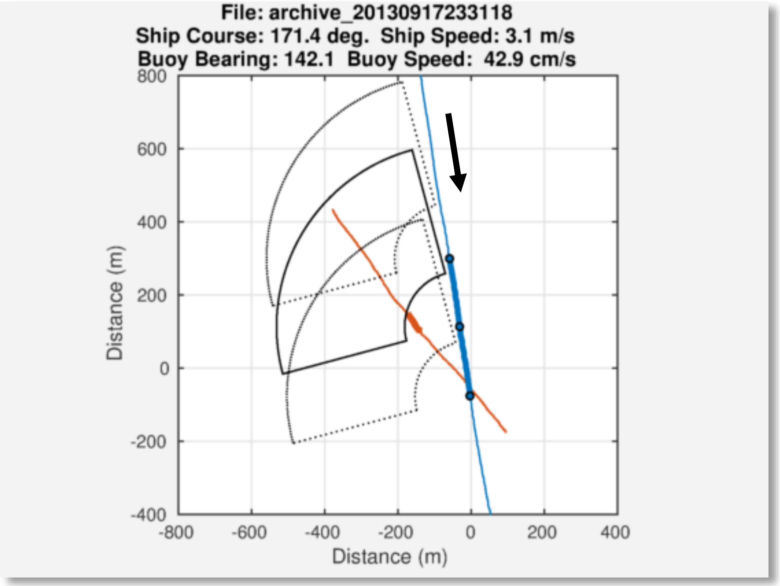
Melville 2013-09-17 Run 3

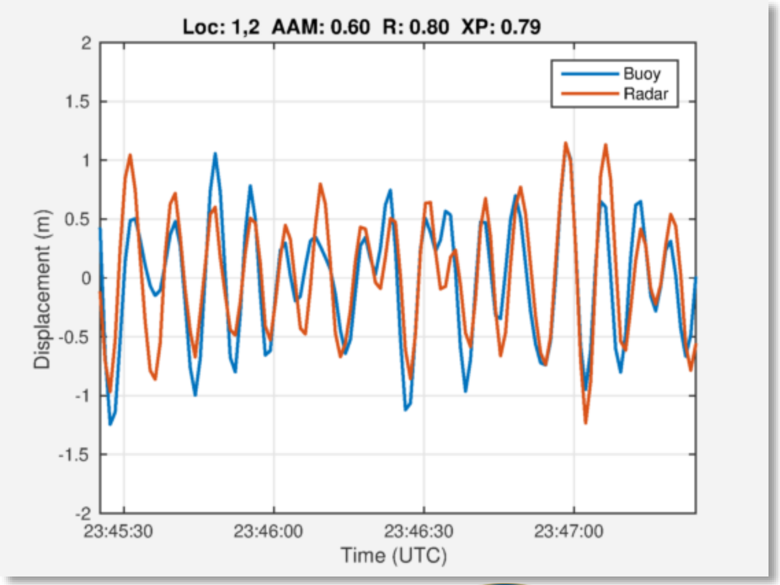




- Outbound waves case – haven't studied how to set up wave retrieval for this case.
- Could set up extraction region on opposite side of track, but distance to buoy is large, so T_E would be large.
- Radar partially blanked in extraction region.

Melville 2013-09-17 Run 4

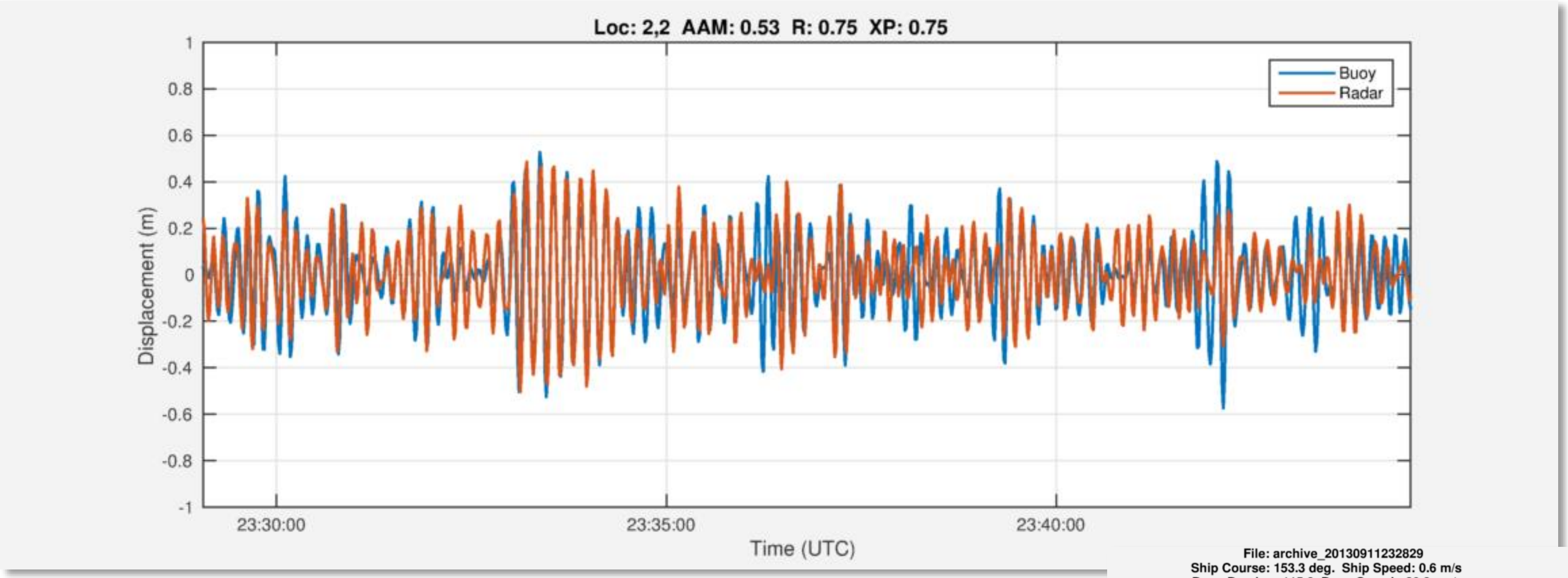




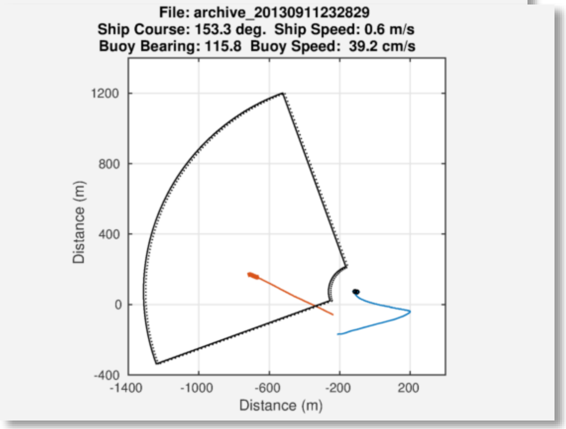
- Radar blanked in extraction region
- Extraction region not optimal for first half of record.
- Buoy within extraction region for latter half of record.

Wave Reconstruction Debugging

- Wave reconstruction at buoy for September 11, 2013



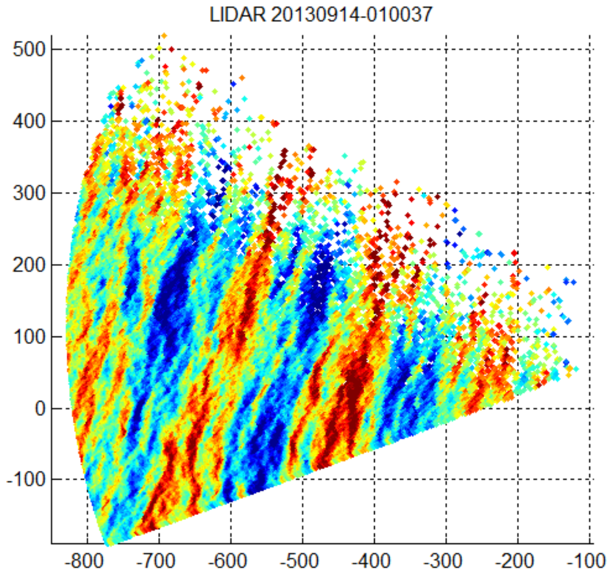
- Investigating the causes for why we are not reconstructing the wave perfectly all of the time



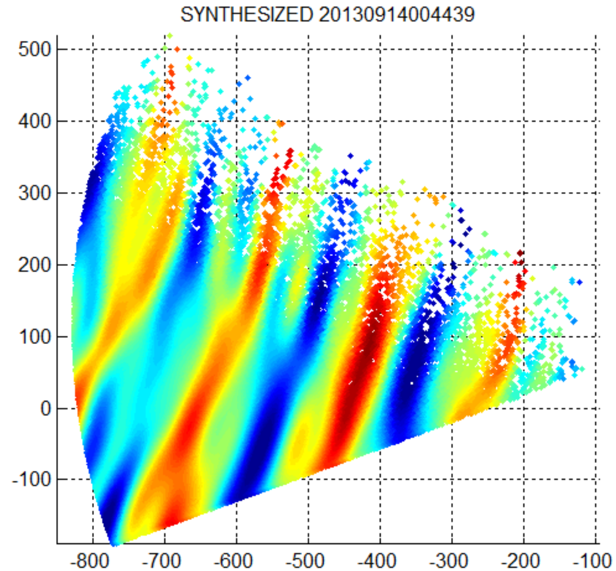
Comparison with Airborne Lidar

- Can reconstruct wave field for (x, y, t), which provides us with a natural way to compare with lidar point cloud data

Lidar



Reconstructed



Lidar data provided by Scripps Institute of Oceanography

Conclusions

- Introduced a radar designed for wave measurements
- New approach to wave reconstruction from radar data
- Wave retrievals compared with buoy data

- Topics not covered in this presentation
  - This algorithm runs in real time, and has been used for wave forecasting
  - Wave reconstruction technique naturally handles multi-modal seas (multiple tiled extraction regions)
  - Wave reconstruction technique naturally handles reconstruction using multiple radars (possibly on different ships)
  - Successfully applied wave retrieval algorithm to data collected by the coherent on receive radar built by University of Michigan / Ohio State University