National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Surface Water and Ocean Topography (SWOT) Mission

http://swot.jpl.nasa.gov

The Effect of Surface Waves on the SSH Signals at 15-150 km Scales

AirSWOT Results

The AirSWOT & SWOT Teams

February 15, 2016

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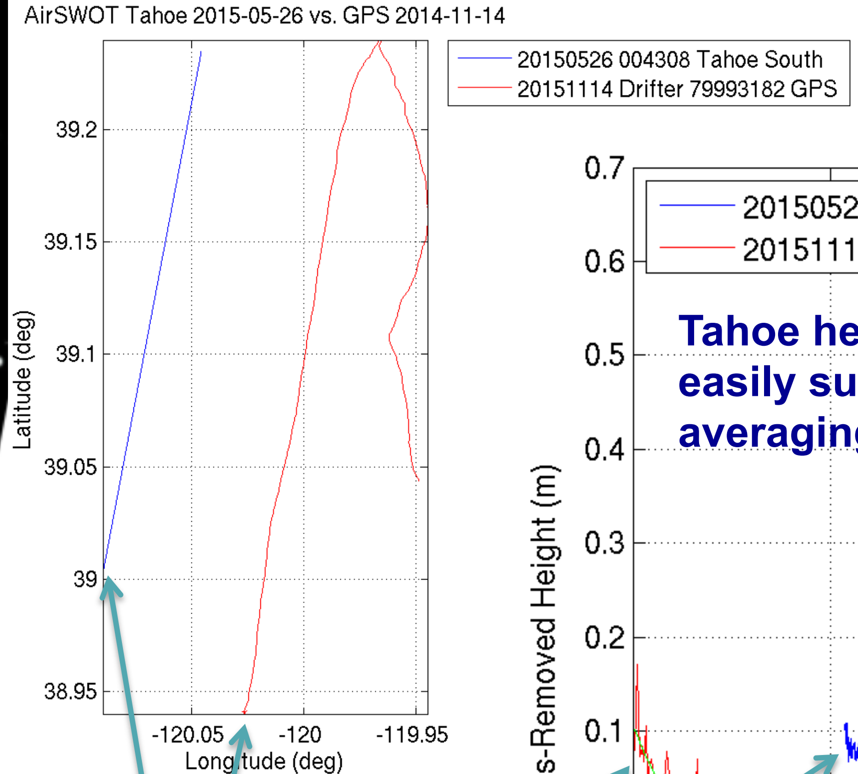
Overview

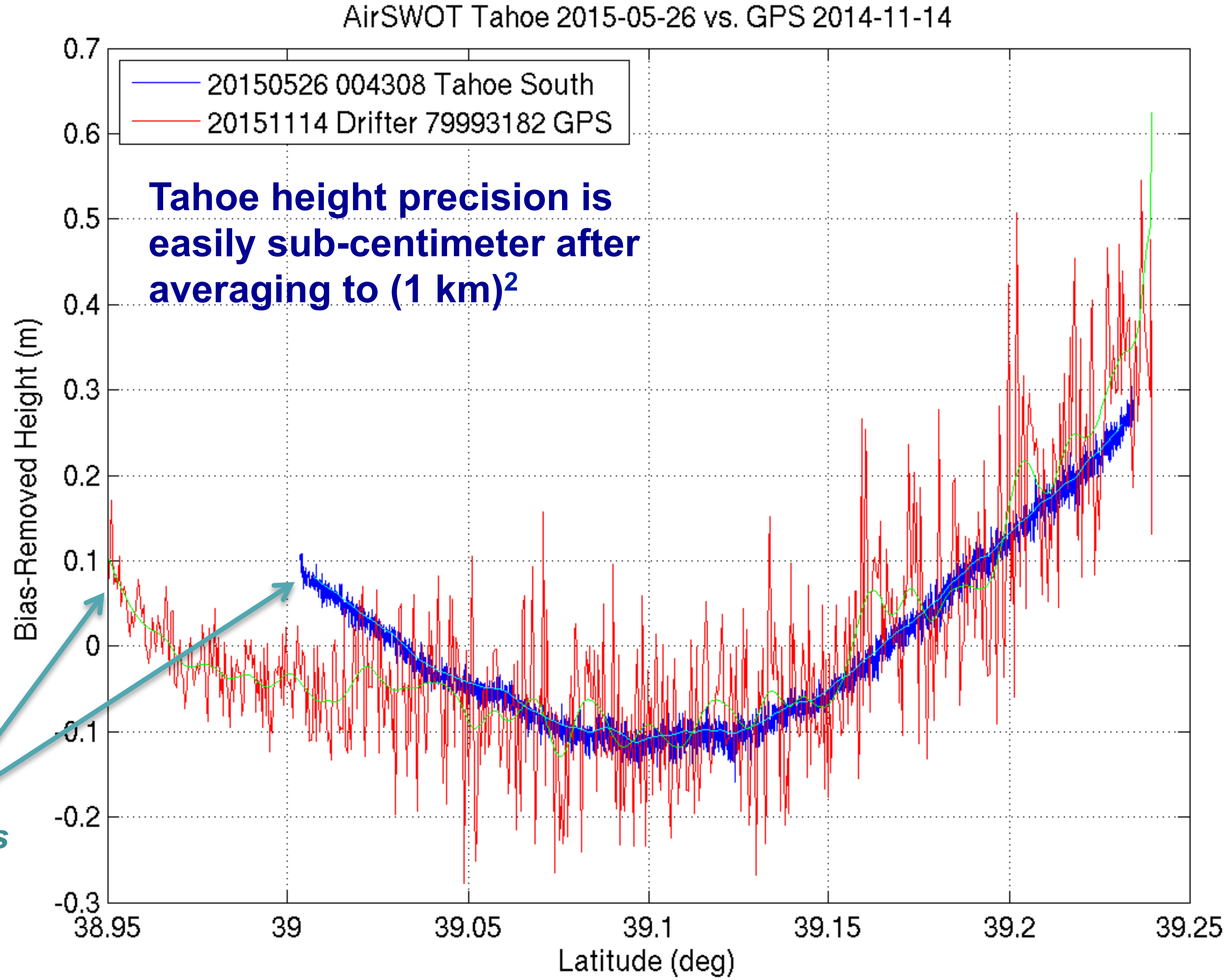
- Review of key AirSWOT observations showing potential links to wave effects:
  - Lake Tahoe: negligible waves
  - CARTHE Altika underflight: ~1.5 m SWH, azimuth traveling waves
  - California Altika underflight: ~3 m SWH, long swell in the range direction
- Mechanisms for wave impact on interferometric measurements
  - **White noise**: not discussed here as it does not impact long wavelengths
  - **Surfboard effect**: effect on the range-direction spectra, not on the long-wavelength along-track spectrum
  - **Location shifts due to radial velocity**:
    - ♦ Height biases due to mean velocity shifts (accounted for in SWOT error budget)
    - ♦ Spectral distortions due to wave bunching
  - **Height biases due to iso-range/iso-phase mismatch**
    - ♦ **Accounted for in SWOT budget**
  - **Non-uniform brightness modulation: EM bias**
    - ♦ Active area of research

Very Small Waves

Lake Tahoe

Tahoe Along-Track Height Profile





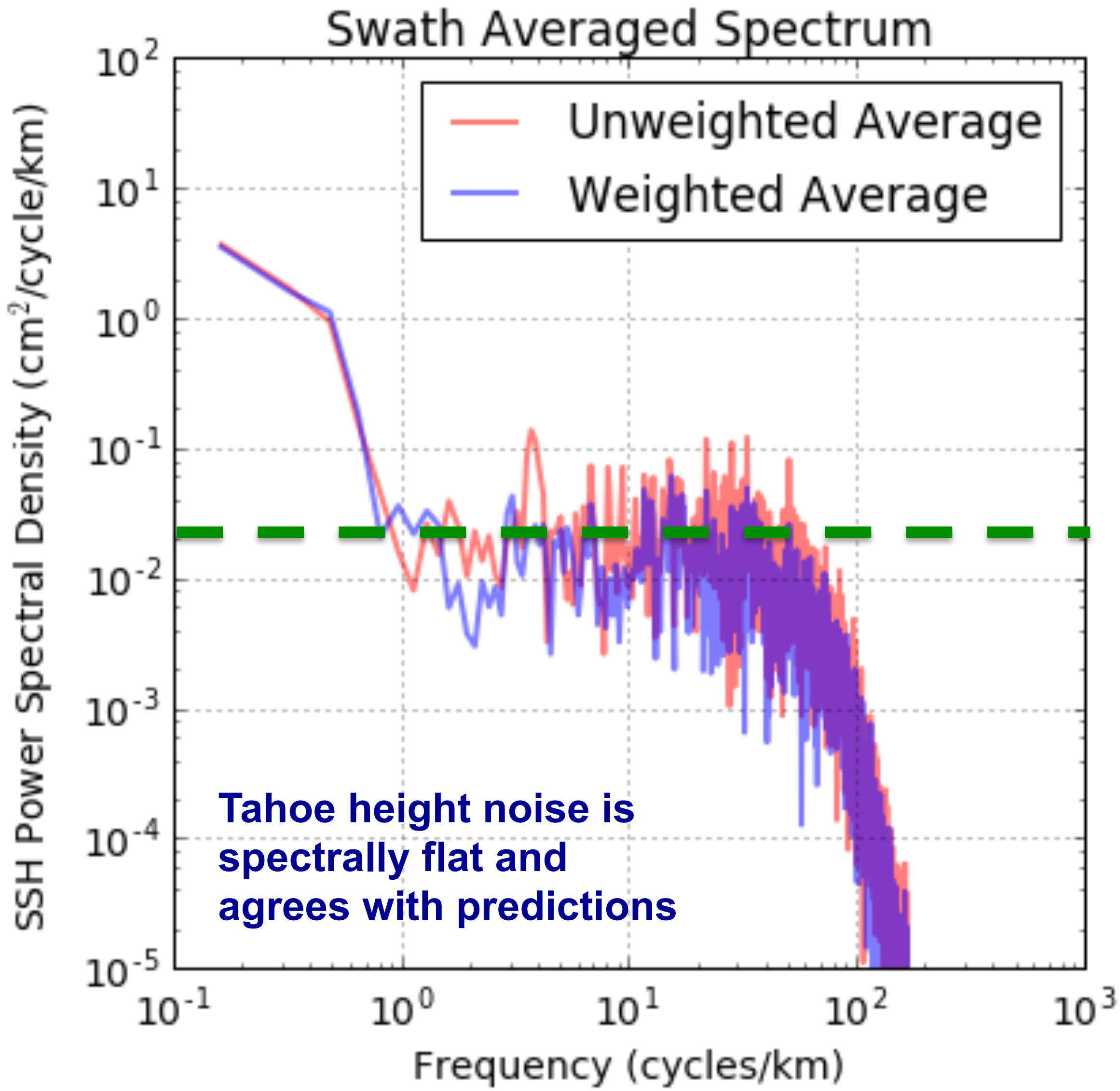
AirSWOT and GPS tracks are spatially offset from one another

Lake Tahoe Anomaly Spectra

Noise floor PSD <0.02cm²/cycle/km

Integrating from 0.01 km this results in an expected standard deviation of 1.4cm

Averaging to 1km will result in height noise of 0.14 cm

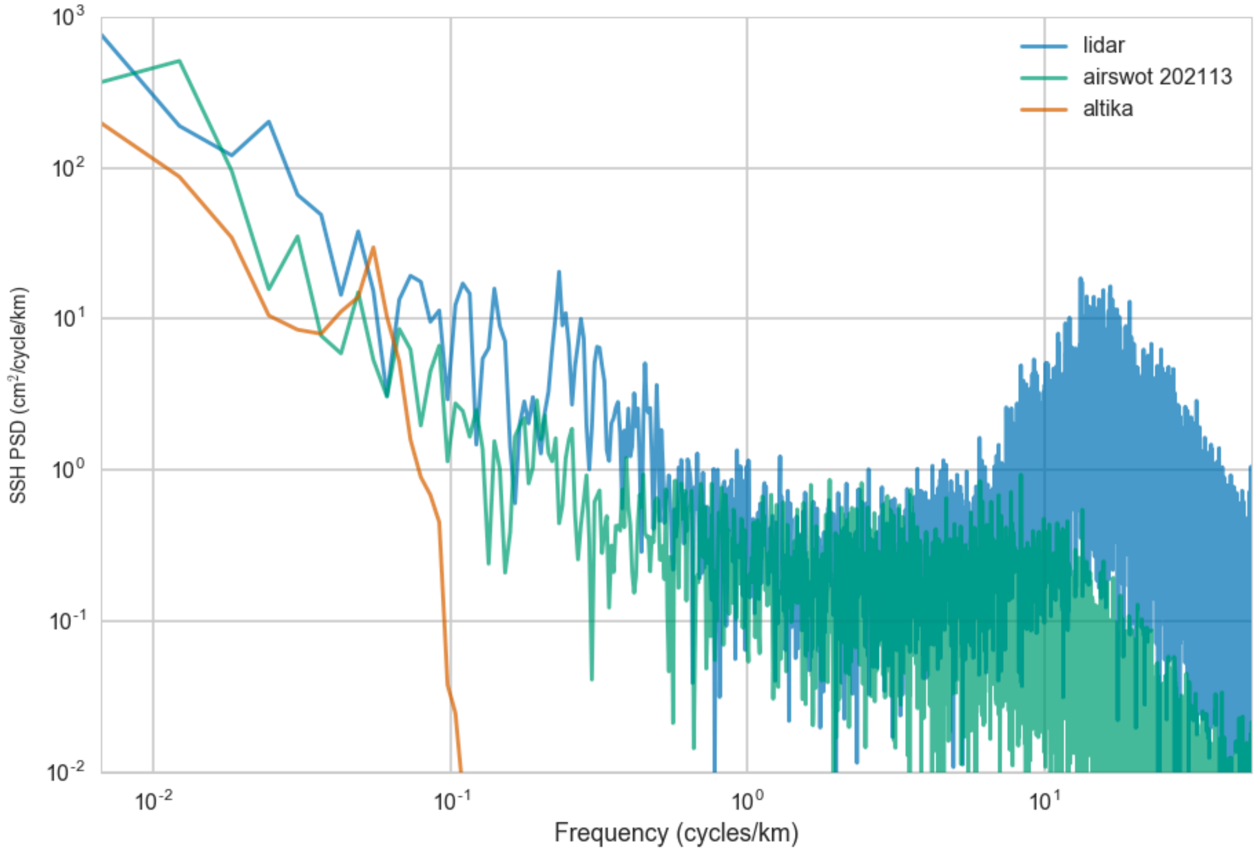


Moderate Waves

Altika Underflight During CARTHE

~1.5 m SWH Azimuth Waves

CARTHE Feb 5, Along-track Spectra



- AirSWOT data average 2 km cross-track
- MASS data averaged 400 m cross-track
- Along-track wave component present for MASS, but very attenuated for AirSWOT above 100m wavelength
- Spectral floor between ~100m and ~1km due to aliasing of cross-track wave energy into lower frequencies for MASS
- Spectral slopes above a few kilometers similar for MASS, AirSWOT, and Altika (preliminary results)

MASS data courtesy of K. Melville, L. Lenain, Scripps

Large Waves

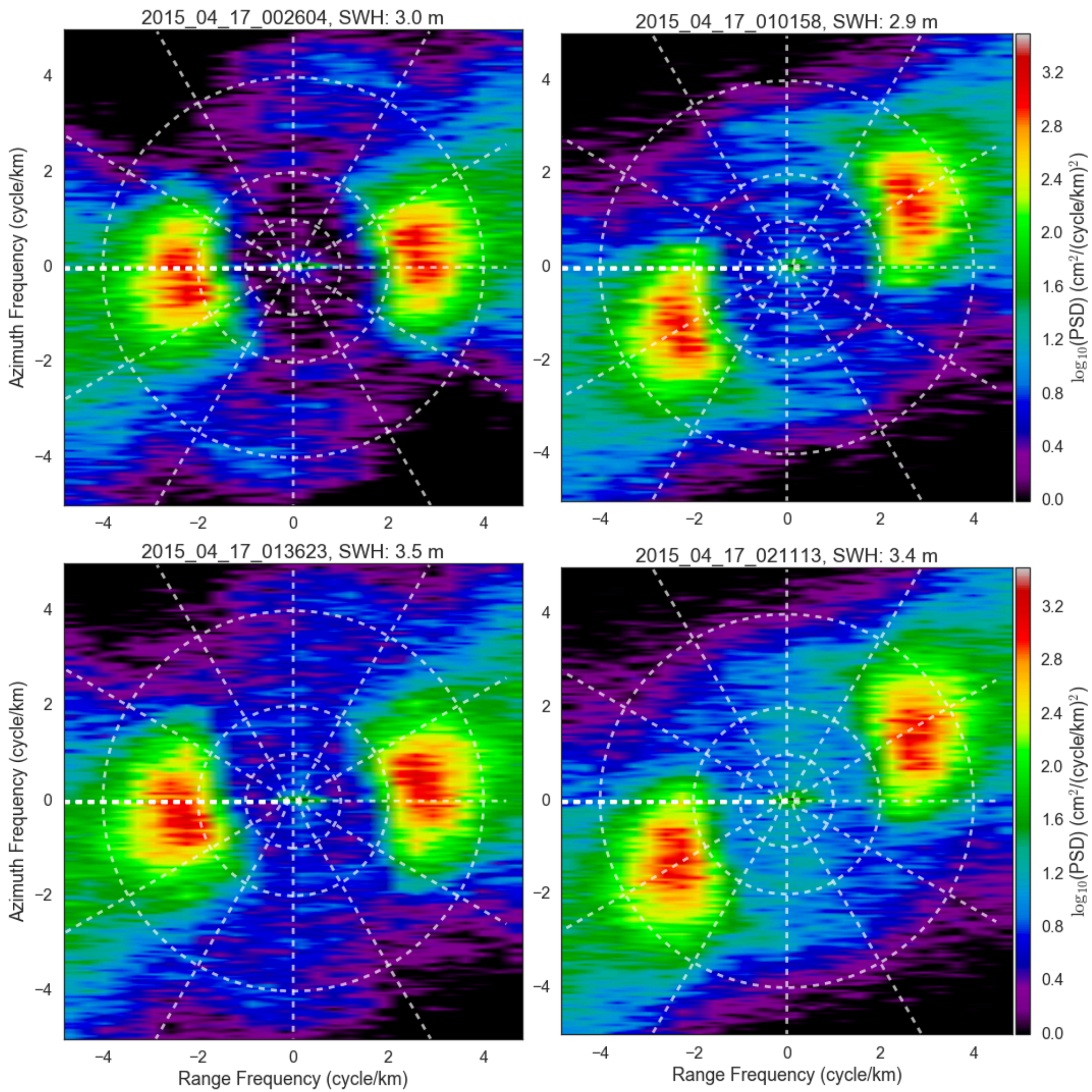
Altika Underflight
California Current

~3 m SWH Range Waves

2D Spectra
SAR Compressed & Velocity Corrected

Circles indicated wavelengths of 1km, 500m, 250m.

Notice wave field is rotated in North vs South lines. This is a well understood kinematic effect, also present in lidar, due to the fact that the wave field moves during the data collection. (This is not due to SAR)

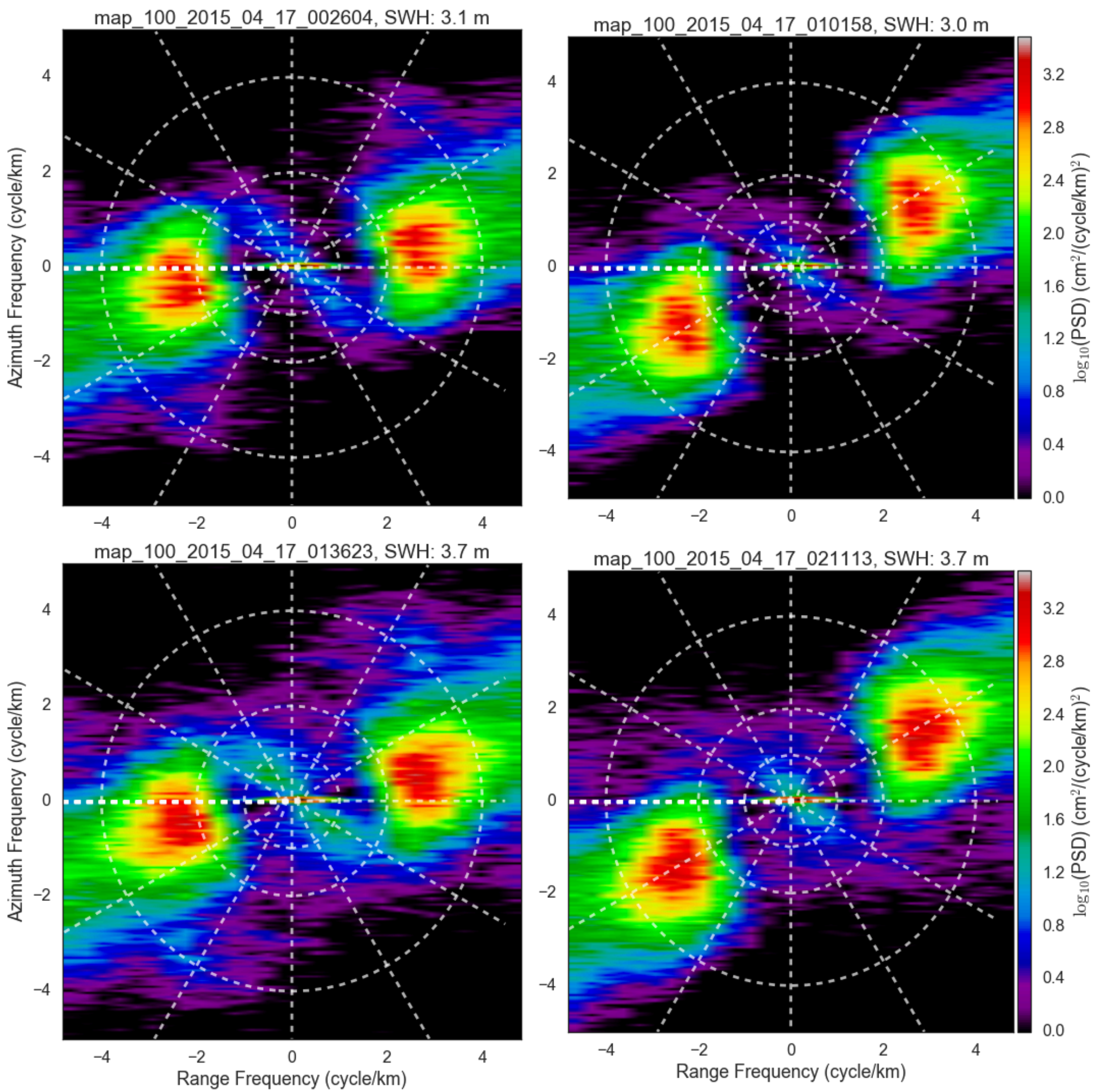


South Lines   North Lines

2D Spectra
Real Aperture

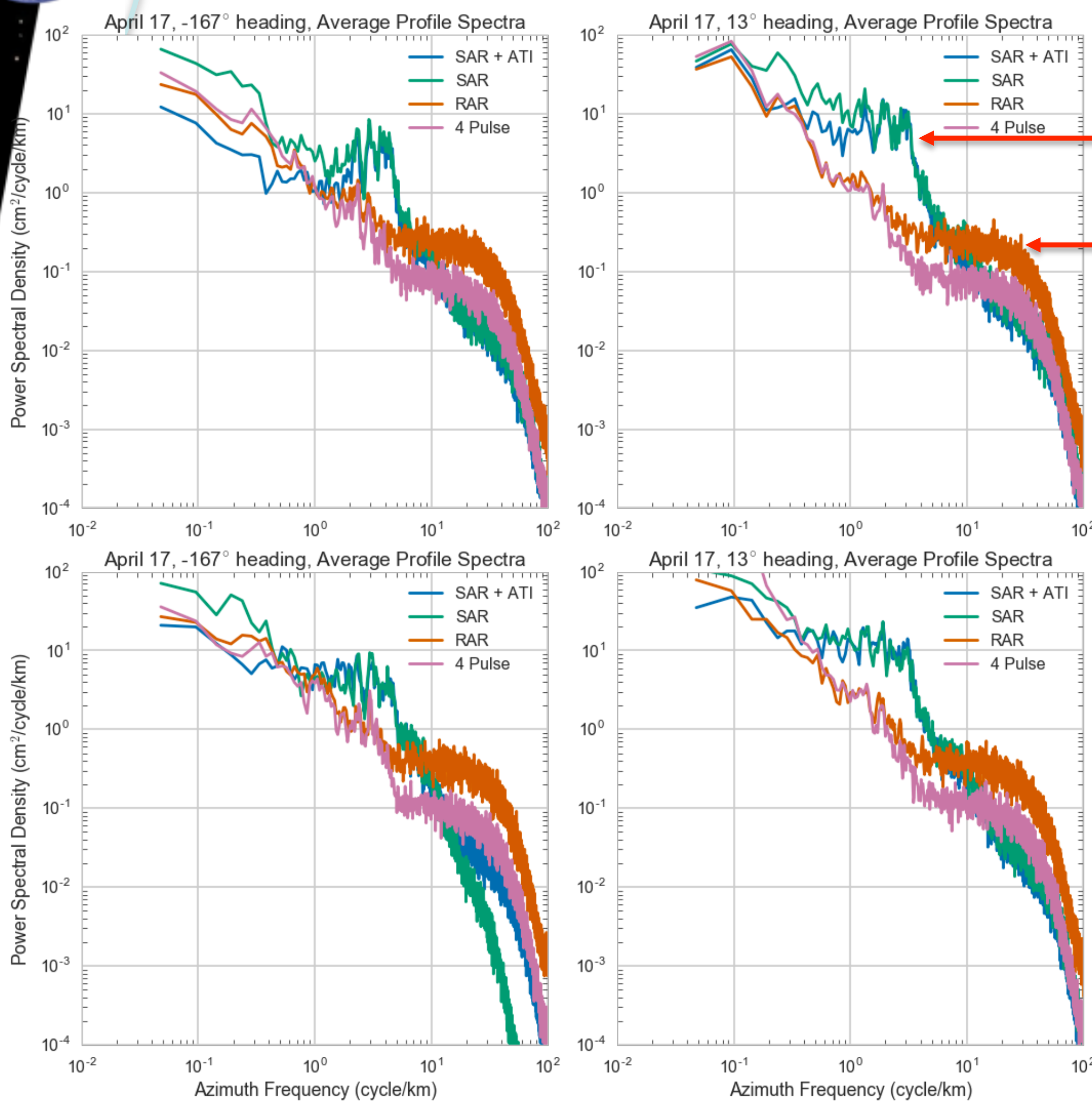
Circles indicated wavelengths of 1km, 500m, 250m.

Notice wave field is rotated in North vs South lines. This is a well understood kinematic effect, also present in lidar, due to the fact that the wave field moves during the data collection. (This is not due to SAR)



South Lines North Lines

1D Spectra for SAR and RAR



South Lines

North Lines

SAR data shows spectral hump

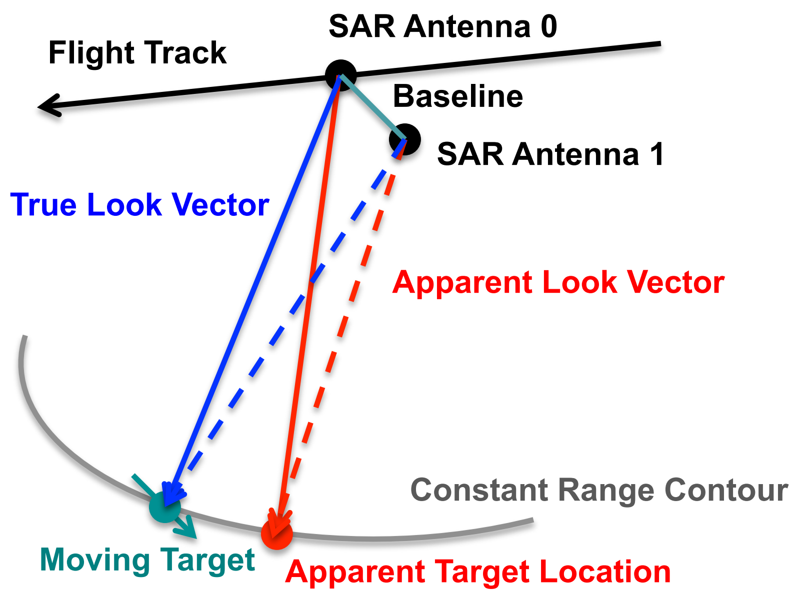
RAR data shows no spectral hump

SAR & RAR exhibit similar long-wavelength behavior

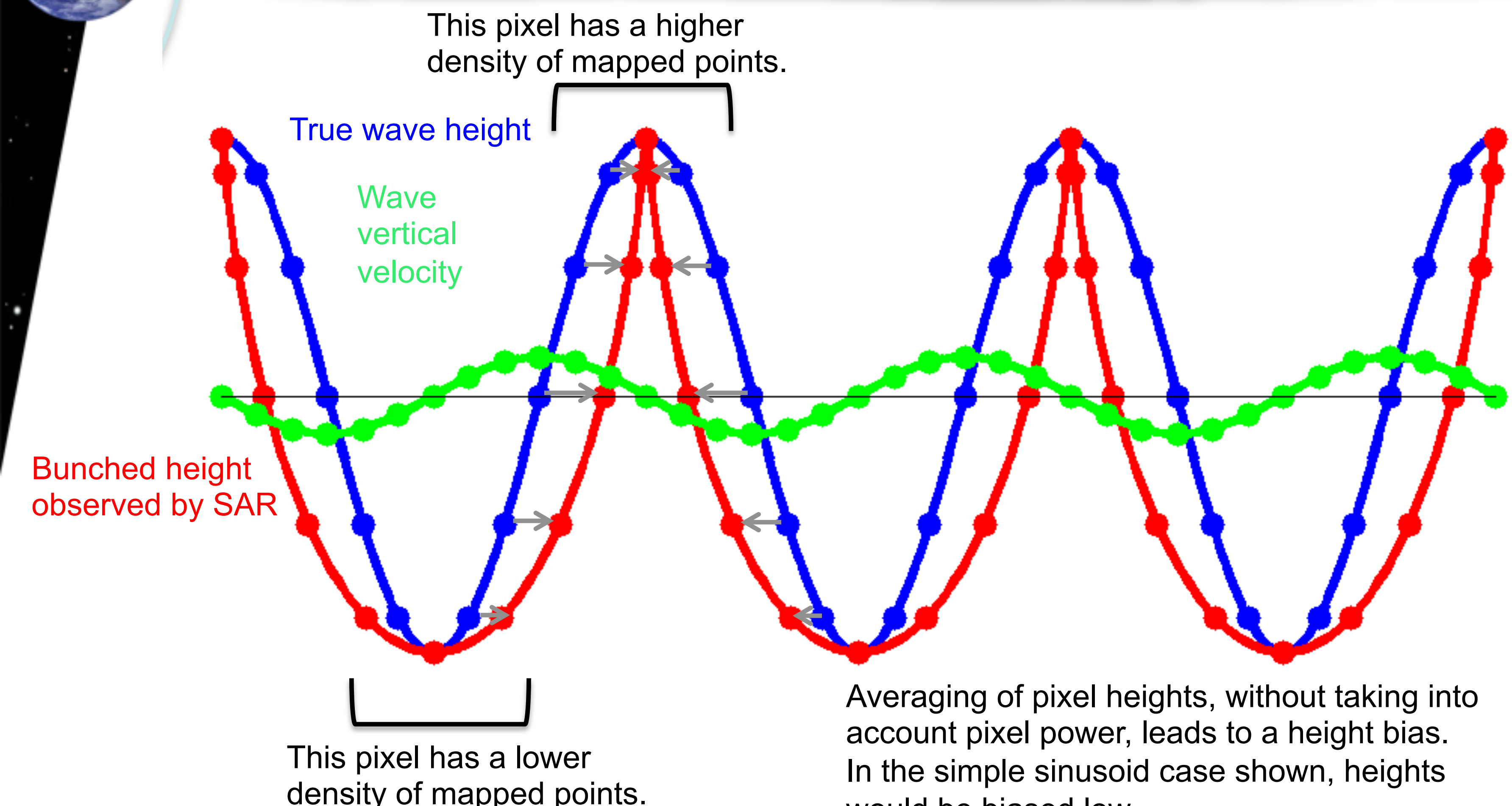
Effects of Surface Radial Velocity on SAR Interferometry

Target Velocity Cross-Track Shift Effect on Interferometric Height

- Interferometry uses 3 separate measurements for 3D point location:
  - Range
  - Doppler
  - Interferometric phase
- The Doppler location assumes that the surface is not moving
- Target motion in the look direction will cause a Doppler shift, so apparent location moves along an iso-range line to the wrong azimuth position
- Interferometric phase depends on true target location
- Mismatch between interferometric phase and apparent range-Doppler position gives height error



Height Distortion From Wave Bunching



Averaging of pixel heights, without taking into account pixel power, leads to a height bias. In the simple sinusoid case shown, heights would be biased low.

Azimuth shift is proportional to line-of-sight target velocity, which is mainly due to wave vertical velocity for near-nadir viewing geometry

Wave bunching is non-linear distortion, so spectrum of observed heights can exhibit energy at spatial frequencies that are not present in the true wave field

Spectral Distortions due to Bunching Model

- An analytical model has been derived using assumptions similar to the ones used in the surfboard paper.
- For long wavelengths (above ~500m for AirSWOT, 1km for SWOT), the measured spectrum is related to the true spectrum by

$$S_M(k_x, k_y) = \left|\tilde{f}_x(k_x)\tilde{f}_y(k_y)\right|^2 \left(S_h + 2\left|i\frac{r}{v_p}k_x\right|^2 \left(|\omega|^2 S_h\right) \otimes S_h\right)$$

Labels on the equation:

- $S_M(k_x, k_y)$: Measured height spectrum
- $\tilde{f}_x(k_x)$: Azimuth PTR spectrum, including blurring due to wave motion
- $\tilde{f}_y(k_y)$: Range PTR spectrum
- S_h: True height spectrum
- r: range
- v_p: Platform velocity
- k_x: Along-track wavenumber
- $|\omega|^2 S_h$: Vertical velocity spectrum

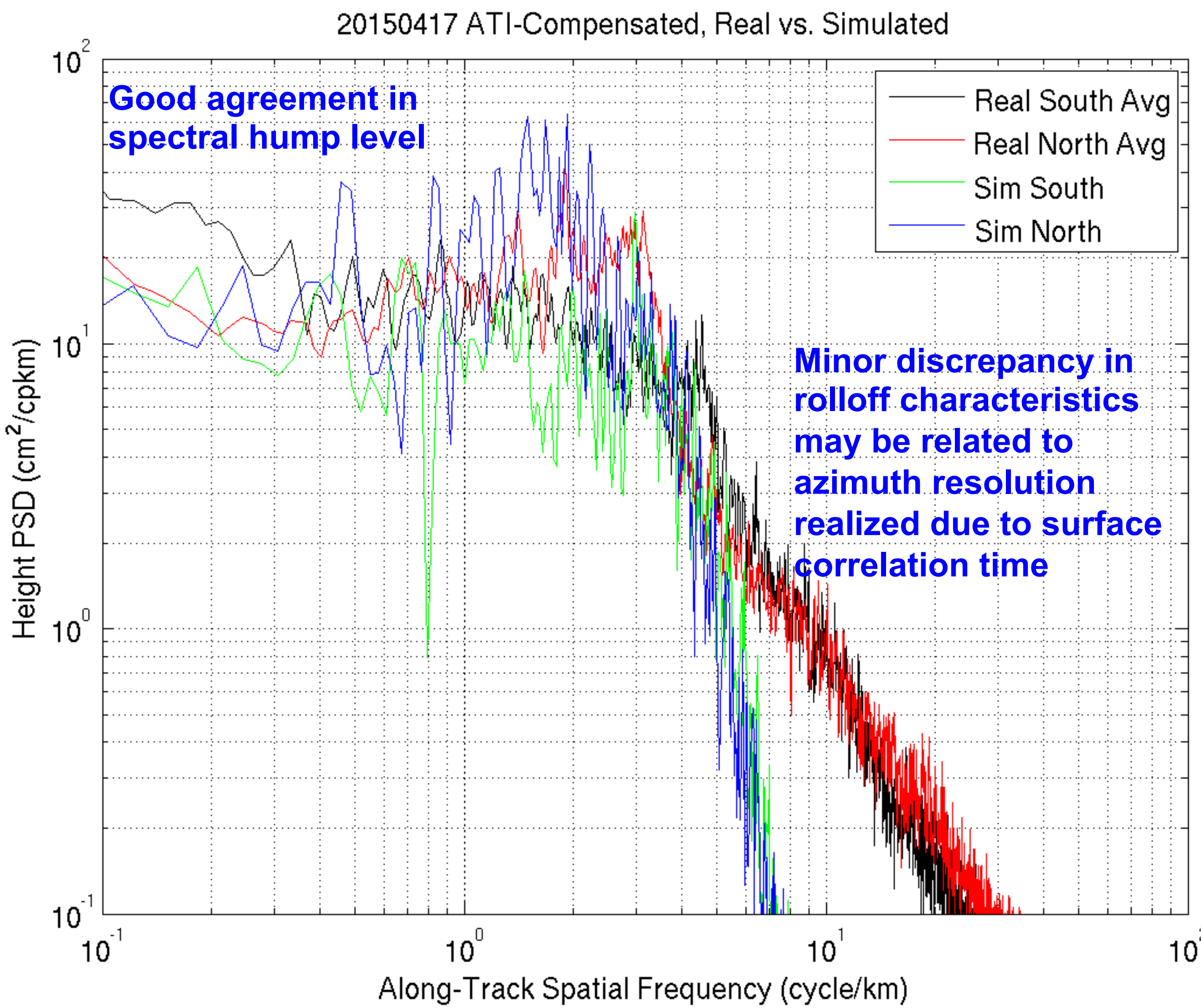
- This result shows that the measured height spectrum is distorted by a term proportional to the convolution of the radial velocity spectrum and the true high spectrum.
- This convolution term will leak into the lower along-track frequencies, producing a spectral hump
- Theory predicts that height averaging must be weighted by the return power to minimize bunching effects.

Need for Simulation

- As in the analytical surfboard effect, this result is only approximate when significant wave-bunching non-linearities occur, leading to strong distortions of the observed backscatter field
- To isolate the impact of the various terms, 3 simulations have been conducted (in increasing order of realism)
  - Point targets shifted in azimuth and mapped to range (SWOT and AirSWOT)
  - Simple interferogram simulated from shifted point targets (range and azimuth), approximate interferometric processing (SWOT and AirSWOT). This also includes ATI based estimation and correction.
  - The full OBP point target simulator with many moving targets has been used (SWOT only)
- All simulators agree (within the limits of their approximations) with each other and predict a spectral hump for AirSWOT
- For SWOT, the spectral hump contribution is significantly smaller than the surfboard effects in the simulations to date
  - More work needs to be done to simulate more cases

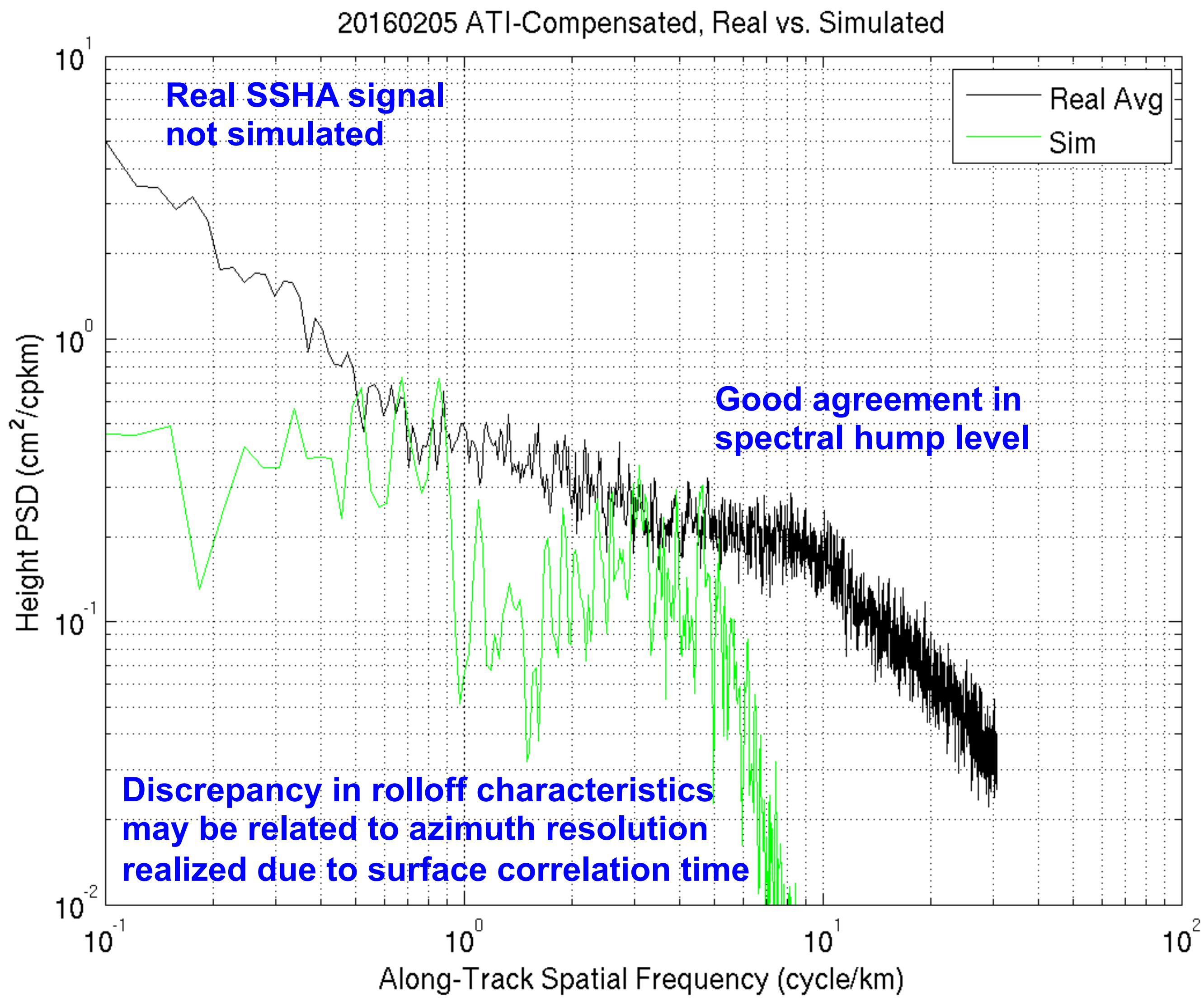
2015-04-17 Monterey Sim Comparison

- Analytical input spectrum to simulation inferred from combination of observed RAR and SAR spectra (hump is not in input spectra)
- Input spectrum dominated by cross-track component
- **3 m SWH** based on AltiKa data
- 1.5˚ antenna pitch based on IMU data
- 100 m AirSWOT along-track resolution (guess, depends on surface correlation time)
- Realistic AirSWOT antenna baselines, altitude, velocity

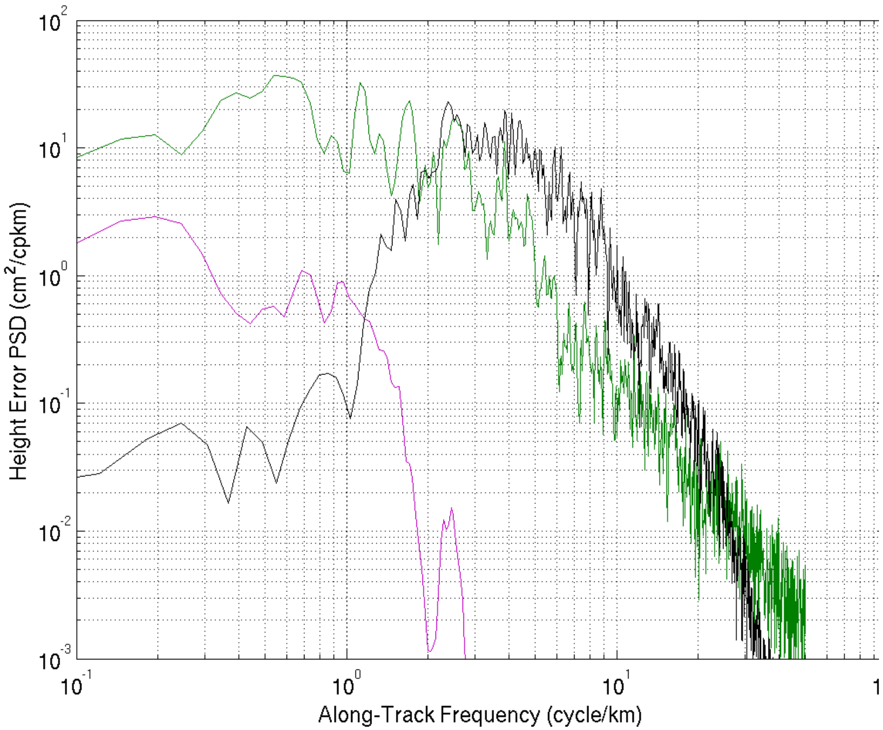


2015-02-05 CARHTE Sim Comparison

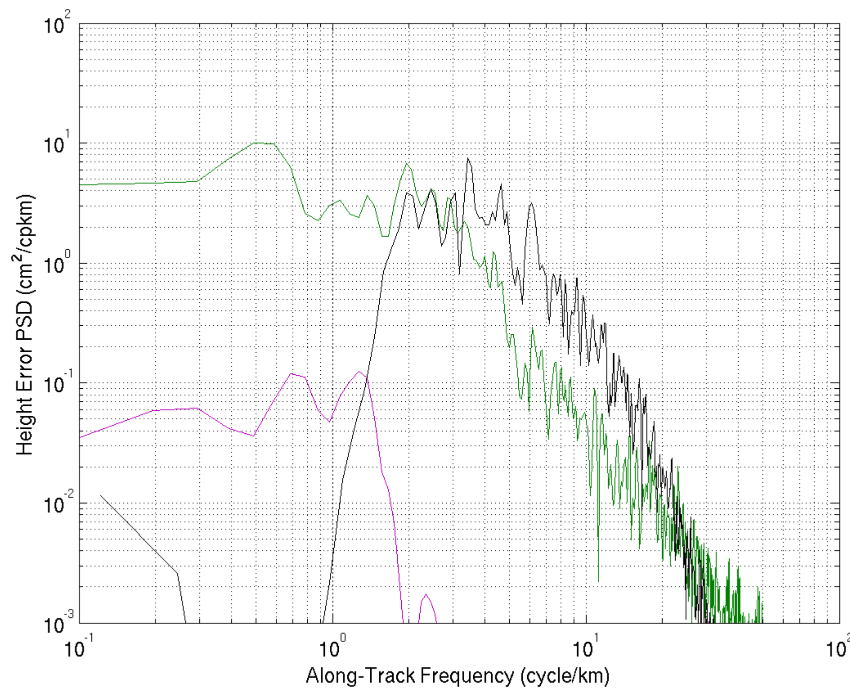
- Input spectrum to simulation was real spectrum estimated from **real lidar data**
- Input spectrum has large along-track component
- **1.6 m SWH** (lidar and AltiKa SWH agree)
- 0.6˚ antenna pitch based on IMU data
- 100 m AirSWOT along-track resolution (guess, depends on surface correlation time)
- Realistic AirSWOT antenna baselines, altitude, velocity



1-D SWOT Spectra On Same Input Spectrum as AirSWOT 20150417 Comparison



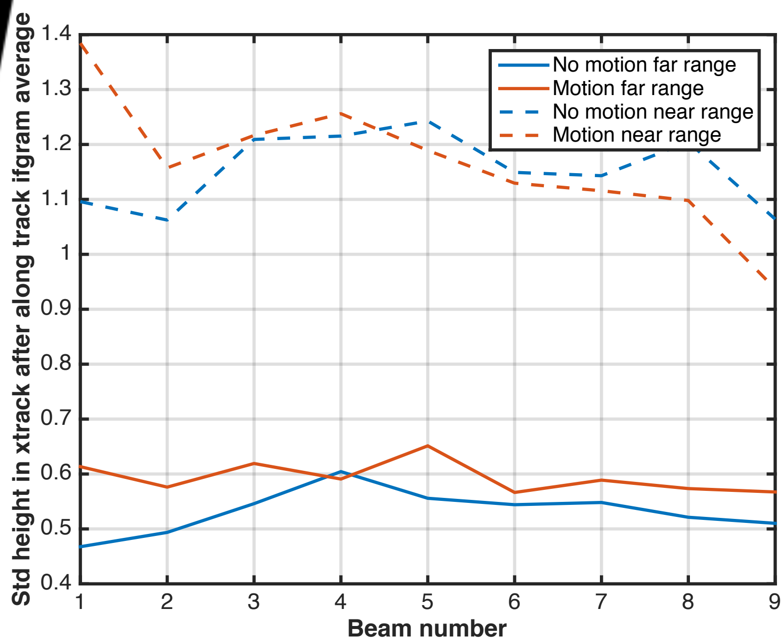
Magenta = (500 m x 500 m) interferogram average, then **1 km** cross track unweighted height average
Green = unweighted height average
Black = truth
(32 km along-track extent)

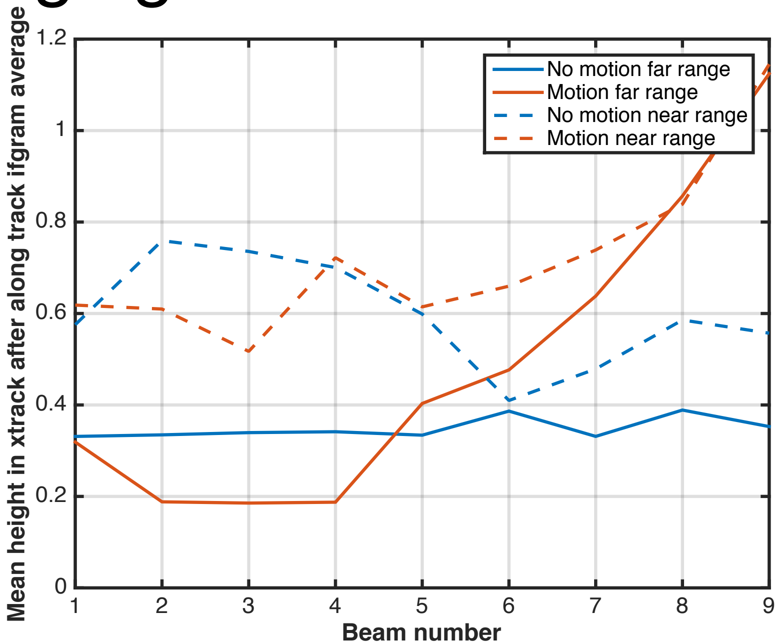


Magenta = (500 m x 500 m) interferogram average, then **3.5 km** cross track unweighted height average
Green = unweighted height average
Black = truth
(**16 km along-track extent; low spatial freqs not believable**)

Wave Motion Effect for SWOT from OBP Simulator with Wave Motion

500m averaging





For SWOT, due to the greater extent of cross-track averaging and the importance of the surfboard for near nadir incidence, the motion induced velocity errors are much smaller than the surfboard effects.

There is still some scatter in these results due to the limited number of realizations that can be simulated.

Summary

- AirSWOT exhibits measurement features that impact the along-track spectrum and which seem to depend on wave height
- Two mechanisms have been identified as potential sources for these errors
  - Velocity dependent shifts combined with unweighted averaging
    - Potential root cause for the observed spectral hump
    - Shift has cross-track (height bias) and along-track (wave bunching) components
  - Iso-range/Iso-phase mismatch couple with attitude variations
    - Potential root cause for mid-wavelength errors
- A preliminary study of the effect of these features on SWOT has been conducted
  - Iso-range/Iso-phase correction in place for SWOT and included in error budget
  - Wave bunching seems to be smaller for the cases examined, but a more detailed investigation is required
  - Real aperture processing does not exhibit spectral hump.
- An extensive data set with spaceborne altimeters and airborne lidars currently exists, including much in situ data from the CARTHE experiment
- The AirSWOT and SWOT teams are working vigorously to address these issues and a resolution plan is in place.