Evaluation of High-Resolution Path Delay Data from the Airborne HAMMR Instrument

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OSTST Reston, VA

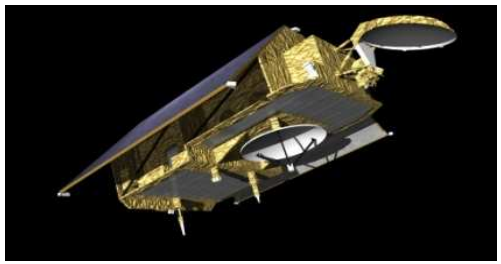
Shannon Brown, Steve Reising, Xavi Bosch, Pekka Kangaslahti
and the HAMMR team

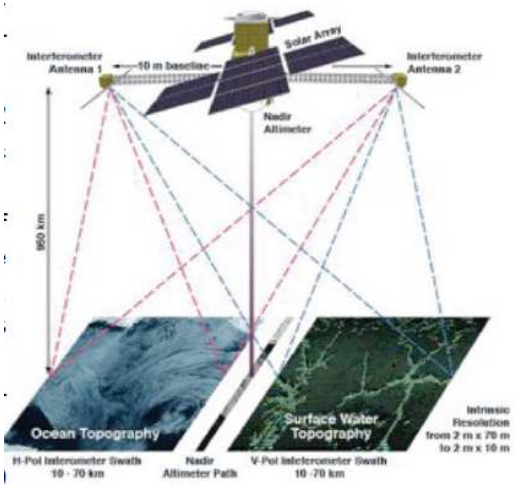
Introduction

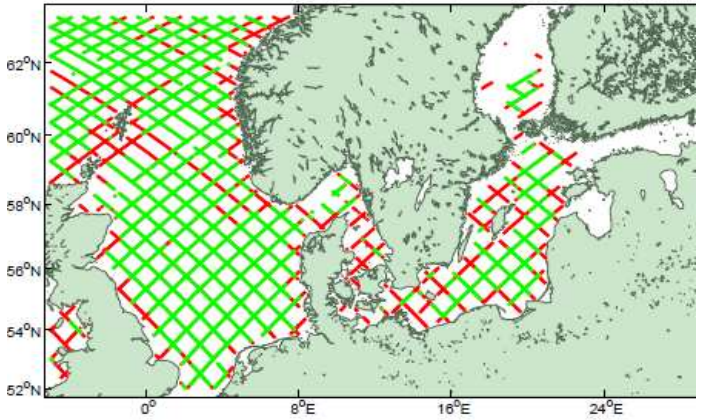
- Next generation altimeter systems feature SAR and InSAR processing to improve altimeter resolution in the open ocean and near land

- As we move to smaller scales and toward typically “data flagged” regions, we need to quantify potential errors from small scale variations in the corrections (e.g. water vapor) and identify instrument improvements, such as enhanced radiometers

- An airborne version of a new generation radiometer system for altimetery was recently completed and conducted science flights in November 2014

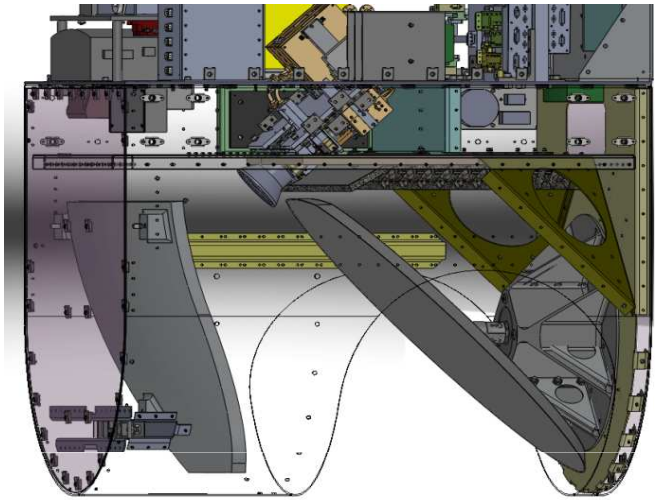




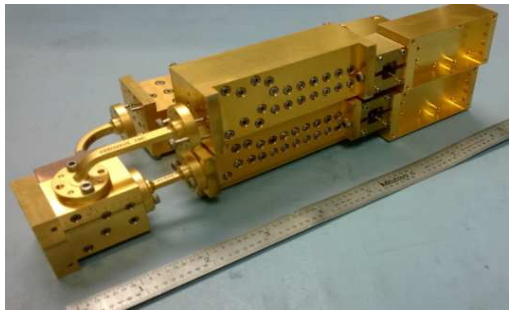


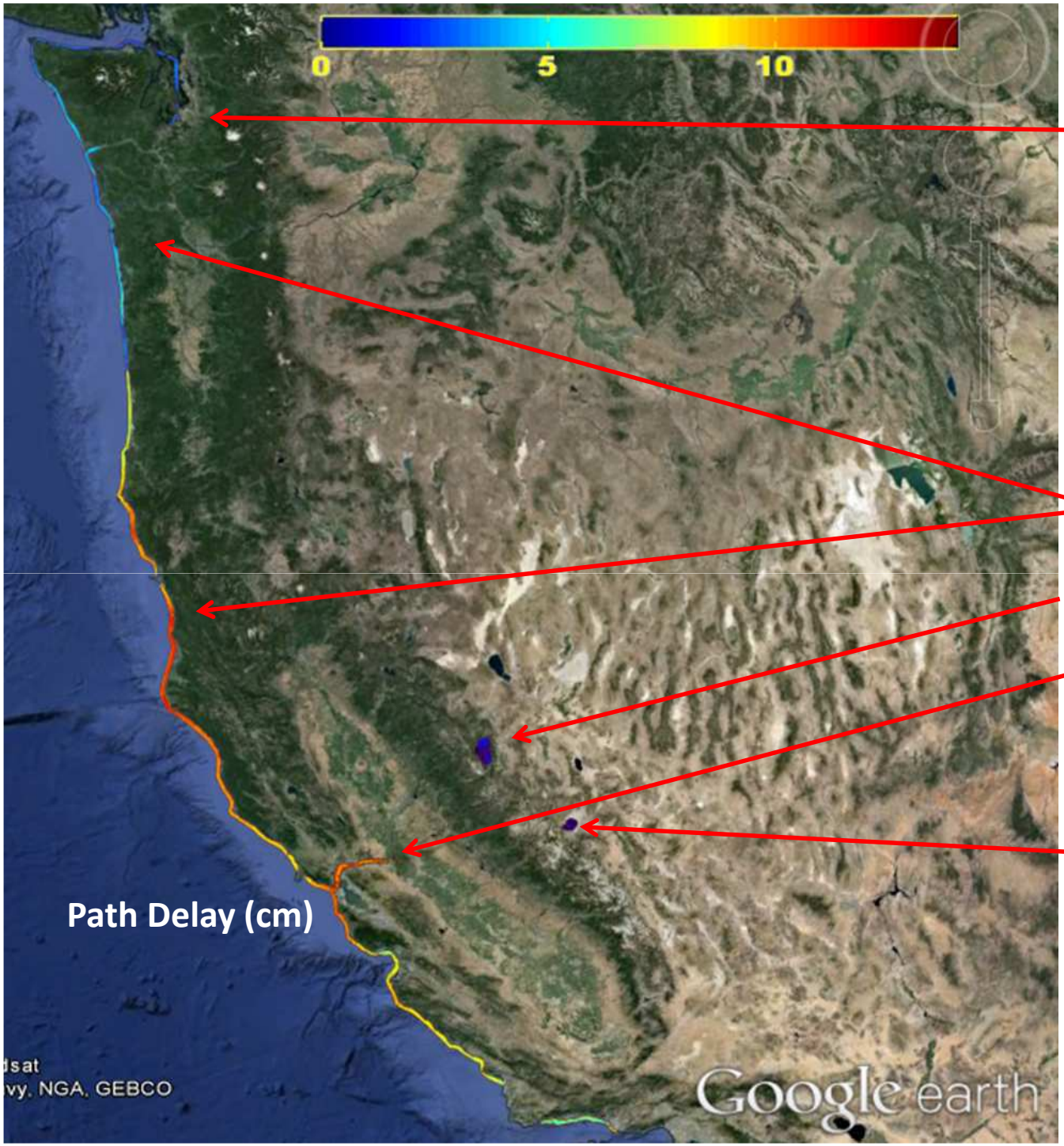
SWOT Airborne Radiometer (HAMMR)

- **Multi-channel high resolution imaging radiometer for measuring PD over ocean, land and in coastal regions (PI – Steve Reising, CSU)**
  - Low-frequency microwave channels - *Identical to Jason AMR*
    - 18.7, 23.8 and 34.0 GHz (H and V)
  - High-frequency mm-wave window channels *(coastal)*
    - 90, 130 and 166 GHz
  - High-frequency mm-wave sounding channels *(over-land)*
    - ASIC analog spectrometer with 8 bands near 118 and 183 GHz
  - Cross track imaging, < 150m spatial resolution



- **Science flights took place in November 2014**
  - Over open ocean and coastal regions to test **coastal wet path delay retrievals** and **evaluate PD spectrum**
  - Over large inland water bodies to test over-land wet path delay retrievals





Puget Sound

West Coast Field Campaign November 2014

Coastal Ocean

Lake Tahoe

San Joaquin River

Mono Lake

Observations at 150m spatial resolution

West Coast Campaign Weather

Generally encountered clear and dry conditions with an occasional marine layer (PDs from 2-15 cm observed)

Near Camarillo, CA
Nov 05, 2014

Near Salem, OR
Nov 07, 2014

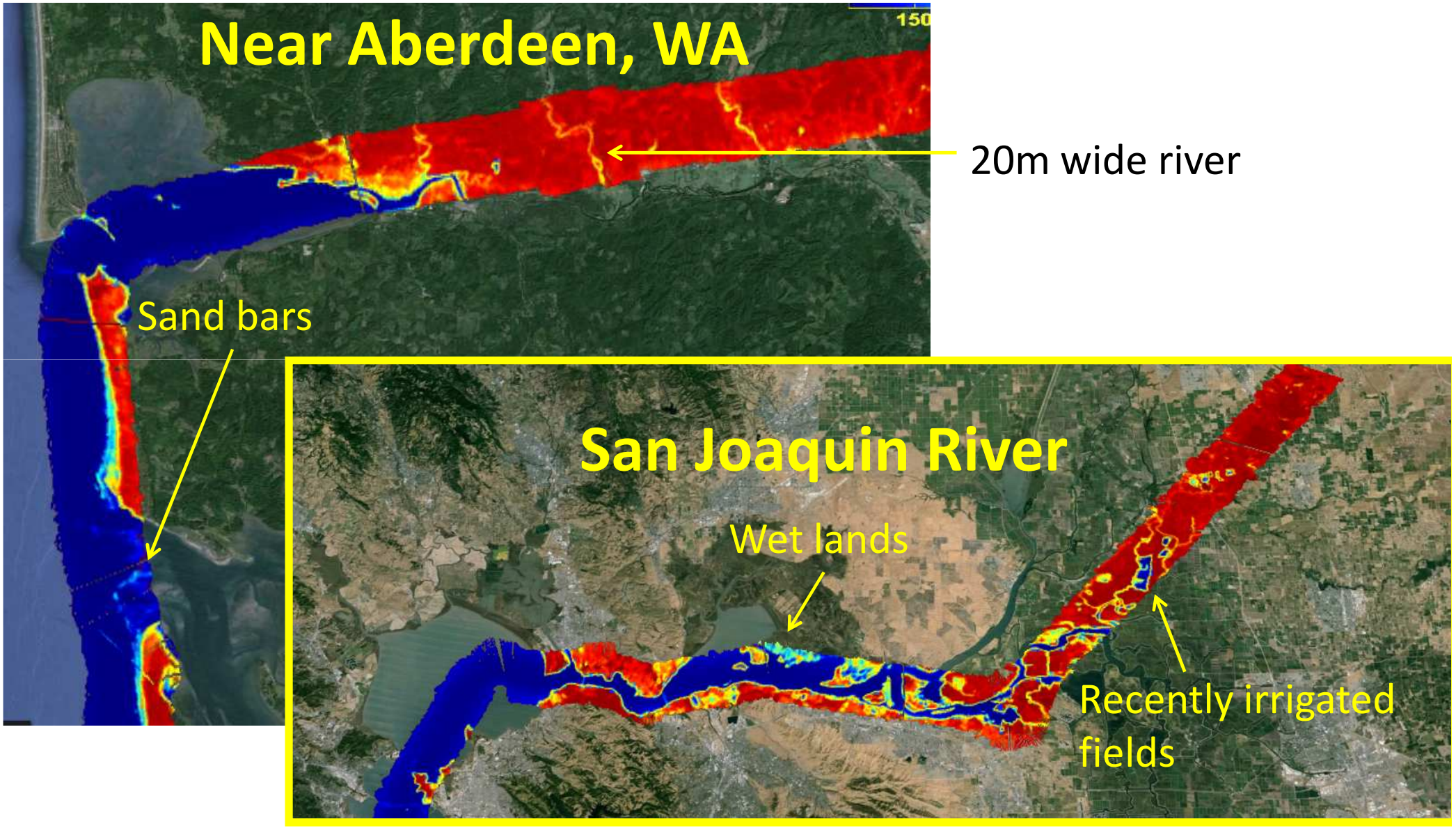
Near Port Angeles, WA
Nov 10, 2014

Near Eureka, WA
Nov 11, 2014

Near Eureka, WA
Nov 11, 2014

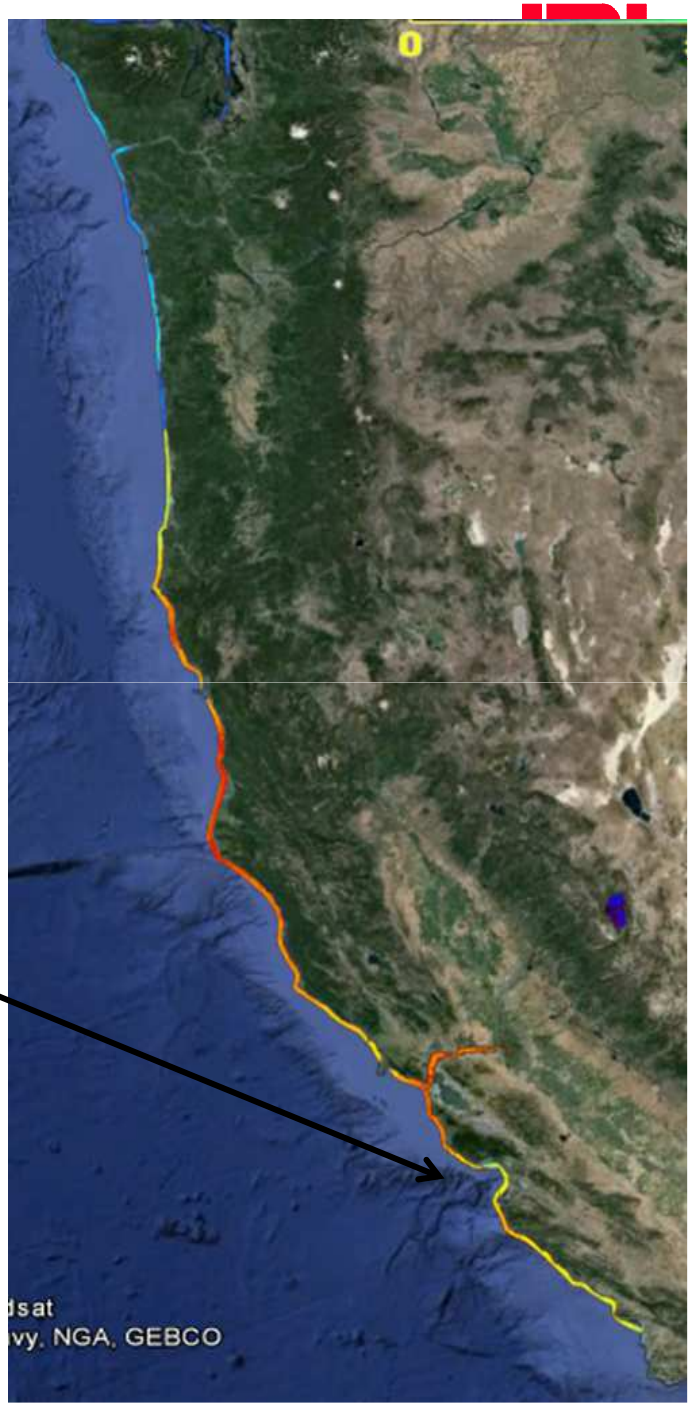
Lake Tahoe, NV
Nov 12, 2014

150m Spatial Resolution Images



Coastal Data

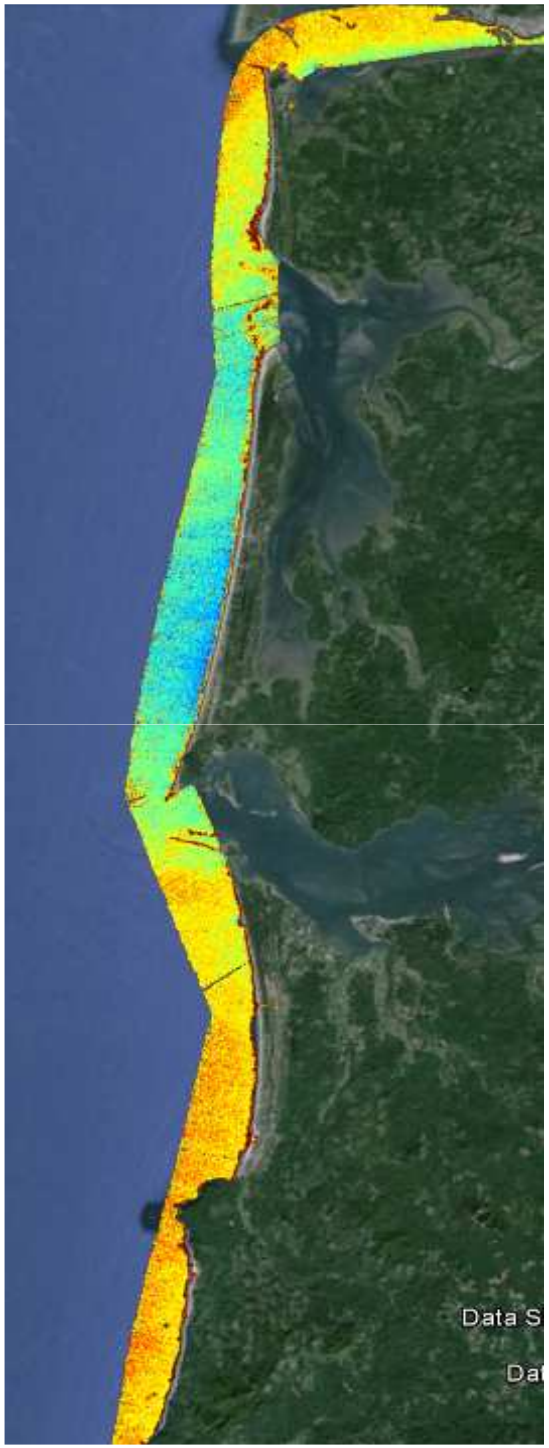
- Data collected along entire US west coast over several days
- Flight rules dictated that the plane had to fly within 1 mile of shore
- Therefore, all data have land in part of the swath



HAMMR Analysis

- **Small-scale spatial variability of wet path delay**
  - Satellite data cannot resolve spatial scales less than about 70km
  - HAMMR data can resolve scales down to 0.3km (though typically noise limited to ~1km for PD)

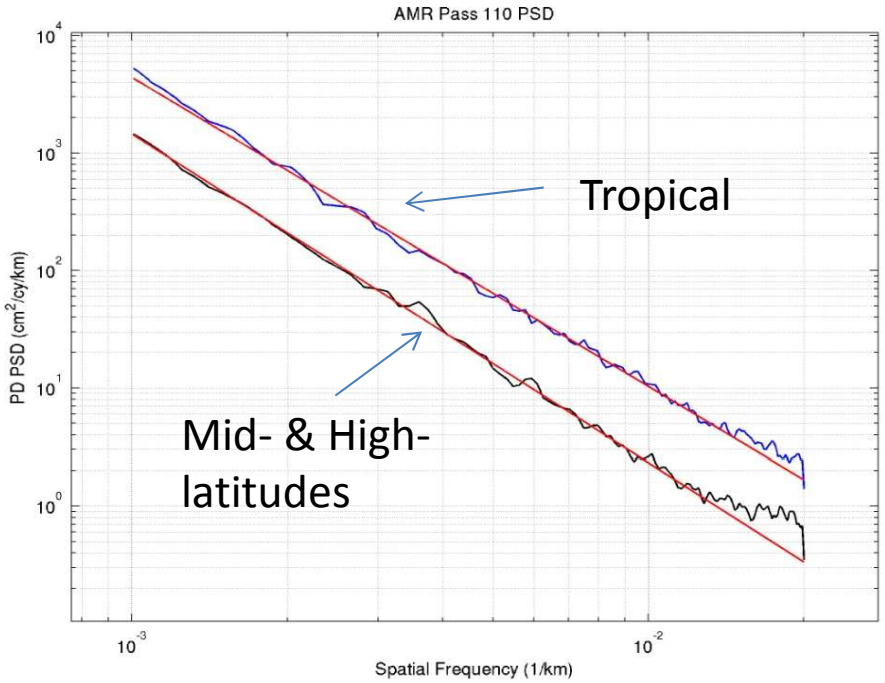
- **Evaluation of high-frequency radiometer observations for improving altimeter systems at the coast (3-50 km from land)**
  - Combination of low-frequency + high-frequency radiometer proposed for future altimeter systems (previous OSTST recommendation)
  - High-frequency algorithms applied to HAMMR data to evaluate potential performance for this system



Spectral Analysis - Small Scale Spatial Variability

- Path delay retrieved over ocean using AMR channels with adapted retrieval algorithm (updated to account for variable incidence angle)
- PDs averaged along-track at 500m resolution and posting
- Data filtered for land, sandbars, piers etc using higher resolution 130 GHz TB data
- PD spectrum computed along the ground track

A Note on PD Spectrum



$$E(f) = \alpha f^{\beta}$$

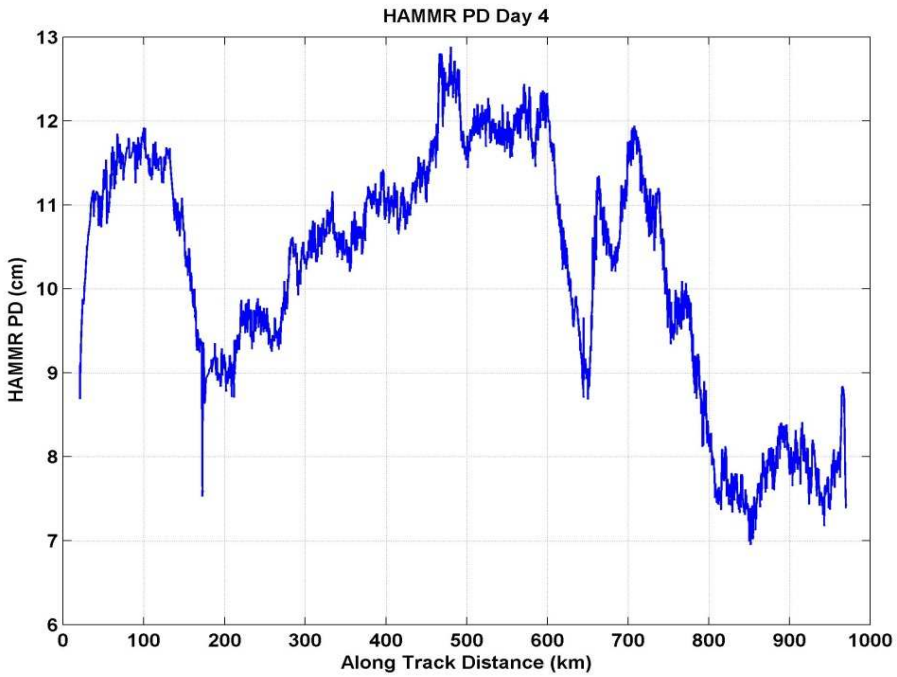
Pacific Jason Pass 110	α	β
Mid-latitude	0.6e-5	-2.8
Tropical	5.7e-5	-2.6

- PD PSD varies regionally and seasonally
- For SWOT, spectra are extrapolated to small scales from global long-wave fit (70-1000km)
- HAMMR data used to verify small-scale slope assumption down to 1km
  - Important for SWOT
  - HAMMR spectrum compared to global average PD spectrum from AMR

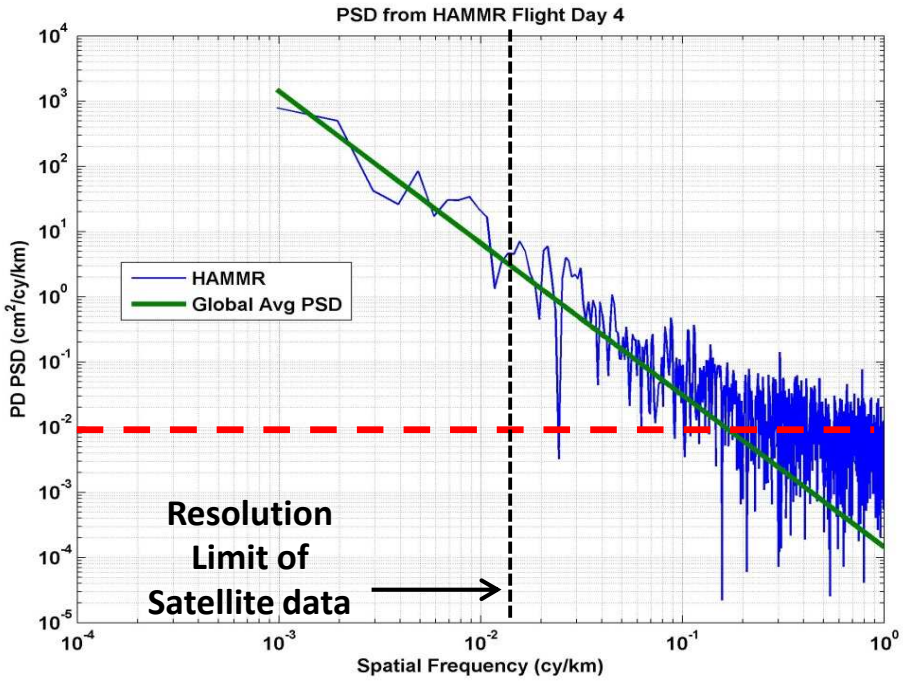
November 8, 2014

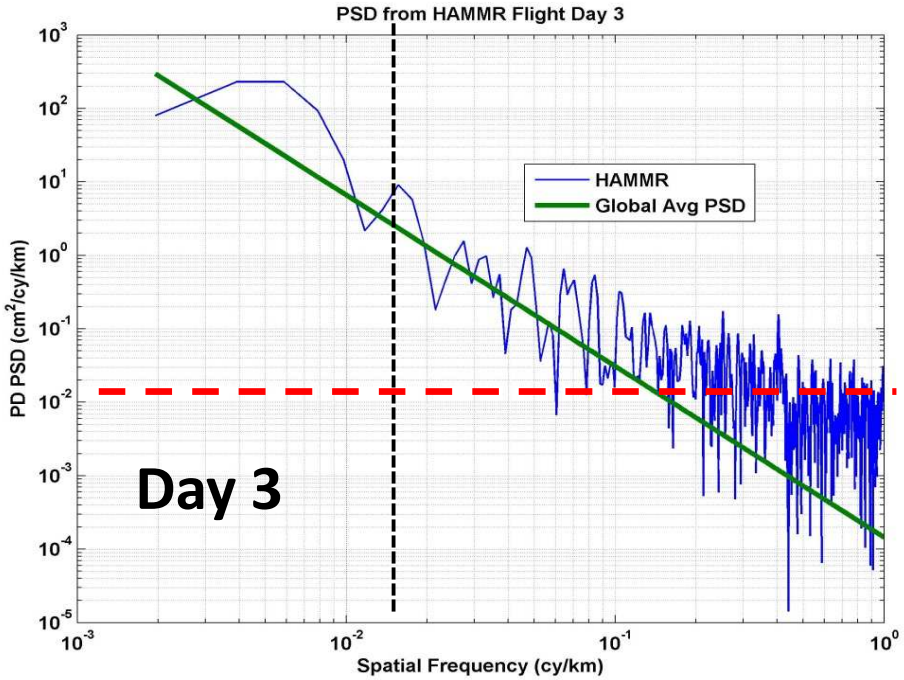
- 1000km flight segment provides good comparison of long-wave to short-wave spectrum
- Noise floor of radiometer is 1mm at 500m resolution
  - For most flights, signal fell below noise floor at ~3-5km
- Signal closely follows global average long-wave spectral slope

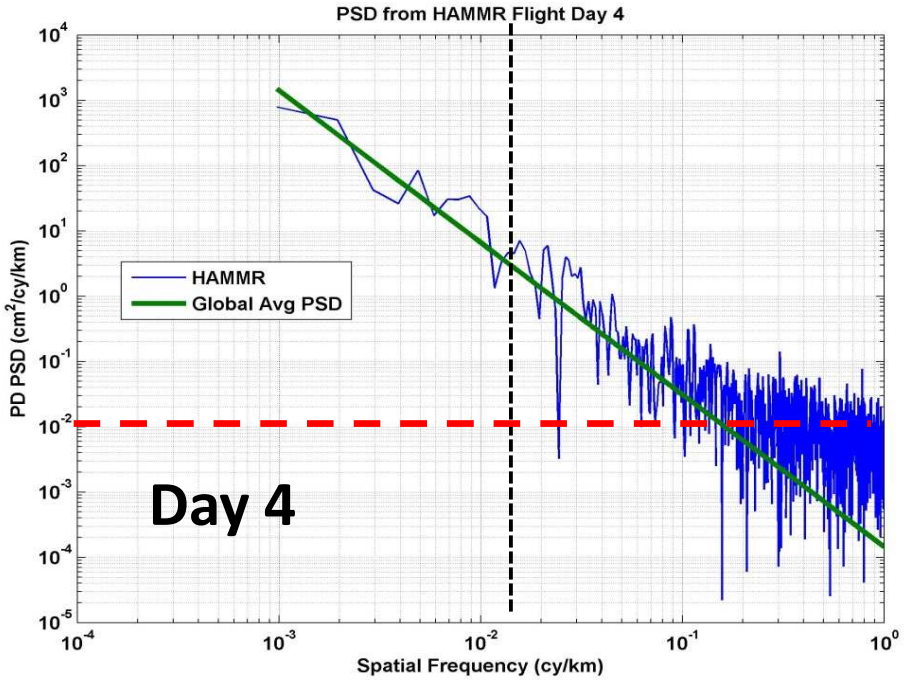
Along Track PD Time Series - California Coast

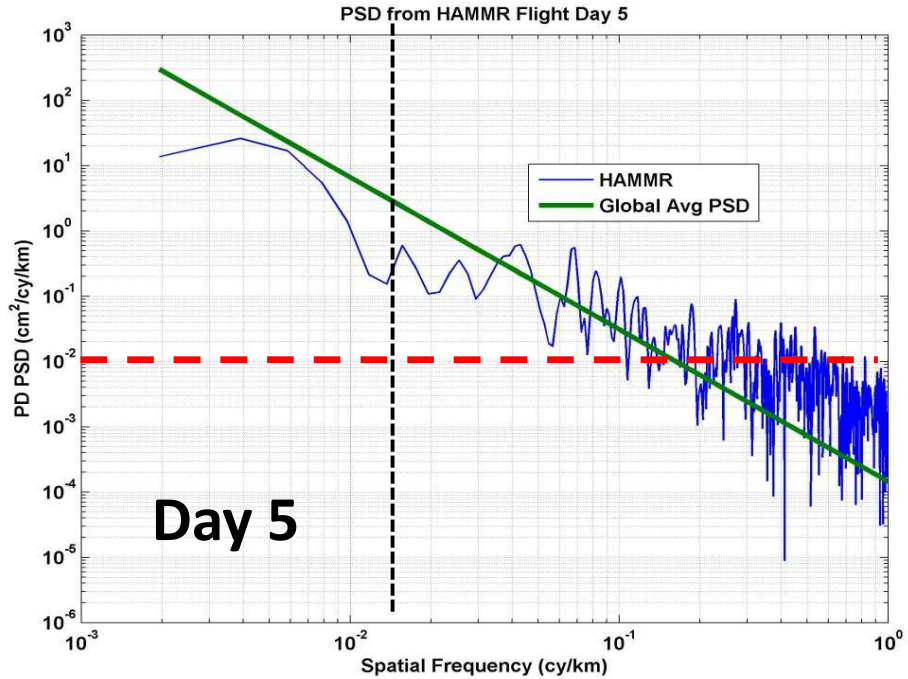


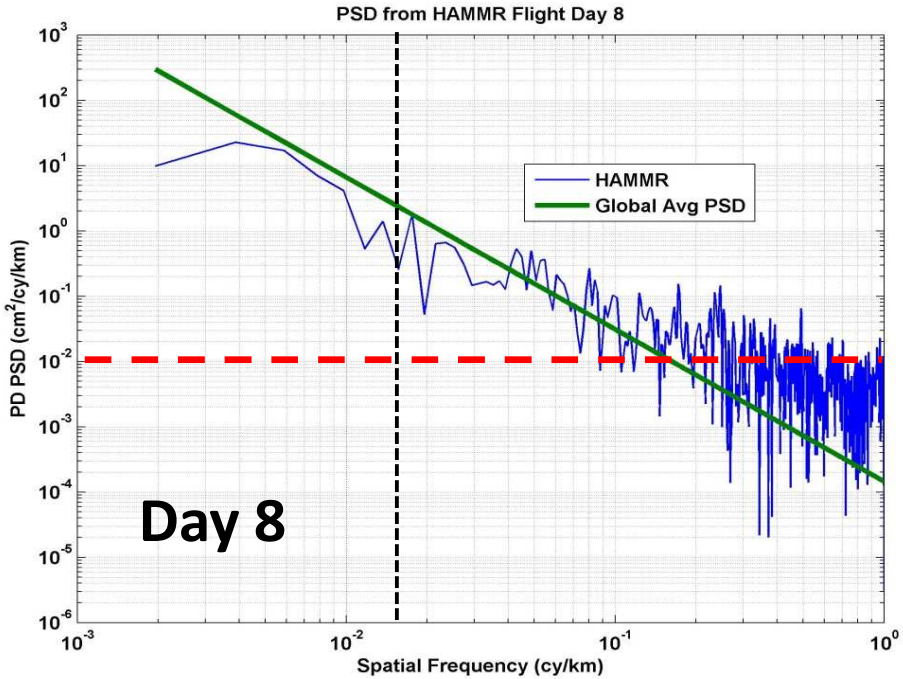
Along Track PD PSD - California Coast




PSD from HAMMR Flight Day 3
HAMMR
Global Avg PSD
Day 3
PD PSD (cm²/cy/km)
Spatial Frequency (cy/km)

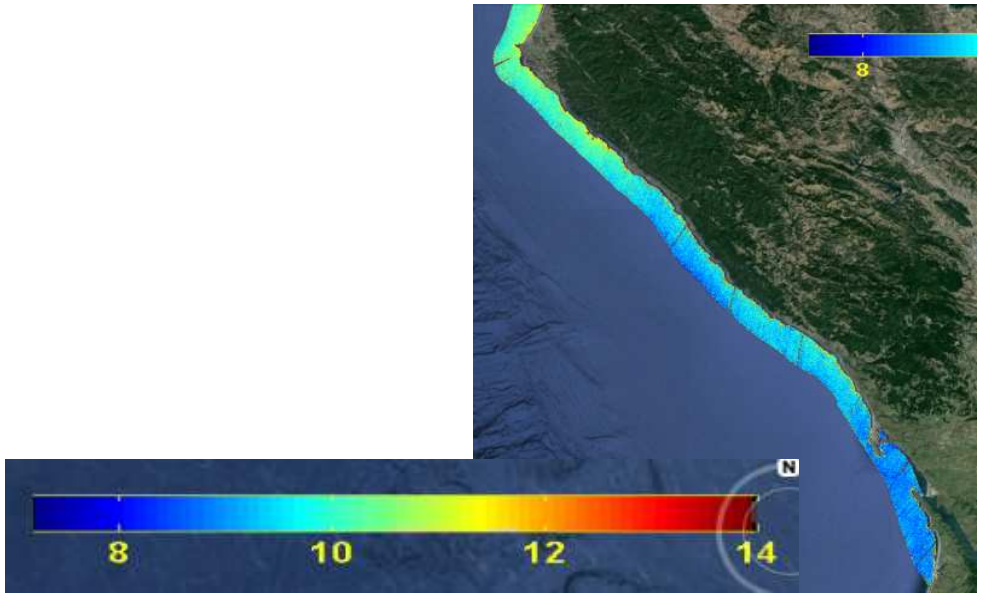

PSD from HAMMR Flight Day 4
HAMMR
Global Avg PSD
Day 4
PD PSD (cm²/cy/km)
Spatial Frequency (cy/km)


PSD from HAMMR Flight Day 5
HAMMR
Global Avg PSD
Day 5
PD PSD (cm²/cy/km)
Spatial Frequency (cy/km)


PSD from HAMMR Flight Day 8
HAMMR
Global Avg PSD
Day 8
PD PSD (cm²/cy/km)
Spatial Frequency (cy/km)

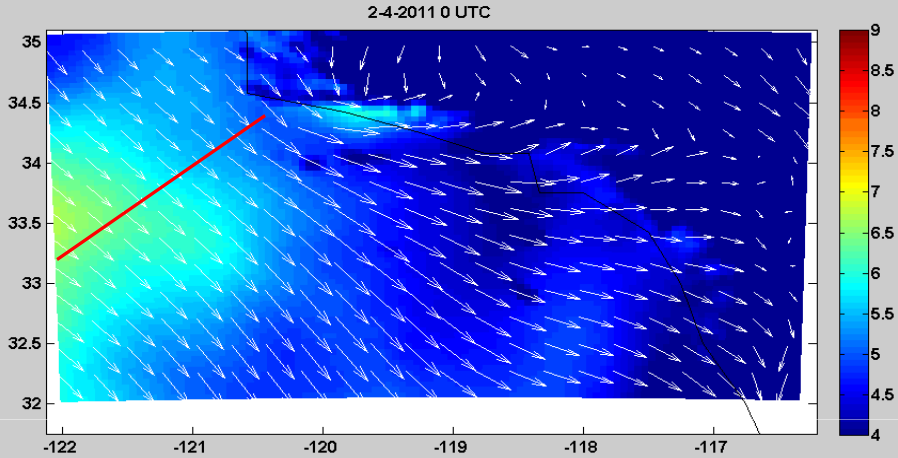
Spectrum Summary

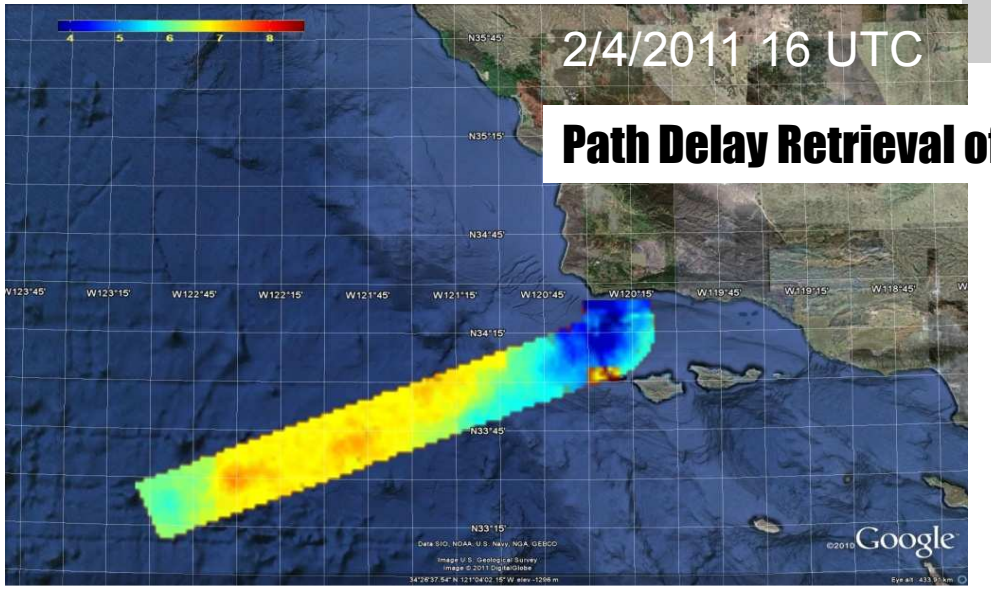
- High-resolution HAMMR PD data support long-wave slope extrapolation assumed by SWOT with the caveat that only a limited data set was available
  - It is recommended that additional HAMMR data are collected in more “active” conditions (e.g. tropical, around convection, near fronts)



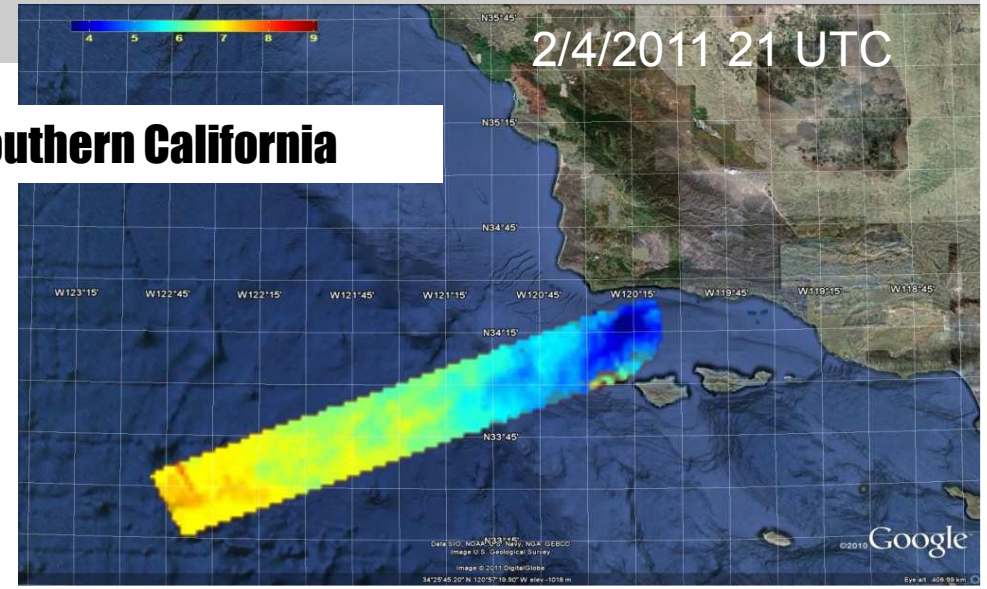
Testing Enhanced Radiometer for Coastal Improvement

- Large local PD biases can arise within 3-50 km from land
- Example of Santa Ana winds off California coast
  - ~3-4 cm bias at the coast



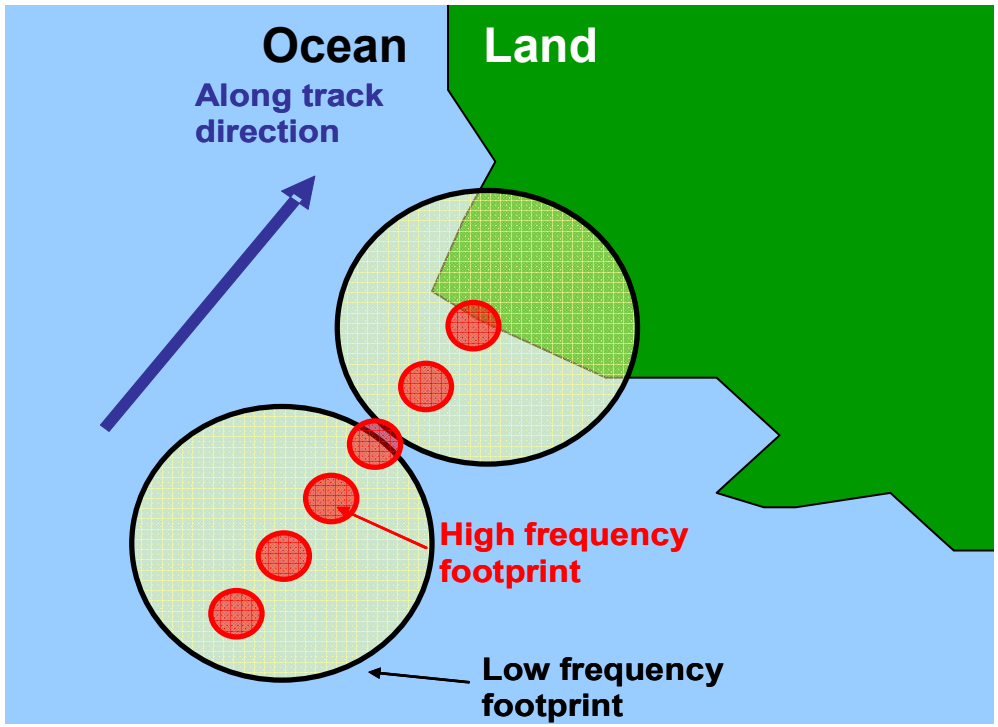


Path Delay Retrieval off Southern California



High-Frequency Radiometer for Coastal Retrievals

- Channels between 90-160 GHz sensitive to water vapor continuum
- Also sensitive more sensitive to cloud liquid water and water vapor scale height
- Hybrid concept developed to use high-frequency channels near land with a dynamically trained retrieval algorithm
- Simulations show PD retrieval error < 7mm to within 3 km from coast in a global average sense, evaluated using HAMMR data



- Standard low-frequency channels (18-34 GHz) used for PD retrieval in open ocean (> 30 km from land)

- High-frequency window channels, 90, 130 and 166 GHz used to continue PD measurement to ~3km from land

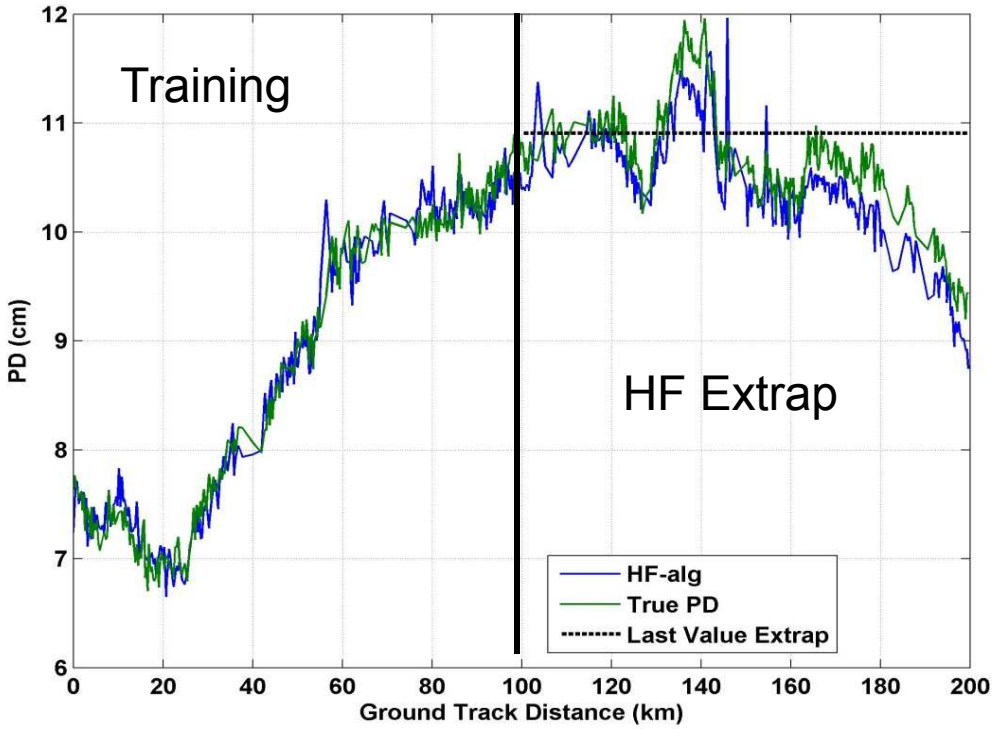
$$PD_{HF} = c_o + \sum_{i=1}^{N_f} c_i T_{Bi}$$

where

$$\vec{c} = \left(A^T A\right)^{-1} A^T PD_{LF}$$

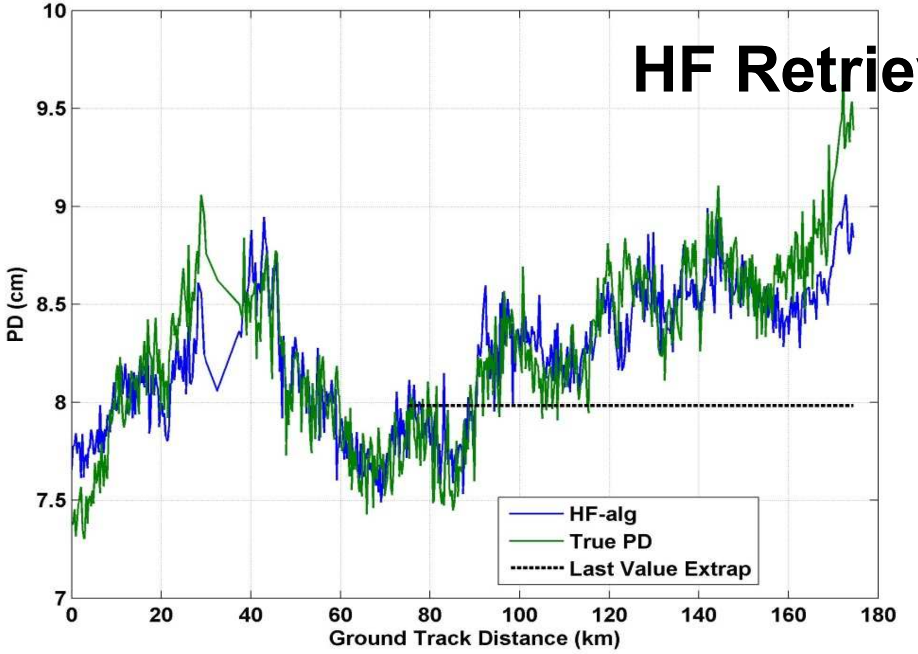
High-Algorithm Testing with HAMMR

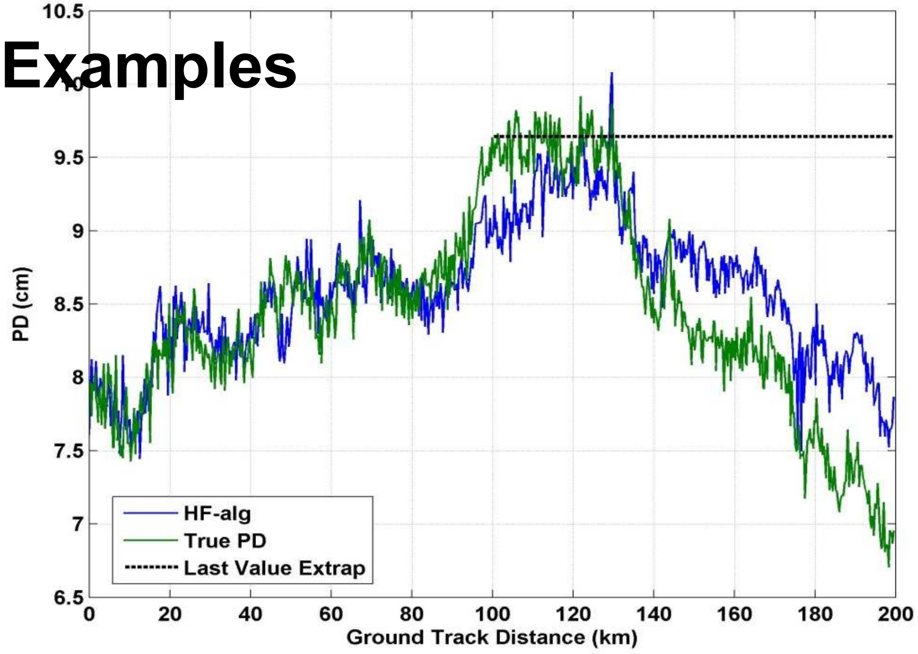
- First retrieved PD over the ocean using low-frequency 18-34 GHz channels
- Then, dynamically trained HF algorithm along track using 100km of along track data and evaluated performance over next 100km
- Evaluated performance by comparing to low-frequency "true" PD over next 100km

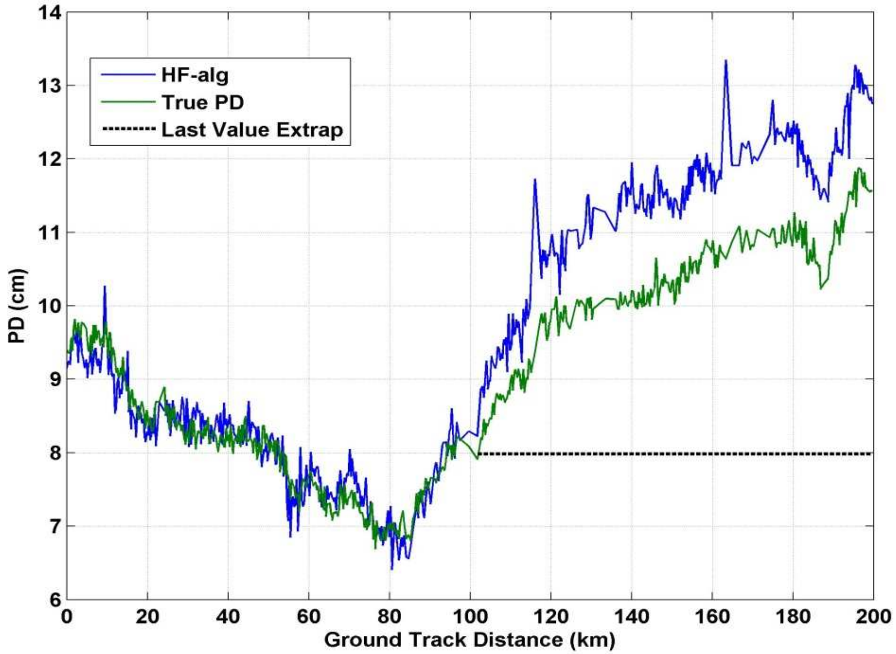


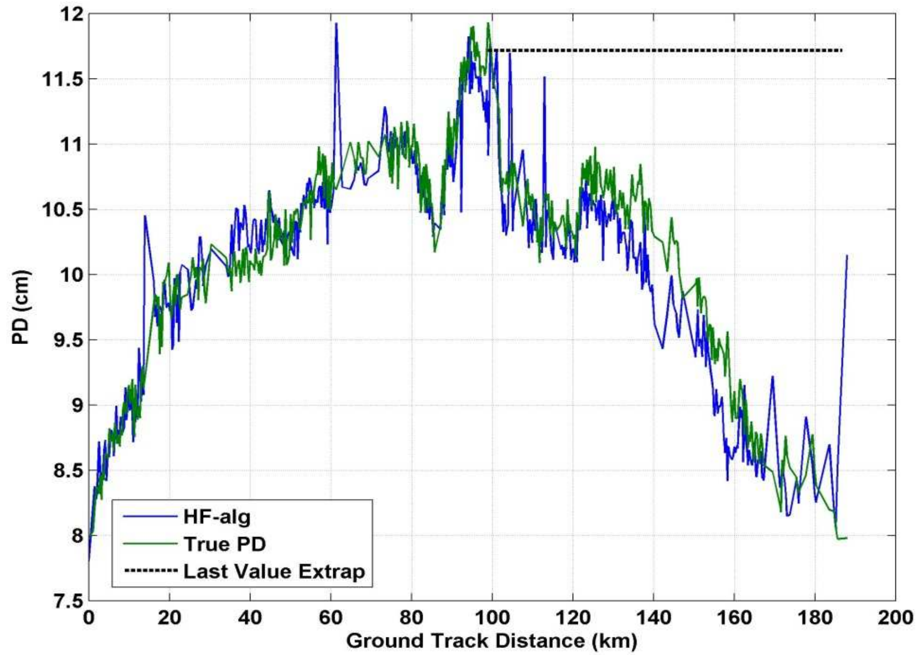
Last valid PD extrapolation

HF Retrieval Examples



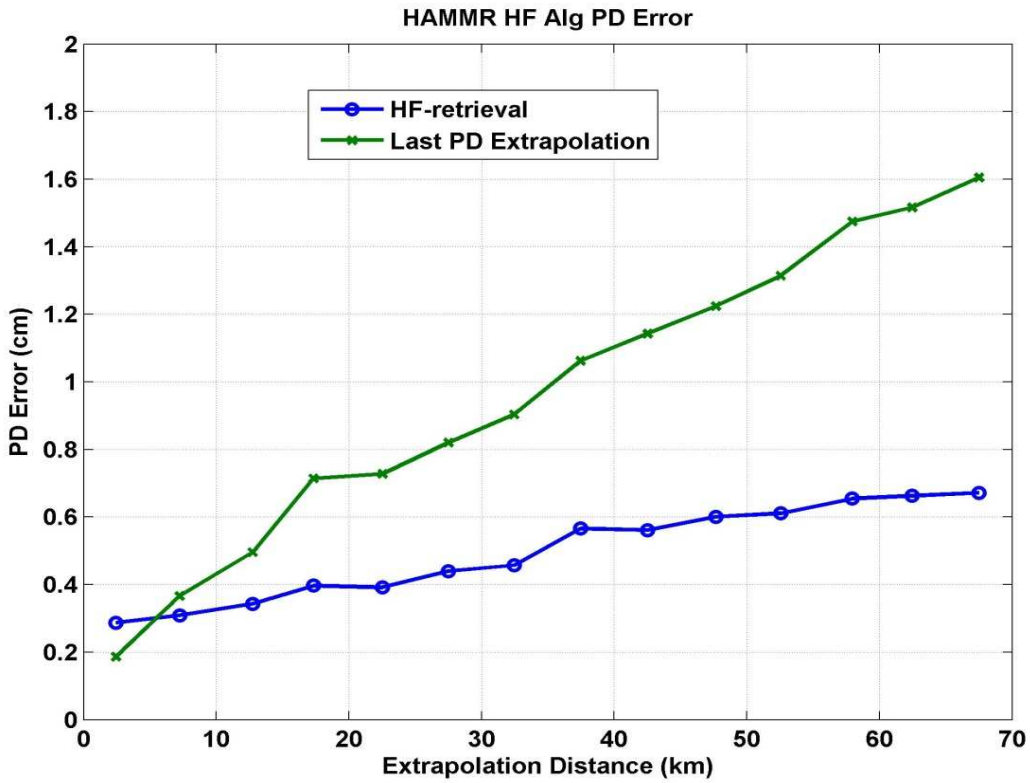






Error Summary vs Extrapolation Distance

- PD error as a function of extrapolation distance computed for both HF algorithm and for using last valid PD value
- Although dataset is limited, the HF algorithm performance is consistent with the simulated performance estimate
- Open ocean performance can be achieved in the coastal zone (<50km) with high frequency channels

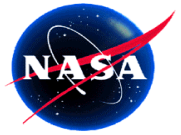


Summary and Conclusions

- Data from new generation airborne radiometer system for altimetry evaluated
  - Assessed PD spectrum from ~3-1000km
  - Tested performance of high-frequency radiometer for improving measurements in the coast zone

- Conclusion 1: Data show small scale spectral slope consistent with large scale slope derived from satellite data, which is currently assumed by SWOT

- Conclusion 2: Evaluation of high-frequency coastal retrieval algorithm demonstrates open-ocean like performance possible with an enhanced radiometer on future altimetry missions
  - ***Conclusion 2.1: More HAMMR data are needed across a diverse set of meteorological conditions***



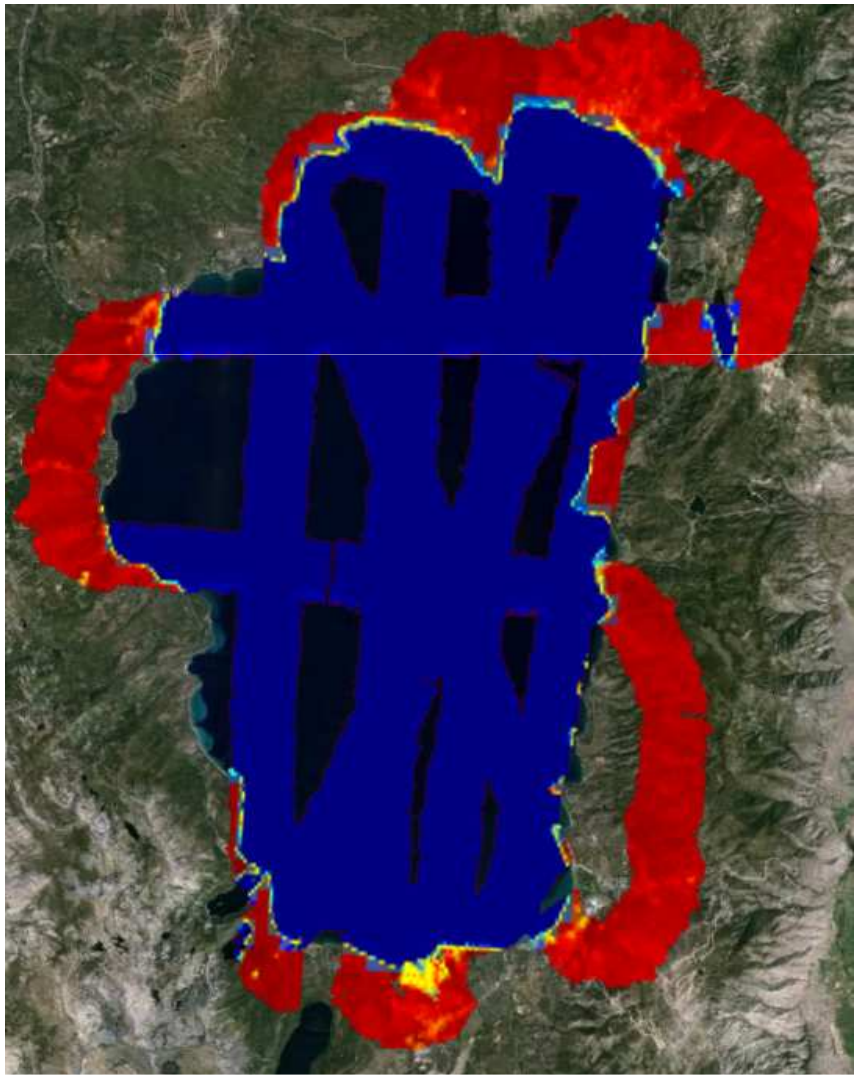
JPL

Backup

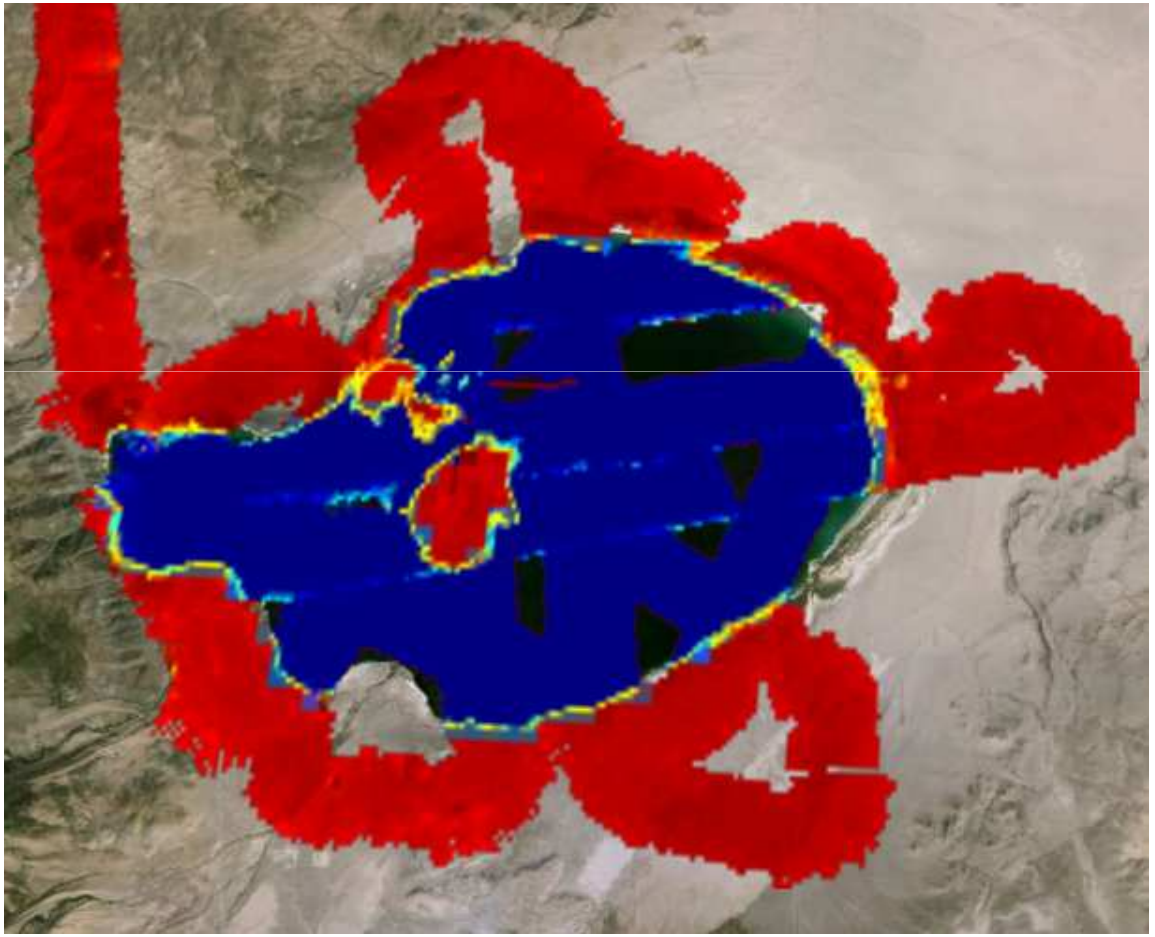
Lakes

18.7 GHz TB imagery

Lake Tahoe



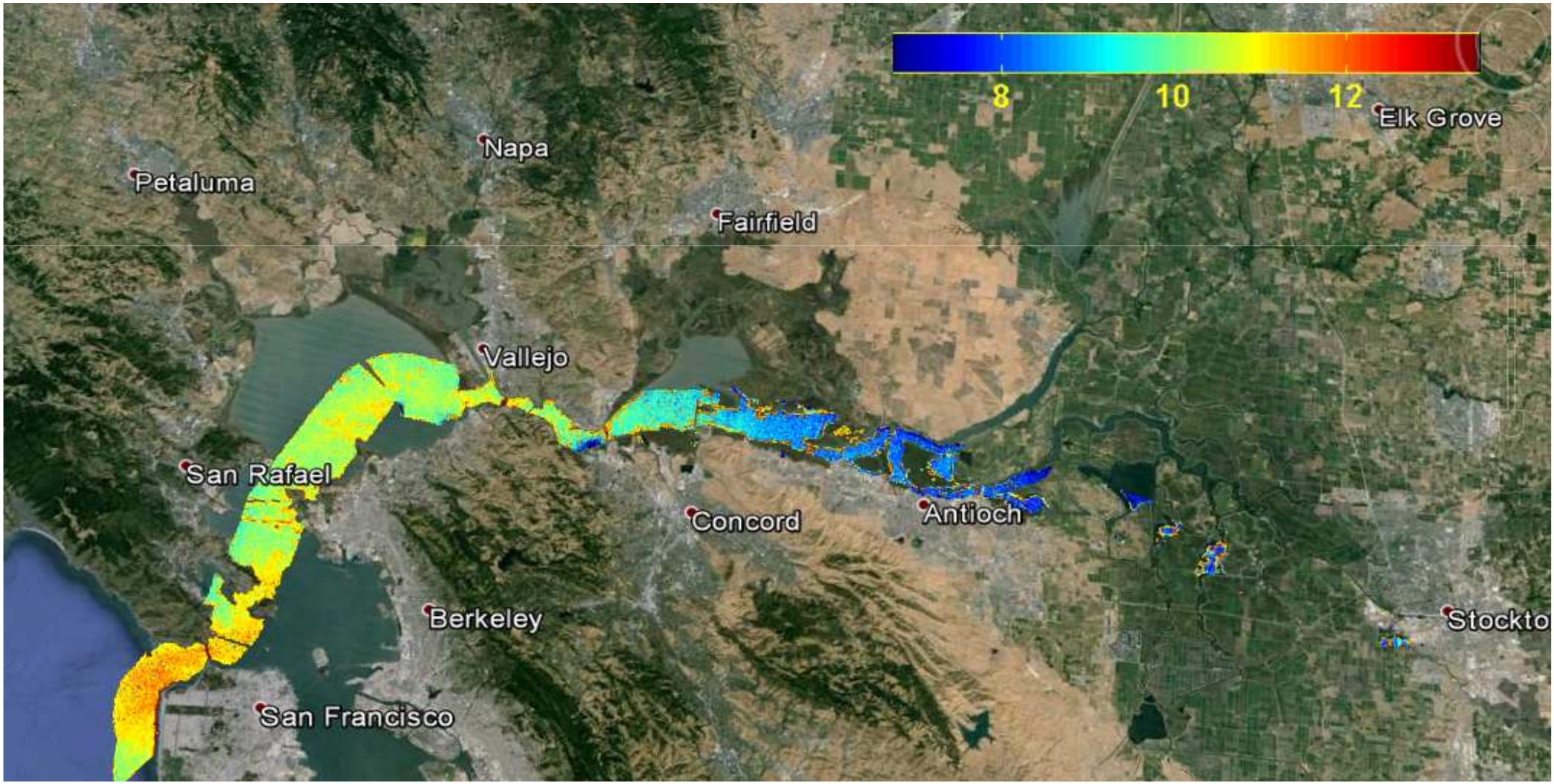
Mono Lake



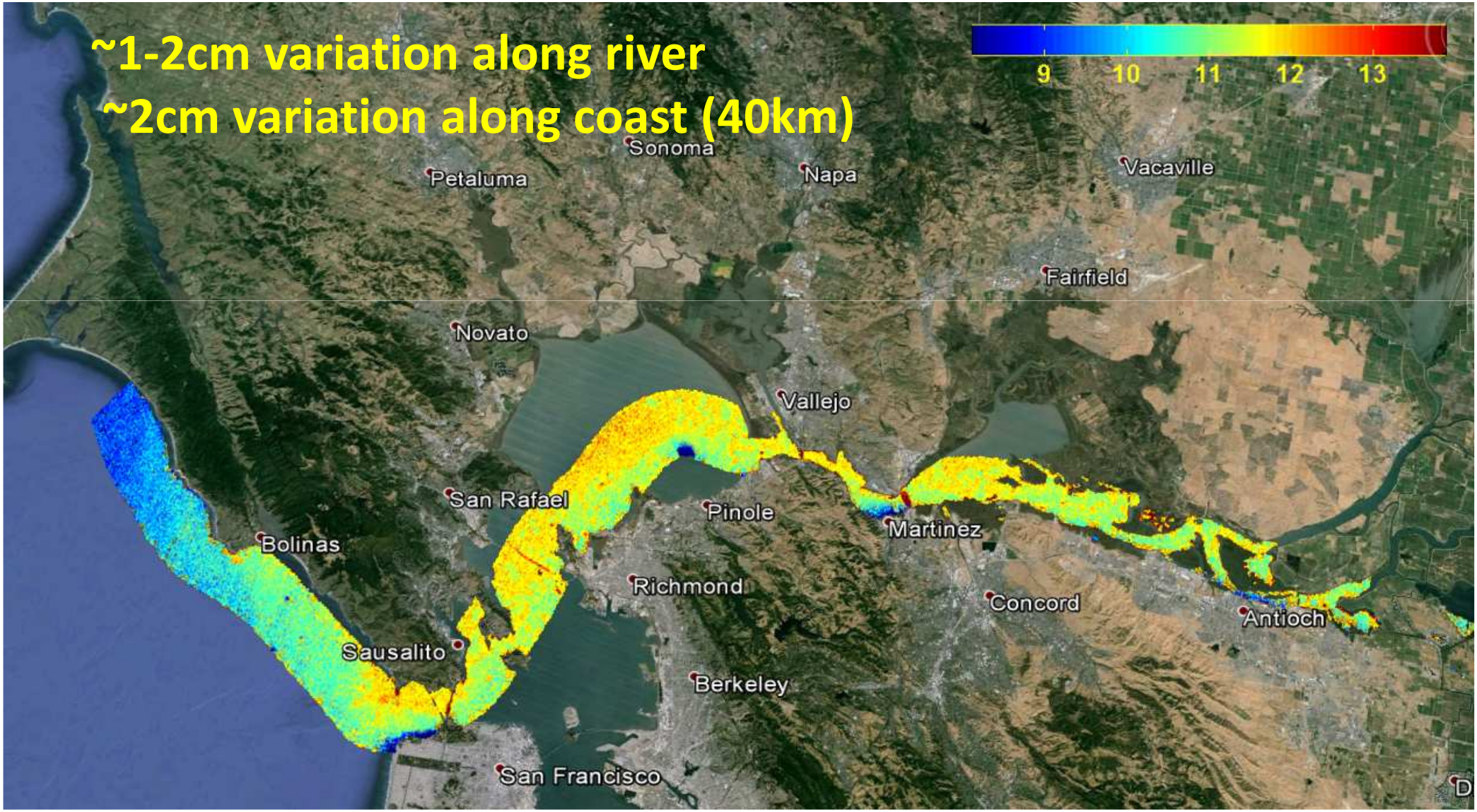
Lake flights under-flew AirSWOT

SJR: November 6, 2014

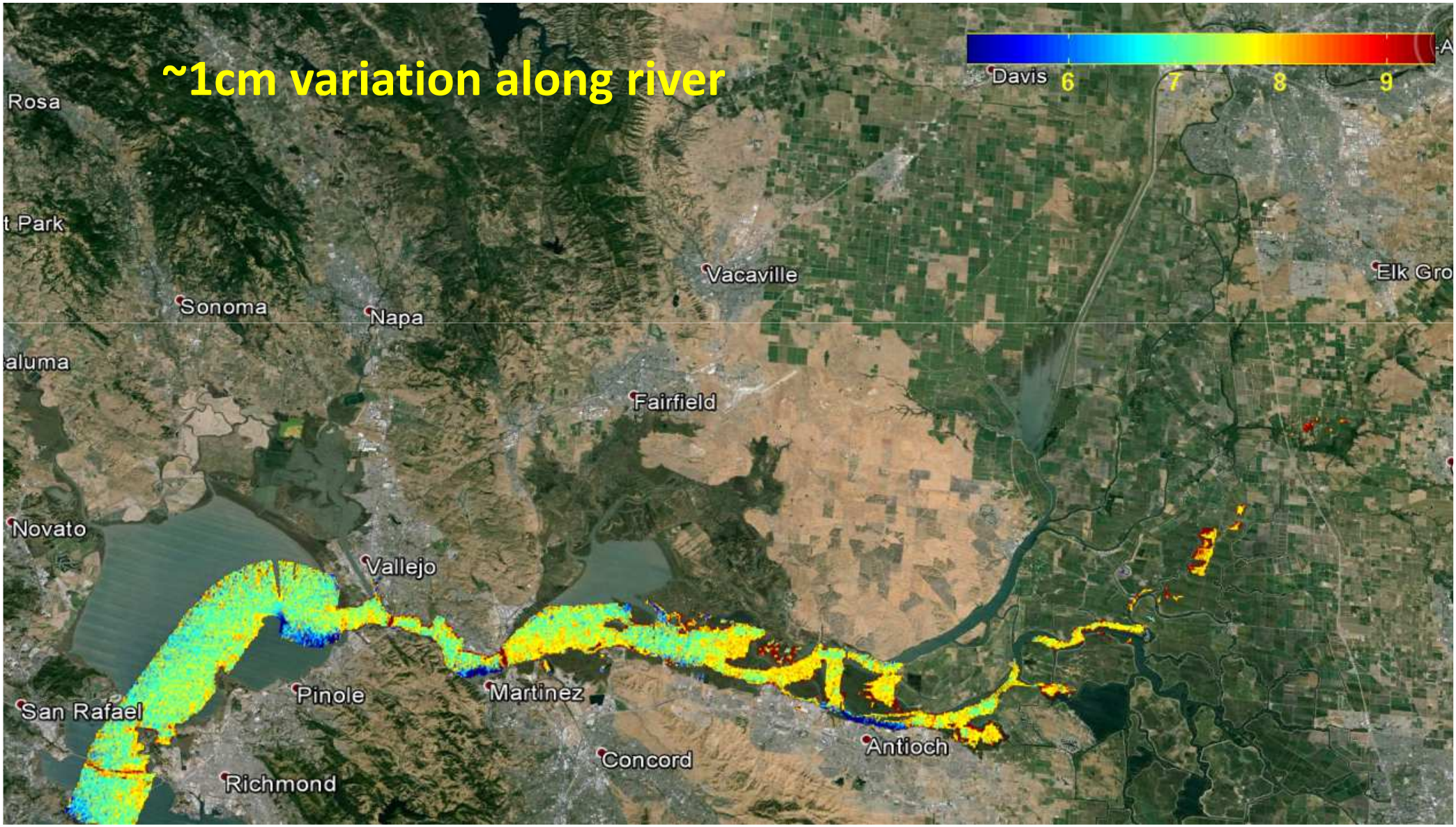
- ~3 cm PD gradient over 50 km
  - 0.6 mrad vs 1.5 mrad req



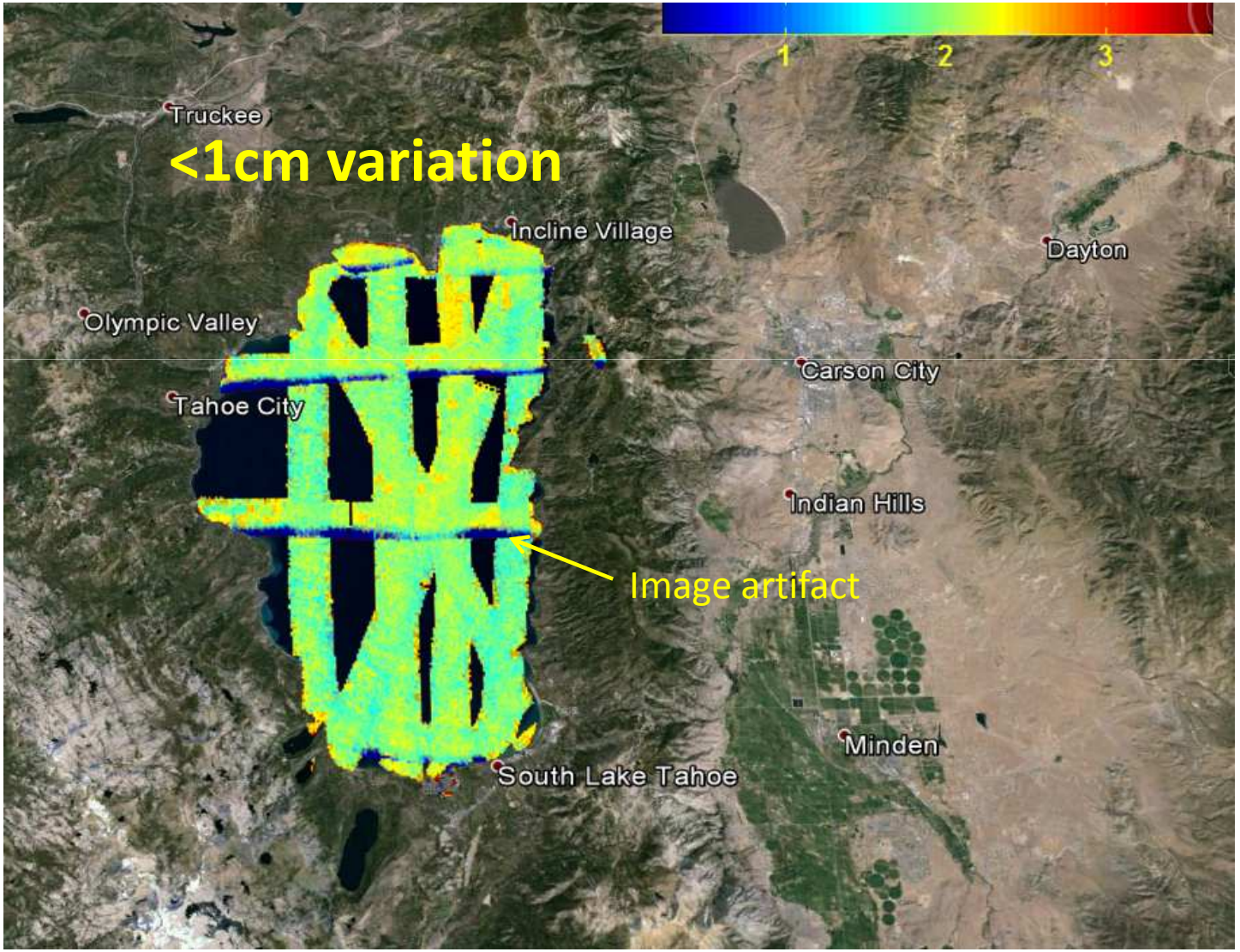
SJR: November 7, 2014



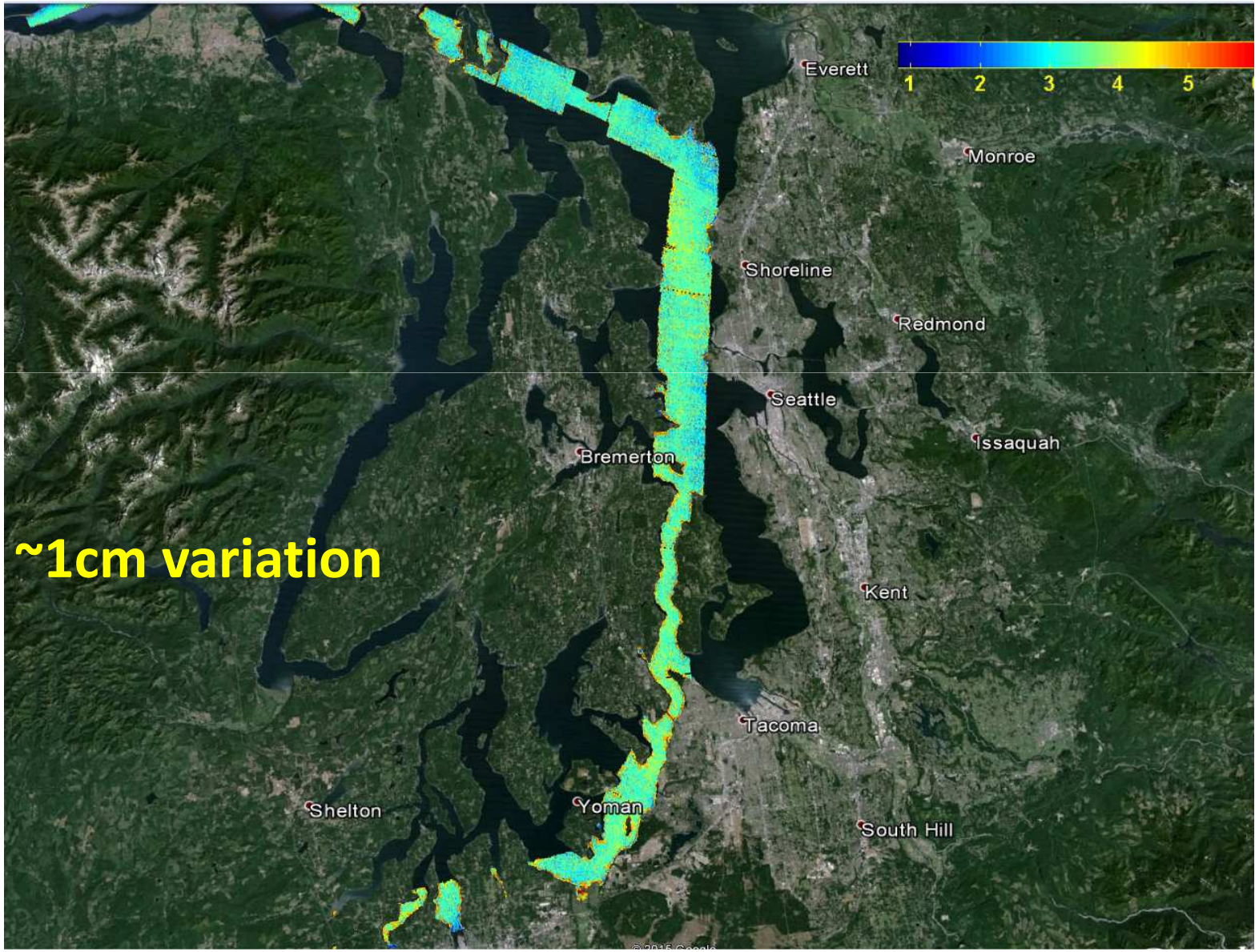
SJR: November 11, 2014



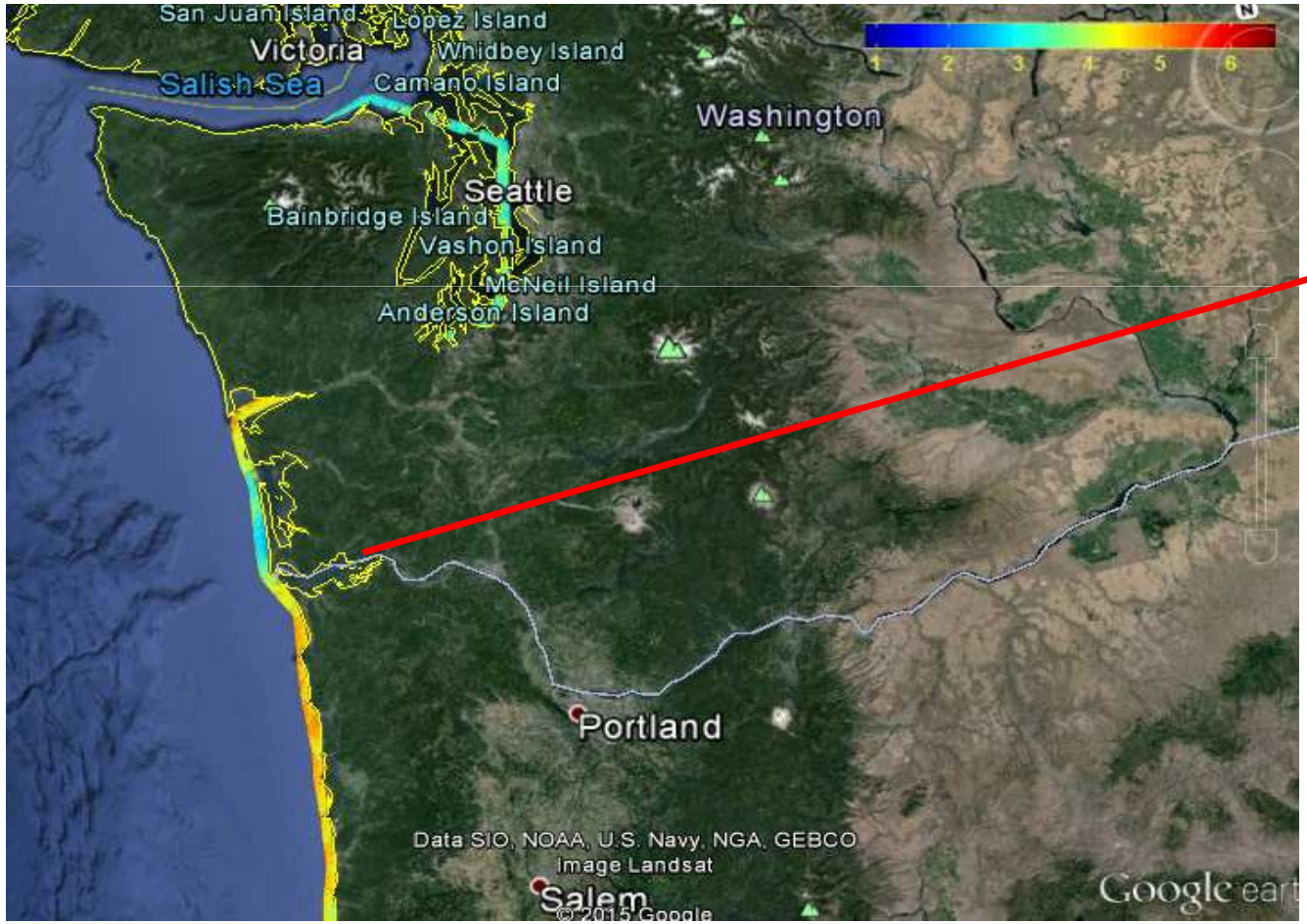
Lake Tahoe: November 12, 2014

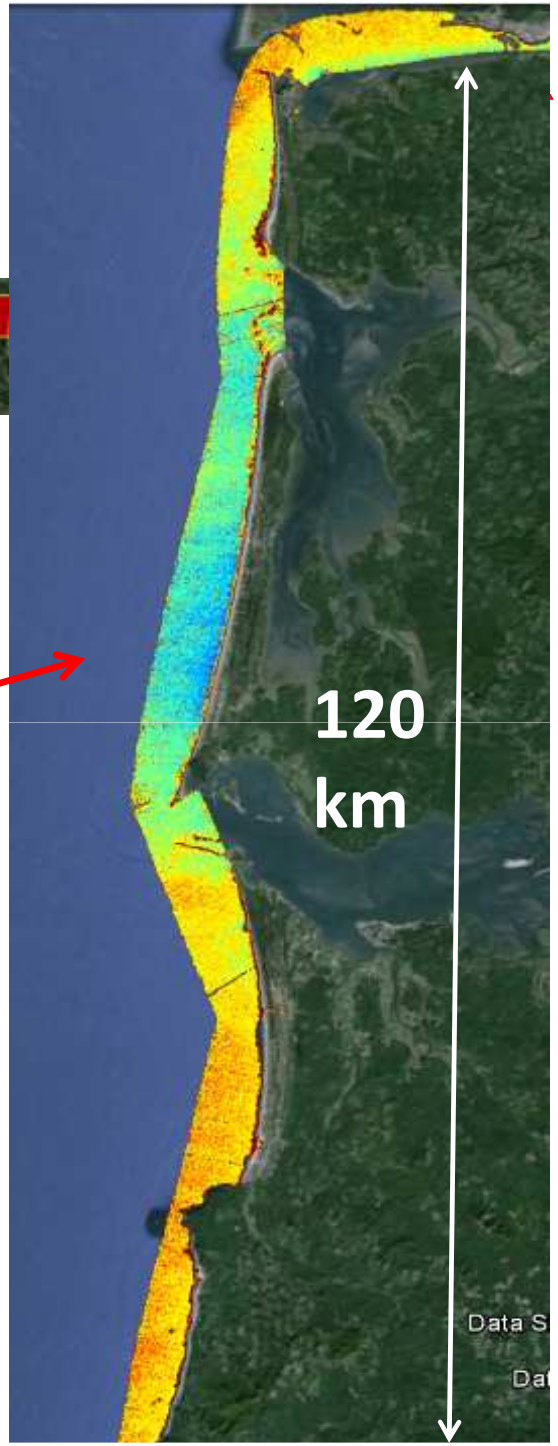


Puget Sound: November 8, 2014

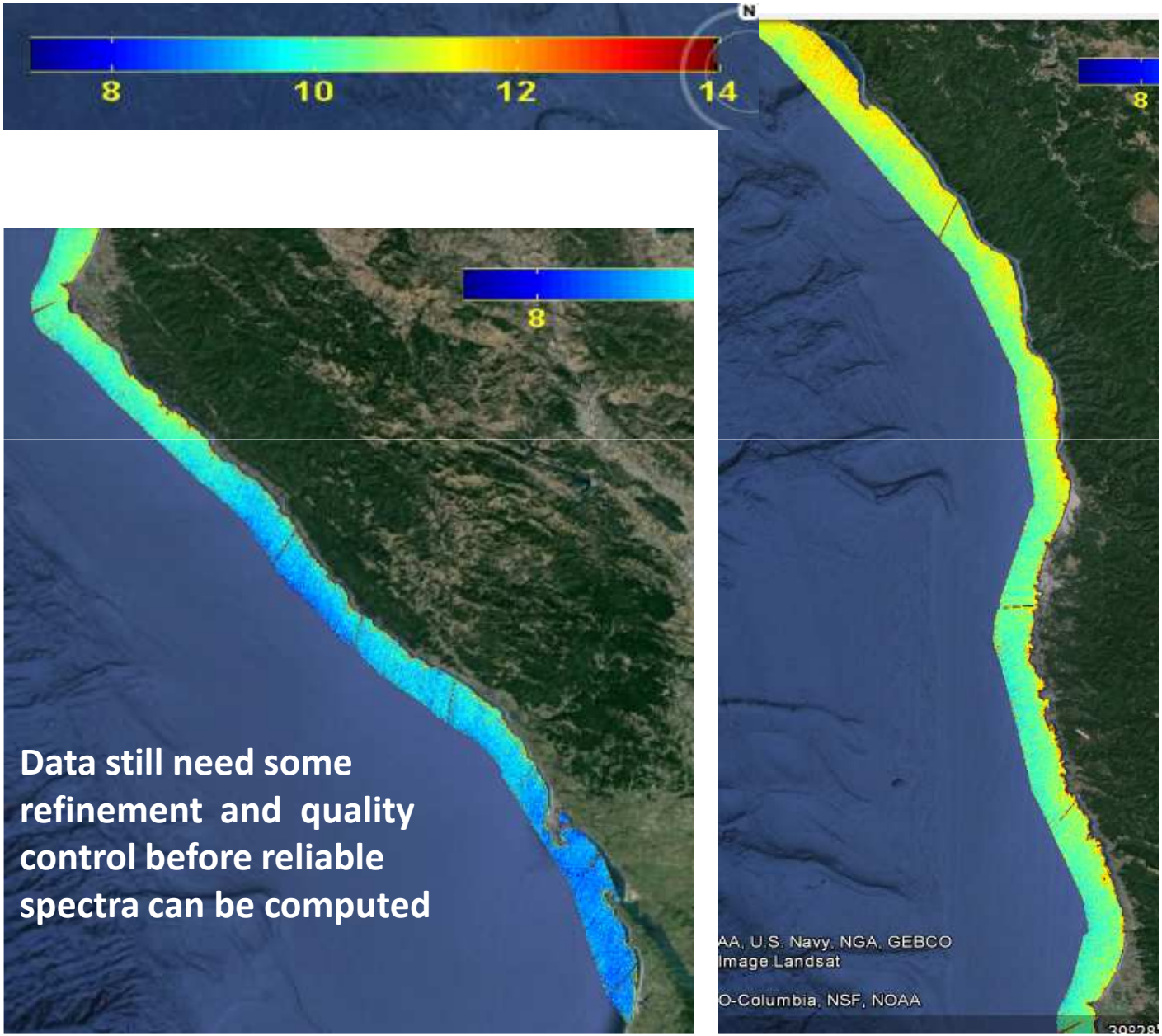


Around Puget Sound and Coast



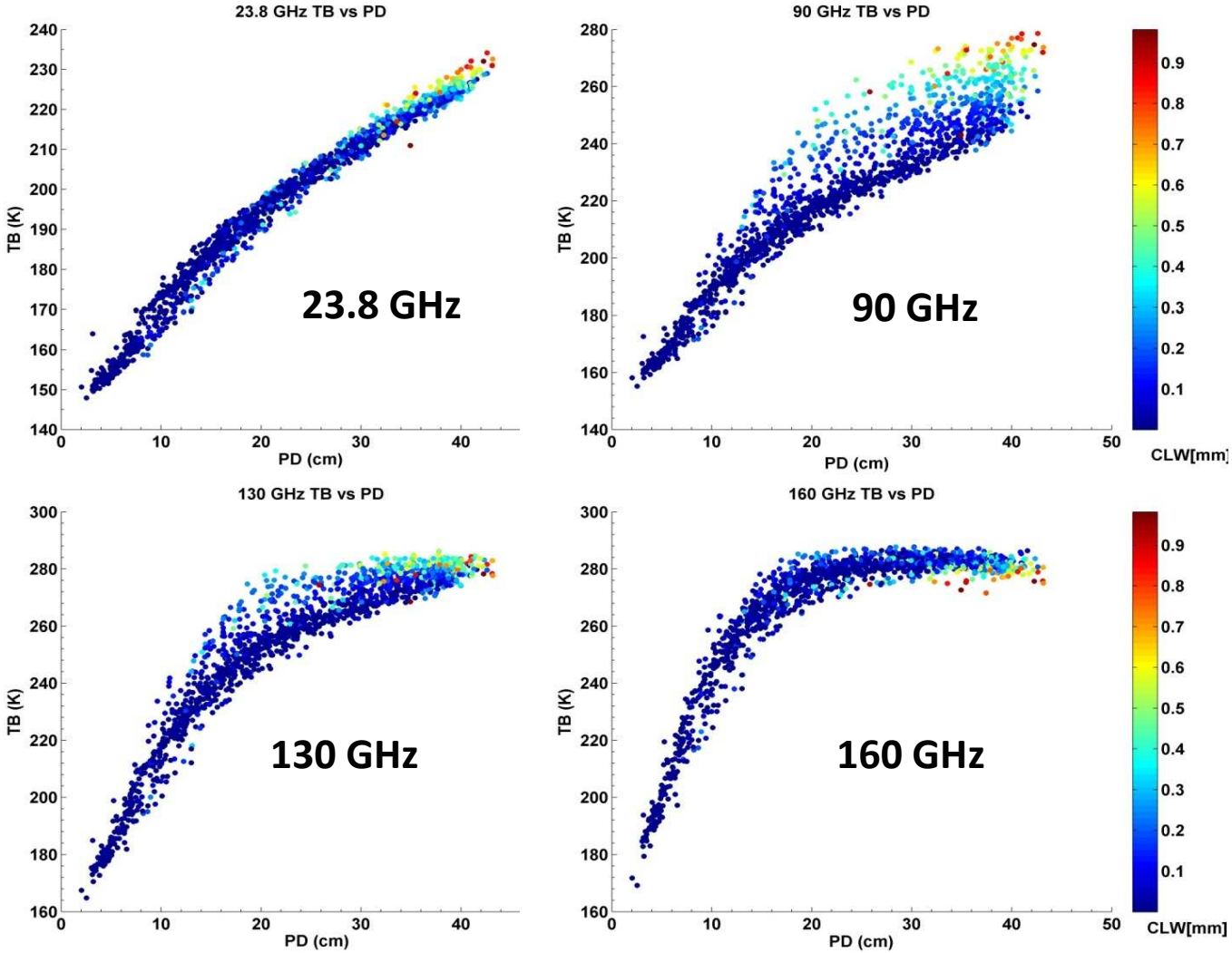


Coast Example (120km segments)



Window Channel Sensitivity to PD

Modeled Brightness Temperature to PD and CLW



- 90 GHz T_B ~8x more sensitive to CLW than 23.8 GHz T_B
- Sensitivity to high PD decreases with frequency