Potential for High Resolution Ocean and Inland Wet Path Delay Measurements using High Frequency Radiometers on Future Altimetry Missions

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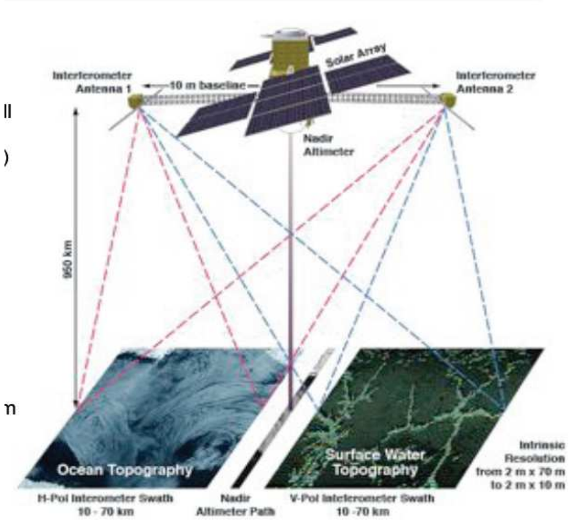
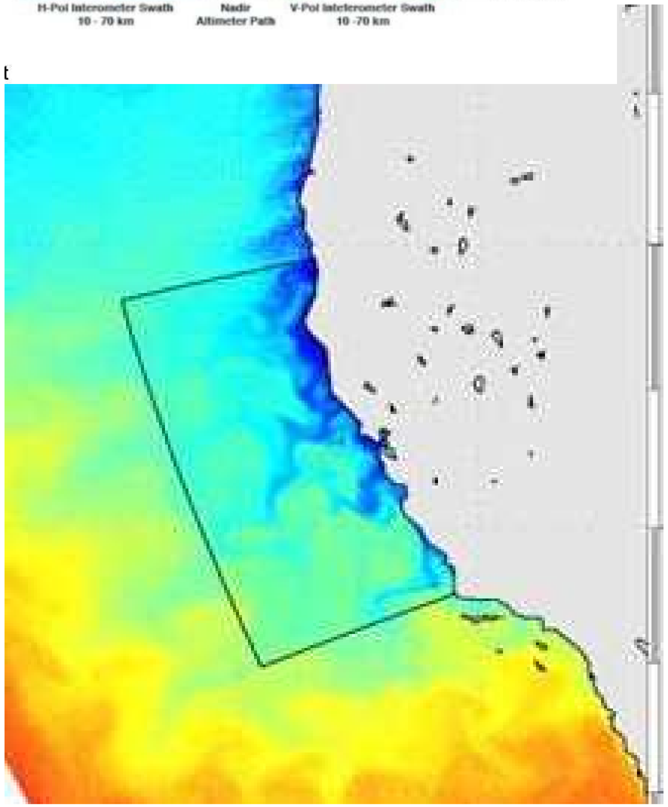
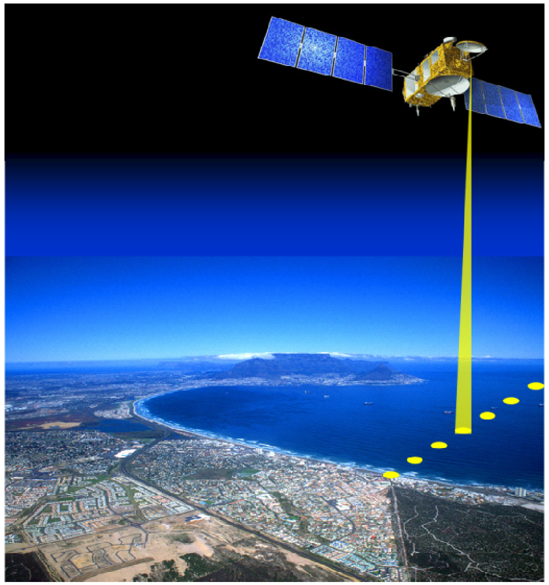
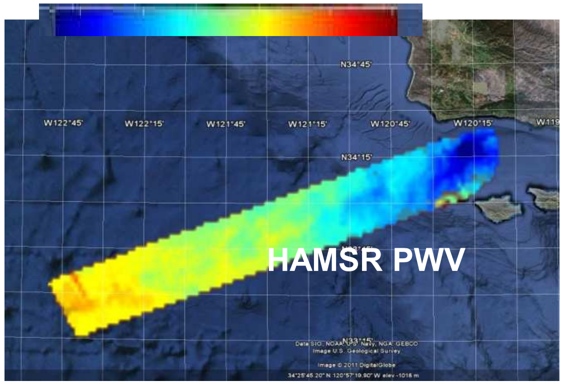
OSTST
October 28, 2014
Konstanz, Germany









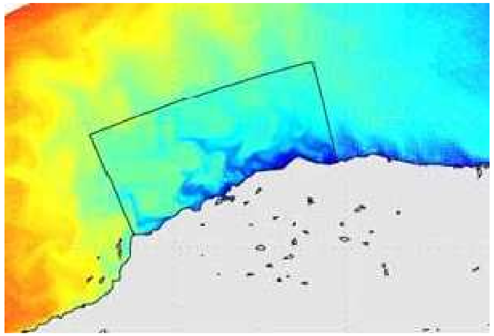
Introduction

- **The next generation of altimeter measurement systems is likely to feature high resolution altimetric observations from SAR and InSAR systems**

- **This enables new science applications in the coastal region, including estuaries and over inland water bodies such as lakes and rivers**
  - **e.g. coastal currents**

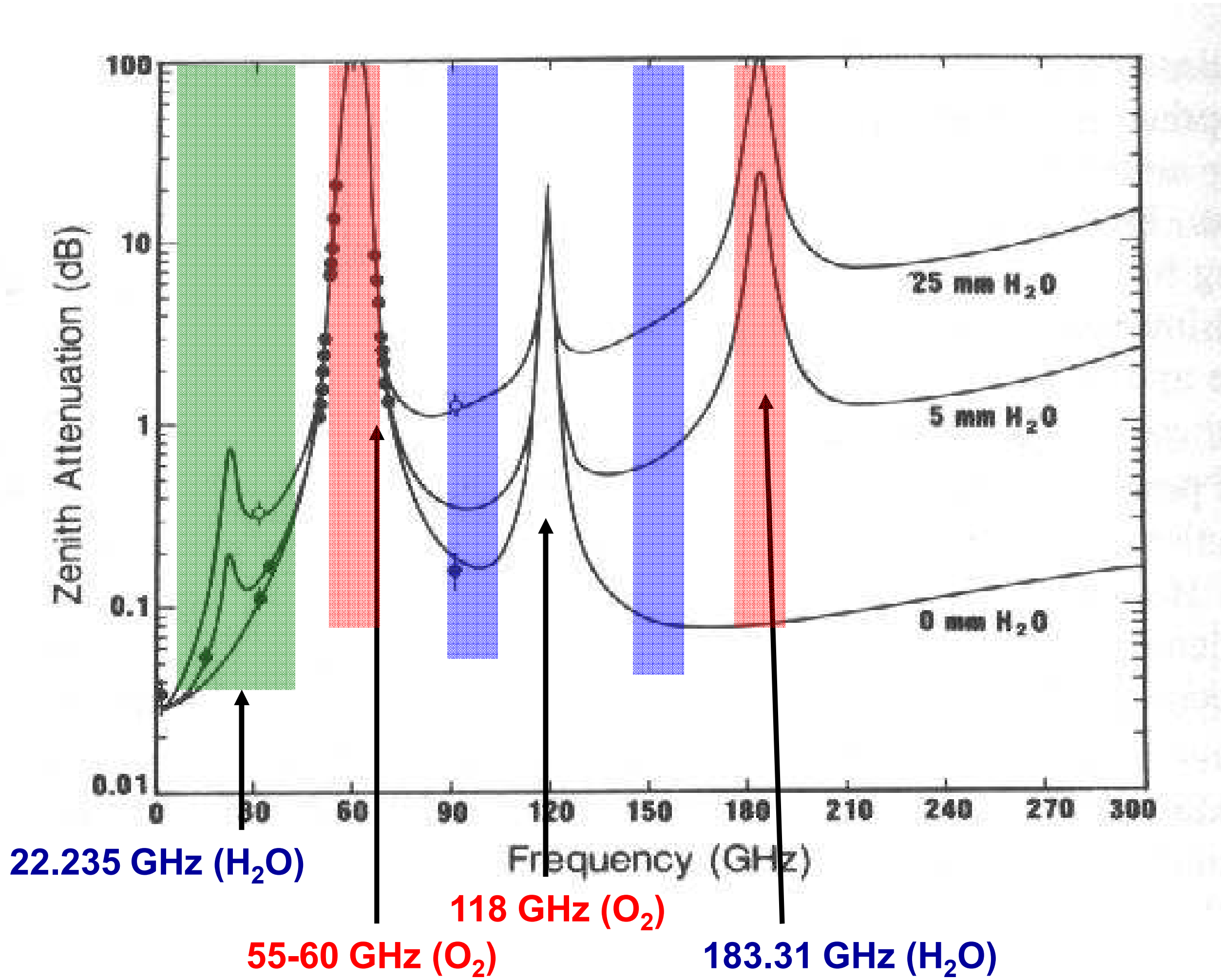
- **Heritage low-frequency radiometer systems are not able to provide valid wet tropospheric path delay correction do not provide valid retrievals close to the coast or over land**

- **High-frequency radiometers offer the potential to fill this measurement gap and improve altimetric observations in the coastal and inland regions**



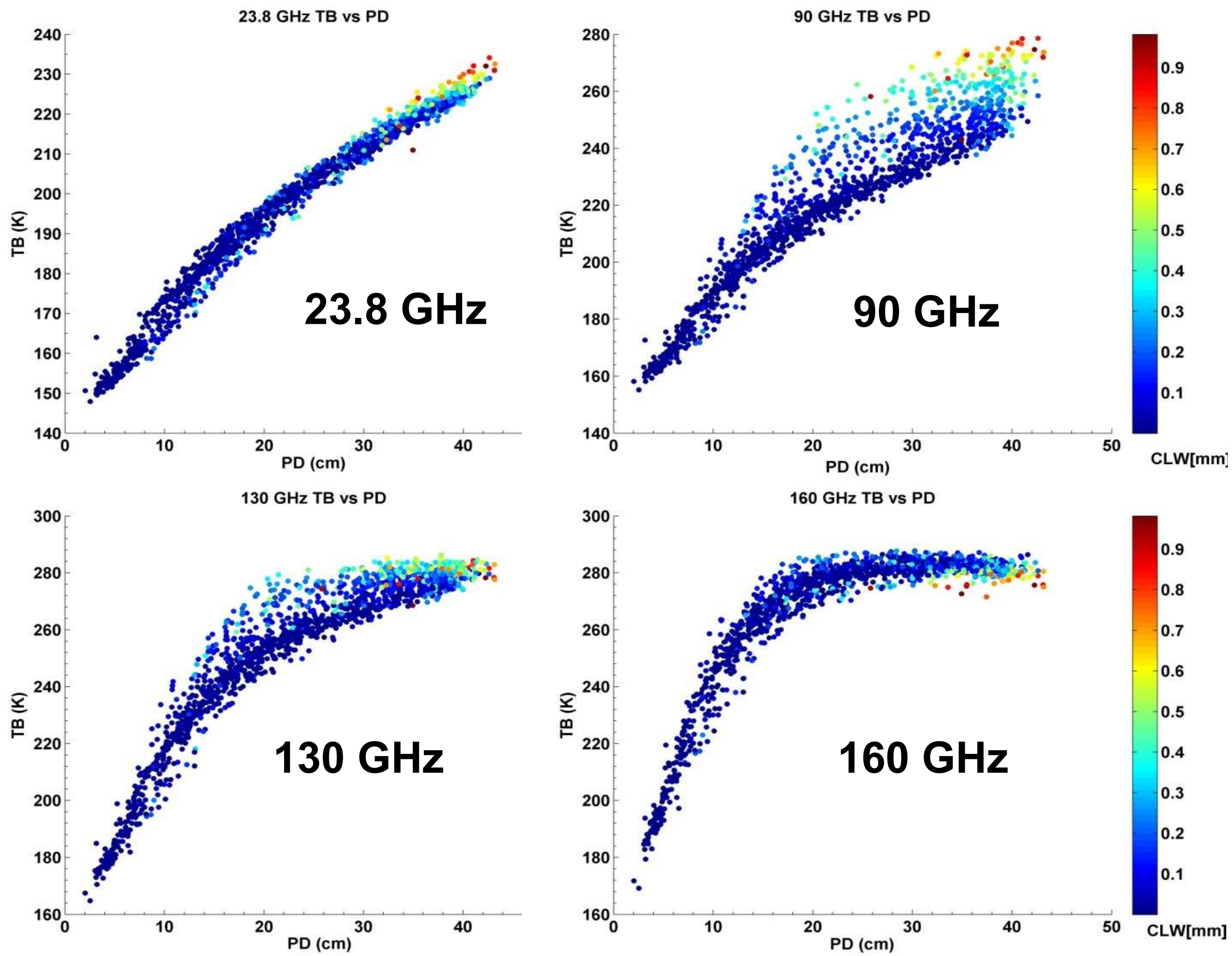
Move to Higher Frequency

- For a given antenna aperture, the spatial resolution scales with frequency
- Can supplement low-frequency, low-spatial resolution channels with high-frequency, high-spatial resolution channels to retrieve PD near coast
- High-frequency window channels sensitive to water vapor continuum
- 183 GHz channels sensitive to water vapor at different layers in atmosphere



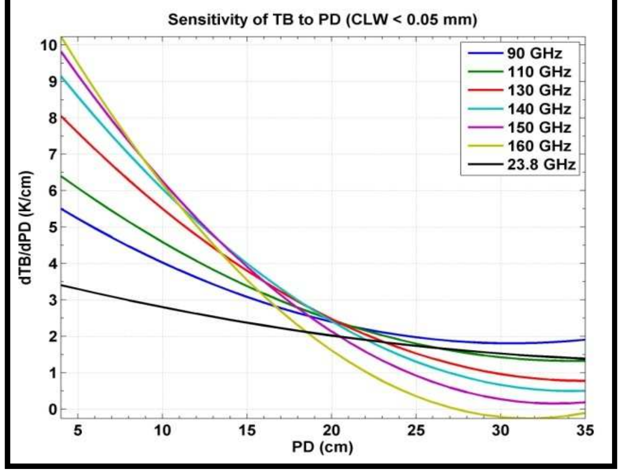
Window Channel Sensitivity to PD

Modeled Brightness Temperature to PD and CLW



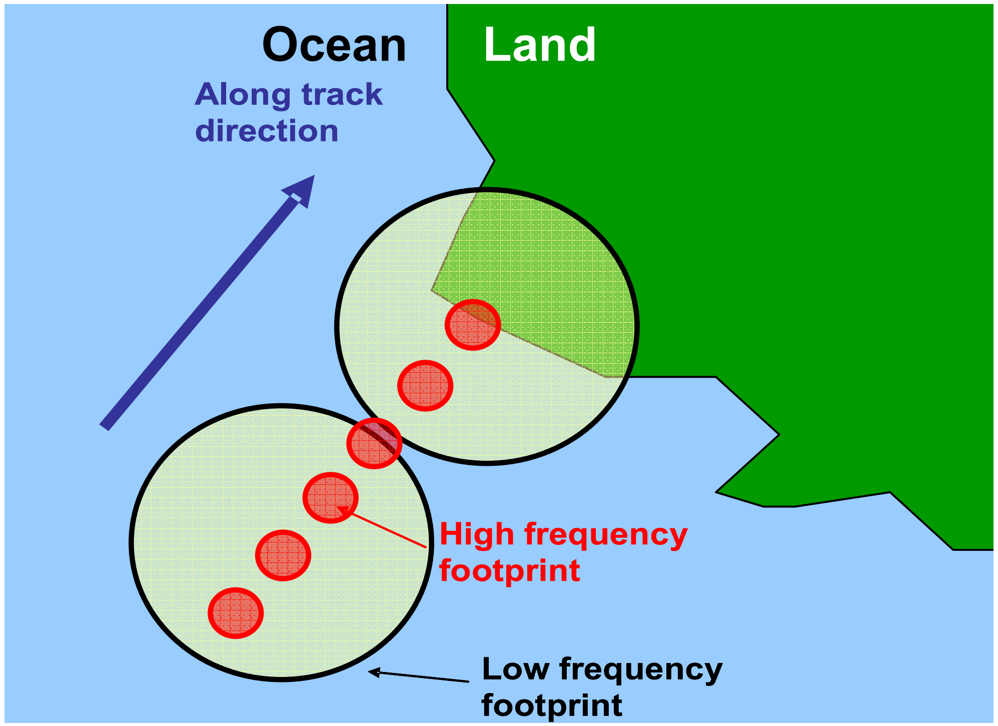
- 90 GHz T_B ~8x more sensitive to CLW than 23.8 GHz T_B
- Sensitivity to high PD decreases with frequency

dT_B/dPD



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



- 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

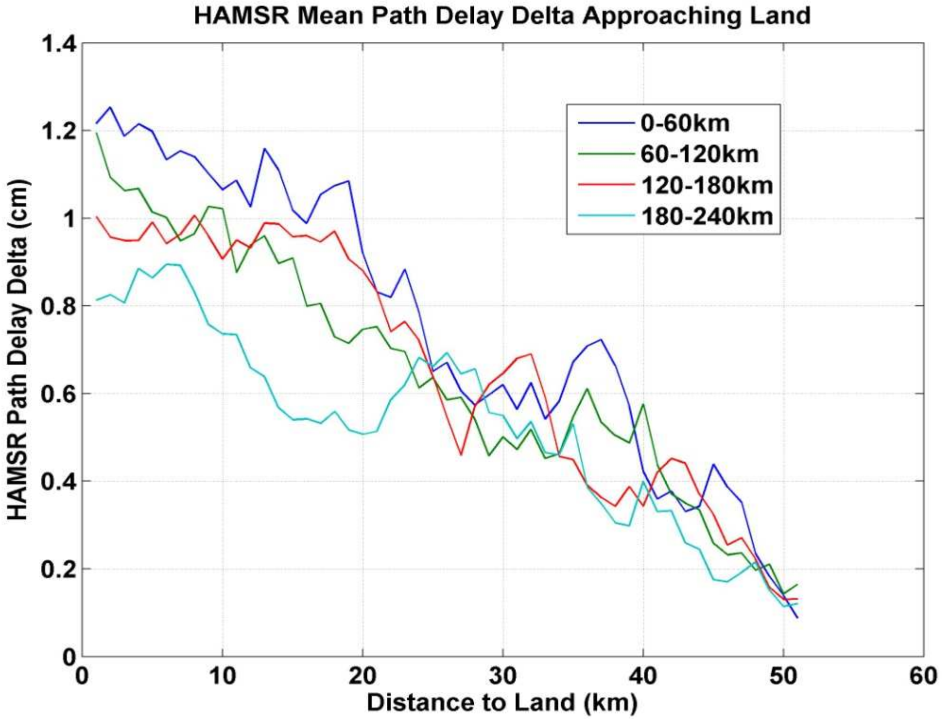
$$PD_{HF} = c_o + \sum_{i=1}^{N_f} c_i T_{Bi}$$

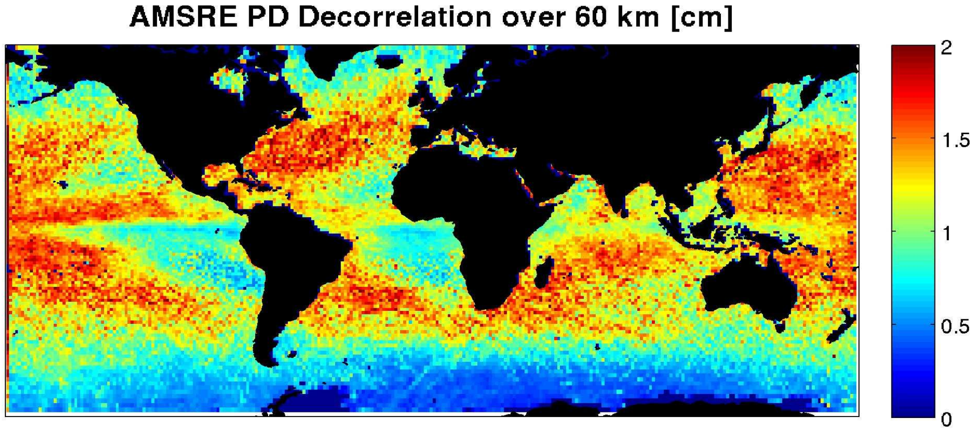
where

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

Coastal Path Delay Variability

- Over-ocean, PD de-correlates by up to 2cm over distances of 60km
- Q: How does the variability over the 50 km nearest to land compare with the open ocean?
- HAMSR data suggest higher variability near land (~60% increase in variance)
- Consistent with analysis using WRF PD fields which showed slight enhancement in variability near land
- Certain areas expected to have systematic errors (diurnal, seasonal)

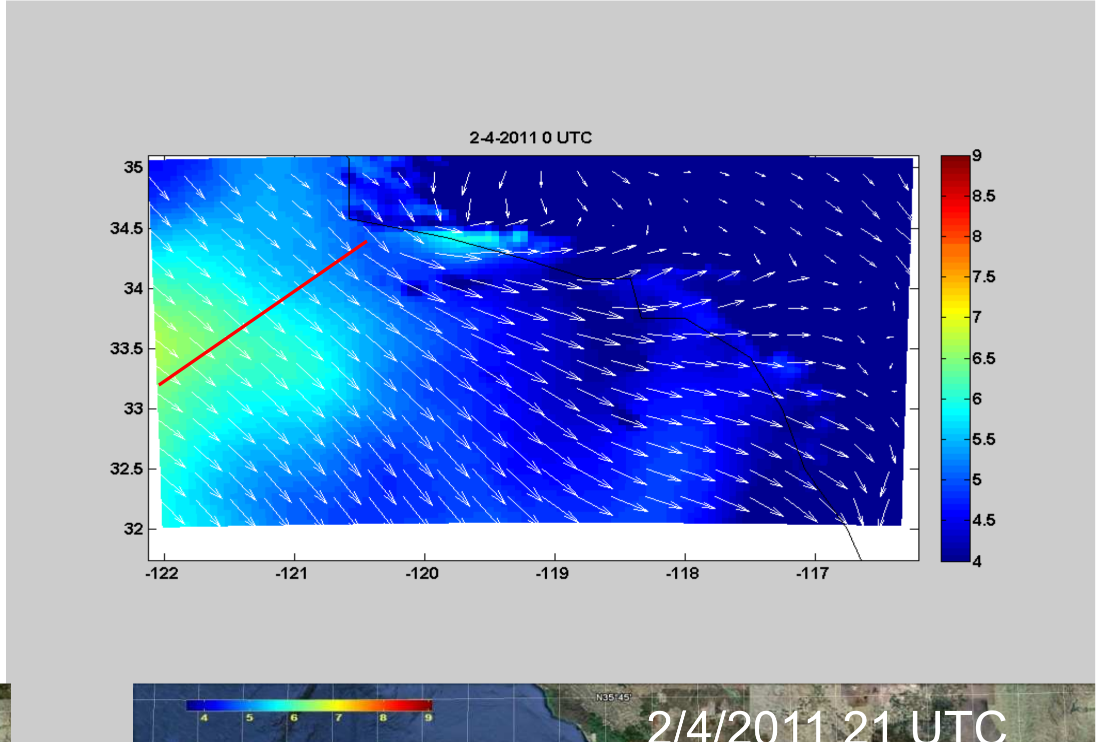


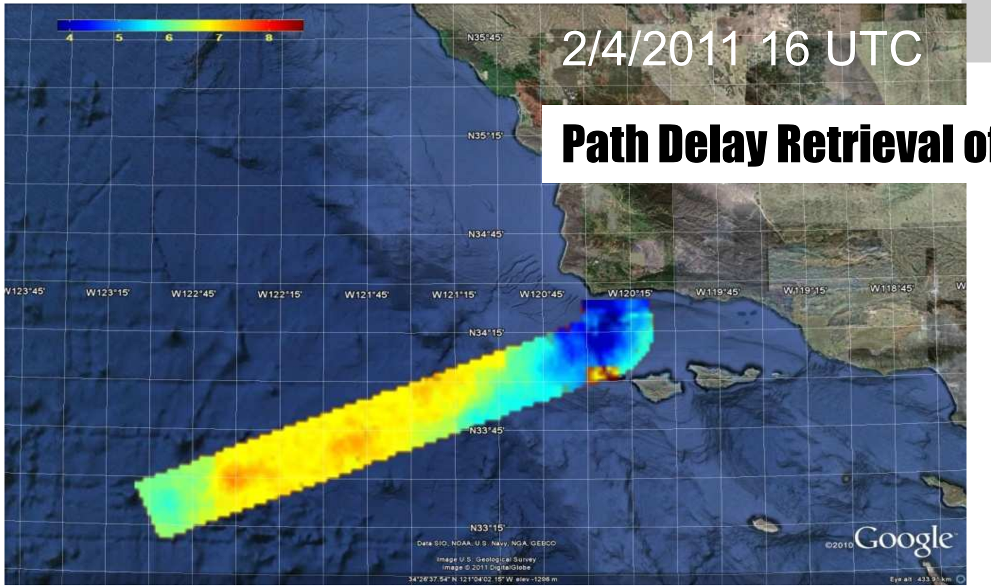


De-correlation error from missing measurements within ~50km from land

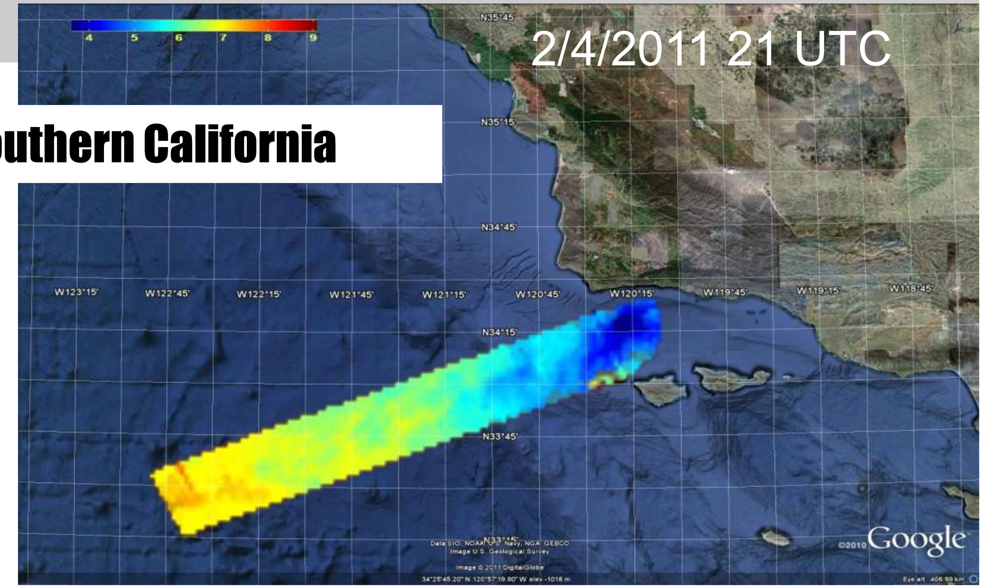
Example: Off-shore Winds

- Certain areas can result in large systematic biases
- Example of Santa Ana winds off California coast
  - ~3-4 cm bias at the coast



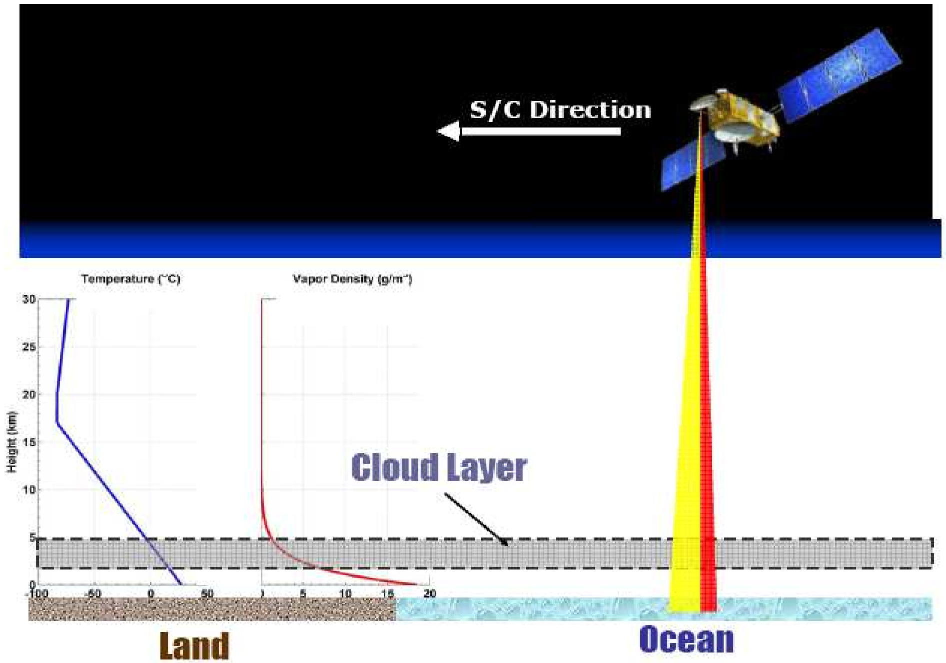


Path Delay Retrieval off Southern California



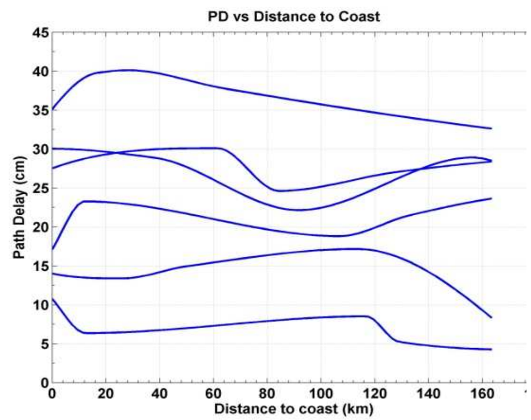
Simulations

- Simulated coastal crossing for AMR-HF concept to assess performance
  - Channels at 18.7, 23.8, 34.0, 92.0, 130.0, 166.0 GHz
  - Antenna patterns generated using AMR 1m reflector
- Generated random profiles of path delay and cloud liquid water content as a function of distance to coast
  - Varied both the total vapor content and vertical distribution
  - Varied SST based on joint probability of SST and PD
  - Varied surface wind speed



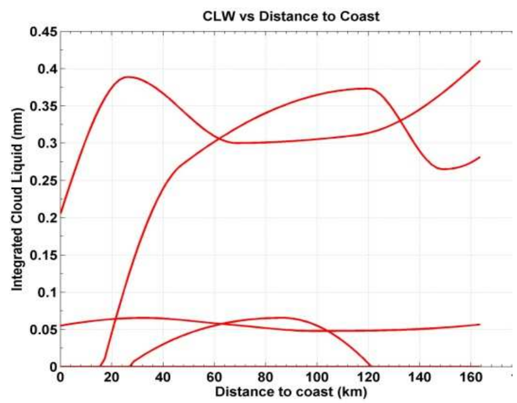
Example of PD and CLW profiles

PD

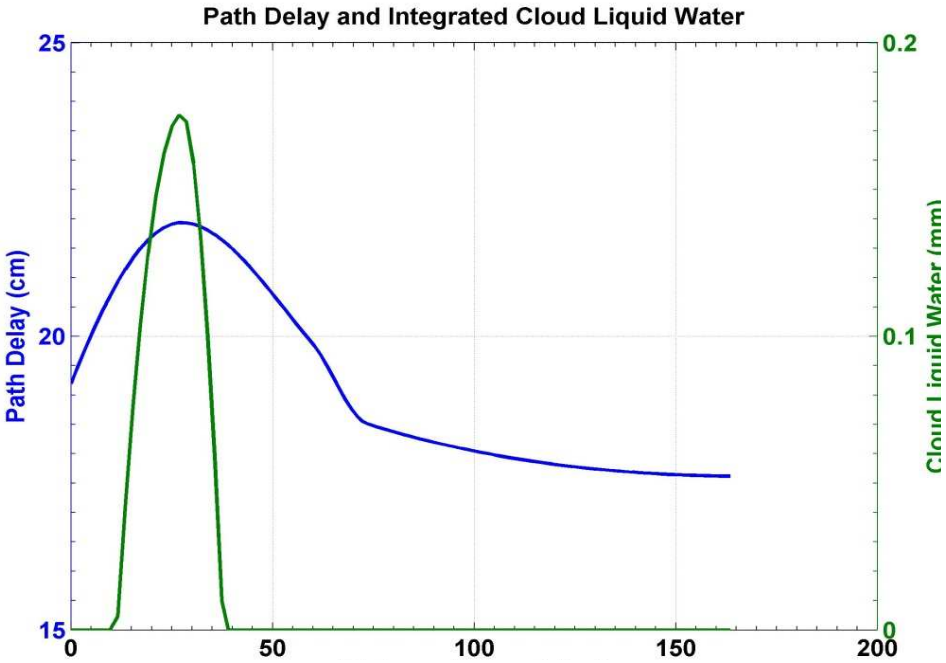


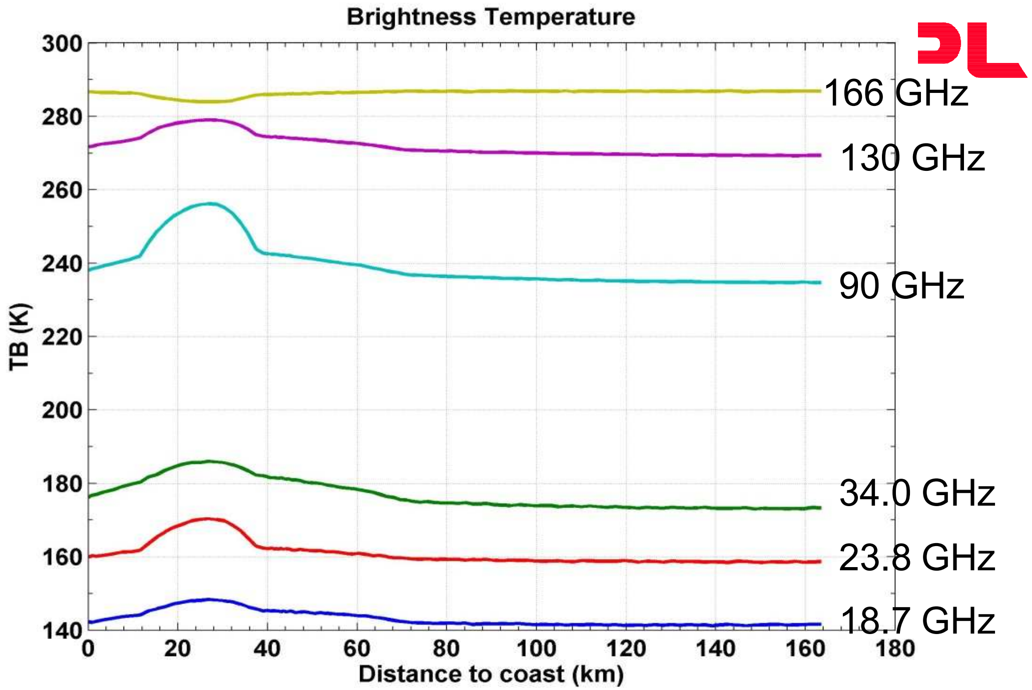
Distance to coast (km)

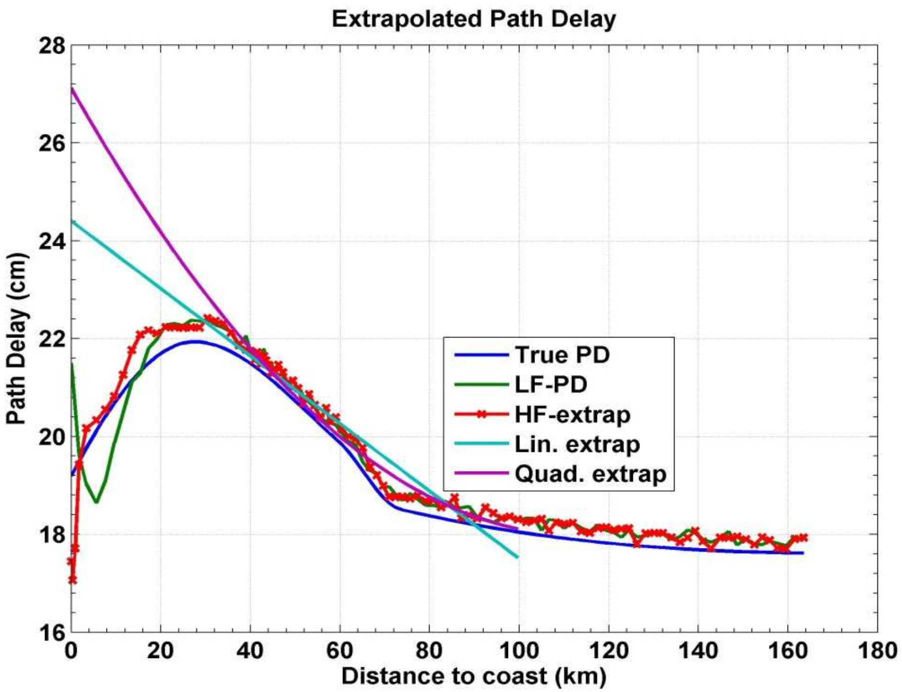
CLW

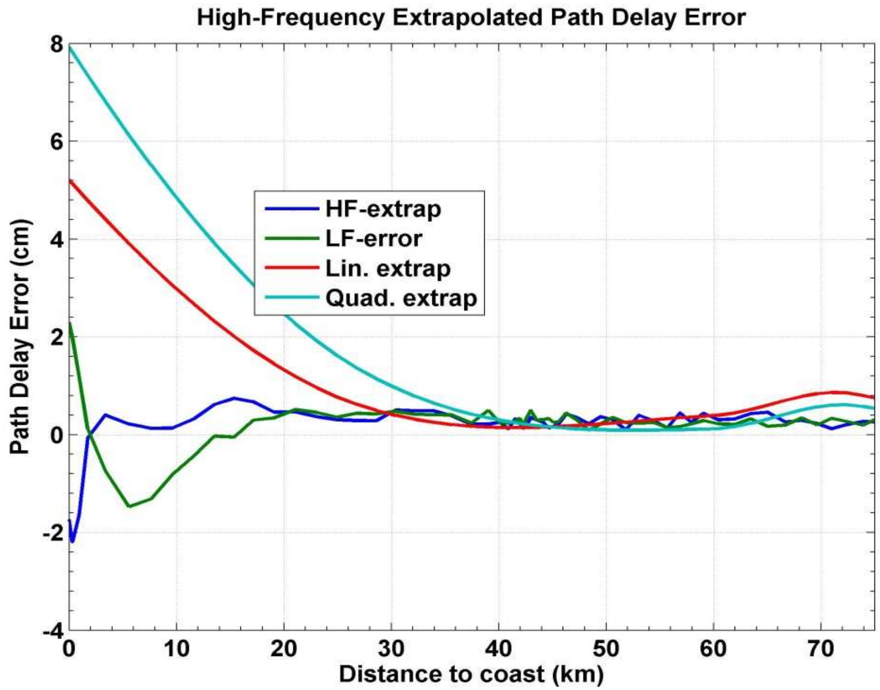


Distance to coast (km)


Path Delay and Integrated Cloud Liquid Water
Path Delay (cm)
Cloud Liquid Water (mm)
25
20
15
0.2
0.1
0
0
50
100
150
200

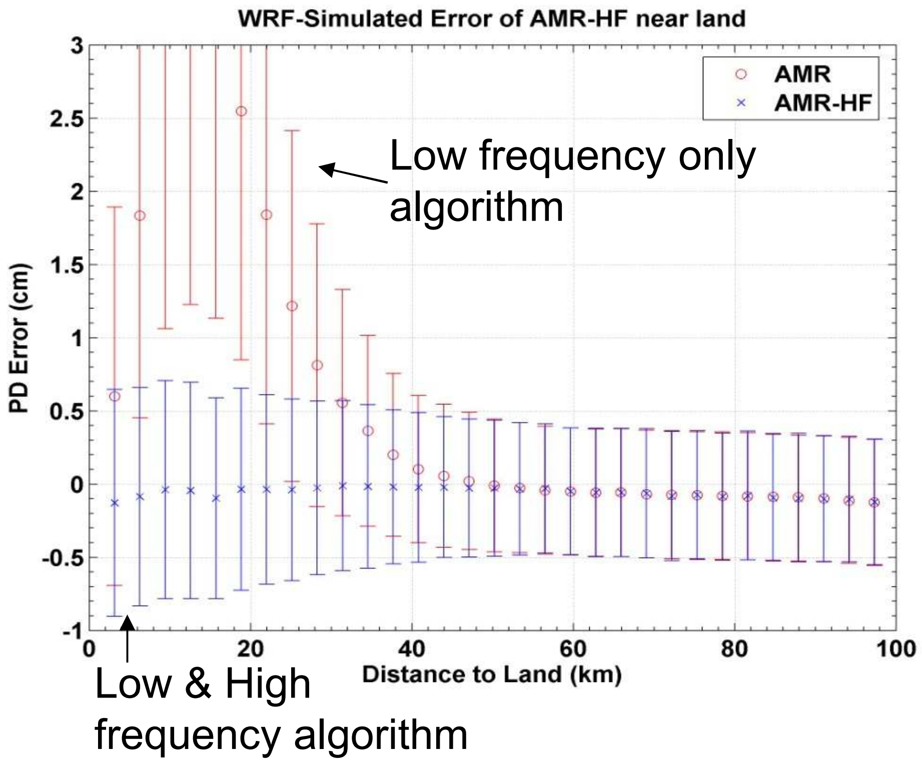

Brightness Temperature
TB (K)
300
280
260
240
220
200
180
160
140
166 GHz
130 GHz
90 GHz
34.0 GHz
23.8 GHz
18.7 GHz
0
20
40
60
80
100
120
140
160
180
Distance to coast (km)

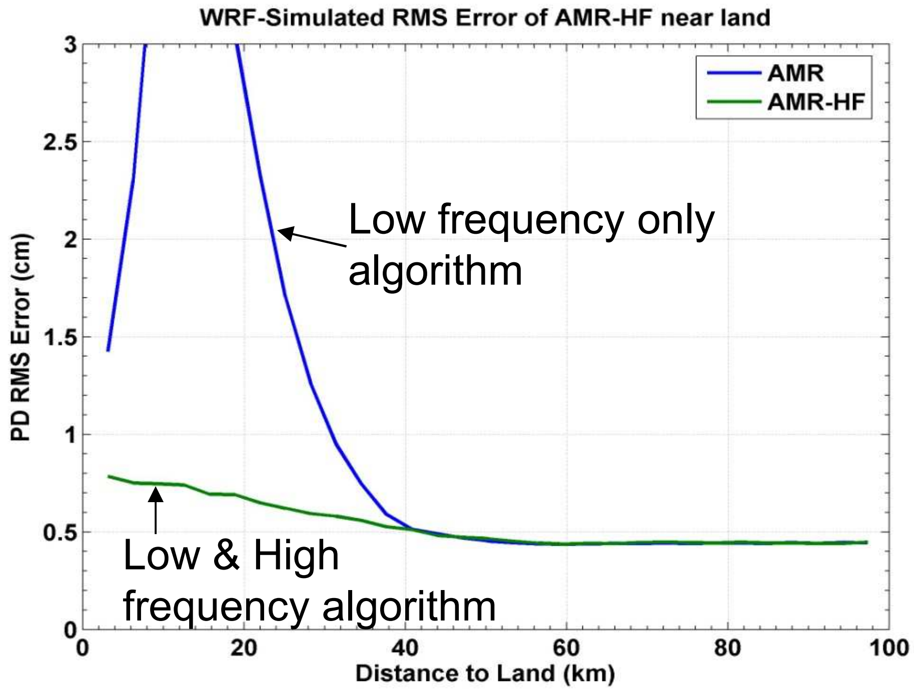

Extrapolated Path Delay
Path Delay (cm)
28
26
24
22
20
18
16
True PD
LF-PD
HF-extrap
Lin. extrap
Quad. extrap
0
20
40
60
80
100
120
140
160
180
Distance to coast (km)


High-Frequency Extrapolated Path Delay Error
Path Delay Error (cm)
8
6
4
2
0
-2
-4
HF-extrap
LF-error
Lin. extrap
Quad. extrap
0
10
20
30
40
50
60
70
Distance to coast (km)

High-frequency Coastal Performance

- **Simulations show PD retrieval error < 7mm to within 3 km from coast in a global average sense**

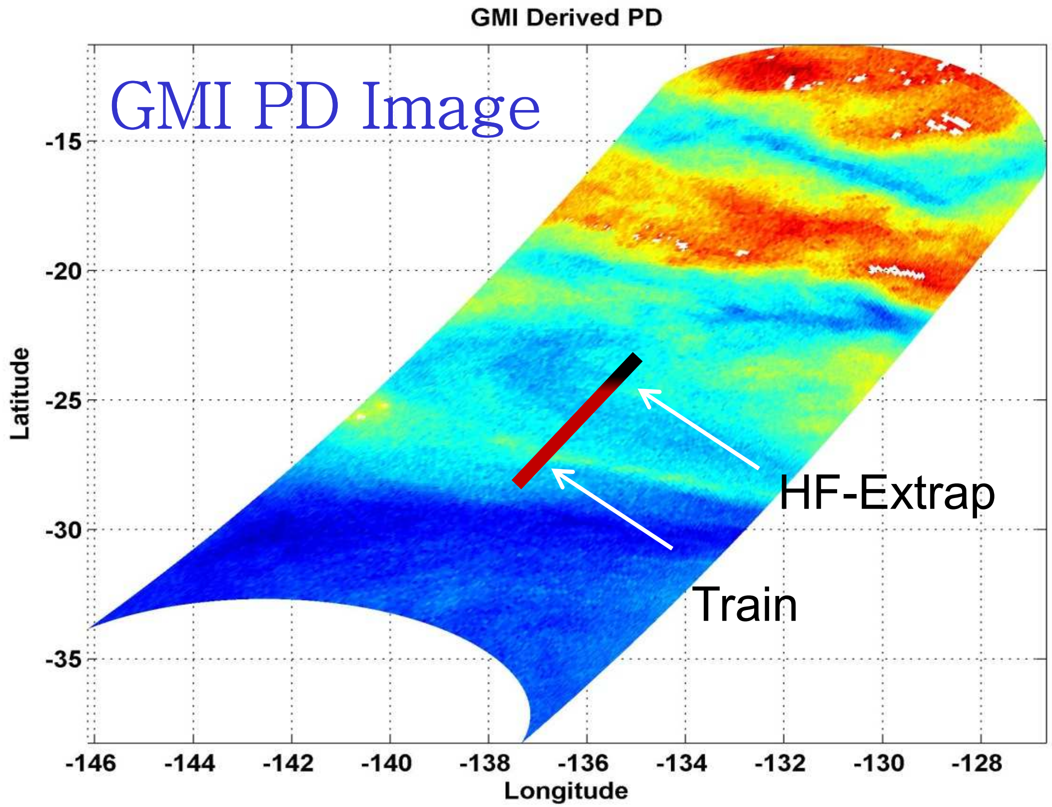




Testing Algorithm with Satellite Data

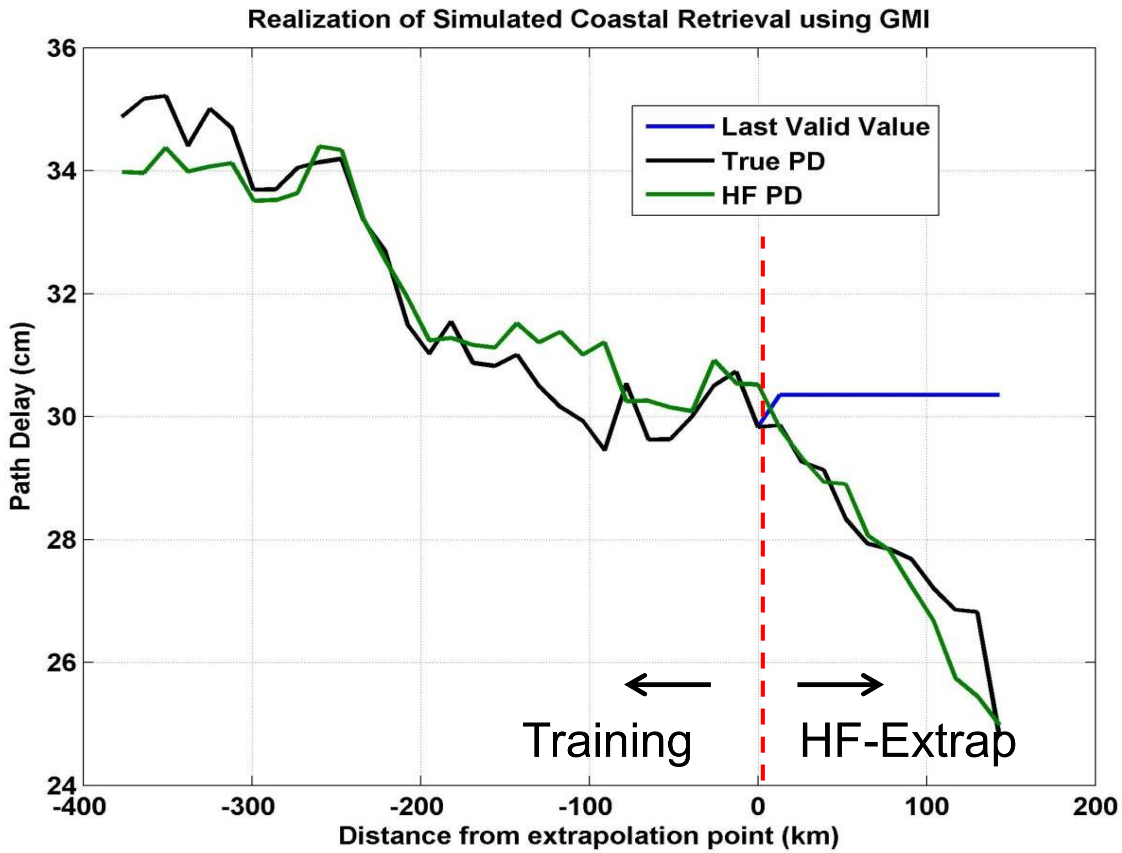
- The Global Precipitation Measurement Microwave Imager (GMI) has 18.7-37 GHz channels and also a high resolution 90 GHz channel
- GMI data used to evaluate algorithm performance in real atmospheres
- Path delay computed from GMI low-frequency (18-37 GHz) channels
- High-frequency (HF) coastal extrapolation algorithm applied to 90 GHz channel

- 500 km segments extracted and used to evaluate algorithm
  - 400 km used to dynamically train HF algorithm
  - HF algorithm then applied to last 100 km and compared to low-frequency PD
  - Data filtered for highly variable clouds since only a single high frequency channel was used



Example Realization

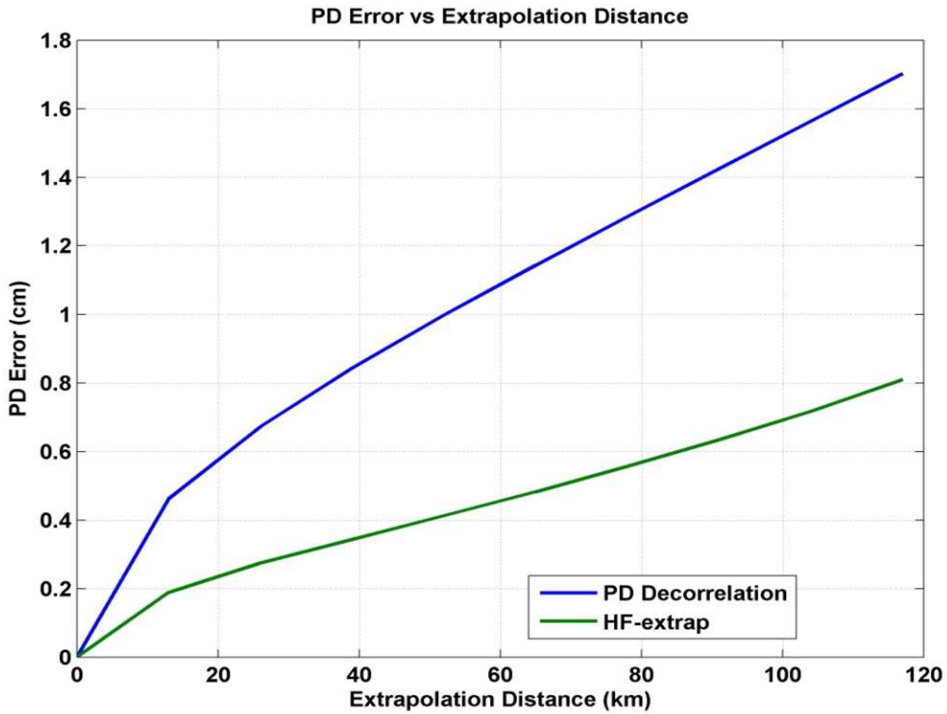
- HF Extrapolation algorithm, using GMI 90 GHz channel, compared to using last valid PD value to the coast



Low-frequency PD
High Frequency PD fit
Extrapolate Last valid value

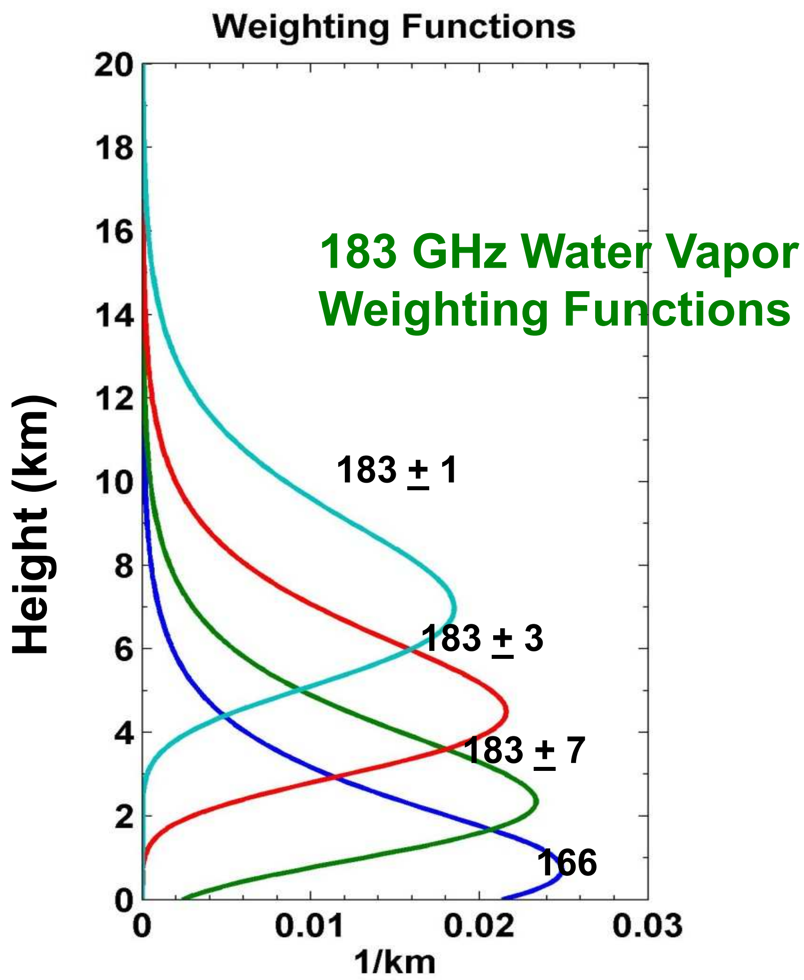
HF Algorithm Performance using GMI

- **Computed statistics for a large number of realizations, encompassing various atmospheric conditions**
- **HF algorithm shows significant reduction in PD variance (e.g. assuming constant PD value to the coast)**
- **Assuming a low-frequency radiometer that is contaminated at 50km from the coast, the HF algorithm reduces the excess extrapolation error from 10mm to 4mm**
  - Validates simulation results



Over Land Retrievals

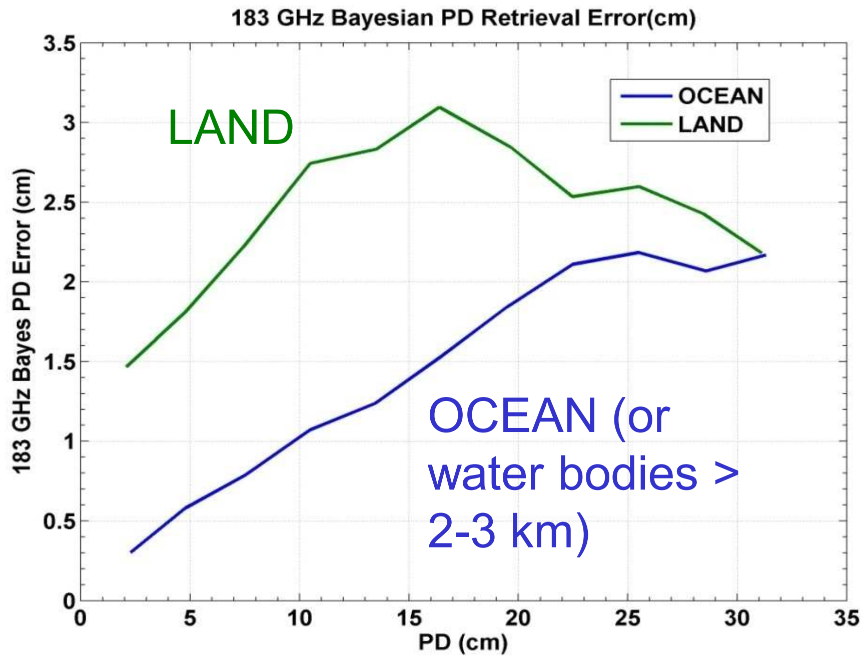
- Overland, emissivity is highly variable and close to 1, reducing the contrast between the land and atmosphere
- Near 183 GHz line center, the surface becomes obscured
- 183 GHz channels used routinely for retrieval vertical moisture profile from AMSU data
- > four 183 GHz channels permit retrievals over land



183 GHz Overland Retrievals

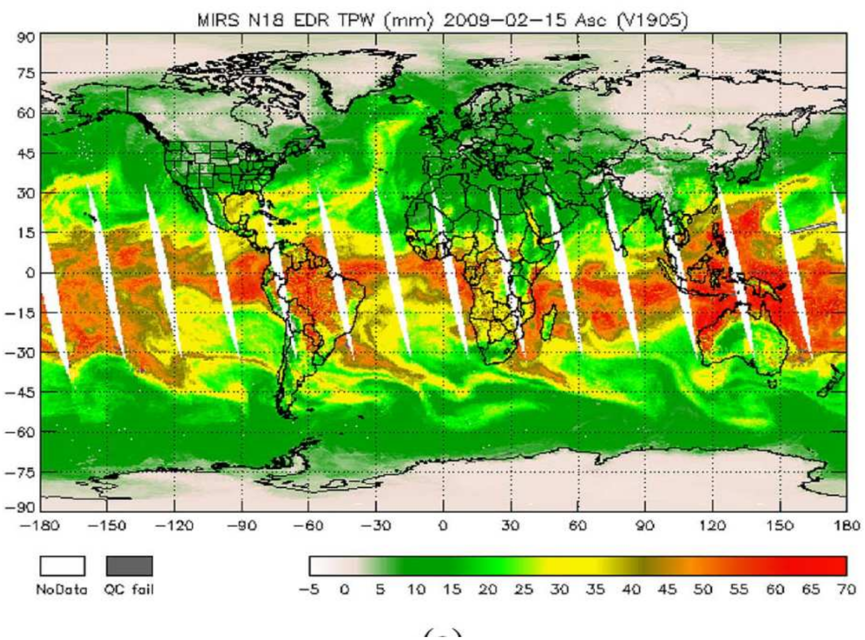
- **Performance of 183 GHz sounding radiometer for over land retrievals assessed via simulation**
- **Used NCEP model fields to generate simulated global 183 GHz TBs**
  - **Evaluated Bayesian retrieval algorithm over land and over ocean**
  - **Errors binned as a function of path delay**

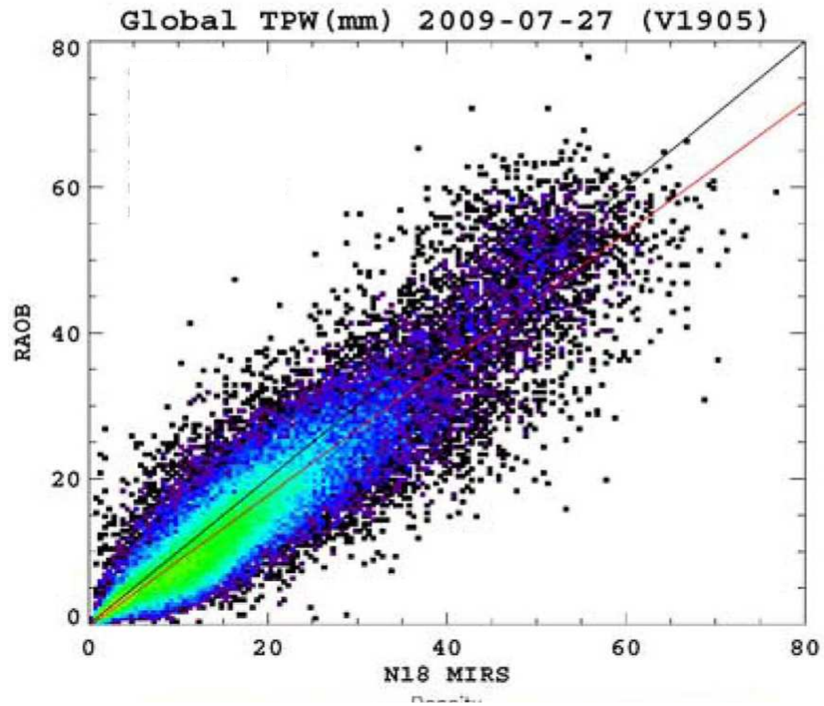
- **RMS errors over land ~3 cm**
  - **Current SWOT requirements assume 10cm error budget over land**
  - **4cm component for wet PD**
- **RMS errors over ocean or large water bodies vary from 0.5 cm at low PDs to 2 cm at high PDs**
  - **Performance can likely be improved using model assimilation**



1-D Var Overland Retrieval

- **MIRS system uses 1-D variational approach to estimate PD from 183 GHz sounding channels over land (Boukabara et al, 2010)**
- **Estimates compared to radiosondes show ~3cm PD error, similar to simulated Bayesian algorithm performance**

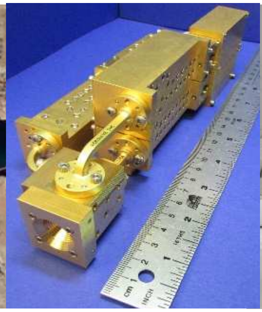


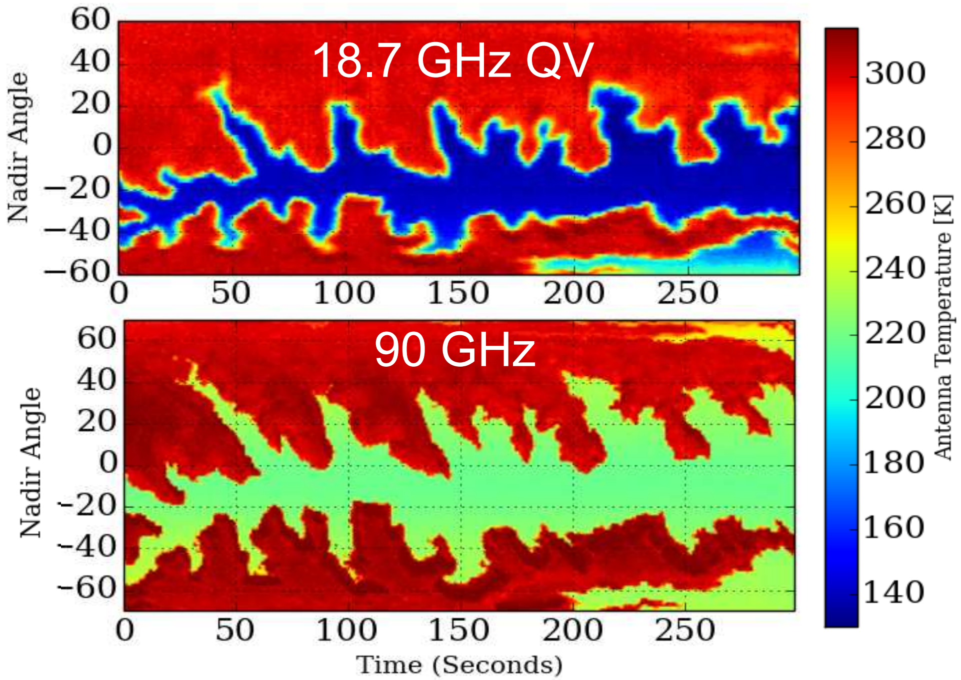


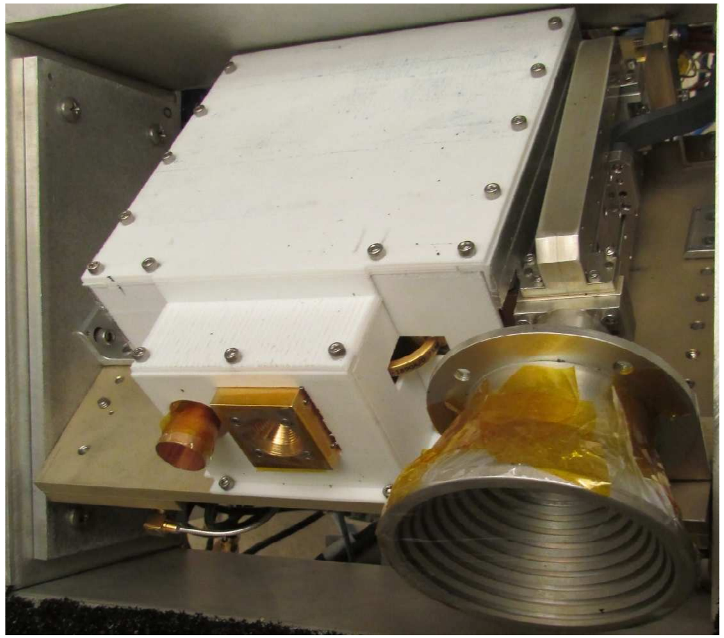
Boukabara et al, 2010

High-frequency Radiometer Airborne Instrument

- CSU/JPL are currently flying airborne high frequency altimeter radiometer system (HAMMR)
  - Includes AMR + high frequency wind and sounding channels
- Just completed engineering flights and science flights are planned in early November







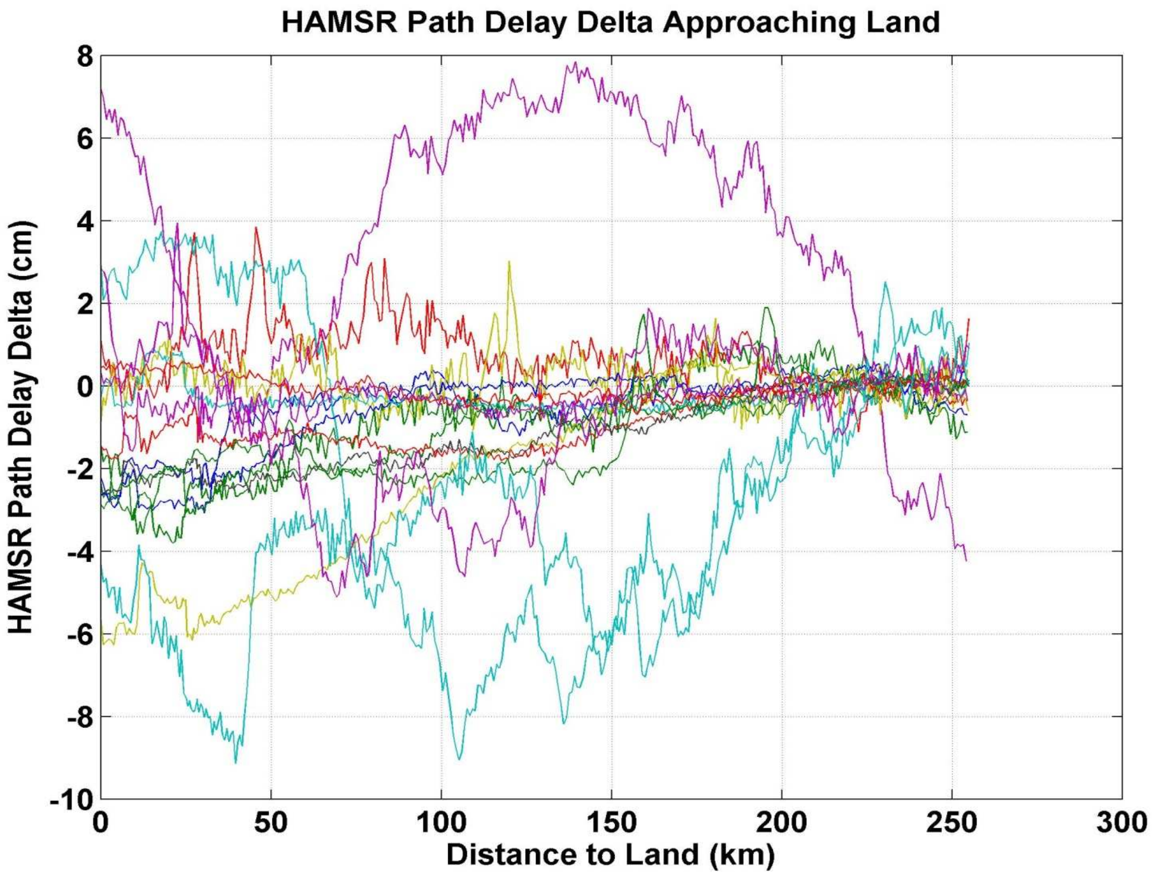
Summary

- High frequency radiometer channels should be integrated into future high resolution altimetry missions for improving observations in the coastal regions and potentially improving observations over land
- Missions such as Jason-CS and SWOT will benefit from these systems
- It is demonstrated that these channels can be used to keep the PD errors below 8mm up to the coastline
- Overland, 183 GHz sounding channels can be used along with model data to reach 2-3 cm level accuracy
- Flights are planned for early November with an airborne low and high-frequency radiometer system to demonstrate coastal and over-land performance

Backup

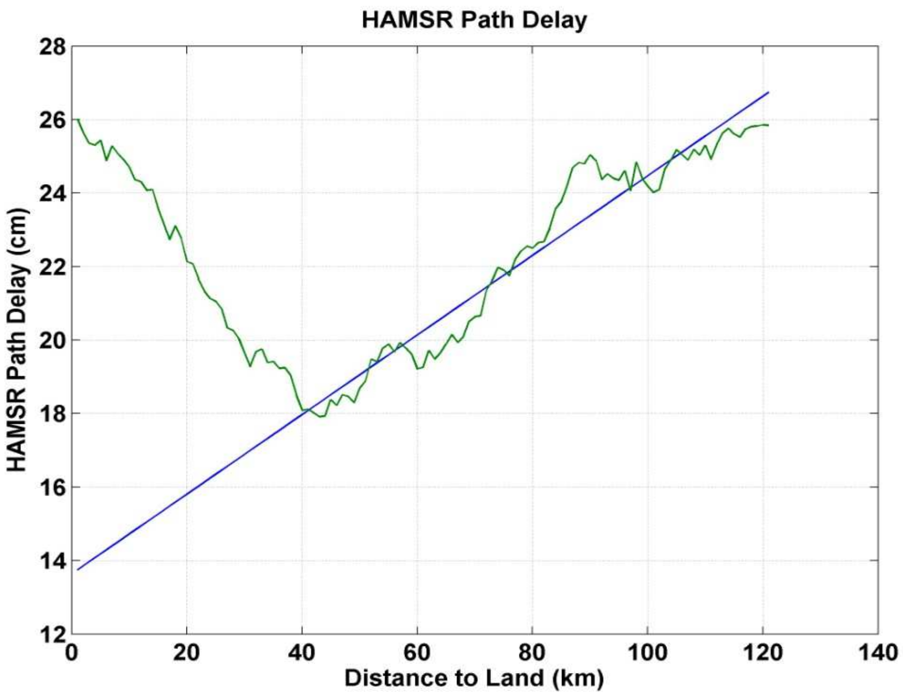
Coastal Path Delay from HAMSR

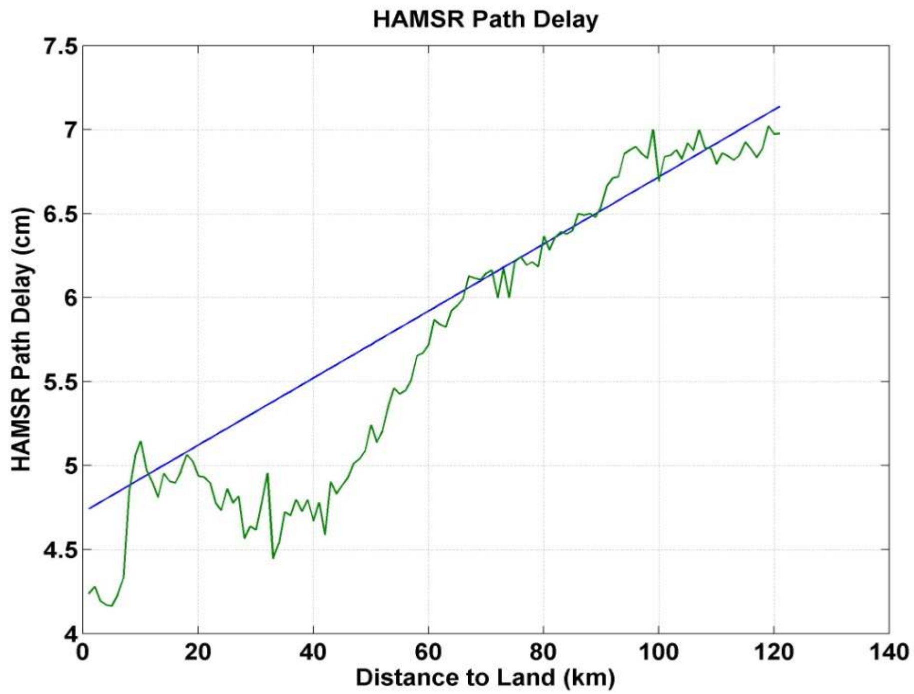
- Analyzed 17 coastal crossings over the broad range of PDs from the HAMSR airborne radiometer
  - Coastal crossings include southern California, Texas, Florida and Alaska
- Differenced each coastal approach from mean PD value between 200-250 km from land
- Large variations observed (up to 9cm), but over all distances and not just near land



Extrapolating to Land

- An approach commonly used is extrapolating the last valid ocean data to the coast
- HAMSR data used to assess errors in this approach





Extrapolation Errors

- Extrapolating did not offer improvement and in some cases increased the errors dramatically
- Only a small number of cases analyzed, but using last valid ocean value appears to be as good as or better than extrapolating from open ocean data