Progress in the Wet Tropospheric Correction for Altimetry: Jason-3 to Sentinel-6 and Beyond

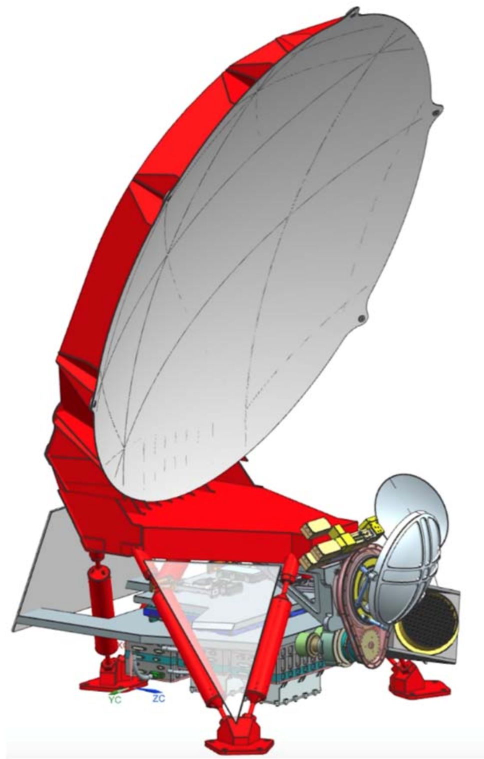
Shannon Brown and Tanvir Islam
Jet Propulsion Laboratory, California Institute of Technology

Topex

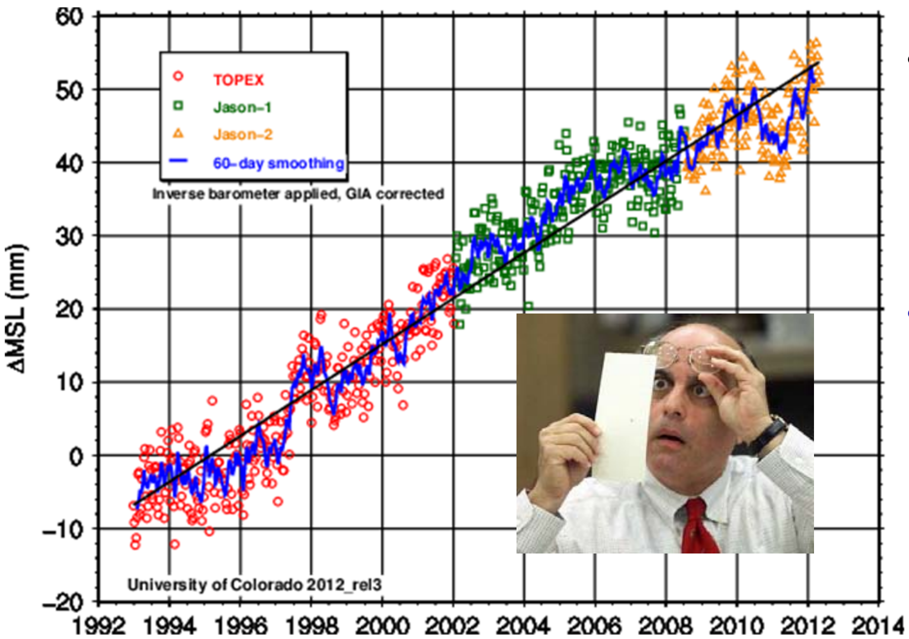
Jason-1

Jason-2/3

Jason-CS



1992 → 2018



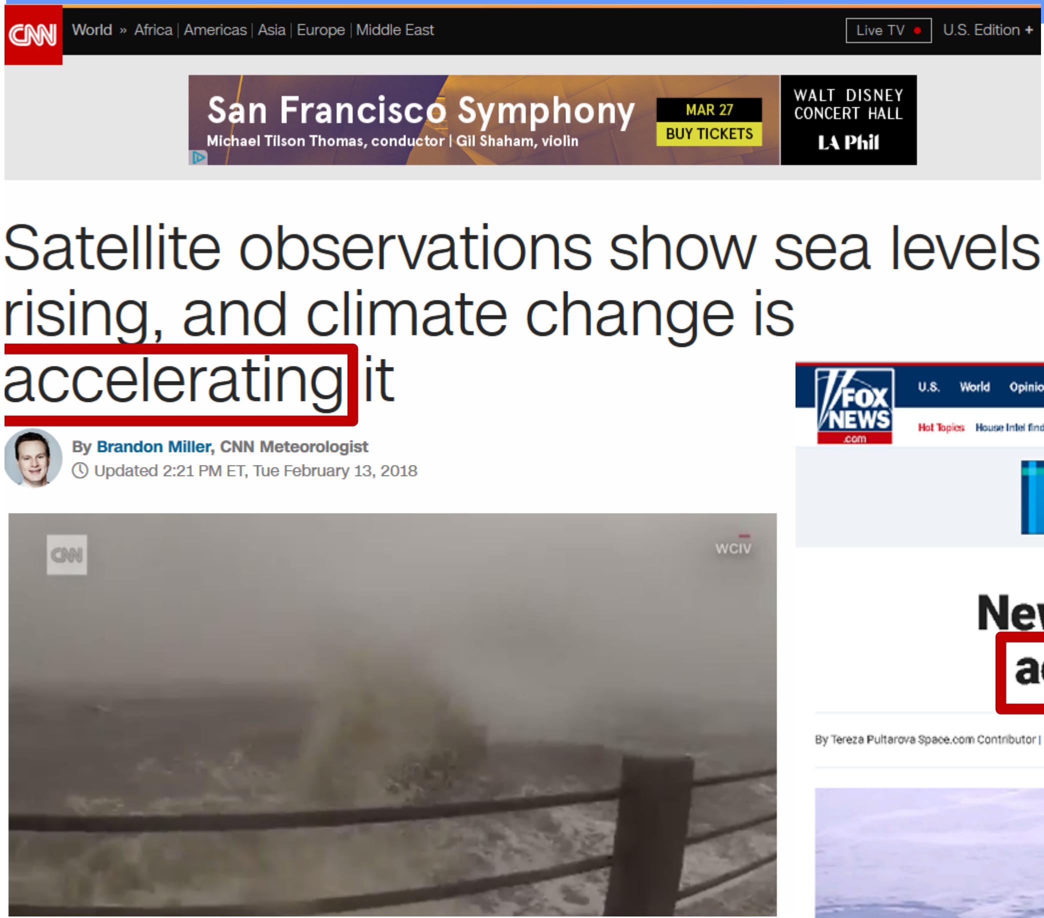
- **Measurement of global mean sea level rise not possible without extremely well calibrated measurement system**

- **Radiometer wet path delay correction generally considered largest source of uncertainty in long term GMSL trend estimate**
  - **Requires careful monitoring and application of periodic post-launch corrections**
  - **Corrections of up to 30x GMSL trend have been applied to radiometer wet PD record**

Table 2. MSL trend uncertainties from 1993 to 2008 for each correction or model impacting the MSL calculation.

Source of error for the MSL calculation		MSL trend uncertainties from 1993 to 2008	
		Minima	Maxima
Orbit:Cnes POE (GDR B) for Jason-1 and GSFC (ITRF2000) for T/P.		0.10 mm/yr	0.15 mm/yr
Radiometer Wet troposphere correction: JMR and TMR (with drift correction).		0.20 mm/yr	0.30 mm/yr
Dynamical atmospheric and dry troposphere corrections using ECMWF pressure fields.		0.05 mm/yr	0.10 mm/yr
Sigma0 drift impacting altimeter wind speed and sea state bias correction		0.05 mm/yr	0.10 mm/yr
Bias uncertainty to link TOPEX A and TOPEX B, and TOPEX and Jason-1.		0.10 mm/yr	0.25 mm/yr
Total error budget	absolute sum	0.50 mm/yr	0.90 mm/yr
	quadratic sum	0.32 mm/yr	0.44 mm/yr
	inverse formalism	0.6 mm/yr in a confidence interval of 90%	

Ablain et al., 2009

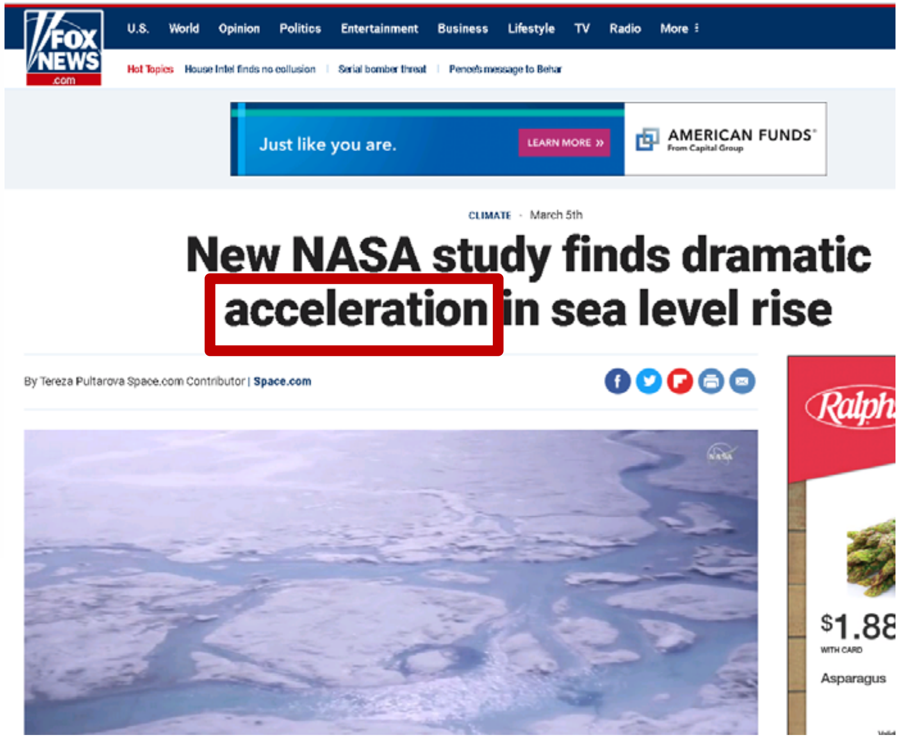

World » Africa | Americas | Asia | Europe | Middle East Live TV U.S. Edition +

Satellite observations show sea levels rising, and climate change is accelerating it

By Brandon Miller, CNN Meteorologist
Updated 2:21 PM ET, Tue February 13, 2018

When the first derivative is no longer enough…..

Nerem et al., PNAS, 2018


U.S. World Opinion Politics Entertainment Business Lifestyle TV Radio More

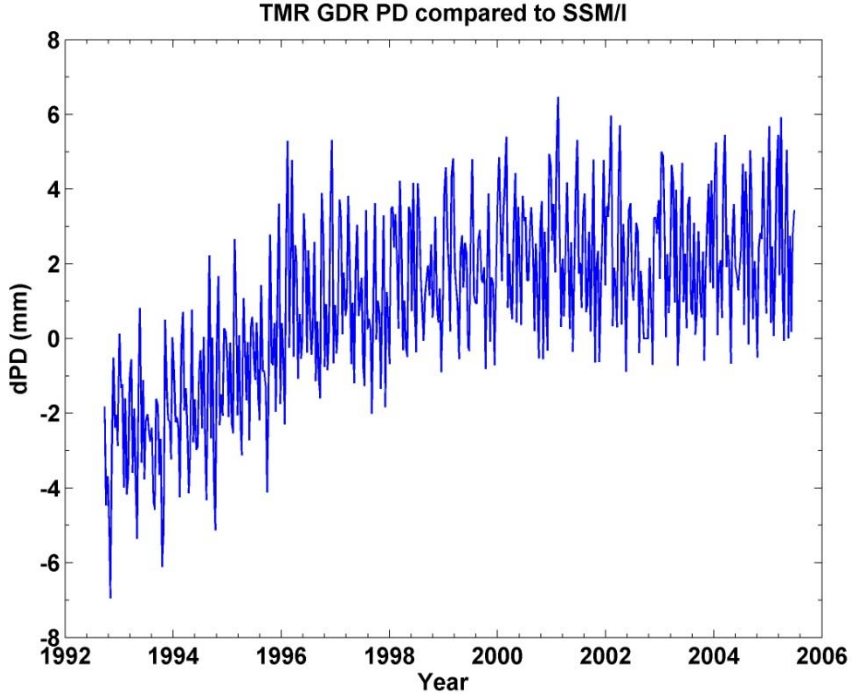
Hot Topics House Intel finds no collusion | Serial bomber threat | Pence's message to Bebar

CLIMATE · March 5th

New NASA study finds dramatic acceleration in sea level rise

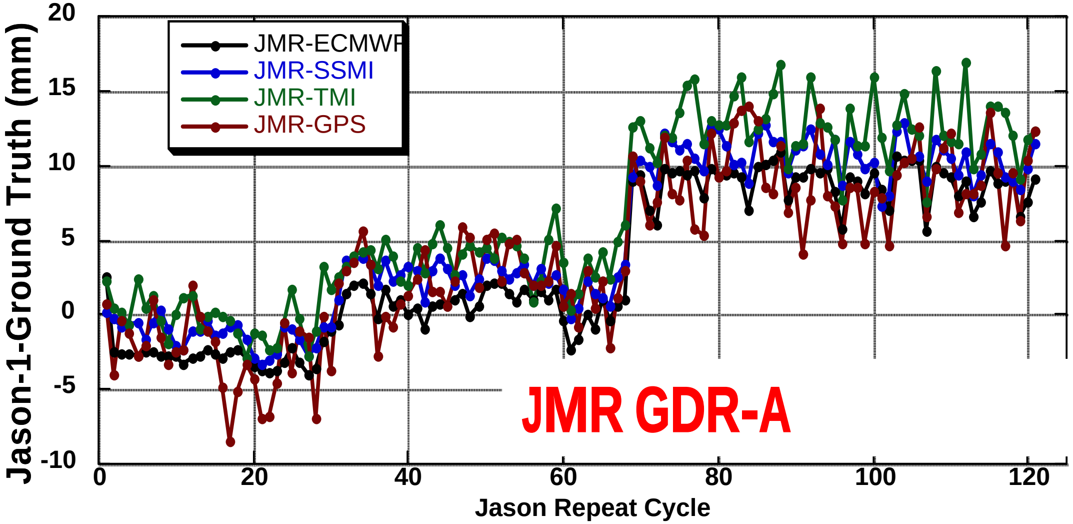
By Tereza Pultarova Space.com Contributor | Space.com

Topex and Jason-1



- **TMR drifted at a rate of about 1 mm/year over the first 6 years of the mission**

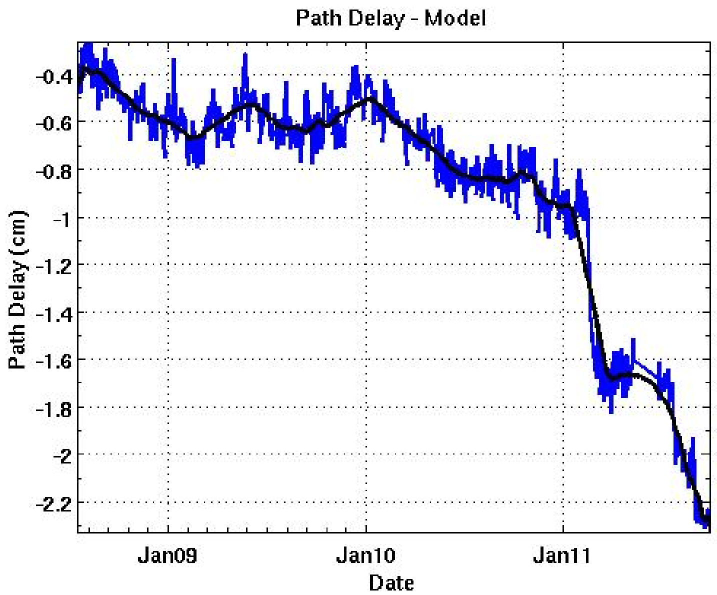
Observed instability significant compared to sea level rise signal



- JMR exhibited two jumps of about 5 mm then an additional 8 mm
  - 6mm/year when treated as drift

.d08

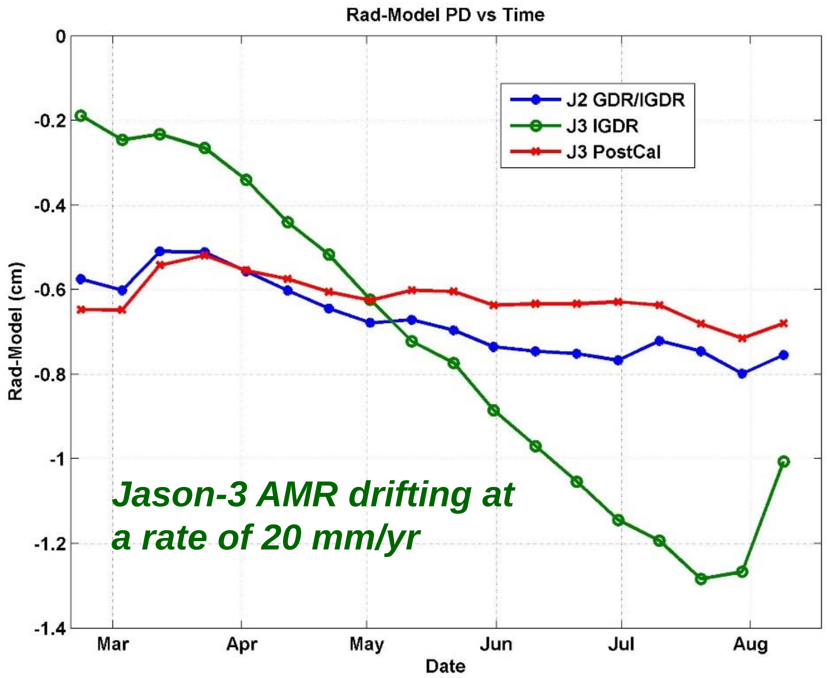
Jason-2 and Jason-3



Jason-2 AMR PD – ECMWF without ARCS Processing

- **Jason-2 AMR had jumps of totaling ~2cm over 3 years**

- **Jason-3 AMR exhibits monotonic drift of 20 mm/yr**



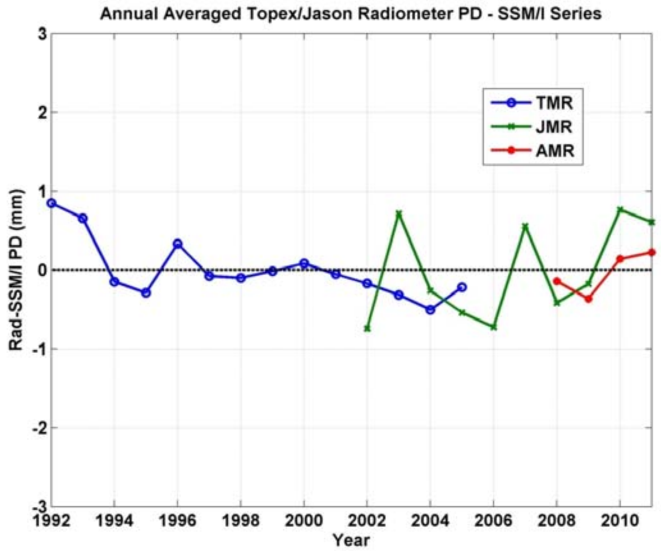
Ancillary Methods for Monitoring Long Term Stability

- **Brightness temperature models**
  - **Vicarious Cold Reference** *(Ruf, 2000, TGARS)*
  - **Amazon pseudo-blackbody regions** *(Brown and Ruf, 2005, JTECH)*
  - **On-orbit references sensitive to climate variability; require corrections; risk of aliasing geophysical signals**

- **Inter-sensor TB comparisons**
  - **AMSR-E, SSMI, TMI, JMR**
  - **Requires model to transfer one sensor's measurement to another**
  - **Requires stability of other systems**

- **Compare geophysical retrievals to in-situ measurements, models and other sensors**
  - **ECMWF, NCEP, SSMI, TMI, AMSR-E, GPS, RaOb**
  - **Dependent on long term stability of other sensors/models**

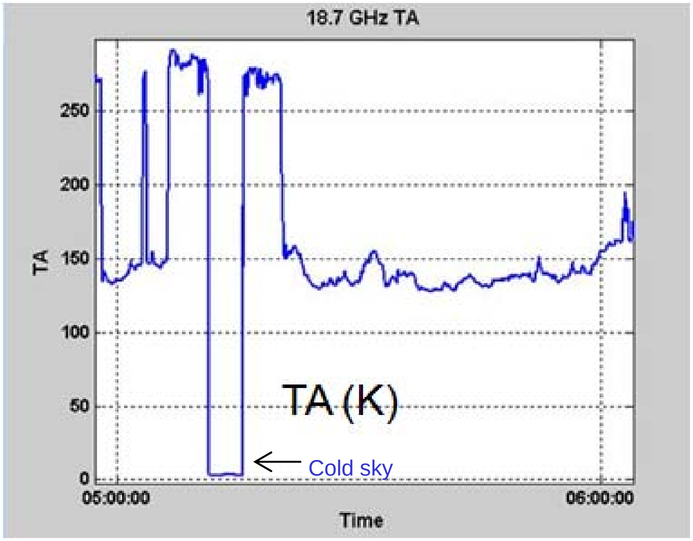
TMR, JMR and AMR compared to SSM/I Series from 1992-2012

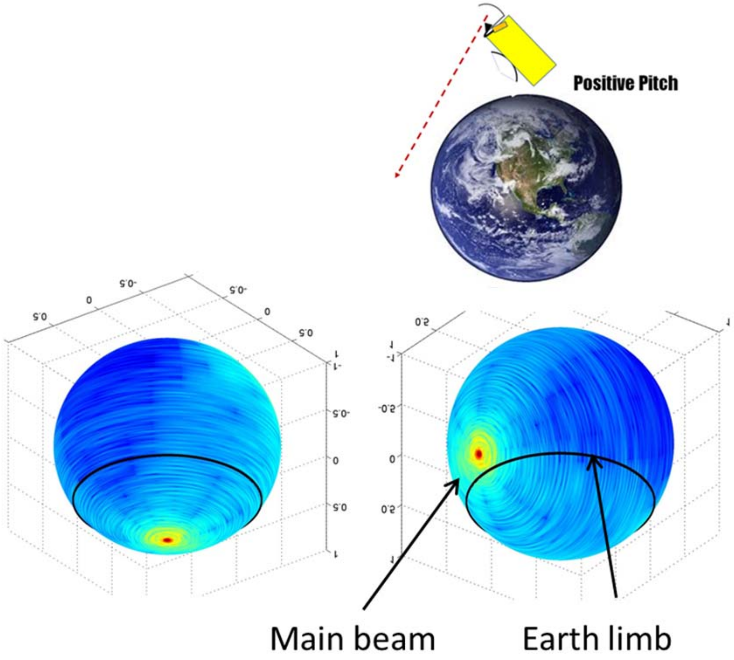


Cold Sky Calibration

- **Cold sky calibration performed by rotating the spacecraft which provides a calibration reference through the same path as the Earth scene**
- **Presents stable 1-point calibration to the radiometer**
- **2-stable points required for complete calibration, therefore cold sky maneuver supplemented by on-Earth references**

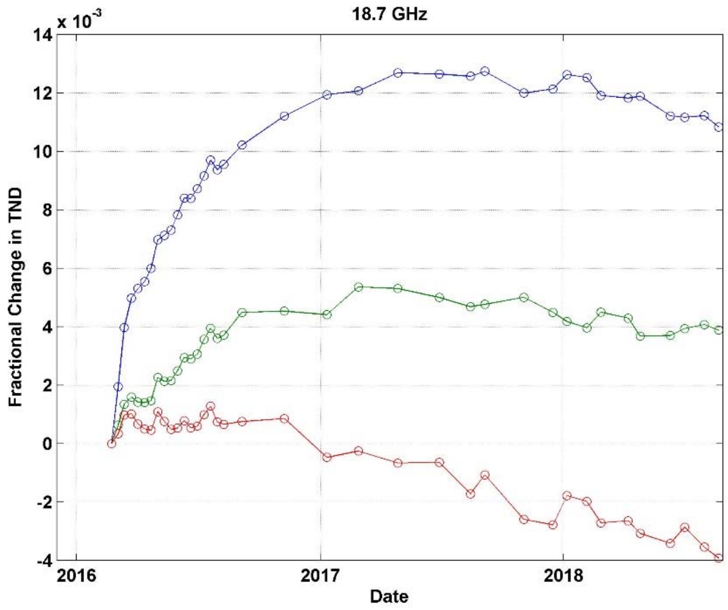
$$\Delta T_B(T_B,t) = (T_B - T_{REF})\frac{\Delta T_{ND}(t,L,\Gamma)}{T_{ND}} + \Delta T_{Offset}(L,\Gamma)$$

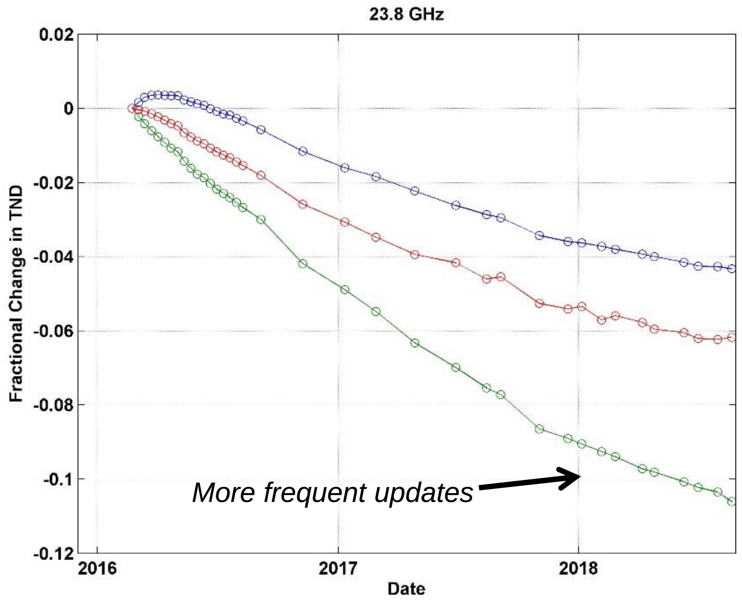


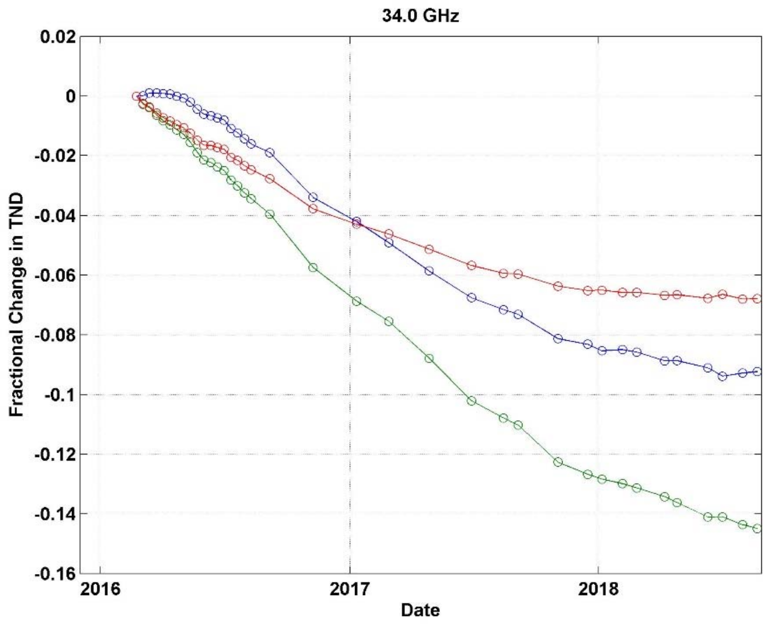


J3 Noise Diode Drift

- **Cold sky maneuvers (CSM) used to characterize and remove drift in J3 AMR noise diodes**
- **Coefficients updated and provided to CNES after each CSM**
- **Latency has improved due to added CSMs**

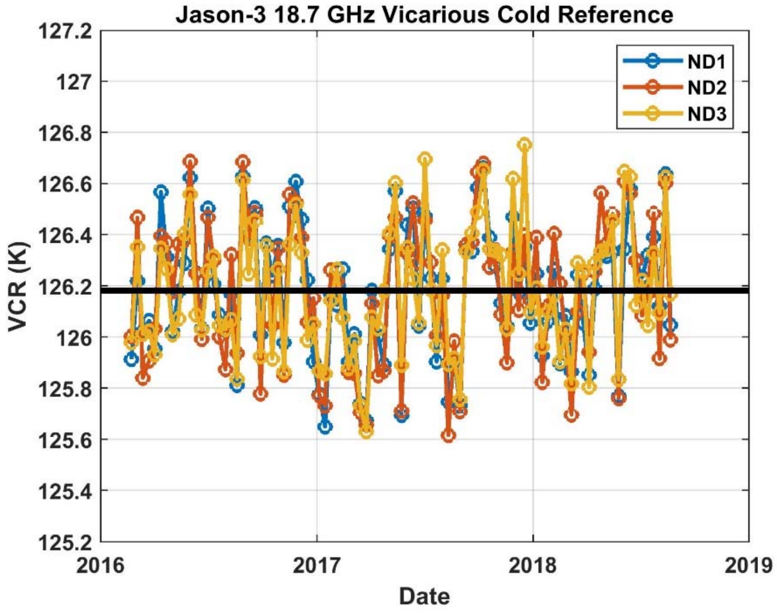


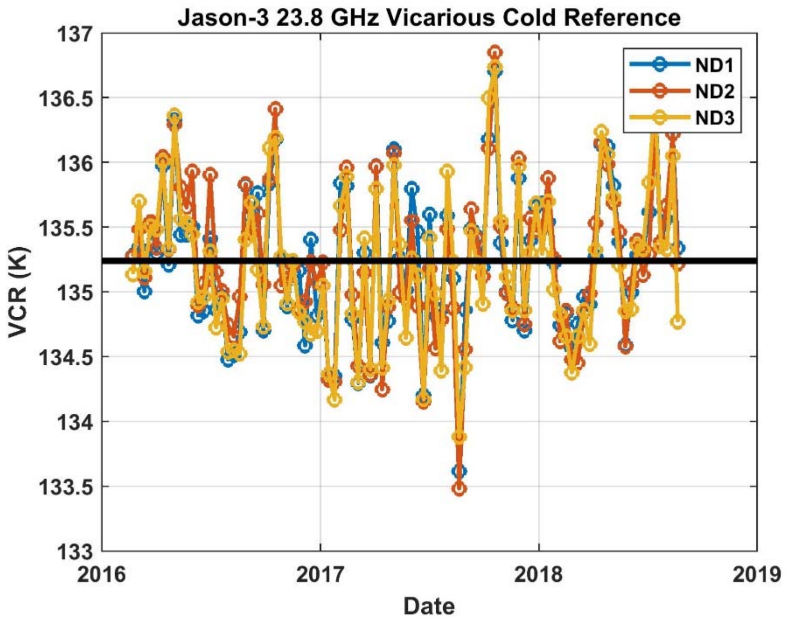


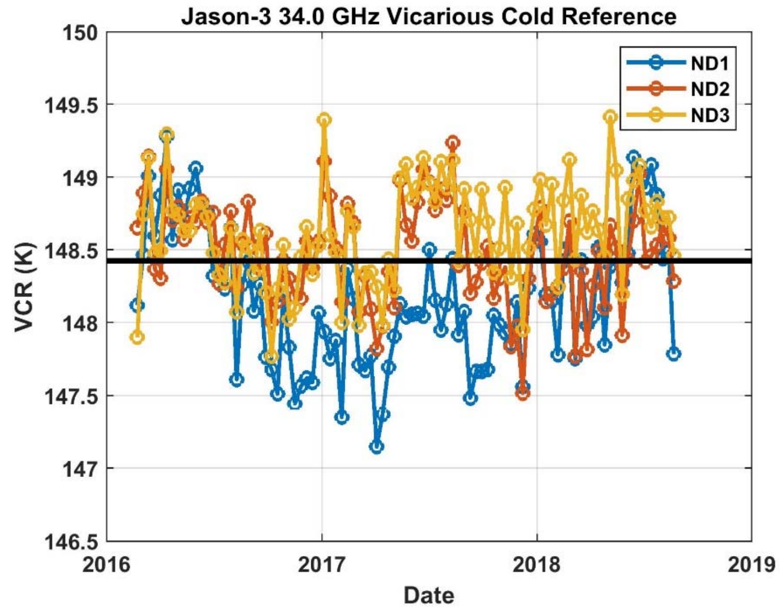


Jason-3 Ocean Reference

- **Vicarious cold ocean reference used as independent validation of cold sky calibration**
- **No statistically significant long-term drift evident after cold sky calibration**

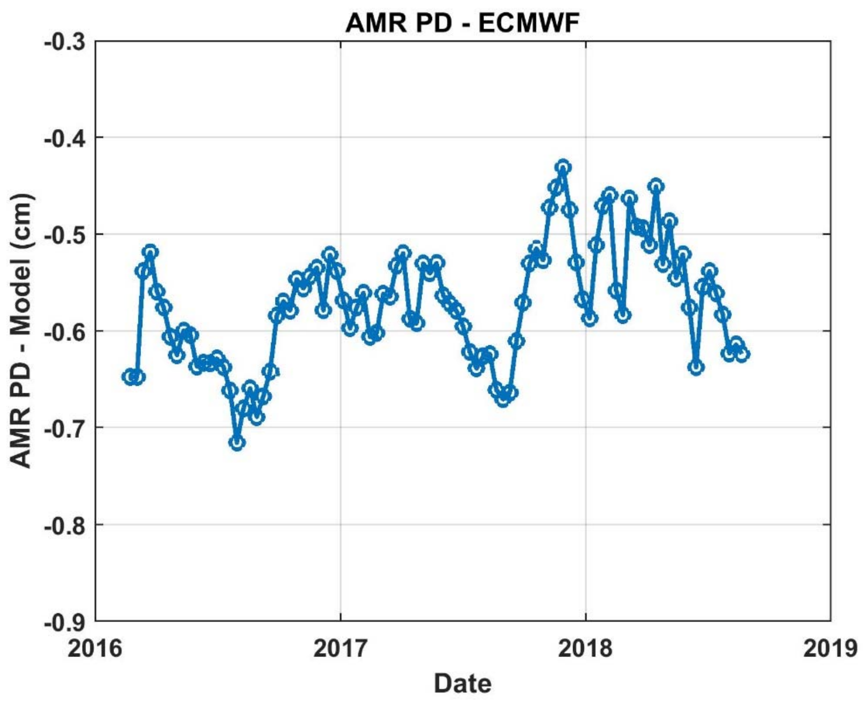


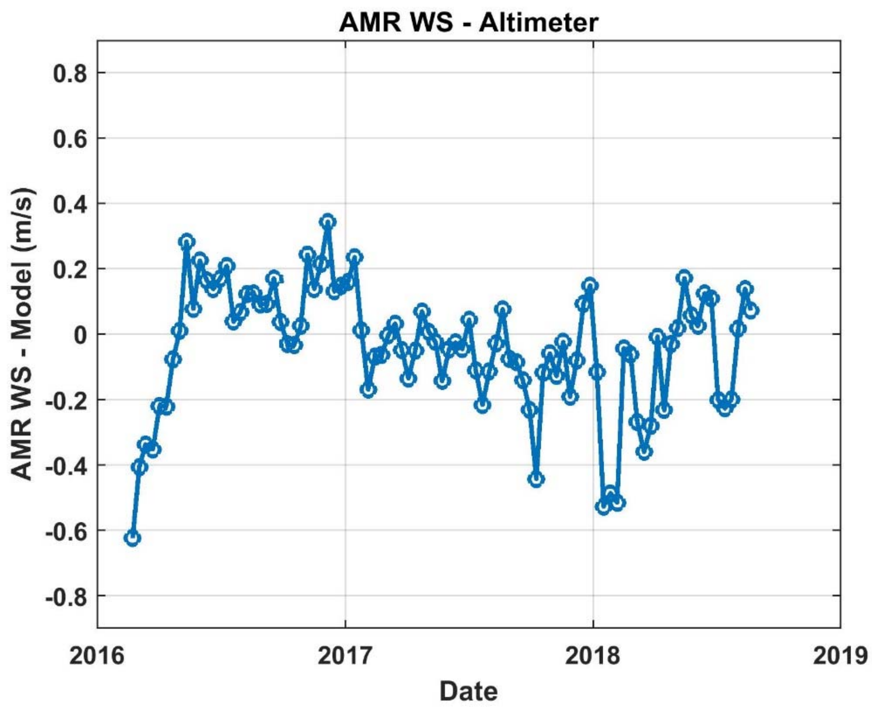




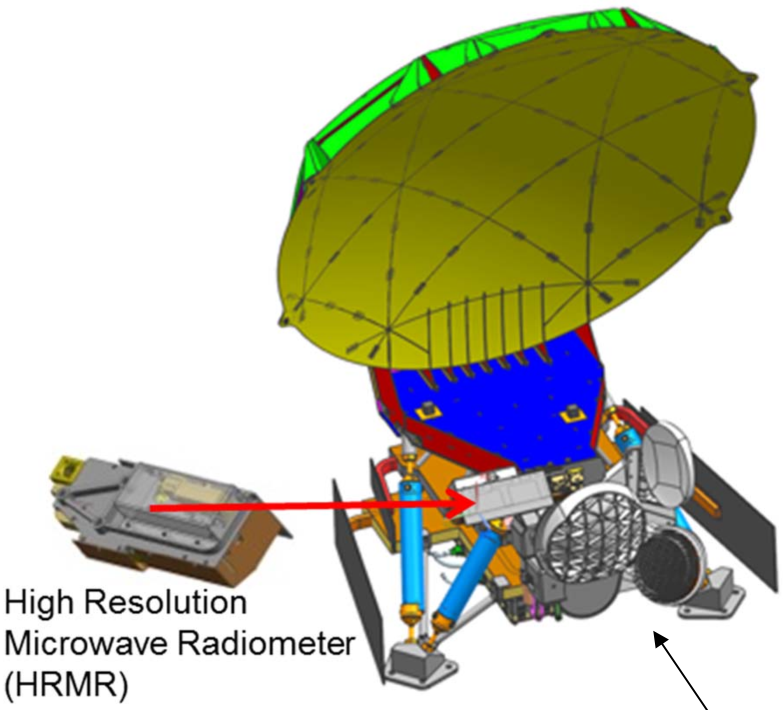
Jason-3 AMR Geophysical Retrievals

- Path delays stable to within ~±1mm over mission
- Wind speed stable to 0.2 m/s

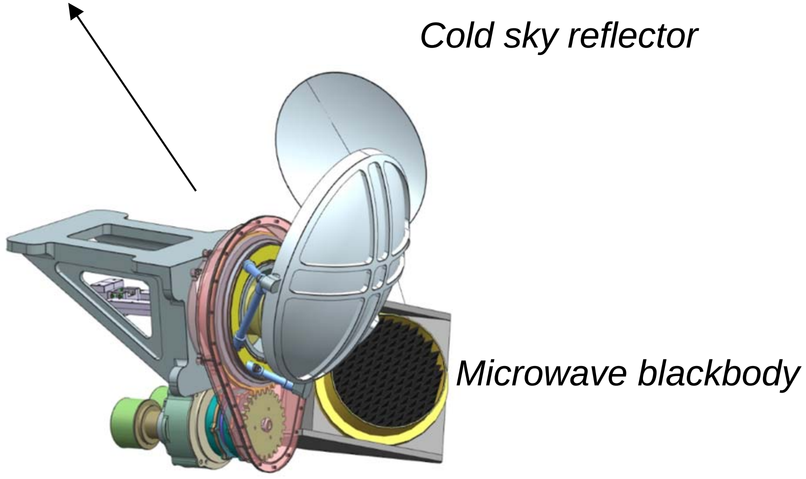




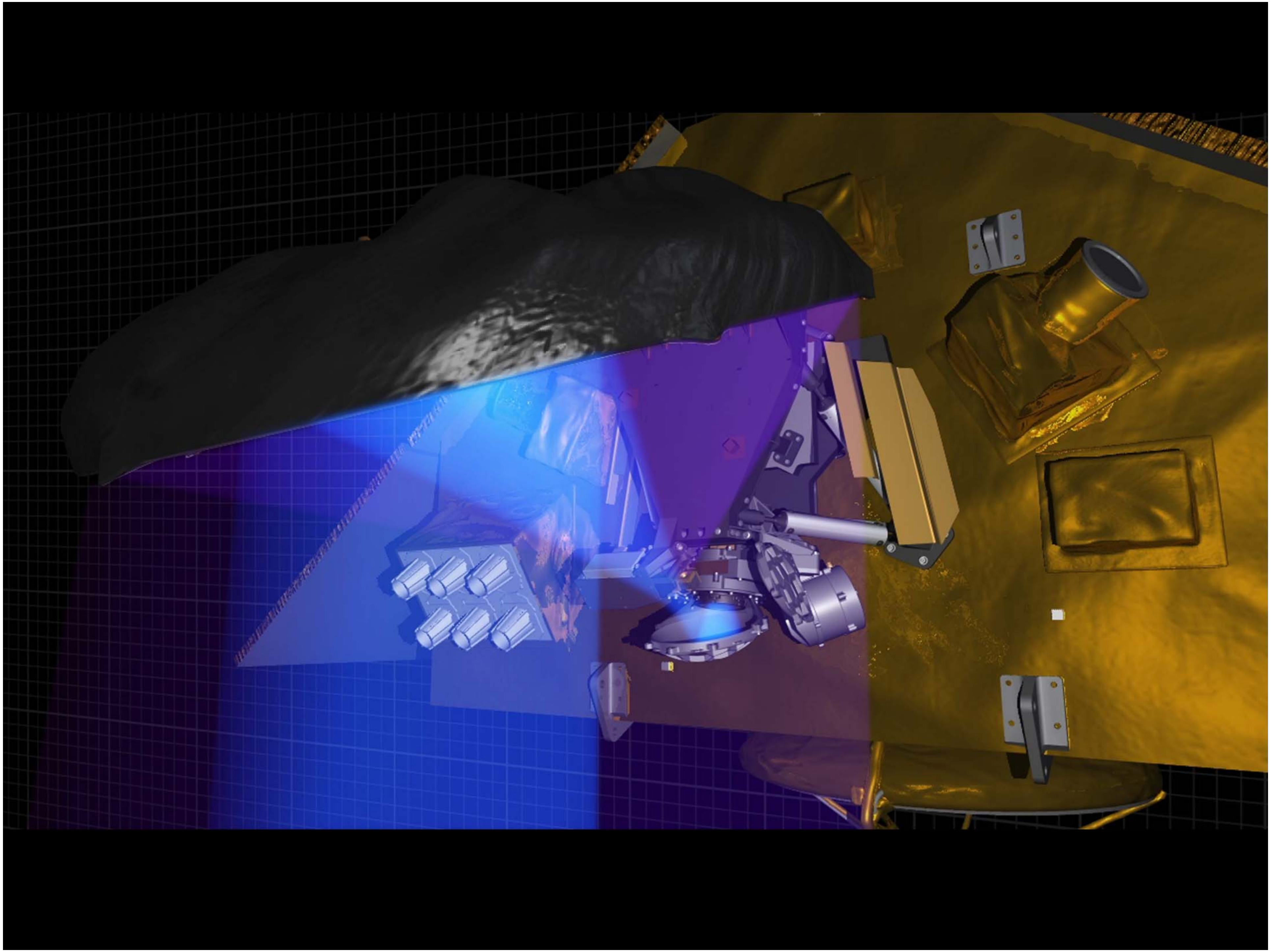
Sentinel-6 AMR-C



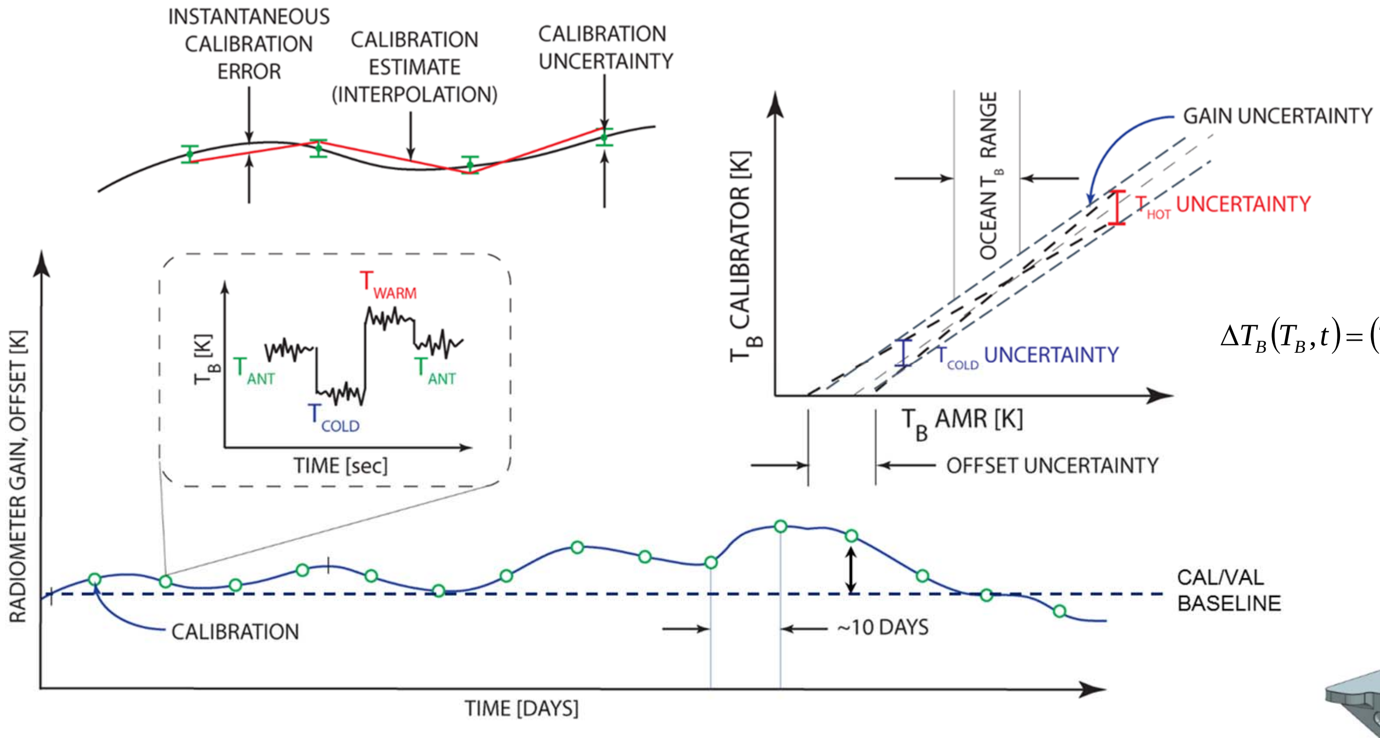
- **Sentinel-6 AMR-C includes two new design features based on OSTST recommendations**
  - External calibration system for long term stability
  - High Resolution Microwave Radiometer for coastal PD – experimental



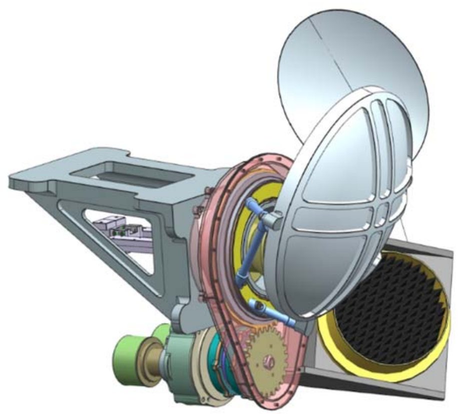
SCS (Supplemental
Calibration System)



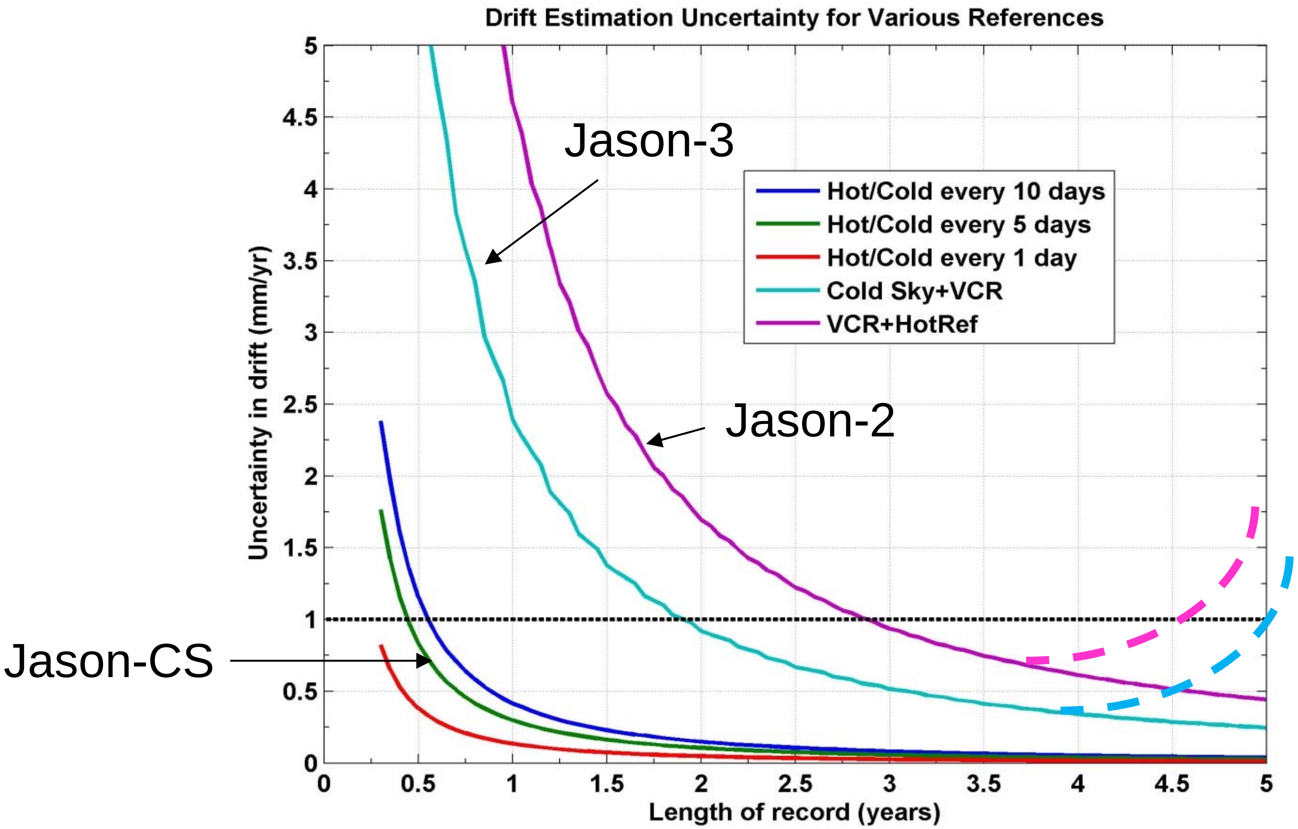
Path delay stability determined by target uncertainty and frequency of calibrations



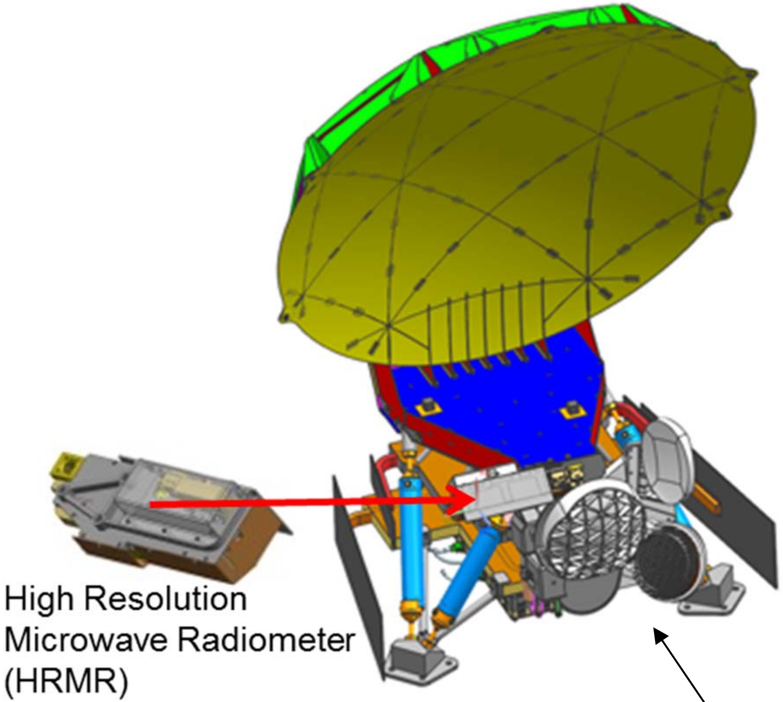
$$\Delta T_B(T_B,t) = (T_B - T_{REF})\frac{\Delta T_{ND}(t,L,\Gamma)}{T_{ND}} + \Delta T_{Offset}(L,\Gamma)$$



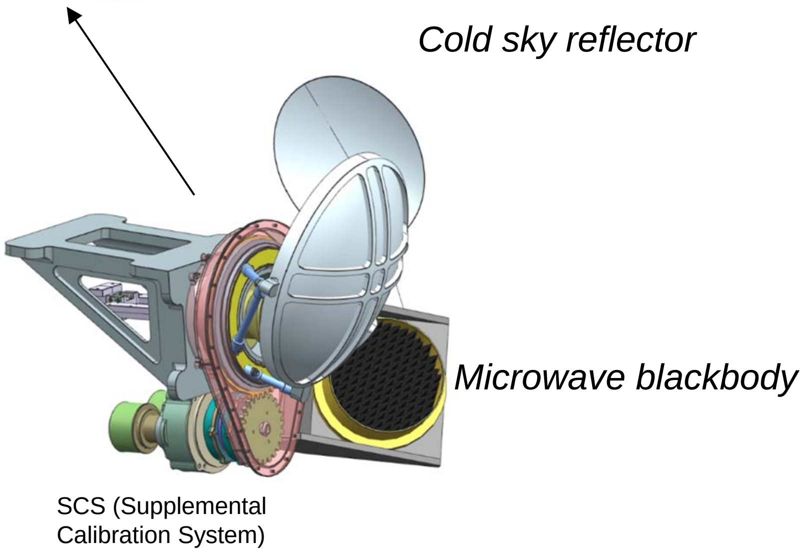
Sentinel-6: The New Climate Reference



Sentinel-6 AMR-C

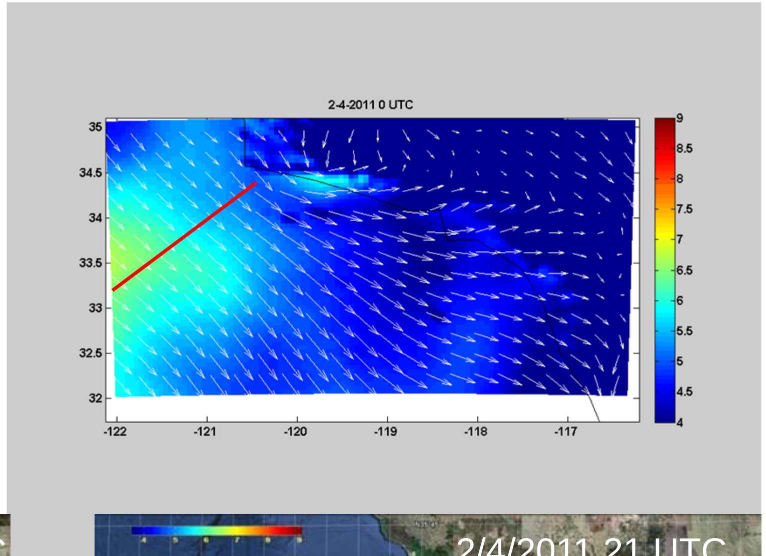


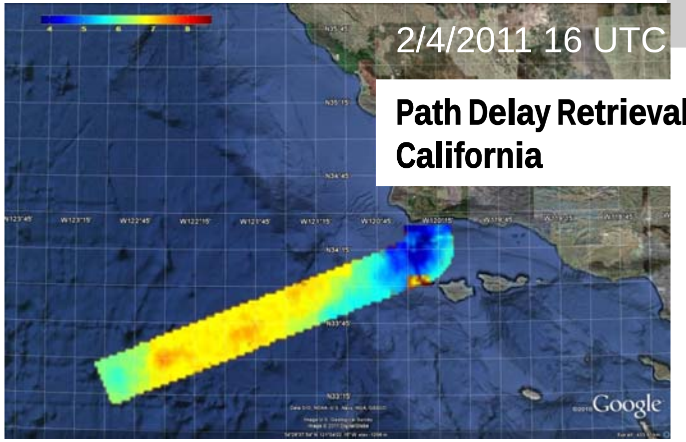
- **Sentinel-6 AMR-C includes two new design features based on OSTST recommendations**
  - External calibration system for long term stability
  - High Resolution Microwave Radiometer for coastal PD – experimental

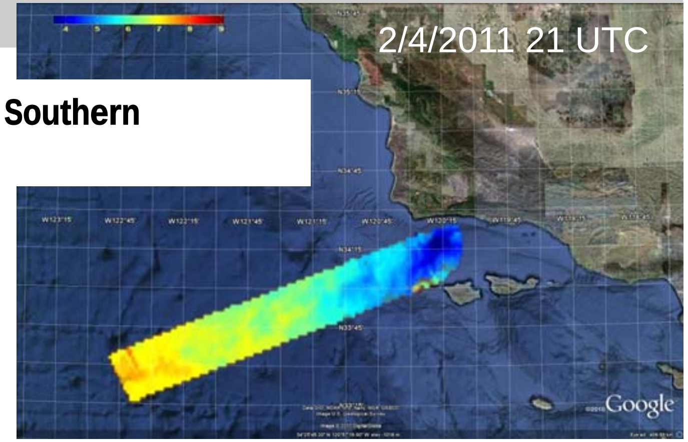


Example: Off-shore Winds

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



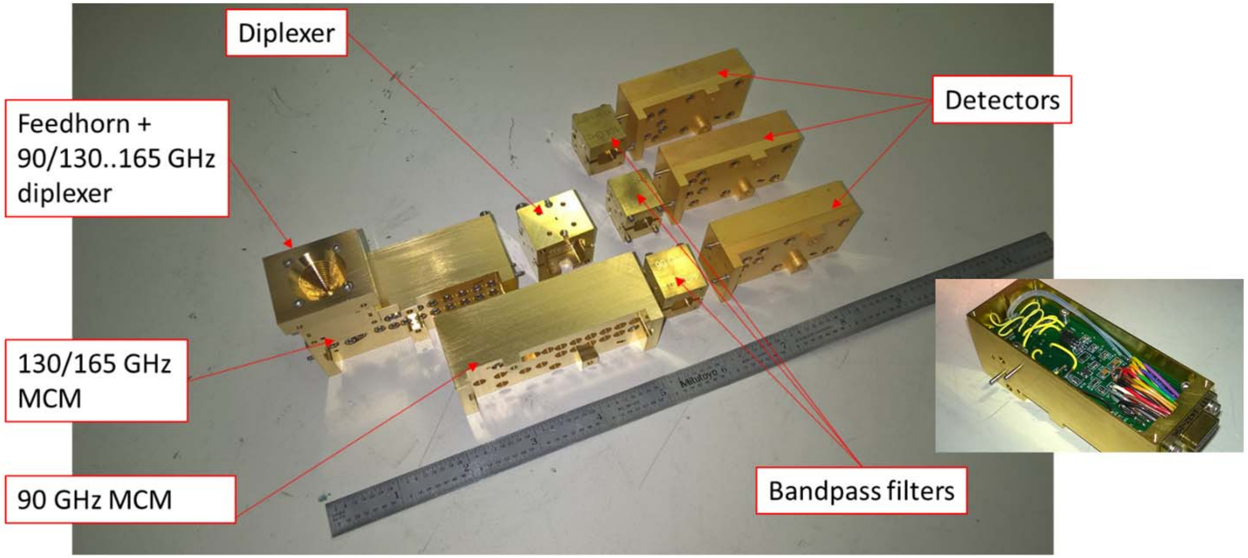




Path Delay Retrieval off Southern California

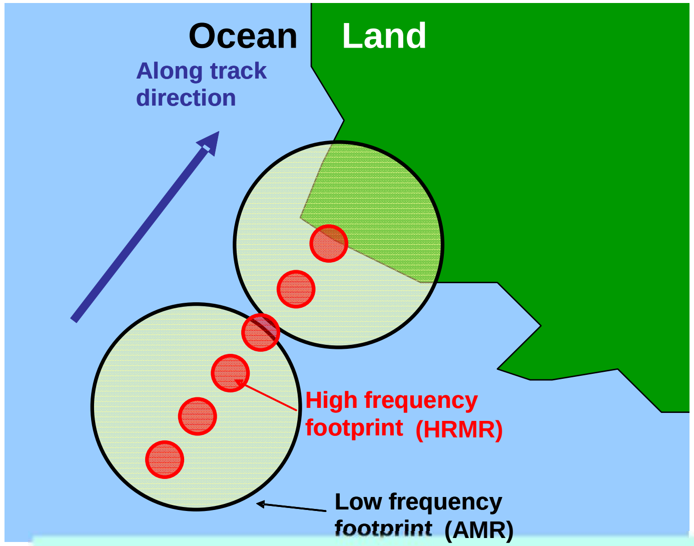
High Resolution Microwave Radiometer

- **3-frequencies at 90, 130 and 166 GHz**
- **Co-located footprints with a spatial resolution of 2-5km**
- **Noise diode and switch to reference load for calibration**
  - **0.2K TB uncertainty**



HRMR Measurement Concept

- Channels between 90-160 GHz sensitive to water vapor continuum
- Also 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 – referenced to AMR low frequency channels

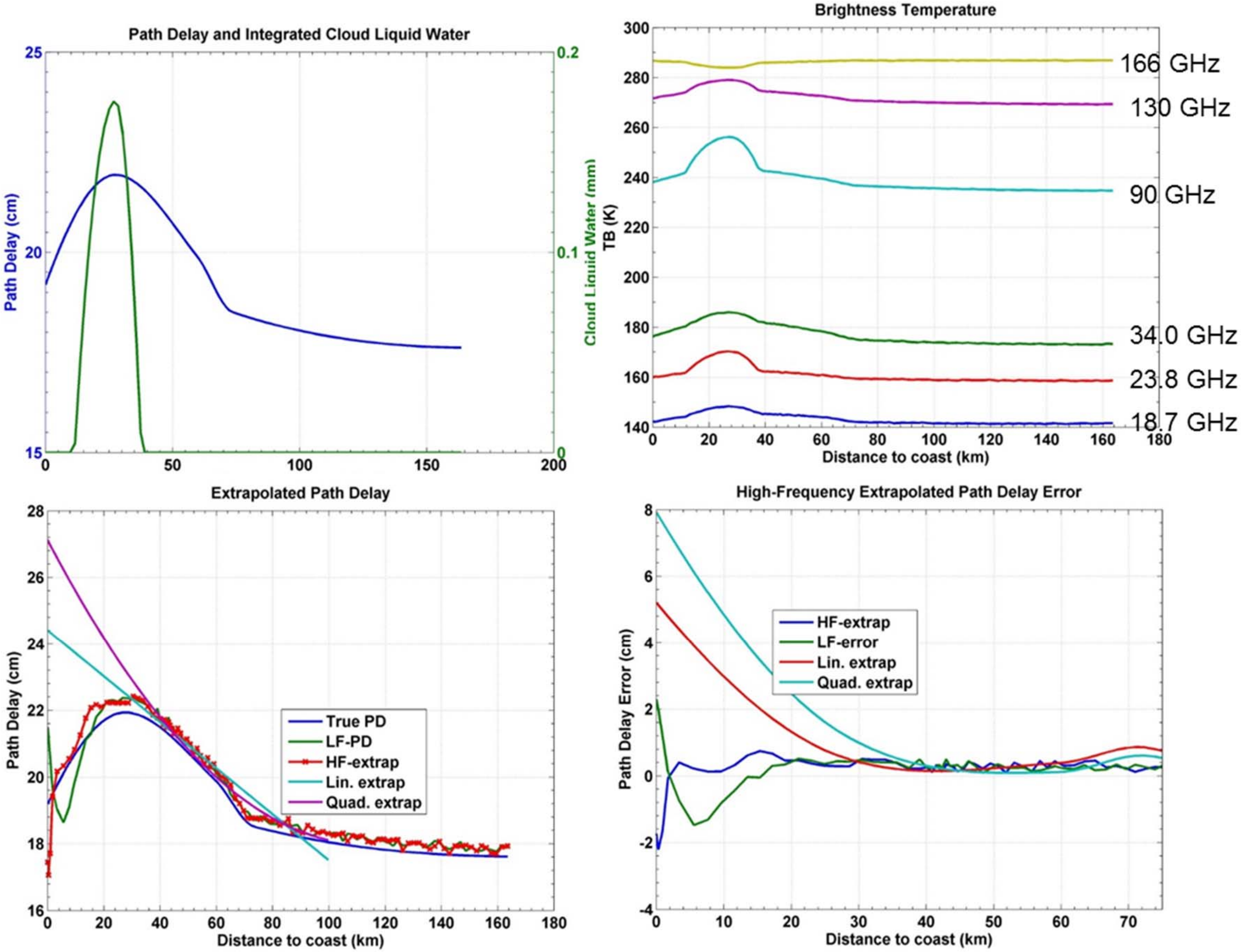


- Standard low-frequency channels (18-34 GHz) used for PD retrieval in open ocean (> 30 km from land)
- High-frequency window channels, 90, 130 and 166 GHz used to continue PD measurement to ~3km from land

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

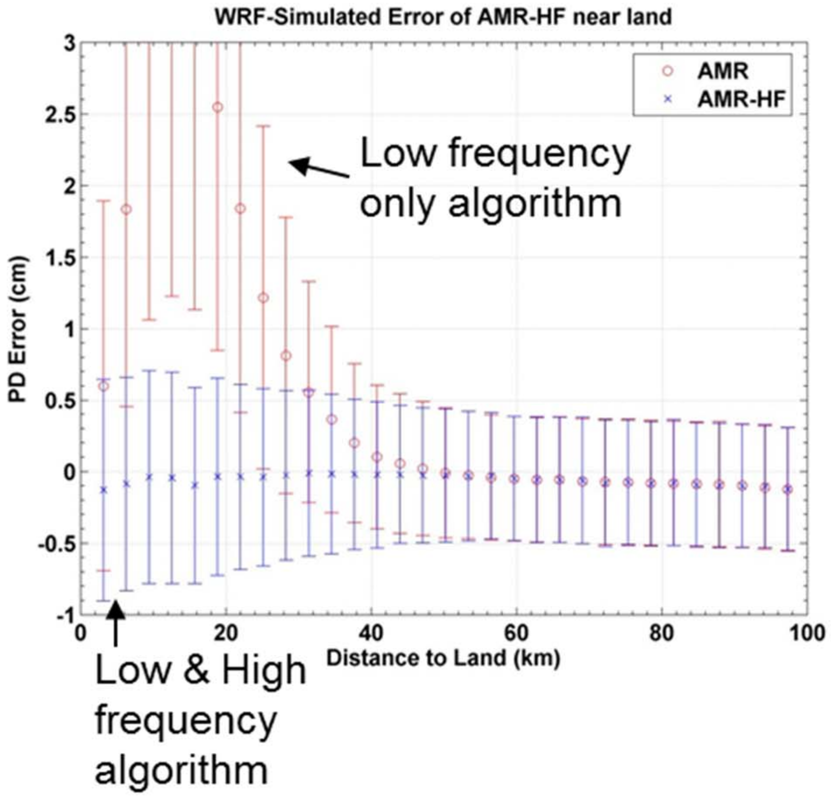
where $\vec{c} = \left(A^T A\right)^{-1} A^T PD_{LF}$

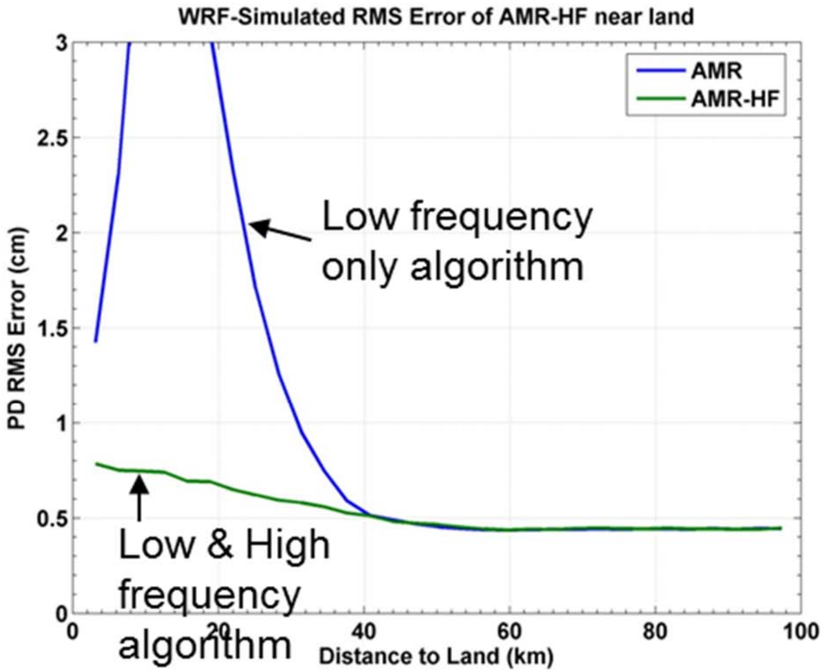
Reduced beam footprint of HRMR enables coastal PD correction

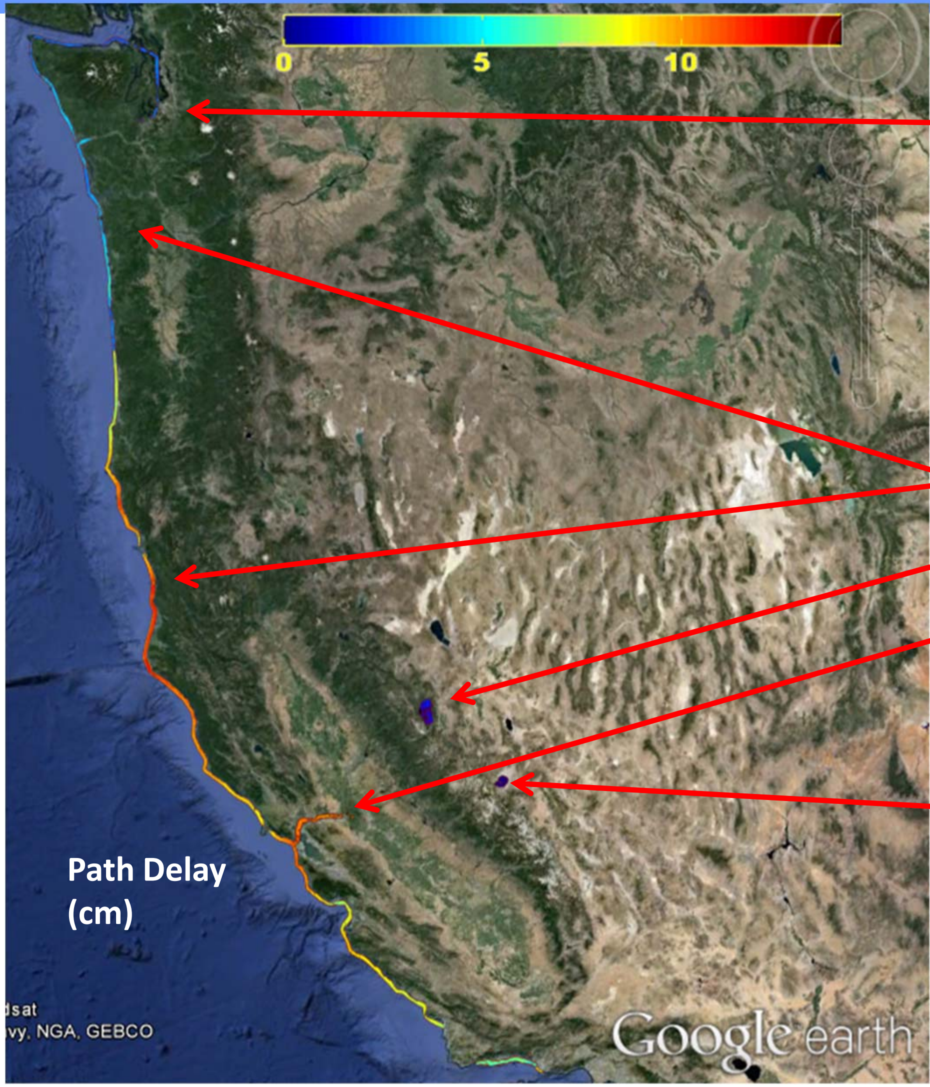

Path Delay and Integrated Cloud Liquid Water
Path Delay (cm)
Cloud Liquid Water (mm)
Brightness Temperature
TB (K)
166 GHz
130 GHz
90 GHz
34.0 GHz
23.8 GHz
18.7 GHz
Distance to coast (km)
Extrapolated Path Delay
Path Delay (cm)
True PD
LF-PD
HF-extrap
Lin. extrap
Quad. extrap
Distance to coast (km)
High-Frequency Extrapolated Path Delay Error
Path Delay Error (cm)
HF-extrap
LF-error
Lin. extrap
Quad. extrap
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**







Puget Sound

West Coast Field Campaign November 2014

Coastal Ocean

Lake Tahoe

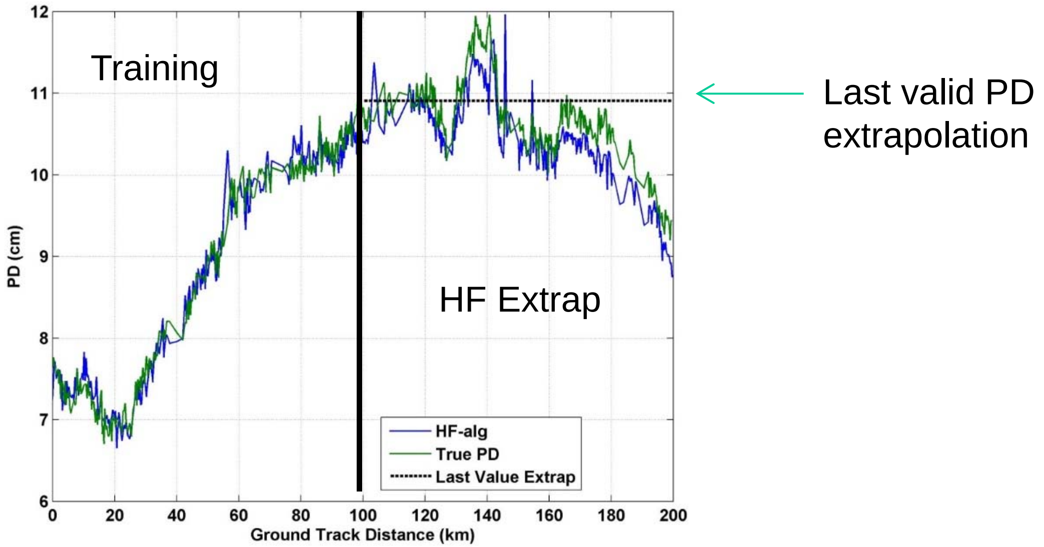
San Joaquin River

Mono Lake

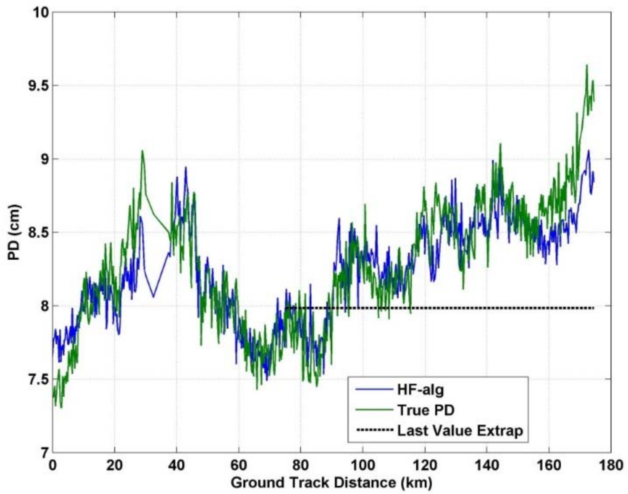
Observations at 150m spatial resolution

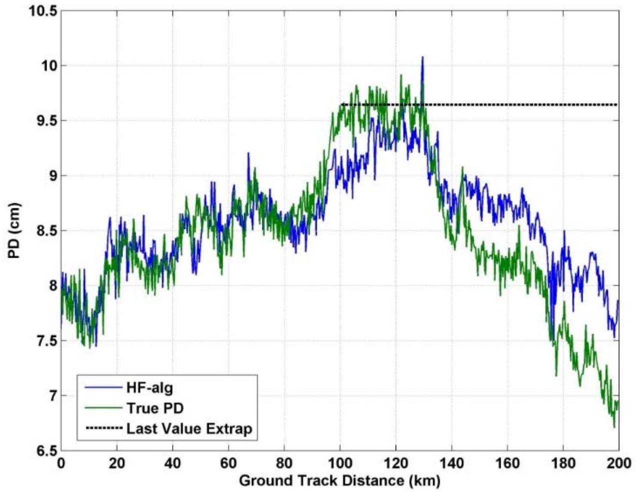
High Frequency Algorithm Testing with HAMMR

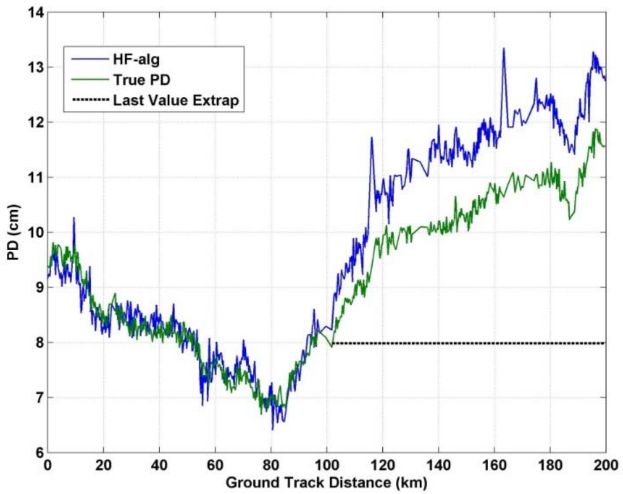
- **First retrieved PD over the ocean using low-frequency 18-34 GHz channels**
- **Then, dynamically trained HF algorithm along track using 100km of along track data and evaluated performance over next 100km**
- **Evaluated performance by comparing to low-frequency “true” PD over next 100km**

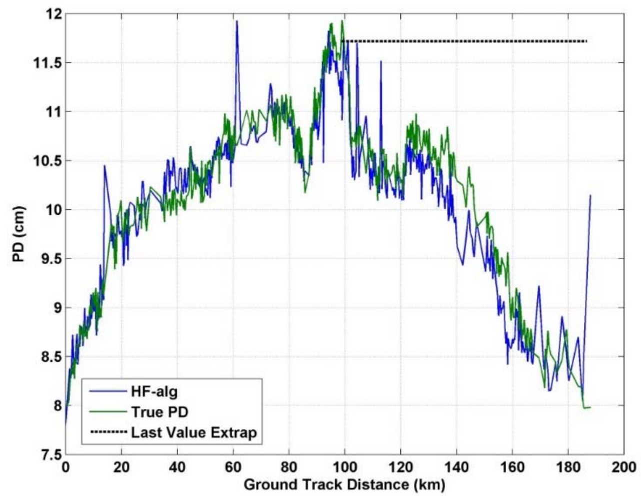


HF Retrieval Examples



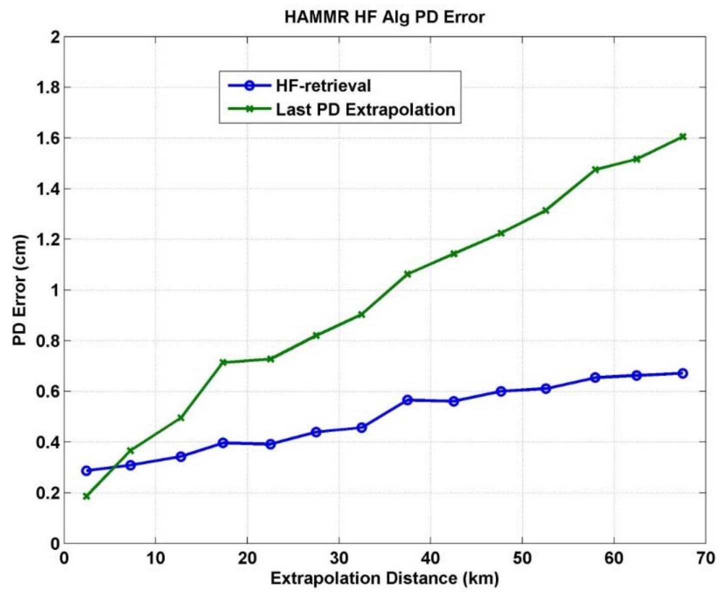






Error Summary vs Extrapolation Distance

- **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

- **We have made significant progress over the past 25 years to align the radiometer capability to the expectations of the science users**

- **Sentinel-6 AMR-C represents a significant advancement for both improving the GMSL trend measurement and for coastal altimetry**

Jason-CS AMR-C

Advanced Microwave Radiometer for Climate

- **AMR-C merges two existing calibration approaches for satellite-borne microwave radiometers to produce a level of performance superior to either approach alone**
  - **External calibration approach excellent for maintaining long term stability**
    - e.g. AMSU, AMSR-E, SSM/I, SSMIS, WindSat, MSU
    - 0.01 K long term TB stability estimated for MSU (Spencer et al., 1990): ~0.01mm/yr
  - **Internal calibration approach excellent for maintaining short term stability**
    - e.g. Jason 1/2, Sentinel, GFO, Envisat, ERS, Topex
  - **Combining both approaches gives stable calibration on all times scales from seconds to decades**
    - AMR-C

- **Highlights of AMR-C design and improvements from Jason-2 AMR**
  - **End-to-end calibration with traceable external calibration standards viewed through the feed for long term calibration (> 10 days)**
  - **High quality internal calibration sources for short time scale calibration (< 10 days)**
  - **Improved thermal stability**