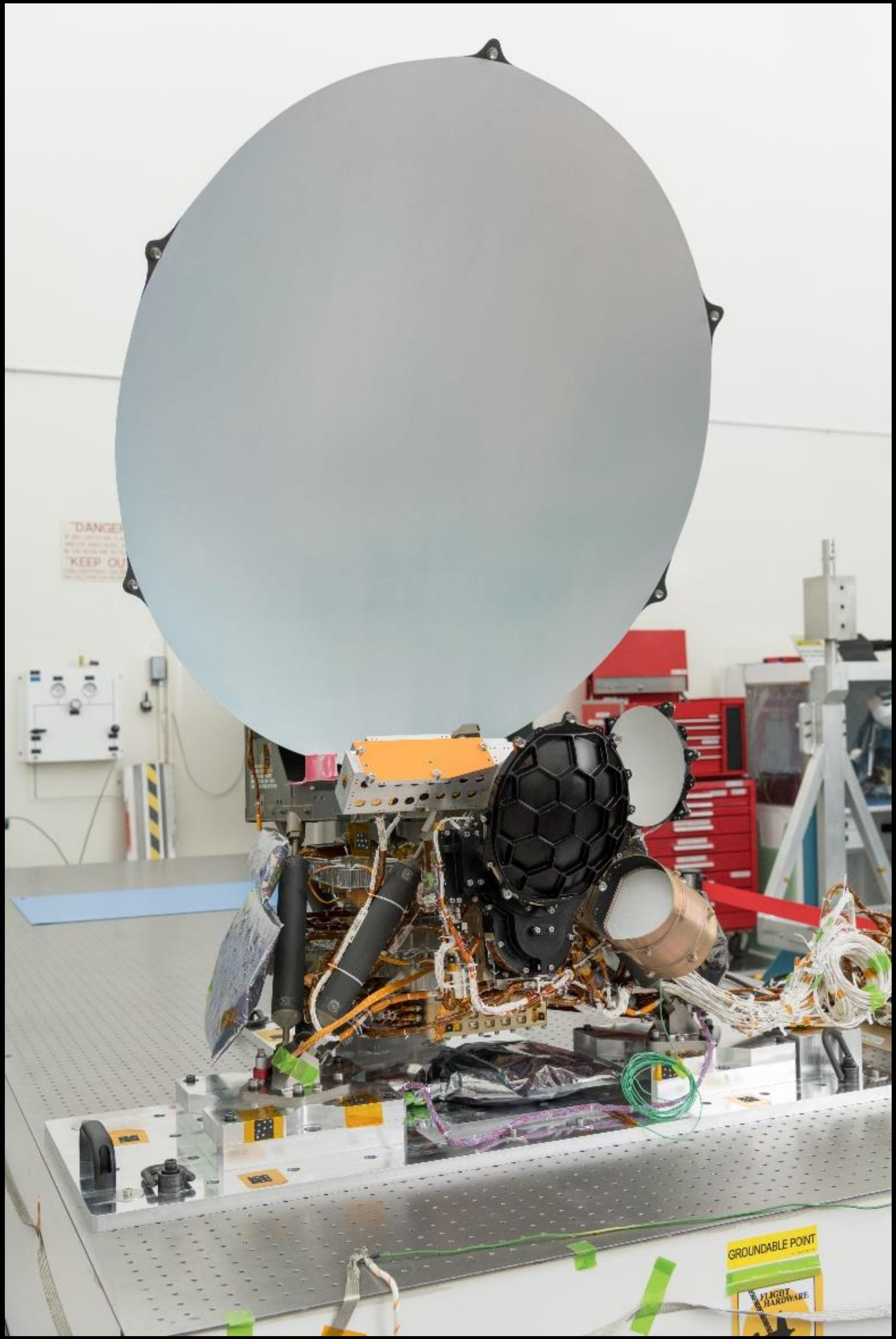


AMR-C Performance after ~2 Years

Shannon Brown, Chun Sik Chae, Shailen Desai

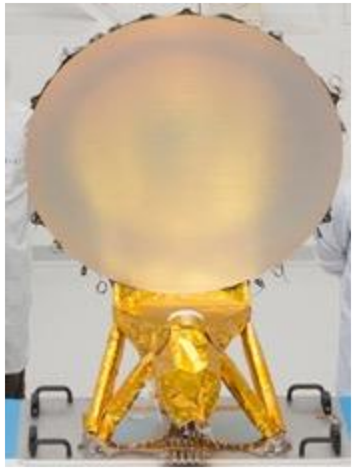
Jet Propulsion Laboratory, California Institute of Technology

Sentinel-6 AMR-C (climate)

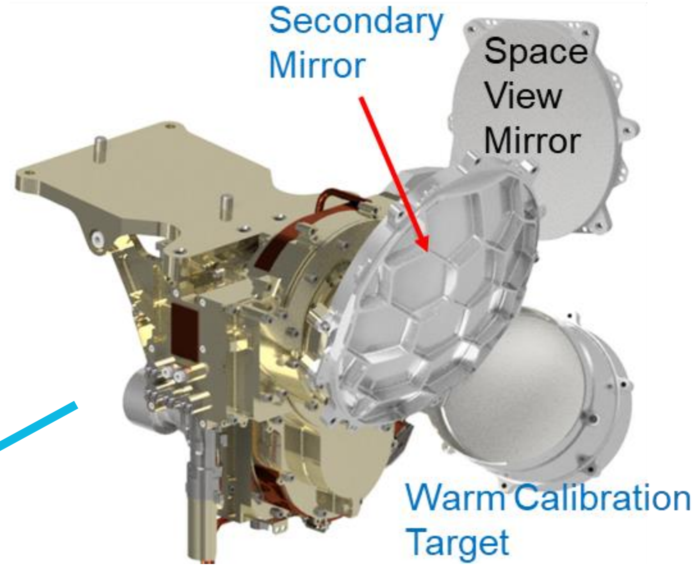
- AMR-C is next generation altimeter radiometer incorporating recommendations from OSTST

- AMR-C includes two innovations from prior generation AMR on Jason-series
  - Supplemental Calibration System (SCS) – *maintain mm/yr stability*
  - High Resolution Microwave Radiometer (HRMR) – *provide coastal path delay to 1cm at 10km from land*

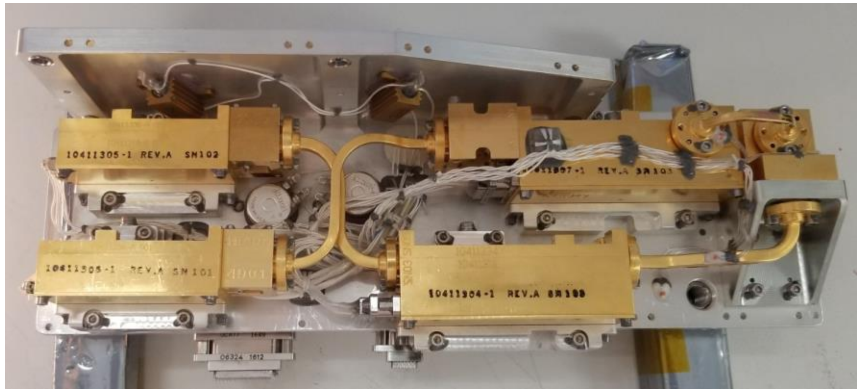
Jason-3 AMR



Sentinel-6 AMR-C



SCS



HRMR

Sea Level Change

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

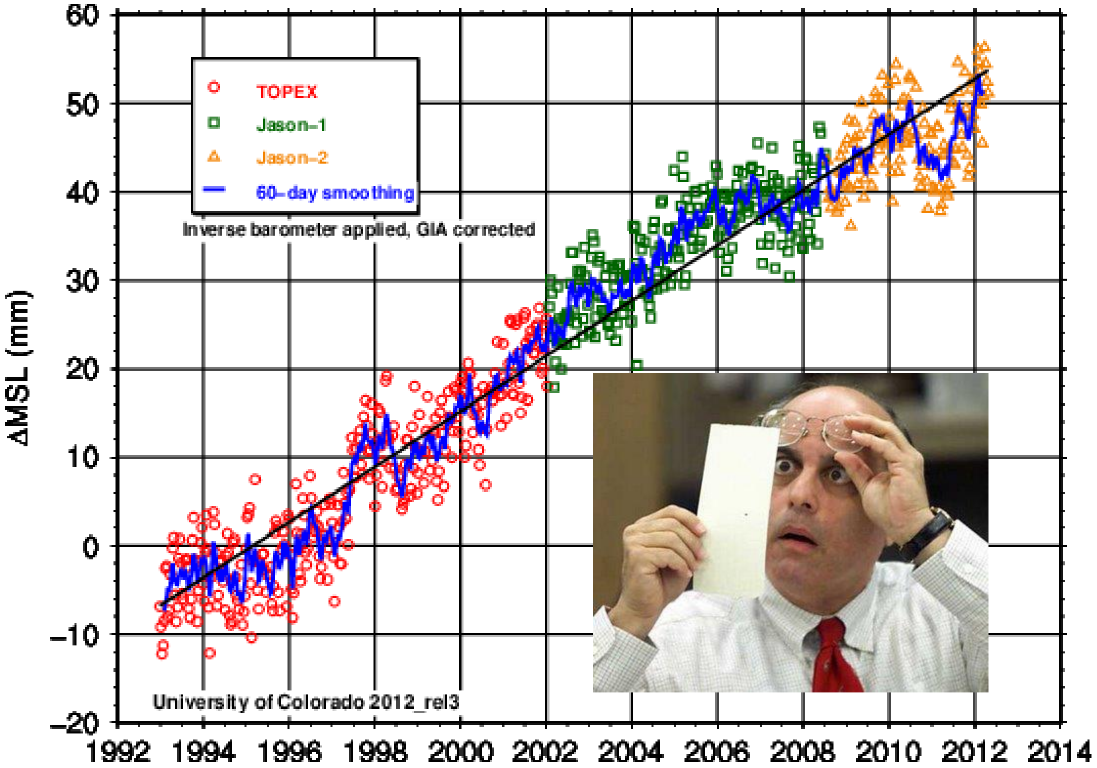
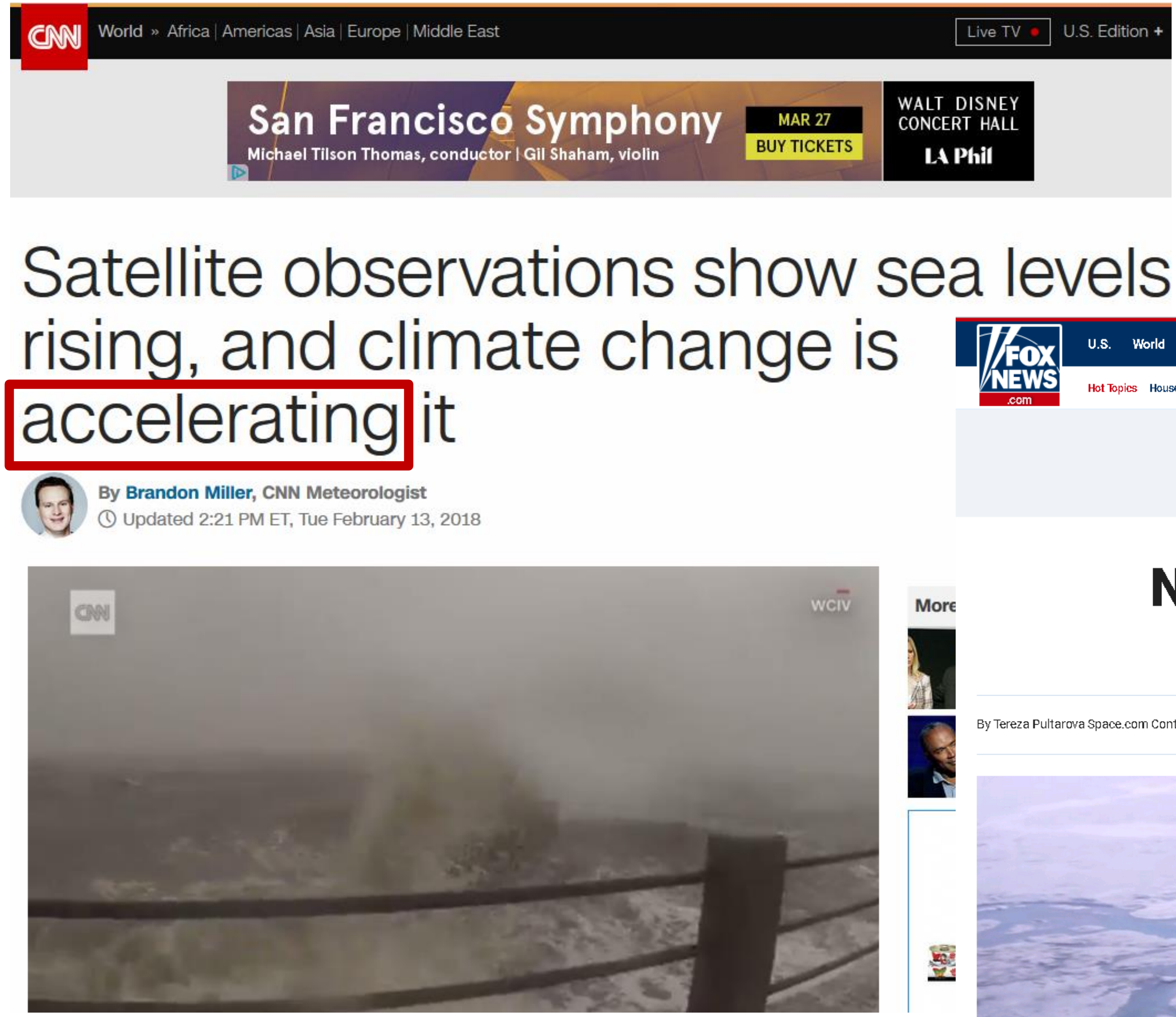


Table 2. MSL trend uncertainties from 1993 to 2008 for each correction or model impacting the MSL calculation.

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

Sea level change may be accelerating….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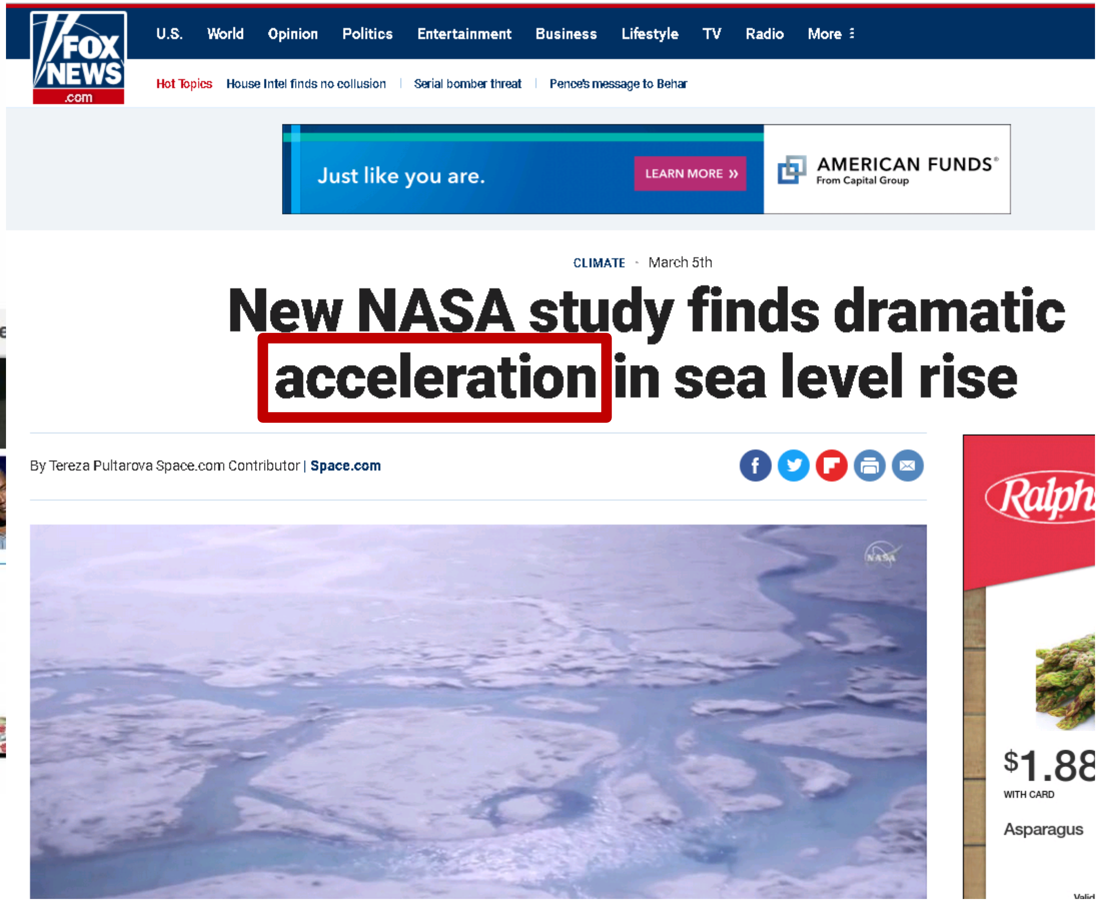
Satellite observations show sea levels rising, and climate change is accelerating it

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

More

When the first derivative is no longer enough…..

Nerem et al., PNAS, 2018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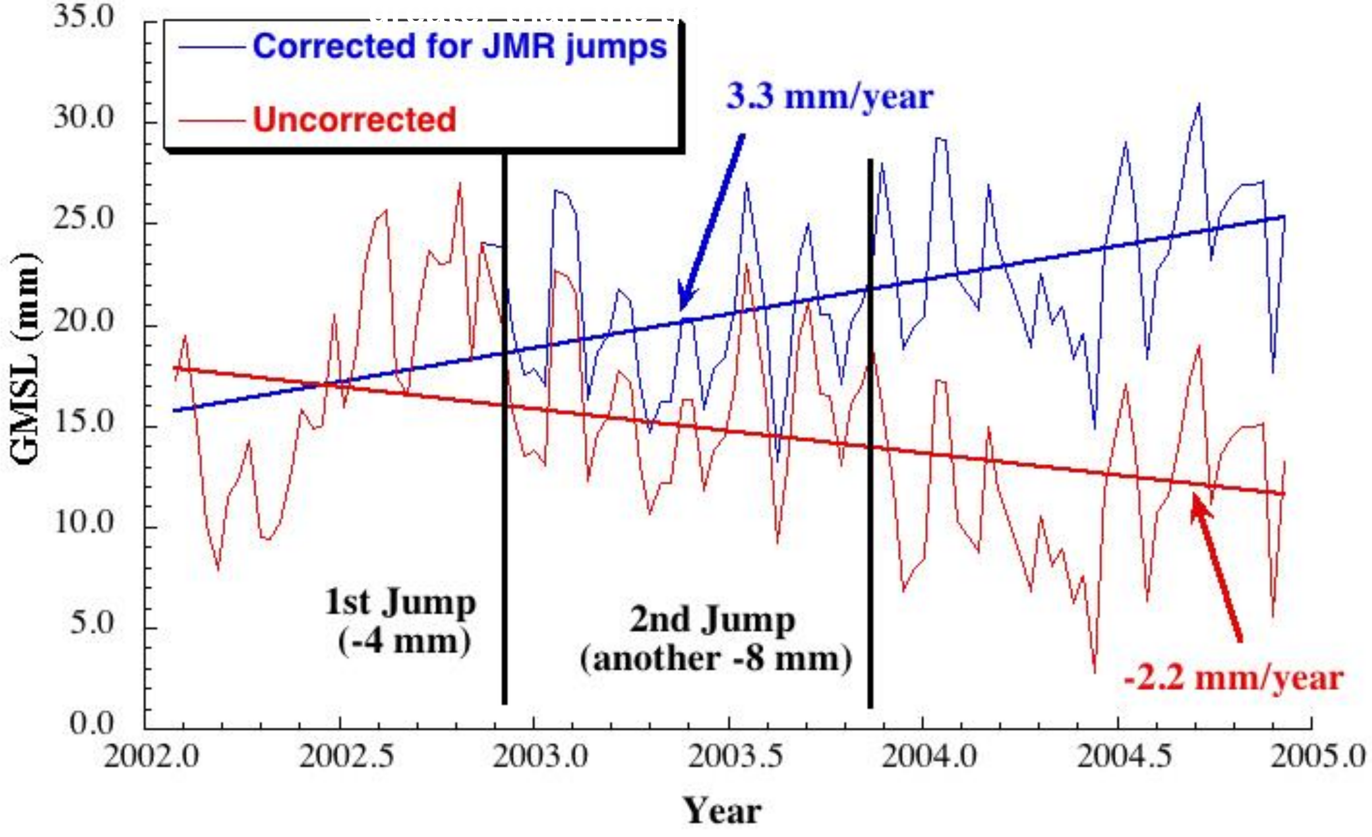
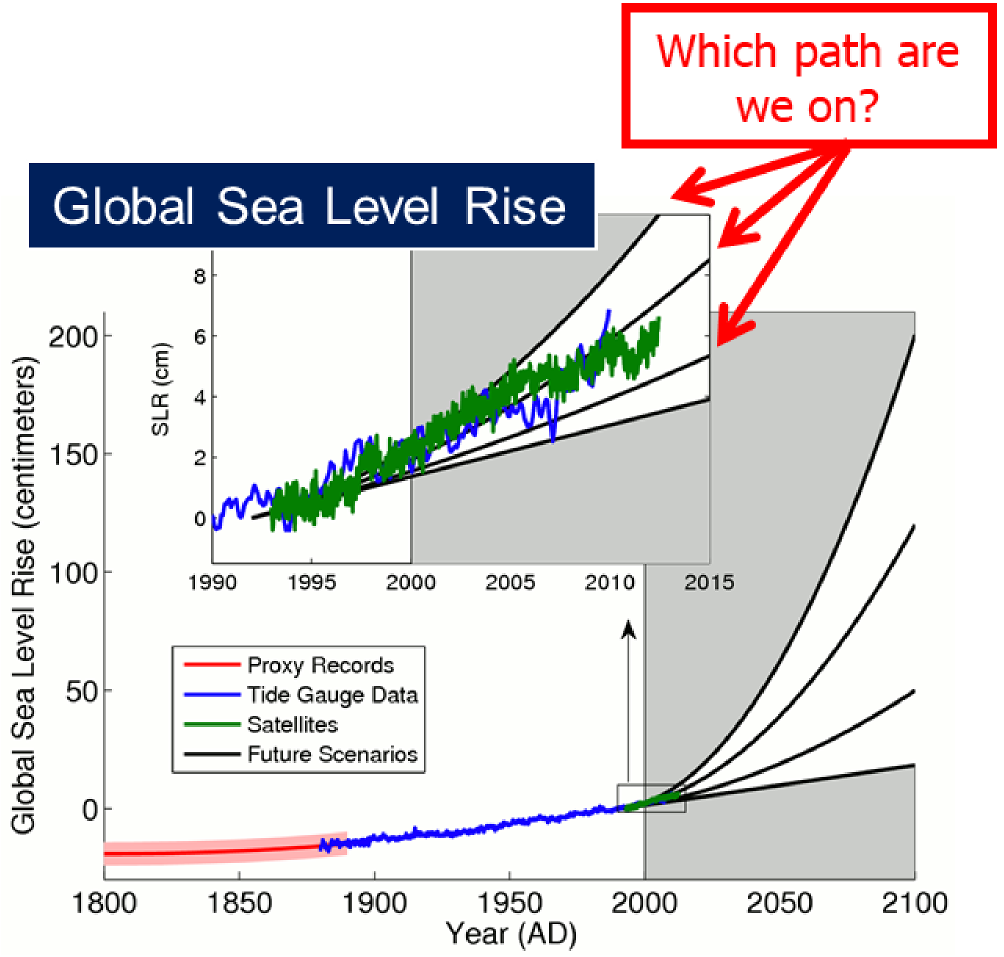
CLIMATE · March 5th

New NASA study finds dramatic acceleration in sea level rise

By Tereza Pultarova Space.com Contributor | Space.com

Sentinel-6 AMR-C Radiometer Drift Requirement

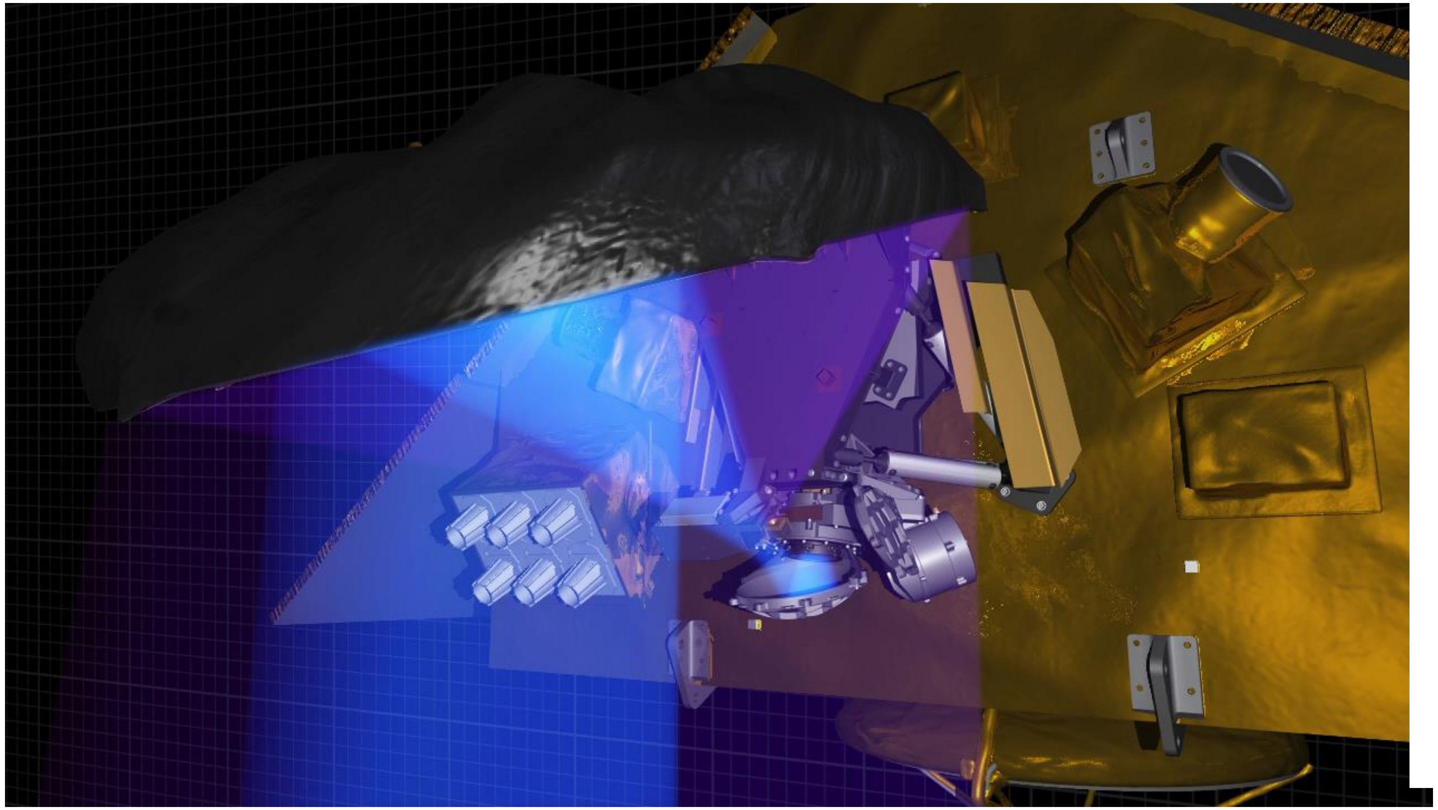


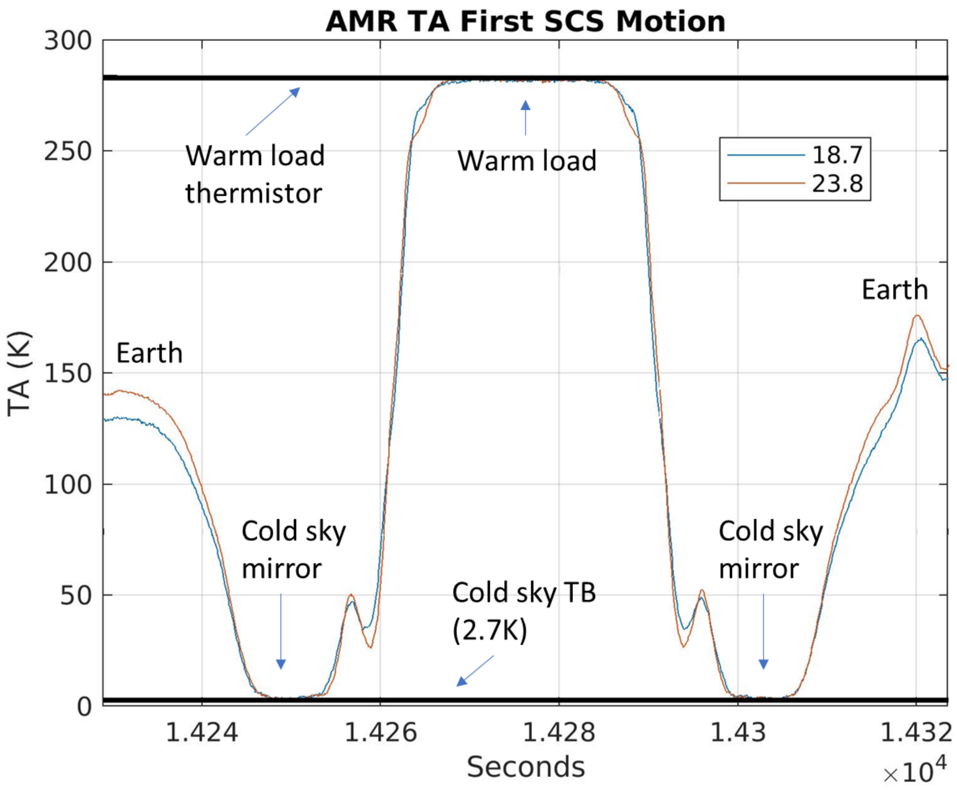


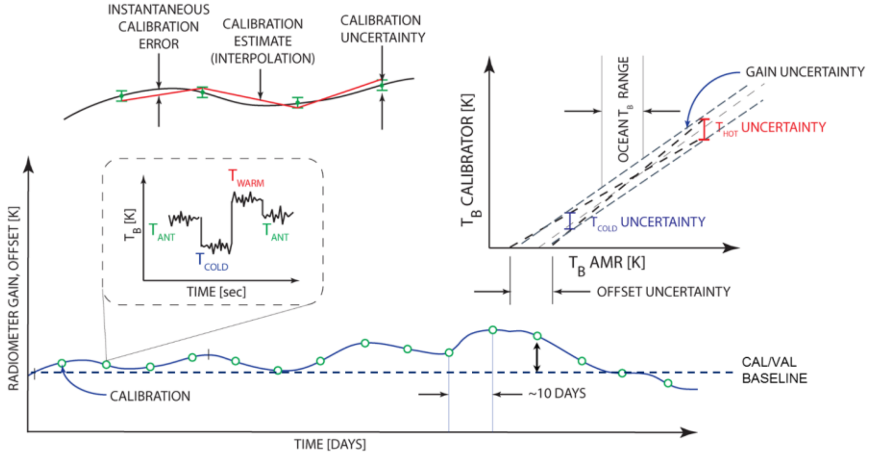
The OSTST has developed a specific requirement:

Measure globally averaged sea level relative to levels established during the cal/val phase with zero bias +/- 1 mm (standard error) averaged over any one year

Supplemental Calibration System







AMR-C includes two redundant calibration sources:

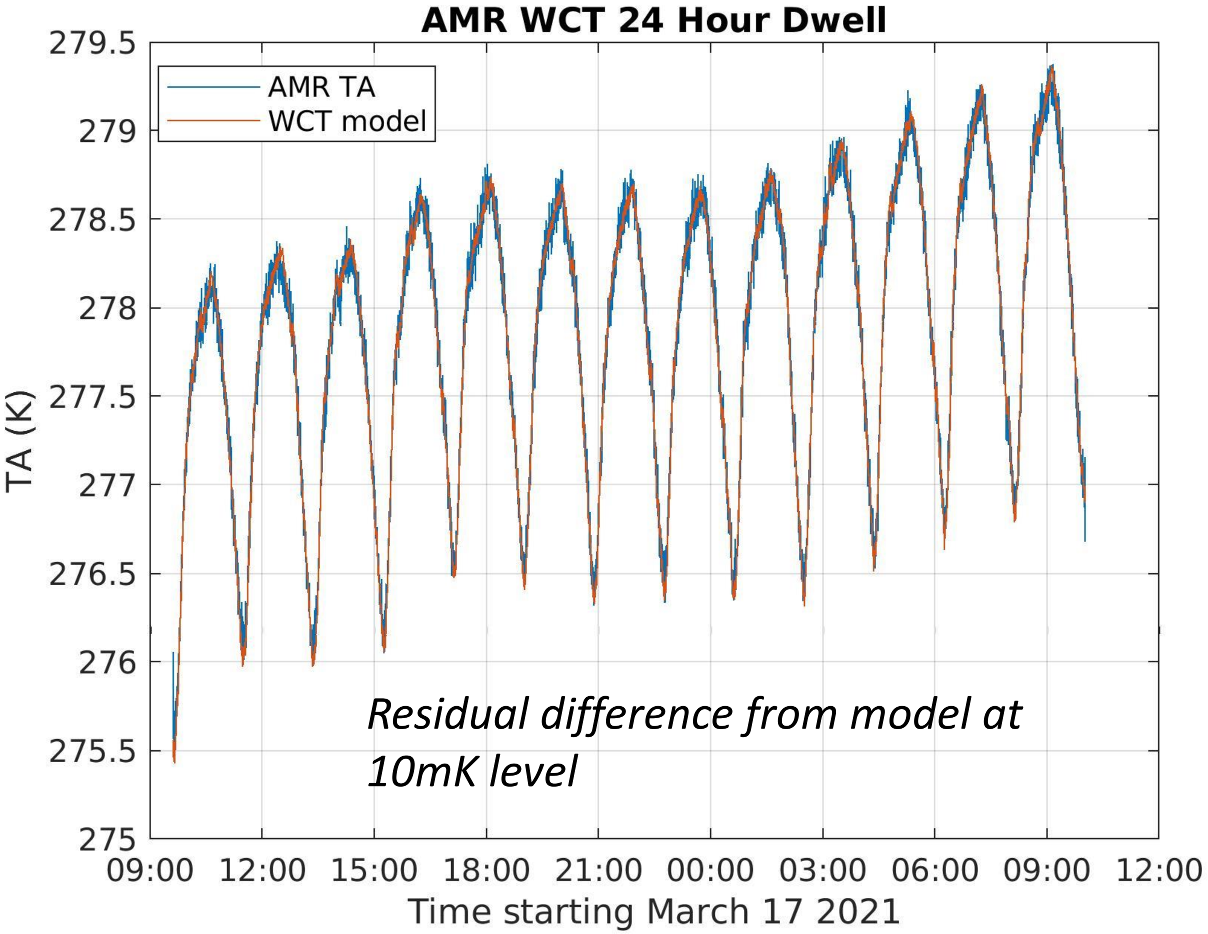
- Internal noise diodes and a switch to a termination
- External cold sky mirror and free-space blackbody target

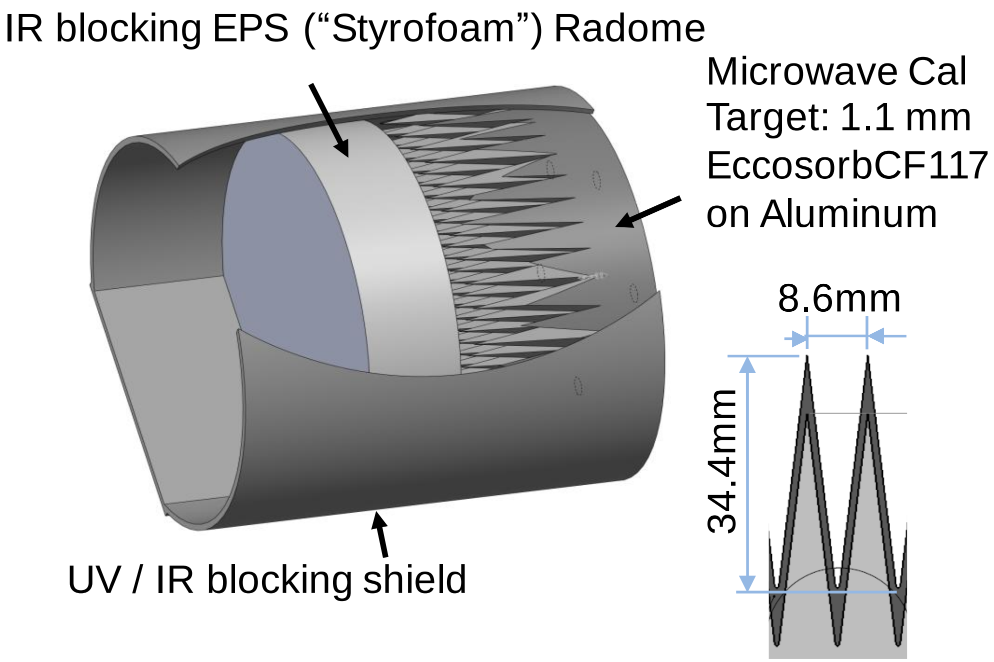
Special In-Orbit Calibration Activities

- 24 hour dwell on warm calibration target
  - Verify model for warm target brightness temperature over orbital thermal cycles (using internal calibration sources)
  - Verify Earth spill-over contributions when viewing warm target
- View sky through main reflector and secondary reflector within minutes
  - Verify Earth contribution in cold sky reflector
- View sky through main reflector during land/ocean transition
  - Verify integrated antenna pattern
- Perform SCS calibration over ocean and land within minutes
  - Verify Earth contributions are properly accounted for

In-flight Warm Target Characterization

- Warm load brightness determined from thermistors on target baseplate
- Earth fractions determined via land/ocean contrast
- **Uncertainty of warm target at 10mK level**



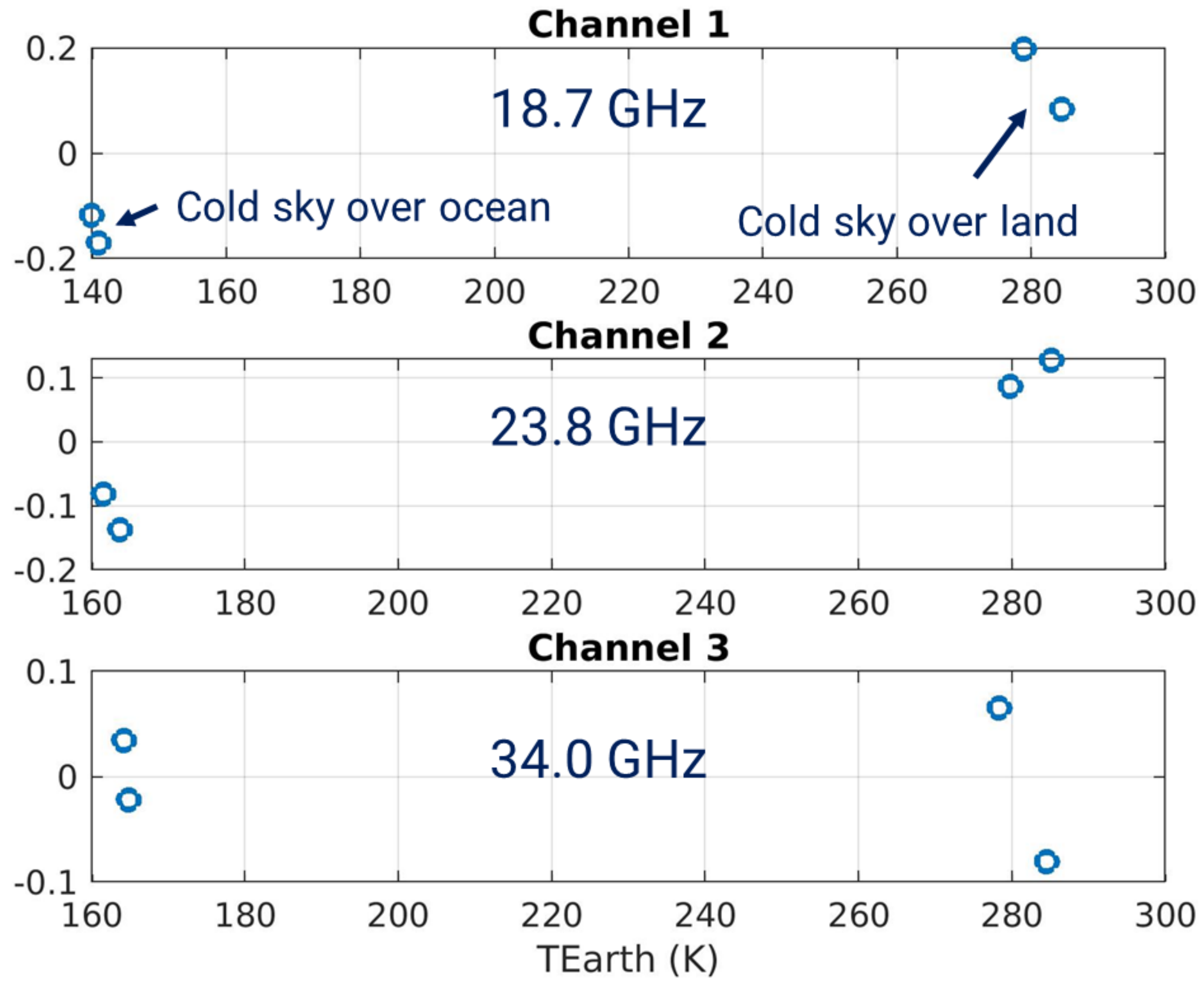


Channel	Earth Spillover Fraction
18.7 GHz	0.0012
23.8 GHz	0.0008
34.0 GHz	0.0004

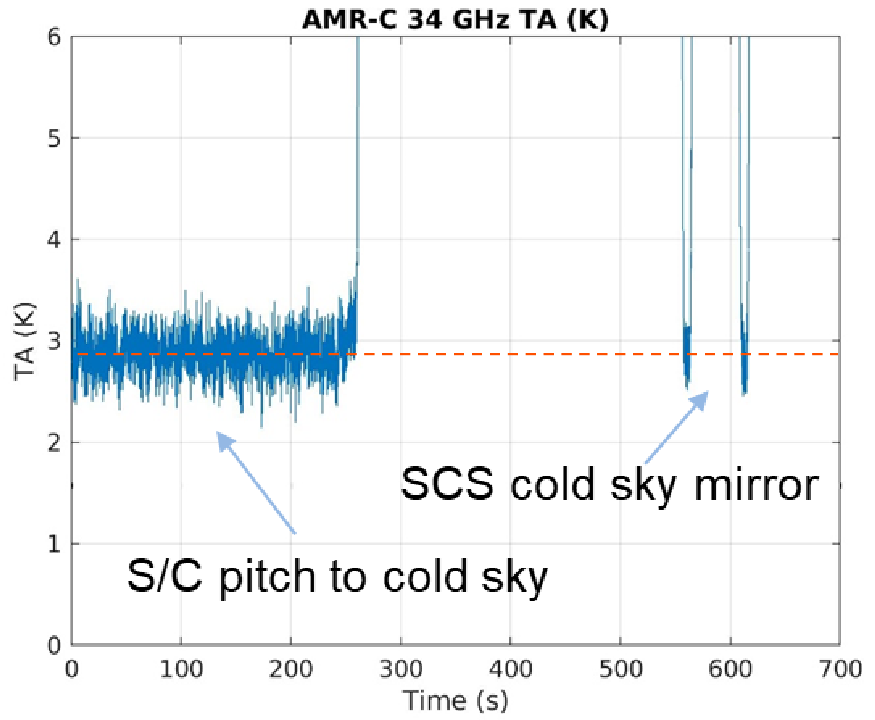
Earth contribution (spillover) consistent with pre-launch values

In-flight Cold Sky Mirror Characterization

- Viewing cold sky mirror during land/ocean transition provides ~150K background contrast to validate Earth spill-over fraction
- Comparing cold sky view between main reflector and secondary reflector is direct validation of calibration model



Channel	Earth Spillover Fraction
18.7 GHz	0.002
23.8 GHz	0.0018
34.0 GHz	0.0000

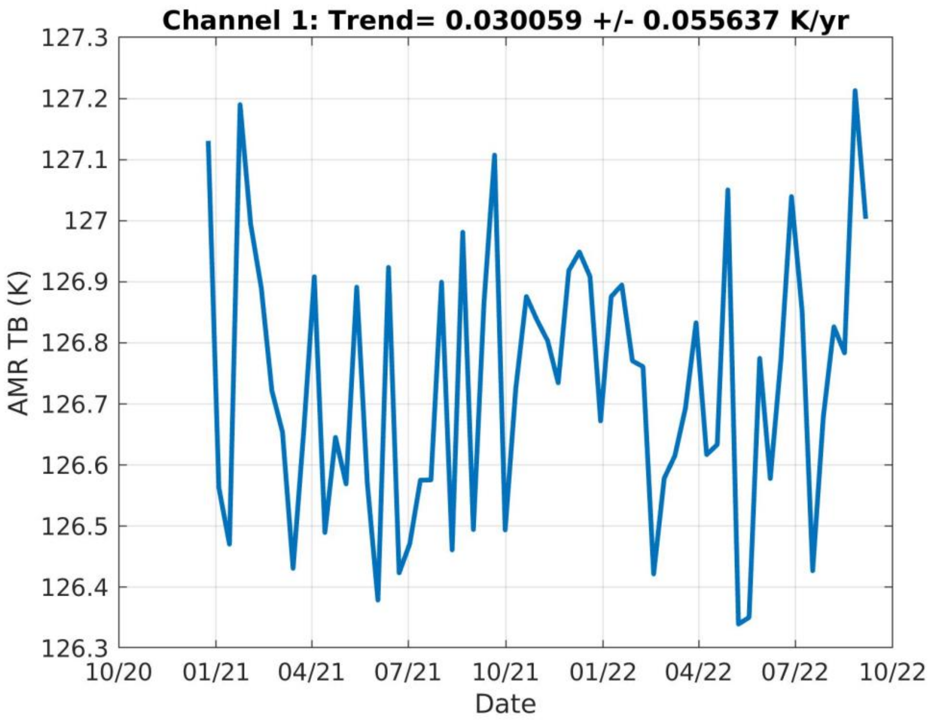


Cold sky view is equivalent between main and secondary reflectors

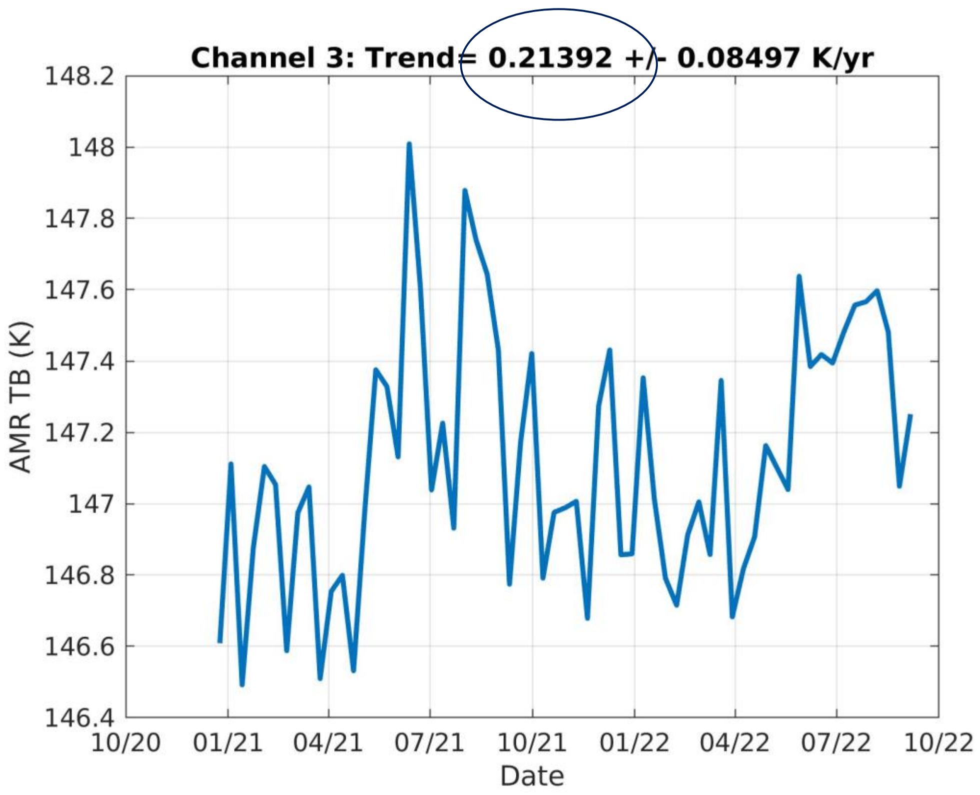
Stability Validation: Vicarious Ocean Reference

- On-Earth references have historically been used to stabilize altimeter radiometer calibration, but are now **independent** sources for Sentinel-6
- With Sentinel-6, their limitations become apparent

18.7 GHz

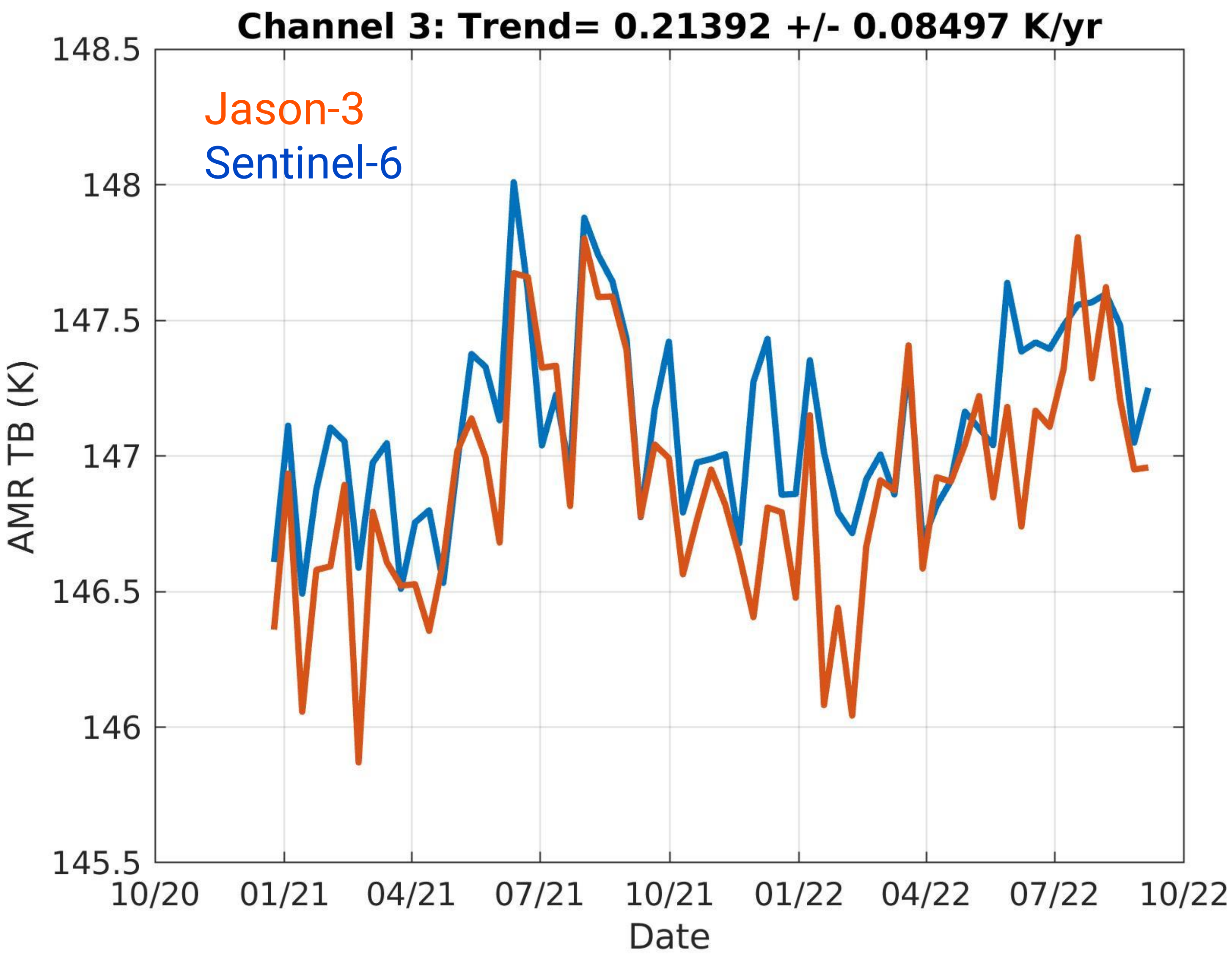


34.0 GHz



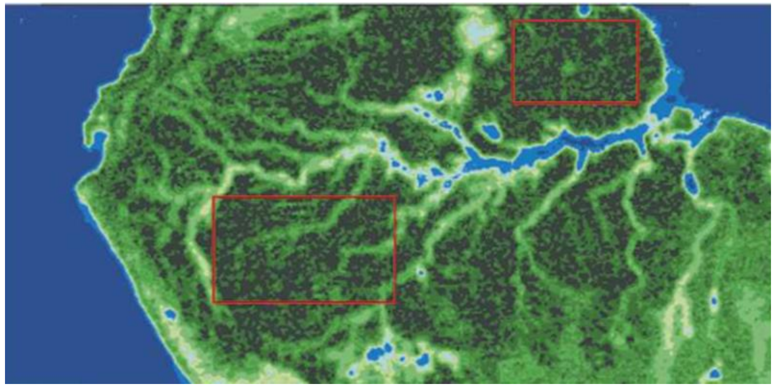
Stability Validation: Vicarious Ocean Reference

- Same spurious trend observed in 34 GHz vicarious ocean reference between Jason-3 and Sentinel-6
  - In the past, we would have introduced this artifact into the GMSL climate record introducing ~1mm/yr drift



Stability Validation: Amazon Region

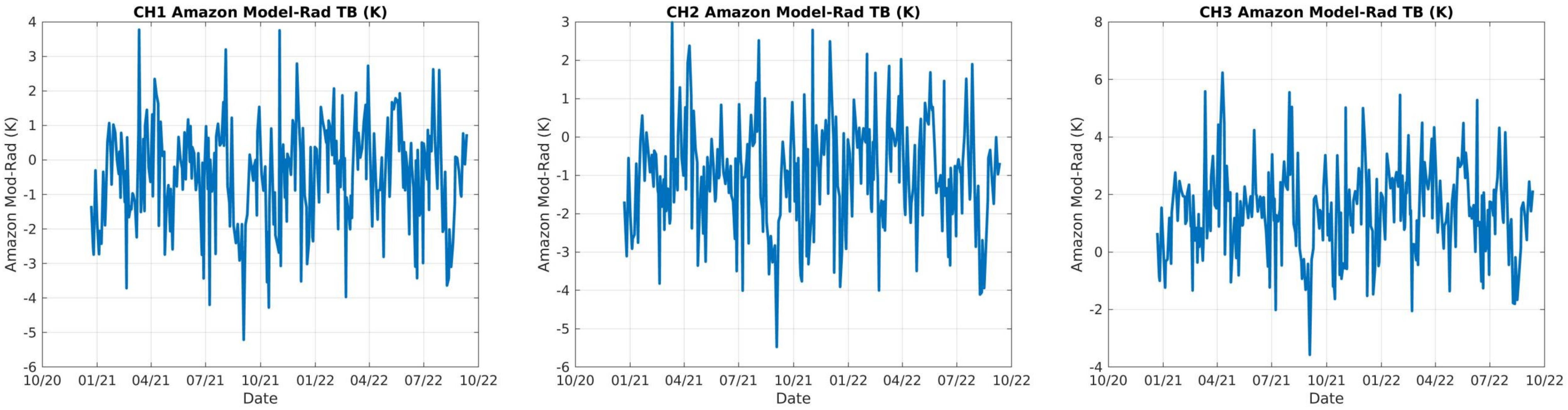
- Amazon rainforest provides blackbody like warm target
- No detectable drift observed at warm end of TB dynamic range



18.7 GHz

23.8 GHz

34.0 GHz

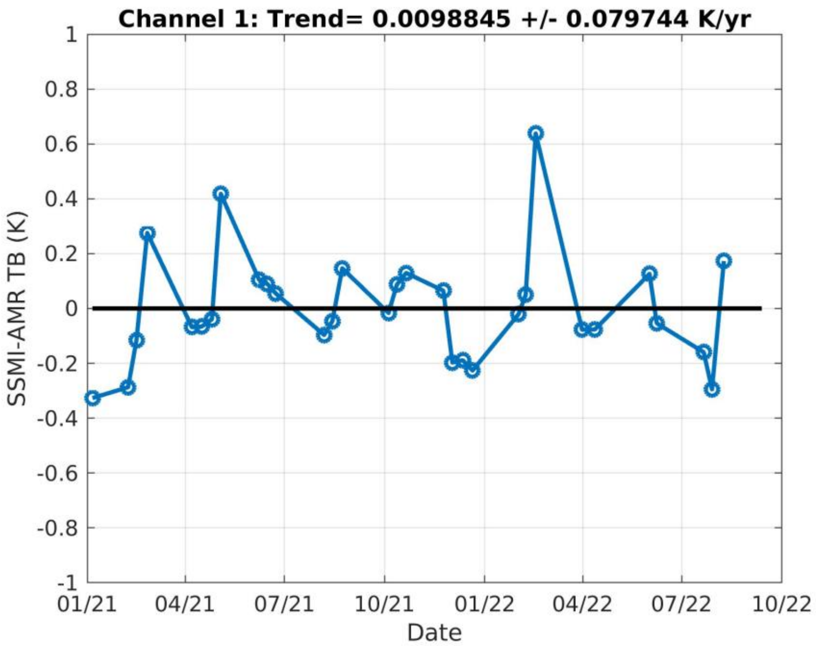


Stability Validation: Inter-satellite Calibration

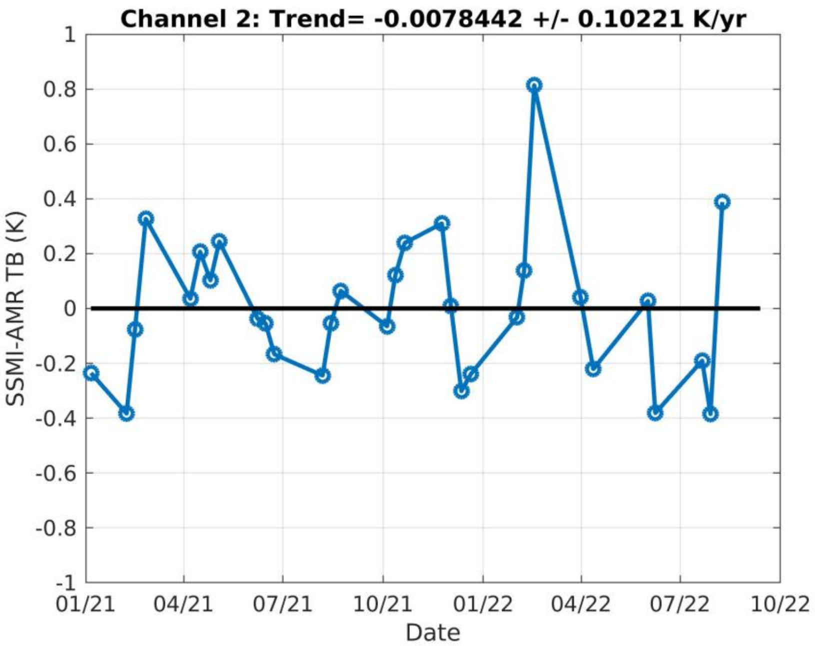
- Inter-satellite calibration most reliable means to verify radiometer stability (Brown et al., 2012)
- Compared co-located observations between AMR and SSMI F16 and F18
  - SSMI TBs converted to equivalent AMR TBs
- **No detectable trends observed in AMR-C TBs with uncertainty < 0.1K/yr**

Channel	Relative Trend to SSMI TB
18.7 GHz	0.01 $\pm$ 0.08 K
23.8 GHz	-0.01 $\pm$ 0.1 K
34.0 GHz	0.03 $\pm$ 0.04 K

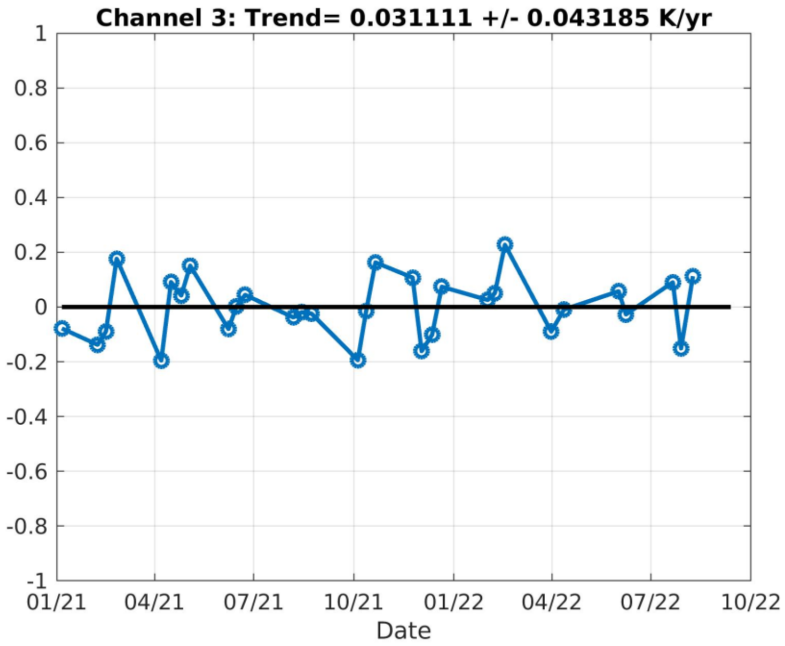
18.7 GHz



23.8 GHz



34.0 GHz

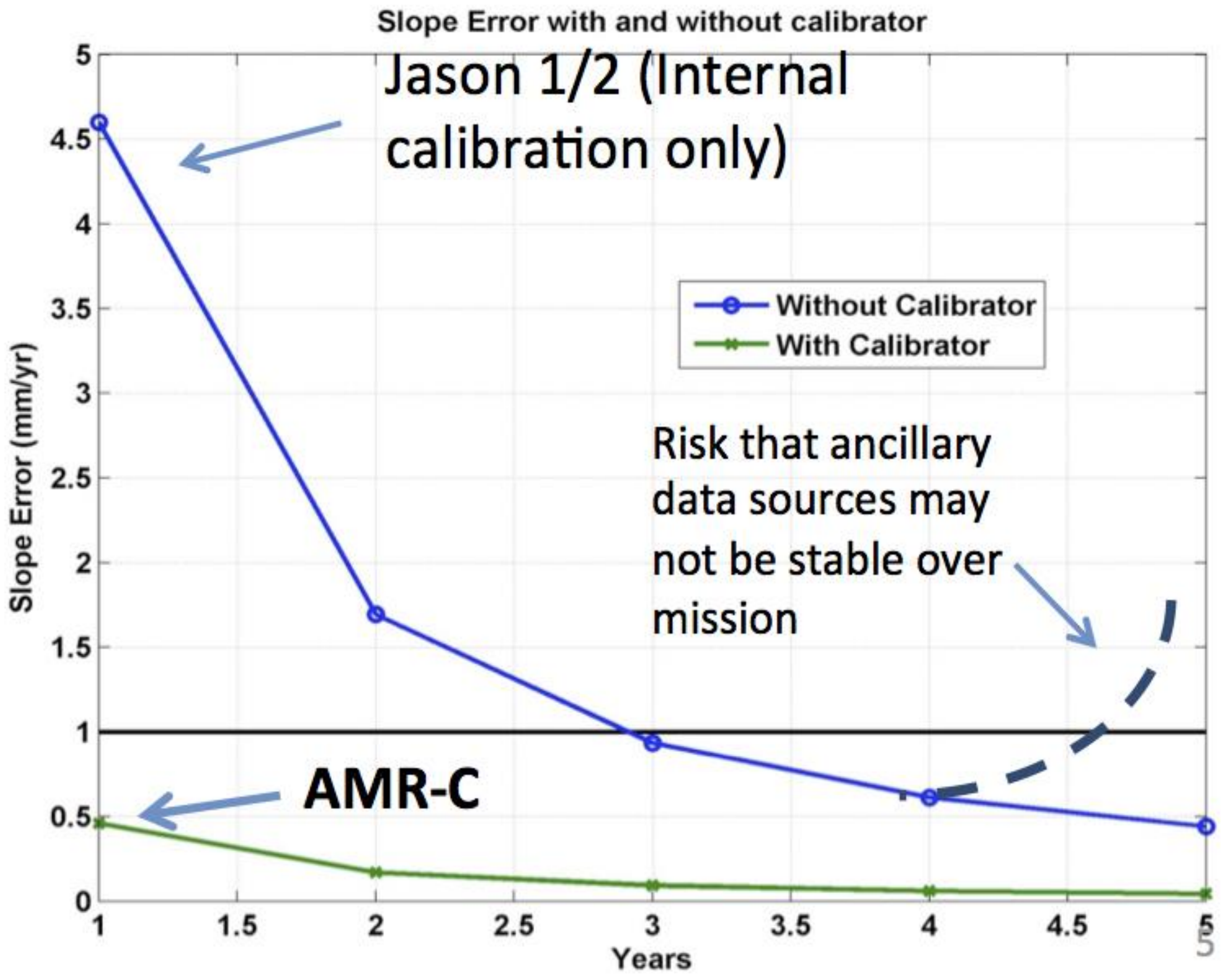


Sentinel-6: The New Climate Reference

- Wet PD long term stability estimated to be better than **0.3mm for any one year period** and eliminates reliance on ancillary data sources for calibration

- For time scales longer than 3 years, stability is << **0.1 mm/yr**

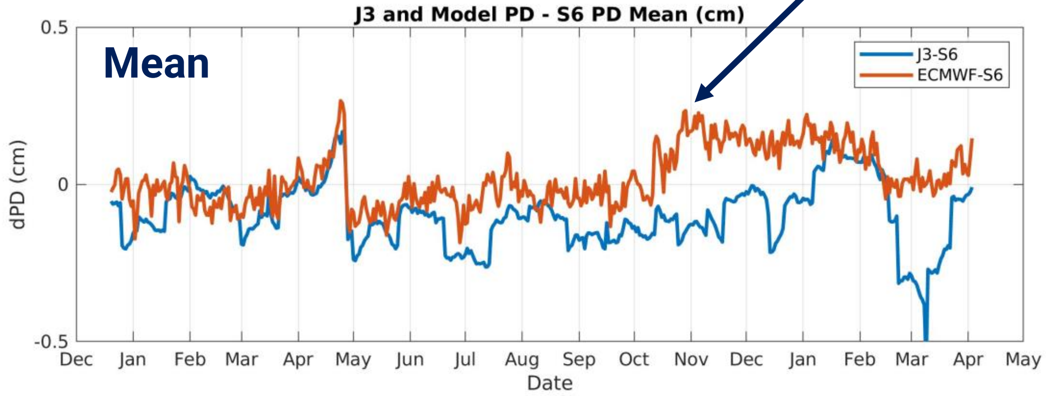
Wet PD Drift Uncertainty vs Time Span

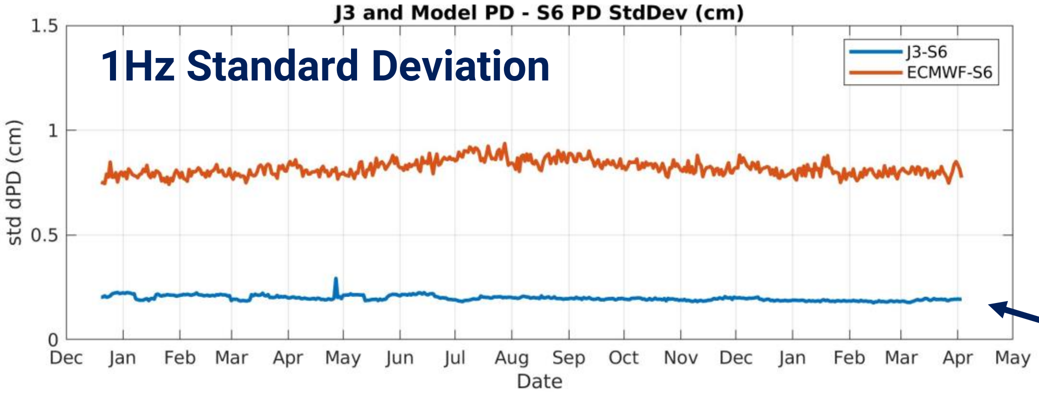


1Hz PD: Sentinel-6 compared to Jason-3 and ECMWF Model

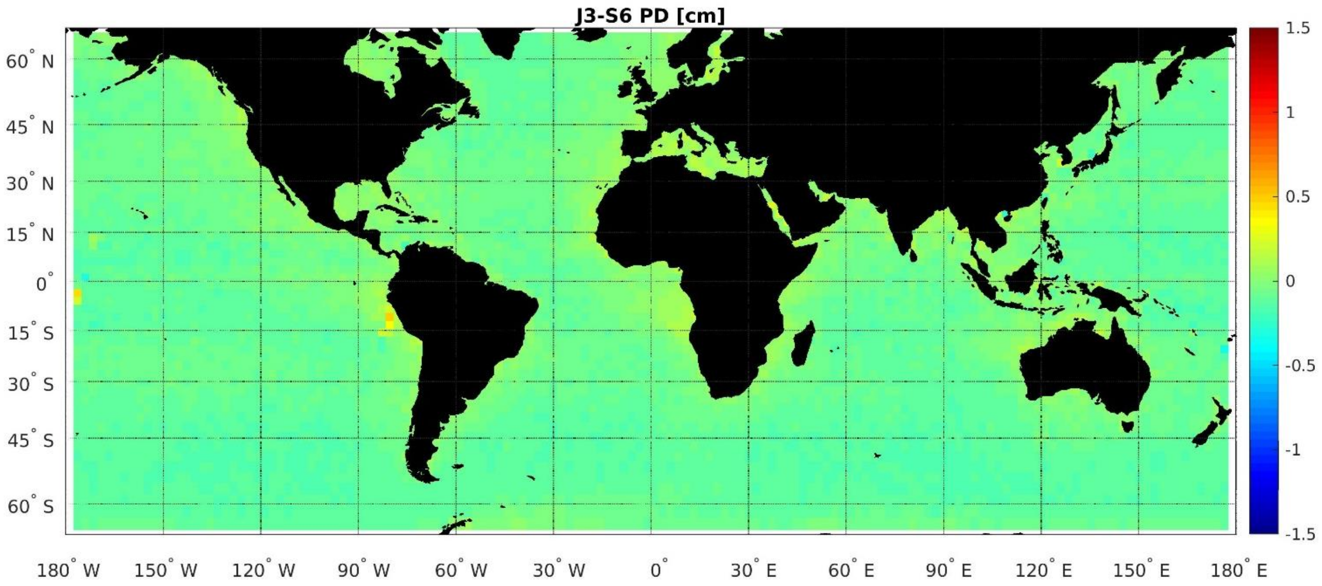
Jason-3 – Sentinel 6
ECMWF – Sentinel 6

ECMWF model change





Mean Jason-3 – Sentinel-6 PD



- Difference between J3 and S6 at mm-level
- **S6 AMR-C PD stable to within our ability to validate**

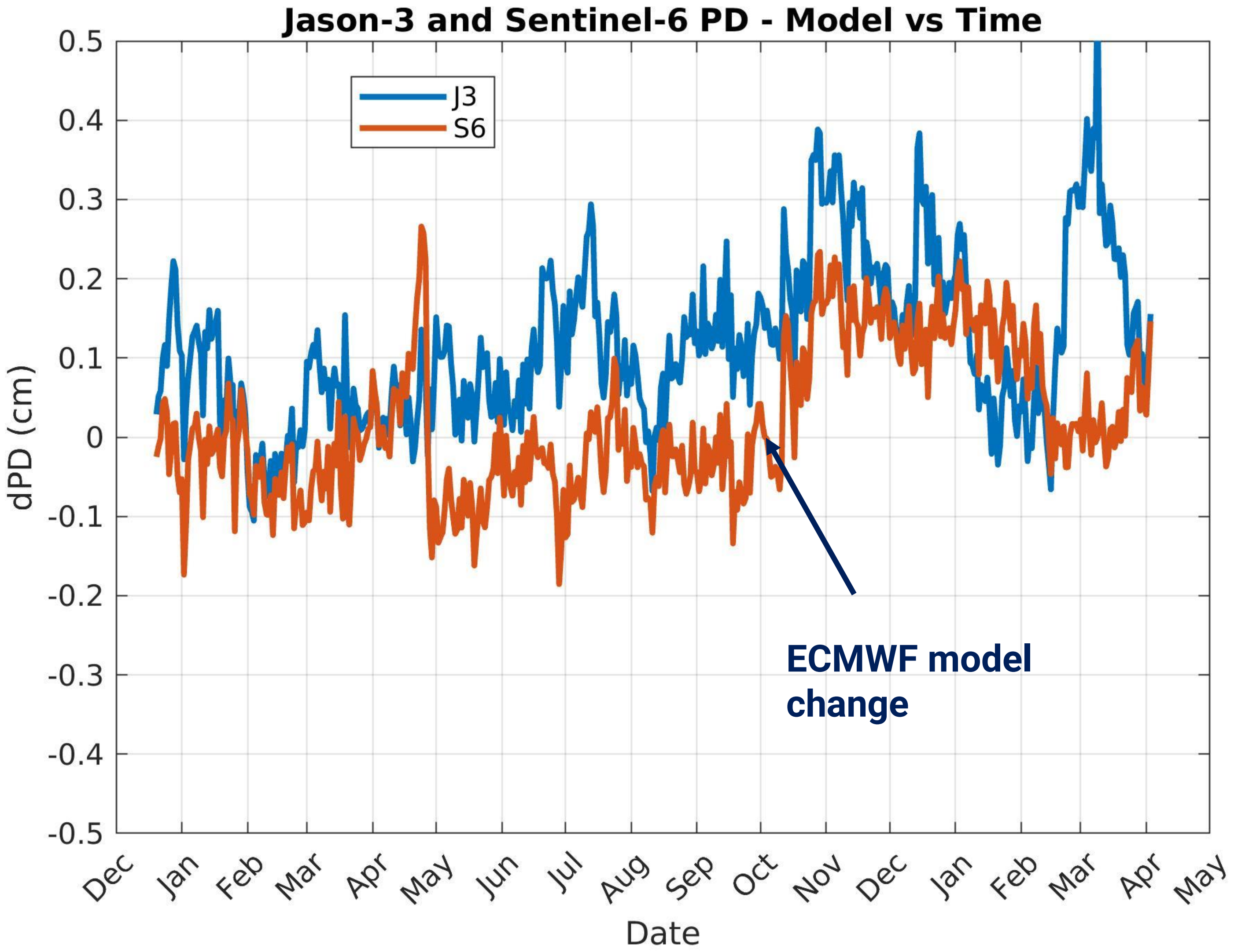
1Hz standard deviation between J3 and S6 stable at **2mm level** over tandem period (sensor noise level)

Jason-3 and Sentinel-6 Compared to ECMWF

- Sentinel-6 more stable than Jason-3 due to SCS system
  - Jason-3 calibrates ~30-60 days via cold sky pitch observations
  - Single calibration source only partially stabilizes Jason-3

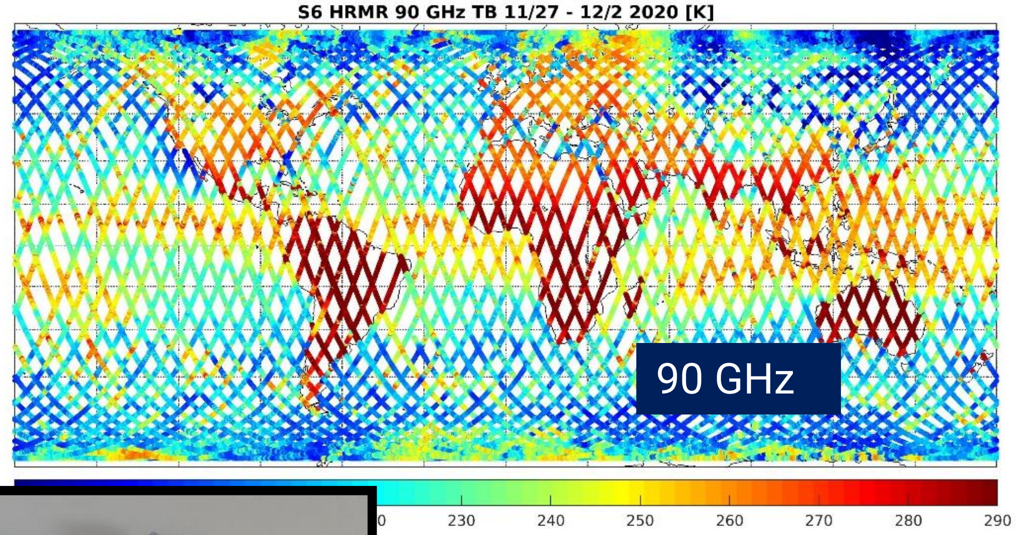
- Jason-3 long term calibration to be re-visited to exonerate or confirm suggested drift

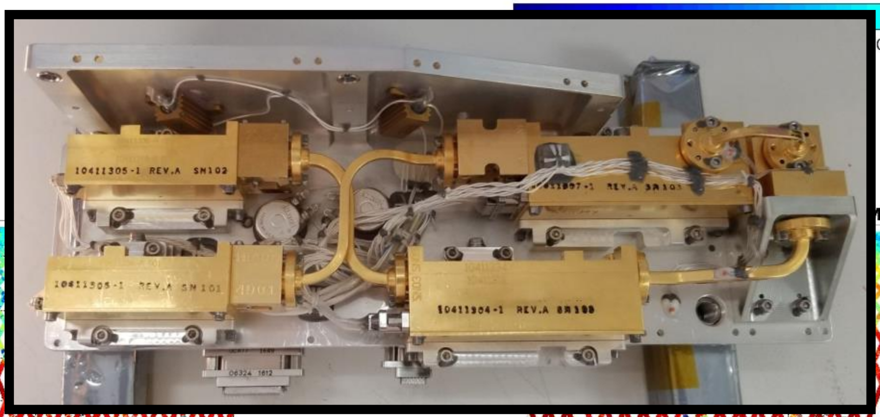
ECMWF - Jason-3
ECMWF – Sentinel 6

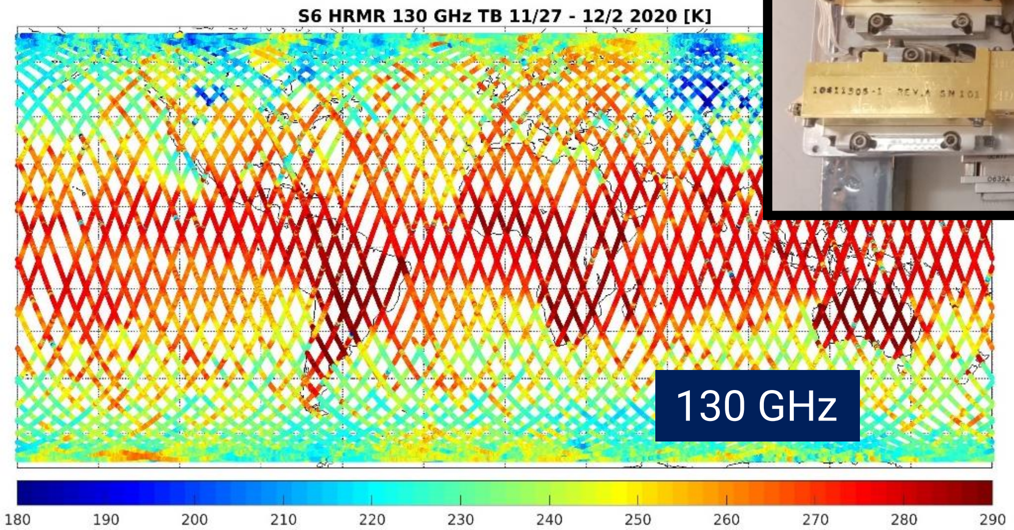


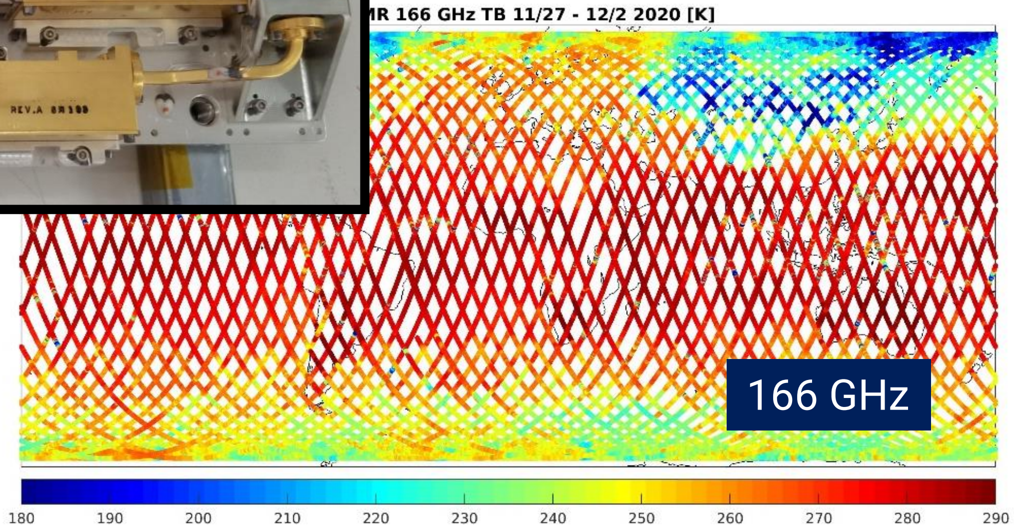
HRMR Performance

- HRMR is experimental payload, performing nominally to date
- Observes at 90, 130 and 166 GHz with <5km spatial resolution
- Data used to extend wet path delay measurement to within 10km from land with 1cm goal



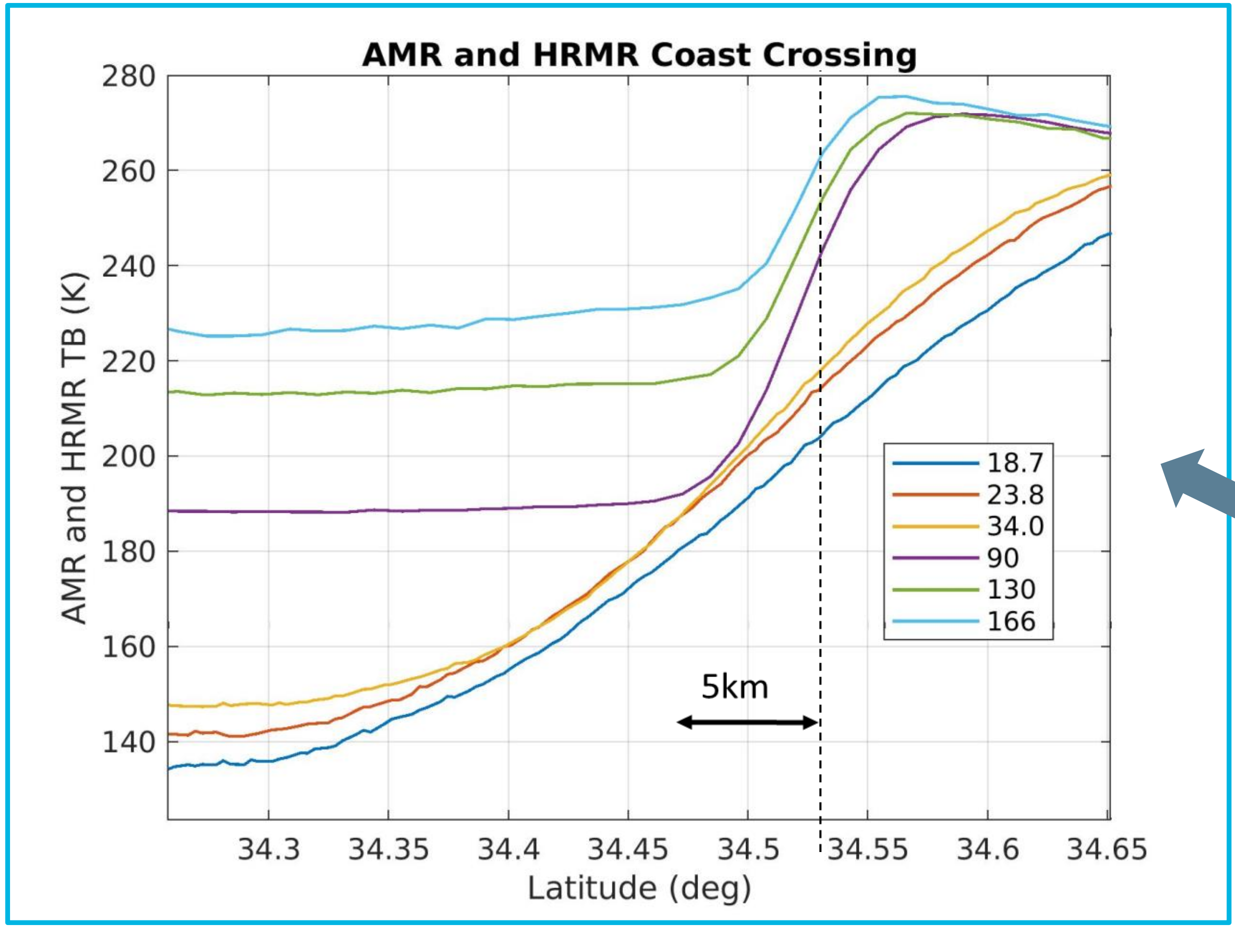


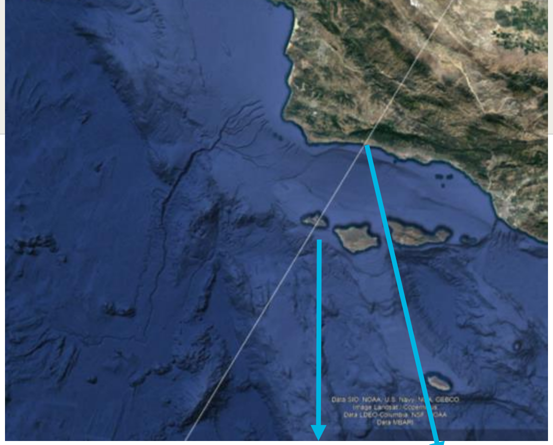


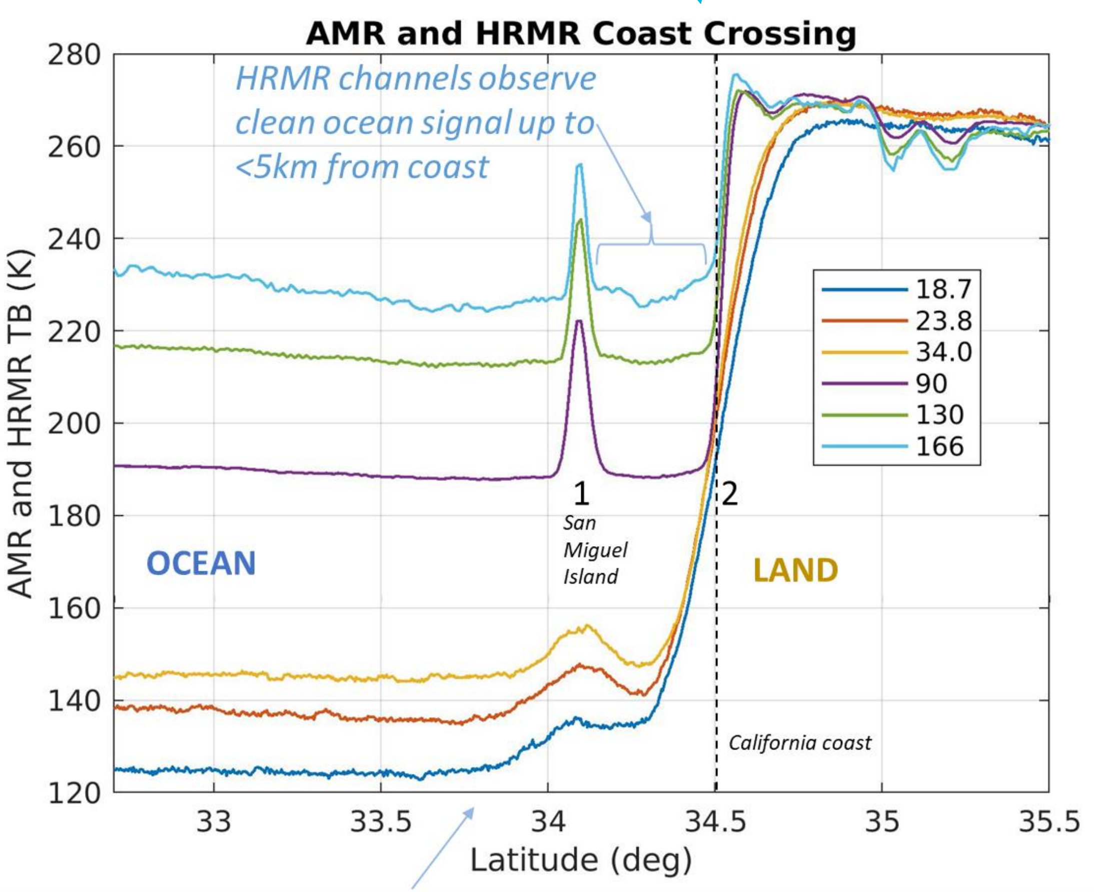


HRMR Performance

HRMR free from land contamination up to 5km from coast

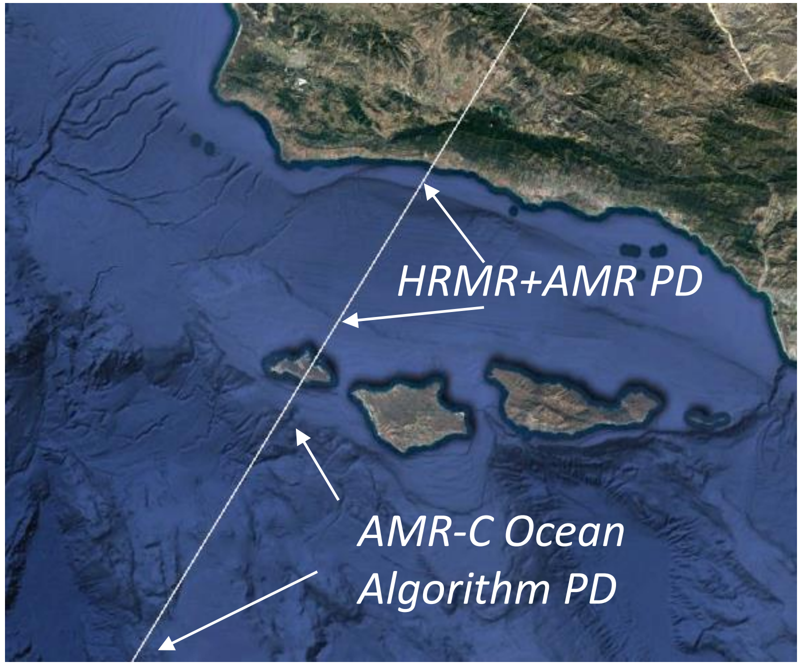






AMR-C channels first impacted by land contamination ~65km from coast

HRMR Path Delay



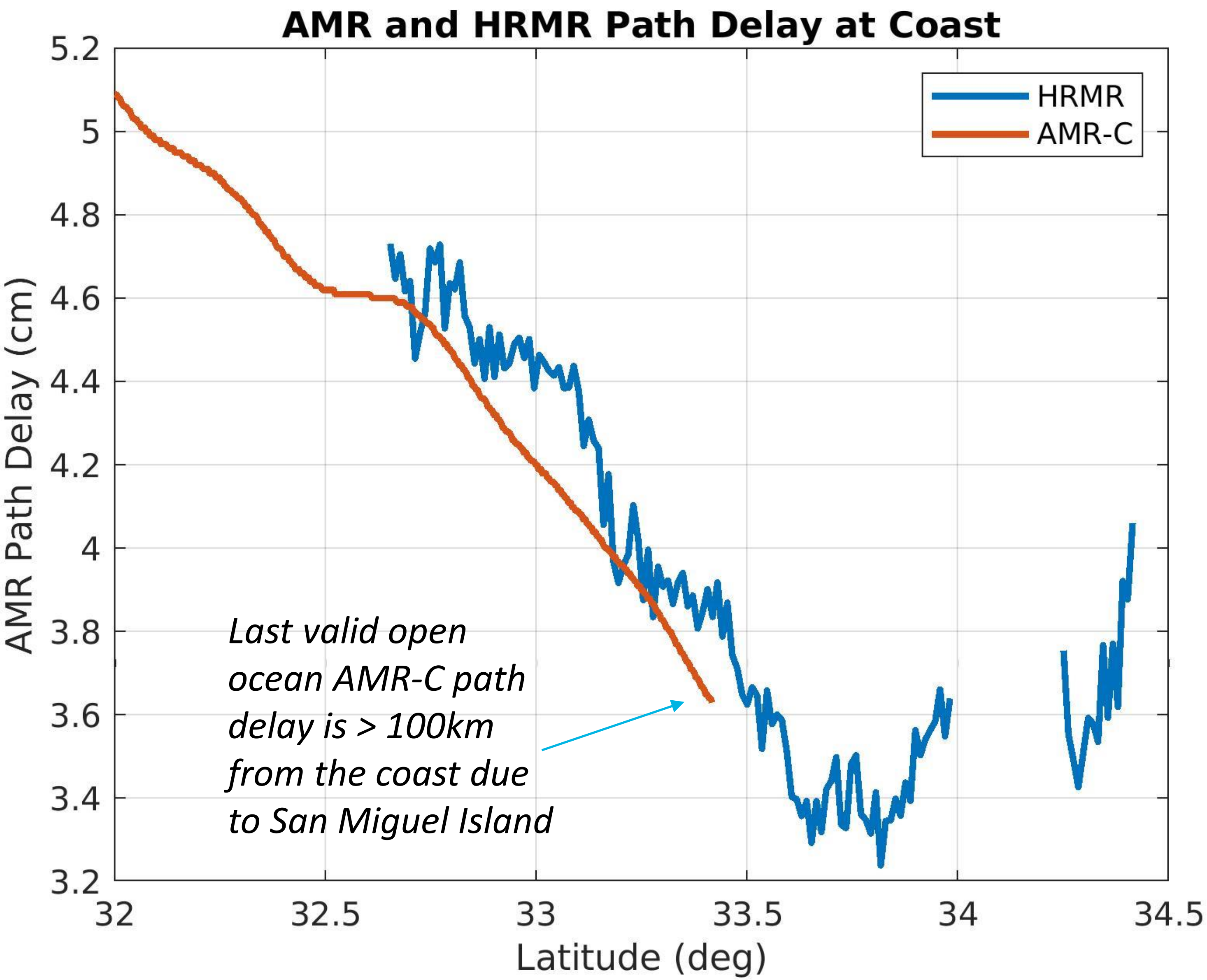
HRMR PD algorithm linearized about first guess PD from AMR-C

$$HRMR_{PD} = c_0(PD) + \sum_{f,p} c_{f,p}(PD)\,(T_{mb}(f))^p$$

Then blended with low-frequency coastal algorithm based on relative errors (Kalman algorithm)

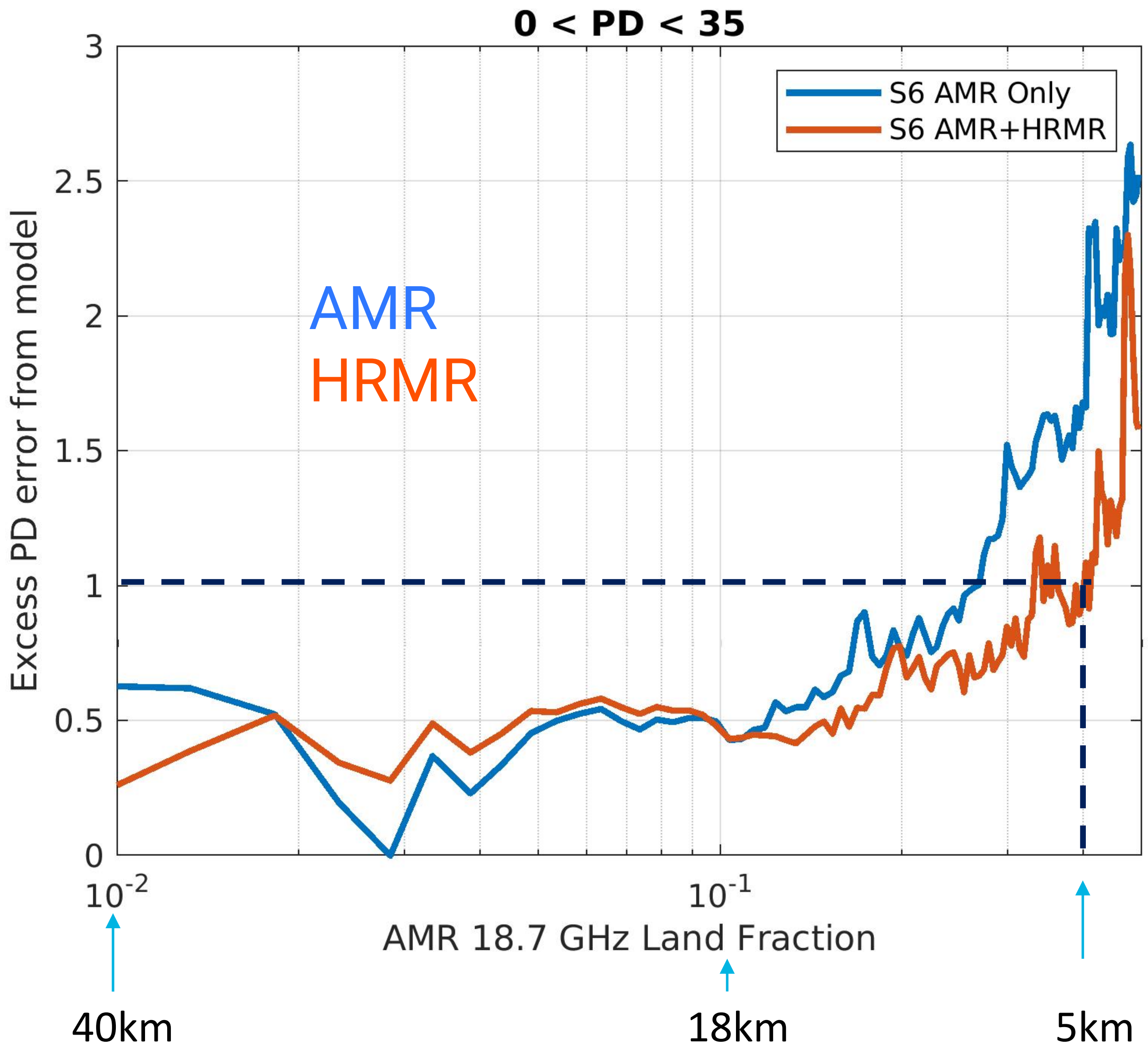
$$PD_{HRMR\_blend} = PD_{AMR}(1-G) + PD_{HRMR}G$$

$$G = \frac{\sigma^2_{AMR}(land\_frac)}{\sigma^2_{AMR}(land\_frac) + \sigma^2_{HRMR}(PD)}$$



HRMR Coastal Path Delay Performance

- Computed excess error from model relative to open ocean as a function of land fraction (distance to coast)
  - Same validation approach used for AMR coastal algorithm currently in use
- HRMR+AMR has up to 50% reduction in variance from AMR only coastal PD to coast
- HRMR+AMR excess error globally less than 1 cm to 5km from land
- HRMR algorithm work on-going

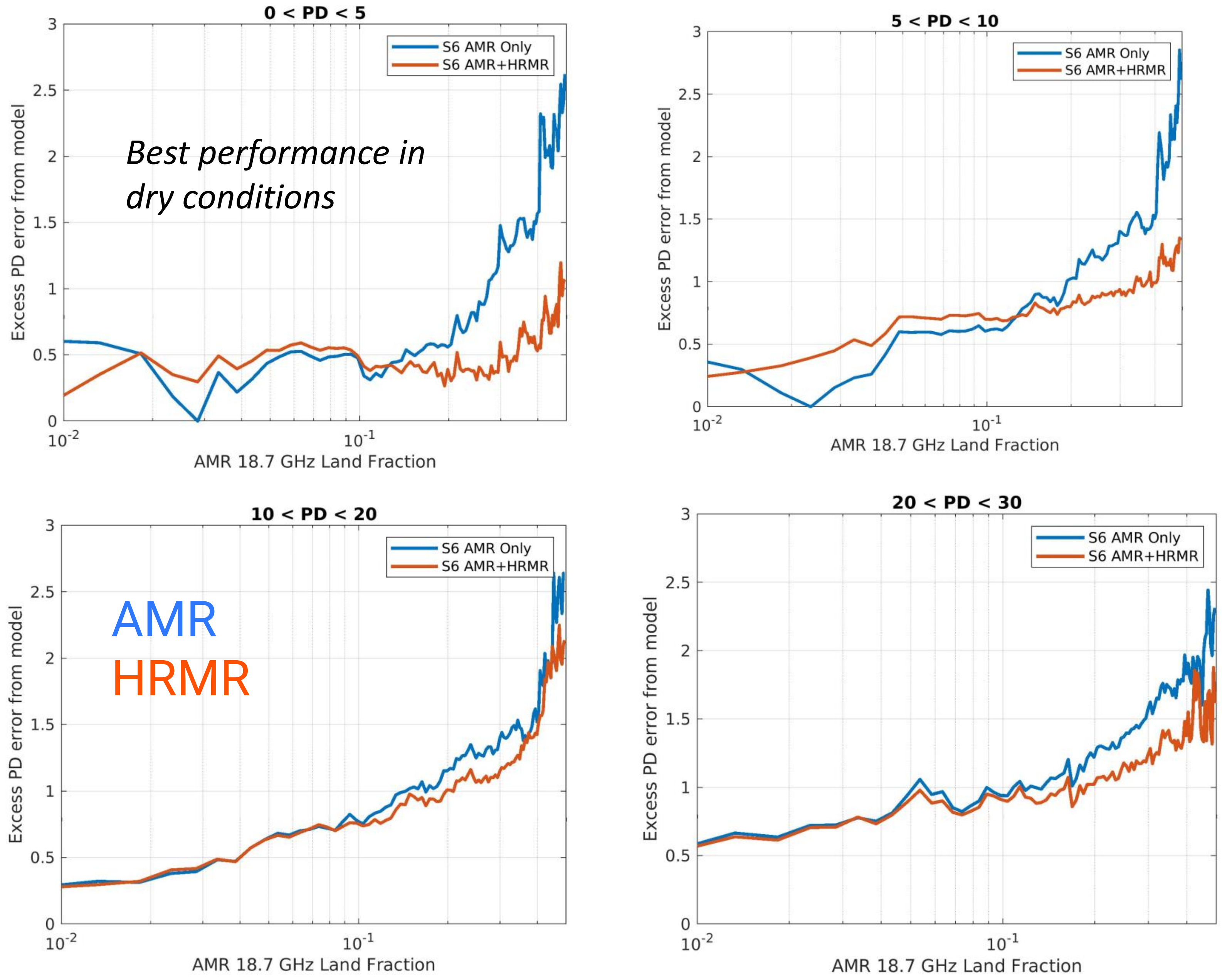


HRMR Coastal Path Delay for different PD ranges

- HRMR improves performance over all PD ranges

- HRMR performance improvement significantly better for PD < 10cm where HRMR has best signal to noise

- For PDs < 5cm, almost no degradation from open ocean performance



Summary

- AMR-C and HRMR meeting requirements/goals, performing nominally
- AMR-C sets new standard for wet path delay stability, all but **eliminating radiometer contribution to GMSL trend error** without latency
  - 0.3 mm/yr for 1 year span
  - << 0.1 mm/yr for >3 year span
- HRMR demonstrating 1cm error to 5km from land
  - HRMR TBs and PDs appearing in next product release
  - **Algorithm evolutions anticipated (OSTST contributions encouraged)**
  - **Exploit HRMR for other applications (e.g. snow/ice/precipitation)**