Early Results and Potential Earth Science Applications: Temporal Experiment for Storms and Tropical Systems Technology Demonstration (TEMPEST-D) 6U CubeSat Mission

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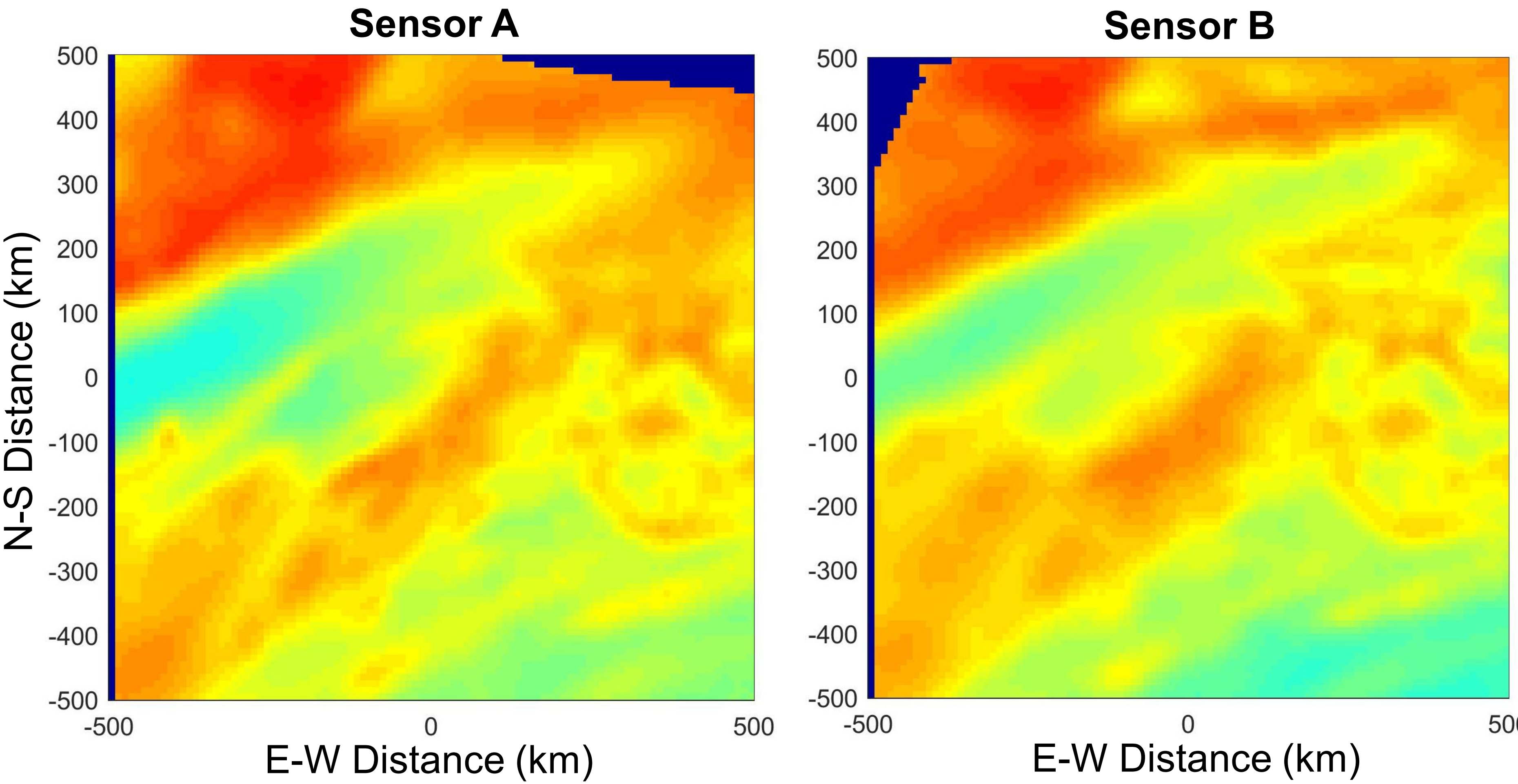
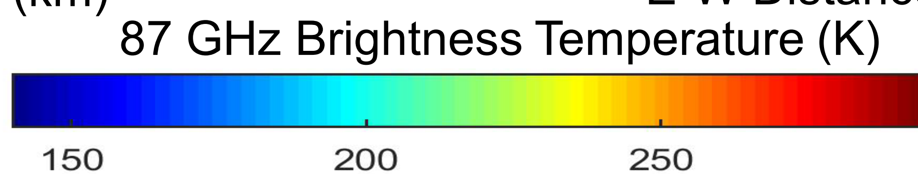
[3]Blue Canyon Technologies, Boulder, CO

Thanks to NASA Wallops for providing ground station communications support.

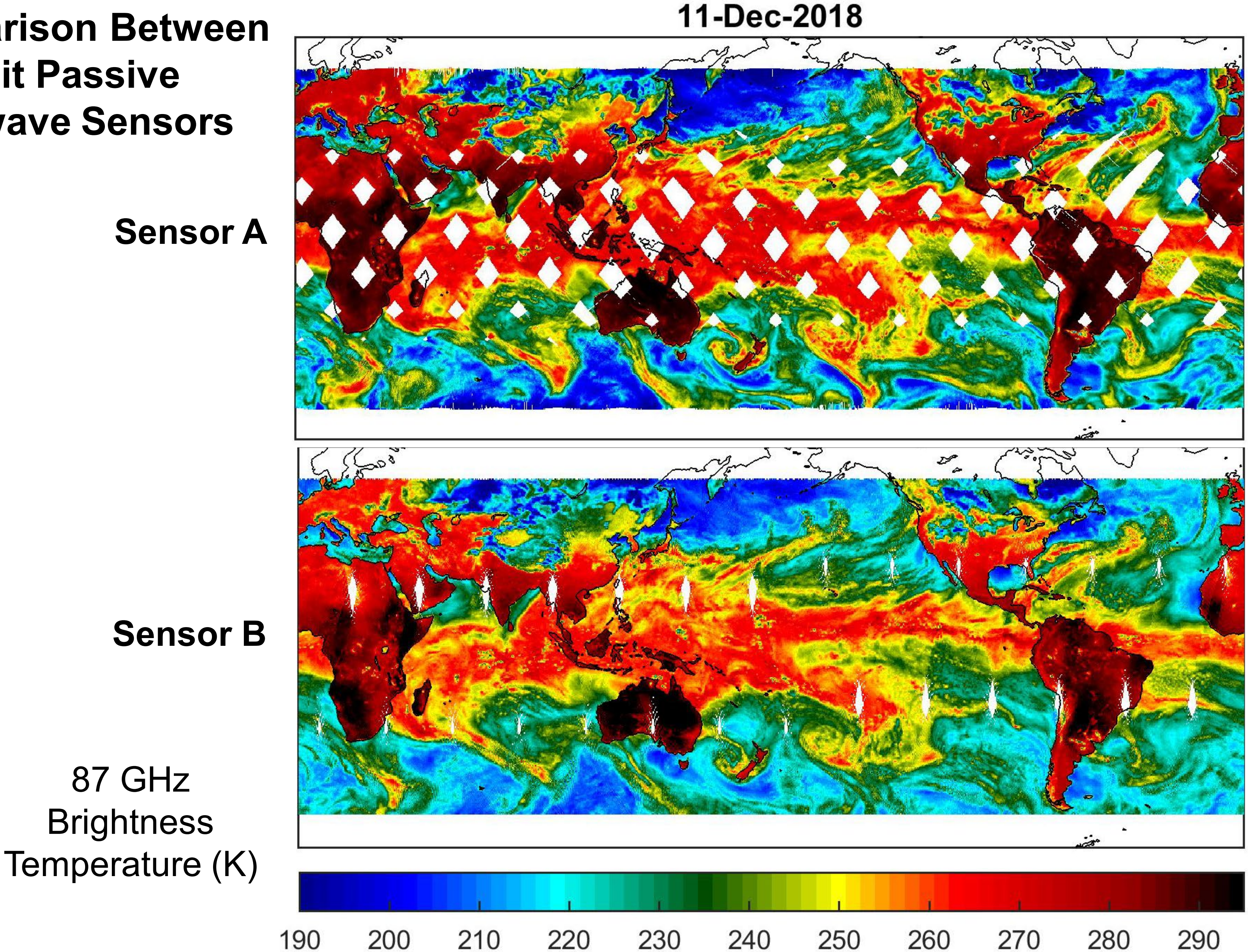
Comparison Between On-orbit Passive Microwave Sensors



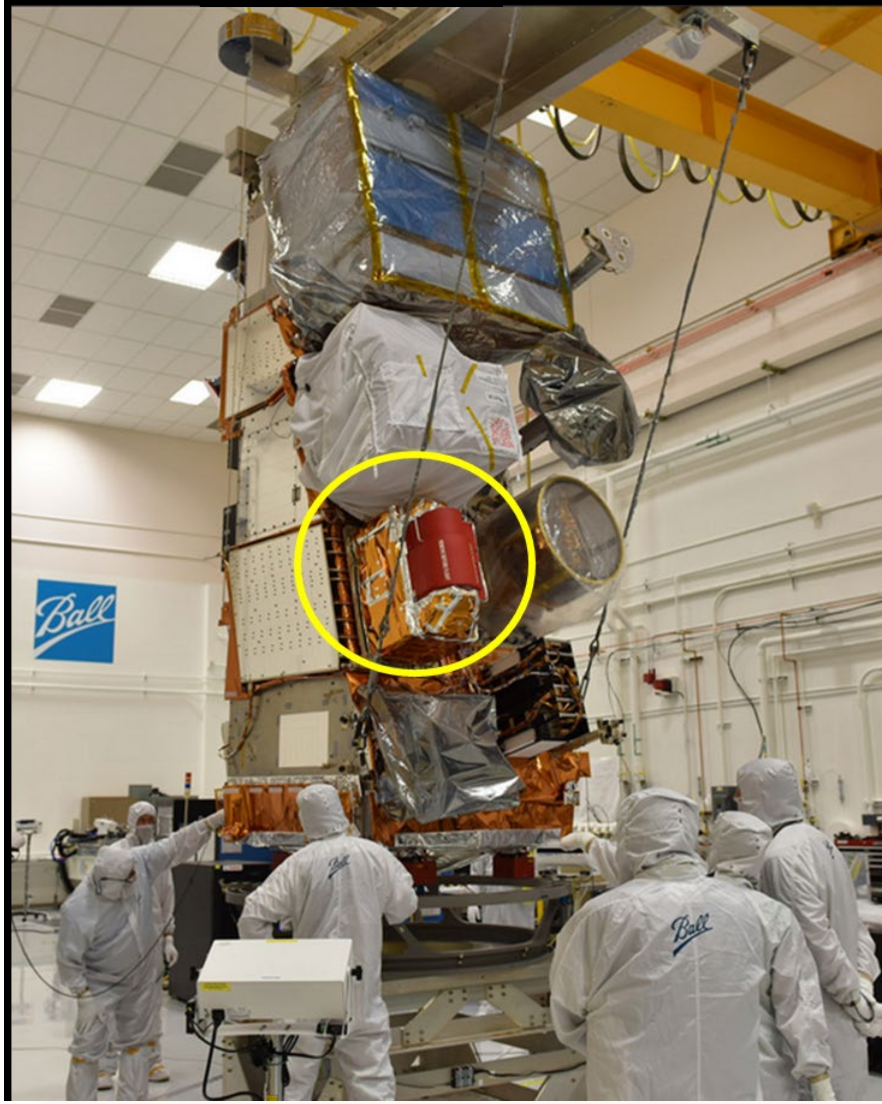
Oct. 16, 2018
12 UTC
Southern Ocean



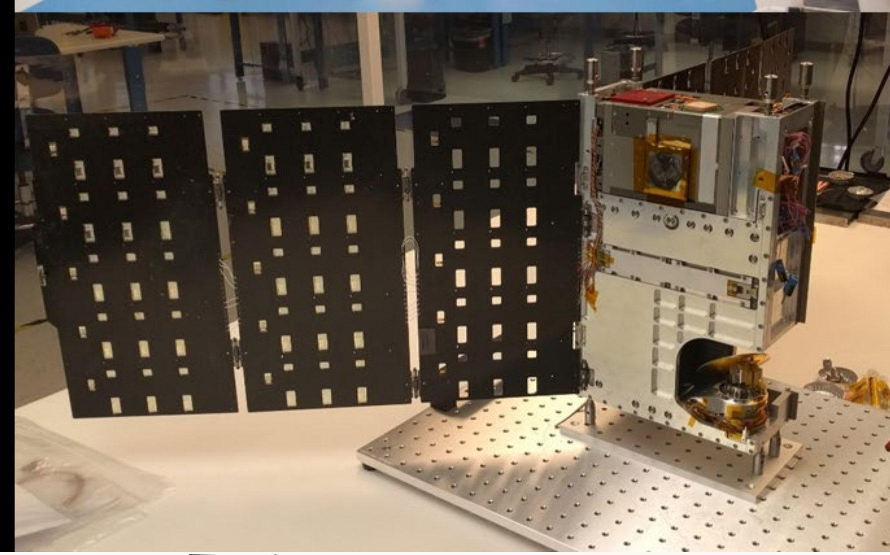
Comparison Between On-orbit Passive Microwave Sensors



Sensor B
NOAA Advanced Technology Microwave Sounder (ATMS)
75 kg, 100 W, $$$$



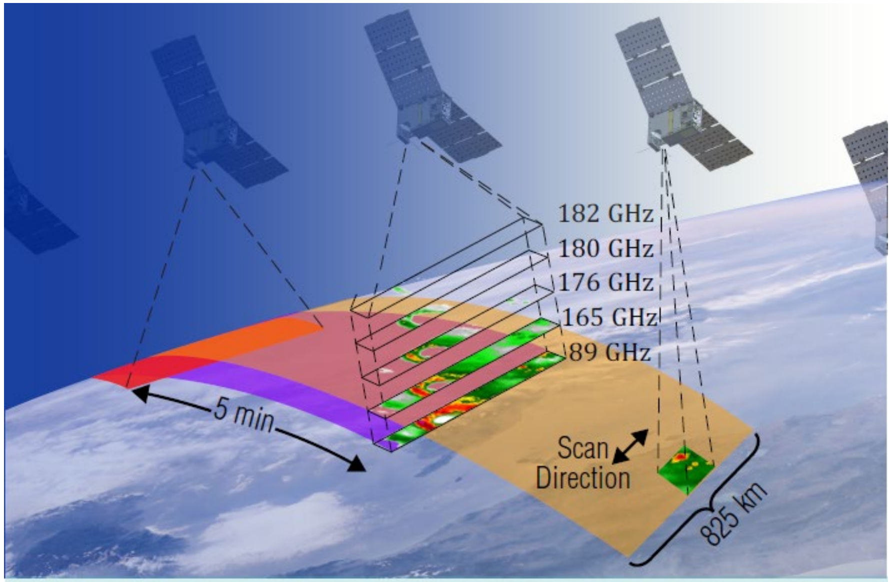
Sensor A
TEMPEST-D
3.8 kg, 6.5 W, $



Temporal Experiment for Storms and Tropical Systems (TEMPEST)

TEMPEST addresses 2017 National Academies Earth Science Decadal Survey:

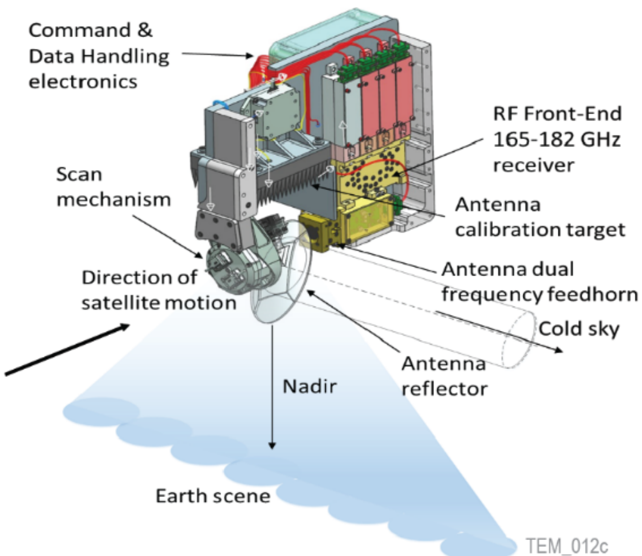
- *Why do convective storms, heavy precipitation, and clouds occur exactly when and where they do?*
  - Providing global, *temporally-resolved observations of cloud and precipitation processes* using a train of 6U CubeSats with millimeter-wave radiometers
  - Sampling rapid changes in convective clouds and surrounding water vapor environment every 3-4 minutes for up to 30 minutes.
- TEMPEST-D, a NASA Earth Venture Tech Demo mission, delivered a 6U CubeSat with radiometer instrument to launch provider 2.5 years after project start.
- Launch provided by CSLI on ELaNa 23
- Launched by Orbital ATK on CRS-9 from NASA Wallops to ISS on May 21, 2018
- Deployed into orbit from ISS by NanoRacks on July 13, 2018
- Demonstrated 7 months of mission lifetime to date since commissioning.



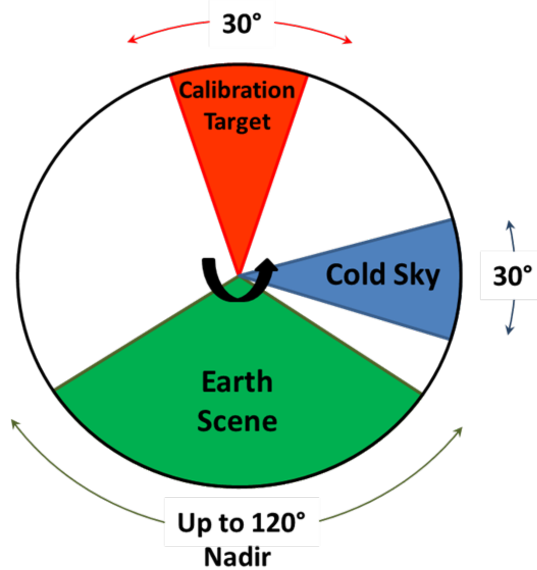
5 identical 6U small sats, each with an identical 5-channel radiometer, flying 5 minutes apart

TEMPEST-D Instrument Performs End-to-End Radiometric Calibration

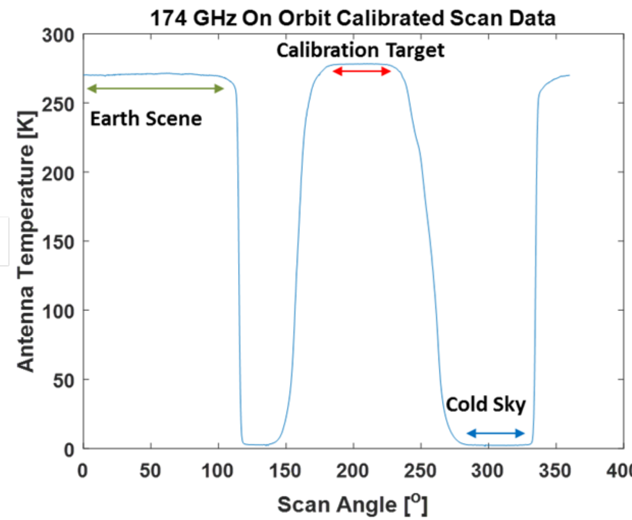
TEMPEST-D Instrument



Observing Profile

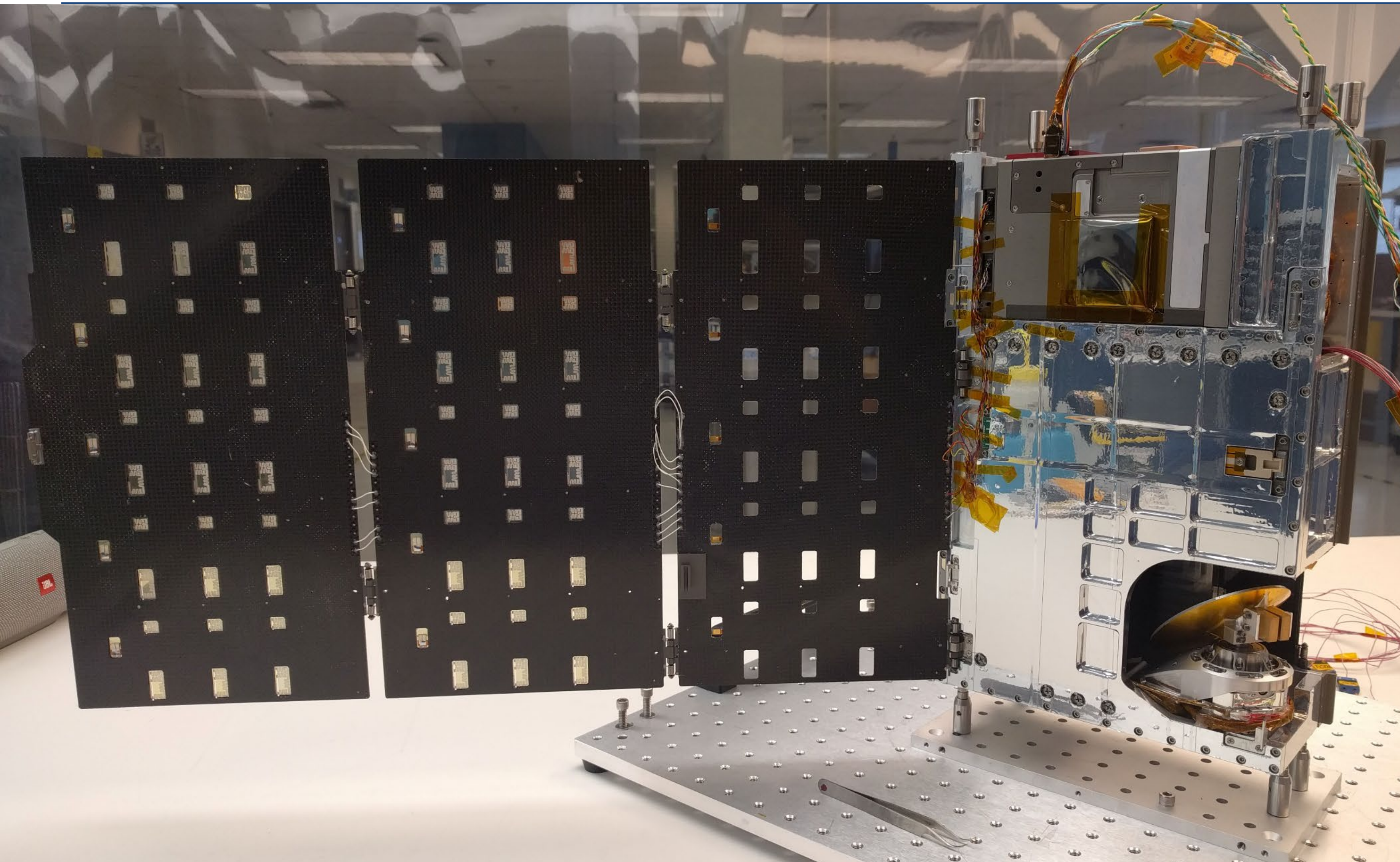


Time Series of Output Data



- Five-frequency millimeter-wave radiometer measures Earth scene up to ±60° nadir angles, for an 1550-km swath width from a initial orbit altitude of 400 km. Spatial resolution ranges from 13 km at 181 GHz to 25 km at 87 GHz.
- TEMPEST-D performs two-point end-to-end calibration every 2 sec. by measuring cosmic microwave background at 2.73 K (“cold sky”) and ambient blackbody calibration target each revolution (scanning at 30 RPM).

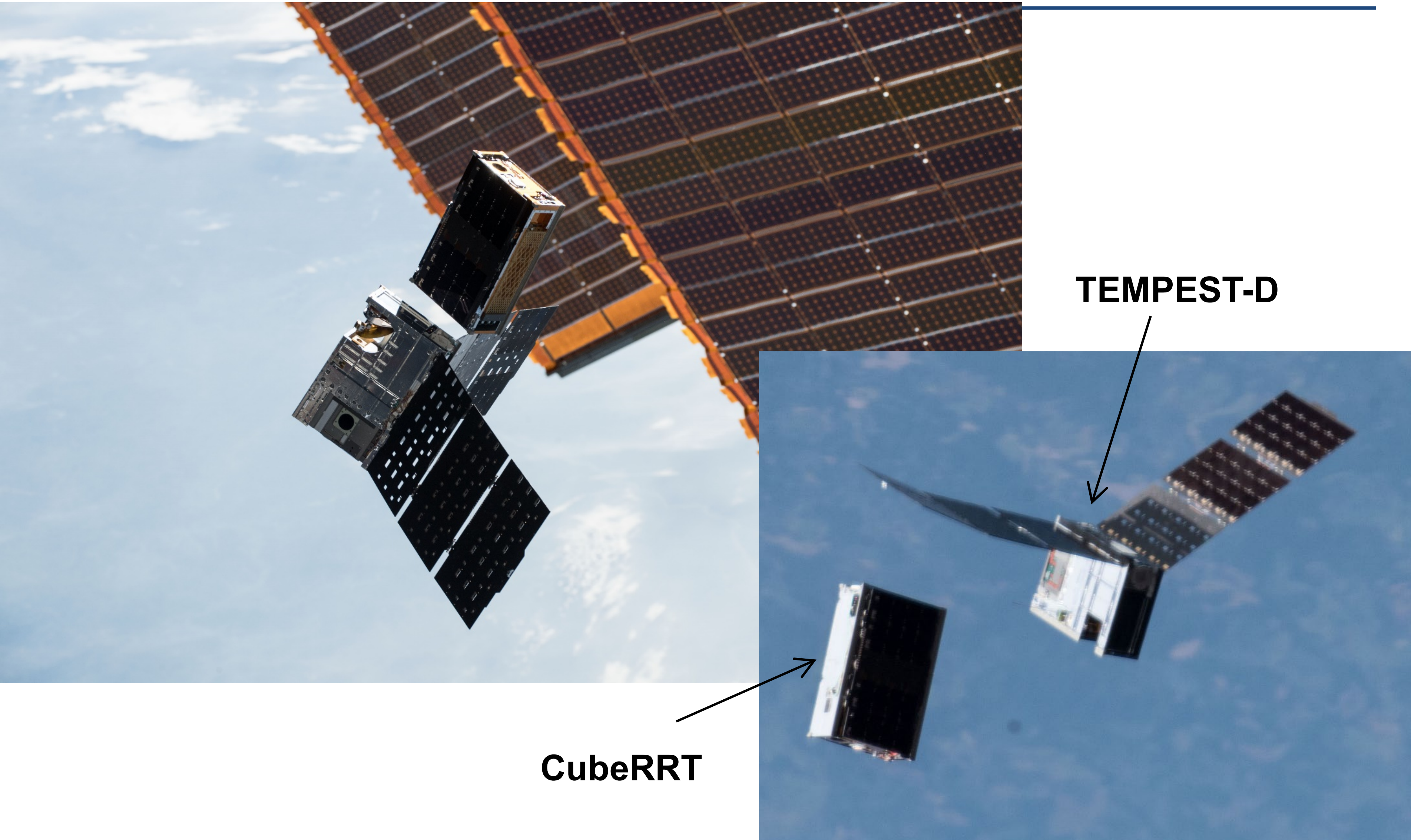
TEMPEST-D Spacecraft Integrated at BCT in Feb. 2018



Launched on NASA ELaNa 23 by Orbital ATK to ISS on May 21, 2018

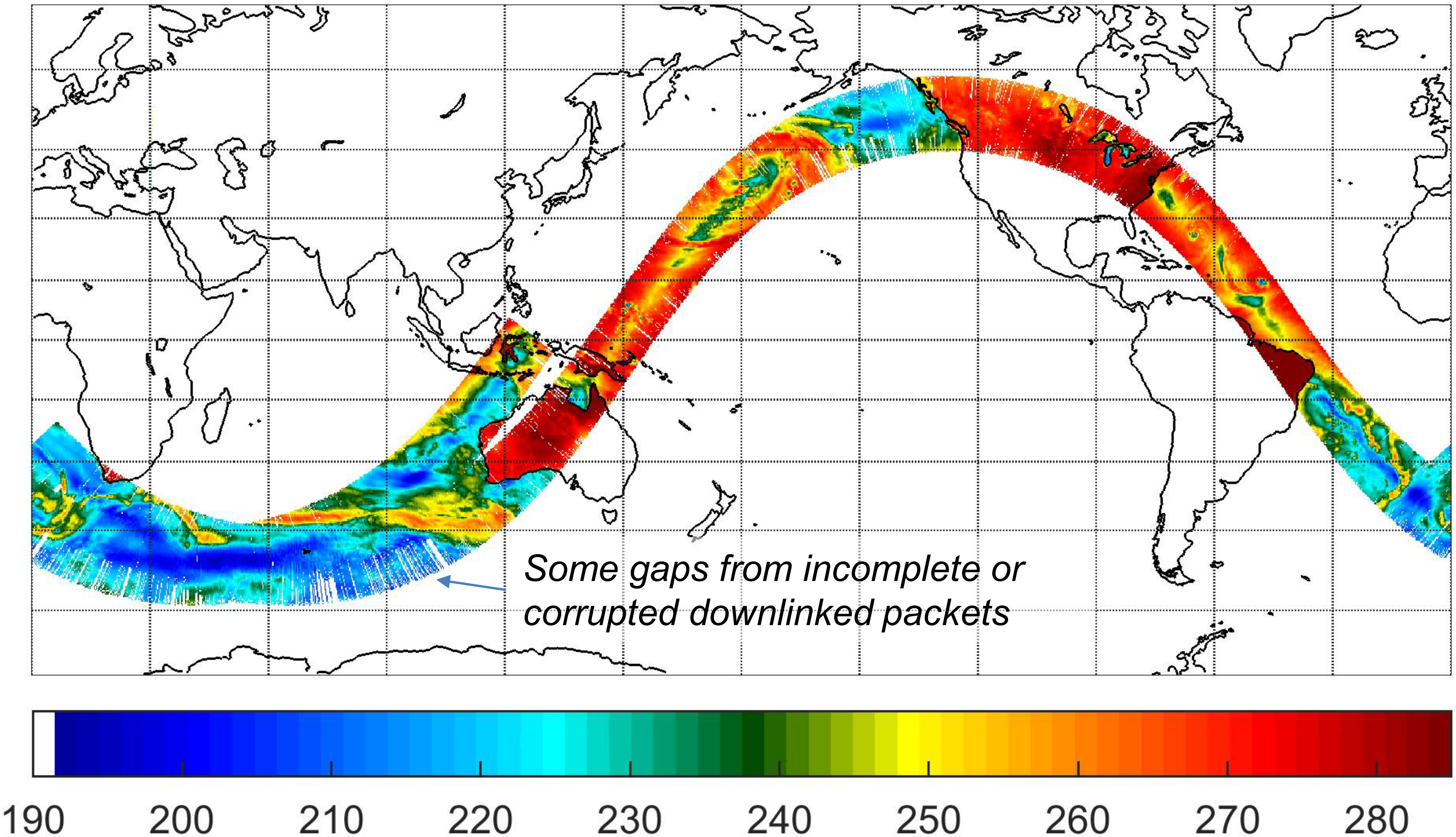
Photo Credit: NASA

TEMPEST-D and CubeRRT Deployed by NanoRacks on July 13, 2018



TEMPEST-D First Full Orbit on Sept. 11, 2018

TEMPEST-D 87 GHz Brightness Temperature (K)

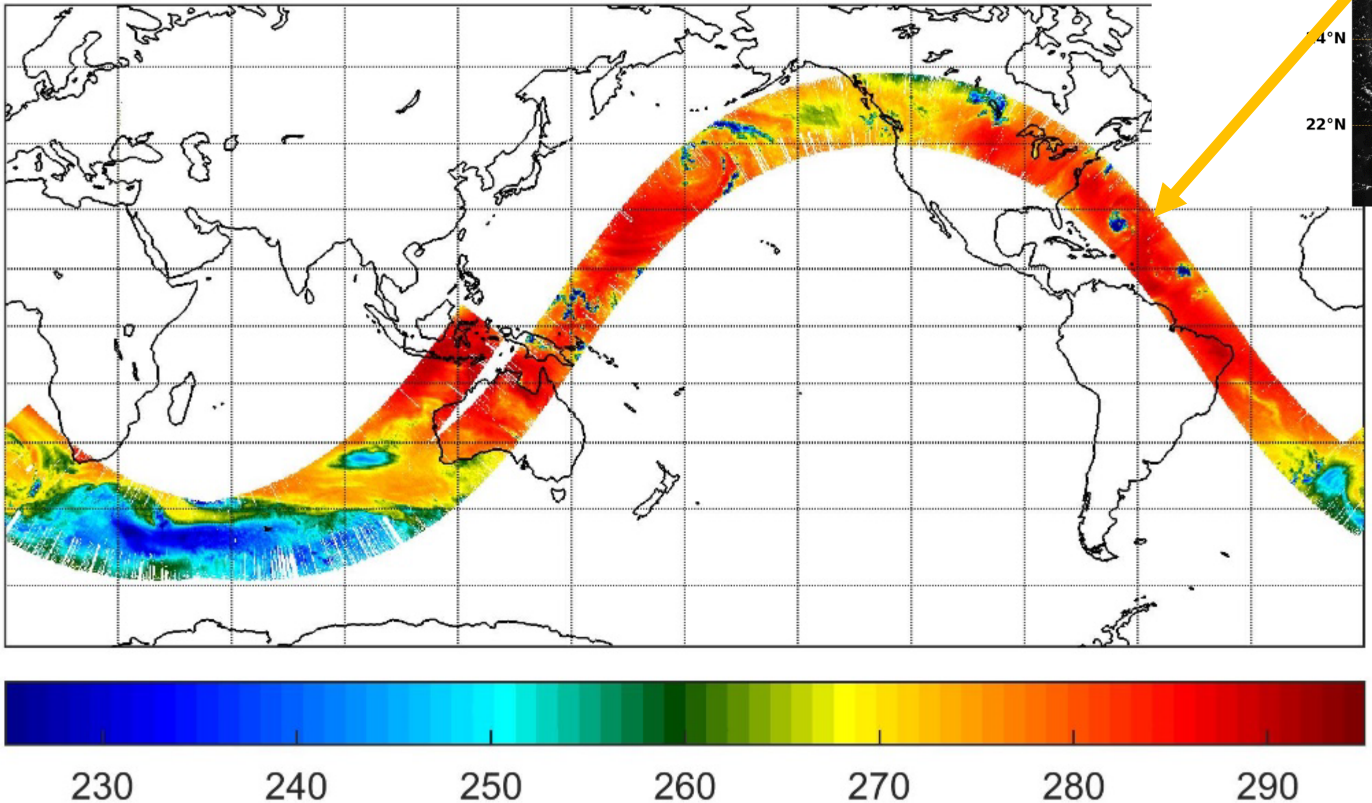


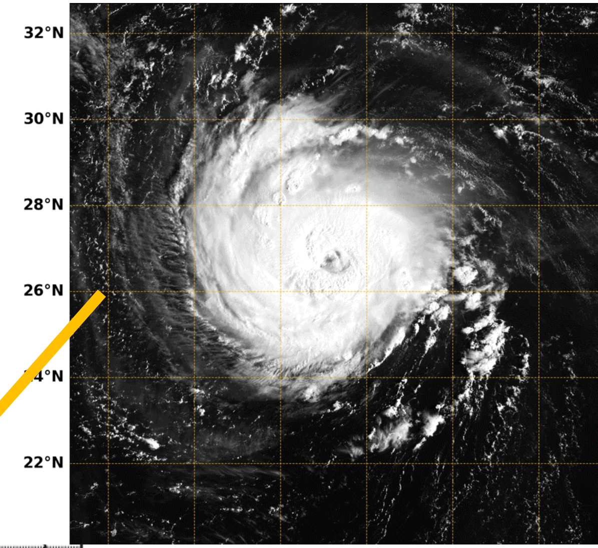
87 GHz window channel sensitive to water vapor, clouds and precipitation.

TEMPEST-D Measured Hurricane Florence on Sept. 11, 2018

TEMPEST-D captured Hurricane Florence in its first full-swath orbit on Sept. 11, 2018

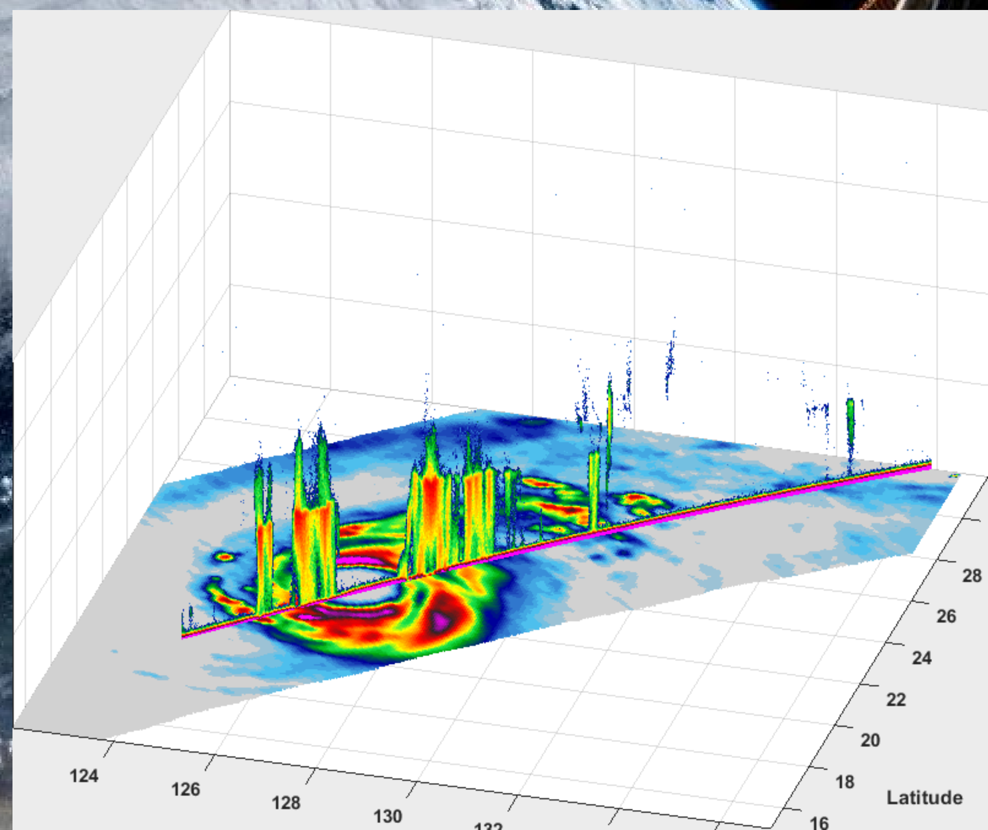
TEMPEST-D 164 GHz Brightness Temp. (K)



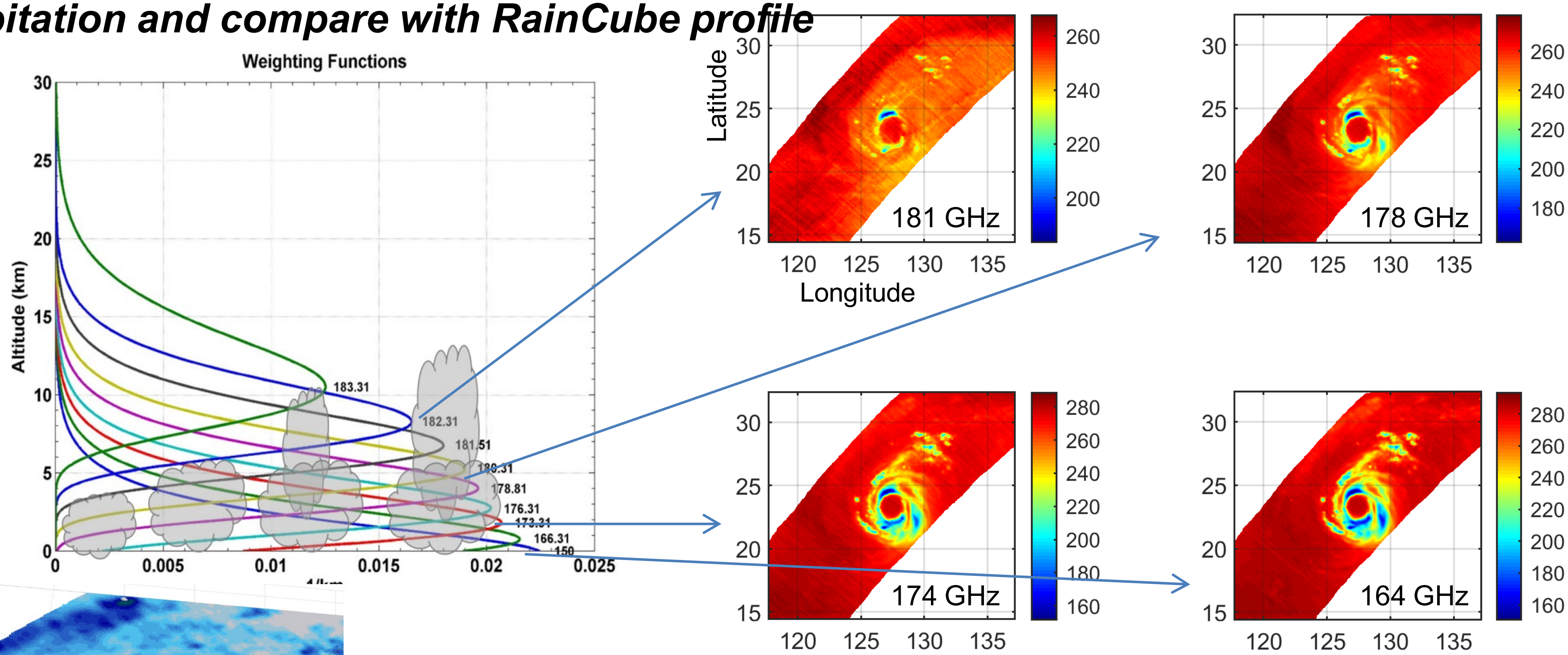


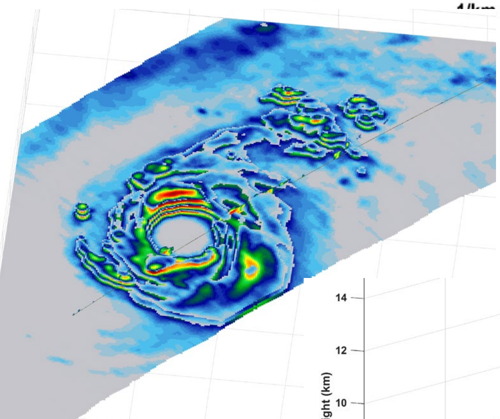
The 164 GHz color image shows the convection and intense rain bands around the inner core through the ice scattering signature. The greyscale image shows geostationary visible signature.

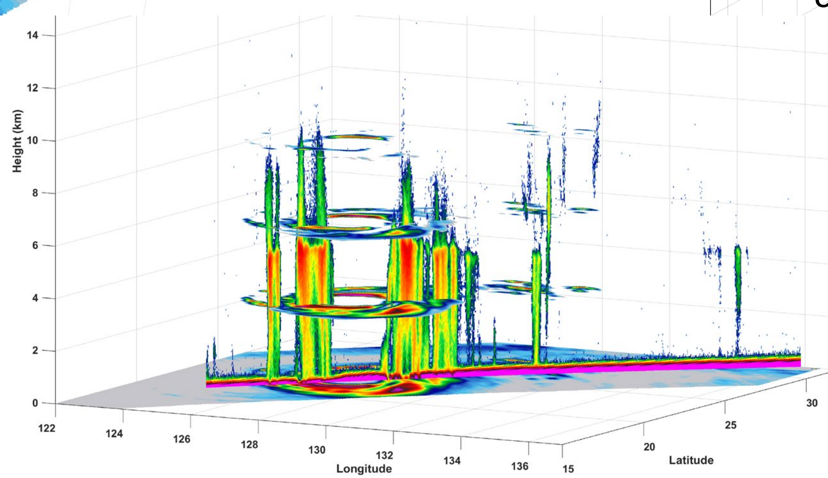
- On 28 Sept. 2018, TEMPEST-D and RainCube overflew Typhoon Trami < 5 minutes apart.
- RainCube nadir Ka-band reflectivity shown overlaid on TEMPEST-D 164 GHz brightness temperature illustrating complementary nature of these sensors and potential for constellation use to observe precipitation.
- Trami observed shortly after it had weakened from Cat 5 to Cat 2.

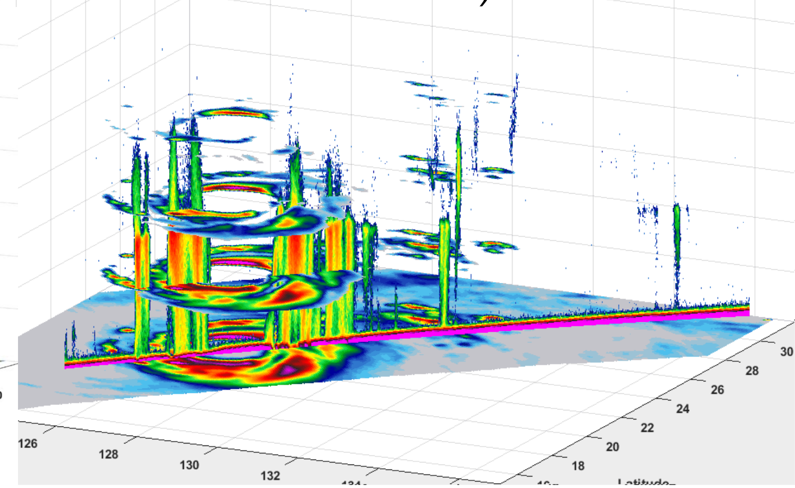


TEMPEST-D Sounding Channels provide 4 levels of vertical resolution to "slice" precipitation and compare with RainCube profile



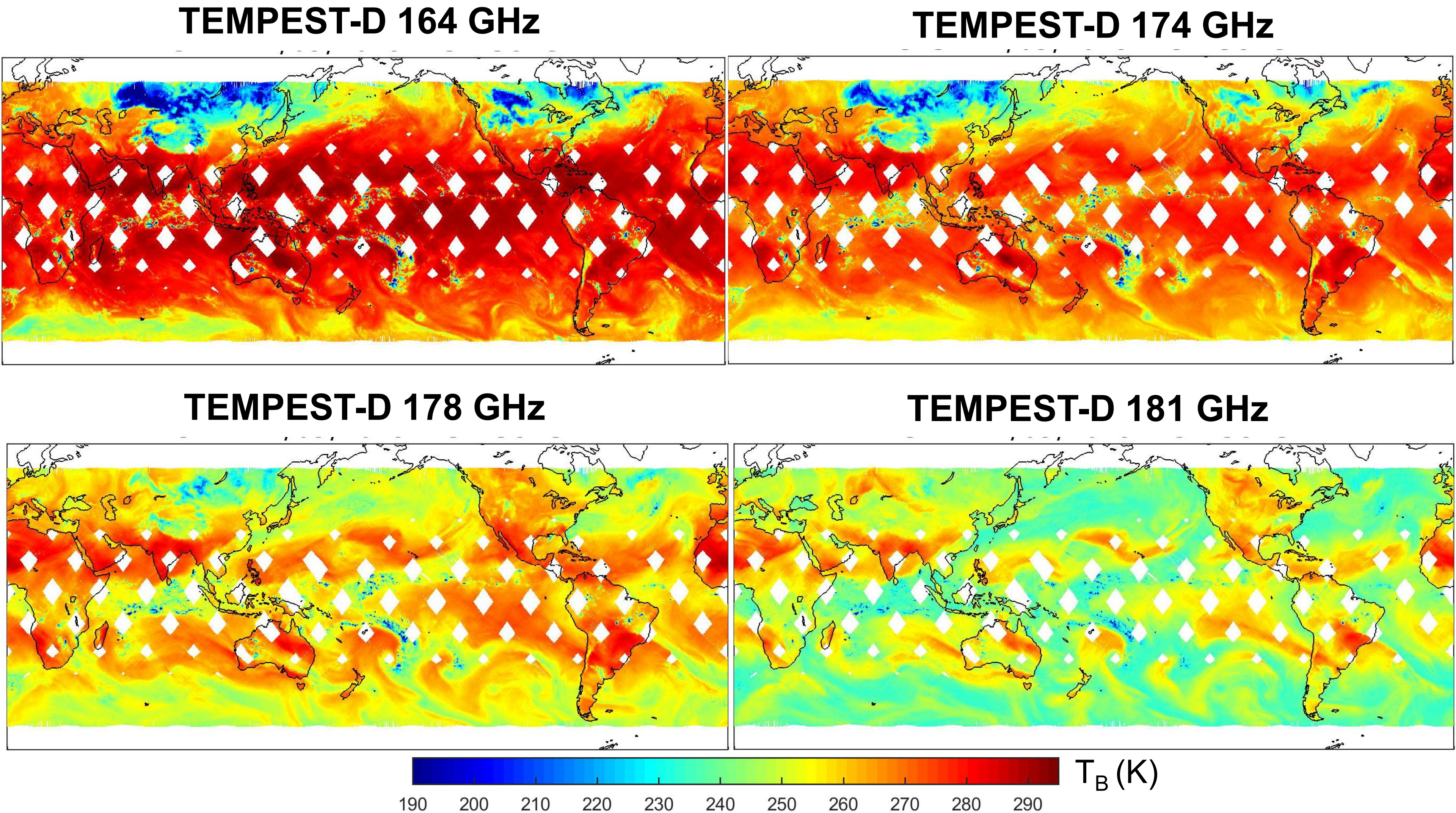




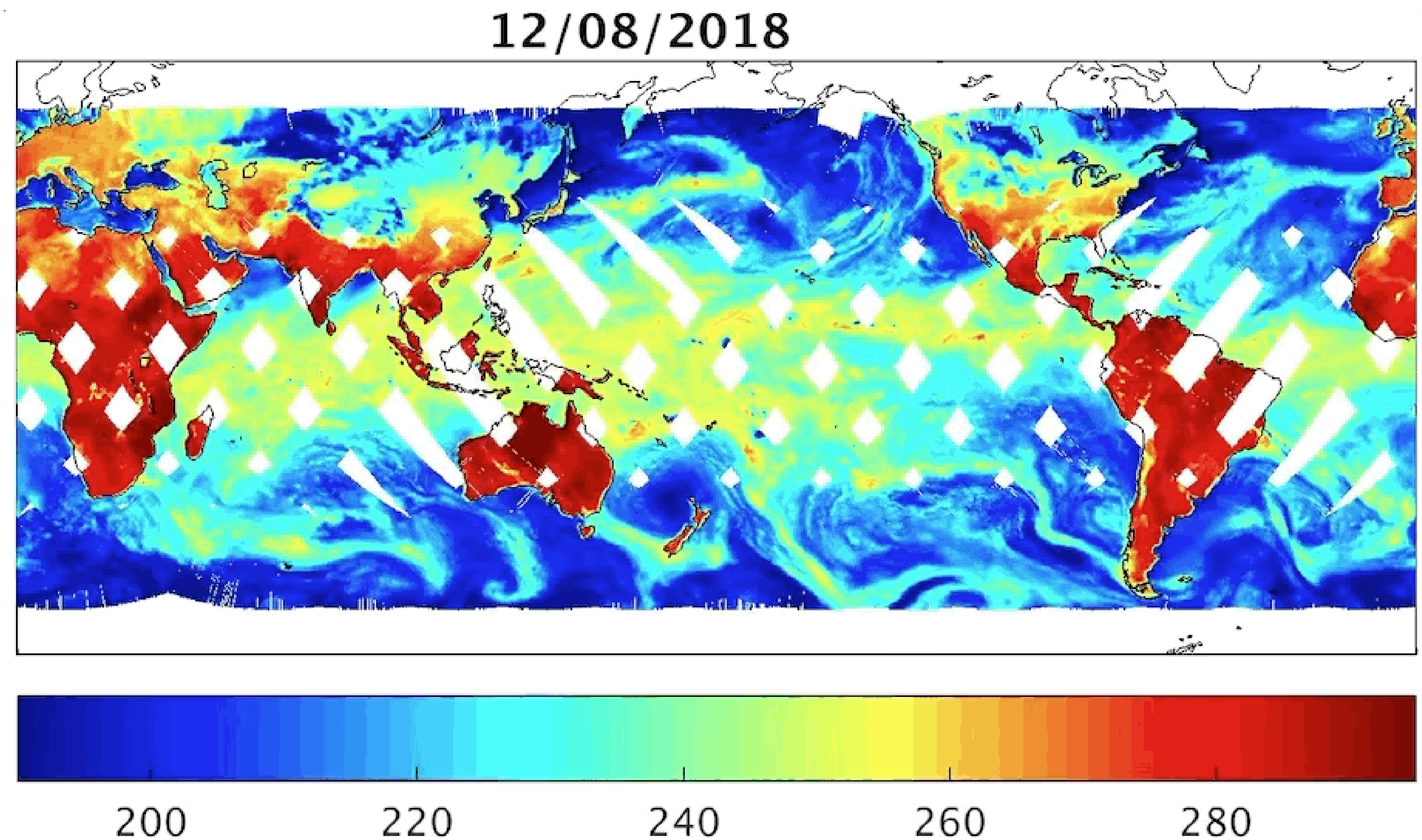


Similar asymmetry observed in depth of eyewall convection between TEMPEST-D and RainCube (strongest on west side and to the south)

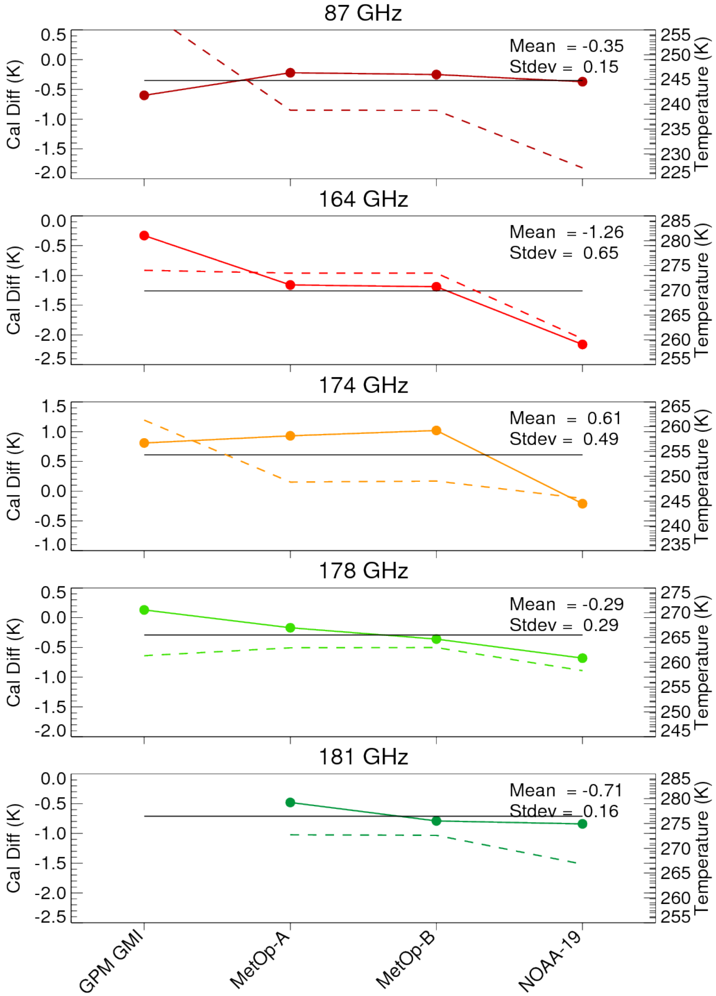
TEMPEST-D Brightness Temperatures at 164-181 GHz on Dec. 9, 2018



TEMPEST-D Brightness Temperatures at 87 GHz from Dec. 8 to 14, 2018



Validation of TEMPEST-D Data using NASA, NOAA & EUMETSAT Sensors



Mean calibration differences between TEMPEST-D and four reference sensors based on 18 days of data. Dashed lines indicate corresponding mean scene brightness temperature.

- Double difference technique developed for GPM used to evaluate TEMPEST-D calibration compared to reference sensors; maps other sensors' observations to TEMPEST frequencies and view angles
- TEMPEST calibration within 1.3 K of reference sensors, meeting accuracy requirement of 4 K.
- TEMPEST stability within 0.7 K of reference sensors, meeting precision requirement of 2 K.
- Model uncertainty contributing to larger differences for 164 GHz channel
- **Results indicate TEMPEST-D is a very well-calibrated radiometer, indistinguishable from operational-class imaging radiometers.**

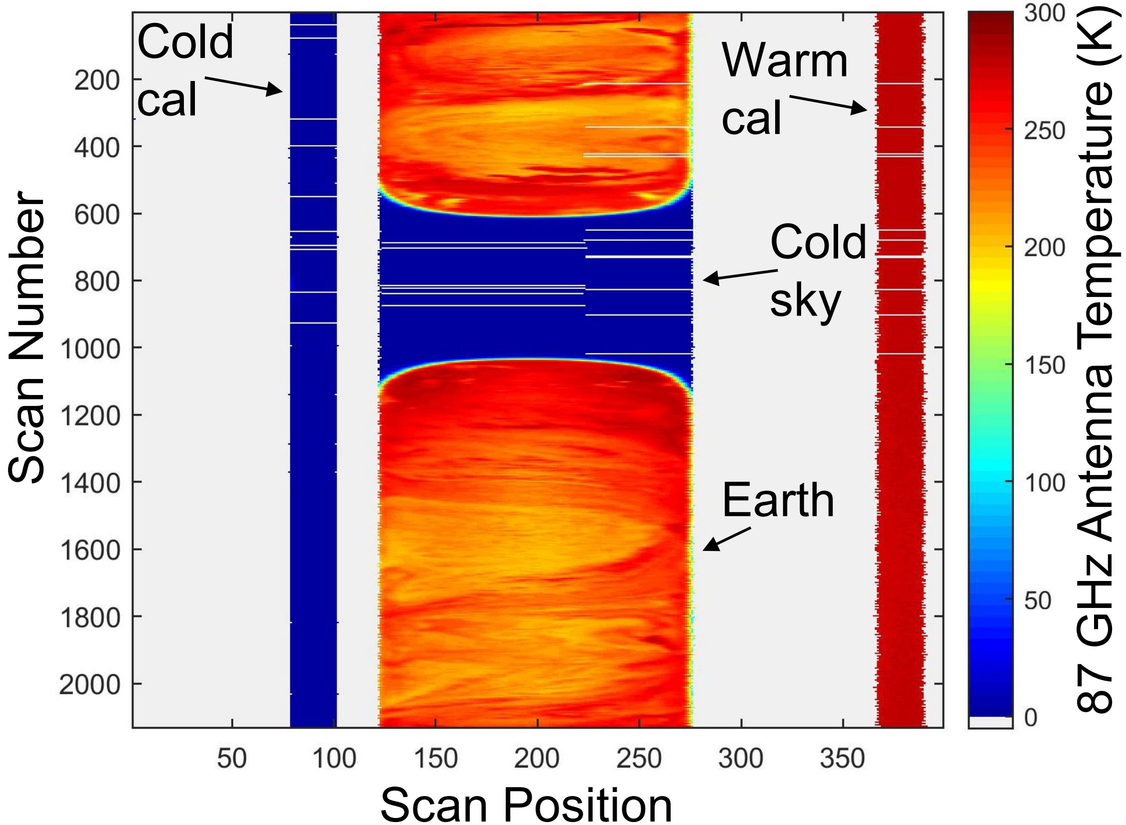
Calibration Differences in Kelvin (Reference – TEMPEST-D)

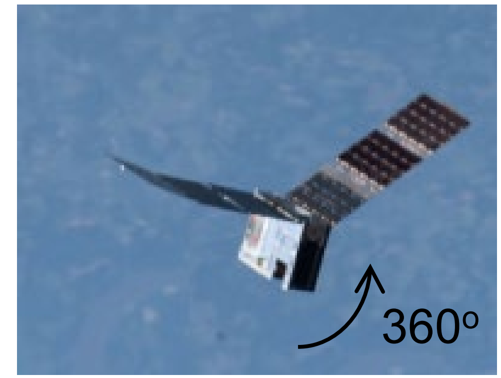
Reference Sensor	87 GHz	164 GHz	174 GHz	178 GHz	181 GHz
GPM GMI	-0.60	-0.33	0.81	0.13	N/A
MetOp-A MHS	-0.22	-1.16	0.93	-0.17	-0.48
MetOp-B MHS	-0.25	-1.19	1.02	-0.36	-0.79
NOAA-19 MHS	-0.37	-2.16	-0.21	-0.68	-0.84
Mean Difference Requirement: 4 K	**-0.35**	**-1.26**	**0.61**	**-0.29**	**-0.71**
Standard Deviation Requirement: 2 K	**0.15**	**0.65**	**0.49**	**0.29**	**0.16**

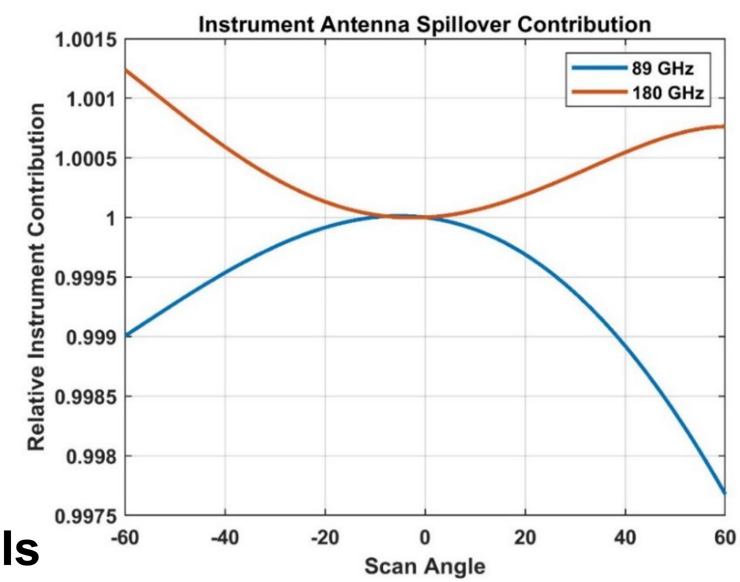
TEMPEST-D Met Mission Success Criteria in First 90 Days

- Demonstrate that TEMPEST-D radiometers remain cross-calibrated with at least one other orbiting radiometer with inter-satellite precision of 2 K and accuracy of 4 K
  - Measured calibration stability within 0.7 K and accuracy within 1.3 K of reference sensors ✓
- Demonstrate the feasibility of orbital drag maneuvers to control 6U CubeSat satellite altitude to 100 m or better, to show ability to achieve relative positioning in an orbiting train
  - Showed that TEMPEST-D altitude can be controlled to 50 m or better using attitude control relative to CubeRRT ✓
- Demonstrate orbital operations for more 90 days after spacecraft and instrument commissioning
  - Demonstrated mission operations since commissioning for more than 7 months to date ✓

TEMPEST-D 360º Pitch Maneuver for Antenna Pattern Correction

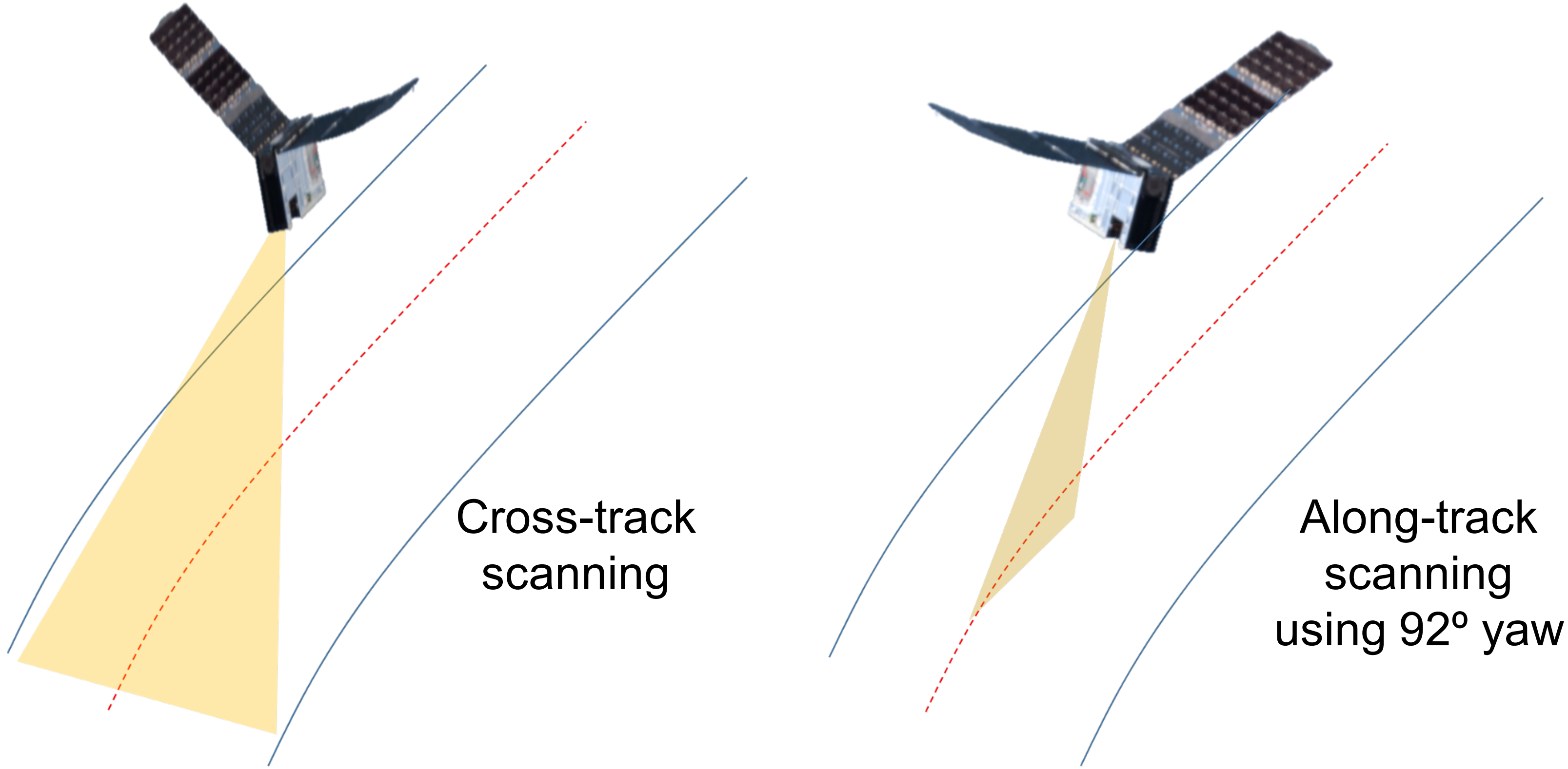






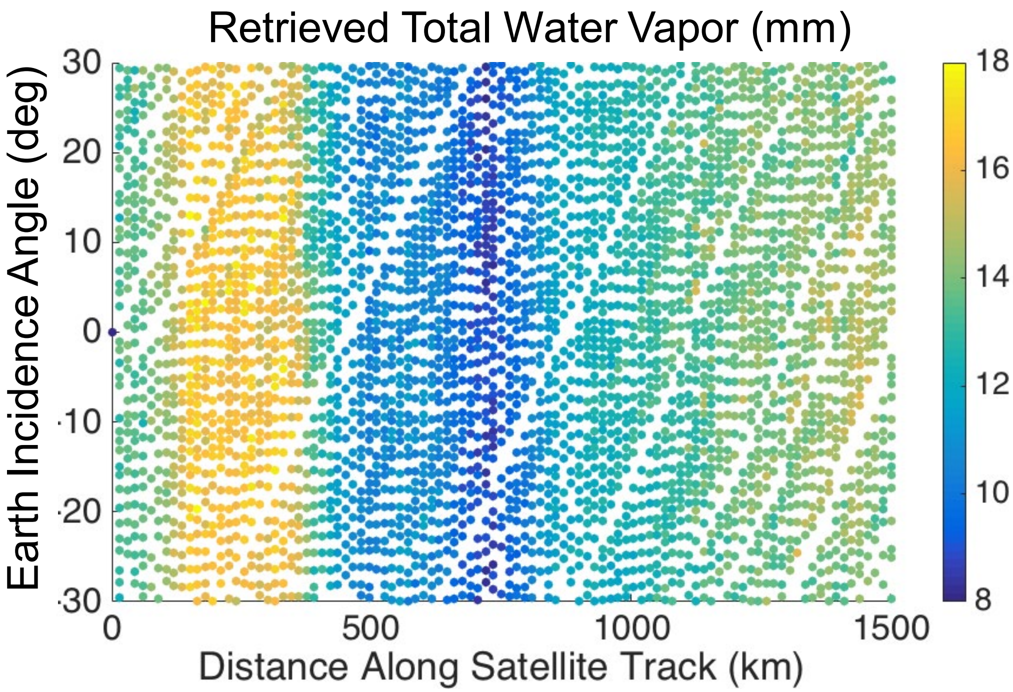
- 360º pitch maneuver performed to characterize antenna pattern correction over scan
- **Scan dependent biases < 0.5 K for all channels prior to antenna pattern correction**

Along-Track Scanning using a Passive Microwave Sounder on a 6U CubeSat

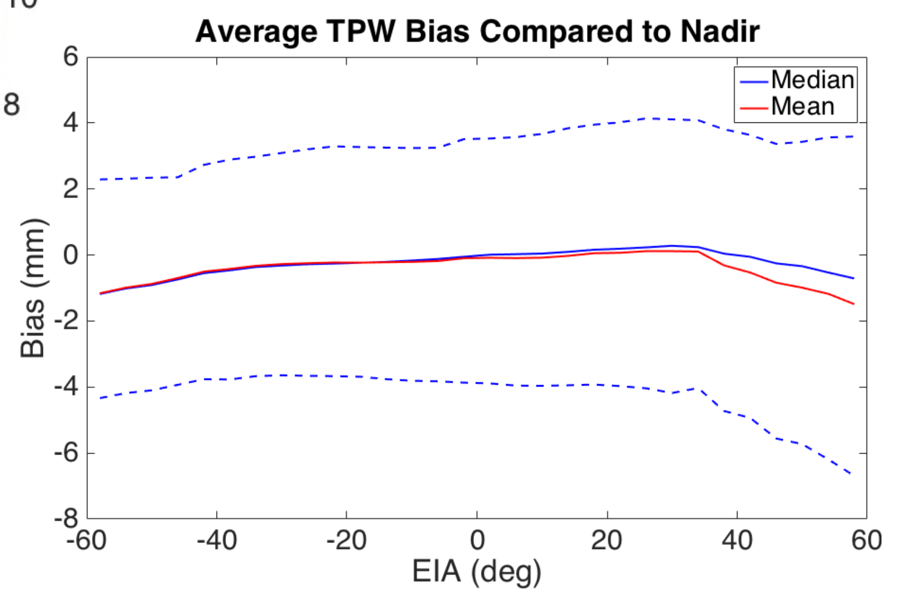


- Cross-track scanning, typical for microwave sounders, provides a wide swath.
- Along-track scanning experiment provides a narrow swath, but any footprint on Earth's surface is observed many times.
- For clear skies, evaluate consistency of the retrieved products.
- For convective activity, investigate effects of different slant path geometries.

Along-Track Scanning using a 6U CubeSat: Preliminary Results



- Performed along-track scanning at 92-degree yaw attitude for more than 12 hours on each of Jan. 29 and 30, 2019.
- Repeated experiment for more than 16 hours on Apr. 8, 2019.



- Retrieved Total Water Vapor (TPW) is stable with Earth incidence angle (EIA), for a short period (above).
- Retrieved TPW is stable over 24 hours (right). EIA bias is still under study.

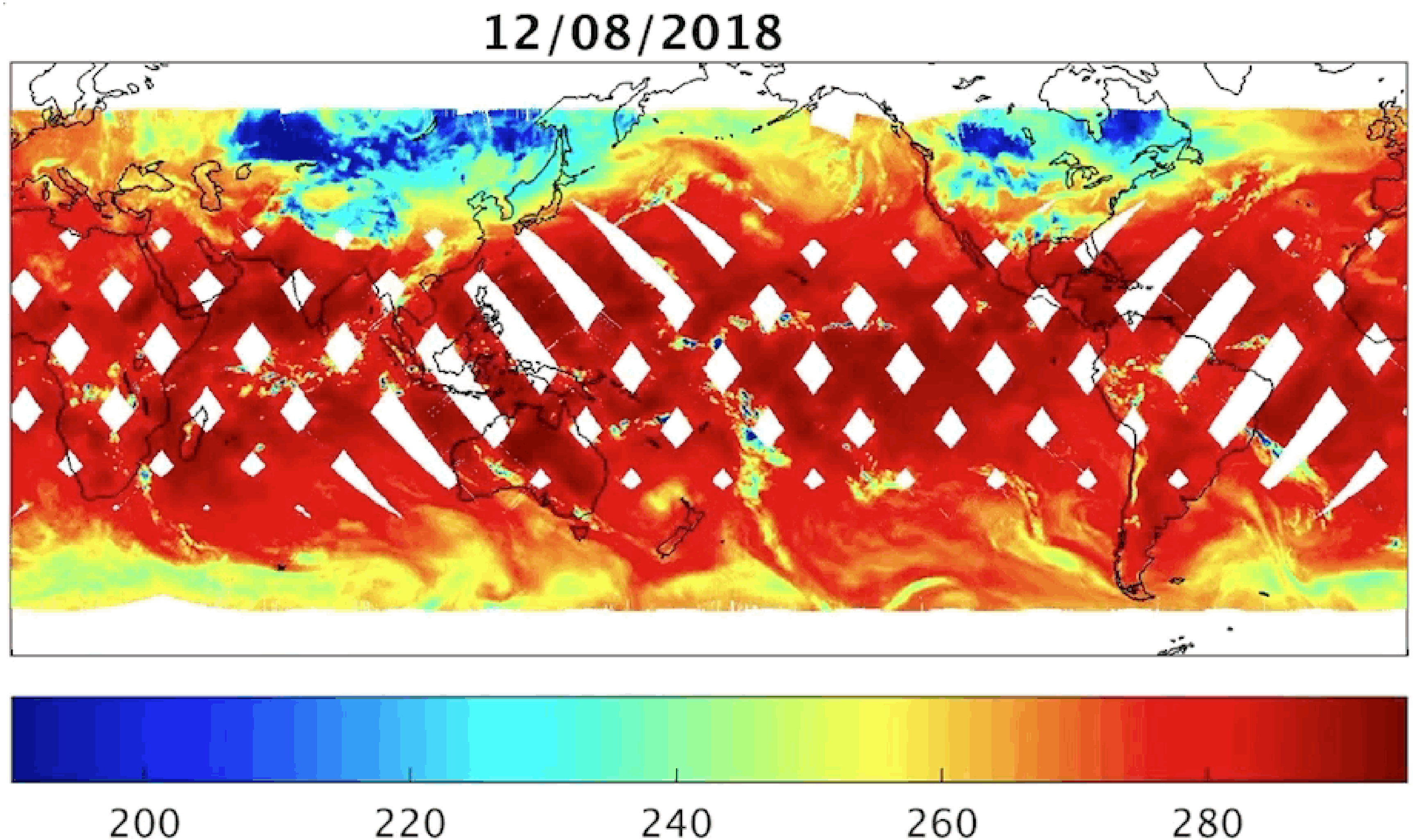
TEMPEST-D Mission Summary

- TEMPEST-D, a NASA Earth Venture Tech Demonstration mission, met its success criteria within the first 90 days of operations.
- Demonstrated potential for a train of identical TEMPEST 6U CubeSats to perform *first temporal* global measurements of clouds and precipitation at 3-4 minute spacing for up to 30 minutes.
- Demonstrated mission operations since spacecraft commissioning for more than 7 months to date
- Demonstrated that quality of TEMPEST-D data is indistinguishable from that acquired by well-established operational radiometers, even though the 6U CubeSat is a fraction of the size and costs significantly less.
- Demonstrated cross-calibration of TEMPEST radiometers with NASA, NOAA and EUMETSAT reference sensors with accuracy of 1.3 K or better and stability of 0.7 K or better.
- Demonstrated rapid development of a 6U CubeSat for Earth Science technology demonstration, 2.5 years from project start to launch delivery.


Thank you for your kind attention. Thanks to the NASA Earth Venture Program and CSLI for their support. Thanks to the NASA Earth Science Technology Office for program management.

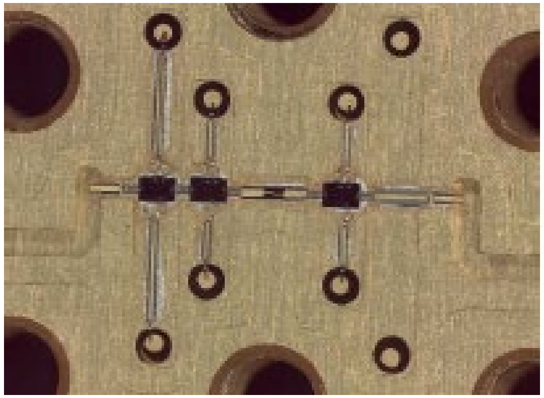
Backup Slides

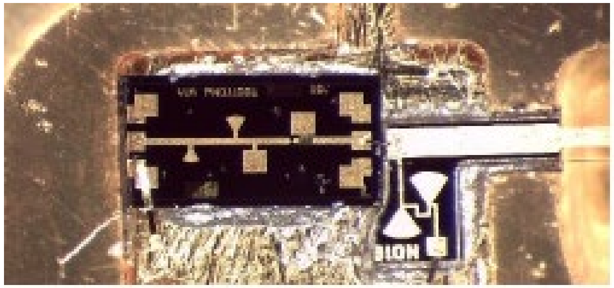
164 GHz Brightness Temperature 08-14 Dec. 2018



TEMPEST-D Noise Performance vs. NOAA Operational Microwave Sounders

TEMPEST-D demonstrates improved receiver performance over the current generation of NOAA operational sensors.



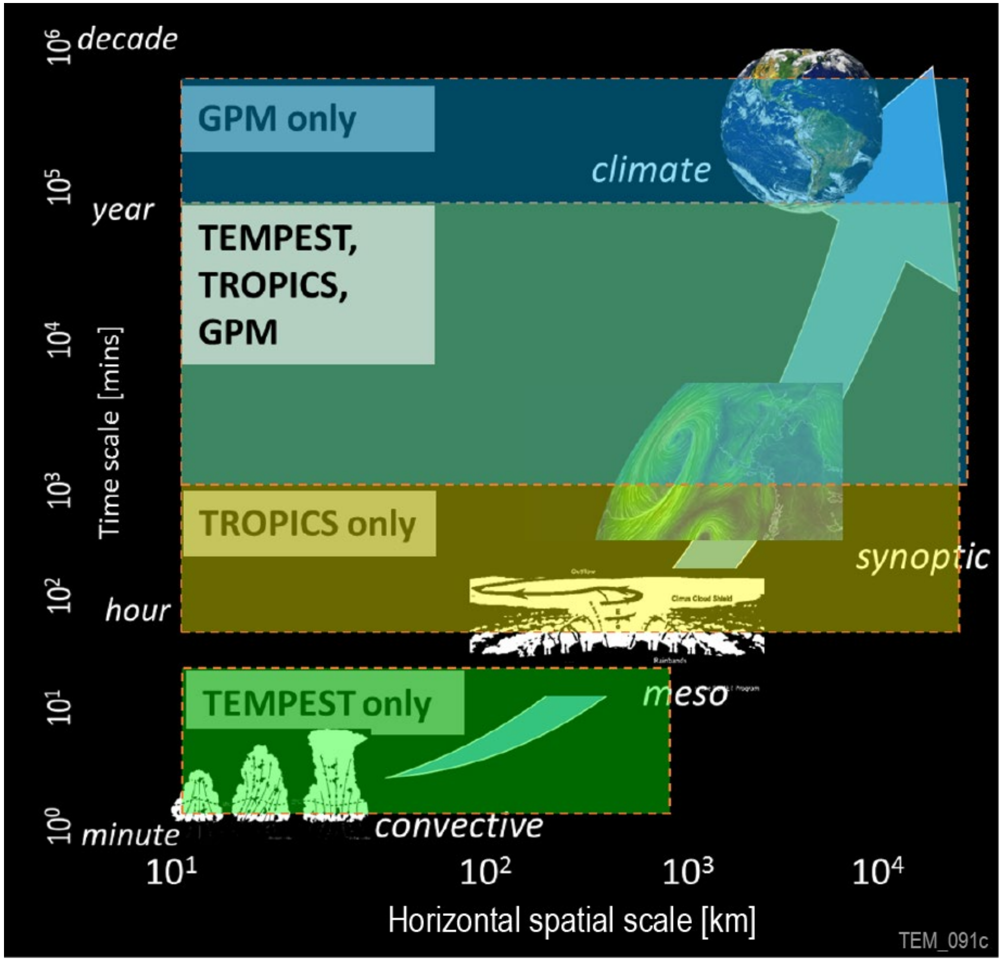


At T_A = 300 K, 18 ms integration time and ATMS receiver BWs	TEMPEST-D[1]	NOAA/NASA NPP Advanced Technology Microwave Sounder[2]
87 GHz	0.13 K	0.29 K
164 GHz	0.25 K	0.46 K
174 GHz	0.2 K	0.38 K
178 GHz	0.25 K	0.54 K
181 GHz	0.7 K	0.73 K

[1] Equivalent NEDT for ATMS bandwidth/integration time

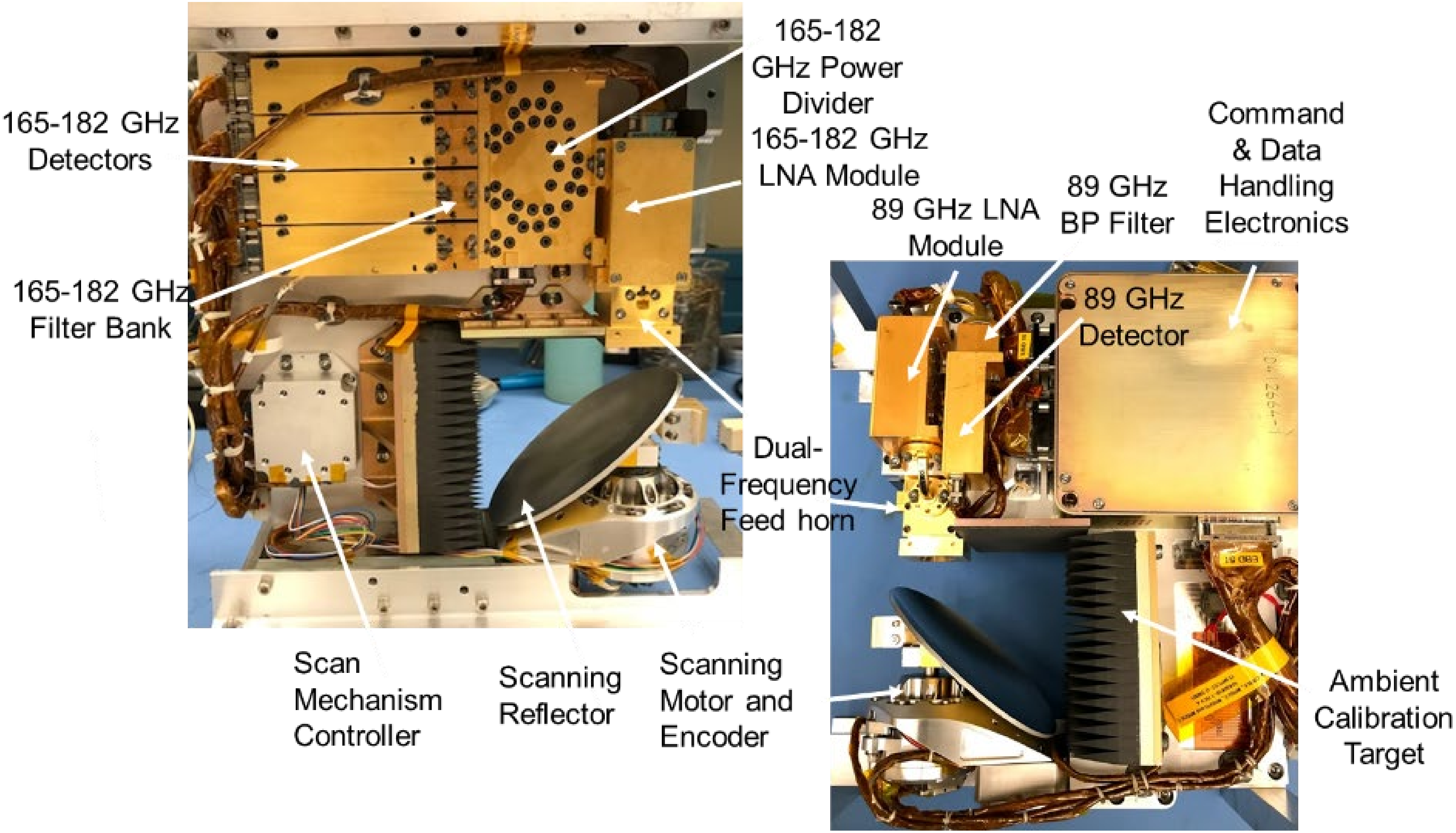
[2] E. Kim et al., 2014

TEMPEST Mission Concept Occupies Unique Observational Space

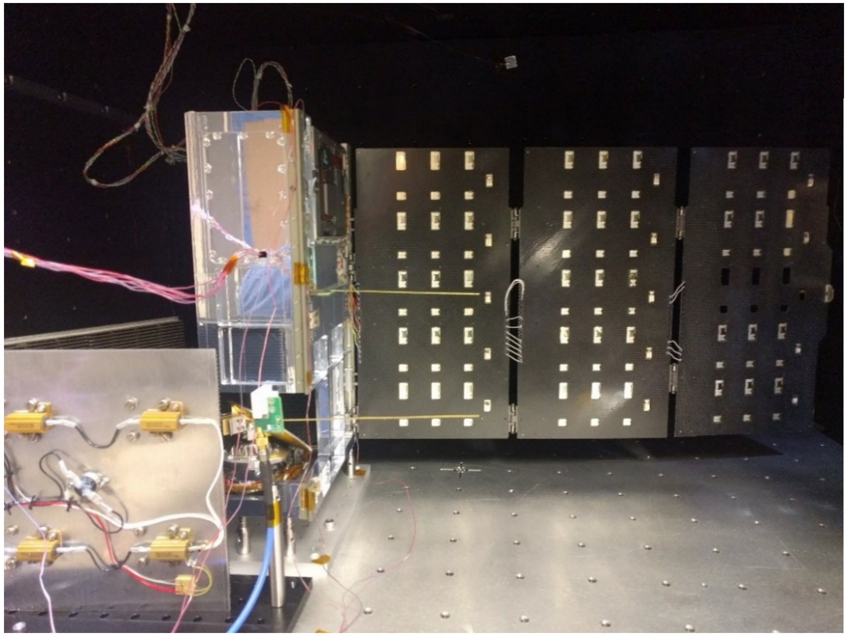


TEMPEST samples developing convection at 14-km horizontal resolution over time scales of 3–30 minutes and from days to a year. TEMPEST occupies a unique observational space and complements sampling of the TROPICS and GPM missions.

Flight Model Radiometer Instrument Built and Integrated at JPL

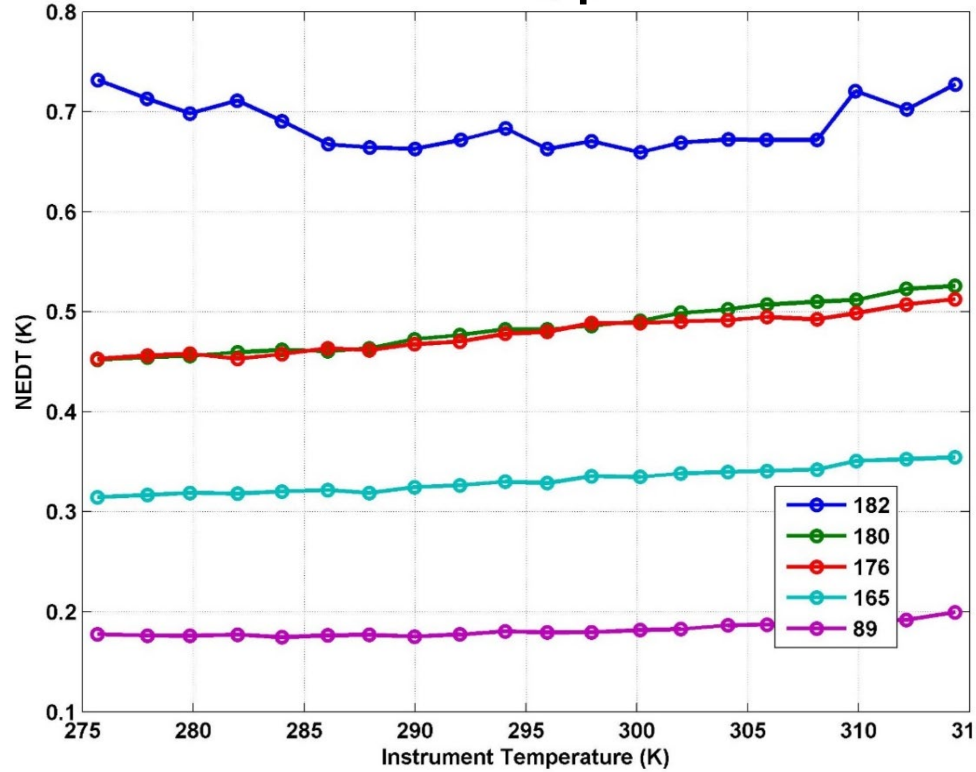


Instrument Performance in Spacecraft TVac at BCT (Jan. 2018)



Frequency (GHz)	Pre-launch NEdT (K)	On-orbit NEdT (K)
87	**0.2**	**0.2**
164	**0.3**	**0.3**
174	**0.5**	**0.4**
178	**0.5**	**0.4**
181	**0.7**	**0.7**

Radiometric Resolution vs. Instrument Temperature

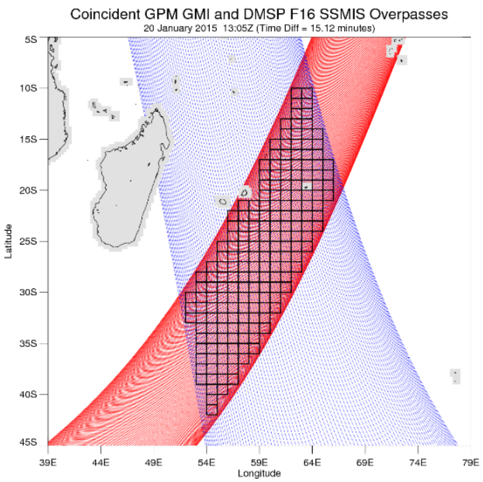


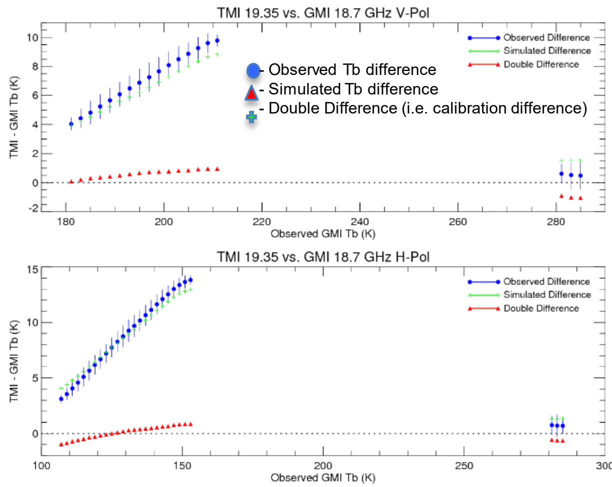
Measured radiometric resolution (NEdT) with **5-ms integration time,** both pre-launch and on-orbit, easily meet total noise requirements of 1.4 K for all five millimeter-wave radiometer channels.

TEMPEST-D Mission: Accomplishments to Date

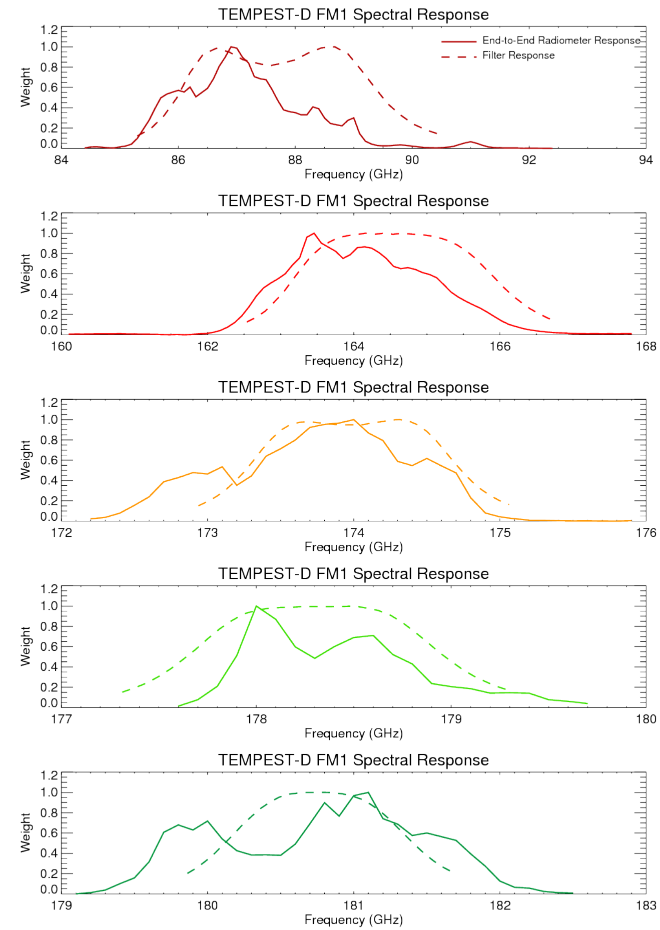
- Demonstrated potential for a train of 6U CubeSats with TEMPEST instruments spaced 3-4 minutes apart to perform the first global *temporally-resolved measurements of cloud and precipitation processes.*
- Reduced the risk, cost and development time for future science missions using 6U CubeSats.
- Demonstrated very well-calibrated, ultra low-noise and stable five-channel radiometer instrument on a 6U CubeSat.
- Raised TRL of low-noise, low-mass, and low-power TEMPEST millimeter-wave radiometer instrument from 5 to 7.
- Performed first in-space demonstration of an InP HEMT LNA front-end mm-wave radiometer with direct-detection for Earth Science.
- Demonstrated mission lifetime of more than 6 months to date since spacecraft commissioning.

Validation: Double Difference Method



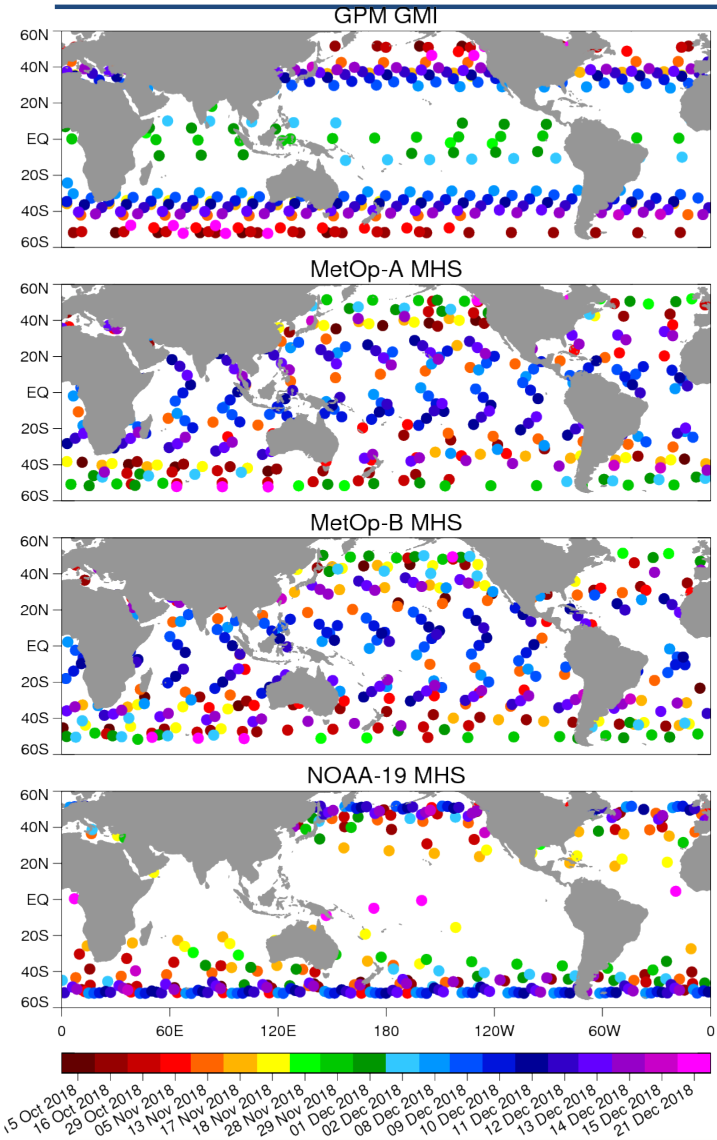


- TEMPEST-D observations are matched in space and time with reference sensors
- Radiative transfer simulations done using geophysical parameters from the NASA GEOS5 global data assimilation model. This is to account for sensor differences (i.e. channel frequencies, spectral response, polarization and view angle).
- Difference between observed and simulated (i.e. expected) differences are averaged over 1°x1° boxes and screened for land, precipitation, significant inhomogeneity, etc.



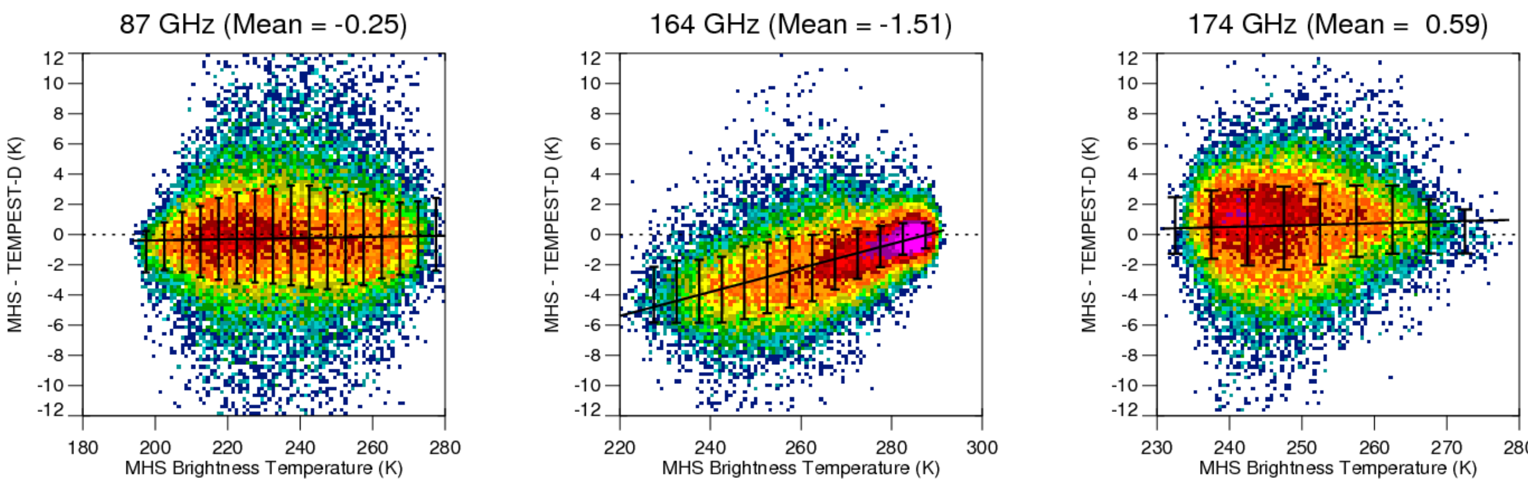
Spectral response functions for the TEMPEST-D channels. The dashed line indicates the filter response, while the solid line shows end-to-end radiometer response.

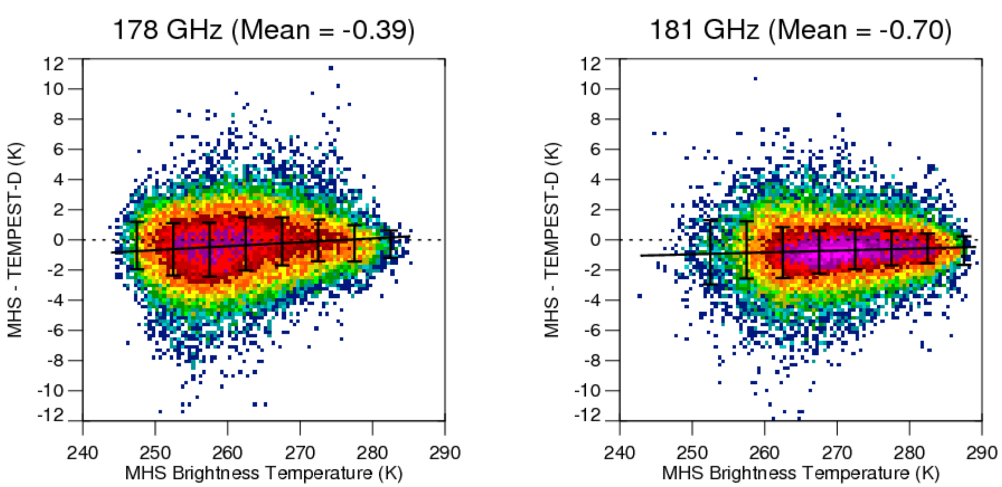
Validation: Coincident Overpasses



- **TEMPEST-D observations from a total of 18 days over a 2-month period from October 15 to December 21, 2018**
- Analysis by the GPM XCAL team indicate that GMI and the MHS sensors are extremely well calibrated and stable (< 0.5 K absolute).
- Typically, **a minimum of 6 months to a year of coincident observations** between the target and reference sensors is used to determine calibration differences.
- Due to the limited data availability from TEMPEST-D, data from all four reference sensors is used.
- Coincident observations from NOAA-19 are limited to high latitude regions. This impacts the results if there are temperature-dependent biases or RTM errors.

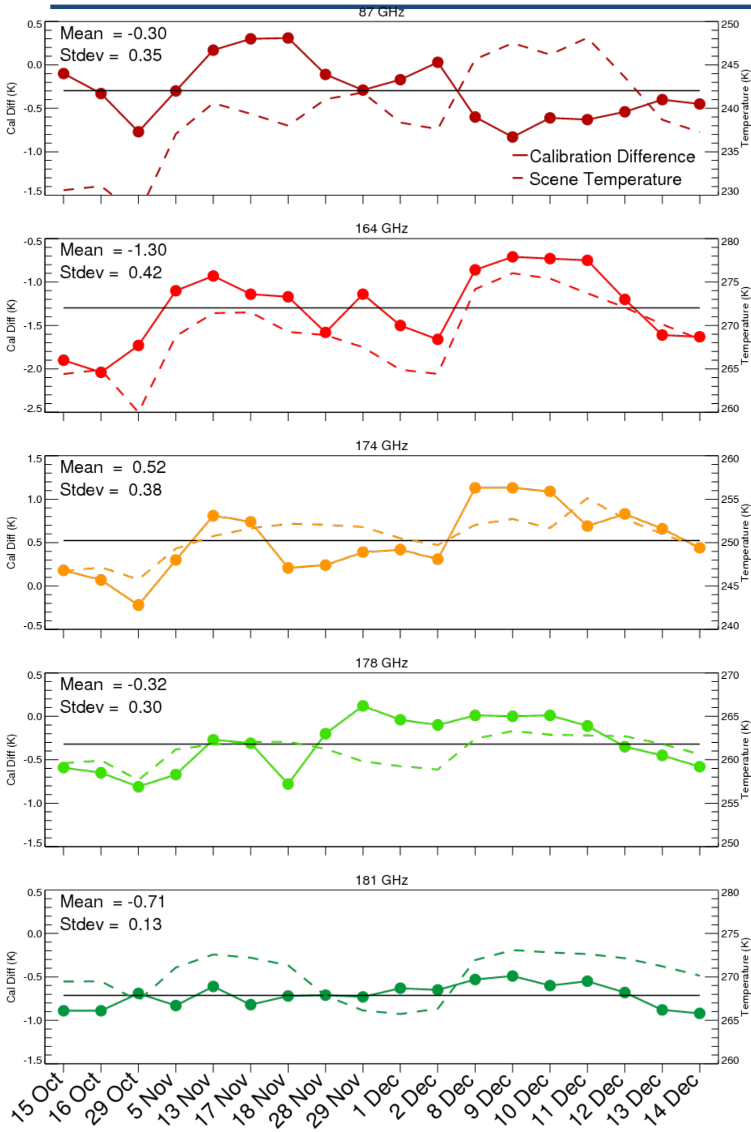
Validation: MHS Composite Results





- Double difference estimates are very noisy, requiring many coincident observations to obtain stable estimates of calibration differences.
- With the exception of the 164 GHz channel, the comparisons are very flat (i.e. no significant scene-temperature dependence) with mean values < 1 K.
- Results for the 164 GHz channel show a significant scene-temperature dependence.
    - ➢ This channel has large expected Tb differences due to sensor differences in frequency and polarization.
    - ➢ Results are inconsistent with 174, 178 and 181 GHz channels, which share much of the same hardware.
    - ➢ Previously observed ocean emissivity model errors are likely responsible for at least part of the issues for this channel.

Validation: Temporal Stability

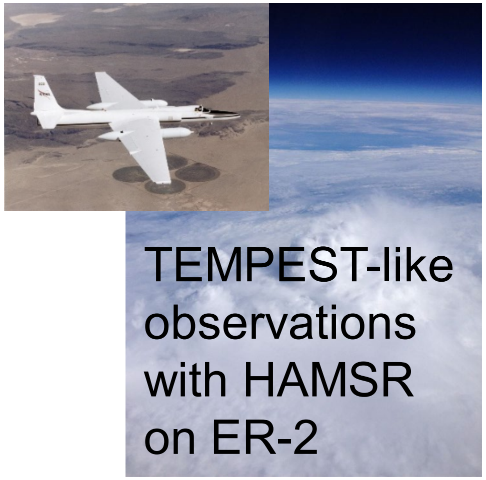


- Variations in calibration difference estimates (i.e. double differences) by day based on composite results using all four reference sensors.
- Dashed lines indicate the mean scene temperature of the reference sensors, which varies based on the locations of the coincident observations.
- Correlation between the calibration differences and scene temperature for 164 GHz channel suggest either brightness temperature-dependent calibration errors or regional errors in the simulated Tb.
- Consistency over the two-month period of available data indicates a stable TEMPEST-D calibration, although uncertainties in the daily double difference estimates are large due to sampling errors.

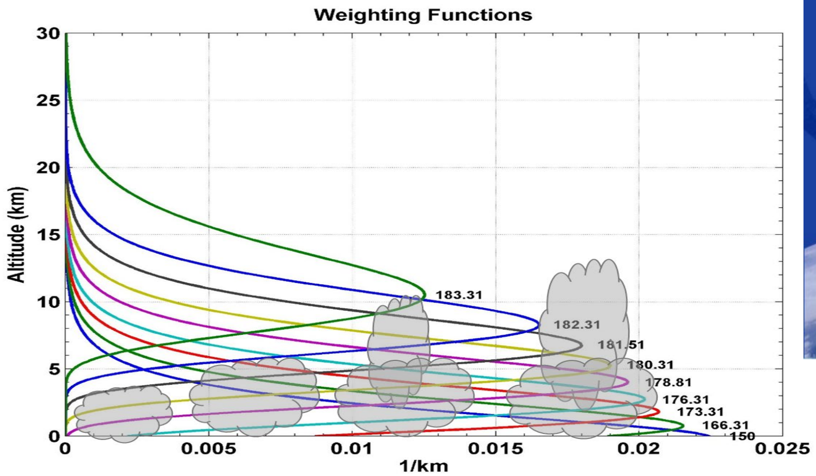
Calibration Differences in Kelvin (Reference – TEMPEST-D)

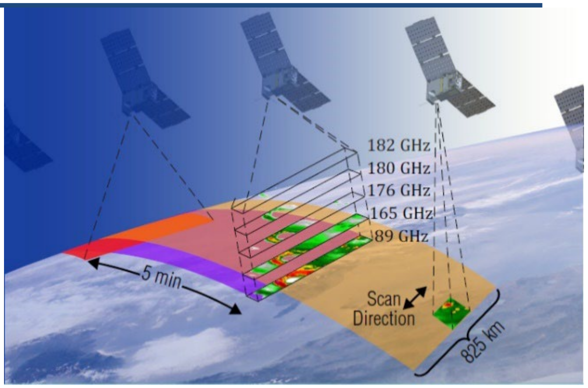
Calibration Difference	87 GHz	164 GHz	174 GHz	178 GHz	181 GHz
Mean Difference Requirement: 4 K	-0.35	-1.26	0.61	-0.29	-0.71
Standard Deviation Requirement: 2 K	0.15	0.65	0.49	0.29	0.16

TEMPEST-Like Measurements from JPL/HAMSR on ER-2 Aircraft



TEMPEST-like observations with HAMSR on ER-2





TEMPEST – enabling rapid revisit radiometry for precipitation processes