# Global Science-Quality Observations from a Passive Microwave Atmospheric Sounder on a CubeSat: Temporal Experiment for Storms and Tropical Systems Technology Demonstration (TEMPEST-D)

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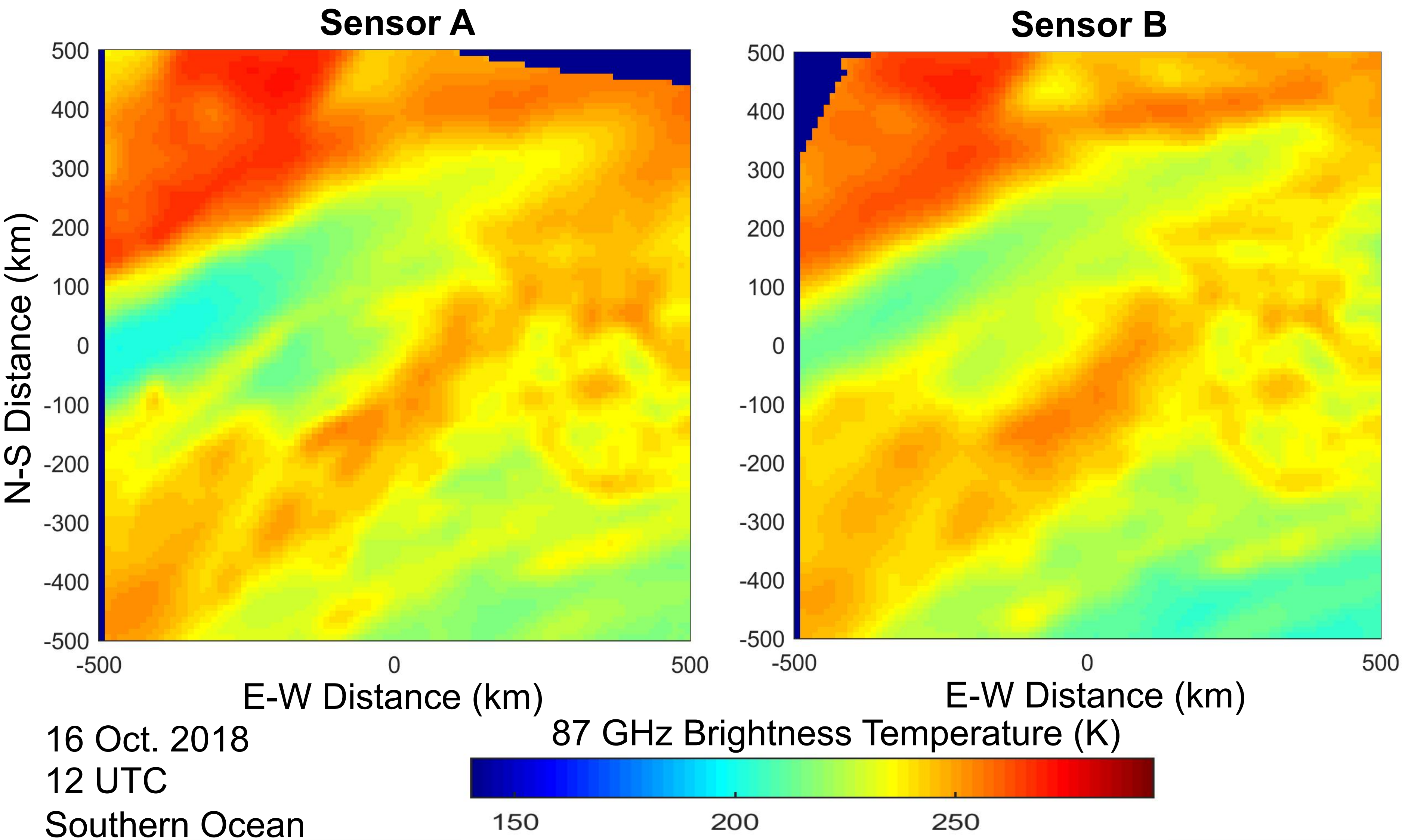
[3]Blue Canyon Technologies, Boulder, CO

*Thanks to NASA Wallops for providing ground station communications support.*

# Comparison Between On-orbit Passive Microwave Sensors



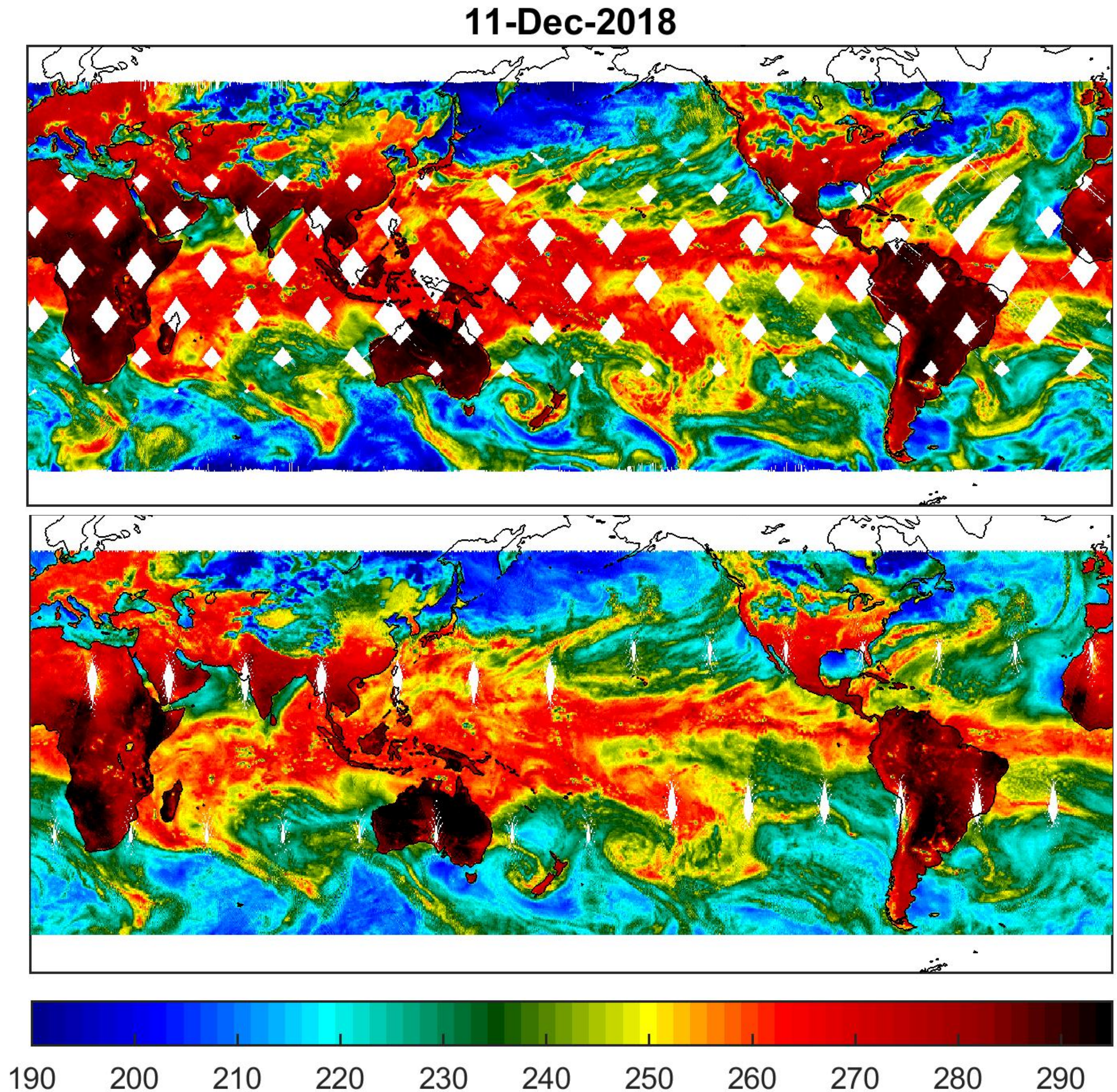

16 Oct. 2018
12 UTC
Southern Ocean

# Comparison Between On-orbit Passive Microwave Sensors

Sensor A

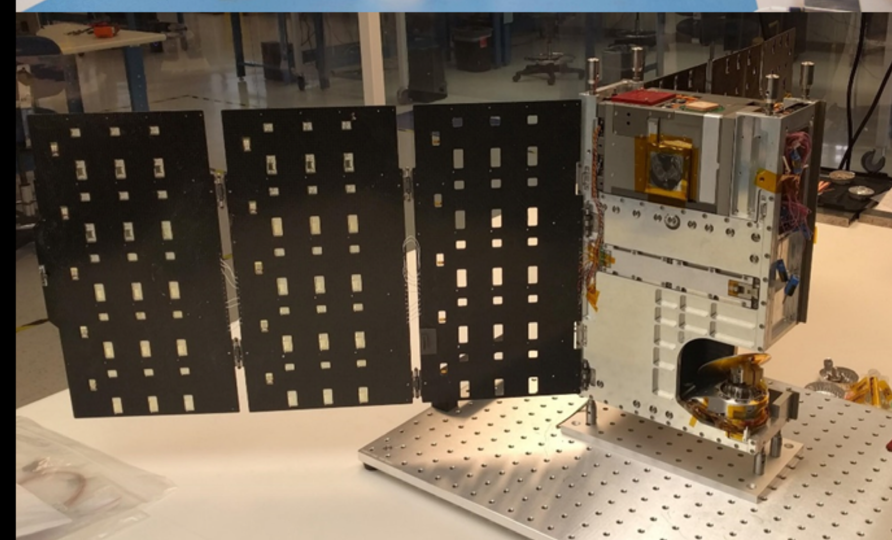
Sensor B

87 GHz
Brightness
Temperature (K)



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

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

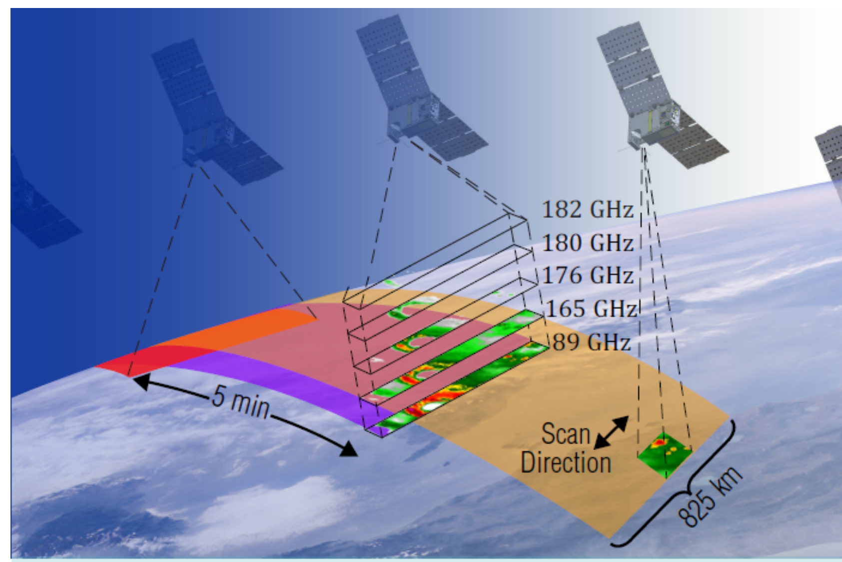


# Temporal Experiment for Storms and Tropical Systems (TEMPEST)

**TEMPEST addresses 2017 National Academies Earth Science Decadal Survey:**

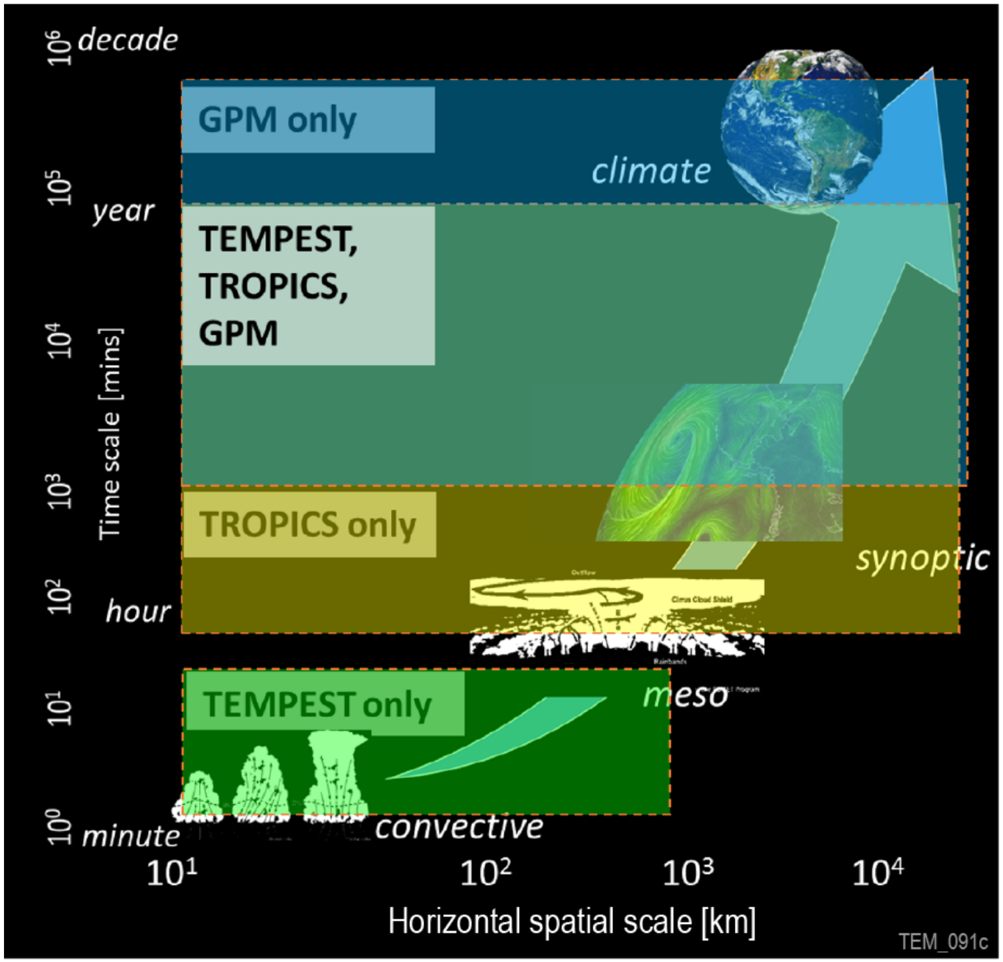
- *Why do convective storms, heavy precipitation, and clouds occur exactly when and where they do?* ("Most Important" Science Question W-4)
    - Providing global, *temporally-resolved observations of cloud and precipitation processes* using a train of 6U CubeSats with millimeter-wave radiometers
    - 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




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

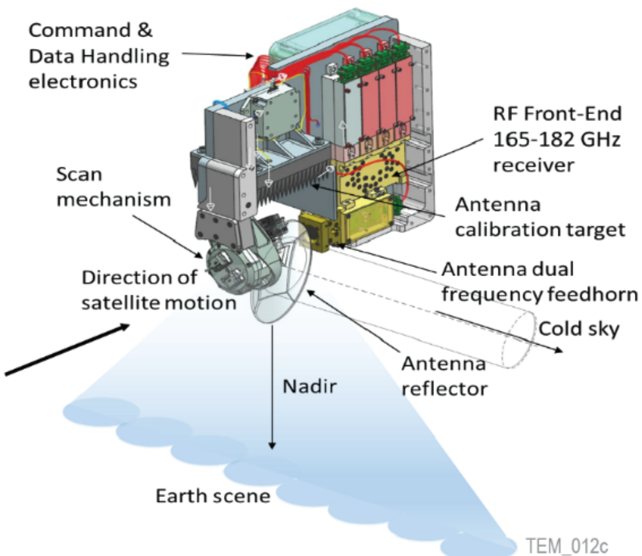
# TEMPEST Mission Concept Occupies Unique Observational Space



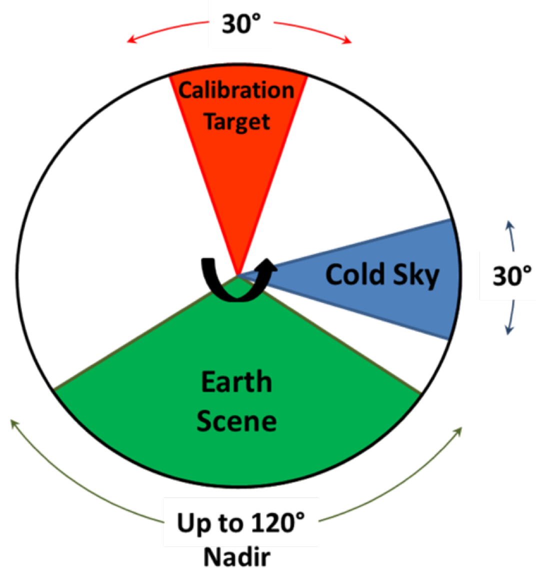

TEMPEST samples developing convection at 14-km horizontal resolution over time scales of 3–30 minutes and from days to a year. TEMPEST occupies a unique observational space and complements sampling of the TROPICS and GPM missions.

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

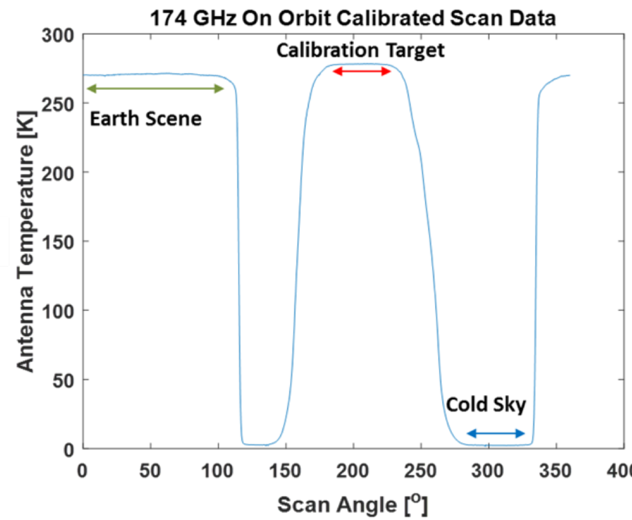
TEMPEST-D Instrument




Observing Profile

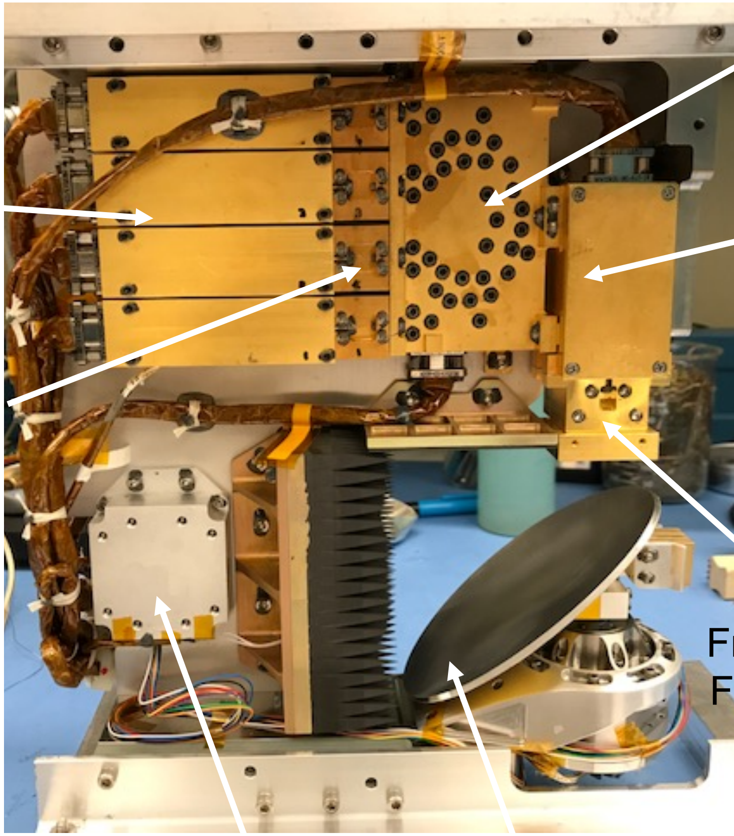


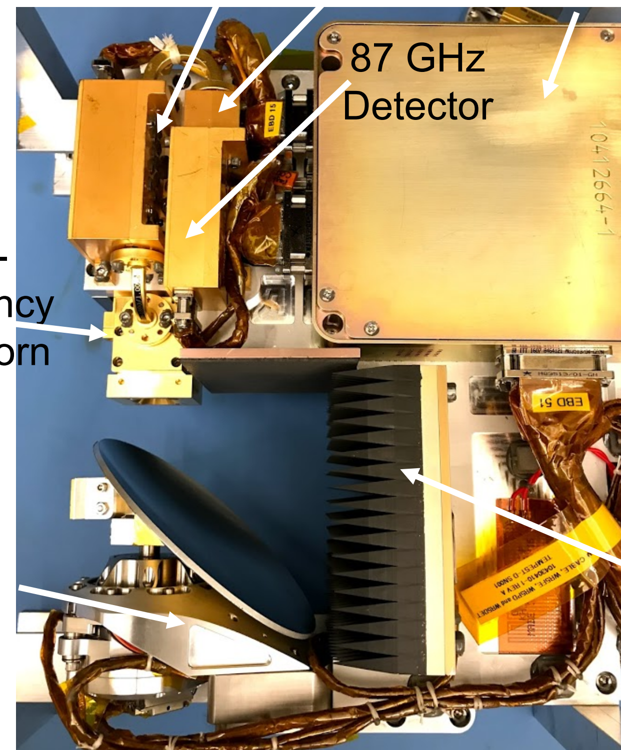

Time Series of Output Data




- 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).

# Flight Model Radiometer Instrument Built and Integrated at JPL





164-181 GHz Detectors

164-181 GHz Filter Bank

164-181 GHz Power Divider

164-181 GHz Radiometer Front-end

87 GHz Radiometer Front-end

87 GHz BP Filter

Command & Data Handling and Power Distribution Subsystem

87 GHz Detector

Dual-Frequency Feed horn

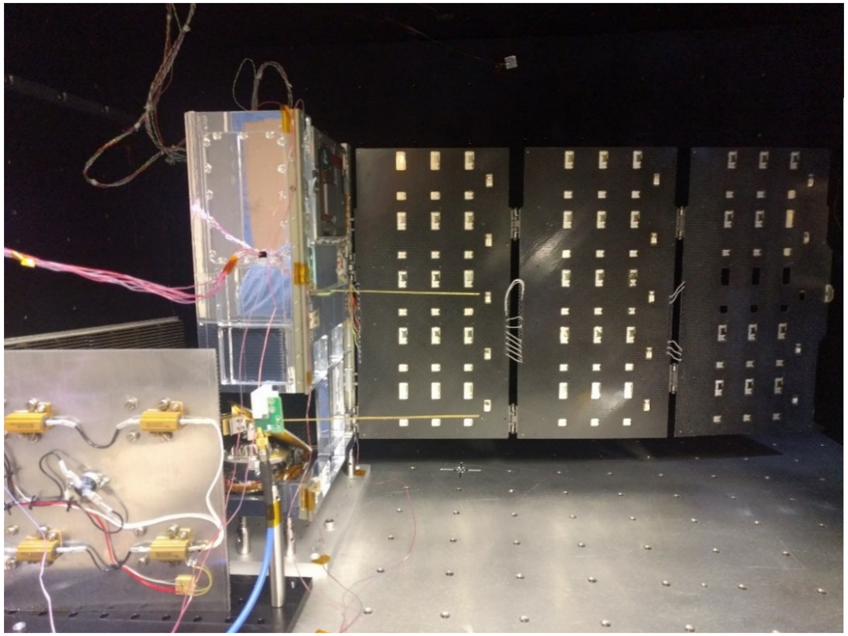
Scan Mechanism Controller

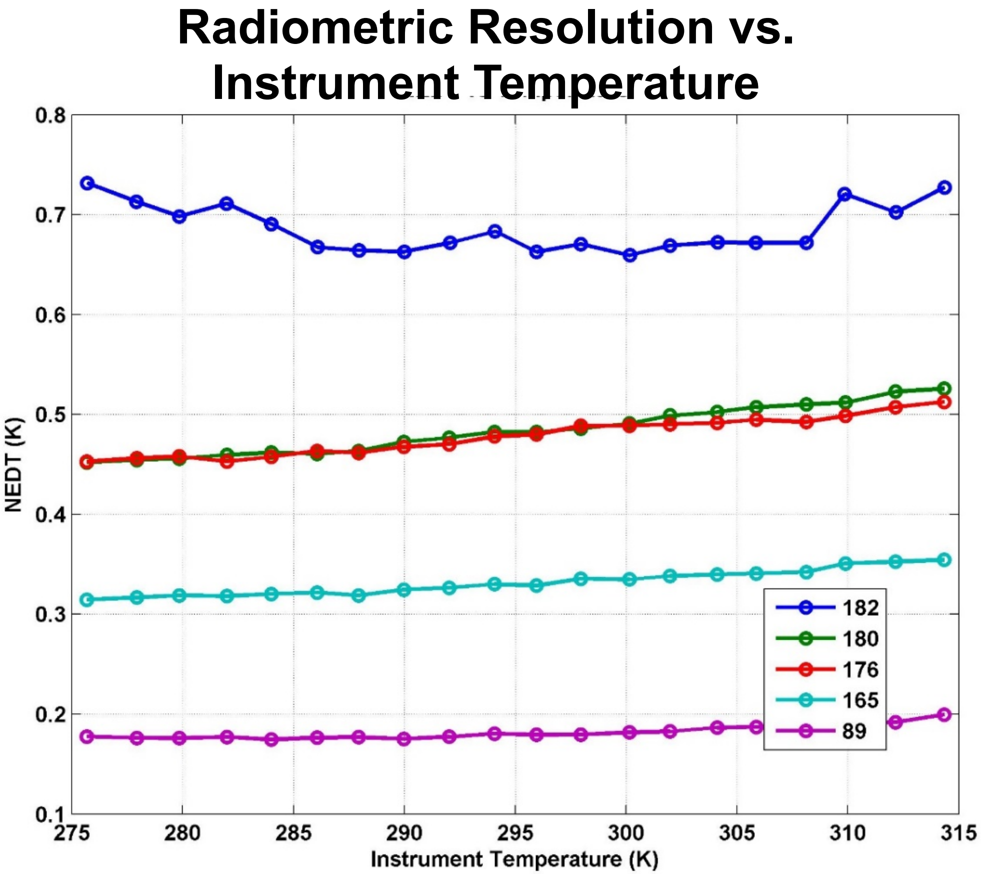
Scanning Reflector

Scanning Motor

Ambient Calibration Target

# TEMPEST-D Instrument TVAC Performance at BCT in 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** |

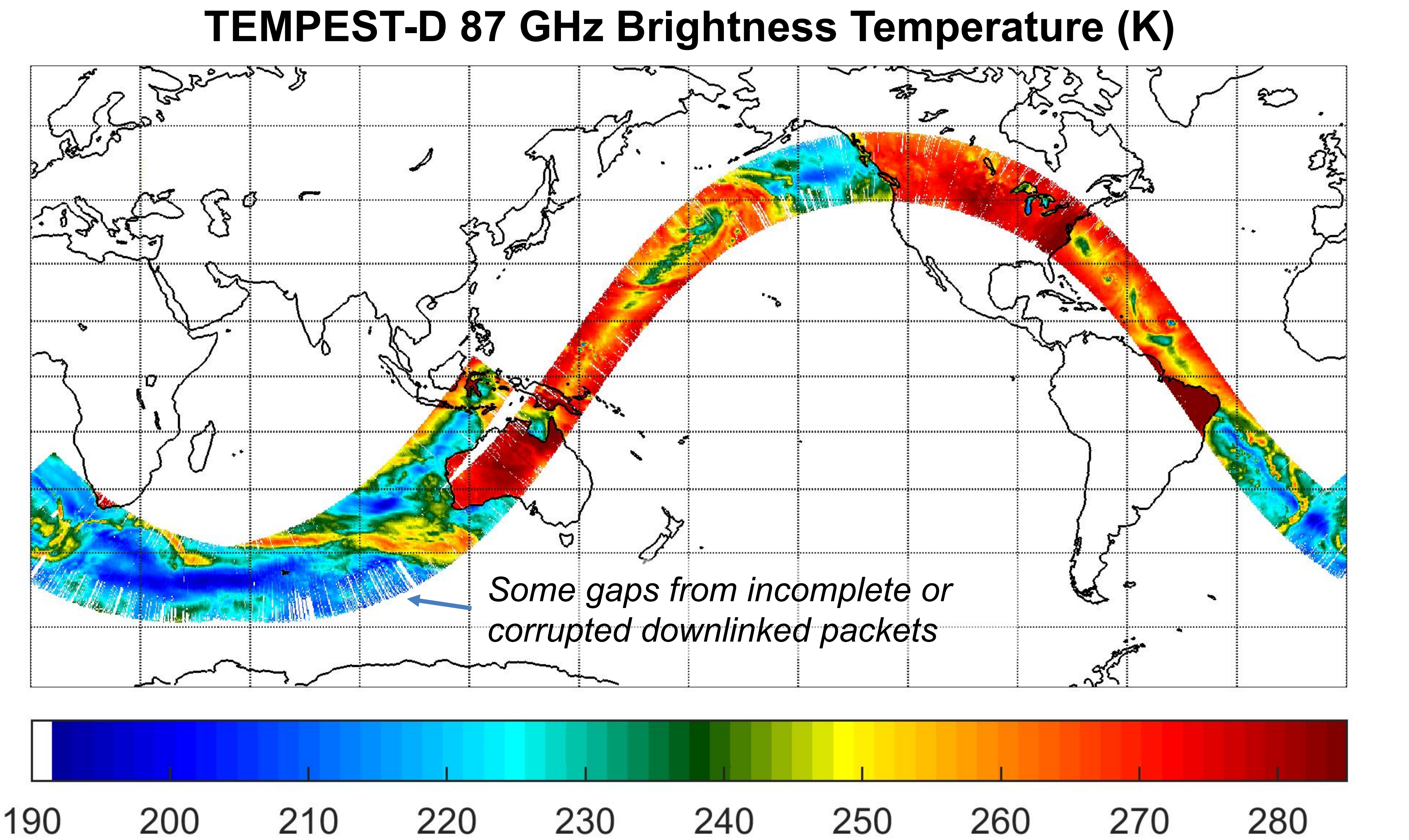
Measured radiometric resolution (NEdT) with **5-ms integration time,** both pre-launch and on-orbit, easily meet total noise requirements of 1.4 K for all five millimeter-wave radiometer channels.

# Launched by Orbital ATK from NASA Wallops 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

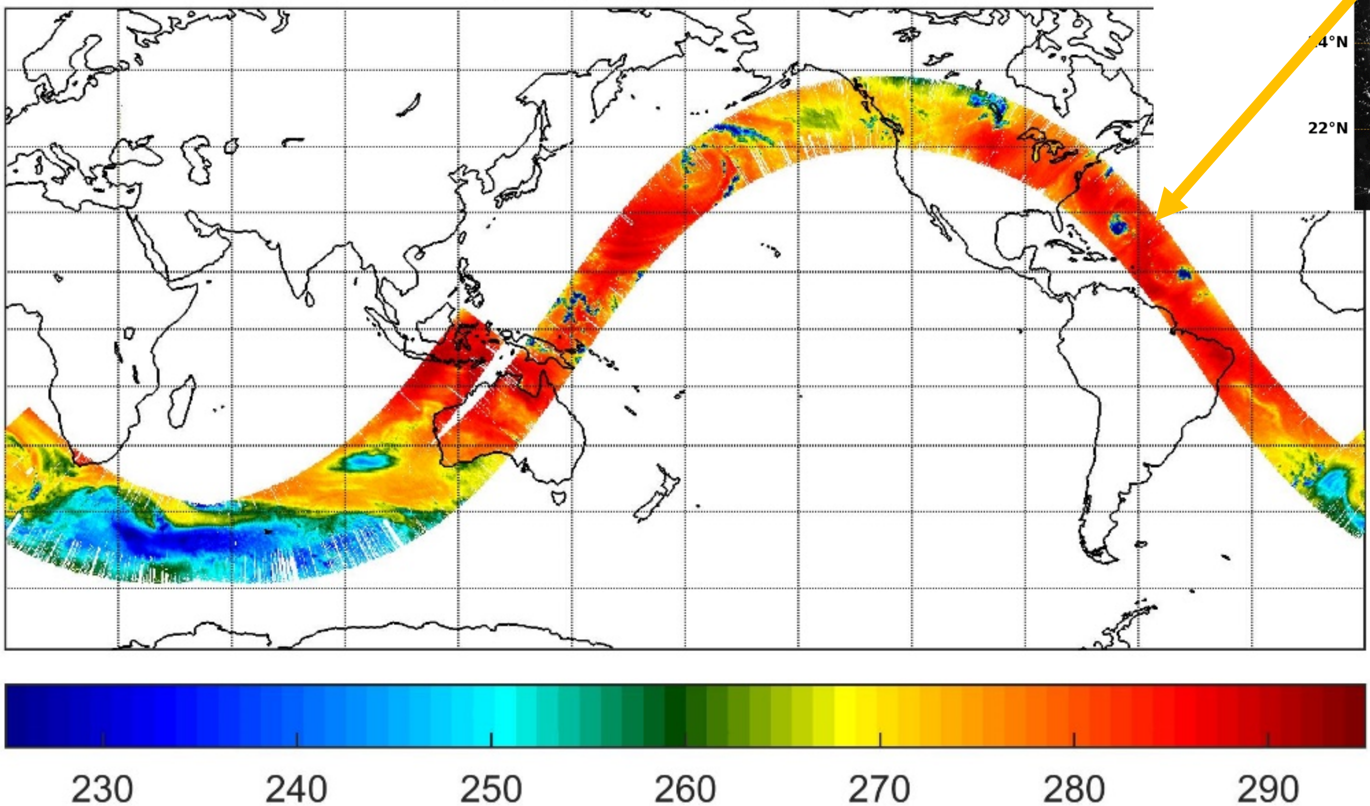


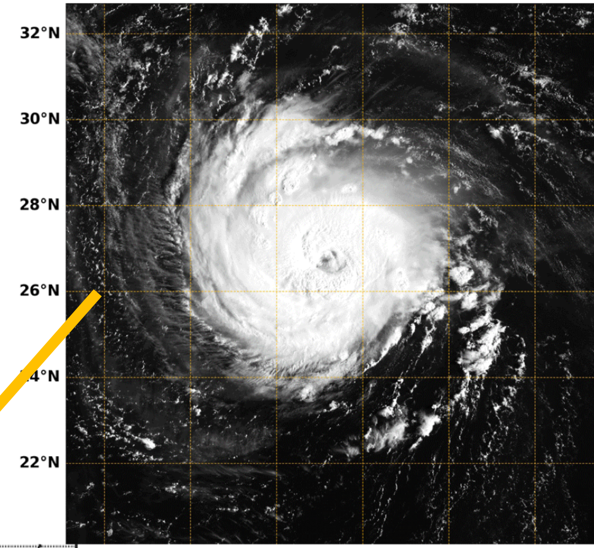

*87 GHz window channel sensitive to water vapor, clouds and precipitation.*

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

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

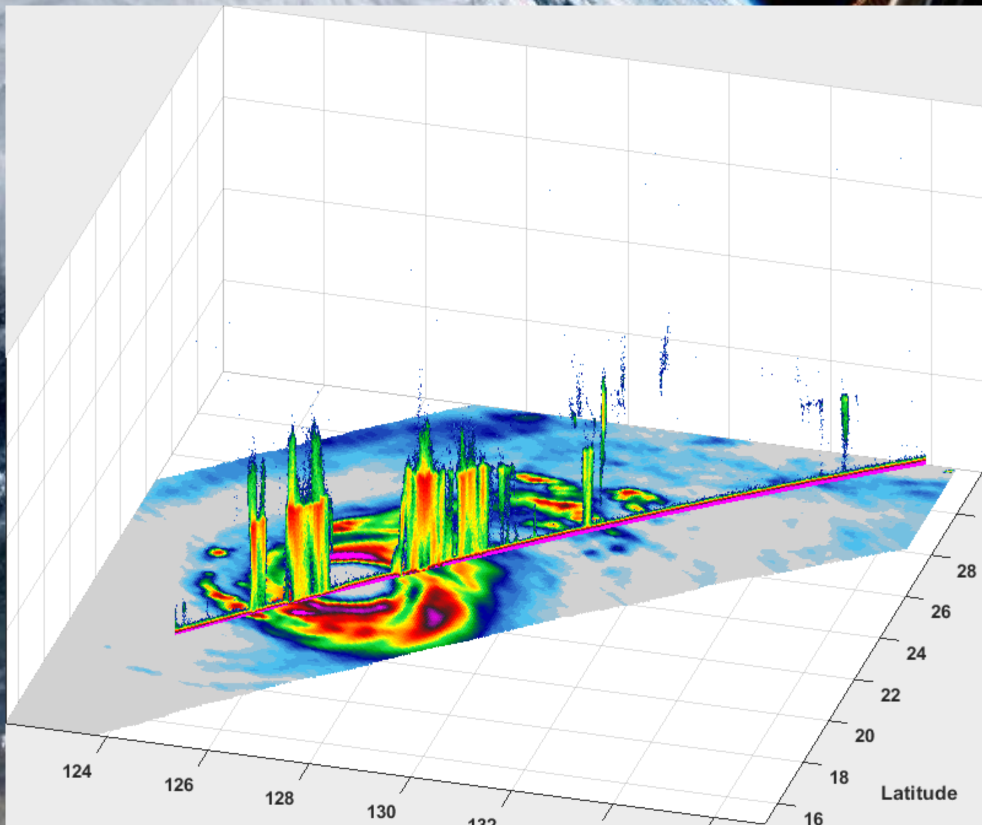
**TEMPEST-D 164 GHz Brightness Temp. (K)**



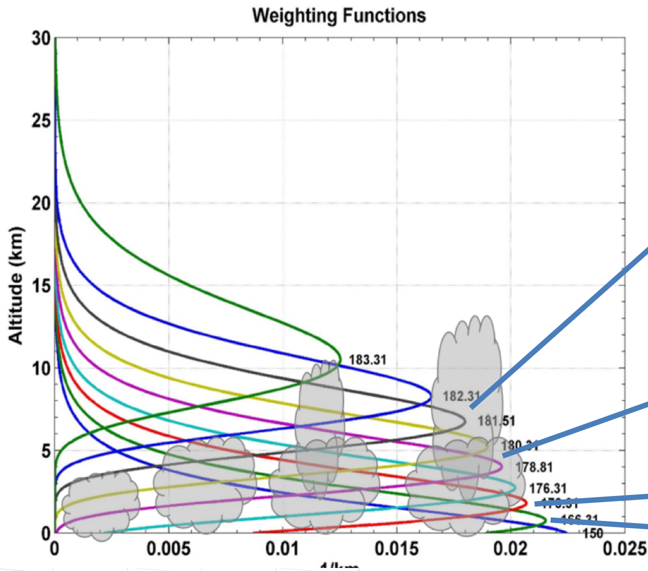



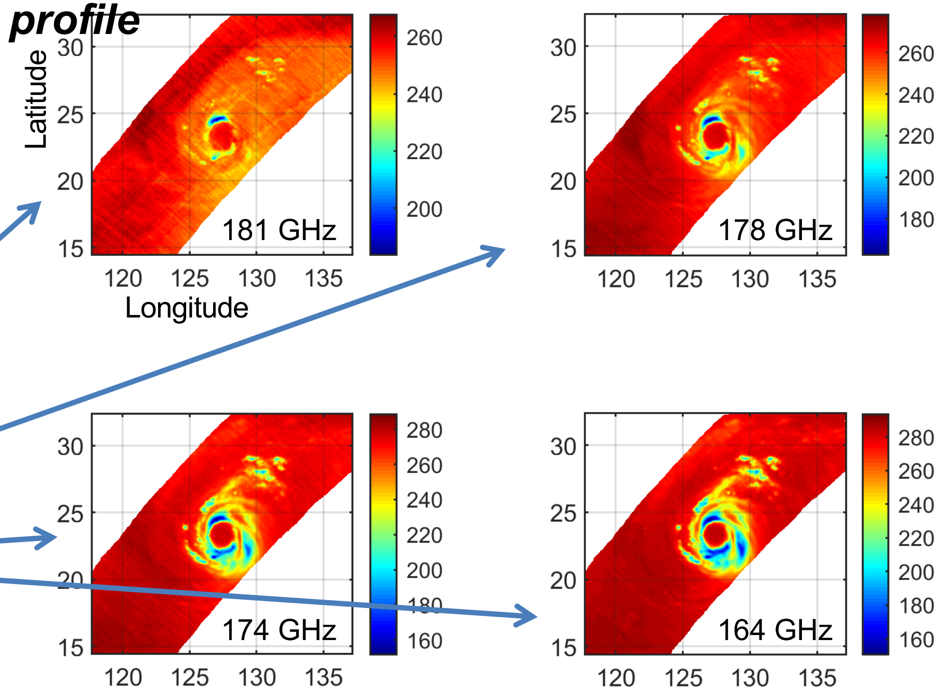

The 164 GHz color image shows the convection and intense rain bands around the inner core through the ice scattering signature. The greyscale image shows geostationary visible signature.

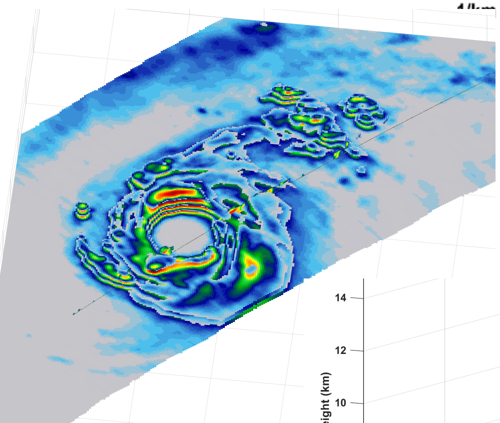
- On Sept. 28, 2018, TEMPEST-D and RainCube overflew Typhoon Trami < 5 minutes apart.
- RainCube nadir Ka-band reflectivity shown overlaid on TEMPEST-D 164 GHz brightness temperature illustrating complementary nature of these sensors and potential for constellation use to observe precipitation.
- Trami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



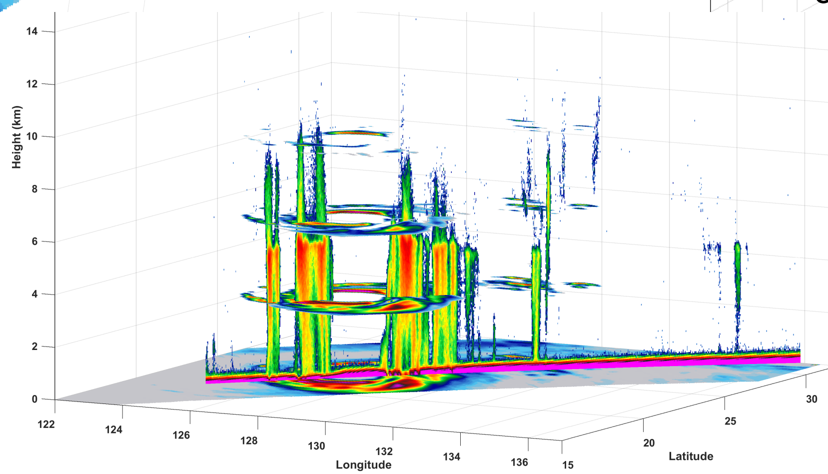
***TEMPEST-D Sounding Channels provide 4 levels of vertical resolution to "slice" precipitation and compare with RainCube profile***

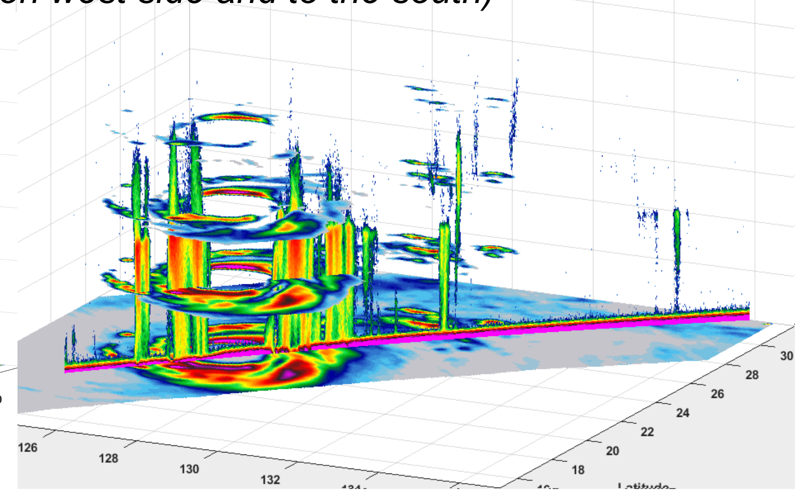


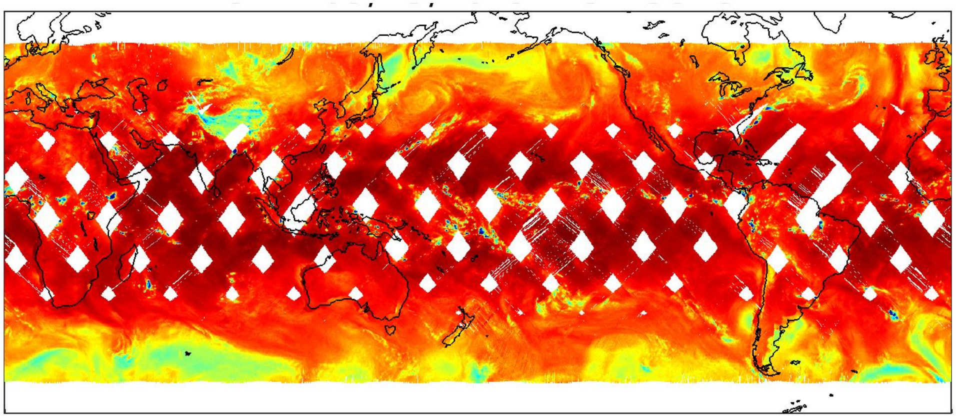
*Similar asymmetry observed in depth of eyewall convection between TEMPEST-D and RainCube (strongest on west side and to the south)*



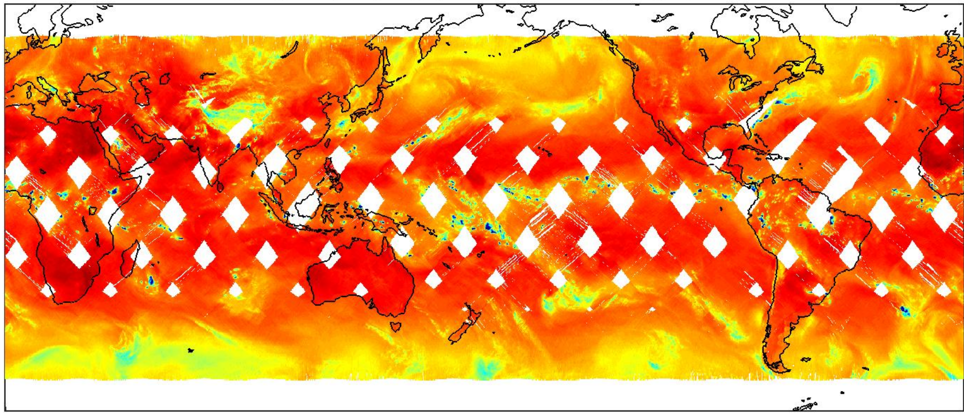



# TEMPEST-D Brightness Temperatures at 164-181 GHz on May 13, 2019

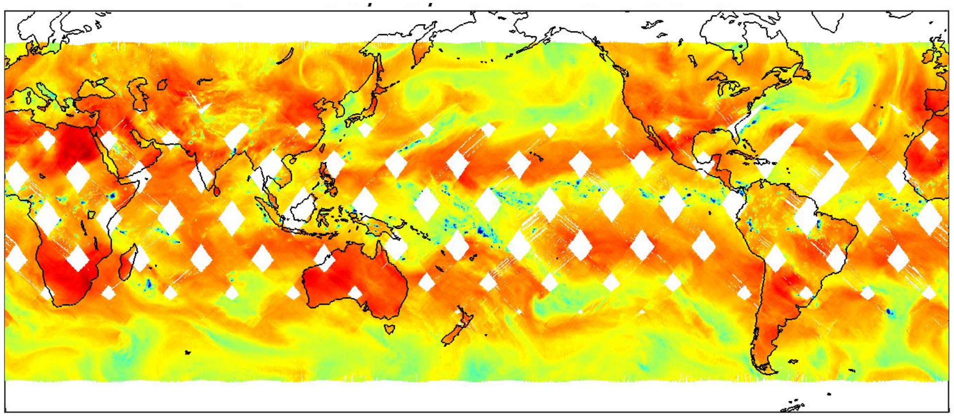
### 164 GHz Brightness Temp.



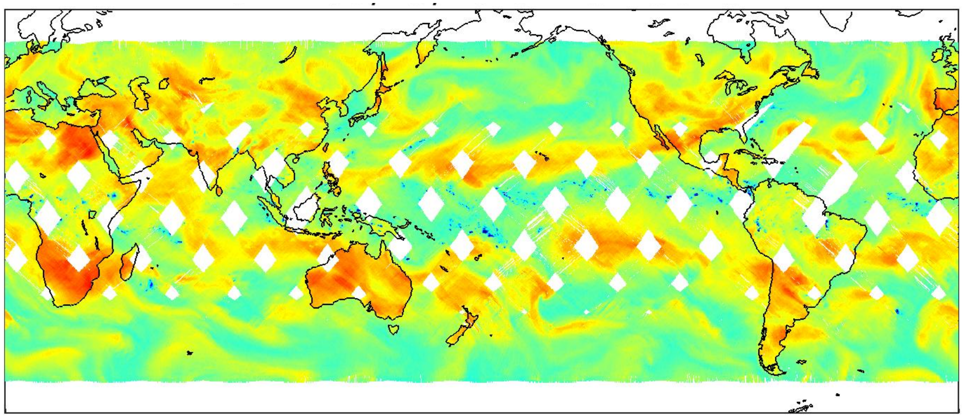
### 174 GHz Brightness Temp.

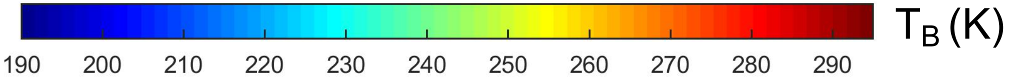


### 178 GHz Brightness Temp.

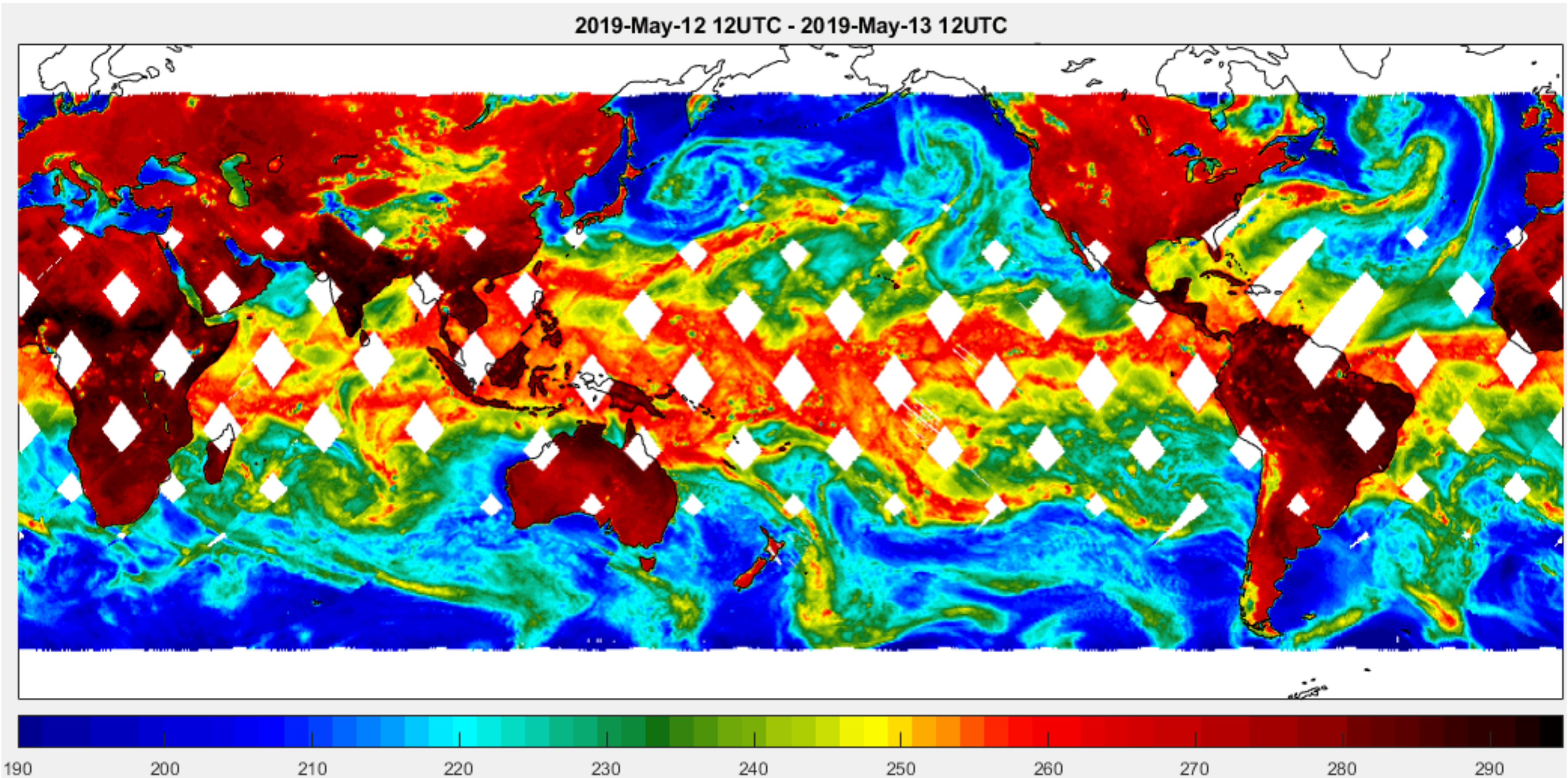


### 181 GHz Brightness Temp.



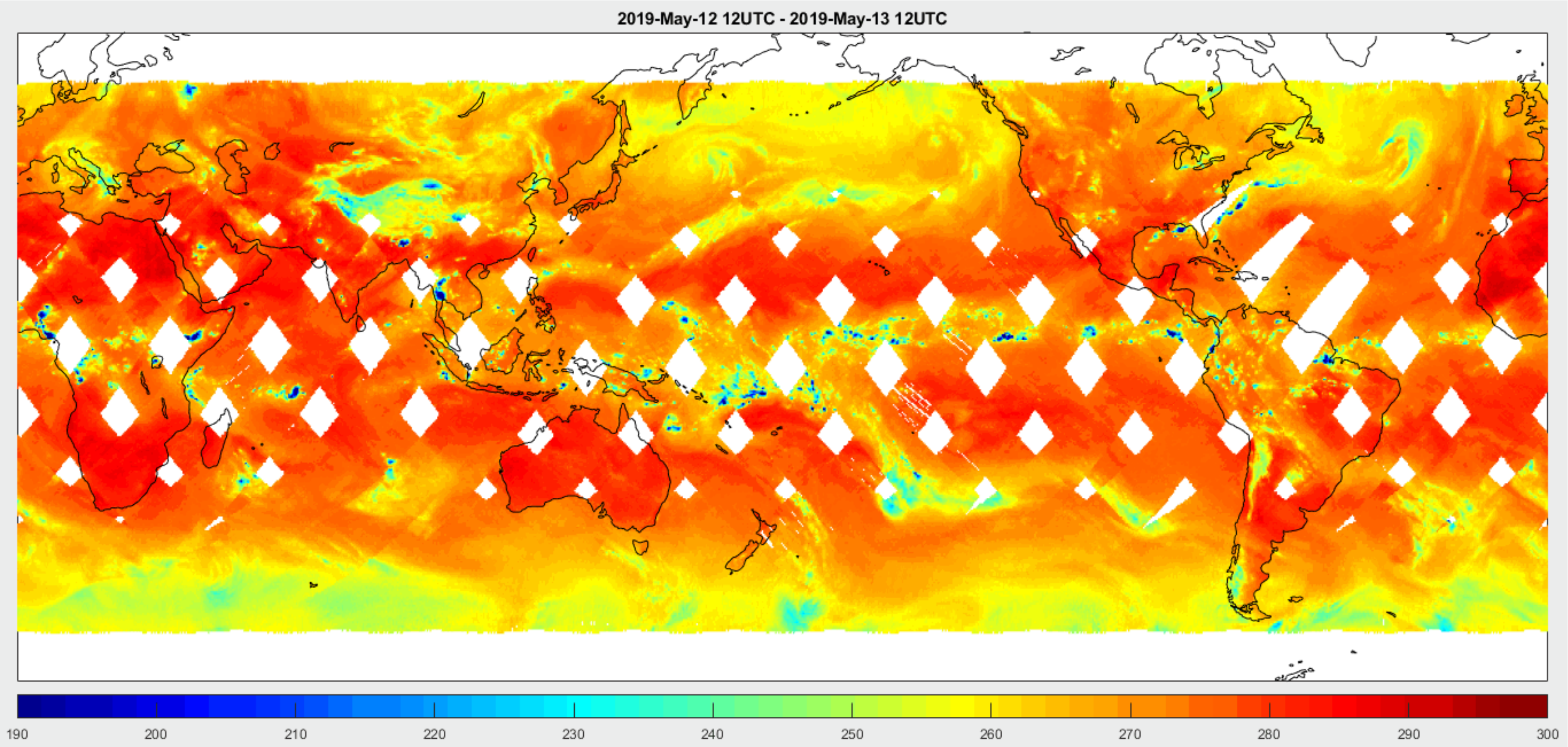


# TEMPEST-D Brightness Temperatures at 87 GHz on May 12-19, 2019



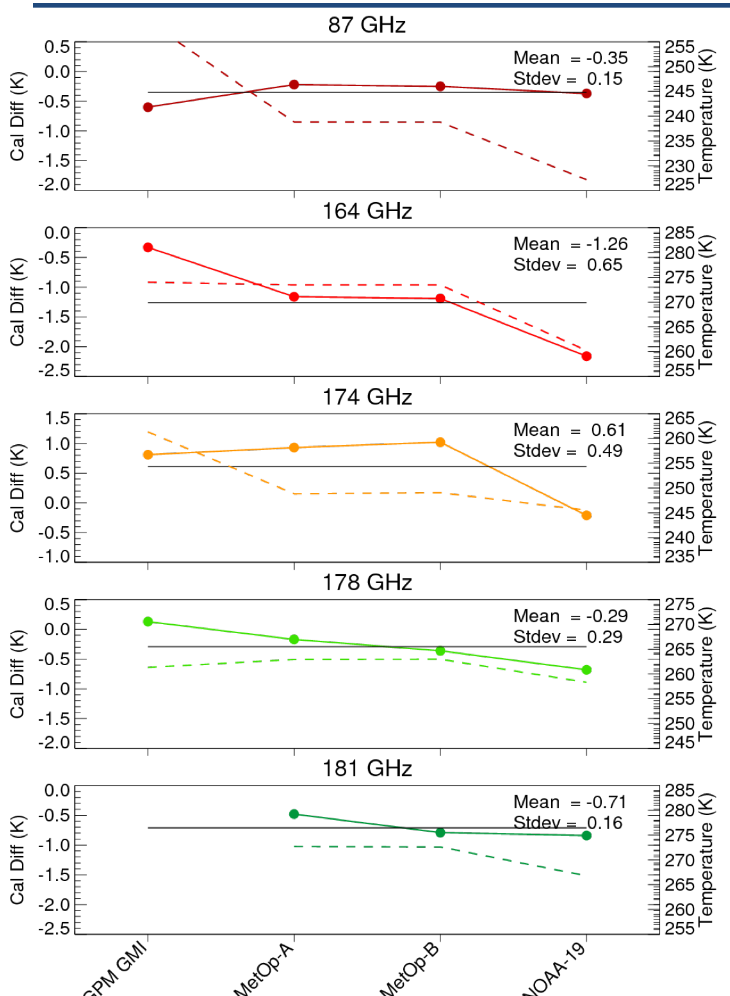

**One Week of Continuous TEMPEST-D Data**

# TEMPEST-D Brightness Temperatures at 174 GHz on May 12-19, 2019




**One Week of Continuous TEMPEST-D Data**

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



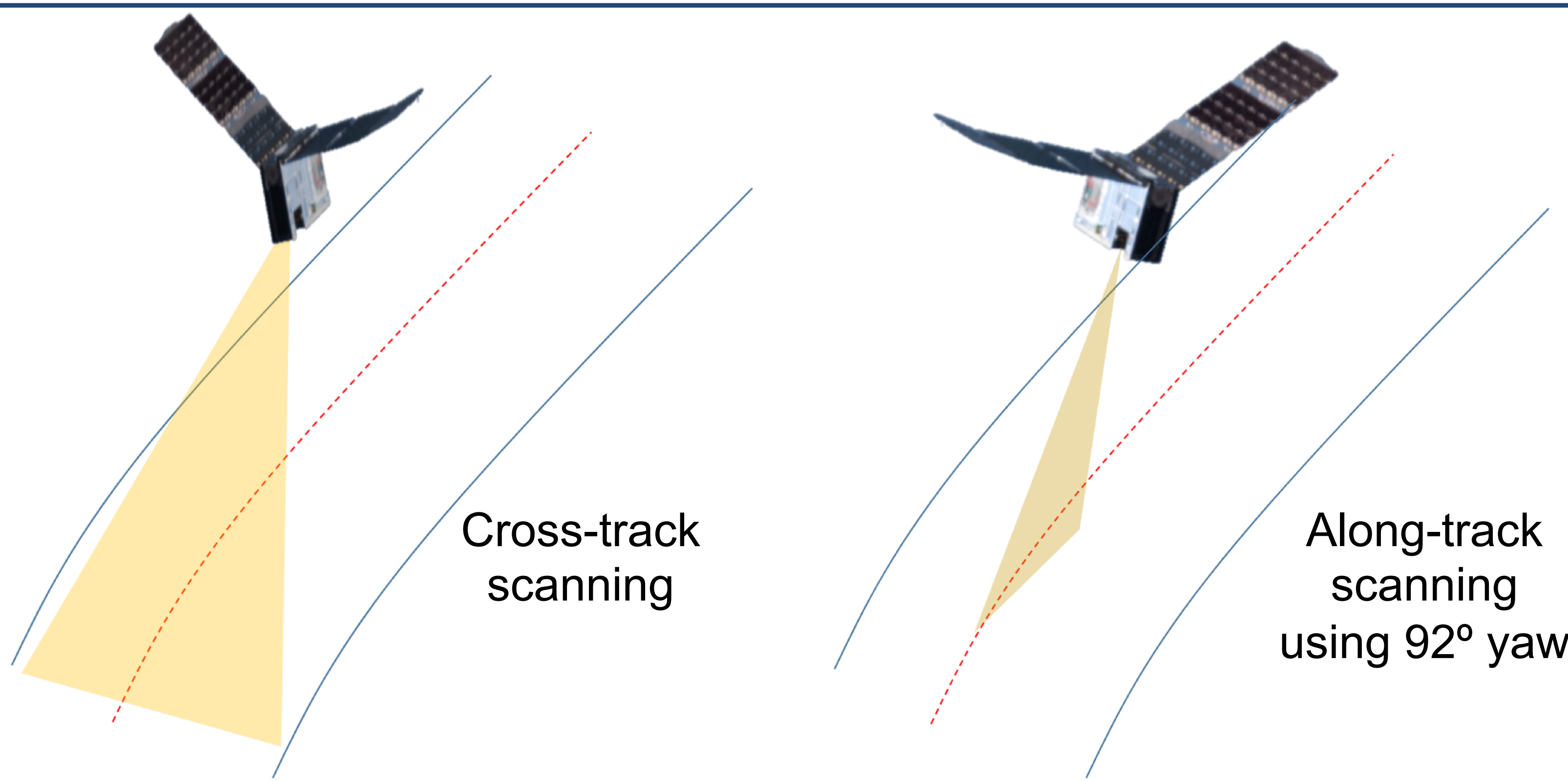

Mean calibration differences between TEMPEST-D and four reference sensors based on 18 days of data. Dashed lines indicate corresponding mean scene brightness temperature.

- 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)**

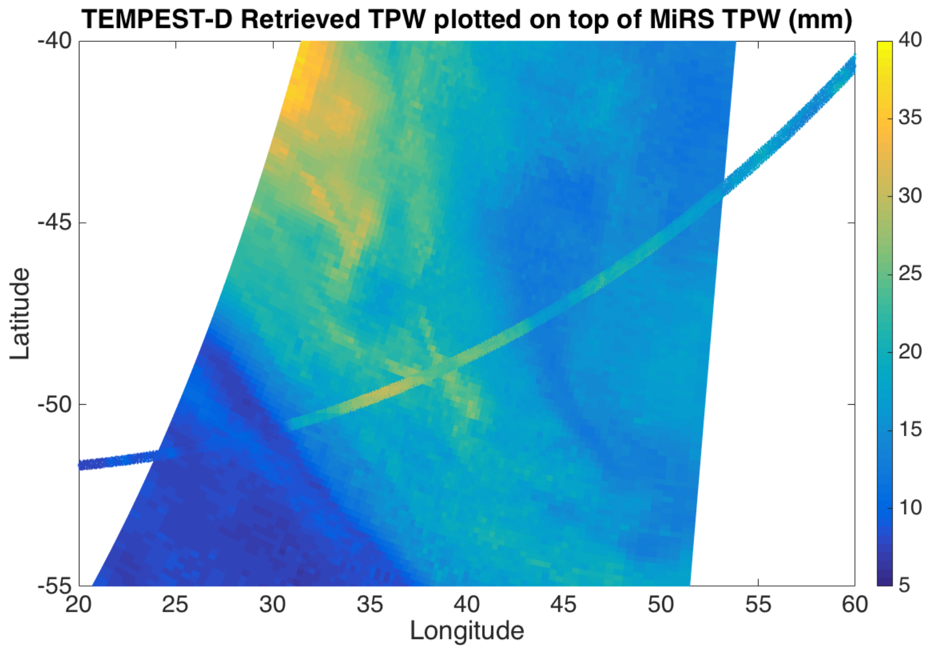
| Reference Sensor | 87 GHz | 164 GHz | 174 GHz | 178 GHz | 181 GHz |
|---|---|---|---|---|---|
| GPM GMI | -0.60 | -0.33 | 0.81 | 0.13 | N/A |
| MetOp-A MHS | -0.22 | -1.16 | 0.93 | -0.17 | -0.48 |
| MetOp-B MHS | -0.25 | -1.19 | 1.02 | -0.36 | -0.79 |
| NOAA-19 MHS | -0.37 | -2.16 | -0.21 | -0.68 | -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** |

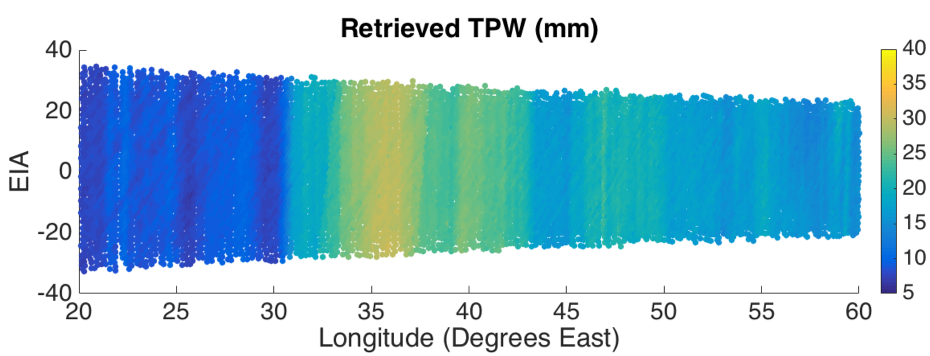
# Along-Track Scanning using a Passive Microwave Sounder on a 6U CubeSat




- 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.

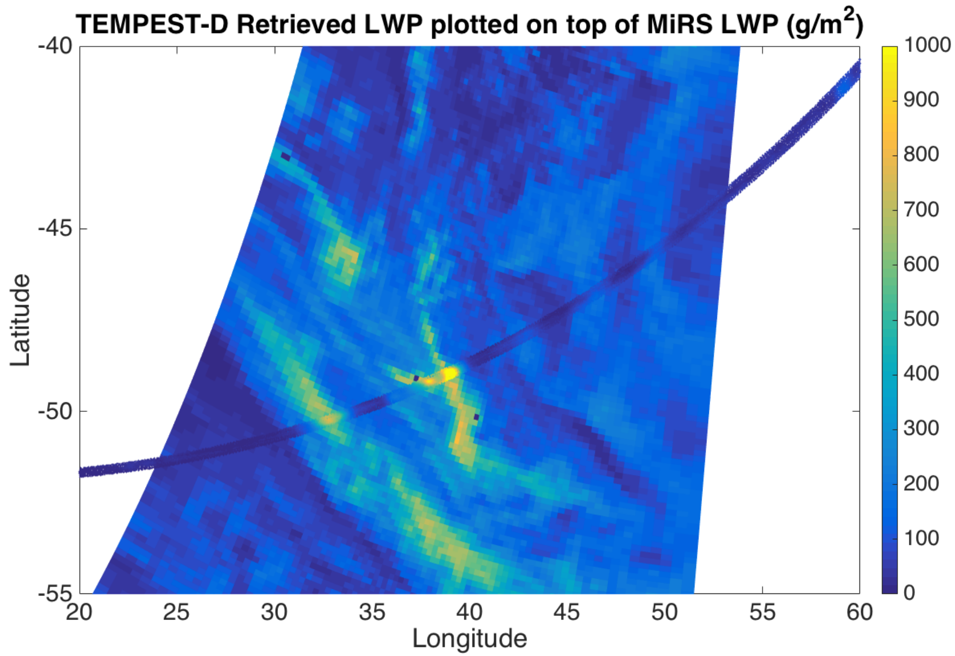
# Along-Track Scanning: Water Vapor Retrieval Results

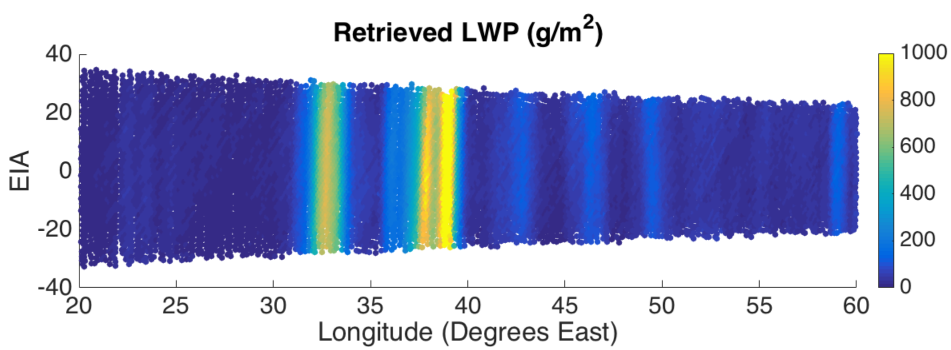



- Coincident observations by TEMPEST-D and MHS on MetOp-B on Jan. 30, 2019
- Background shows total precipitable water (TPW) retrieved from MHS using NOAA/NESDIS MiRS algorithm
- Narrow swath contains TPW retrieved from TEMPEST-D data in along-track scanning mode, showing good agreement between TPW products
- Lower plot shows TEMPEST-D data within 10 km of ground track, with very consistent retrieved values over a range of incidence angles

# Along-Track Scanning: Cloud Water Retrieval Results




- Similar consistency observed in retrievals from MHS using MiRS and TEMPEST-D of cloud liquid water path (LWP) on Jan. 30, 2019
- Results suggest that the uncertainty/noise inherent in making two measurements with different slant paths is rather small compared to the spatial variability of LWP over only a few km.

# TEMPEST-D Mission Status and Summary

- TEMPEST-D, a NASA Earth Venture Tech Demonstration mission, met all of its success criteria during the first 90 days of operations.
- Demonstrated 9 months of on-orbit operations to date of TEMPEST-D, with a five-channel millimeter-wave radiometer (87-181 GHz) on a 6U CubeSat.
- Demonstrated TEMPEST-D data quality indistinguishable from data acquired by well-established operational radiometers, even though the 6U CubeSat is a fraction of the size/weight 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 retrieval of total water vapor and liquid water over a range of Earth incidence angles, showing good agreement with operational weather products.
- Demonstrated rapid development of a CubeSat technology demonstration mission for Earth Science, i.e. 2.5 years from start to launch readiness.

# TEMPEST-D Future Plans

- Based on JPL orbital calculations, TEMPEST-D is expected to remain in orbit well into 2021 before it burns up upon atmospheric re-entry.
- The TEMPEST-D Team would like to continue operations to use valuable opportunities to produce valuable science-quality data.
- CSU/CIRA SmallSat project funded by NOAA/NESDIS is producing initial results from assimilation of TEMPEST-D data into NOAA numerical weather prediction models.
- Based on the 9 months of successful TEMPEST-D operations, many new opportunities exist for new scientific investigations providing improved temporal resolution using closely-spaced constellations.
- The TEMPEST instrument can be combined with other sensors, such as cloud and precipitation radars or the TWICE instrument for cloud ice particle sizing on small satellite platforms larger than typical CubeSats.
- Public data release of TEMPEST-D data is planned for the end of July to coincide with IGARSS 2019.

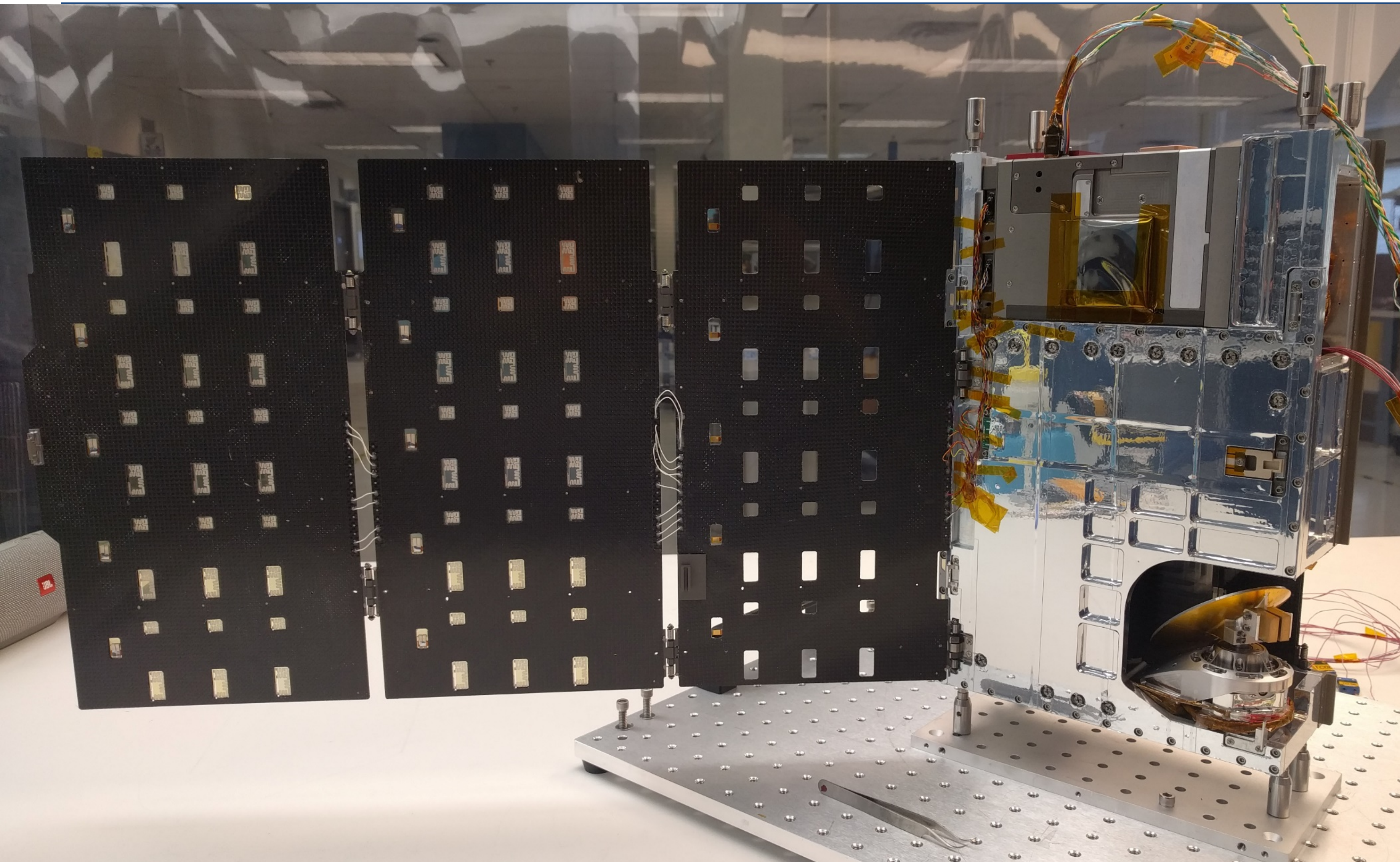
*Thank you for your kind attention. Thanks to the NASA Earth Venture Tech Program for their support. Thanks to the NASA Earth Science Technology Office for program management.*

# Backup Slides

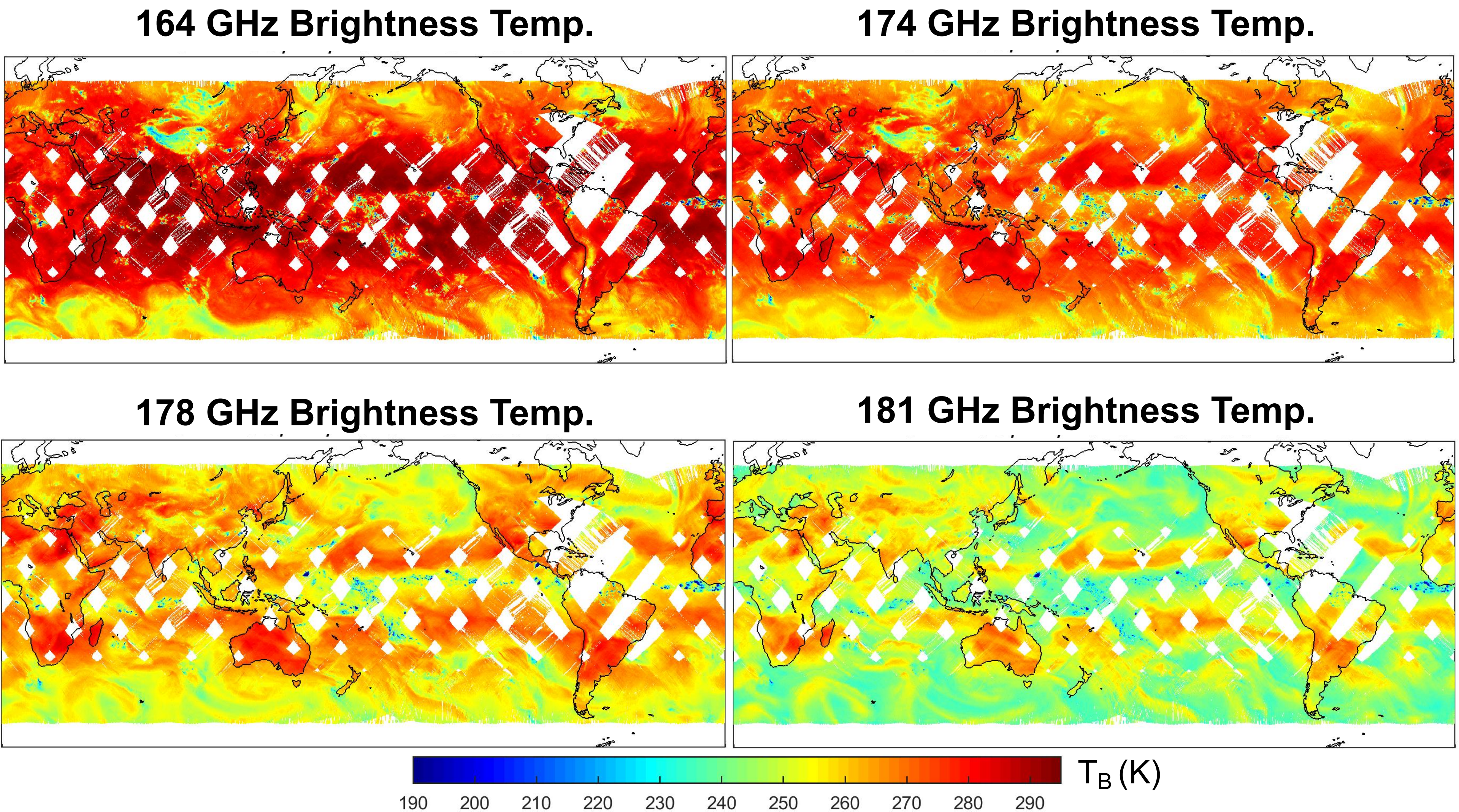
# TEMPEST-D Met Mission Success Criteria in First 90 Days

- 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 8 months since first light to date ✓

# TEMPEST-D Spacecraft Integrated at BCT in Feb. 2018

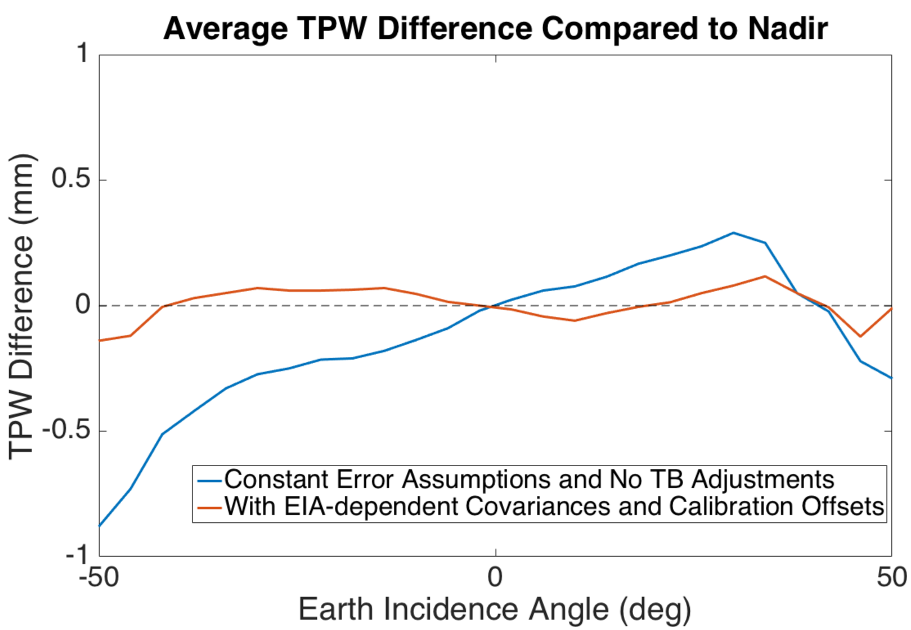


# TEMPEST-D Brightness Temperatures at 164-181 GHz on May 14, 2019

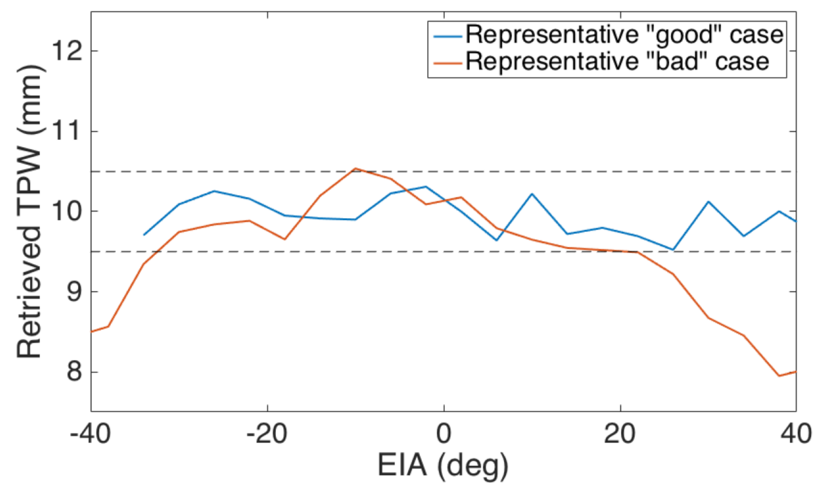


# Along-Track Scanning using a 6U CubeSat: Preliminary Results

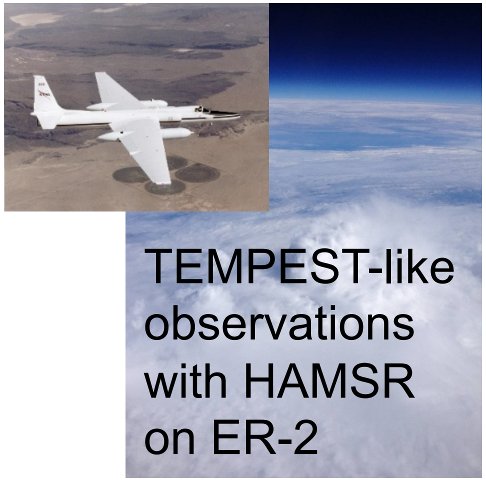
- Statistical analysis of more than 70 hours of yaw maneuver data from Jan and April 2019 reveals that TPW retrievals have almost zero bias as a function of EIA, once EIA-dependent forward model TB biases and instrument calibration offsets are accounted for (consistent with *Schulte and Kummerow*, 2019).

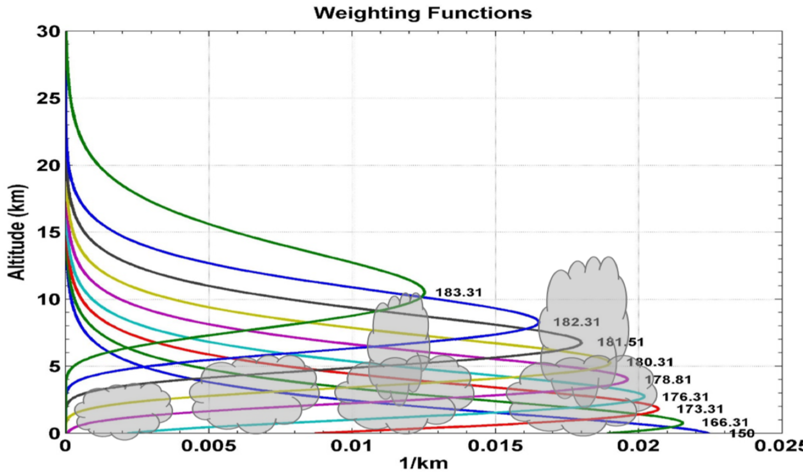


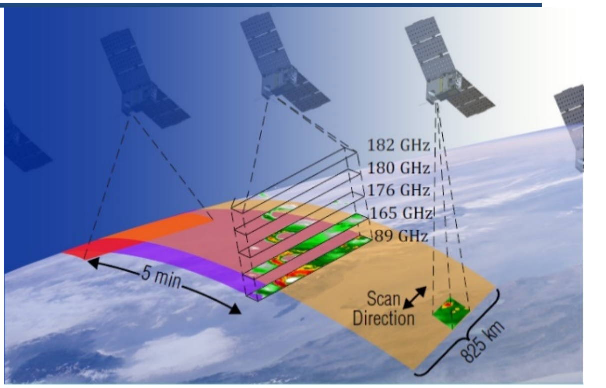

- At the pixel level, individual values usually within 5% of the nadir value but in some cases LWP is substituted for TPW or vice versa



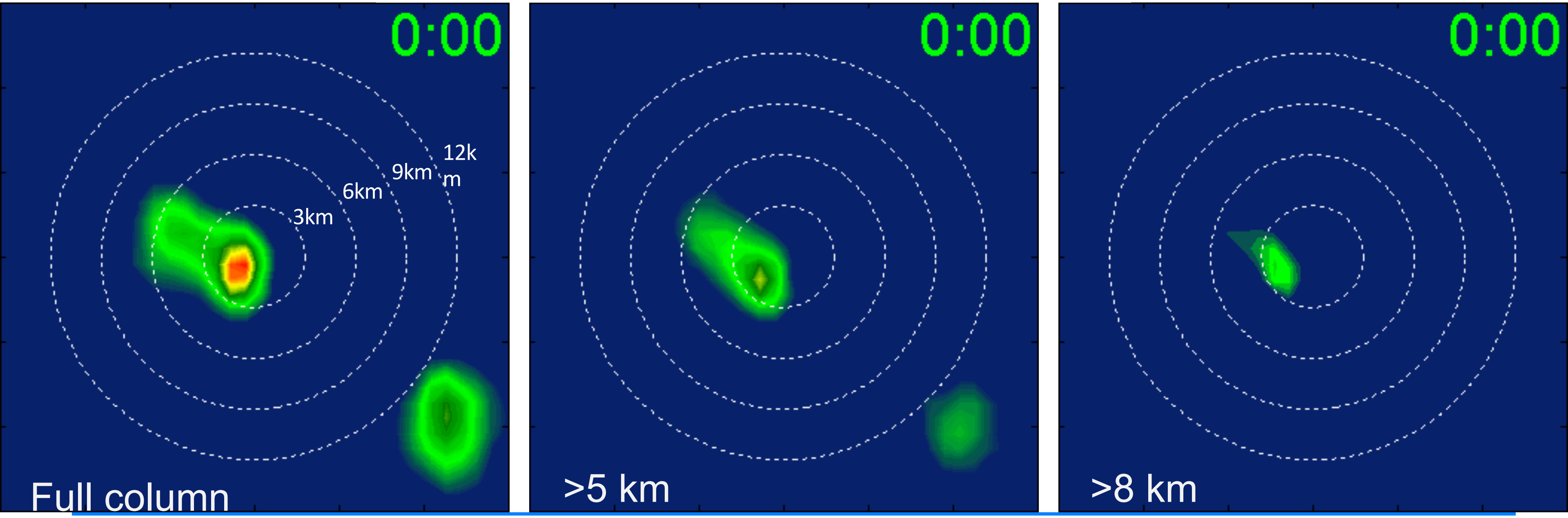
# TEMPEST-Like Measurements from JPL/HAMSR on ER-2 Aircraft



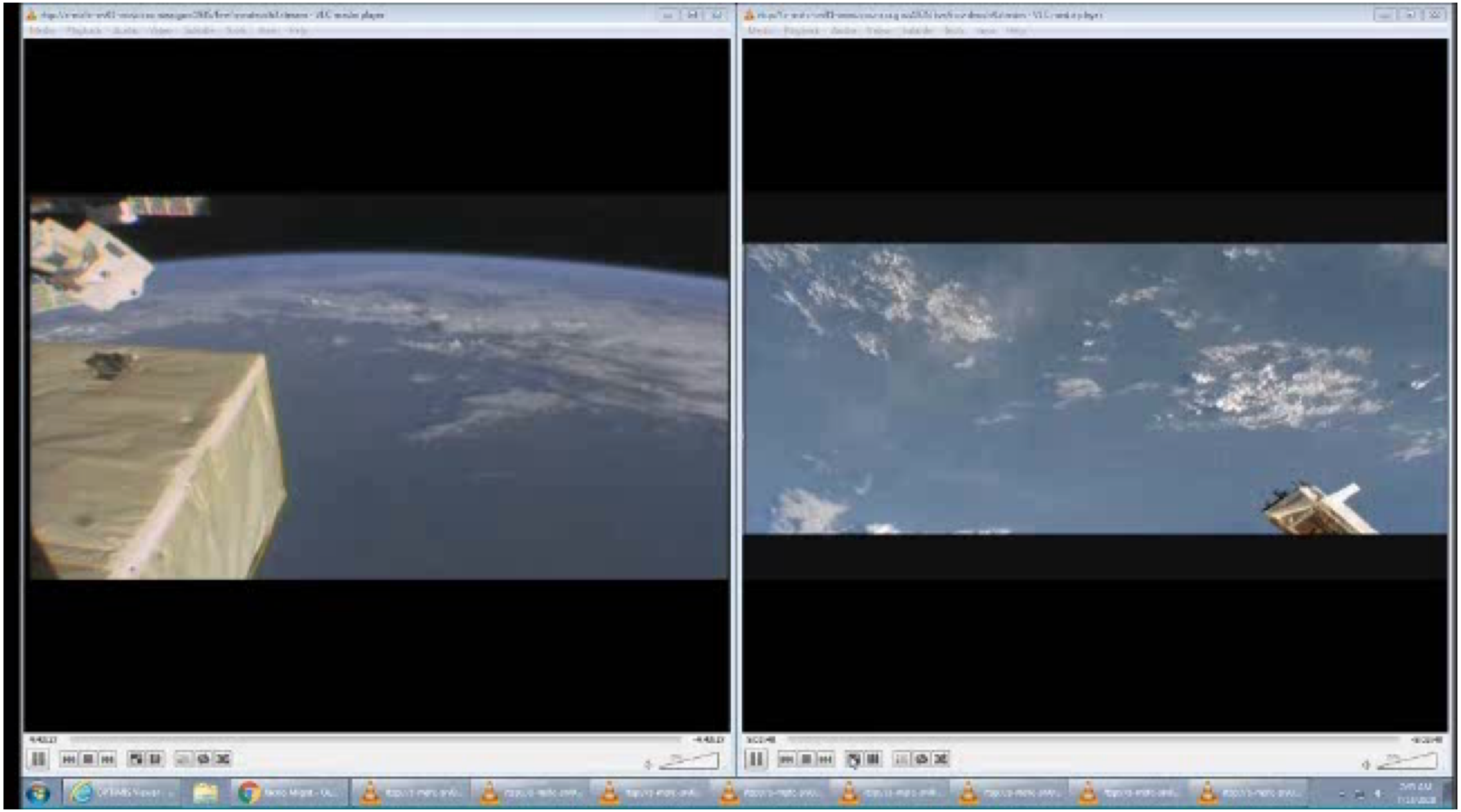




*TEMPEST – enabling rapid revisit radiometry for precipitation processes*

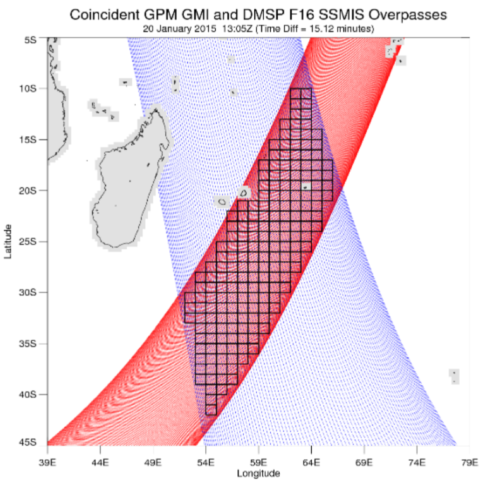


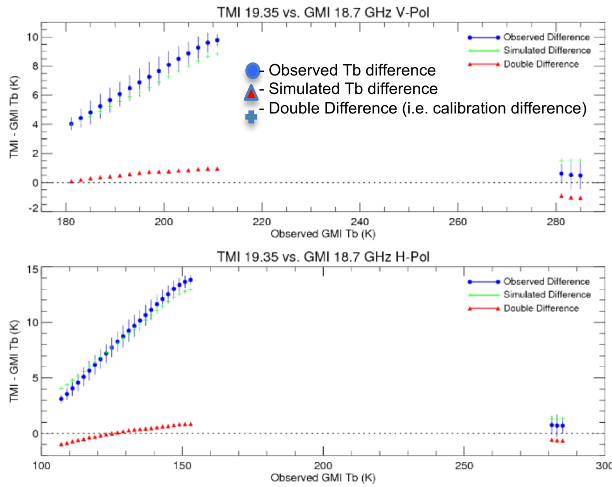
# Deployment of TEMPEST-D and CubeRRT into Orbit from ISS



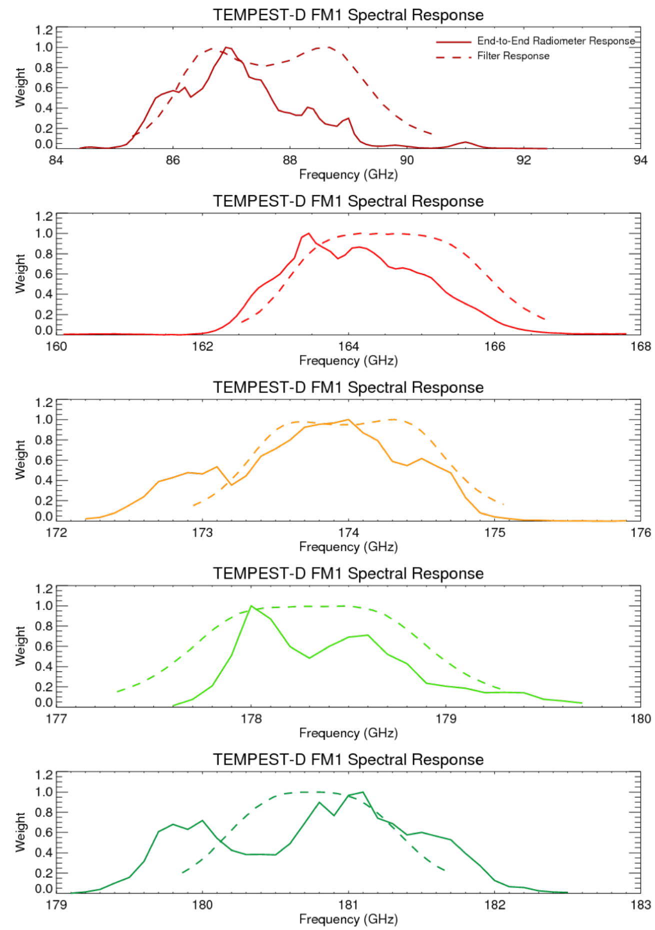
Recorded on International Space Station on 13 July 2018      Credit:  NASA

# Validation: Double Difference Method



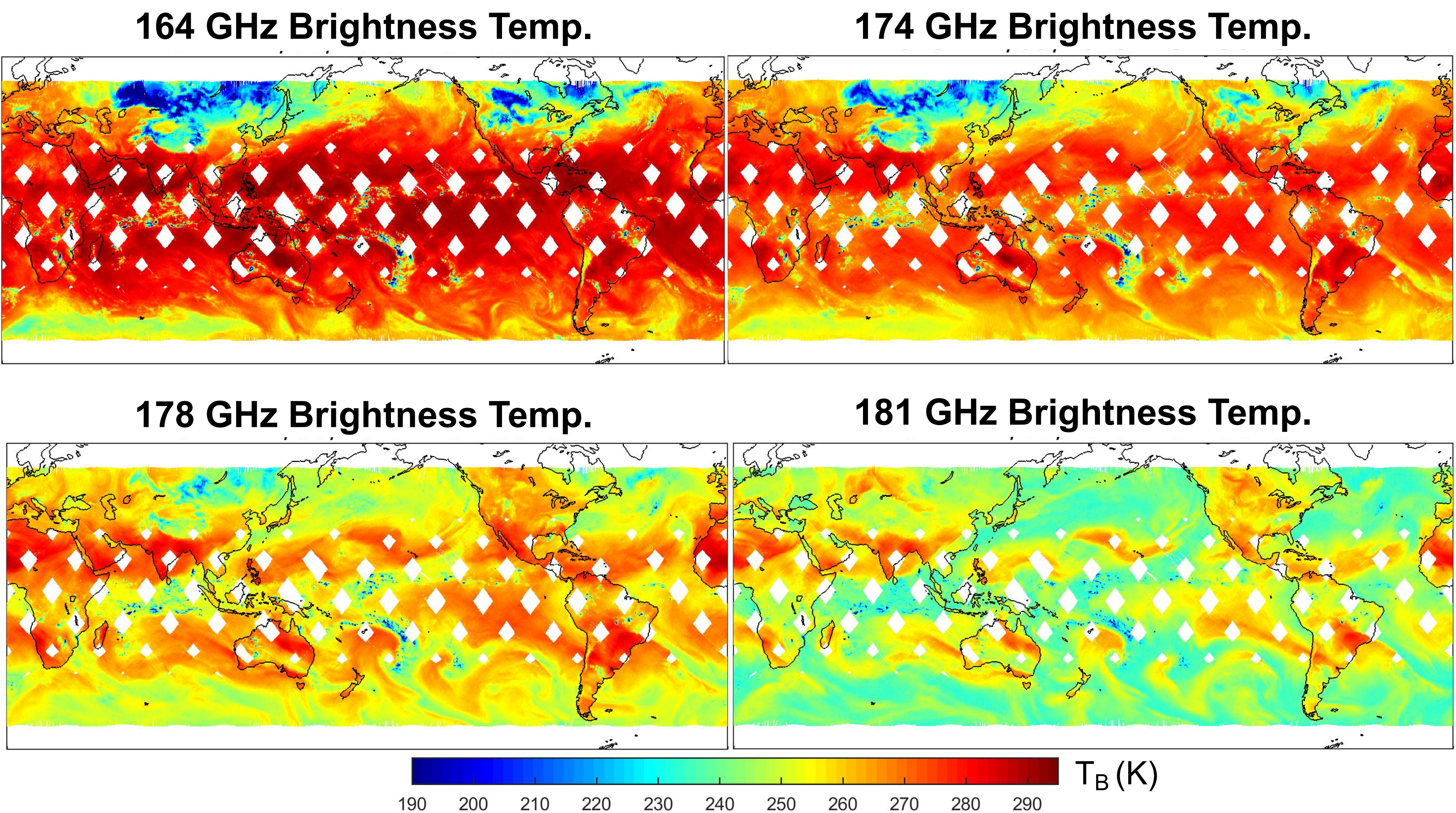




- TEMPEST-D observations matched in space and time with reference sensors
- Radiative transfer simulations using geophysical parameters from the NASA GEOS5 global data assimilation model, to account for sensor differences (i.e. channel frequencies, spectral response, polarization and view angle).
- Difference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

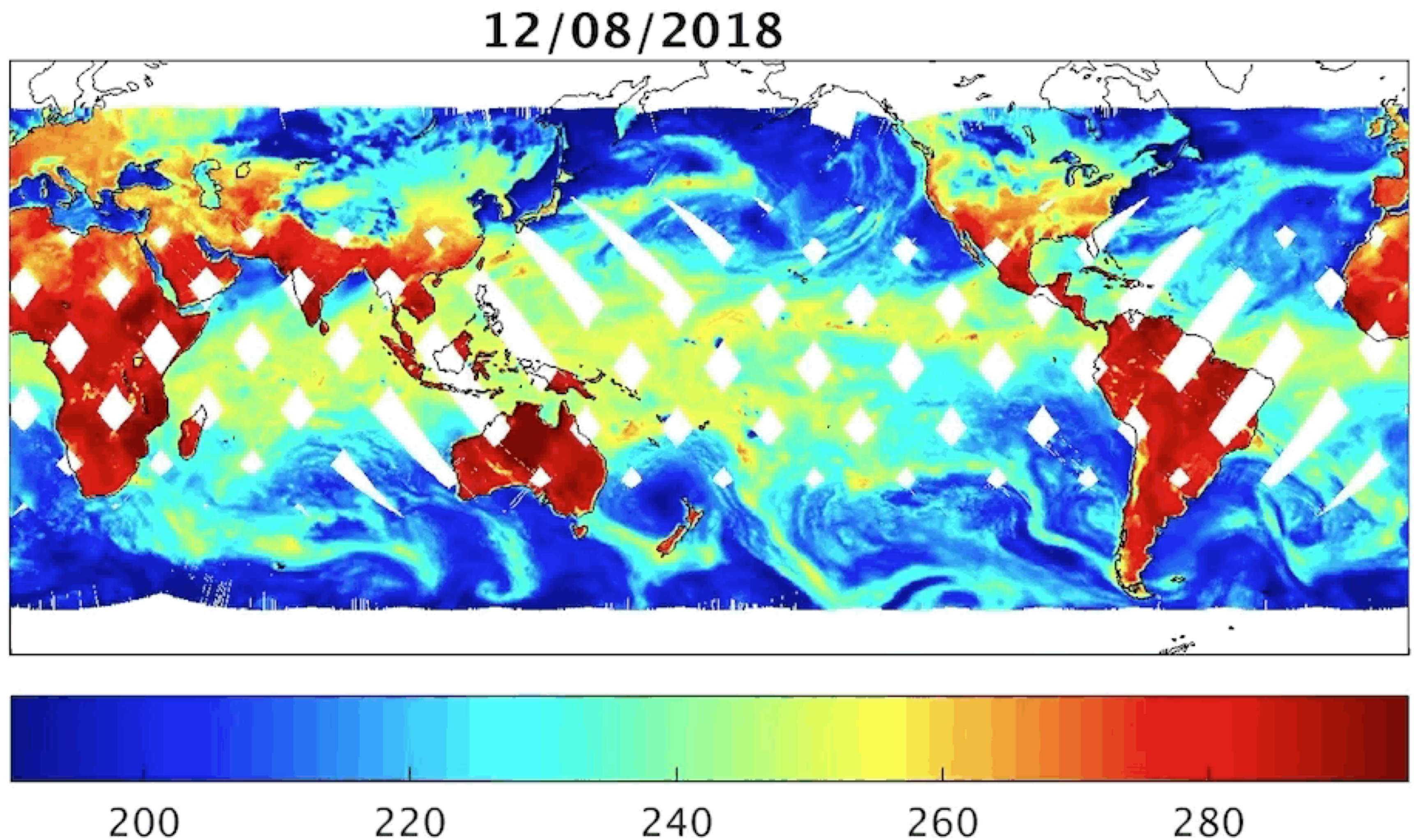



Spectral response functions for TEMPEST-D. Dashed lines indicate filter response, and solid lines show end-to-end radiometer response.

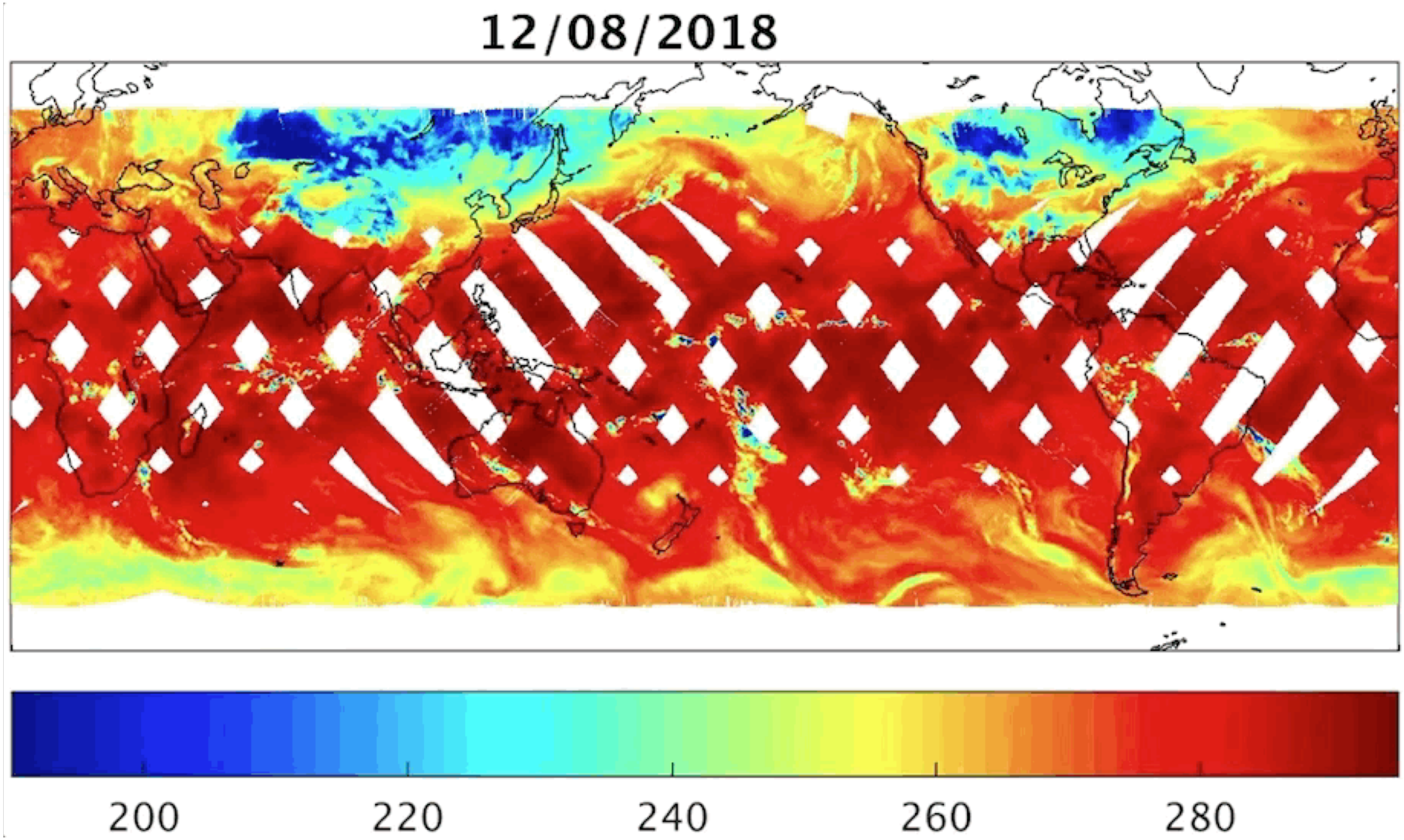
# TEMPEST-D Brightness Temperatures at 164-181 GHz on Dec. 9, 2018



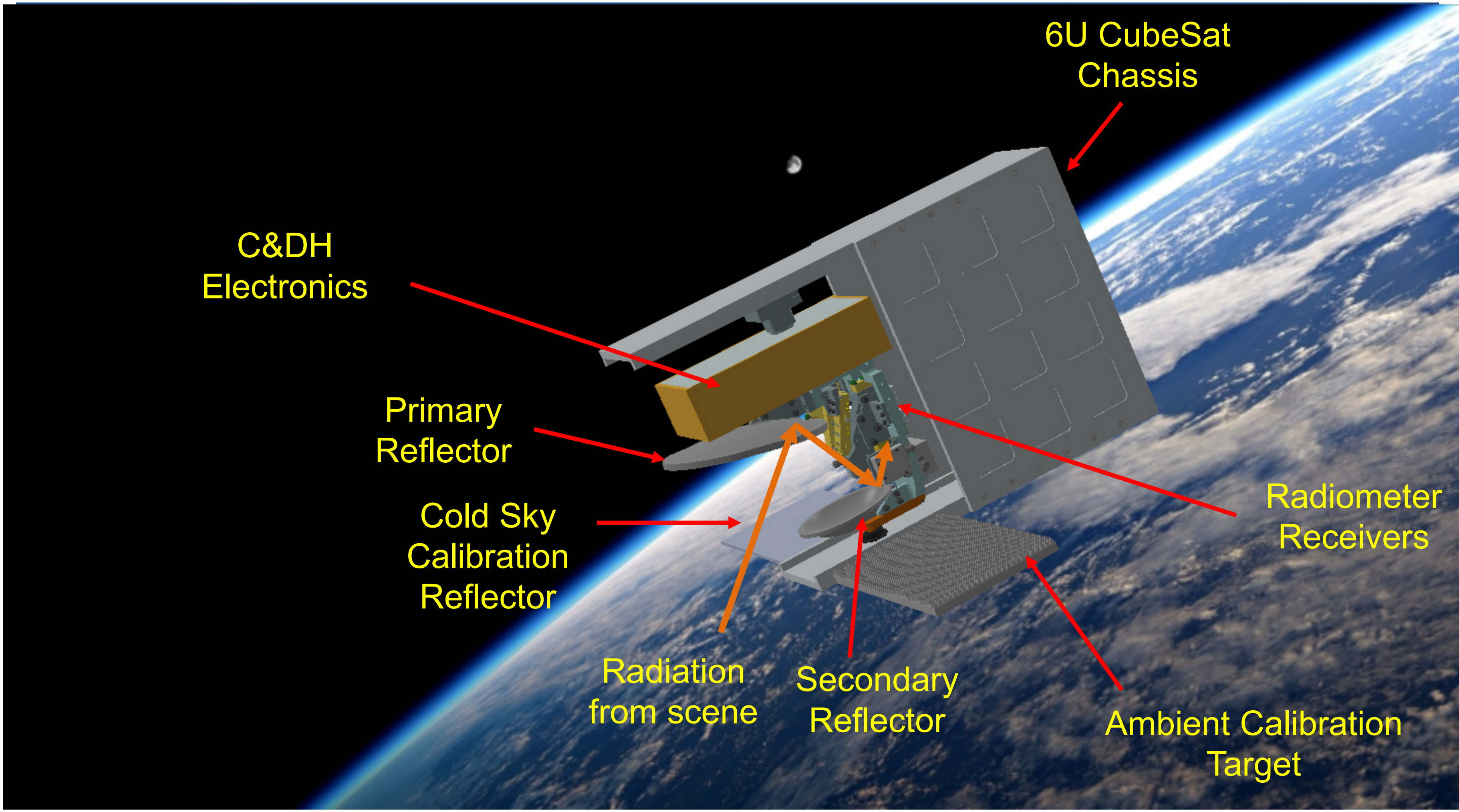
# TEMPEST-D Brightness Temperatures at 87 GHz from Dec. 8-14, 2018



# TEMPEST-D Brightness Temperatures at 164 GHz from Dec. 8-14, 2018



# Tropospheric Water and Cloud ICE (TWICE) Instrument for 6U CubeSats




- Conically-scanning radiometer with 16 frequencies from 118 GHz to 850 GHz
- Radiometer instrument has 3 kg mass and 12 W power consumption