Millimeter-wave Remote Sensing of the Atmosphere: Results from TEMPEST-D

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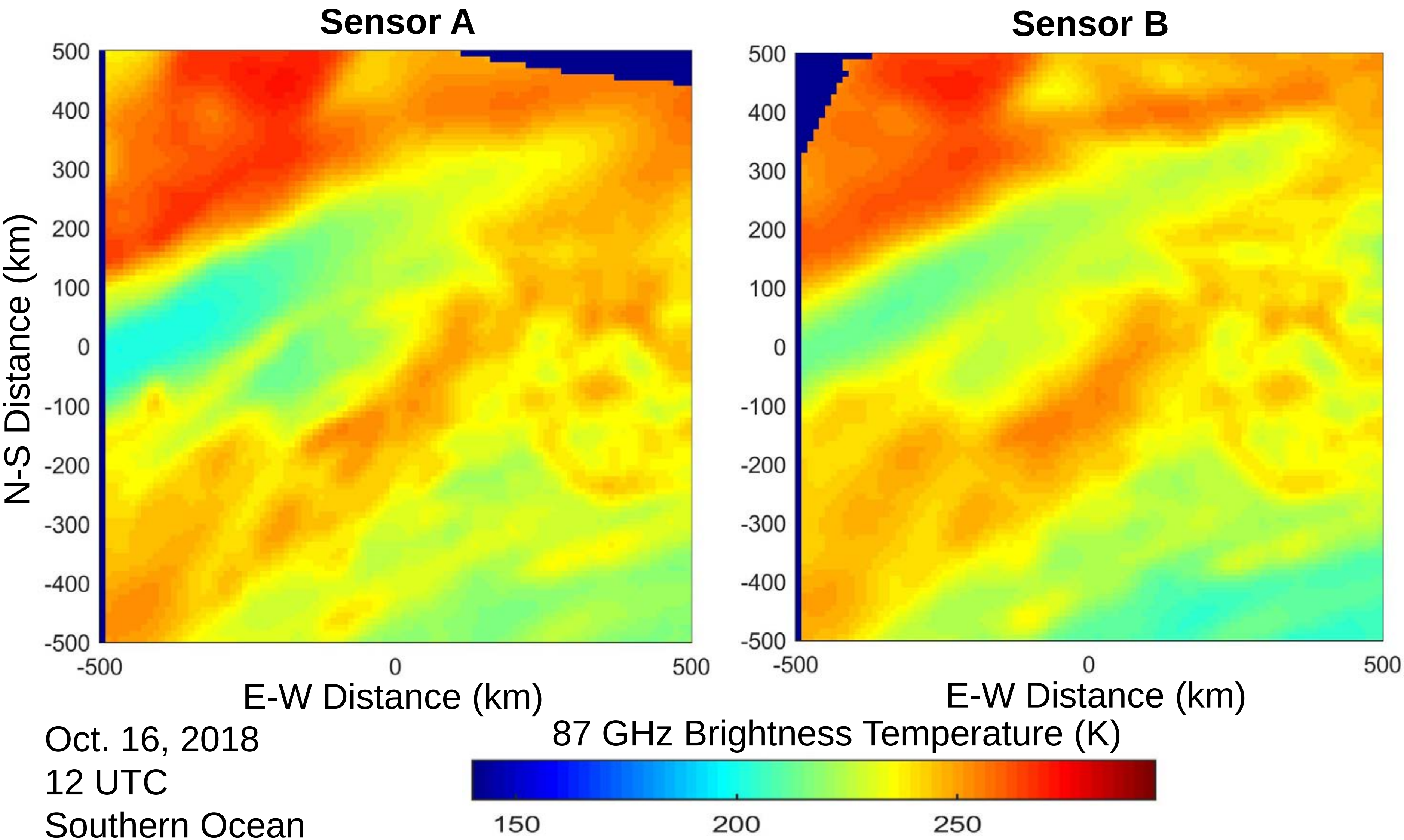
Thanks to NASA Wallops for providing ground station communications support for the TEMPEST-D mission.

Comparison Between On-orbit Passive Microwave Sensors



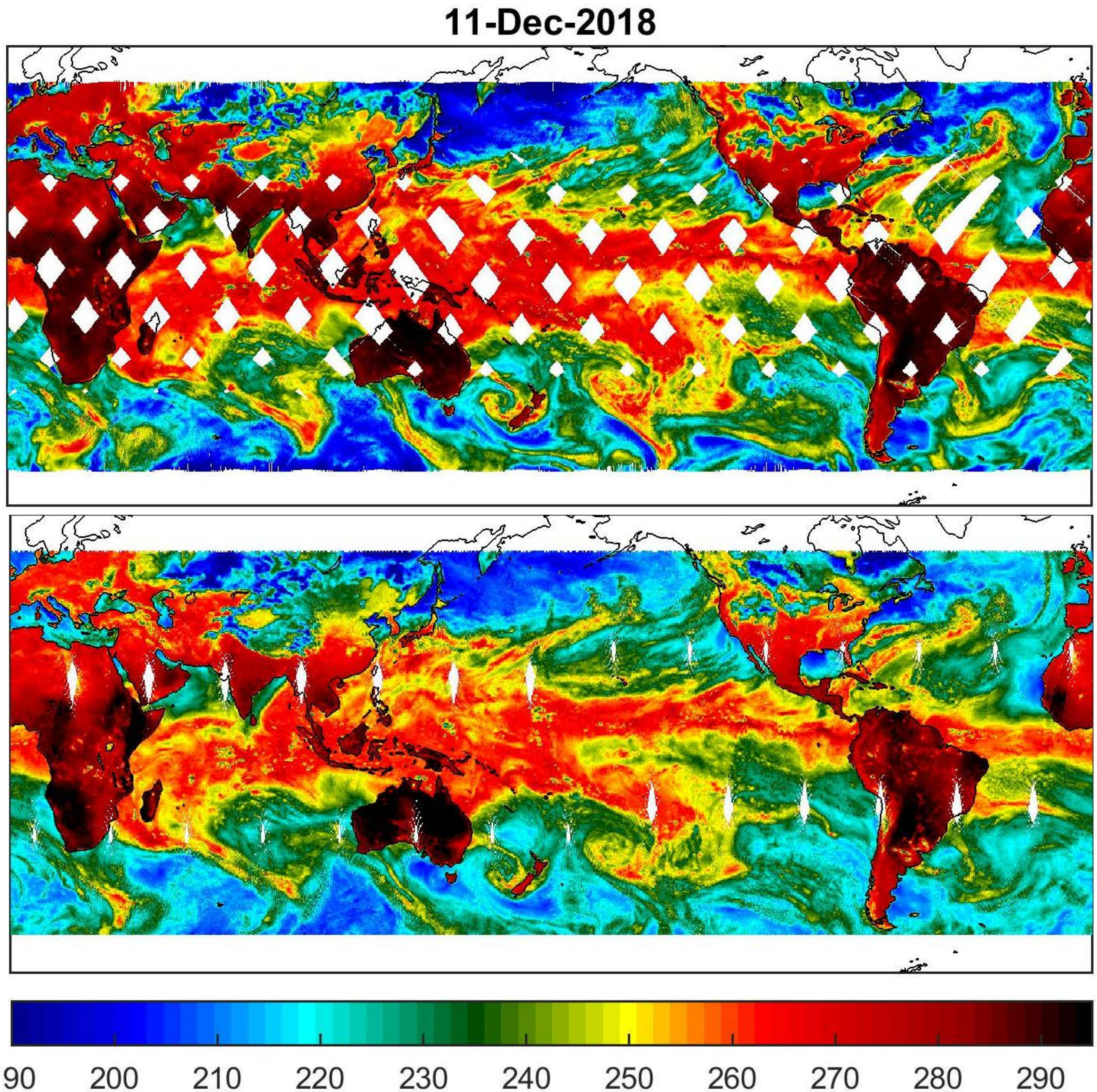
Oct. 16, 2018
12 UTC
Southern Ocean

Comparison Between On-orbit Passive Microwave Sensors

Sensor A

Sensor B

87 GHz
Brightness
Temperature (K)



Sensor B

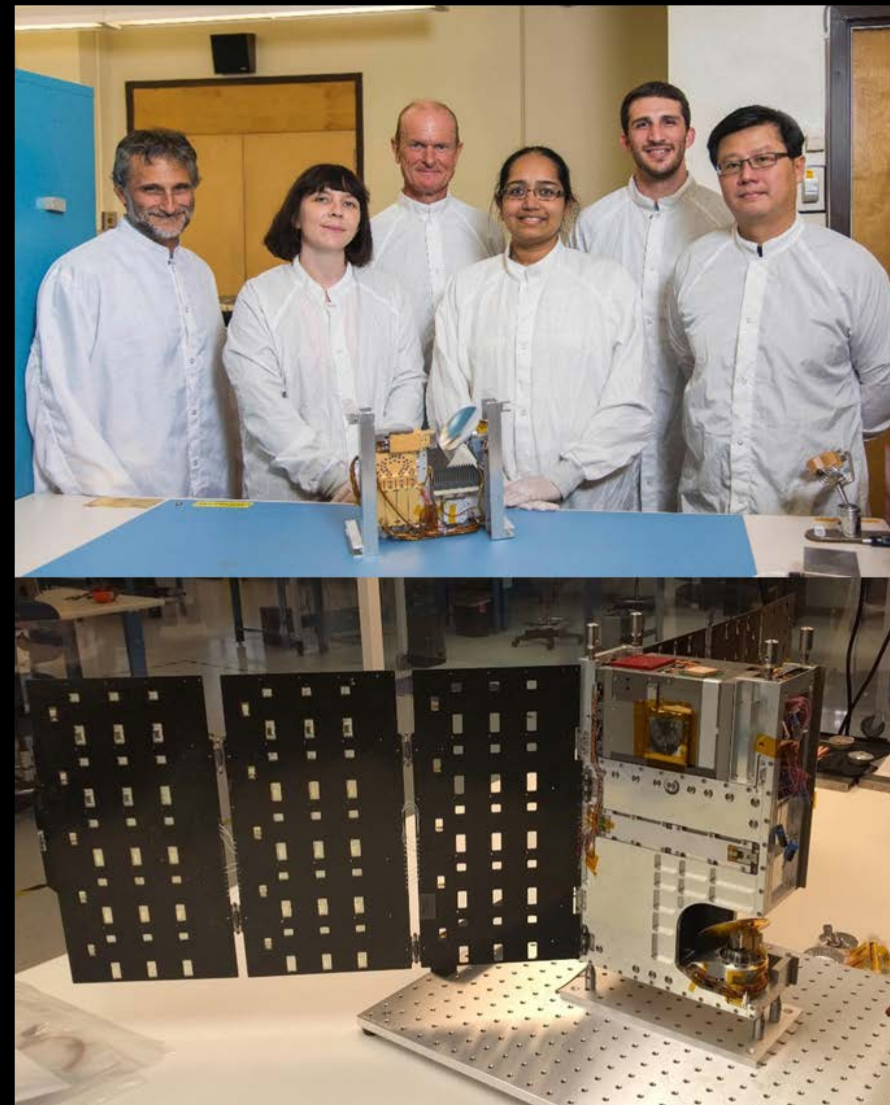
NOAA Advanced Technology Microwave Sounder (ATMS)

75 kg, 100 W, $$$$

Sensor A

TEMPEST-D

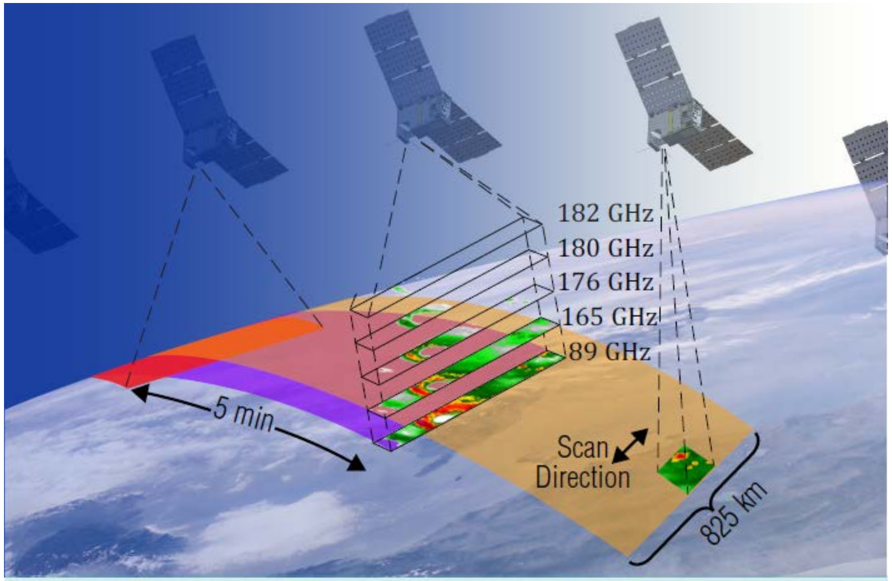
3.8 kg, 6.5 W, $



Temporal Experiment for Storms and Tropical Systems (TEMPEST)

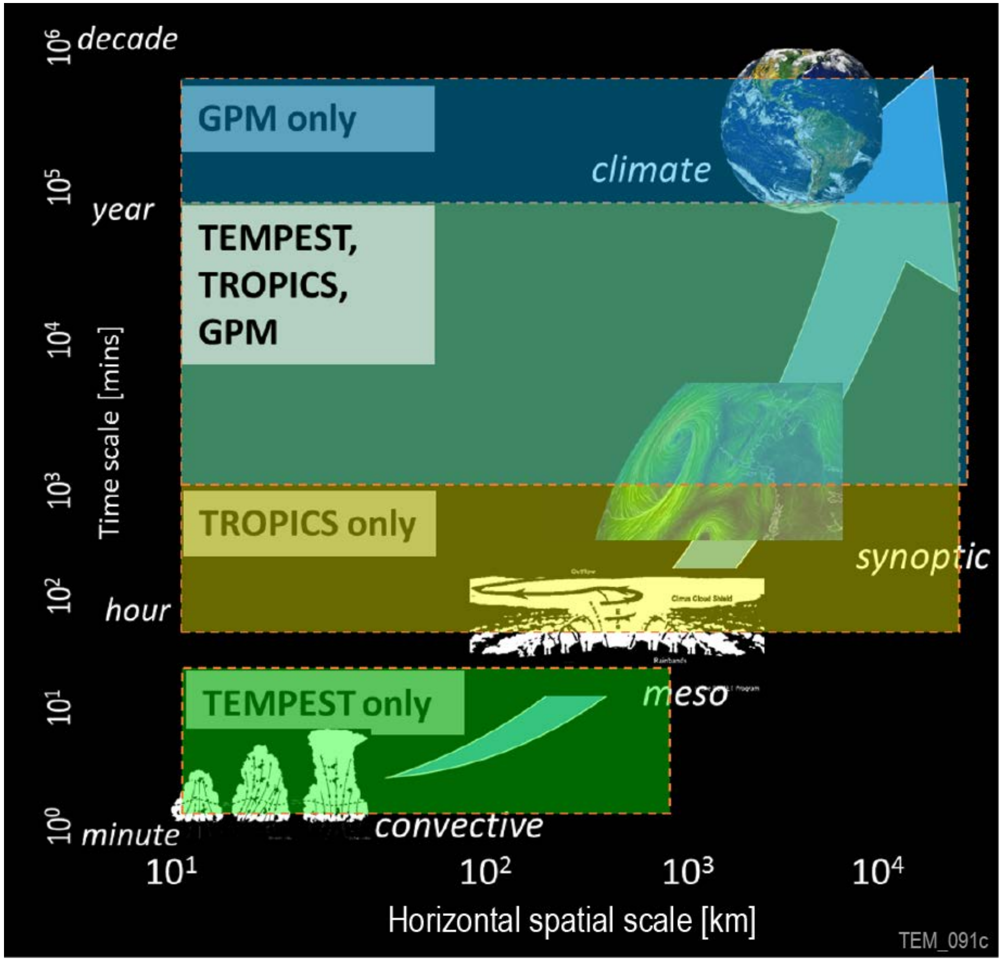
TEMPEST addresses 2017 National Academies Earth Science Decadal Survey:

- *Why do convective storms, heavy precipitation, and clouds occur exactly when and where they do?* (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
- Demonstrated 8 months of mission operations to date since first light data



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

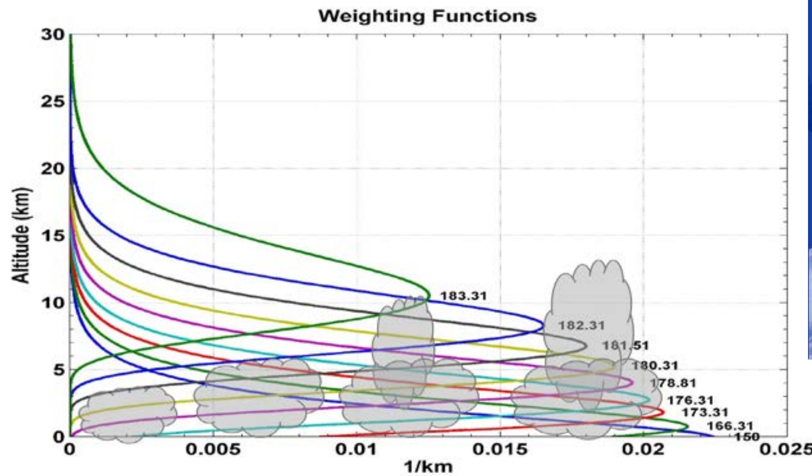
TEMPEST Mission Concept Occupies Unique Observational Space

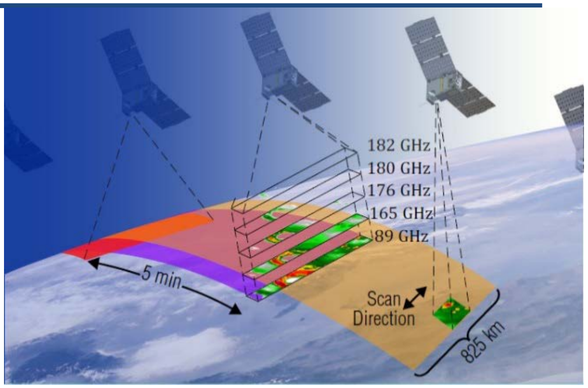


TEMPEST samples developing convection at 14-km horizontal resolution over time scales of 3–30 minutes and from days to a year. TEMPEST occupies a unique observational space and complements sampling of the TROPICS and GPM missions.

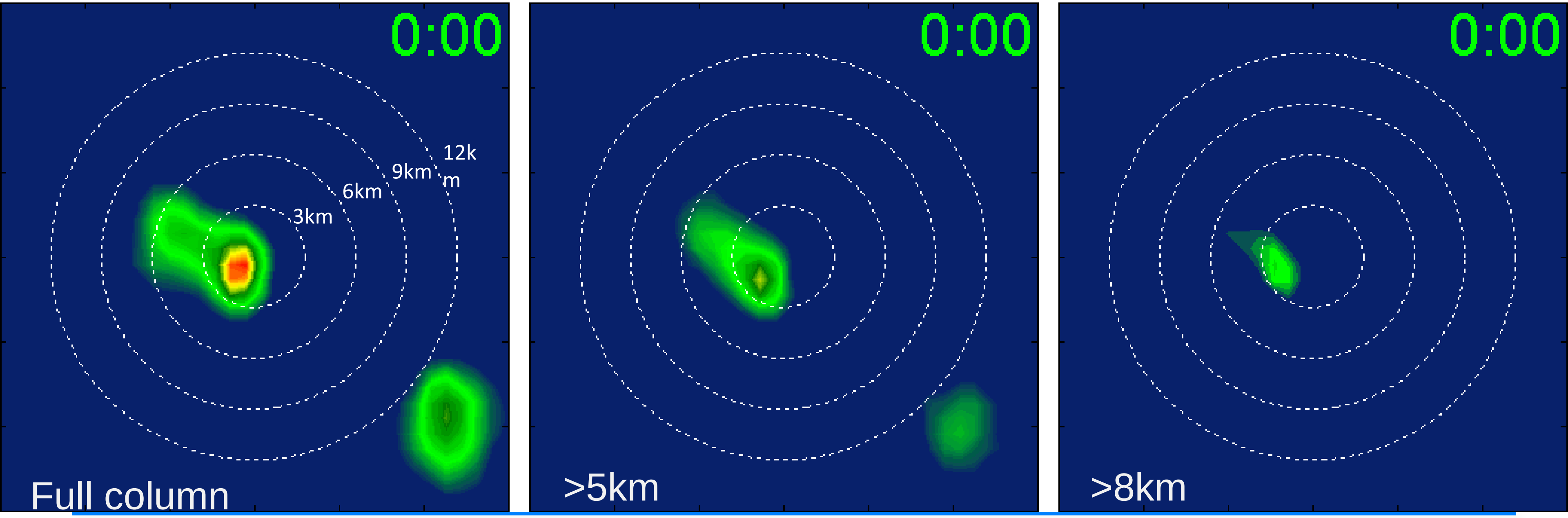
TEMPEST-Like Measurements from JPL/HAMSR on ER-2 Aircraft

TEMPEST-like observations with HAMSR on ER-2



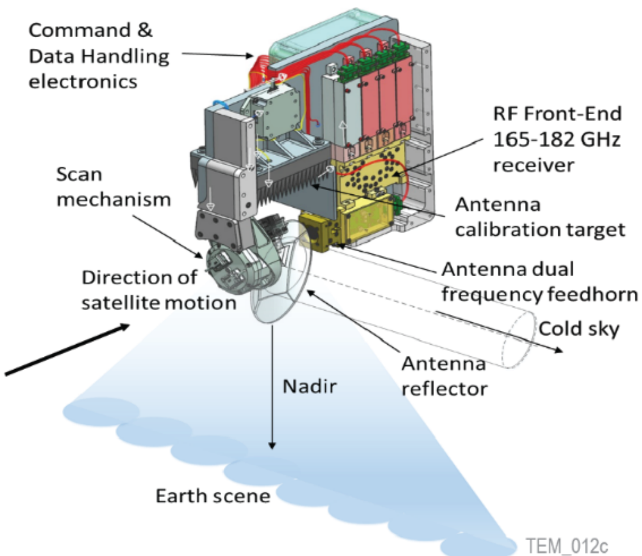


TEMPEST – enabling rapid revisit radiometry for precipitation processes

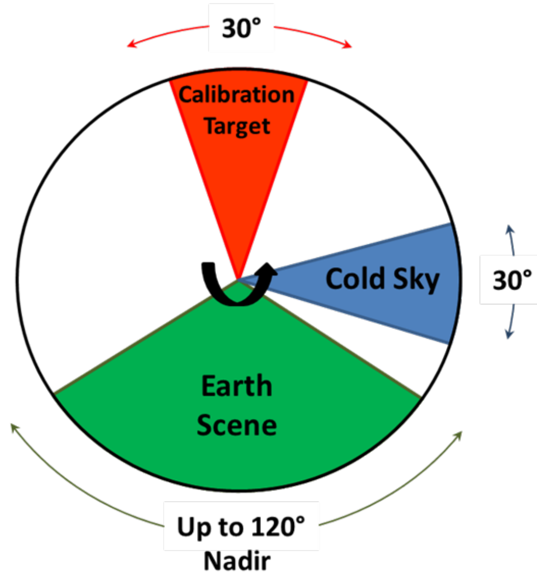


TEMPEST-D Instrument Performs End-to-End Radiometric Calibration

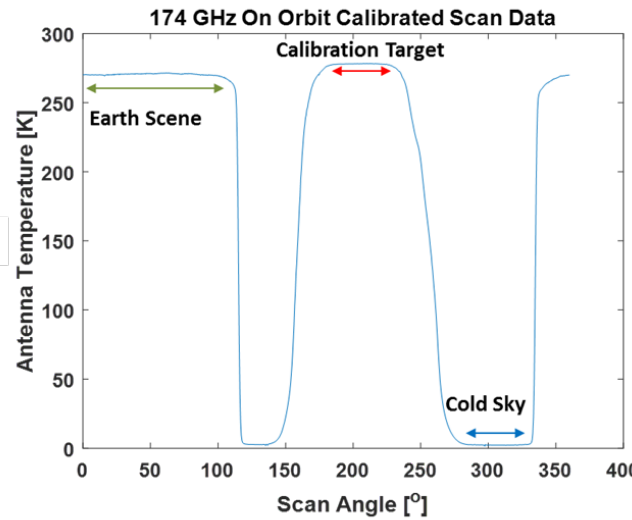
TEMPEST-D Instrument



Observing Profile

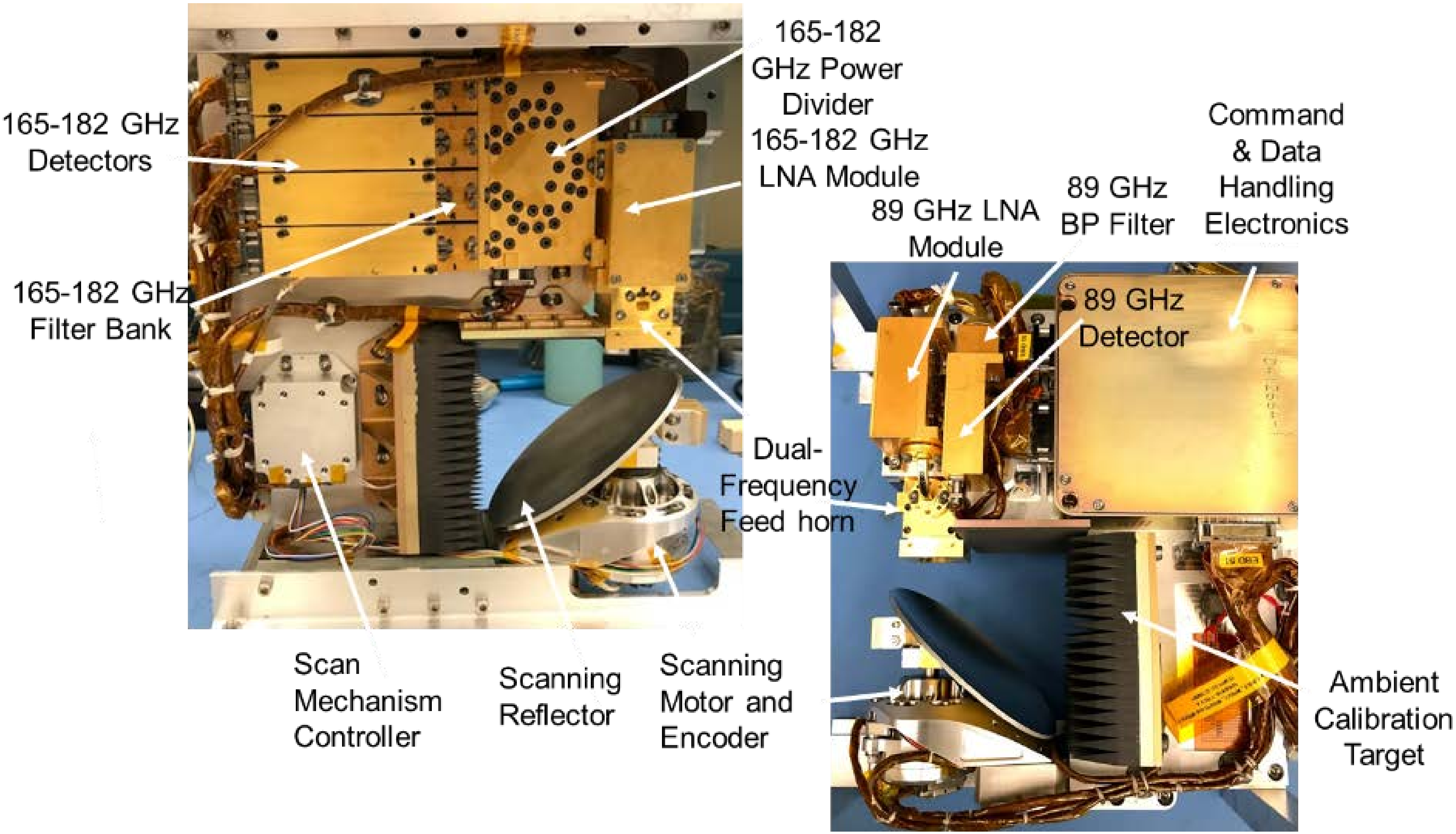


Time Series of Output Data

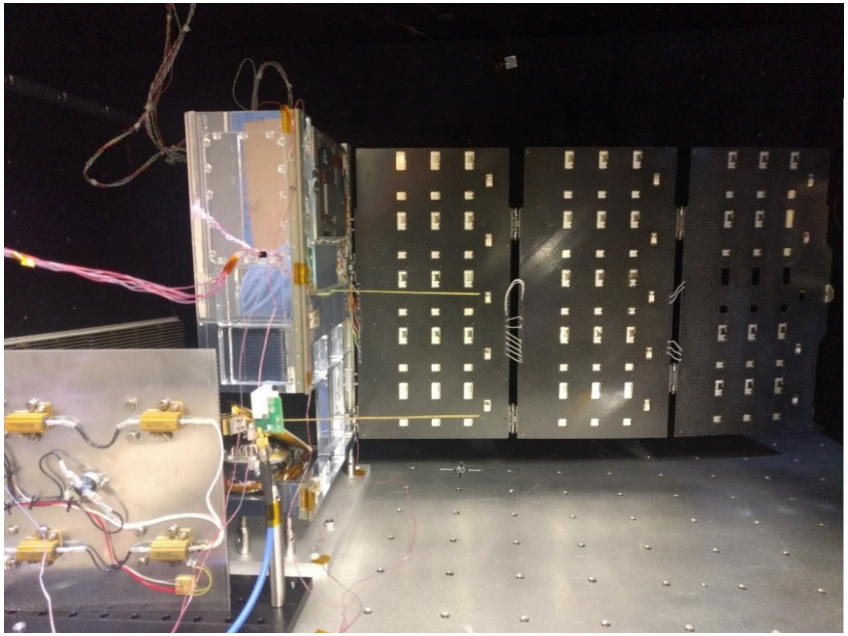


- Five-frequency millimeter-wave radiometer measures Earth scene up to ±60° nadir angles, for an 1550-km swath width from a initial orbit altitude of 400 km. Spatial resolution ranges from 13 km at 181 GHz to 25 km at 87 GHz.
- TEMPEST-D performs two-point end-to-end calibration every 2 sec. by measuring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

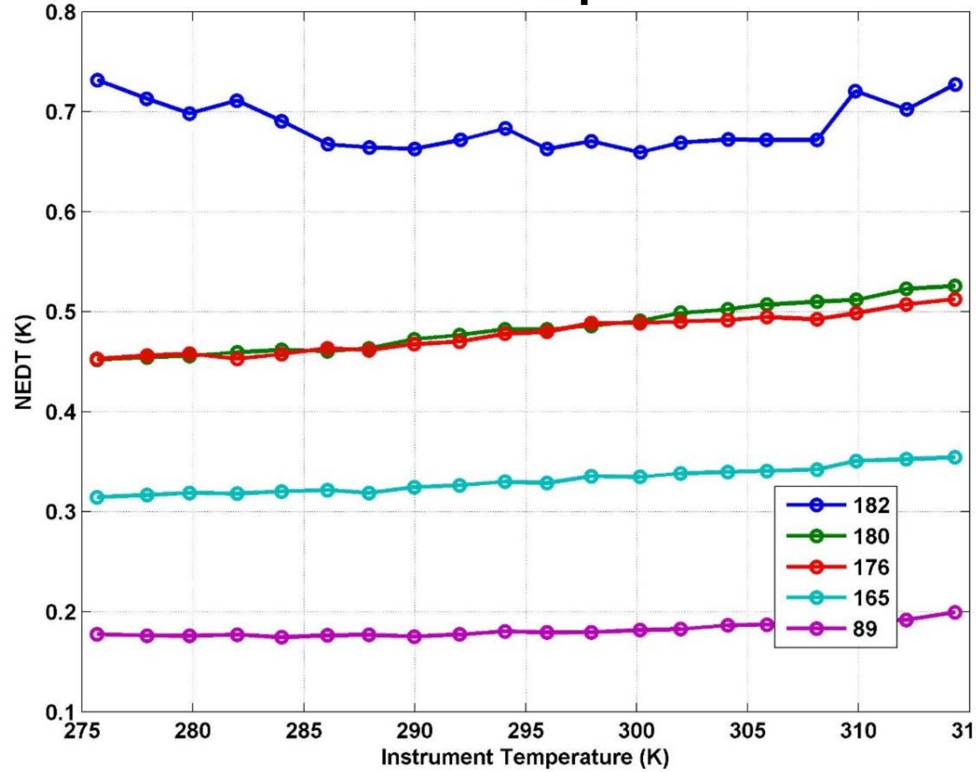
Flight Model Radiometer Instrument Built and Integrated at JPL



TEMPEST-D Instrument TVAC Performance at BCT in Jan. 2018



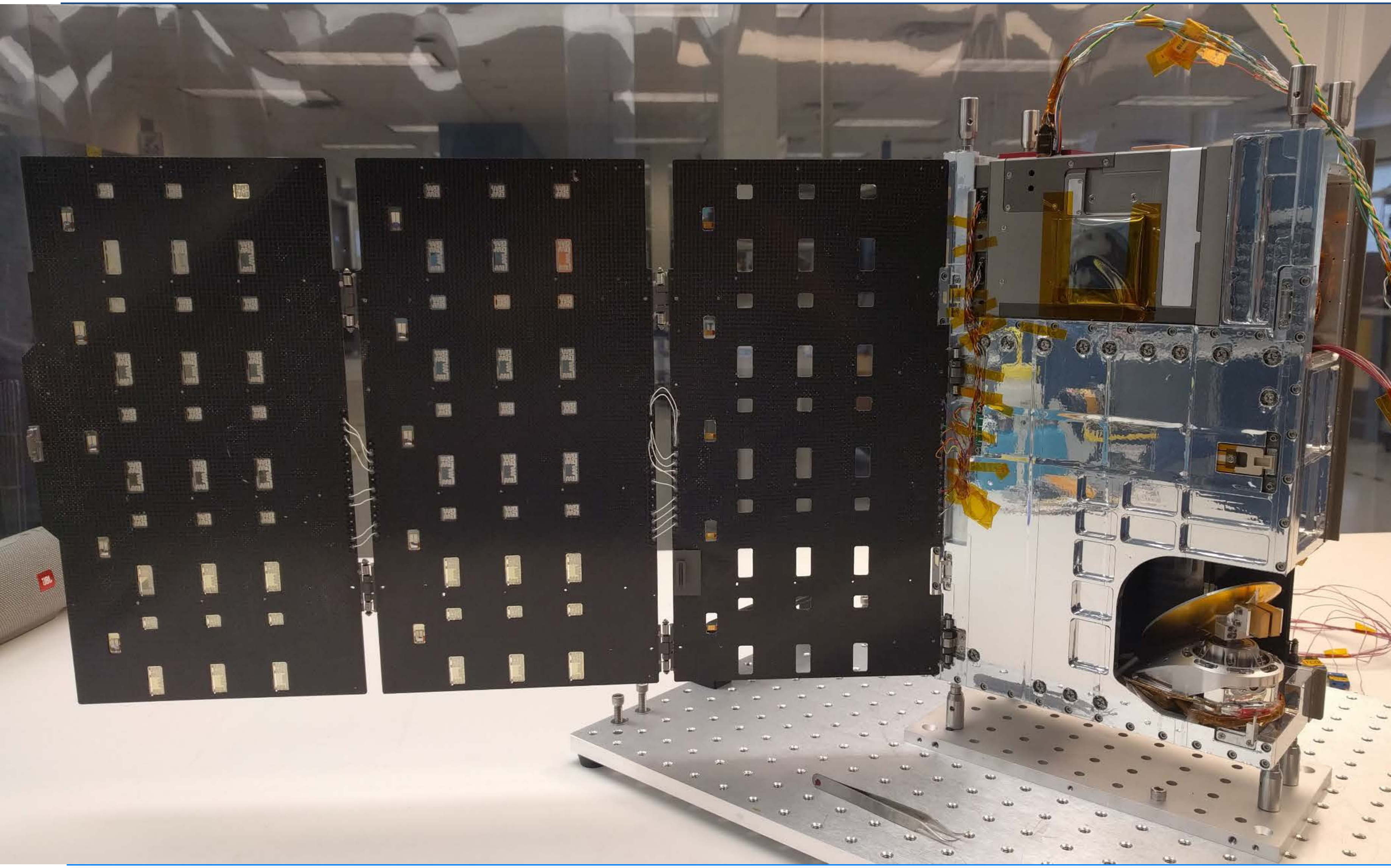
Radiometric Resolution vs. Instrument Temperature



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.

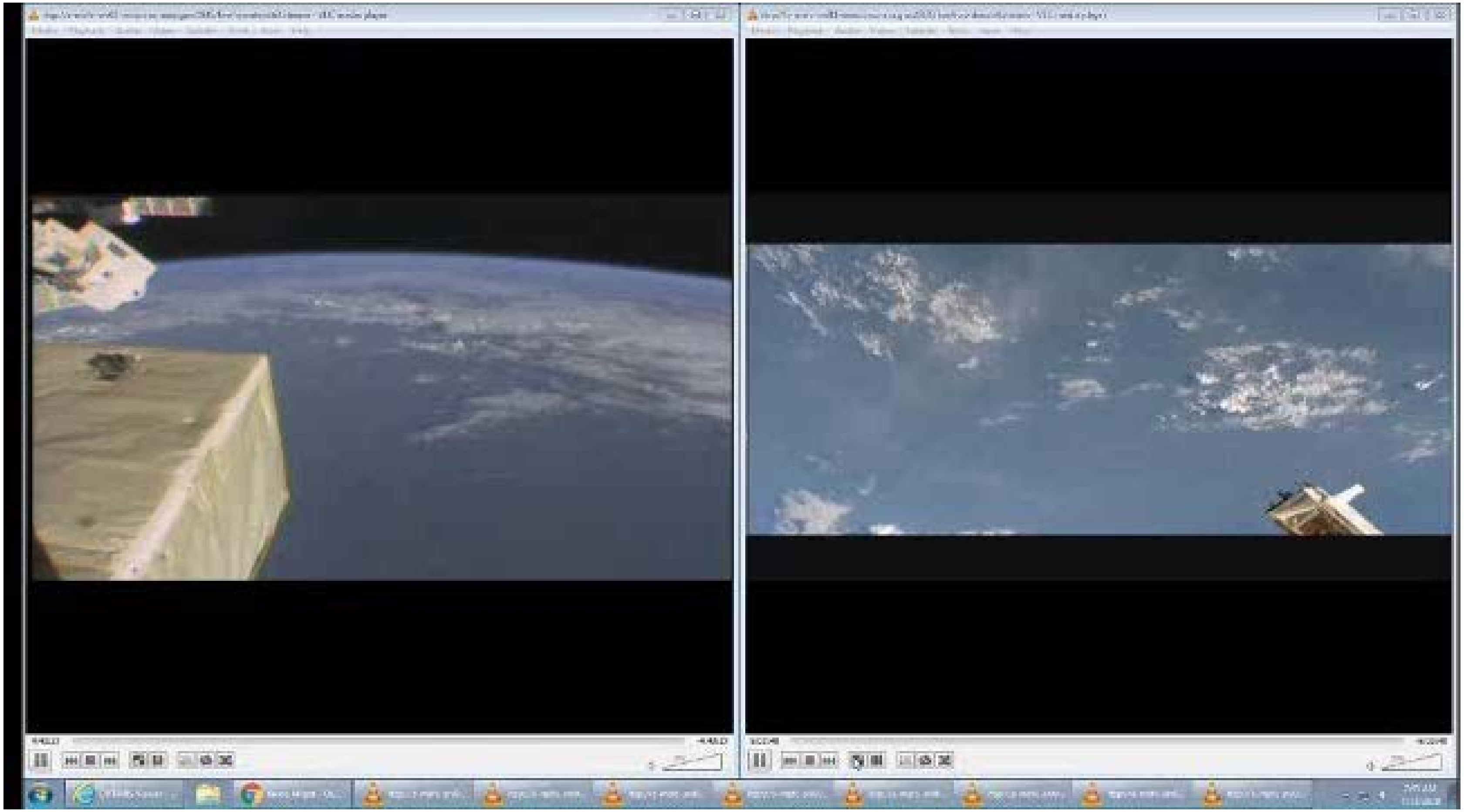
TEMPEST-D Spacecraft Integrated at BCT in Feb. 2018



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

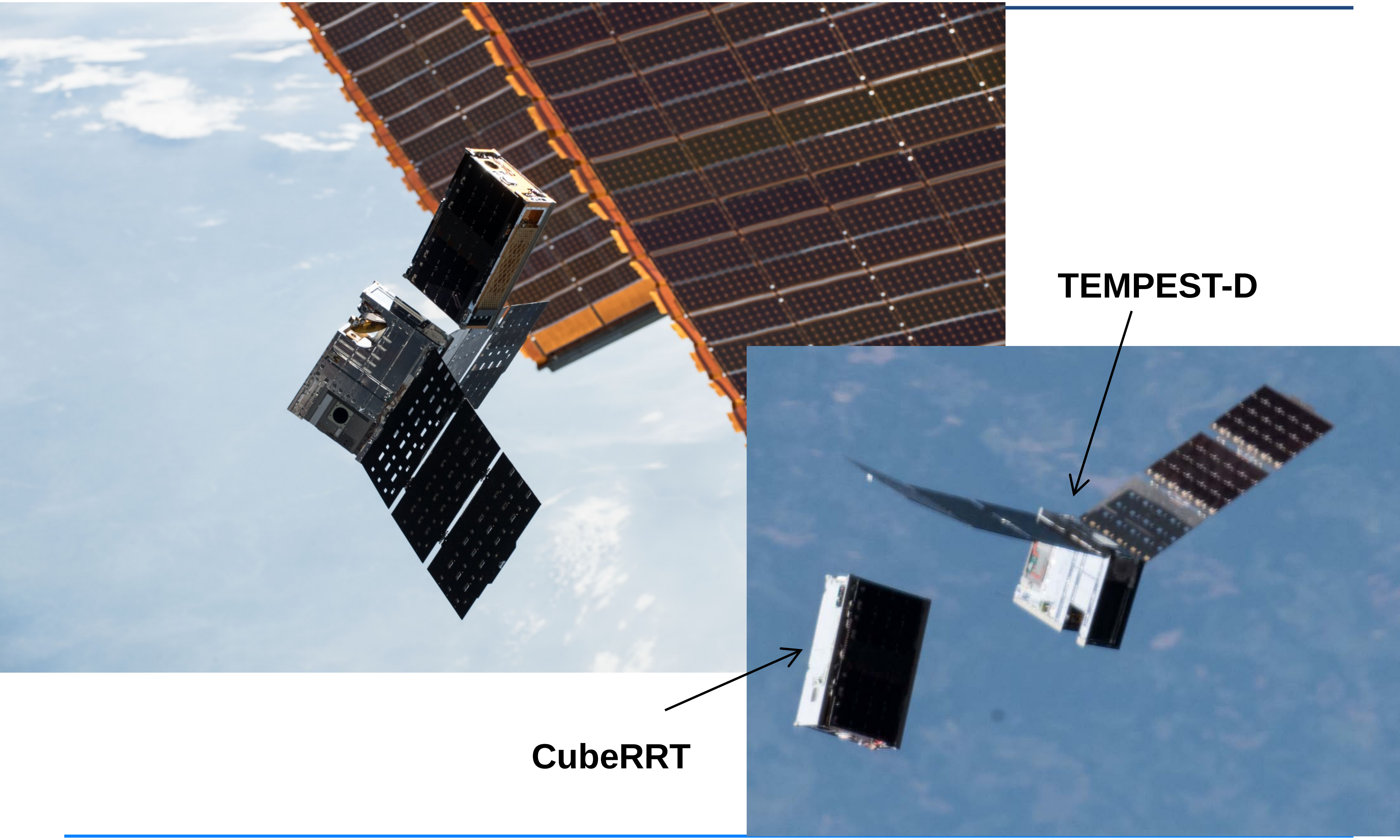
Photo Credit: NASA

Deployment of TEMPEST-D and CubeRRT into Orbit from ISS



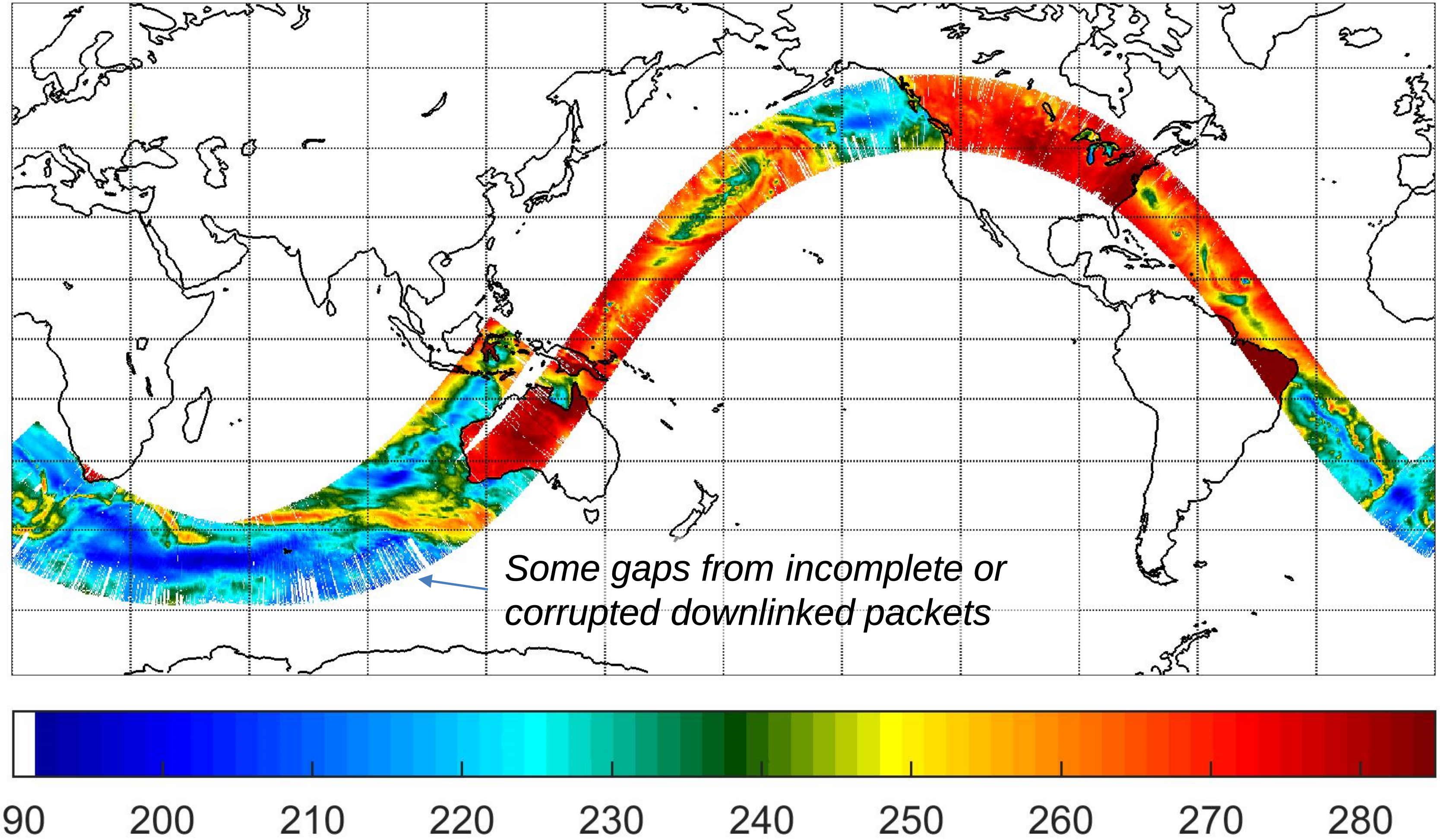
Recorded on International Space Station on 13 July 2018 Credit: NASA

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)

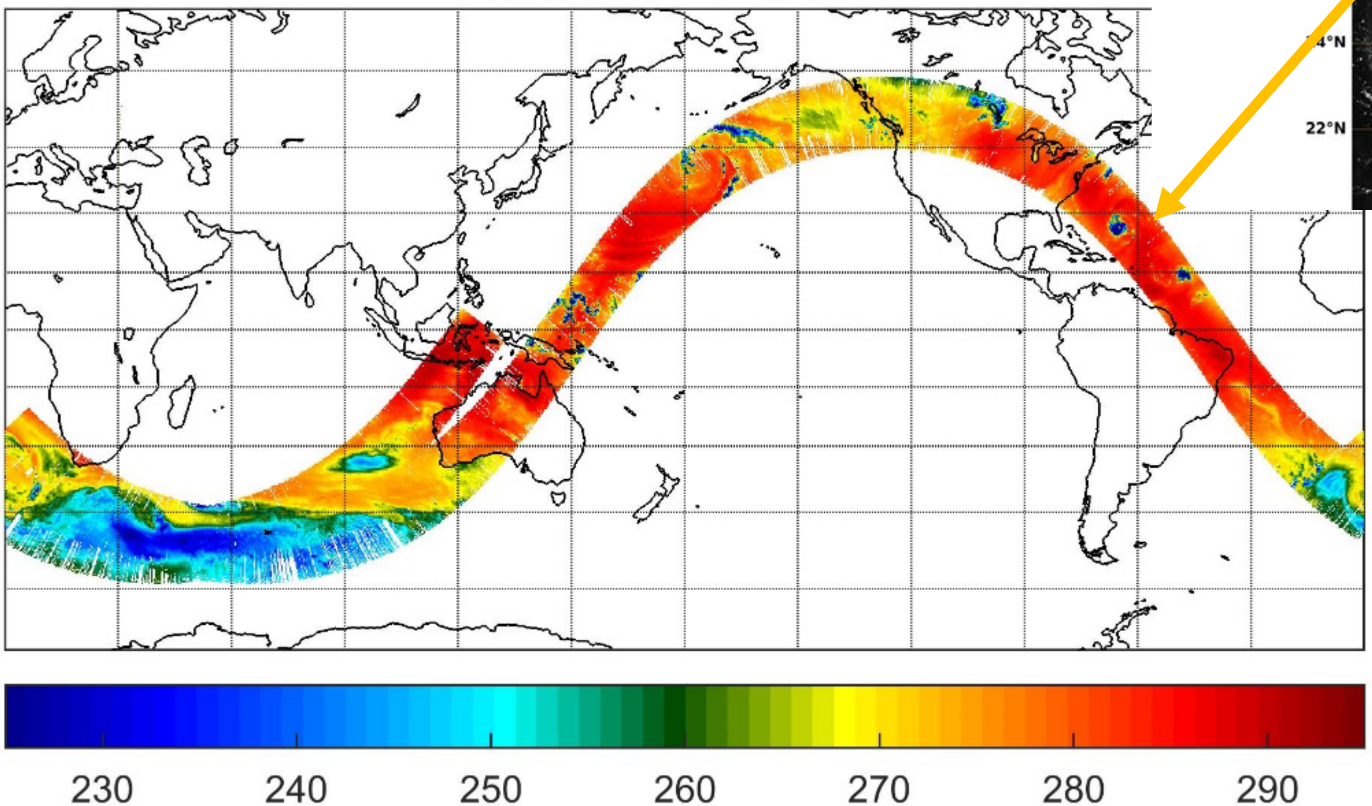


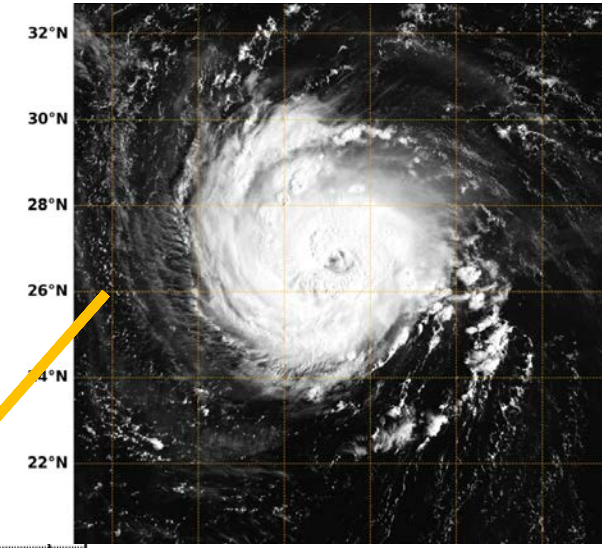
87 GHz window channel sensitive to water vapor, clouds and precipitation.

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

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

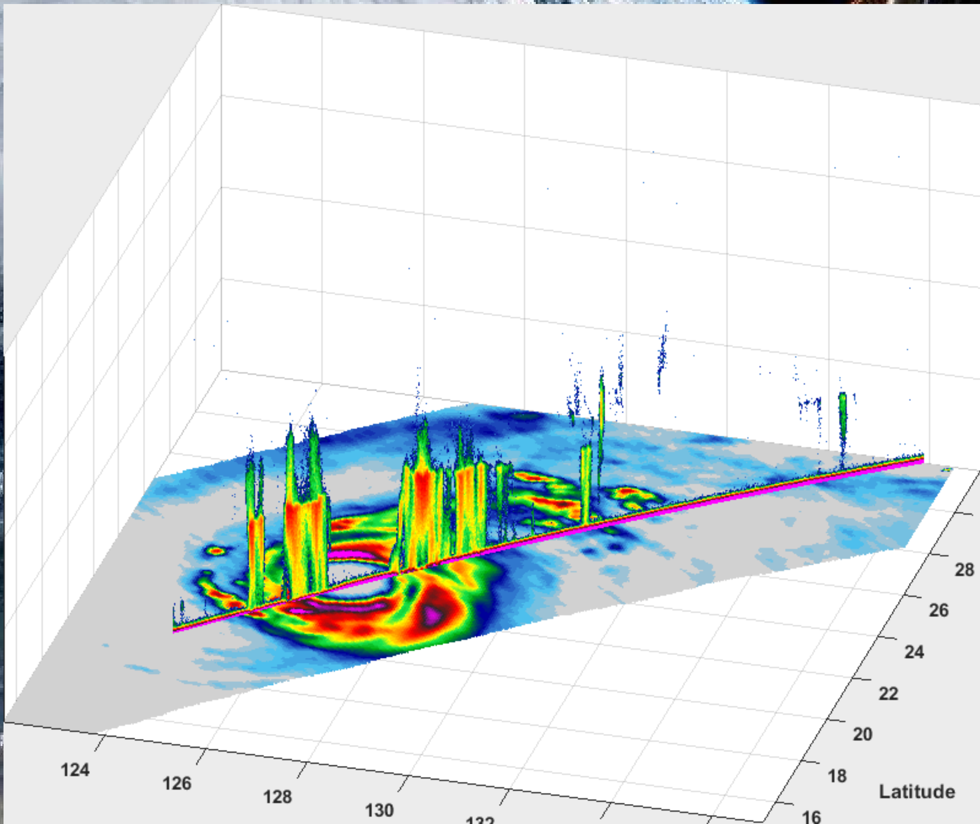
TEMPEST-D 164 GHz Brightness Temp. (K)



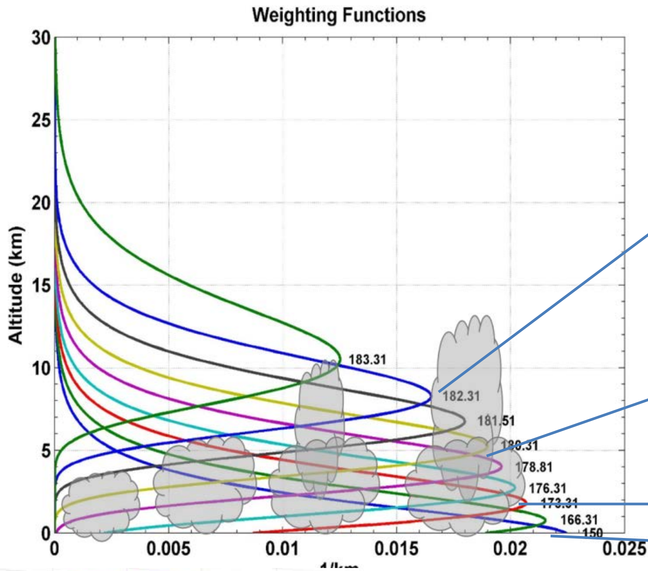


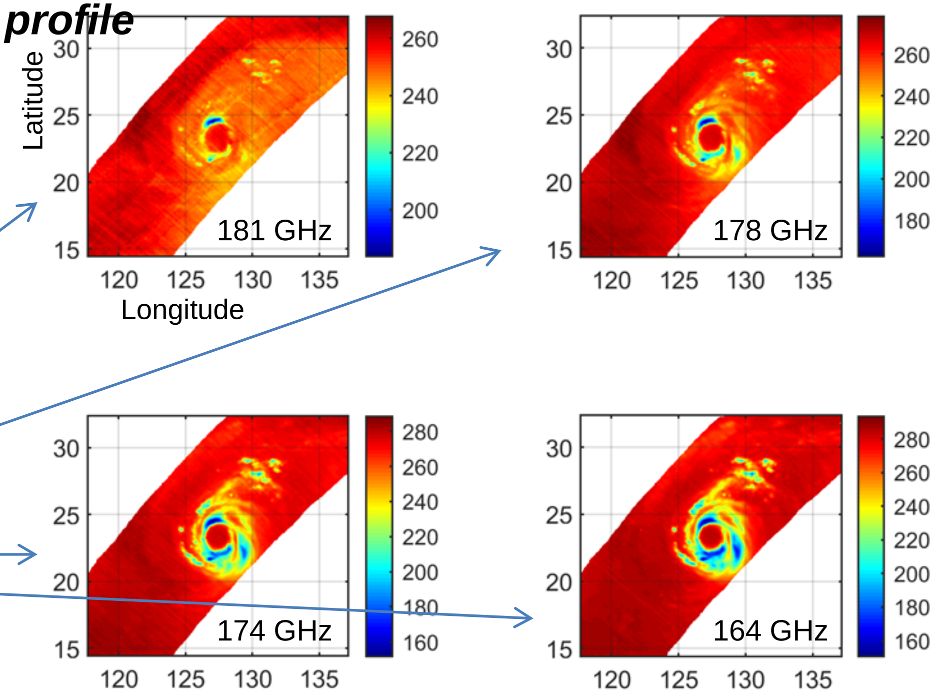
The 164 GHz color image shows the convection and intense rain bands around the inner core through the ice scattering signature. The greyscale image shows geostationary visible signature.

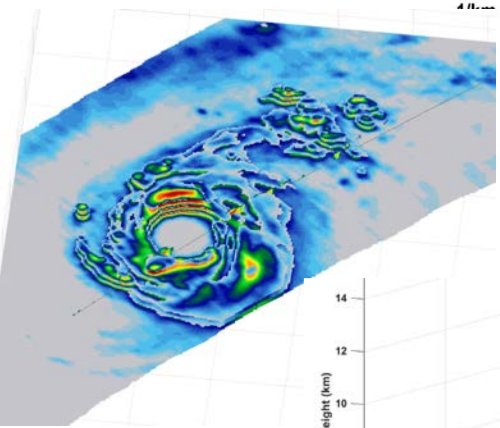
- On 28 Sept. 2018, TEMPEST-D and RainCube overflew Typhoon Trami < 5 minutes apart.
- RainCube nadir Ka-band reflectivity shown overlaid on TEMPEST-D 164 GHz brightness temperature illustrating complementary nature of these sensors and potential for constellation use to observe precipitation.
- Trami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

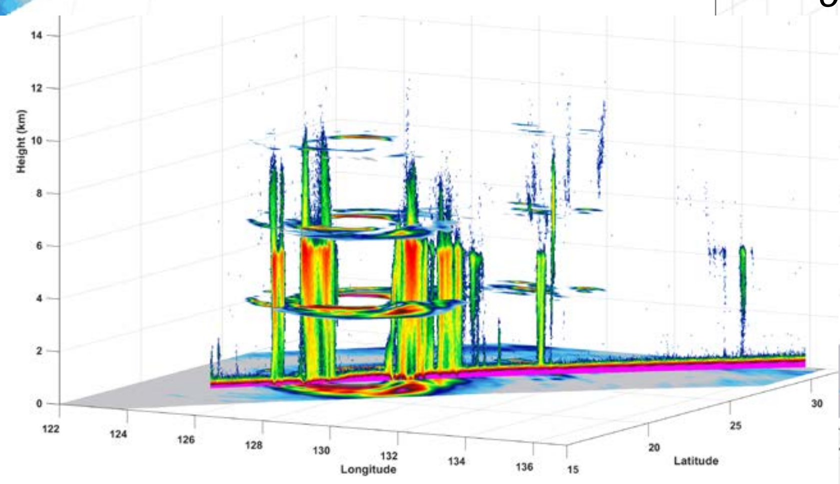


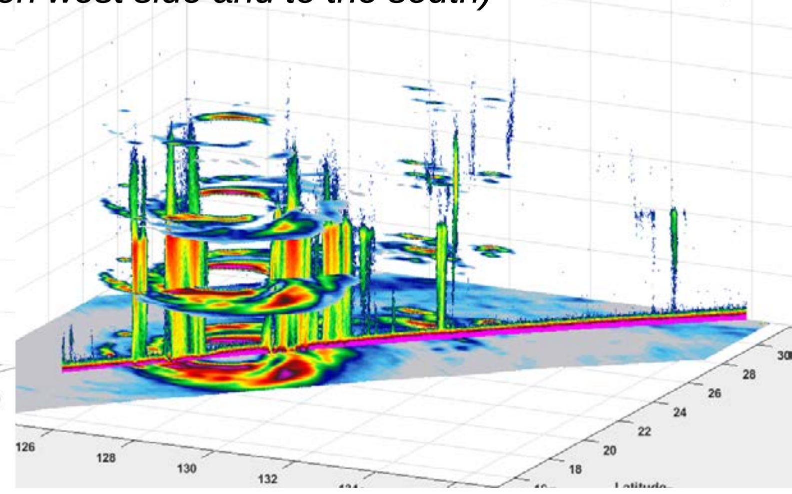
TEMPEST-D Sounding Channels provide 4 levels of vertical resolution to "slice" precipitation and compare with RainCube profile







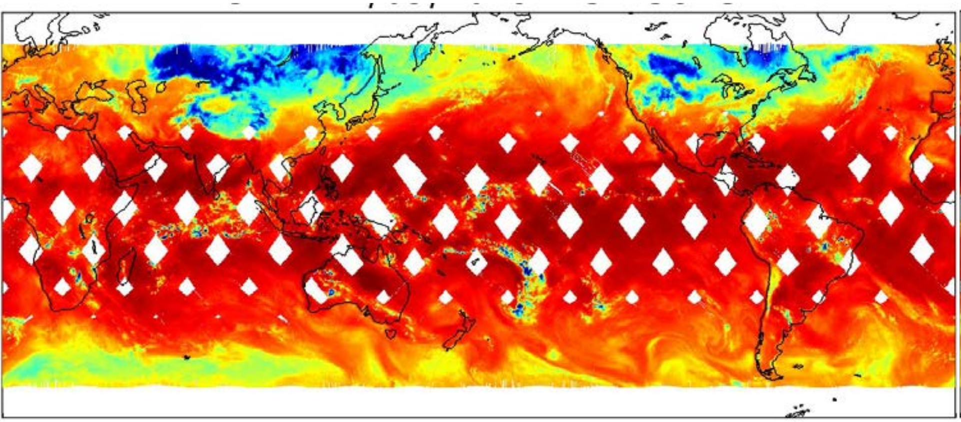




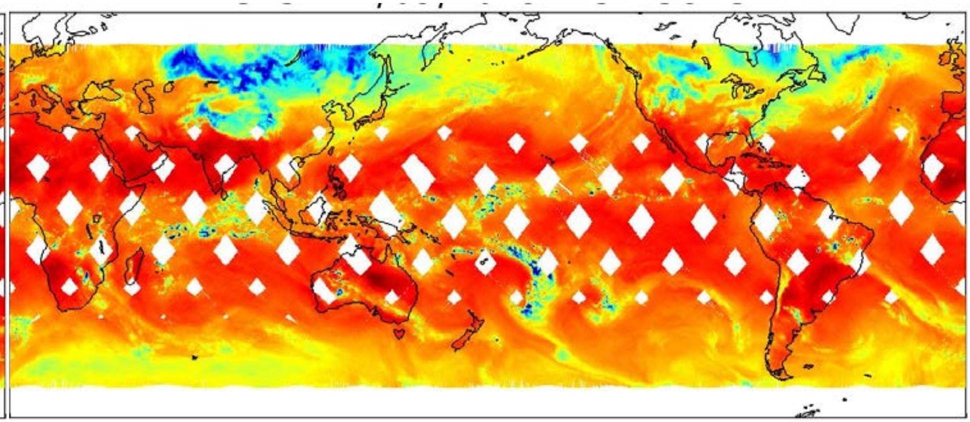
Similar asymmetry observed in depth of eyewall convection between TEMPEST-D and RainCube (strongest on west side and to the south)

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

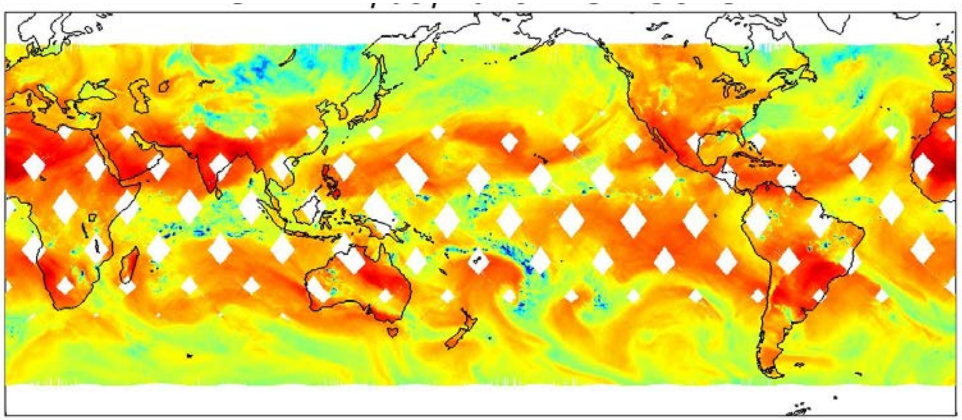
164 GHz Brightness Temp.



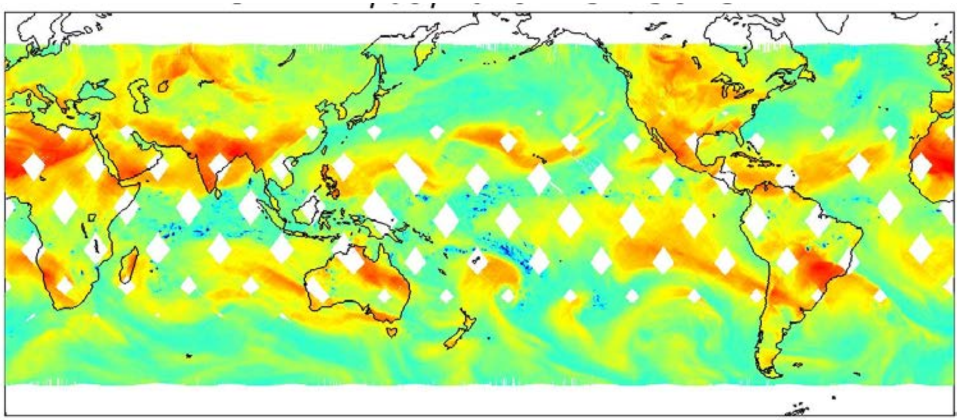
174 GHz Brightness Temp.

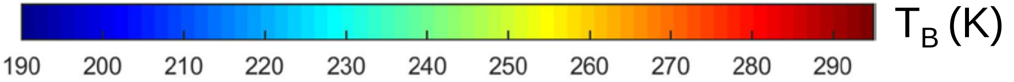


178 GHz Brightness Temp.

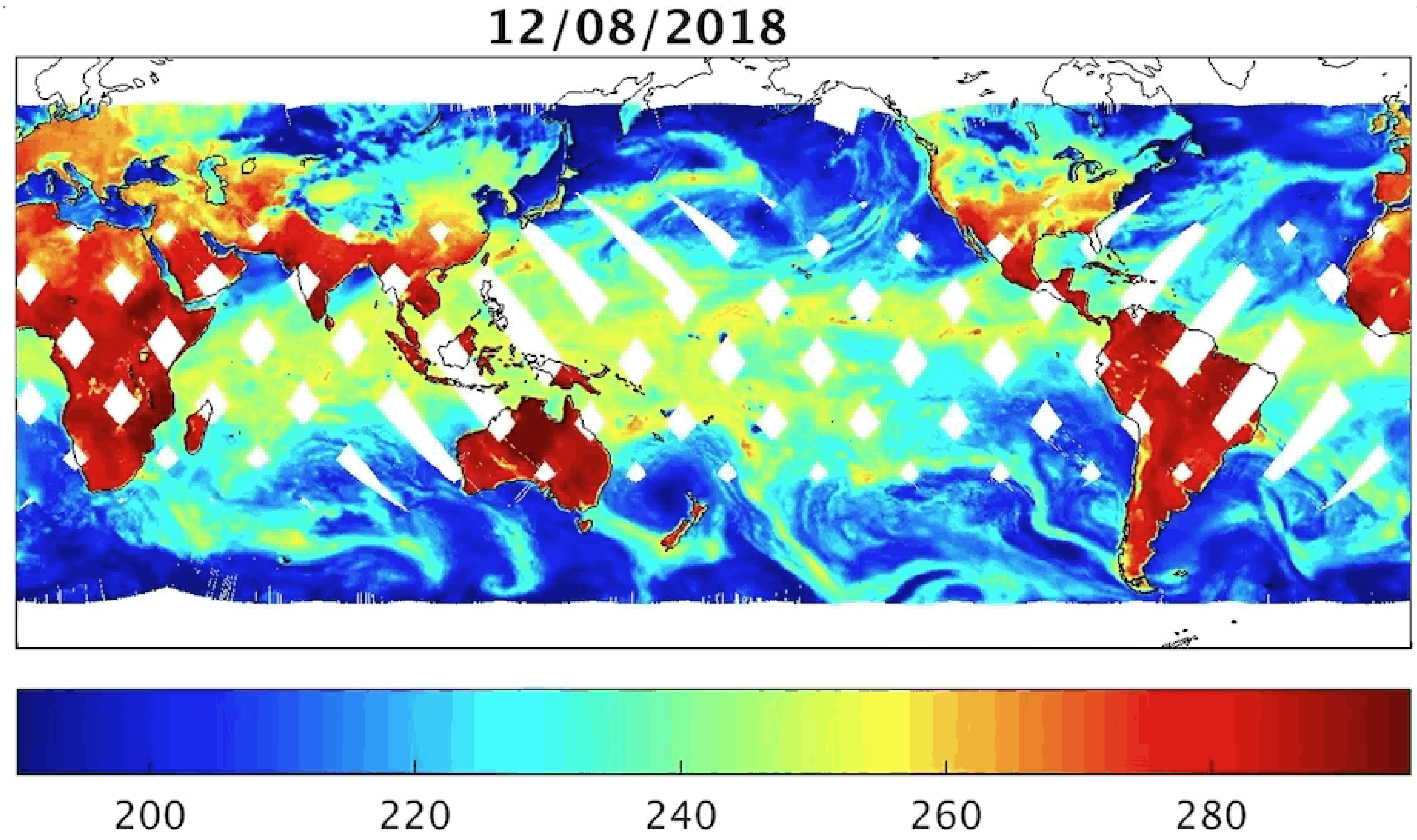


181 GHz Brightness Temp.

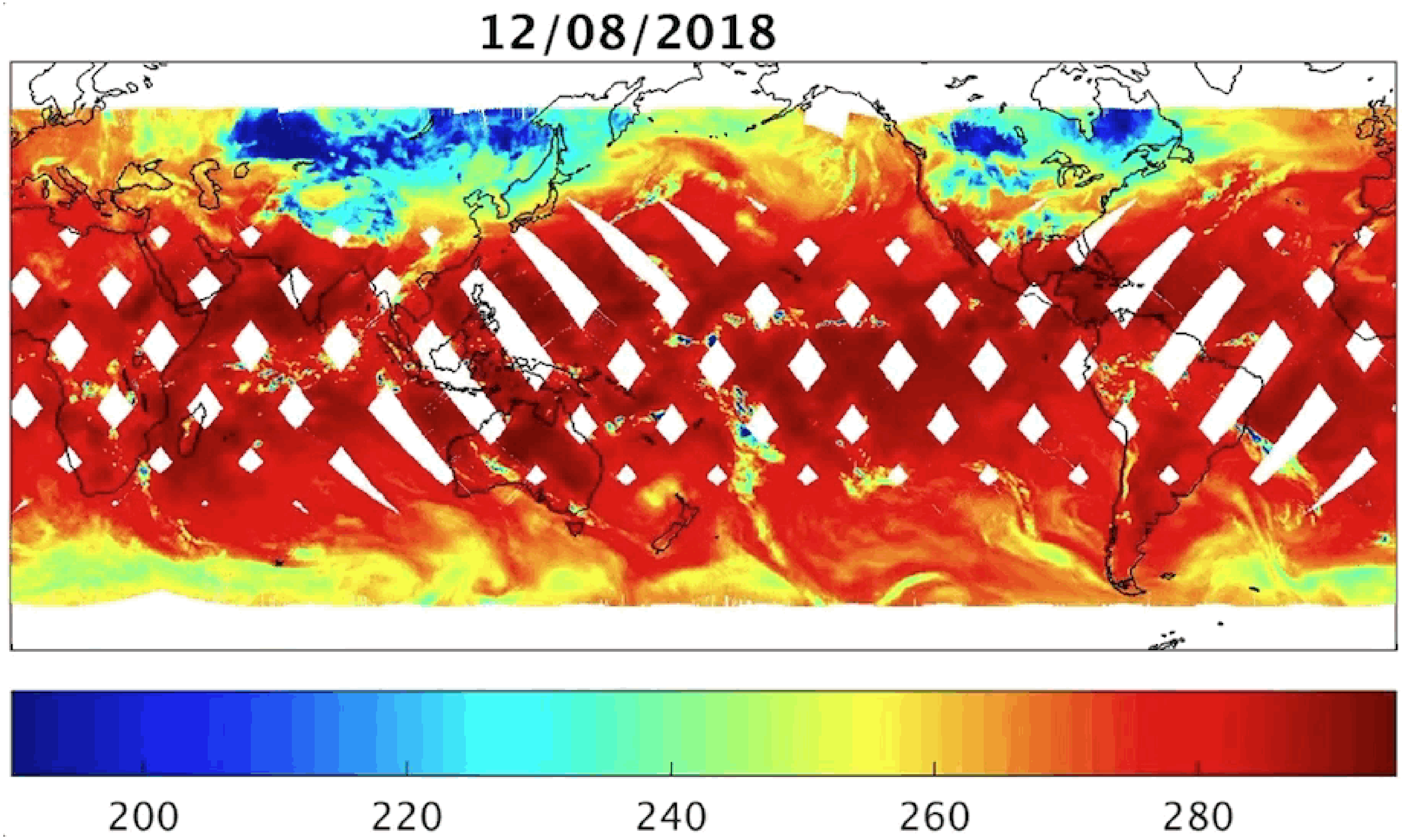




TEMPEST-D Brightness Temperatures at 87 GHz from Dec. 8 to 14, 2018

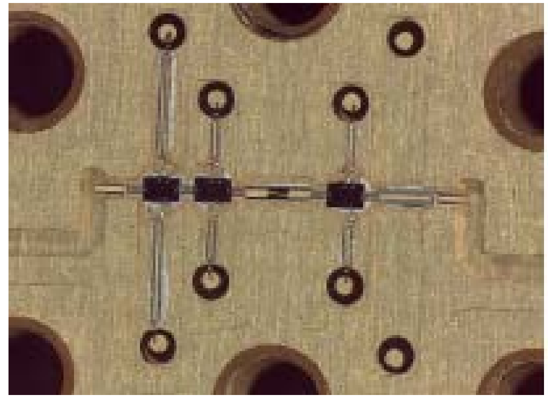


164 GHz Brightness Temperature
08-14 Dec. 2018



TEMPEST-D Noise Performance vs. NOAA Operational Microwave Sounders

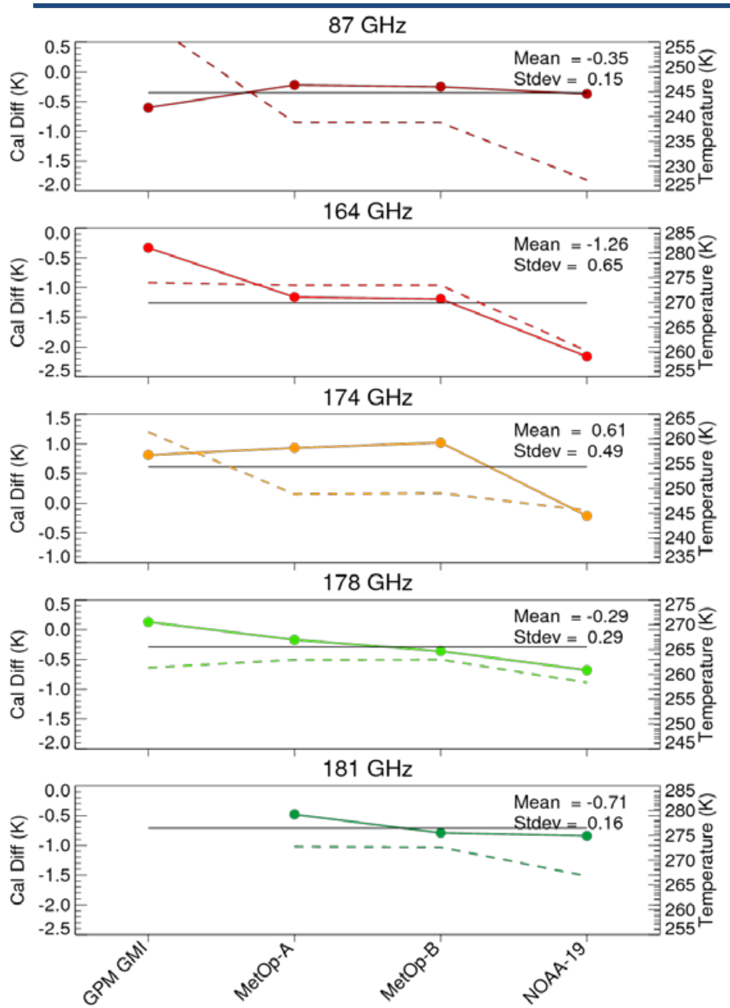
TEMPEST-D demonstrates improved receiver performance over the current generation of NOAA operational sensors.



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

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.**

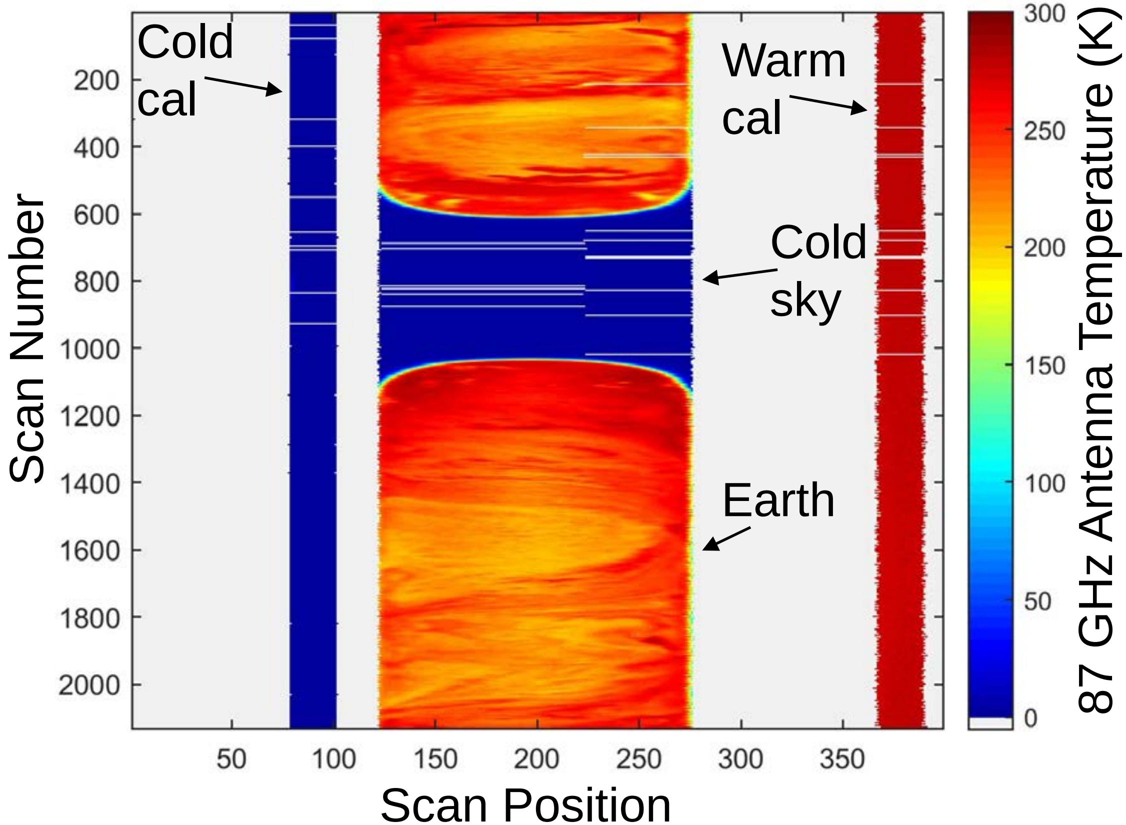
Calibration Differences in Kelvin (Reference – TEMPEST-D)

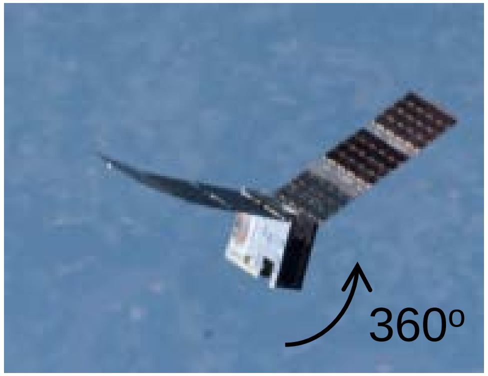
Reference Sensor	87 GHz	164 GHz	174 GHz	178 GHz	181 GHz
GPM GMI	-0.60	-0.33	0.81	0.13	N/A
MetOp-A MHS	-0.22	-1.16	0.93	-0.17	-0.48
MetOp-B MHS	-0.25	-1.19	1.02	-0.36	-0.79
NOAA-19 MHS	-0.37	-2.16	-0.21	-0.68	-0.84
Mean Difference Requirement: 4 K	**-0.35**	**-1.26**	**0.61**	**-0.29**	**-0.71**
Standard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

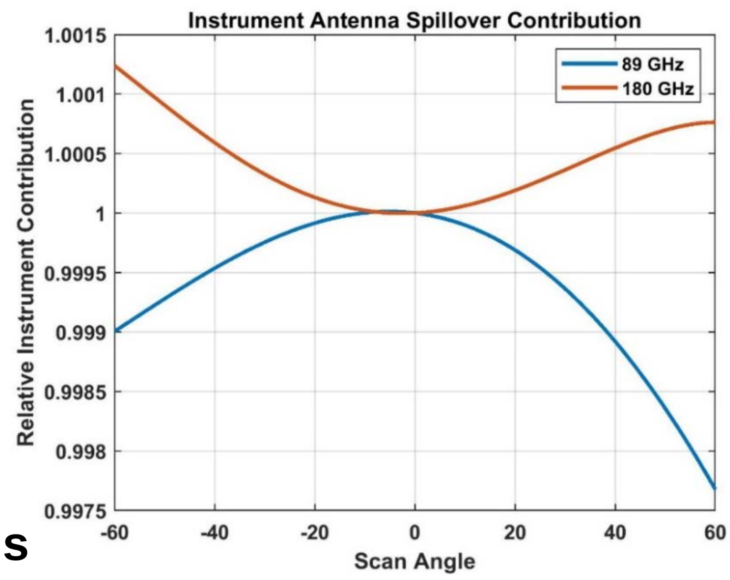
TEMPEST-D Met Mission Success Criteria in First 90 Days

- 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 8 months since first light to date ✓

TEMPEST-D 360º Pitch Maneuver for Antenna Pattern Correction

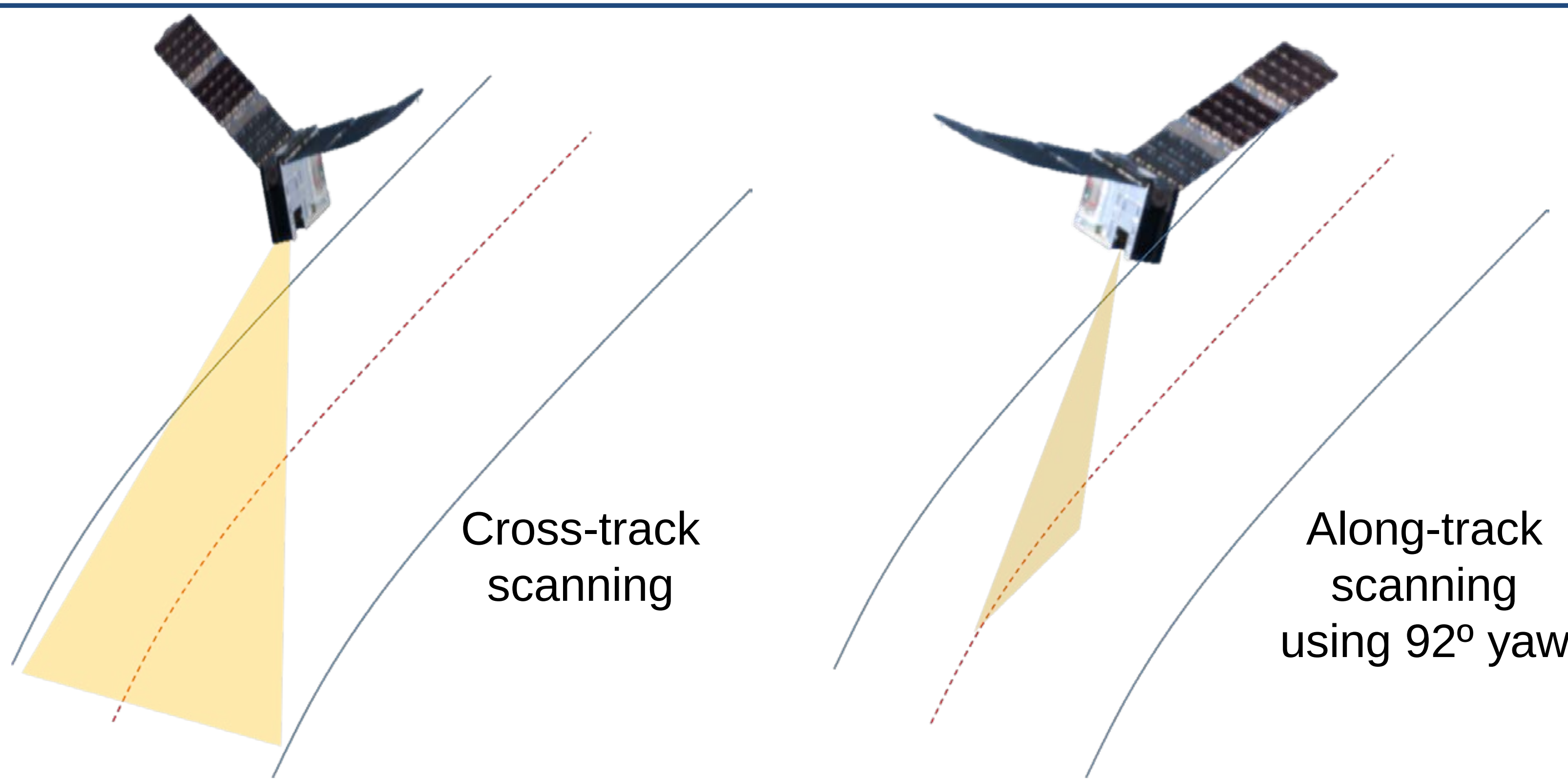






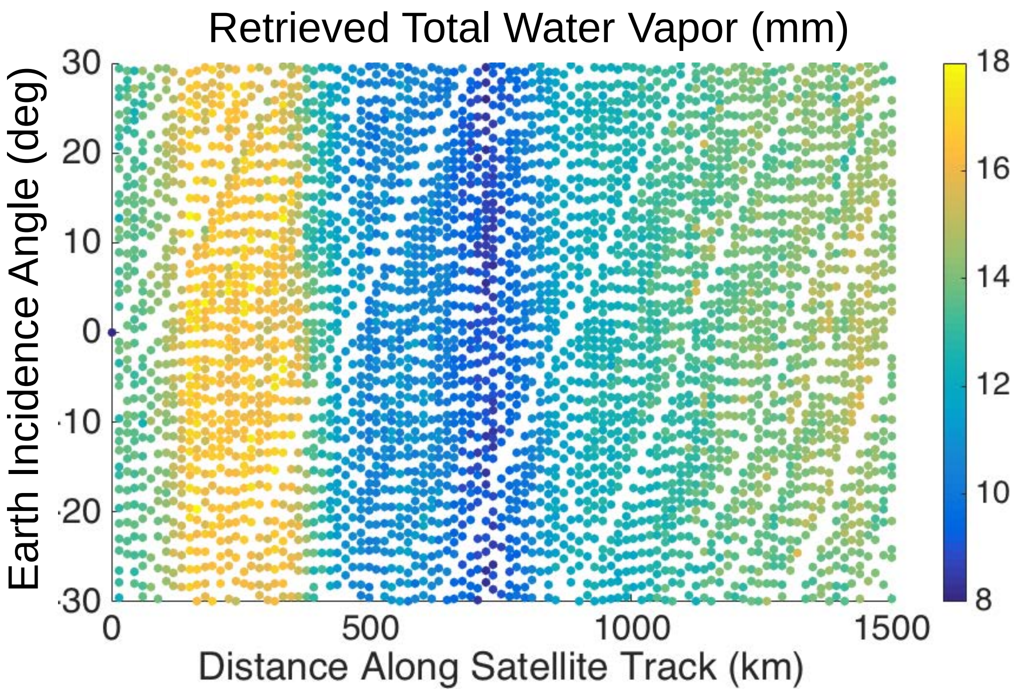
- 360º pitch maneuver performed to characterize antenna pattern correction over scan
- **Scan dependent biases < 0.5 K for all channels prior to antenna pattern correction**

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

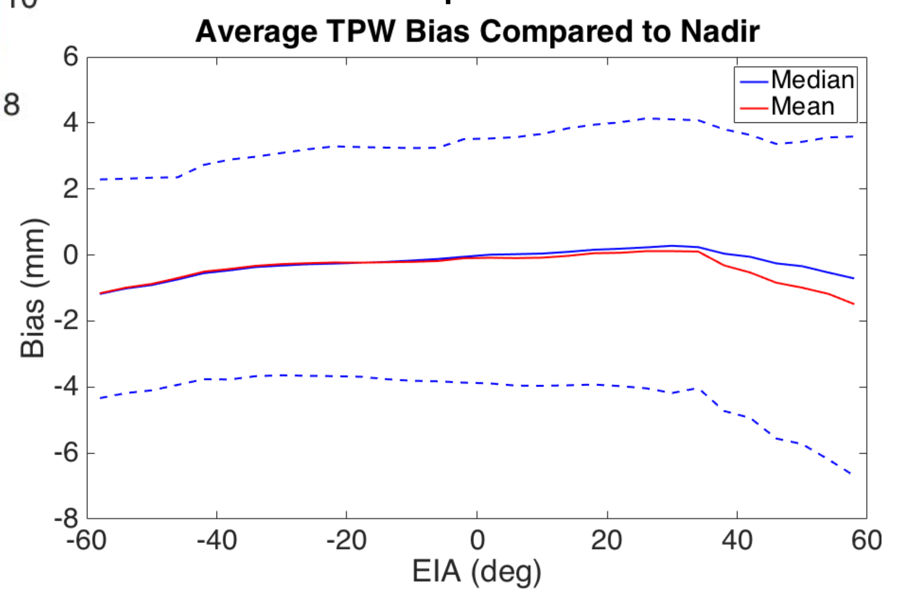


- Cross-track scanning, typical for microwave sounders, provides a wide swath.
- Along-track scanning experiment provides a narrow swath, but any footprint on Earth's surface is observed many times.
- For clear skies, evaluate consistency of the retrieved products.
- For convective activity, investigate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

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



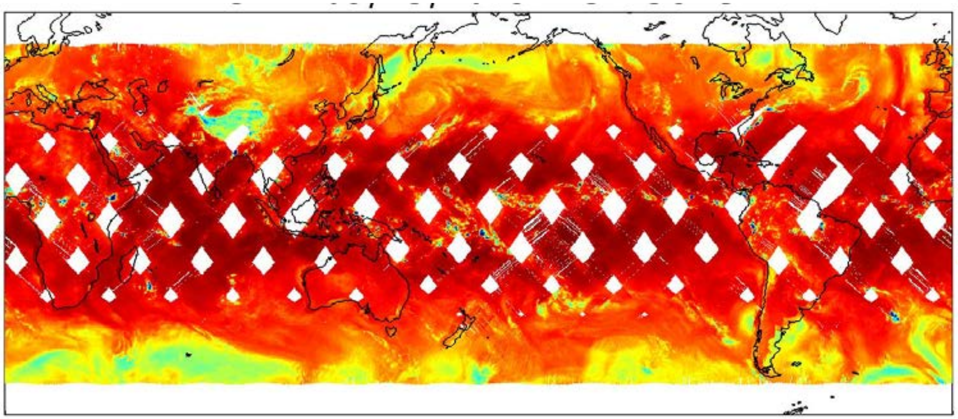
- Performed along-track scanning at 92-degree yaw attitude for 12 hours on each of Jan. 29 and 30, 2019
- Repeated for 16 hours on Apr. 8 and more than 60 hours during weekend of Apr. 26-29.



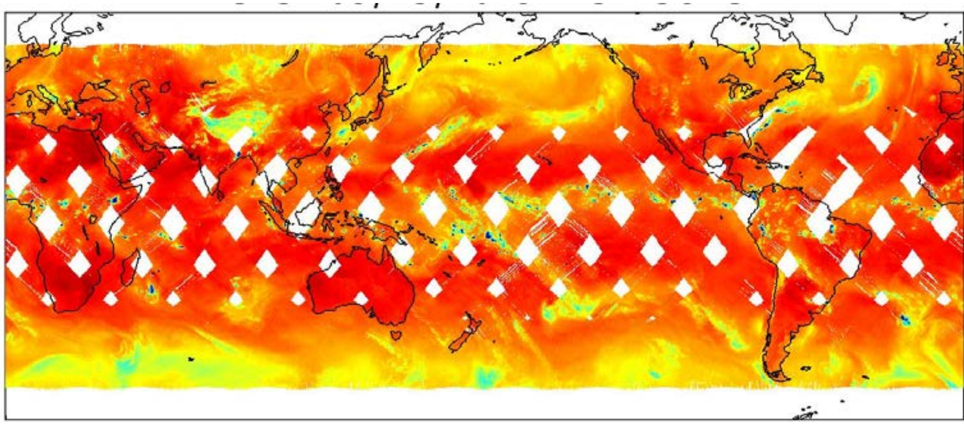
- Retrieved Total Water Vapor (TPW) is stable with Earth incidence angle (EIA), for a short period (above).
- Retrieved TPW is stable over 24 hours (right). EIA bias is still under study.

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

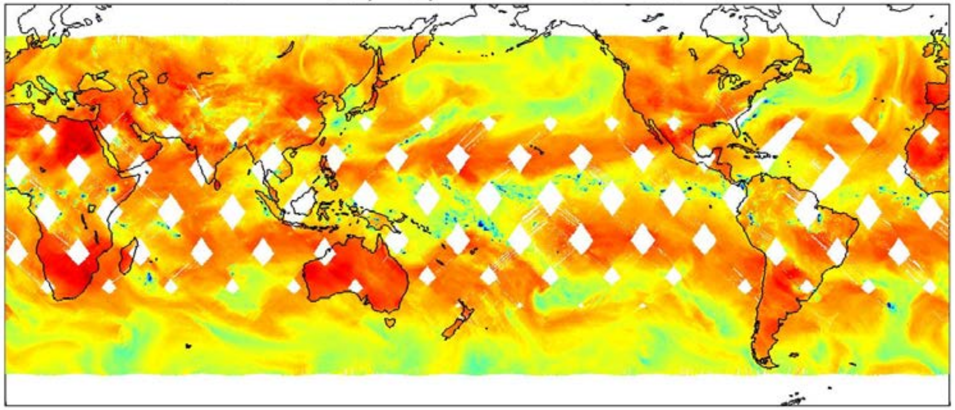
164 GHz Brightness Temp.



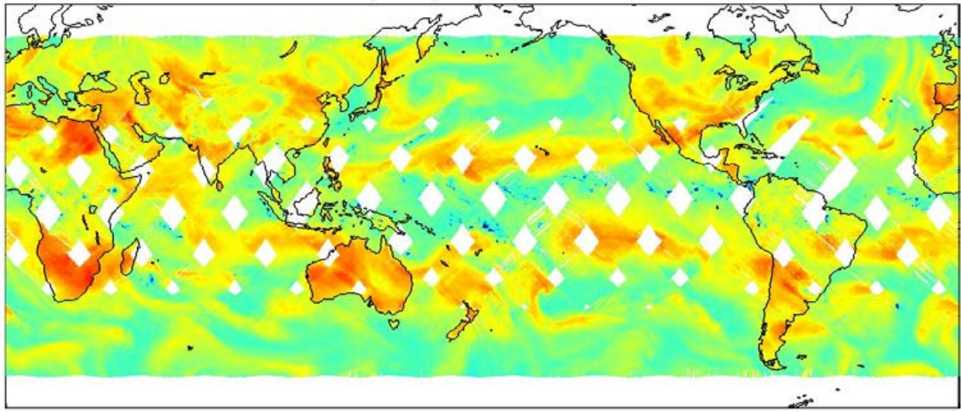
174 GHz Brightness Temp.

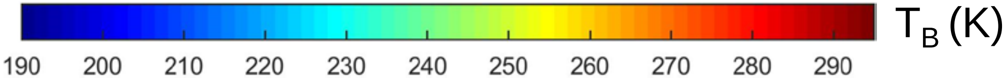


178 GHz Brightness Temp.



181 GHz Brightness Temp.

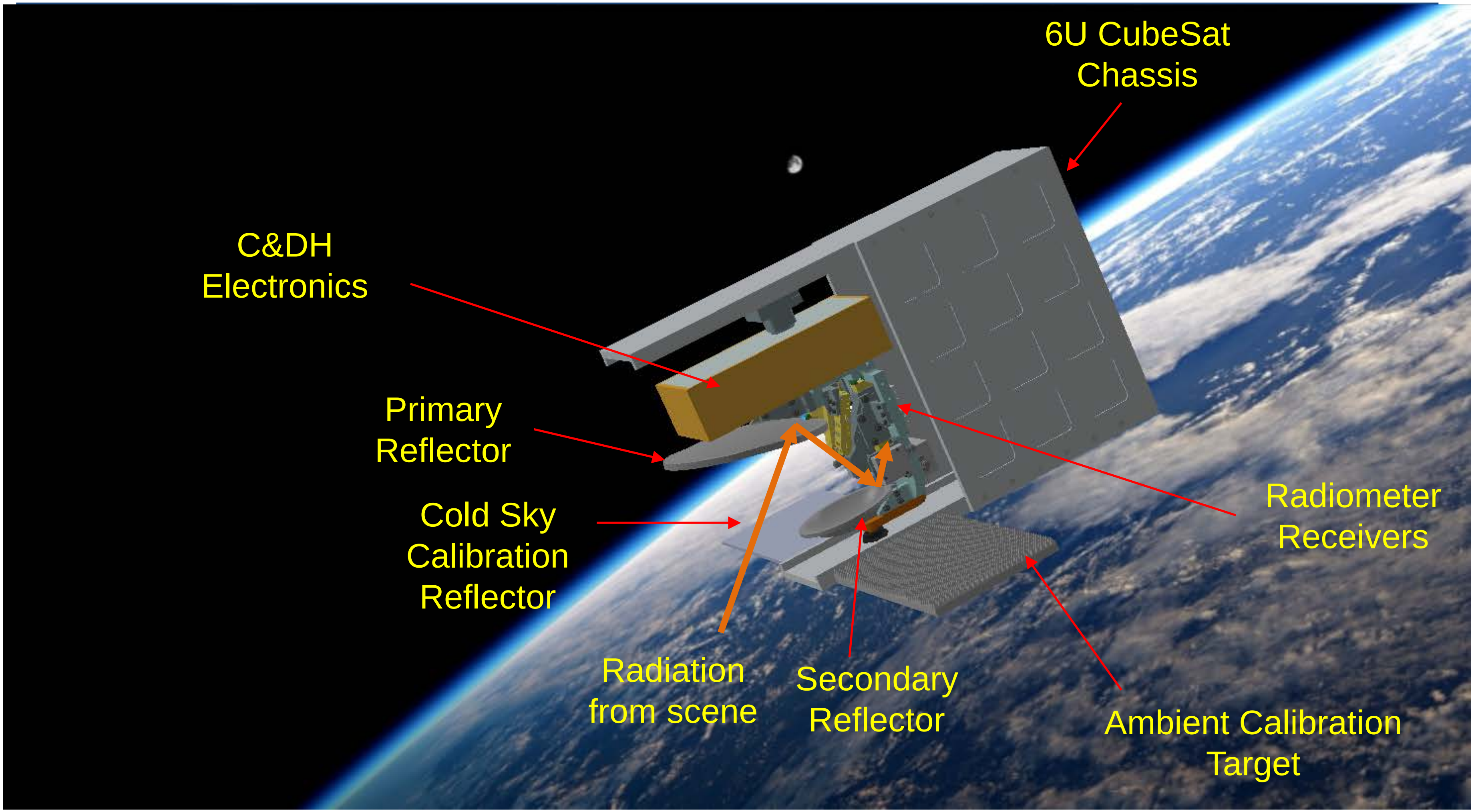




TEMPEST-D Mission Summary

- 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 more than 8 months of mission operations to date since first light data
- 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.

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

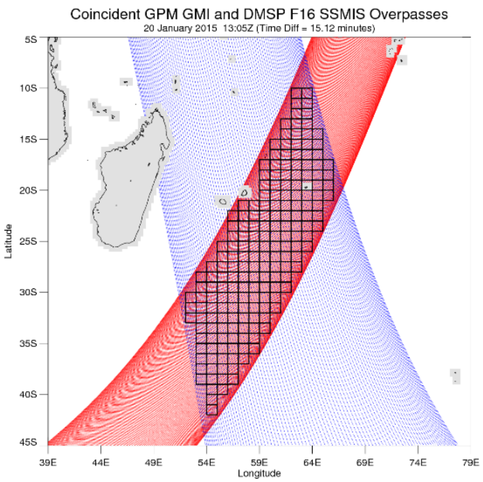


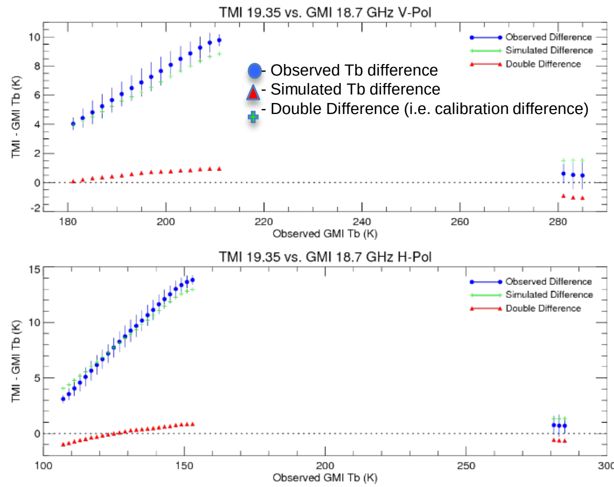
- Conically-scanning radiometer with 16 frequencies from 118 GHz to 850 GHz
- Radiometer instrument has 3 kg mass and 12 W power consumption

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.

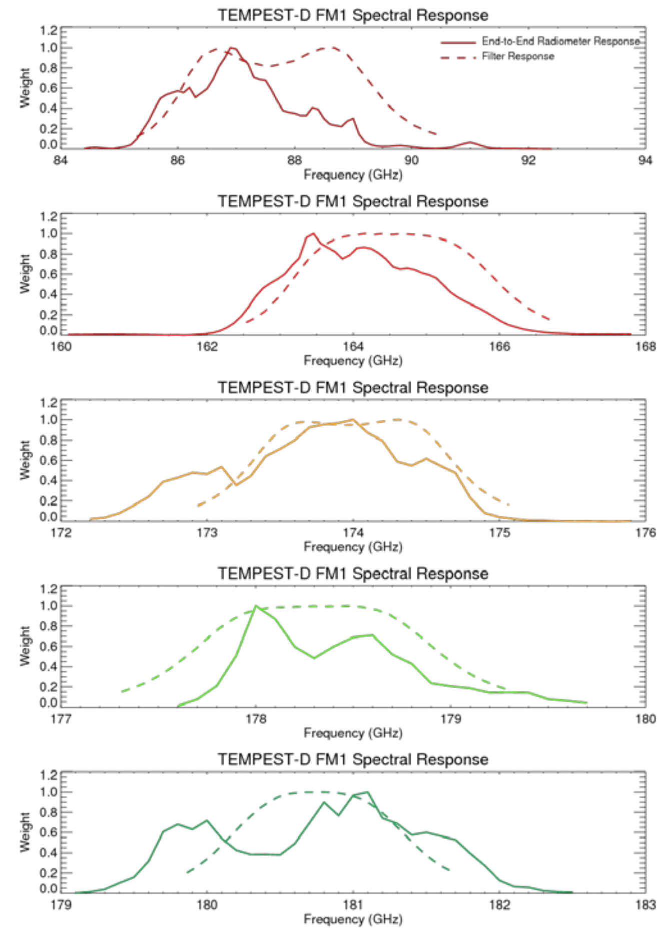
Backup Slides

Validation: Double Difference Method





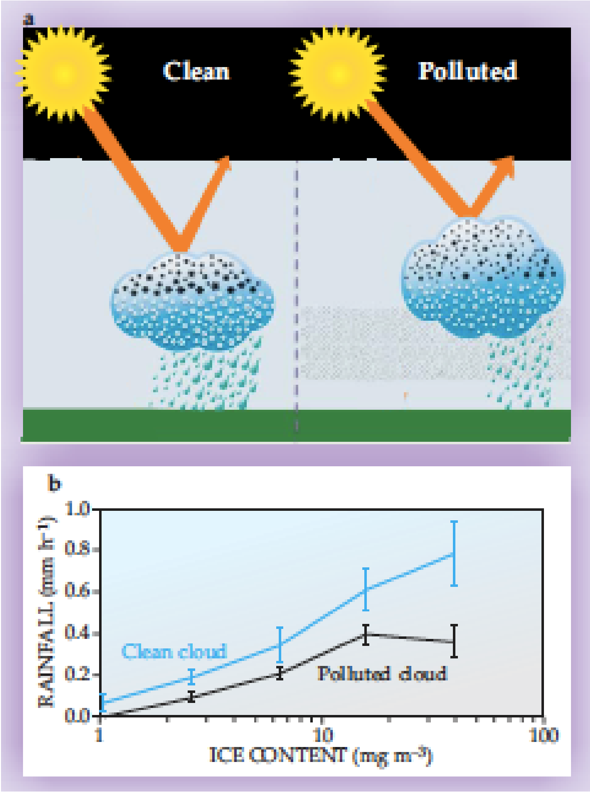
- TEMPEST-D observations are matched in space and time with reference sensors
- Radiative transfer simulations done using geophysical parameters from the NASA GEOS5 global data assimilation model. This is to account for sensor differences (i.e. channel frequencies, spectral response, polarization and 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.

Tropospheric Water and Cloud ICE (TWICE) Scientific Motivation

- **Aerosols and Clouds**
  - Clouds represent arguably the largest uncertainty in climate predictions.
  - Clouds in polluted environments tend to have smaller water droplets and ice crystals than those in cleaner environments (“first indirect effect”).
  - Polluted clouds are less likely to generate rainfall, increasing the cloud water content (“second indirect effect”) and are brighter (have higher albedo) than clean clouds



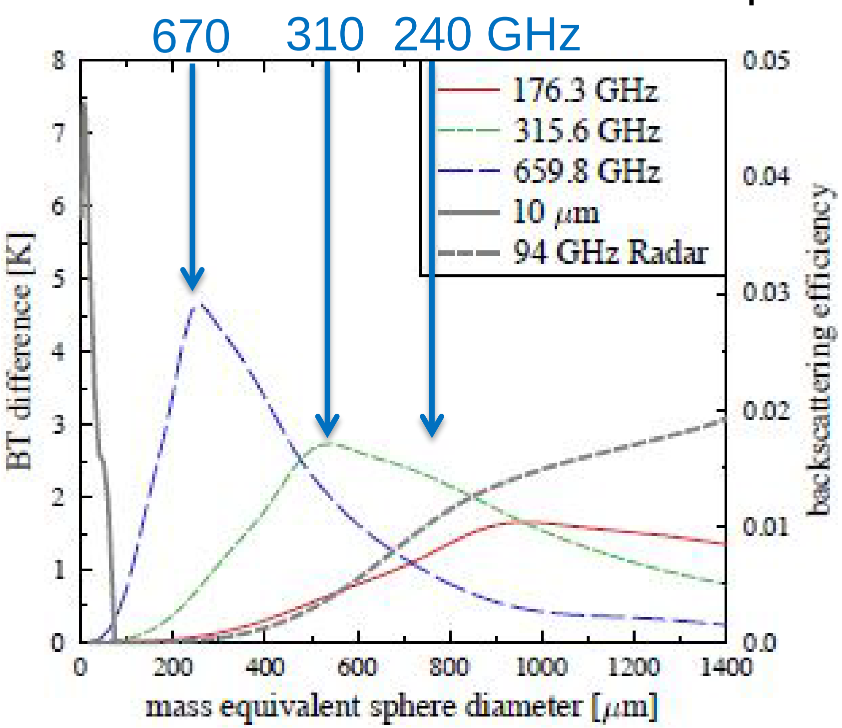
- **TWICE Radiometer Instrument**

  In tandem with other instruments providing aerosol information, the TWICE instrument:
  - Can provide cloud ice particle size information in both polluted and clean environments
  - Help to determine the influence of aerosol pollution on cloud particle size spectrum

TWICE Cloud Ice Particle Size Information

Sub-millimeter wave radiometry fills the sensitivity gap between infrared (cloud tops) and microwave (lower troposphere) measurements

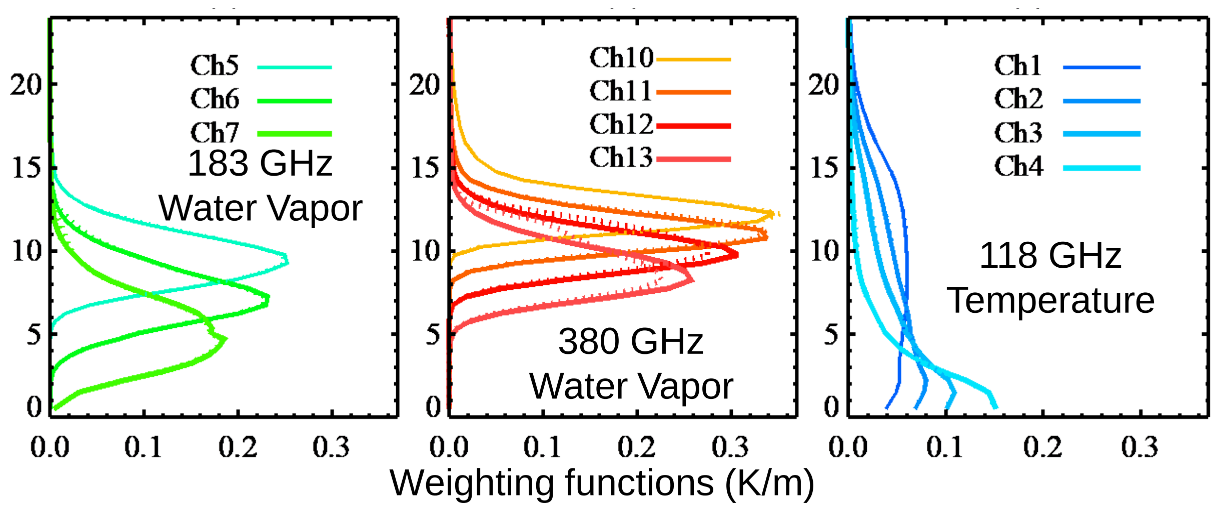
- NASA's A-Train provides limited cloud particle size information.
  - CloudSat: 94-GHz radar (particle sizes > 1 mm)
  - Aqua's MODIS: 10-µm infrared radiometer (particle sizes < 100 µm)
- Sub-millimeter wave provides ice particle size information between ~50 µm and ~1000 µm.
- High atmospheric opacity at sub-millimeter wavelengths allows the measurement of ice in clouds above the freezing level through *scattering.*
- Measured brightness temperatures *decrease* due to ice particle scattering at sub-mm-wave frequencies.
- Modeled brightness temperature decrease due to scattering shown at right; adapted from S. Buehler et al., *QJRMS*, 2007 for ICI MetOp SG-B.



TWICE Water Vapor Profiling

- Measurements near water vapor absorption lines provide vertical profile information through pressure broadening.
- 183 GHz and 380 GHz were chosen to retrieve water vapor in the troposphere and upper troposphere / lower stratosphere (UTLS).
- To constrain the water vapor retrievals, 118 GHz channels measure temperature information using the O_2 absorption line.

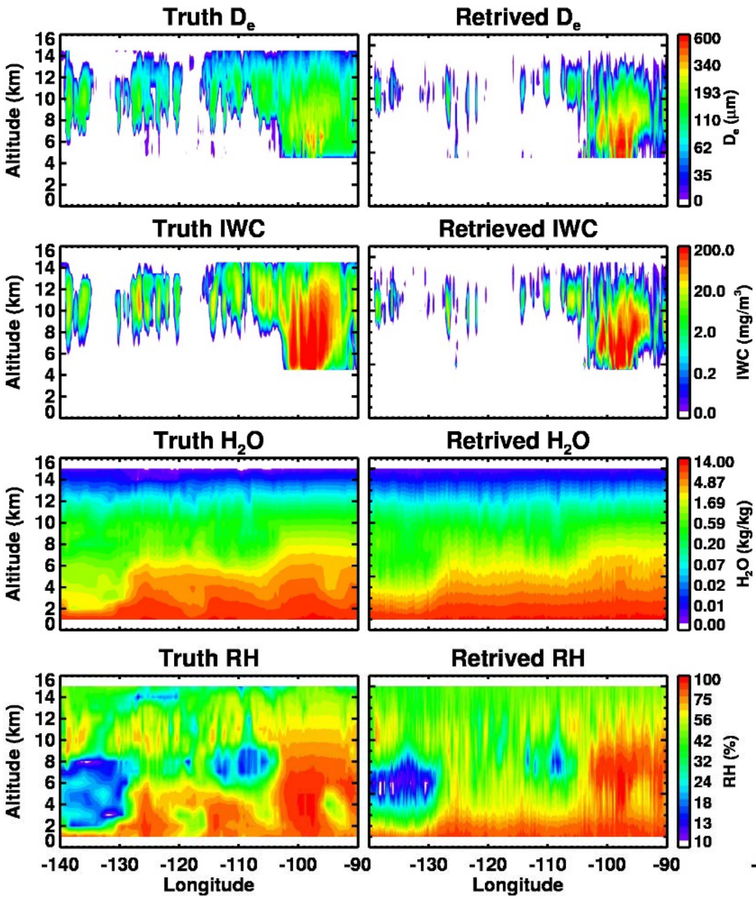
[Jiang et al., *Earth & Space Science, 4, doi:10.1002/2017EA000296, 2017]*



Channel	Center frequency	±Offset frequency	Bandwidth
1	118.75	1.1	0.4
2	118.75	1.5	0.4
3	118.75	2.1	0.8
4	118.75	5.0	2.0
5	183.31	1.0	0.5
6	183.31	3.0	1.0
7	183.31	6.6	1.5
8	243.20	2.5	3.0
9	310.00	2.5	3.0
10	380.20	0.75	0.7
11	380.20	1.80	1.0
12	380.20	3.35	1.7
13	380.20	6.20	3.6
14	664.00	4.20	4.0

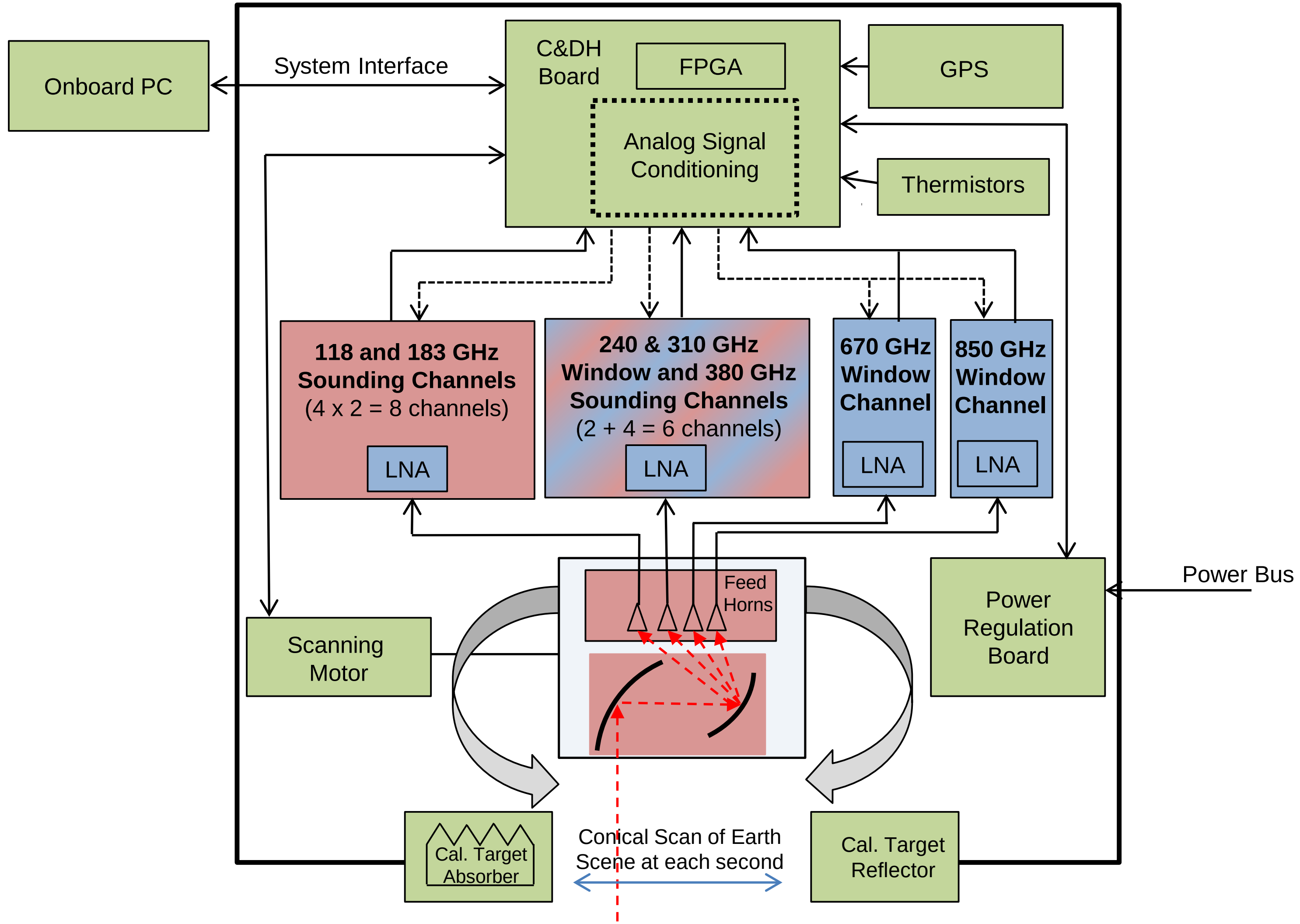
Retrieval of Cloud Ice and Humidity Profiles from TWICE Measurements

- We have developed and applied a Bayesian-based simulation and retrieval system [*Evans et al.*, 2002; 2012] for TWICE frequencies. Simultaneous retrievals are performed for these quantities:
- Cloud ice particle size (D_e), ice water content (IWC), water vapor content (H2O), and relative humidity (RH) profiles.
- Results show that the TWICE instrument is capable of retrieving ice particle size in the range of ~50 μm to 1000 μm with better than 50% uncertainty, filling the gap in ice cloud particle size retrieval using existing space-borne remote sensing modalities.
- Uncertainties for other TWICE retrievals are < 50% for IWC and < 20% for H_2O.



[Jiang et al., *Earth & Space Science*, *4*, doi:10.1002/2017EA000296, 2017]

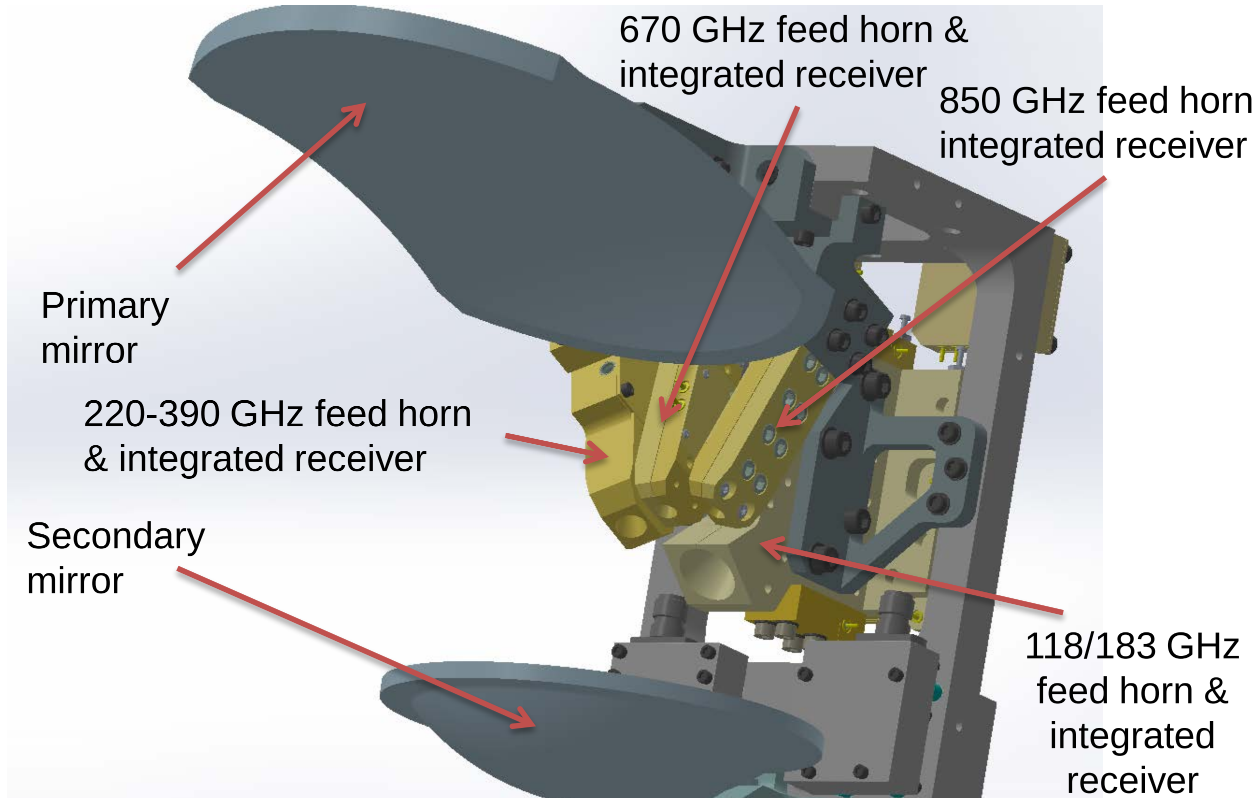
Tropospheric Water and Cloud Ice Instrument Block Diagram



Green = CSU; Red = JPL; Blue = NGC;

TWICE Instrument Quasi-Optics Design

- Large focal plane enabled by oversized secondary reflector.
- Feed horns angled to minimize the total area of the antenna beams on the primary reflector.
- Four feed horns, all fabricated inside front-end modules to minimize waveguide loss:
    - 850 GHz
    - 670 GHz
    - 230–390 GHz
    - 118–183 GHz



Primary and Secondary Reflectors for TWICE