Small Satellite Constellations to Provide Rapid-Refresh, Precise Observations of Severe Storms, Hurricanes and Tropical Cyclones

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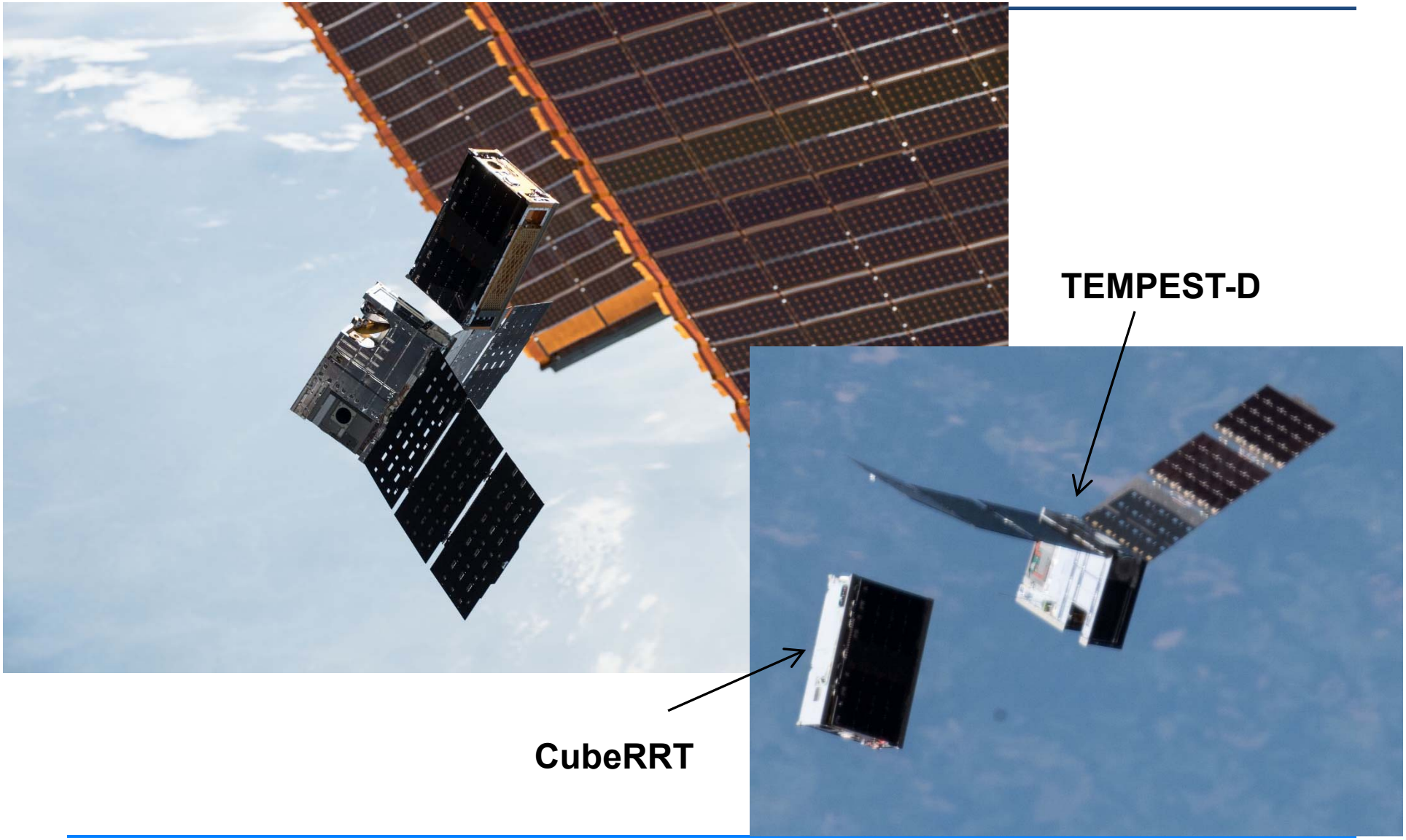
[3]Blue Canyon Technologies, Boulder, CO

Thanks to NASA Wallops for providing ground station communications support.

TEMPEST-D and CubeRRT Shortly After Deployment, July 13, 2018



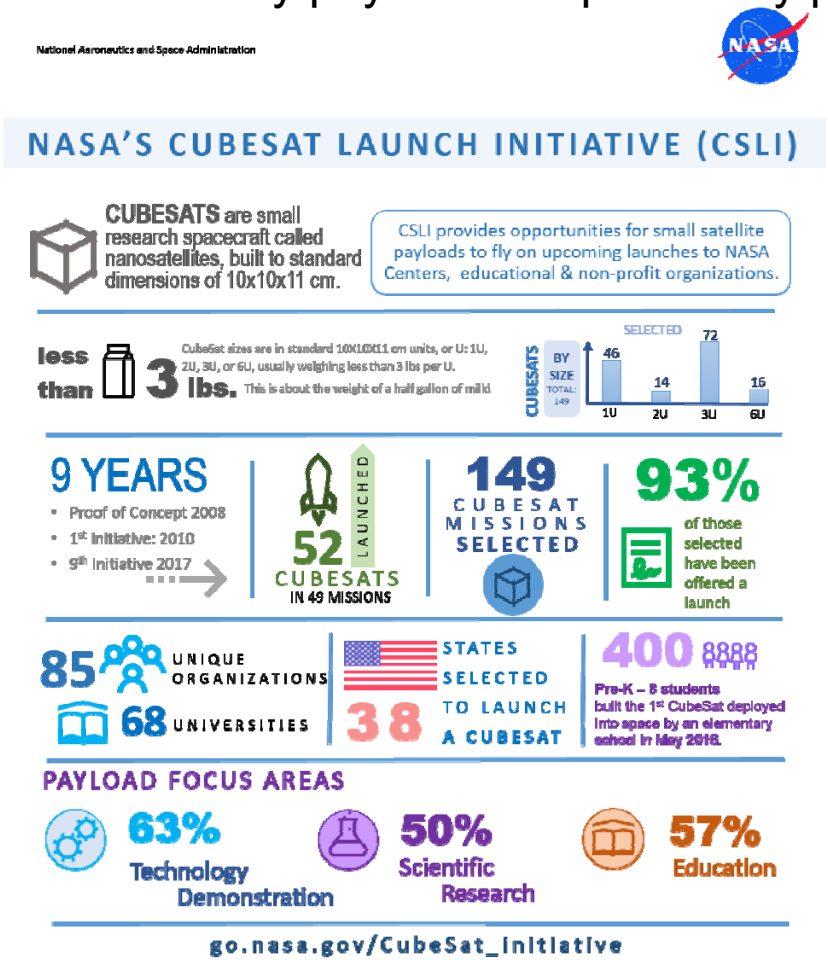
CubeSat Standard for Nanosatellites to Small Satellites

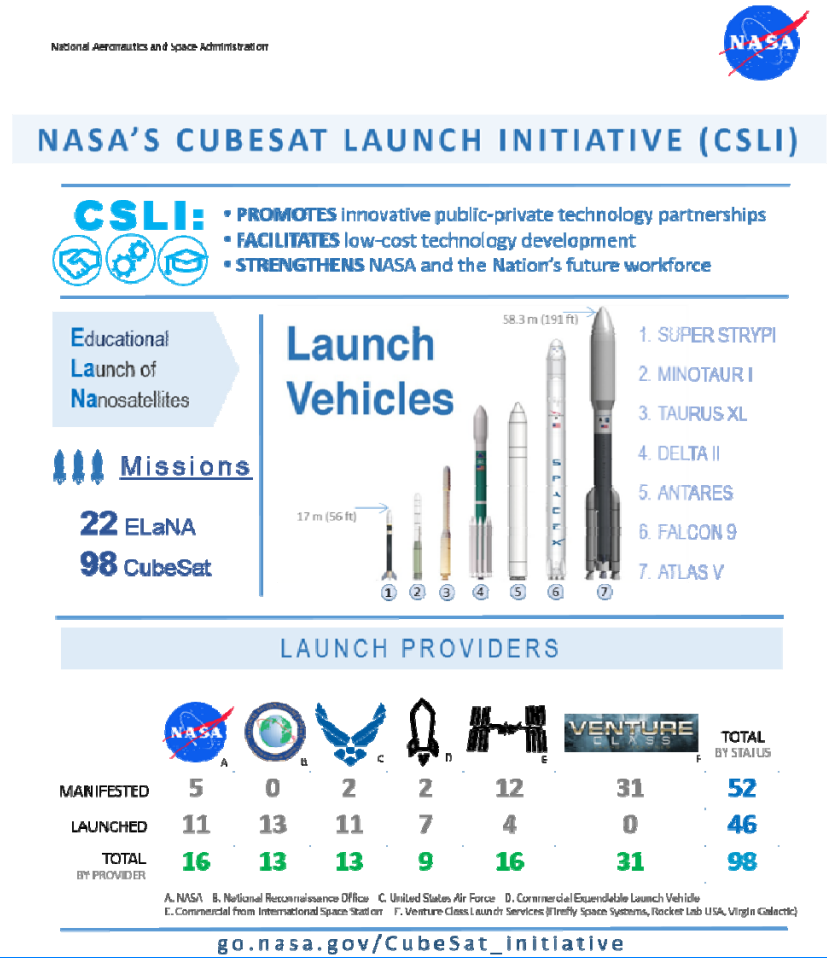
- The CubeSat standard was defined in 1999 by Bob Twiggs of Stanford and Jordi Puig-Swari of Cal Poly as a 10-cm unit cube with 1.3 kg of mass.
- CubeSats are a class of nanosatellites to small satellites. CubeSats are built to standard dimensions (Units or “U”) of 11.35 x 10 x 10 cm. They can be 1U, 2U, 3U, 6U or larger in size, typically weighing up to 1.3 kg (2.9 lbs.) per U.
- Science and technology demonstration payloads have typically used the 3U CubeSat form factor of 34 x 10 x 10 cm and up to 4 kg.
- The 6U CubeSat form factor of 34 x 20 x 10 cm can have mass up to 12 kg, with a 50% increase in allowable mass density.
- Additional science capability is provided by 6U CubeSats, with increased solar panel area for battery charging, as well as the potential for increased capacity and redundancy of satellite-to-ground communications, mass and volume.

Image from http://www.nasa.gov/content/set-of-nanoracks-cubesats-deployed-from-space-station

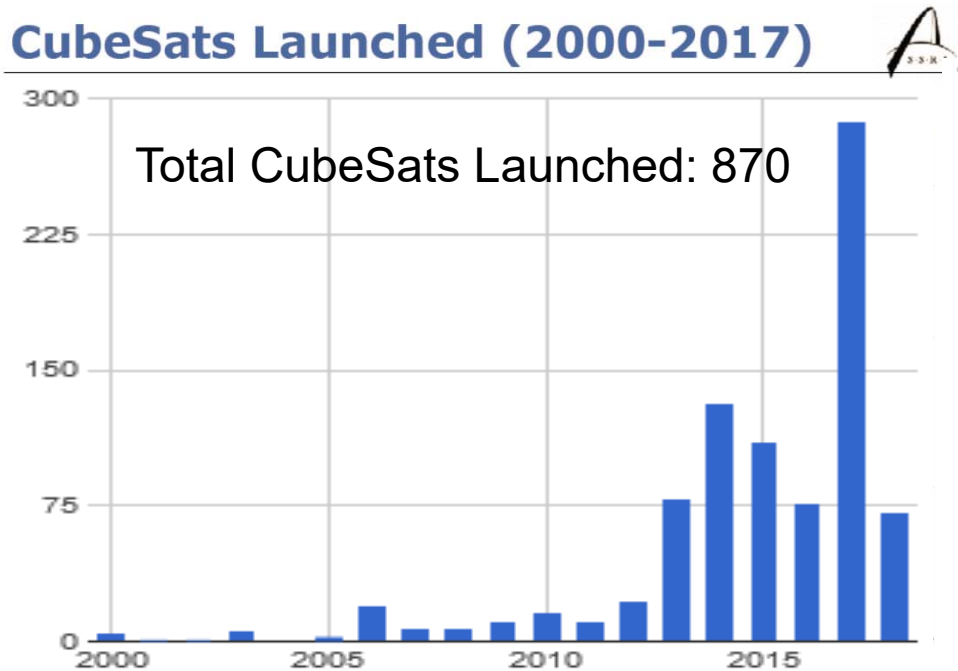
NASA's CubeSat Launch Initiative

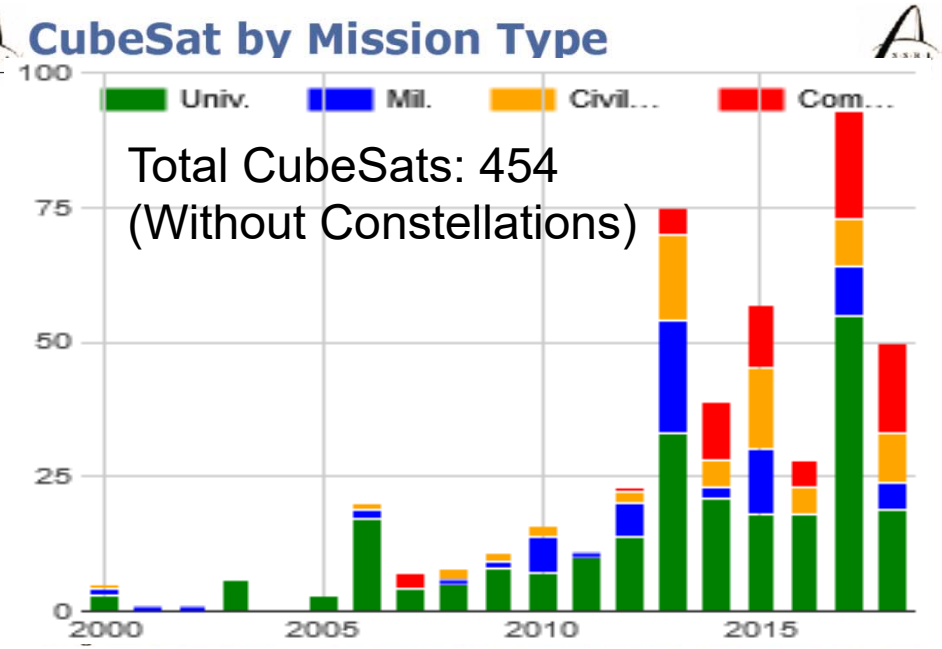
NASA's CubeSat Launch initiative (CSLI) provides opportunities for small satellite payloads to fly on rockets planned for upcoming launches. These CubeSats are flown as auxiliary payloads on previously planned missions.





Number and Type of CubeSats Launched Worldwide by Year

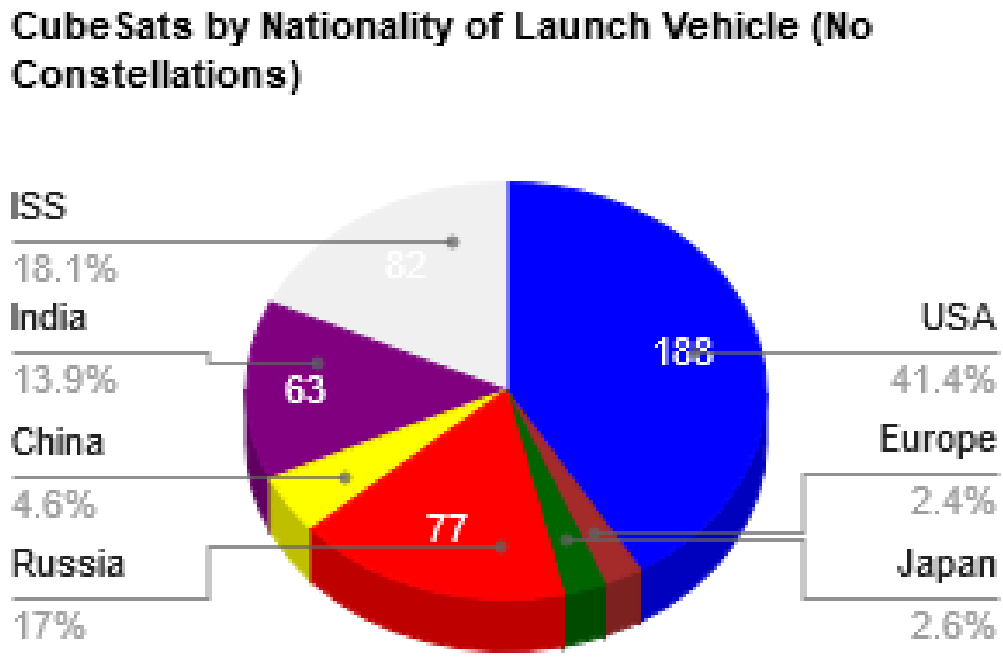




University (green) Civil Space (yellow)
Military (blue) Commercial Space (red)

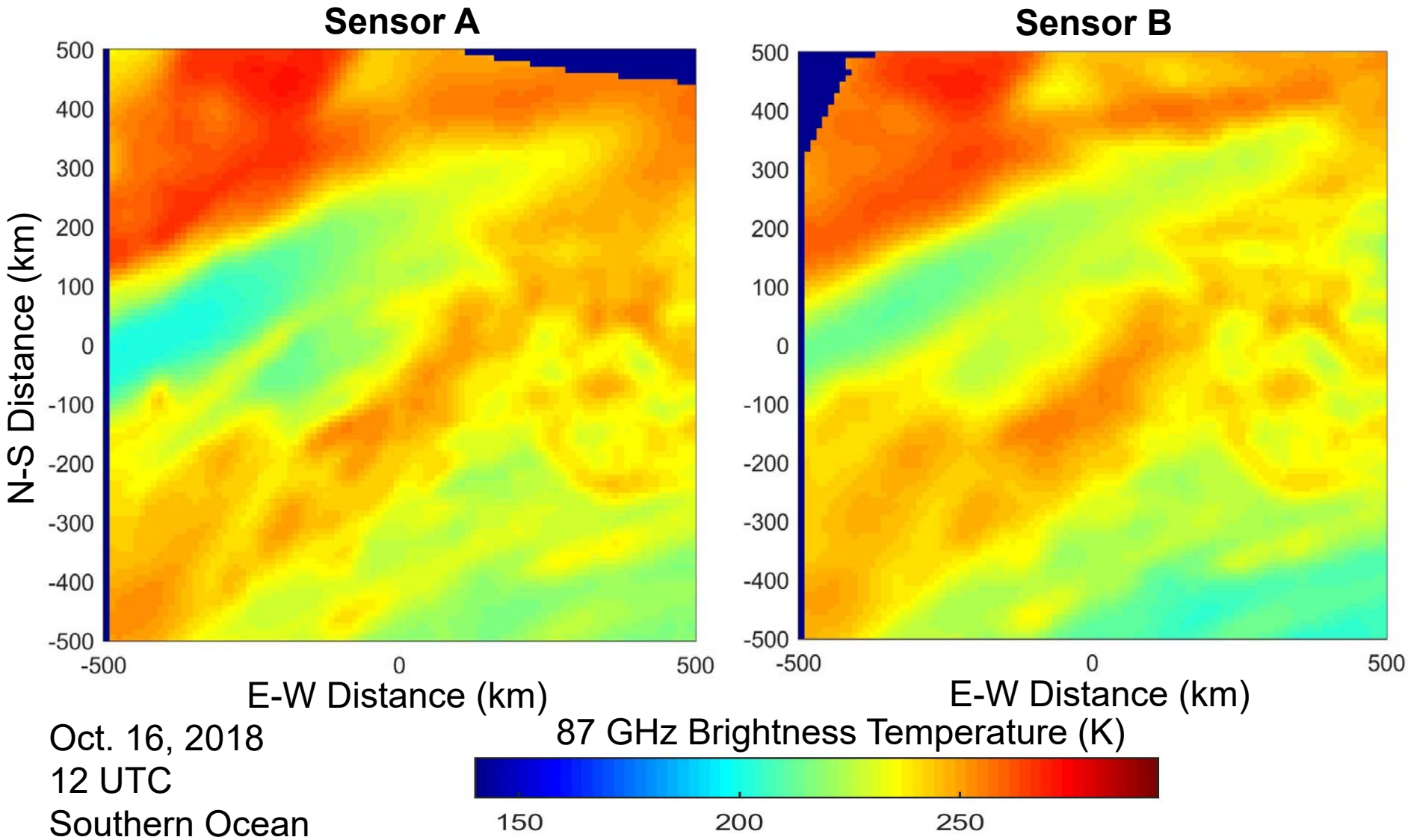
From Michael Swartout, "CubeSat Database," Saint Louis University.
Available online at https://sites.google.com/a/slu.edu/swartwout/home/cubesat-database

CubeSat Missions by Nationality of Launch Vehicle



From Michael Swartout, "CubeSat Database," Saint Louis University.
Available online at https://sites.google.com/a/slu.edu/swartwout/home/cubesat-database

Comparison Between On-orbit Passive Microwave Sensors



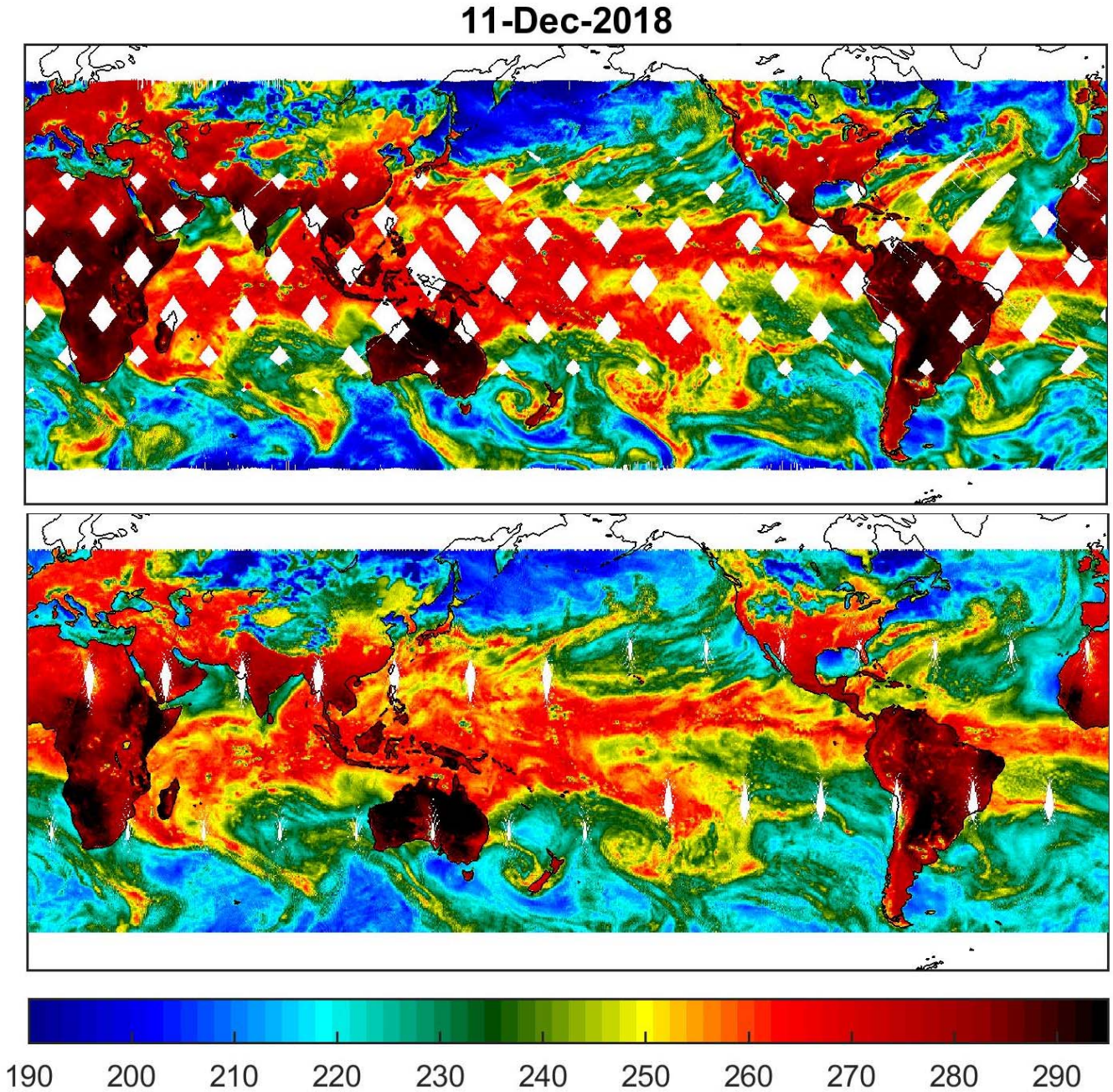
Oct. 16, 2018
12 UTC
Southern Ocean

Comparison Between On-orbit Passive Microwave Sensors

Sensor A

Sensor B

87 GHz Brightness Temperature (K)



Sensor B

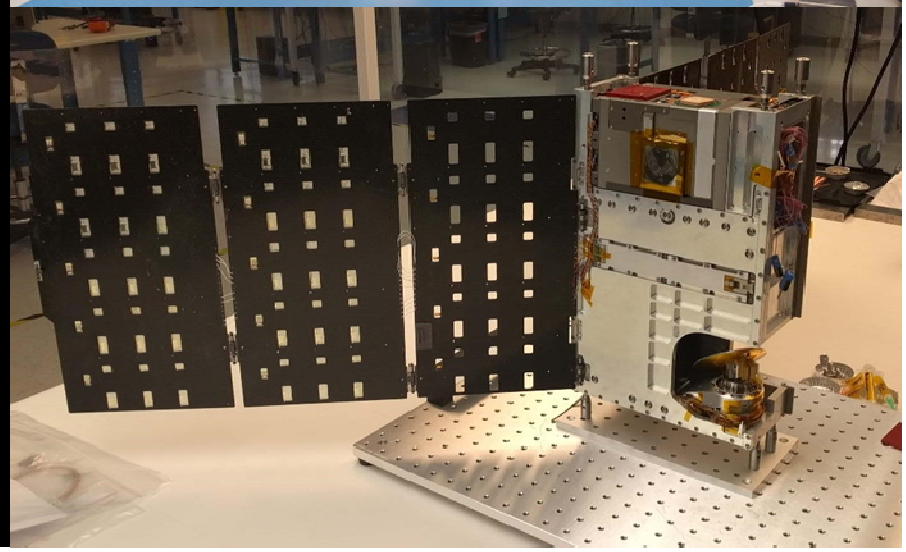
NOAA Advanced Technology Microwave Sounder (ATMS)

75 kg, 100 W, **$$$$**

Sensor A

TEMPEST-D

3.8 kg, 6.5 W, $

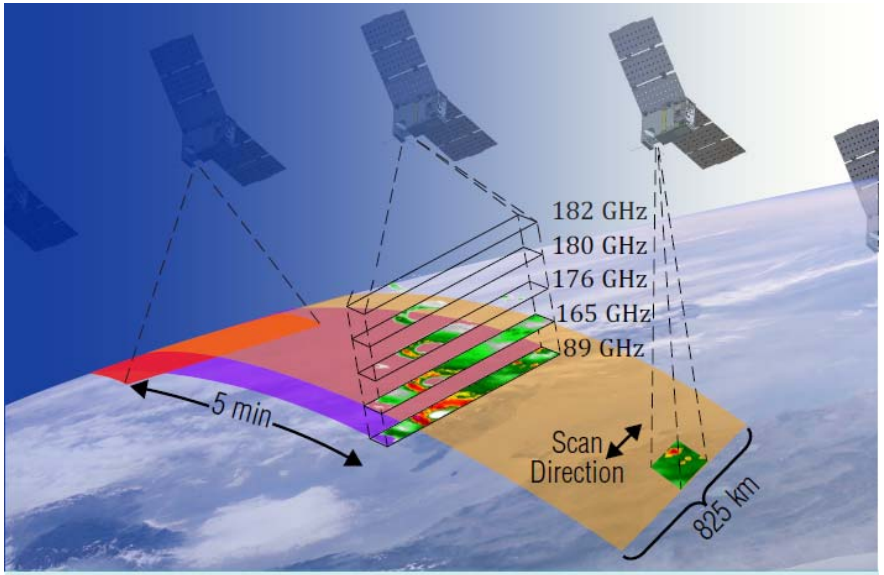


Temporal Experiment for Storms and Tropical Systems (TEMPEST)

TEMPEST addresses 2017 Earth Science Decadal Survey Question W-4:

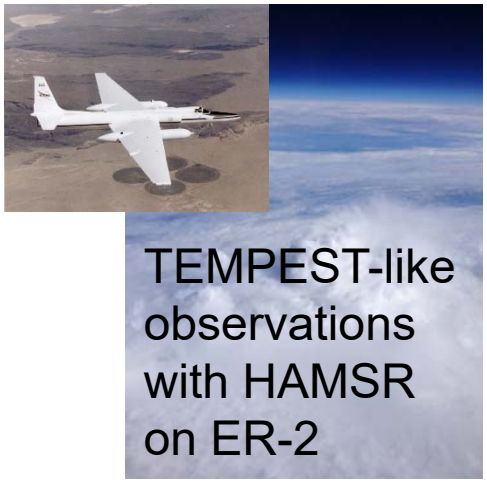
- *Why do convective storms, heavy precipitation, and clouds occur exactly when and where they do?*
  - Providing global, *temporally-resolved observations of cloud and precipitation processes* using a train of 6U CubeSats with millimeter-wave radiometers
  - Sampling rapid changes in convection and the surrounding water vapor environment every 3-4 minutes for up to 30 minutes.

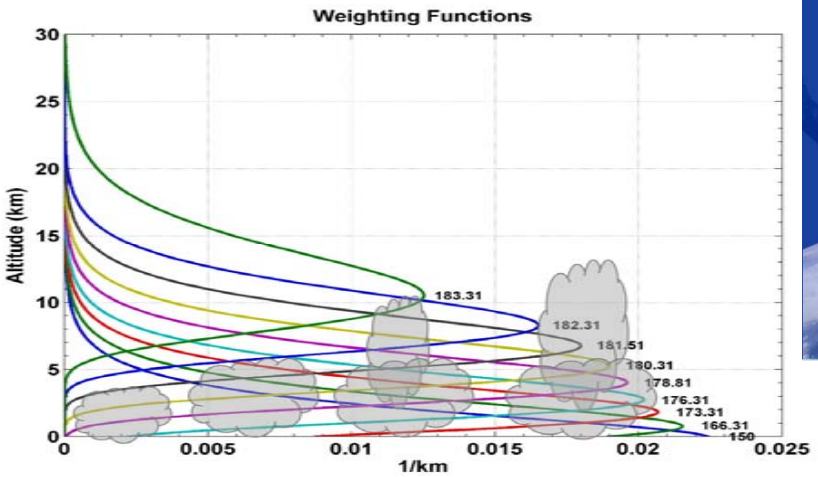
- TEMPEST-D technology demonstration mission delivered a single 6U CubeSat with mm-wave instrument for launch integration 2.5 years from start of project.
- Launched by Orbital ATK on CRS-9 from NASA Wallops to ISS on May 21, 2018
- Deployed into orbit from ISS by NanoRacks on July 13, 2018
- Demonstrated mission lifetime of more than 180 days on orbit to date.

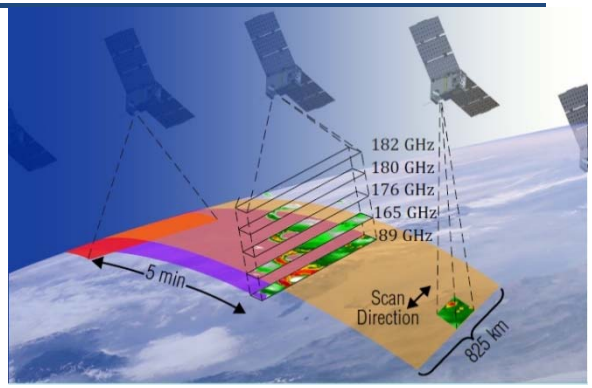


5 identical 6U small sats, each with an identical 5-channel radiometer, flying 5 minutes apart

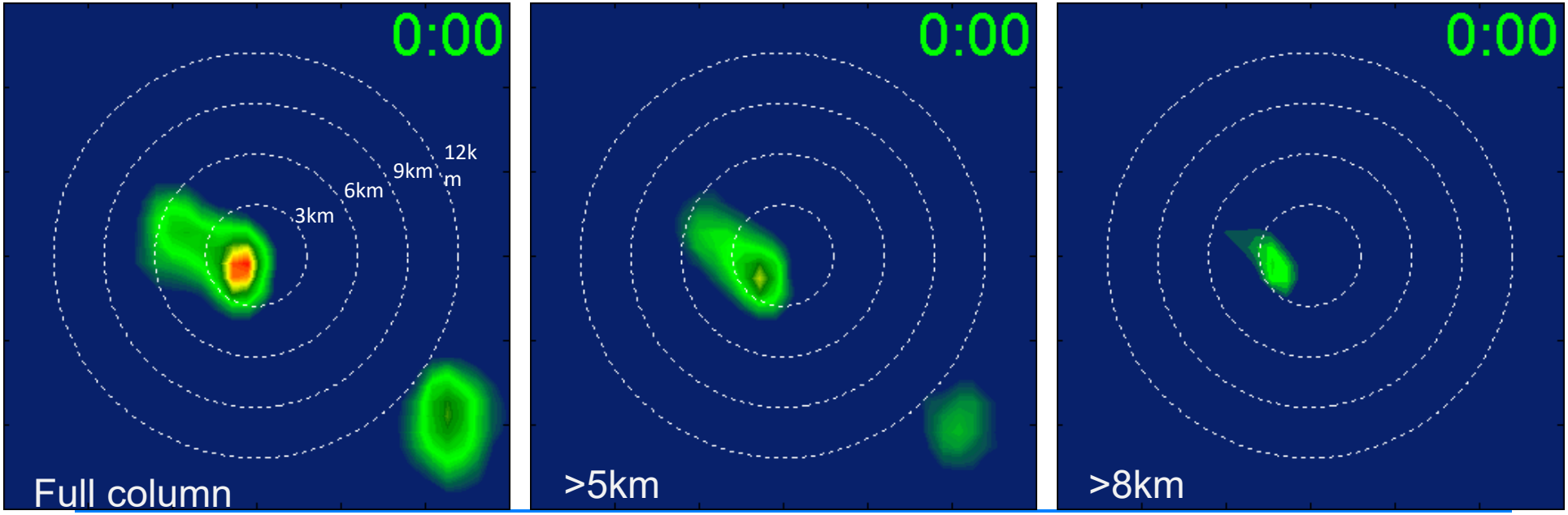
TEMPEST-Like Measurements from JPL/HAMSR on ER-2 Aircraft



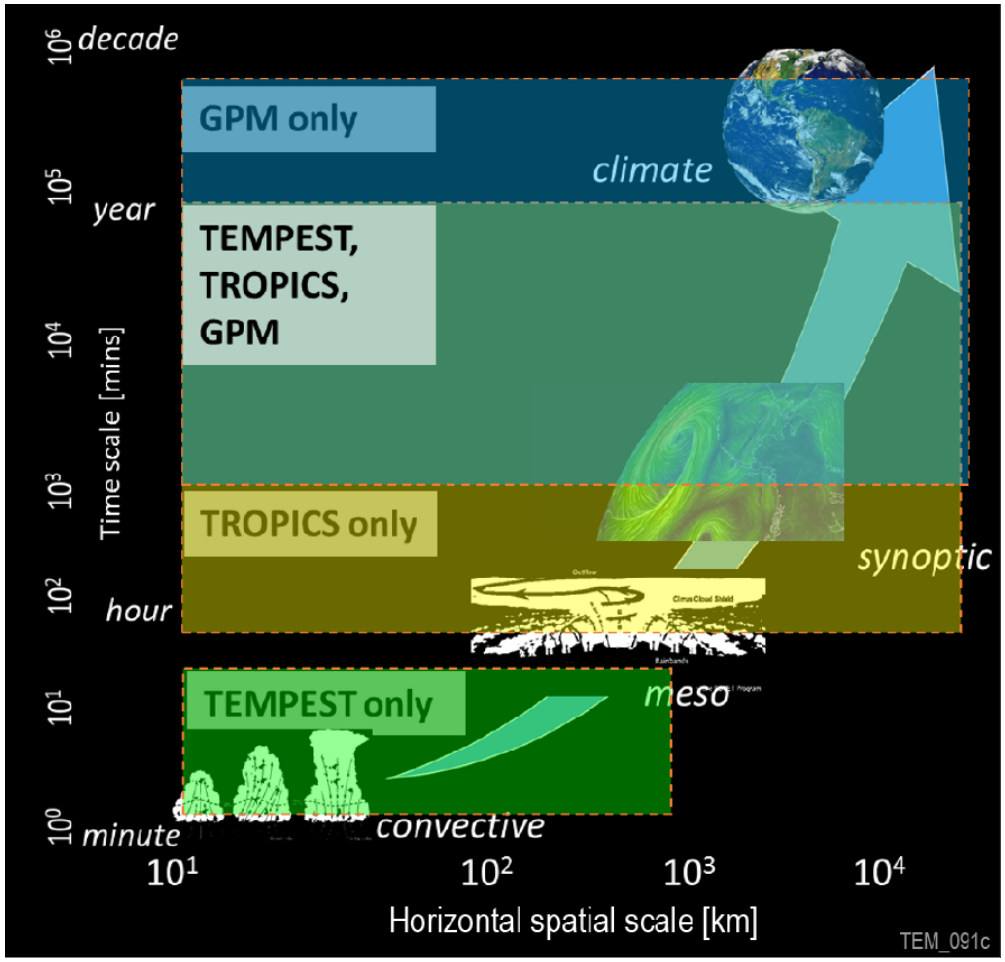




TEMPEST – enabling rapid revisit radiometry for precipitation processes

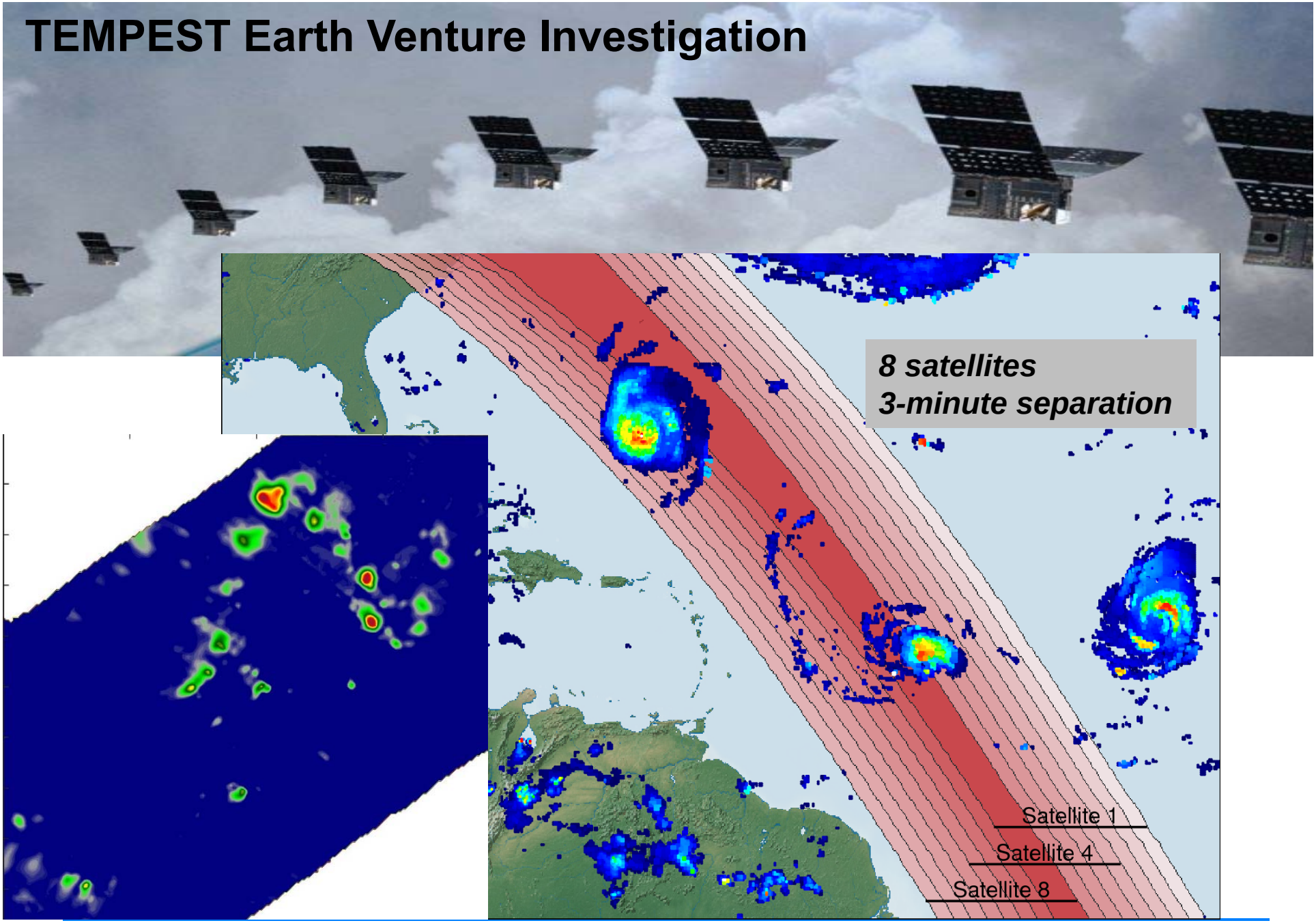


TEMPEST Mission Concept Occupies Unique Observational Space



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.

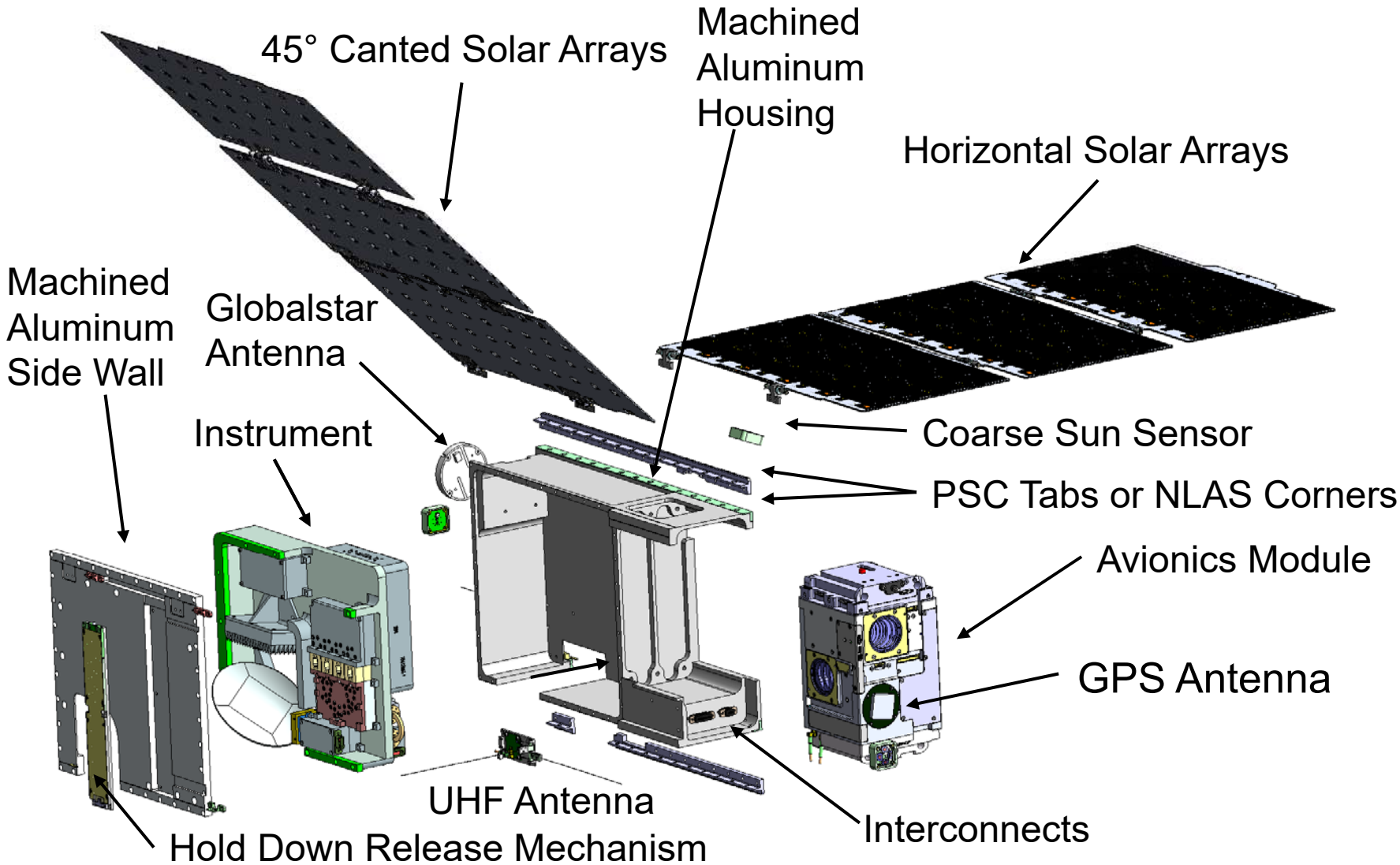
TEMPEST Earth Venture Investigation



TEMPEST-D Tech Demo Mission: Accomplishments to Date

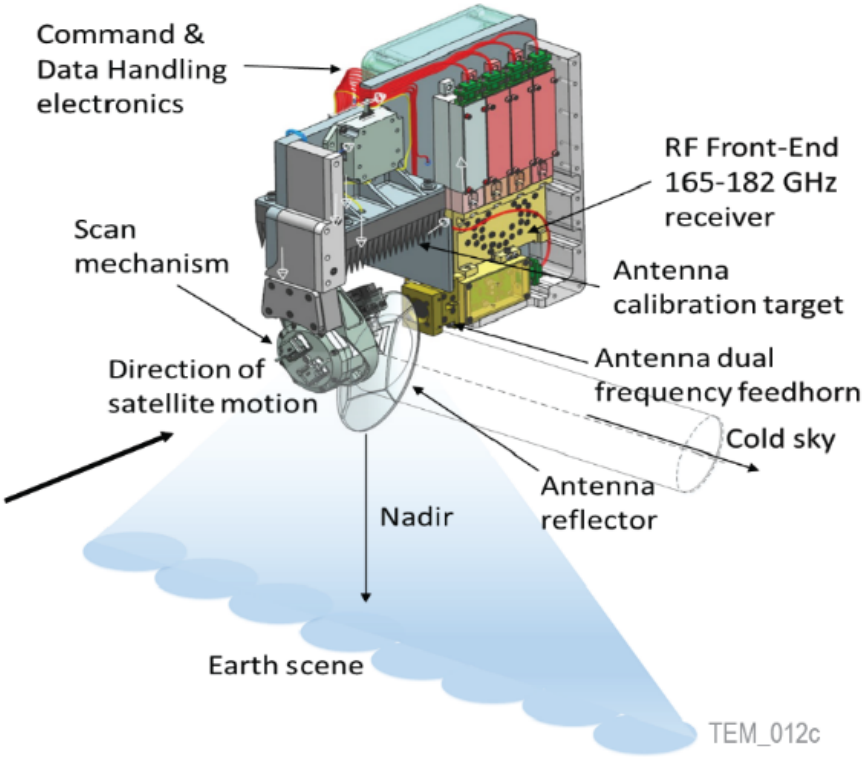
- Reduced the risk, cost and development time for future science missions using TEMPEST CubeSats.
- Demonstrated potential for a train of 6U CubeSats with TEMPEST instruments spaced 3-4 minutes apart to perform the first global *temporally-resolved measurements of cloud and precipitation processes.*
- 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 180 days to date.

TEMPEST-D 6U-Class BCT Spacecraft Bus based on XB1

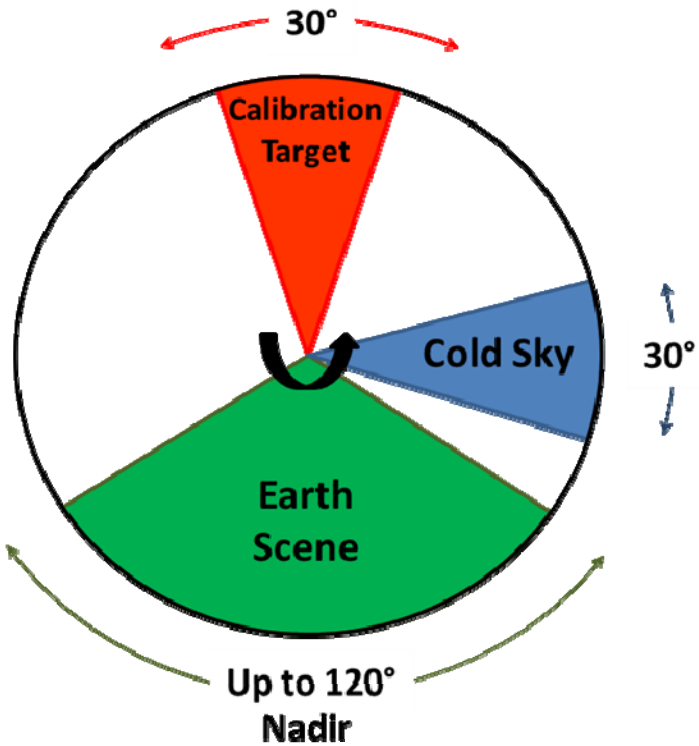


TEMPEST-D Instrument Performs End-to-End Radiometric Calibration

TEMPEST-D Instrument

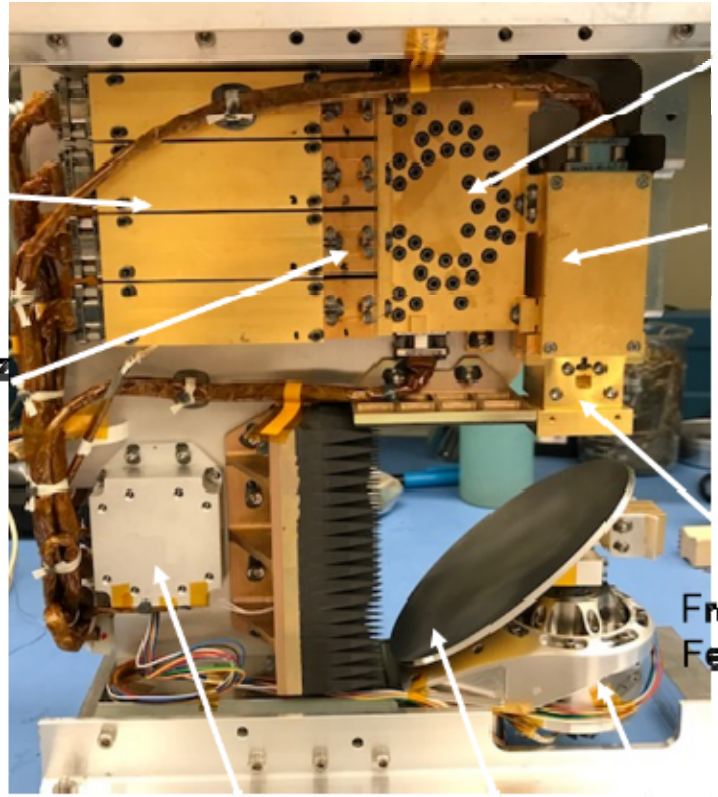


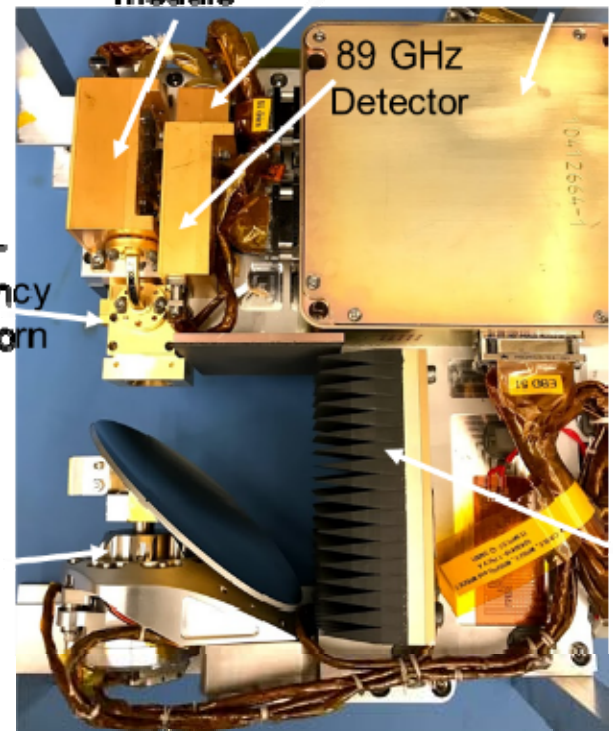
Observing Profile



- Cross-track scanning over ±65° nadir angles
- Spatial resolution ranges from 13 to 25 km for 87 to 181 GHz.
- Performs two-point end-to-end calibration every 2 sec. by measuring cold sky at 2.73 K and ambient blackbody calibration target every 2 sec (scanning at 30 RPM).

Flight Model Radiometer Instrument Built and Integrated at JPL

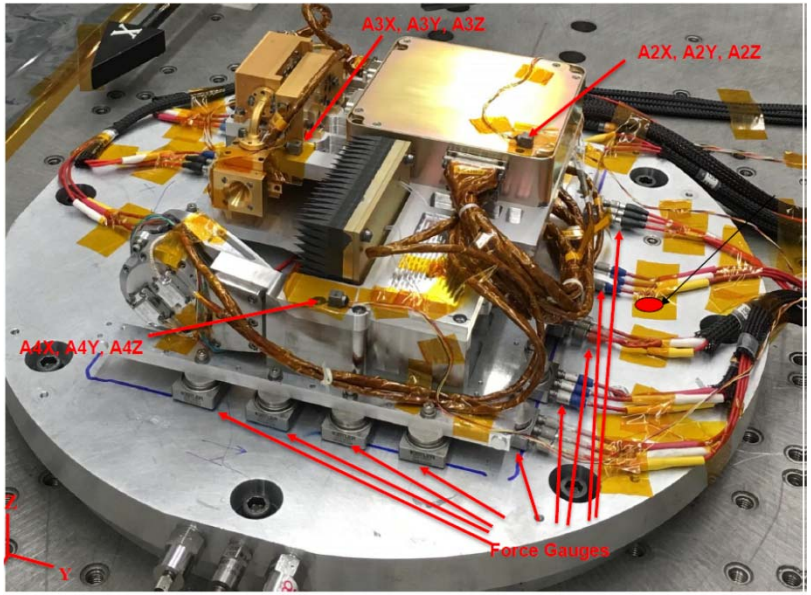




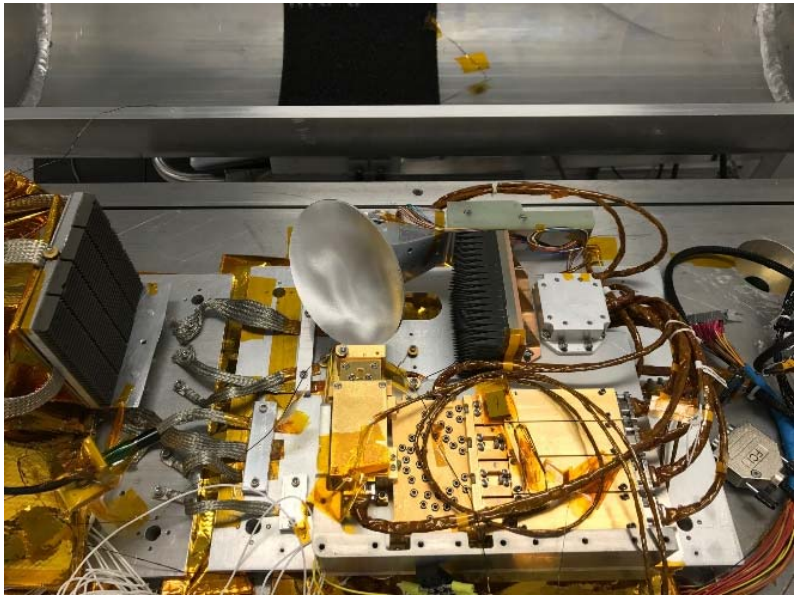
TEMPEST-D Instrument Testing

Flight instrument:

- End-to-end receiver bandpass and linearity measurements (June 2017)
- Integrated and vibration testing completed (June 2017)
- Thermal vacuum testing successfully completed (July 2017)
- Antenna pattern validation measurements performed (July 2017)
- Delivered to BCT for integration with spacecraft bus & testing (July 2017)

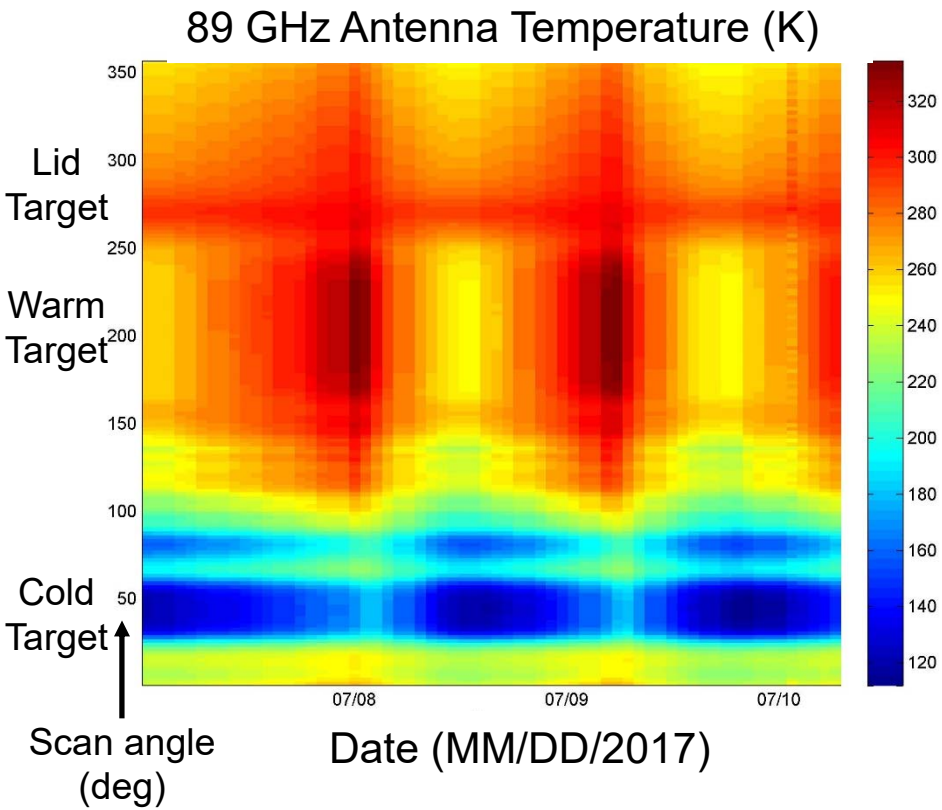


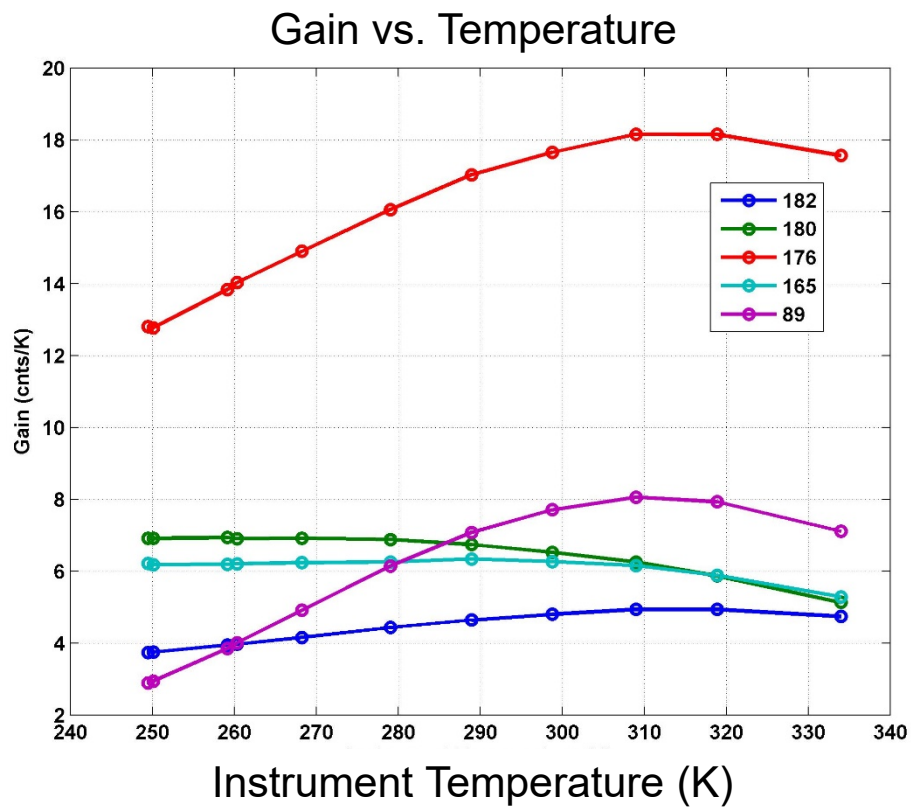
Vibration Testing



TVAC Testing

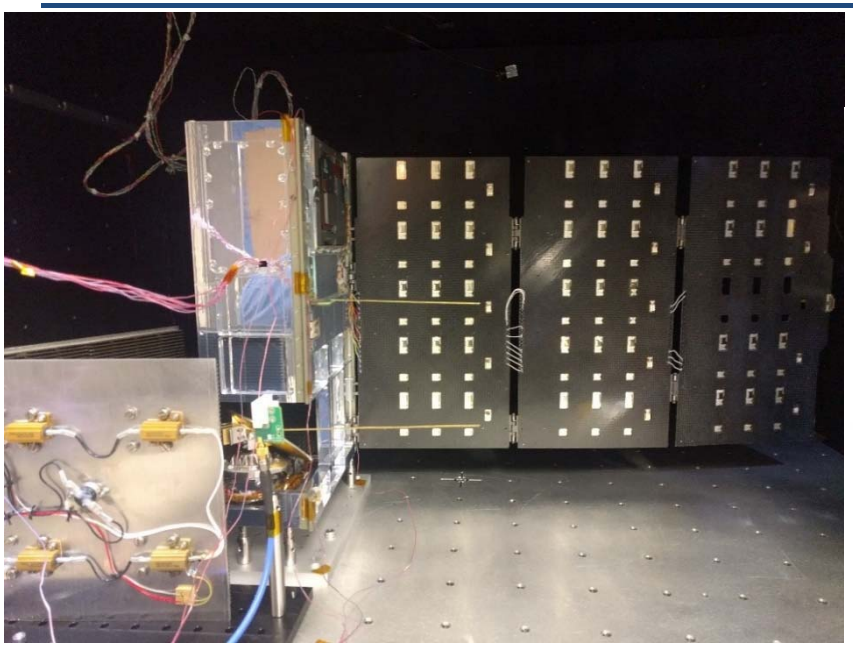
Thermal Vacuum Testing Results for Flight Instrument, Jul. 2017

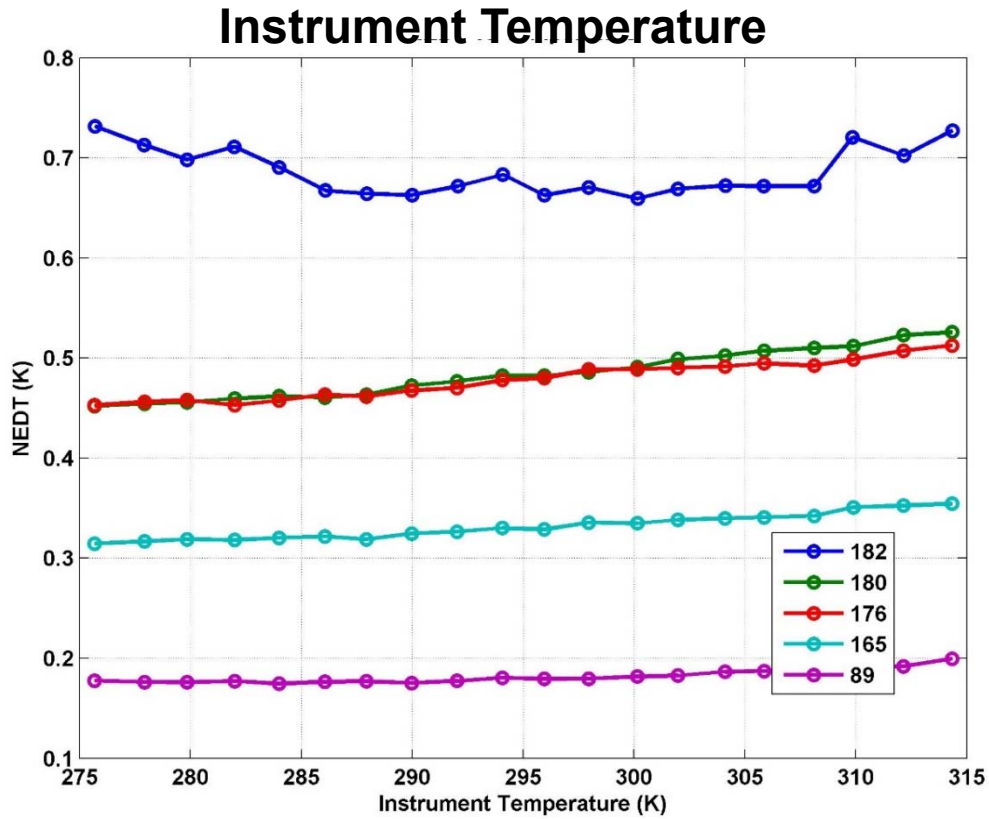




Gain and receiver noise temperature measured while viewing blackbody calibration target at chamber temperature varying from -25°C to +60°C.

Instrument Performance in Spacecraft TVac at BCT, Jan. 2018

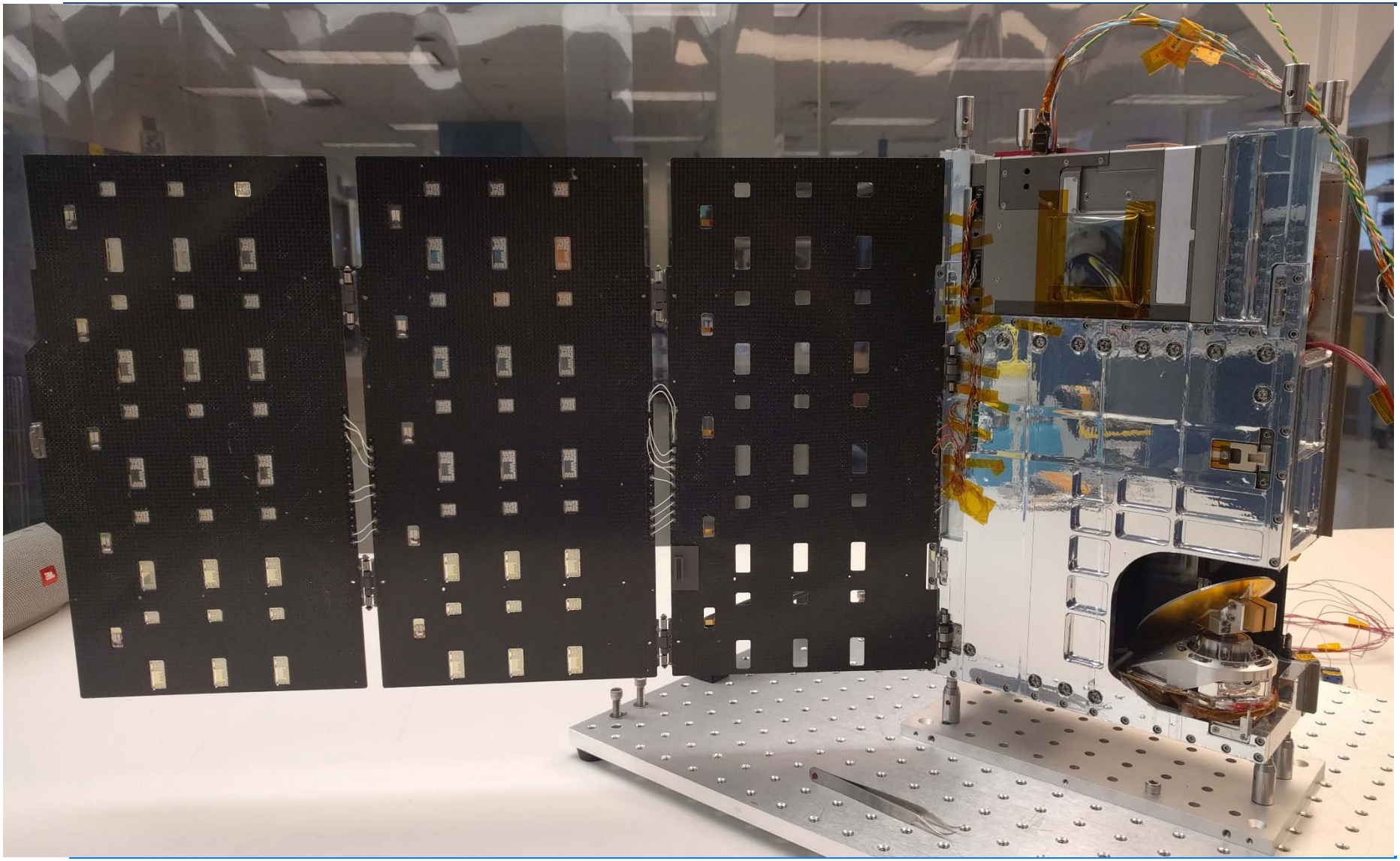




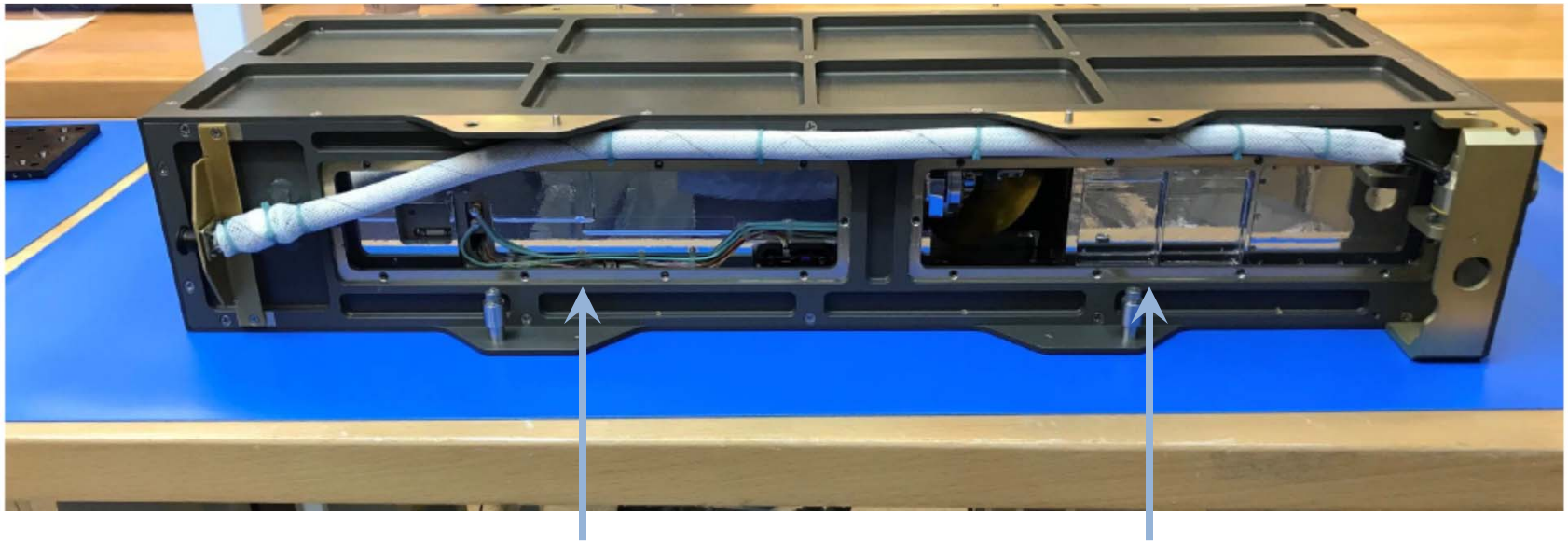
Frequency (GHz)	Pre-launch NEdT (K)	On-orbit NEdT (K)
87	**0.2**	**0.2**
164	**0.3**	**0.3**
174	**0.5**	**0.4**
178	**0.5**	**0.4**
181	**0.7**	**0.7**

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 Fully- Integrated Flight Unit, Feb. 2018



Final Installation in Deployer at NanoRacks in Houston, Mar. 2018



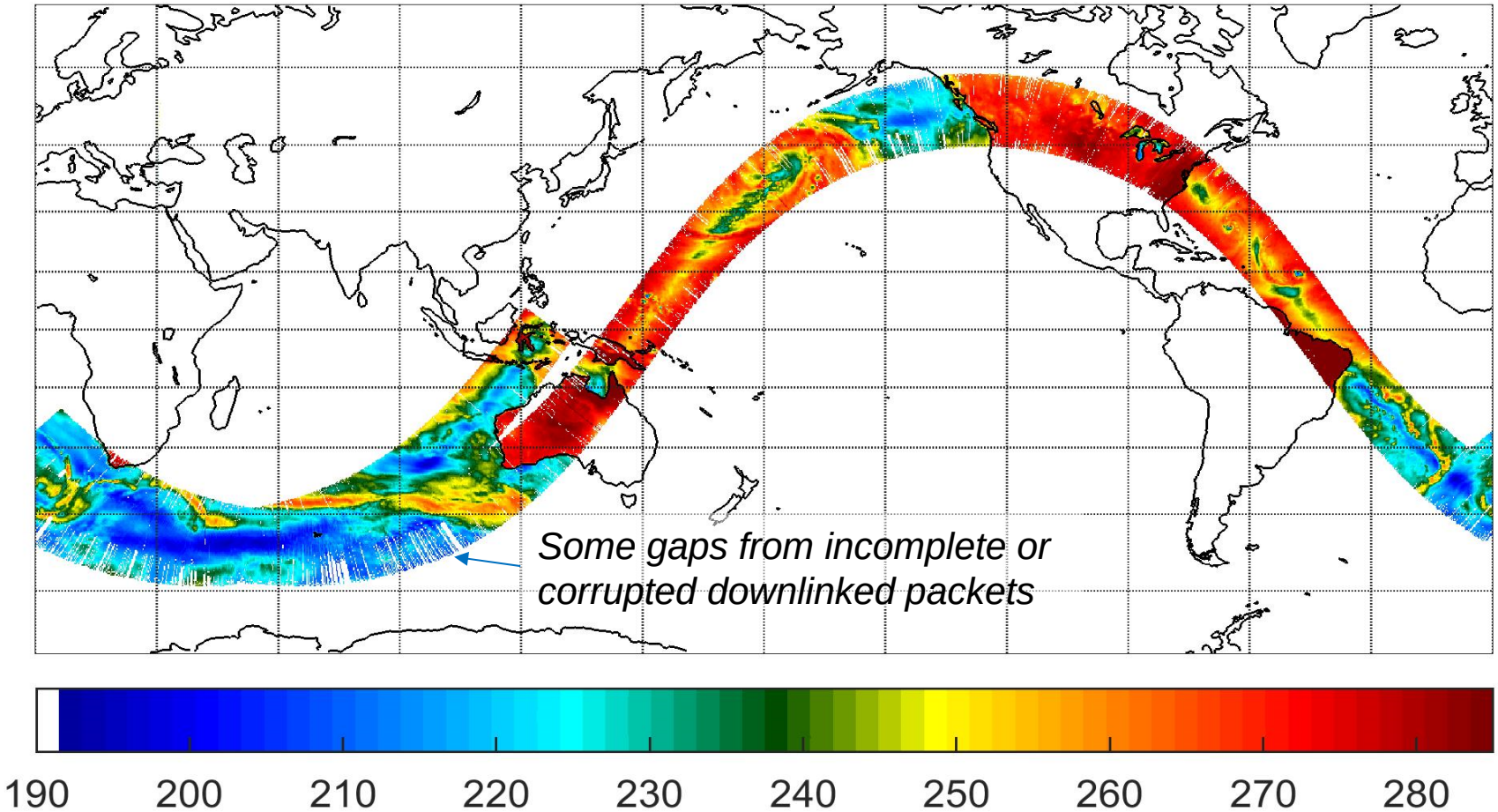
CubeRRT **TEMPEST-D**

Launched on Orbital ATK OA-9 from NASA Wallops to ISS, May 21, 2018

Photo Credit: NASA

TEMPEST-D First Full-Swath Data Sept. 11, 2018

TEMPEST-D 87 GHz Brightness Temperature (K)



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

TEMPEST-D Data
Sept. 11, 2018

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

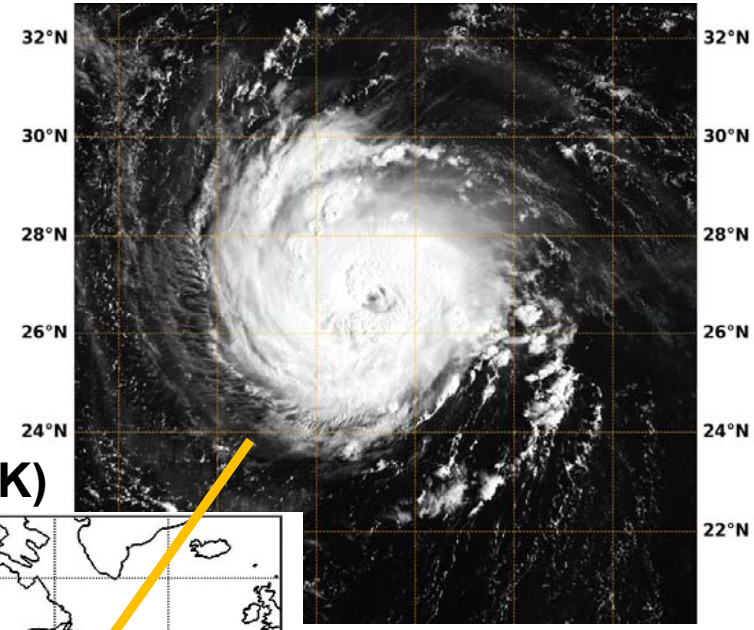
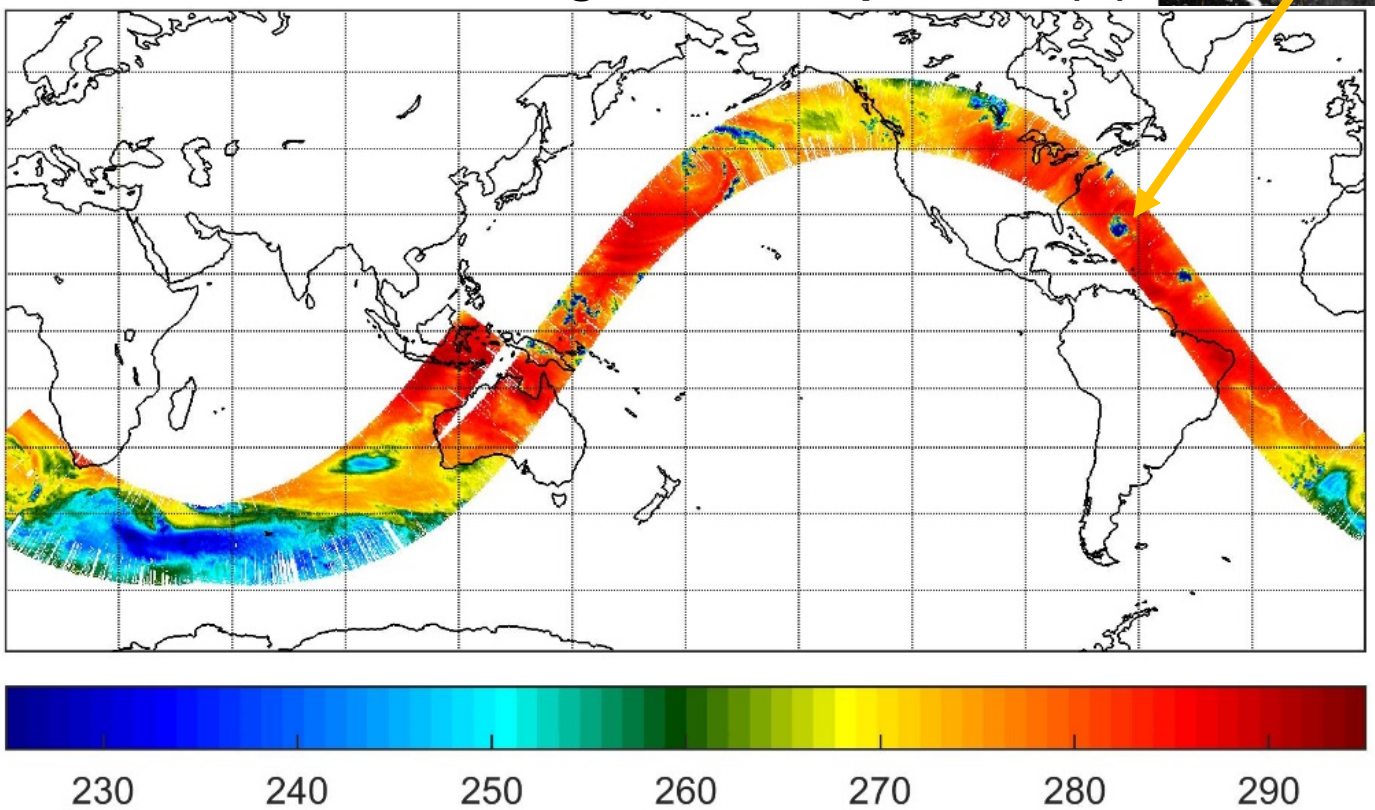
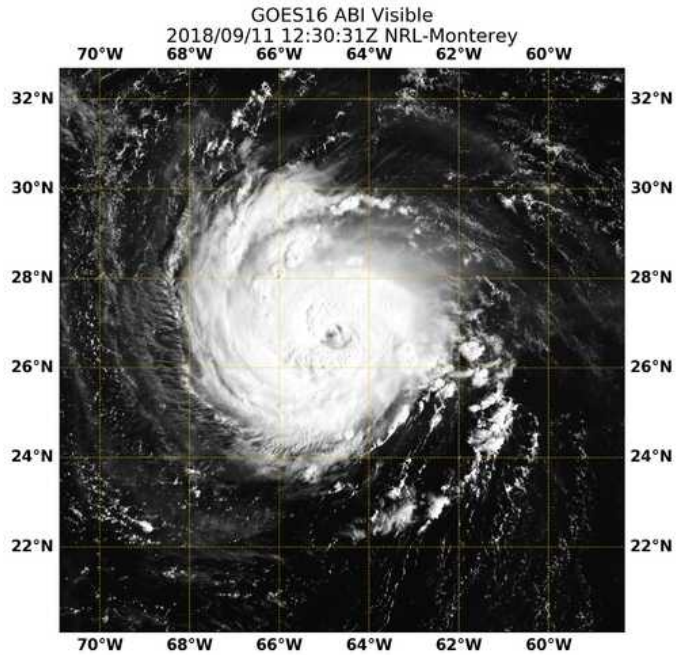


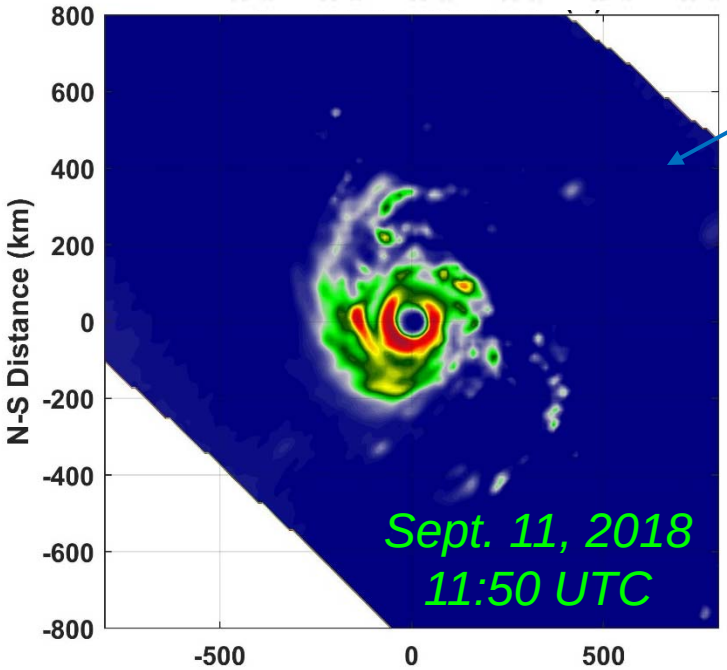
Image Credit: NASA/NOAA/Naval Research Laboratory Monterey/JPL-Caltech

TEMPEST-D 164 GHz Brightness Temperature (K)



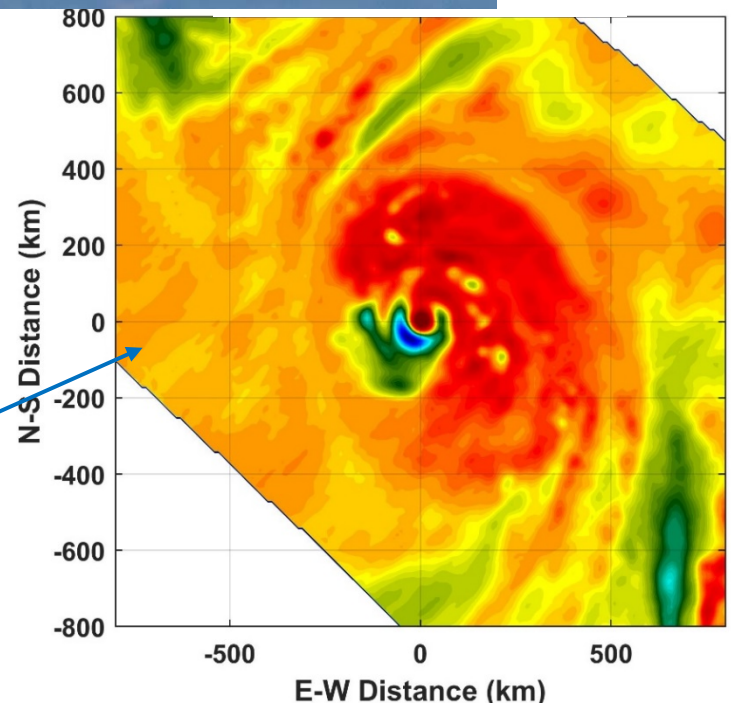
Hurricane Florence



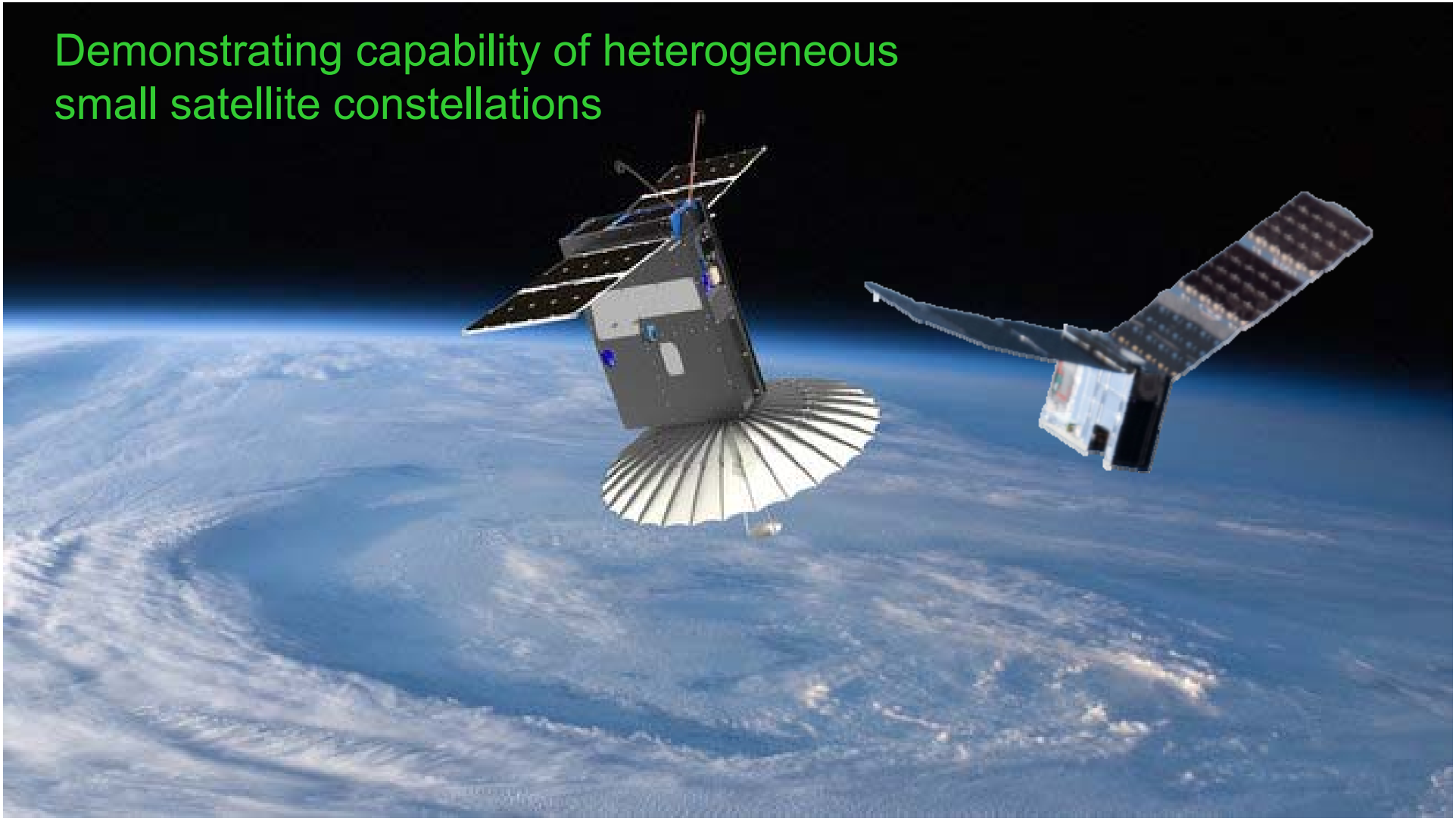


164 GHz images convection around inner core through ice scattering signature

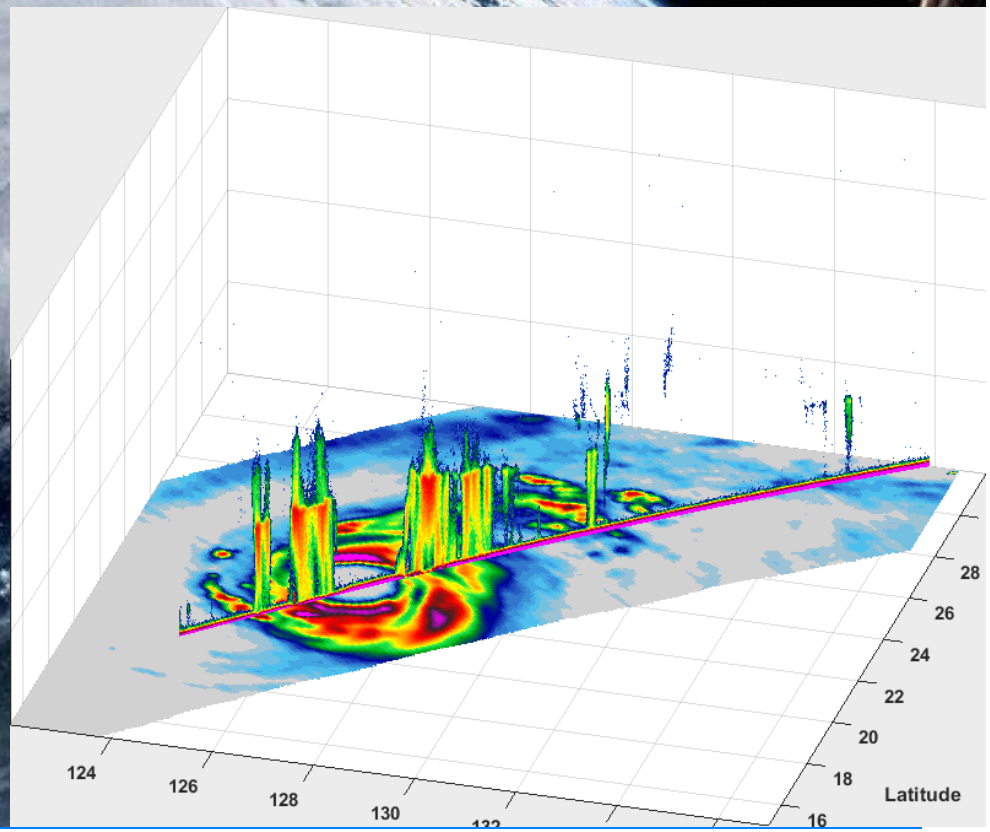
87 GHz sensitive to clouds, precipitation, water vapor and strong convection



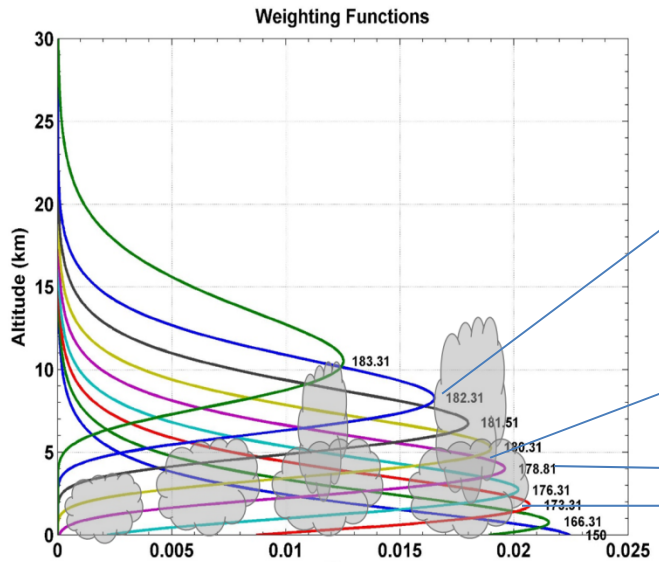
TEMPEST-D and RainCube, Ka-band Radar on a 6U CubeSat

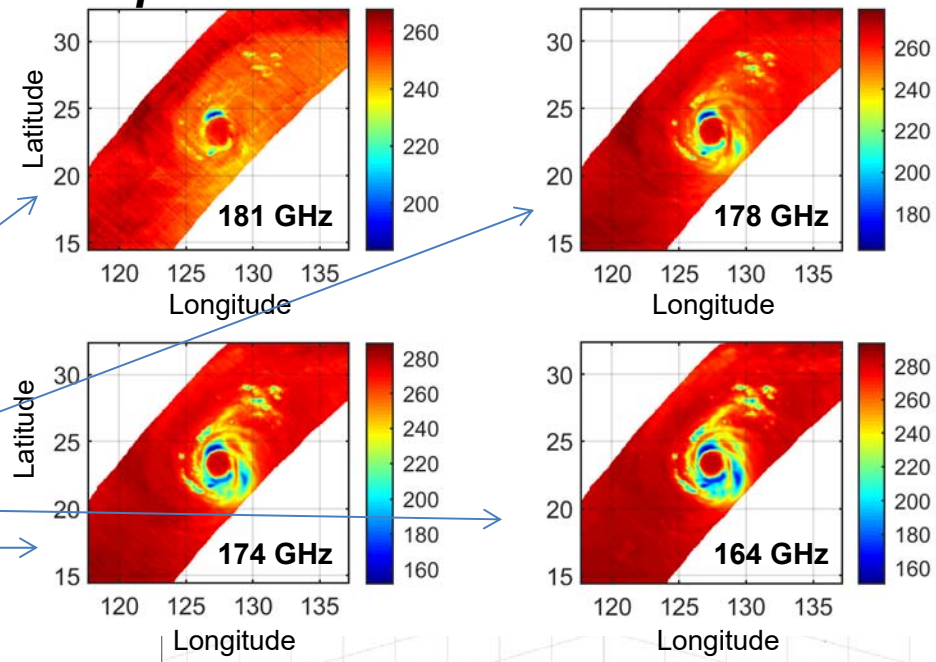


- TEMPEST-D and RainCube overflew Typhoon Trami < 5 minutes apart on September 28, 2018,
- RainCube nadir Ka-band reflectivity shown overlaid on TEMPEST-D 164 GHz brightness temperature illustrating complementary nature of these sensors in constellation for observing precipitation
- Trami observed shortly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

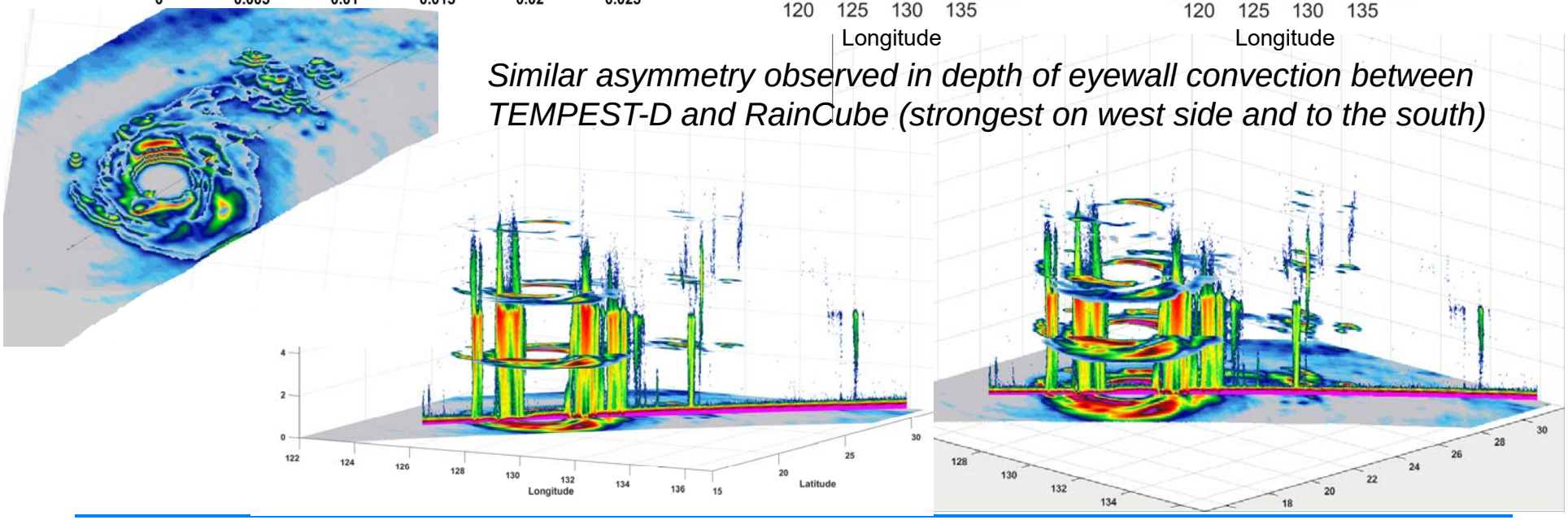


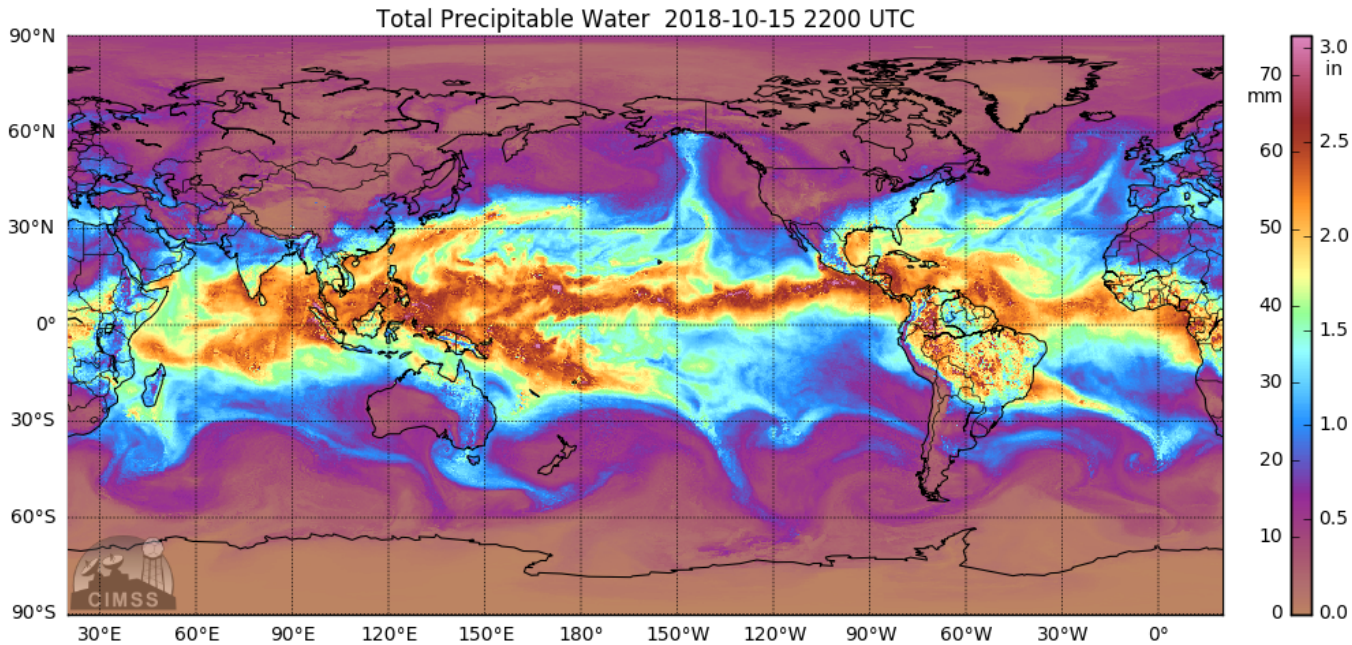
TEMPEST-D Sounding Channels provide 4 levels of vertical resolution to "slice" precipitation and compare with RainCube profile





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

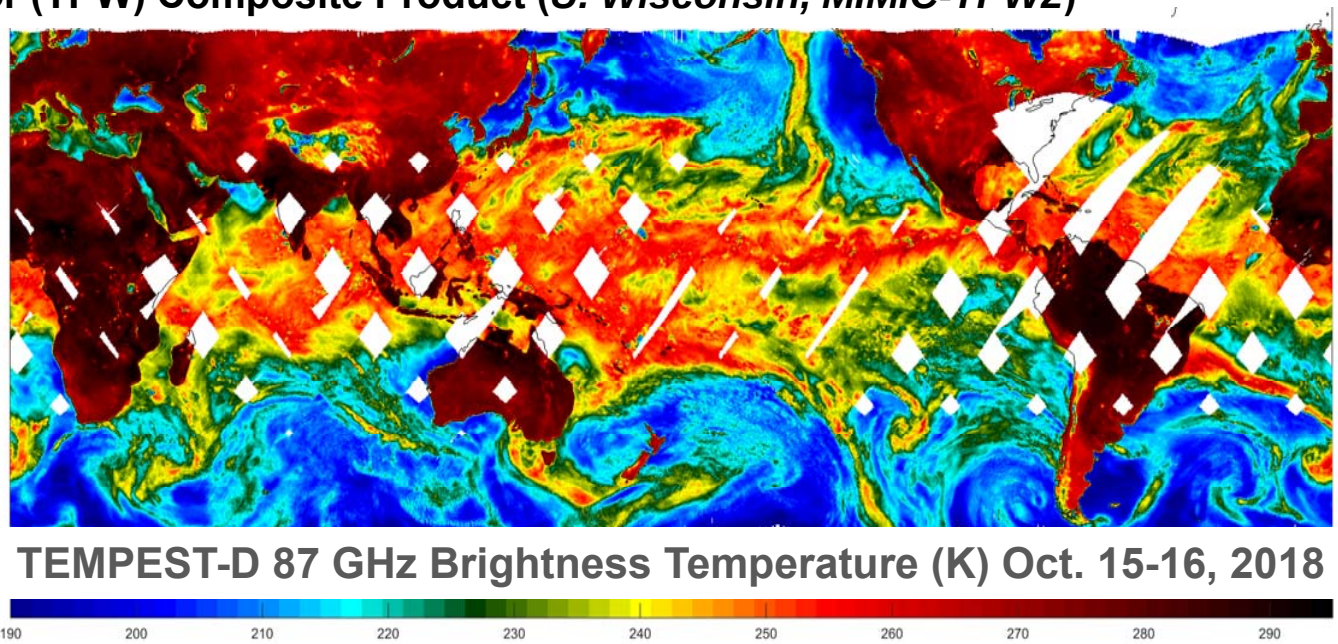




TEMPEST-D data shows high-quality calibration and pointing stability over multiple orbits from a CubeSat platform right out of the box

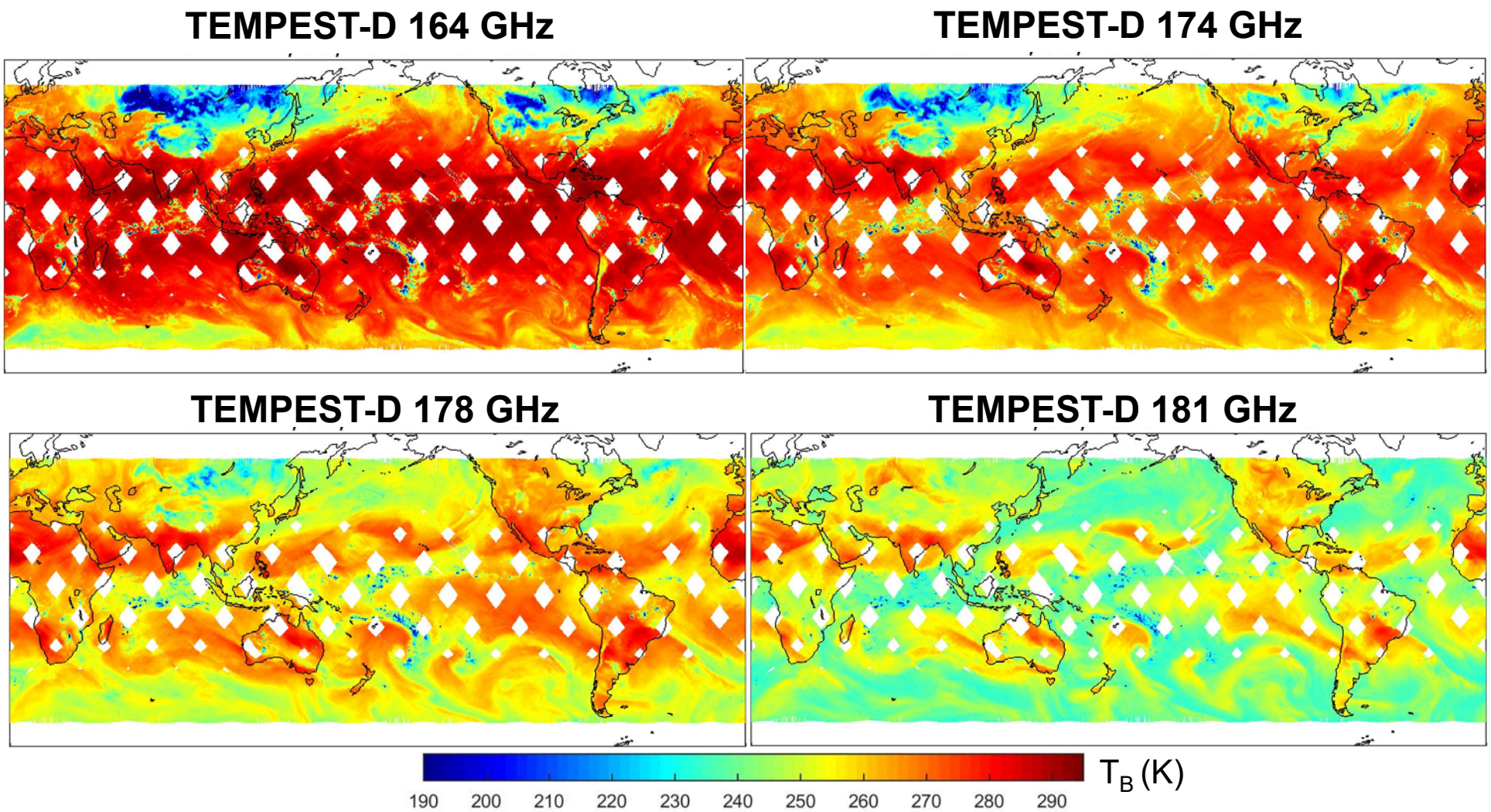
Total Precipitable Water Vapor (TPW) Composite Product (*U. Wisconsin, MIMIC-TPW2*)

The 87 GHz channel is primarily sensitive to integrated water vapor and therefore correlates well with the satellite-derived TPW product.



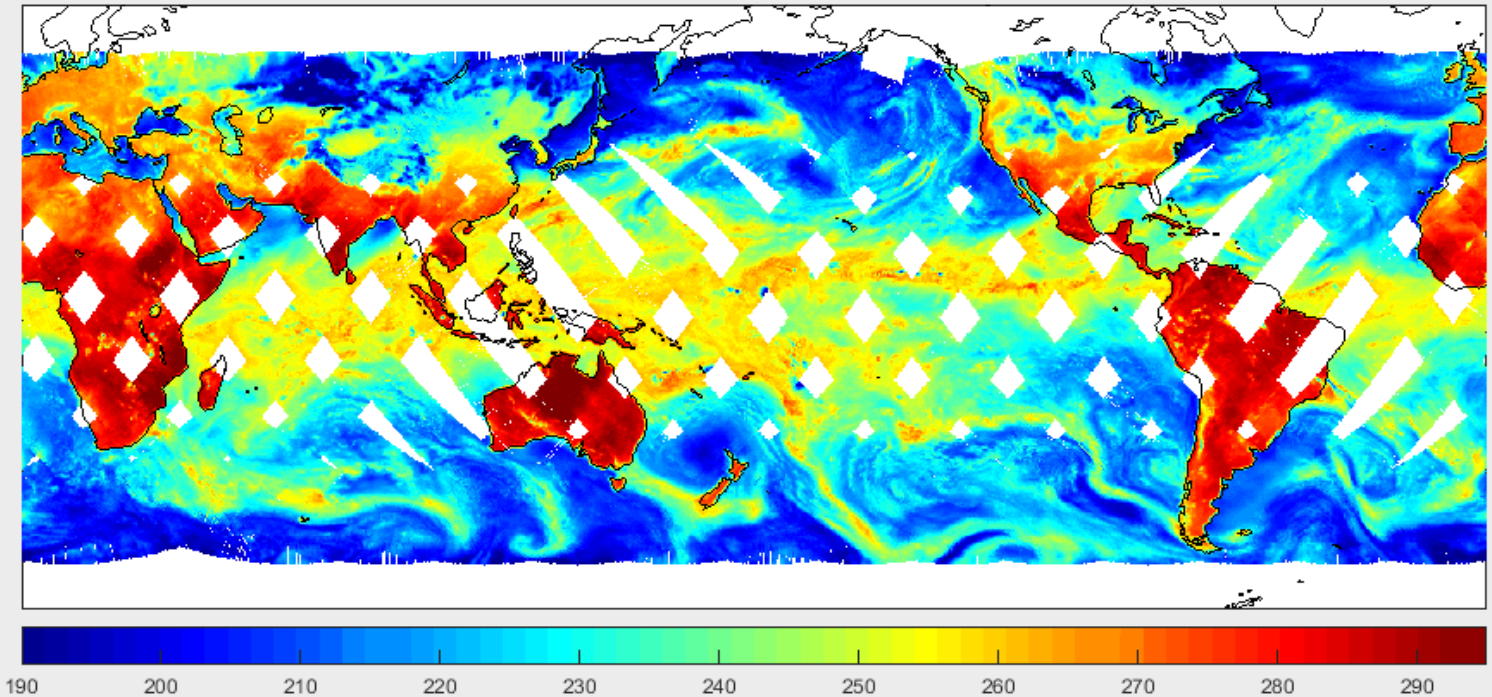
TEMPEST-D 87 GHz Brightness Temperature (K) Oct. 15-16, 2018

TEMPEST-D Brightness Temperatures, Dec. 9, 2018
Water Sounding Channels near 183 GHz

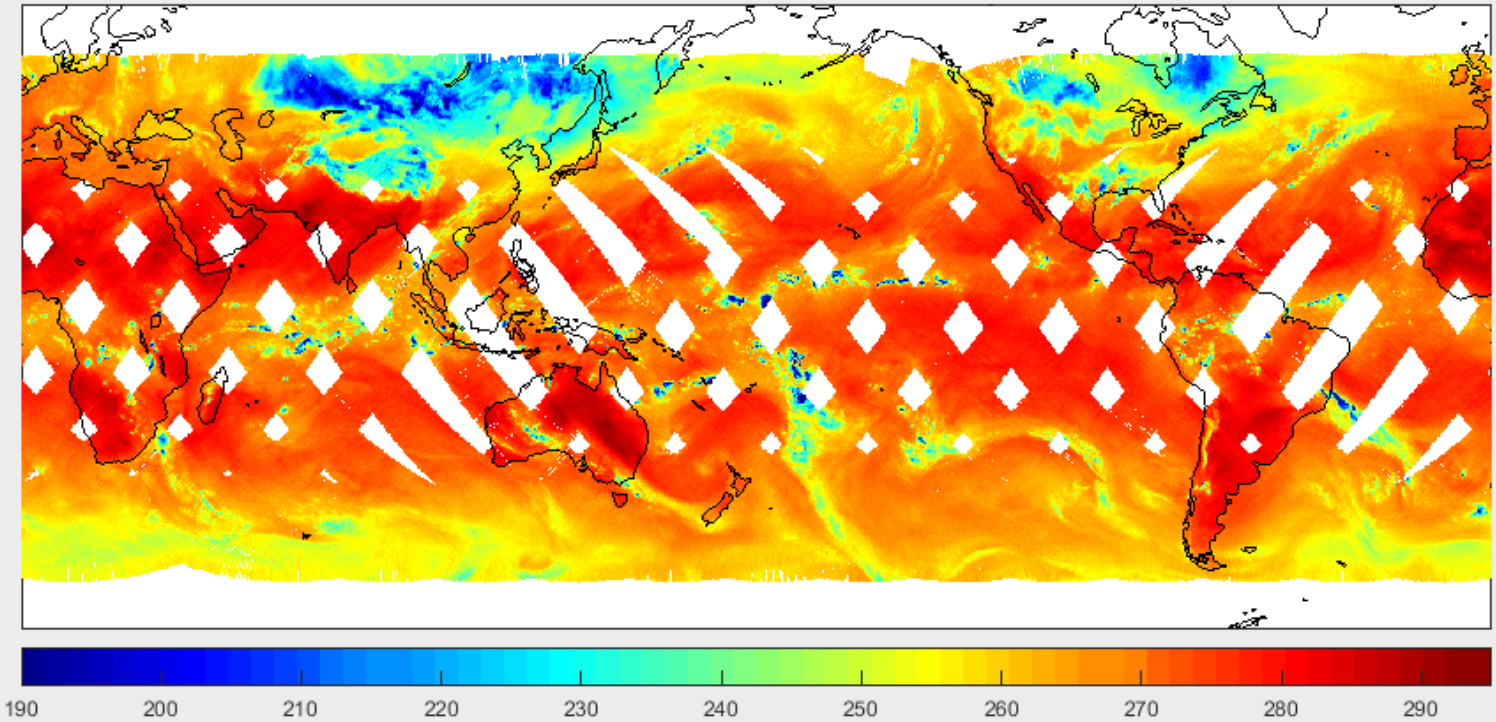


Sounding channels are sensitive to water vapor at increasing altitudes in the atmosphere up to 10 km. A band of convection in the inter-tropical convergence zone (ITCZ) is clearly evident near the equator.

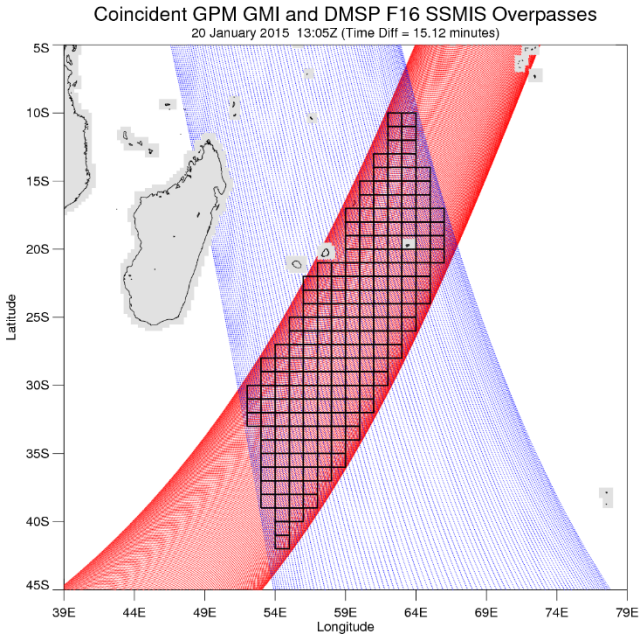
TEMPEST-D 87-GHz Brightness Temperatures December 8-12, 2018

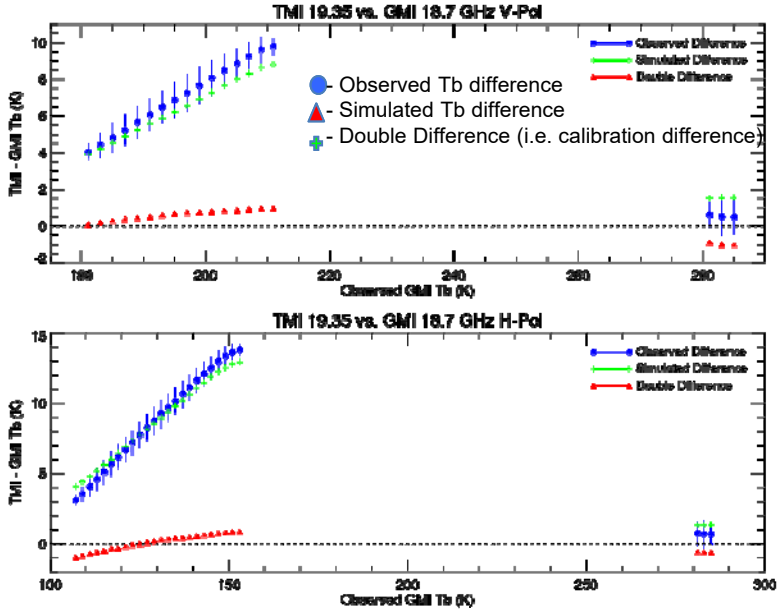


TEMPEST-D 174-GHz Brightness Temperatures December 8-12, 2018



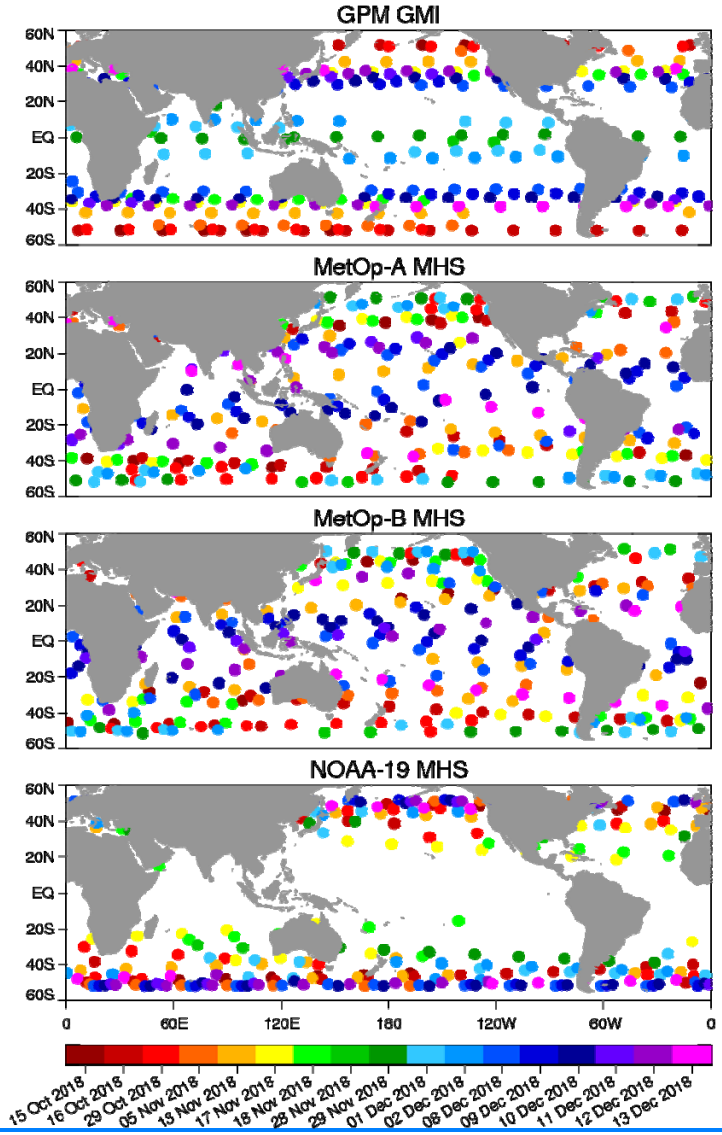
Comparison of TEMPEST-D with Reference Sensors: Double Difference Approach

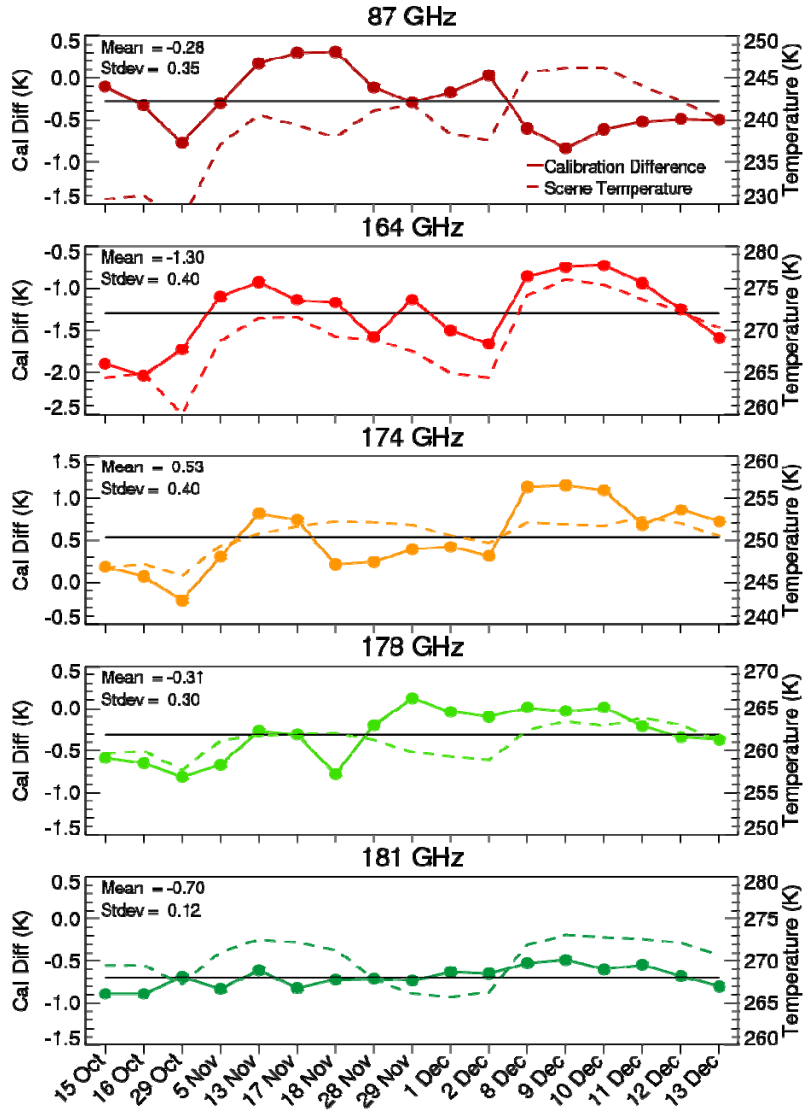




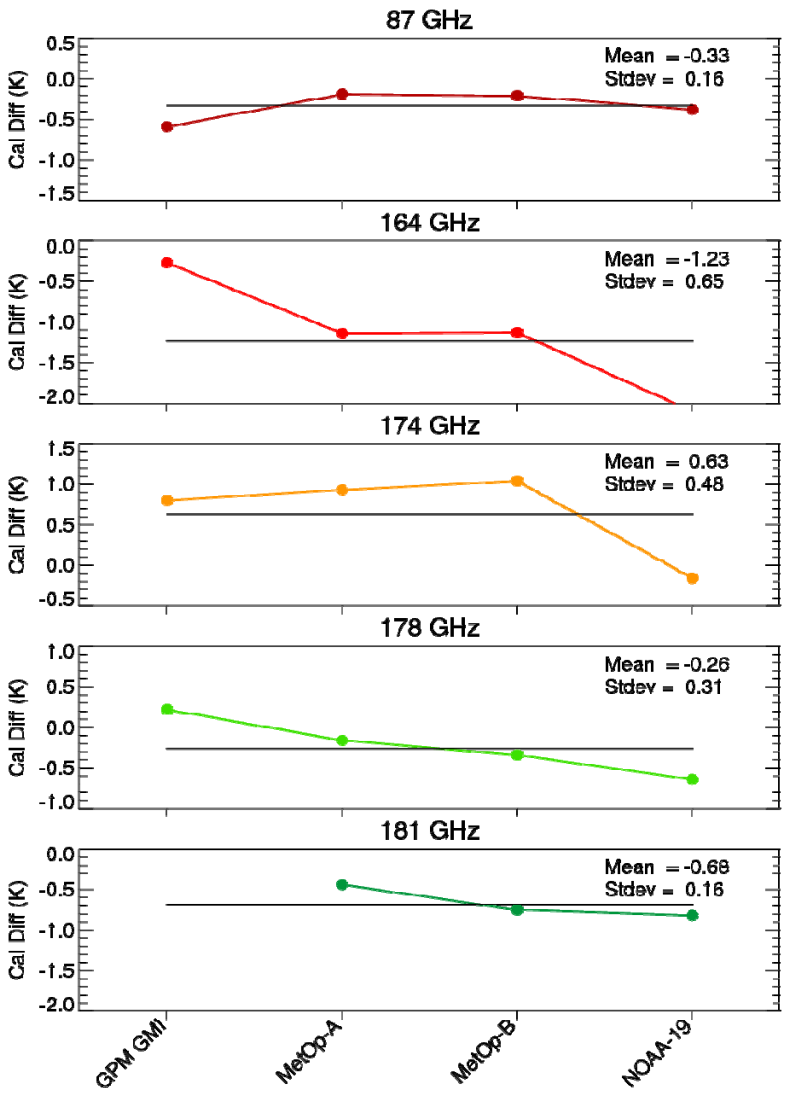
- Observations between TEMPEST-D and the reference sensors are matched in space and time.
- Forward model radiative transfer simulations are performed using geophysical parameters from NASA GEOS5 global data assimilation model for coincident pixel observations, thereby accounting for differences in channel frequencies, spectral response, polarization and incidence angle.
- Differences between observed and simulated (i.e. expected) differences are averaged over 1°x1° boxes and screened for land, precipitation, significant inhomogeneity, etc.

Comparison of TEMPEST-D with Reference Sensors from NASA, NOAA & EUMETSAT





Comparison of TEMPEST-D with Reference Sensors from NASA, NOAA & EUMETSAT



- Estimates of sensor calibration differences using double difference technique for coincident observations between TEMPEST-D and reference sensors.
- Although results are based on only ~0.5 months of data, except for the 164 GHz channel, the composite differences (i.e. 4 reference sensors) are <1 K, well below the TEMPEST-D requirement of 4 K for absolute calibration.
- Lower values for NOAA-19 for 164 and 174 GHz channels likely due to high-latitude coincident observations and sensitivity to ocean surface.
- TEMPEST-D calibration work is ongoing, including analysis of on-orbit data from a pitch maneuver. These results, however, **indicate a very well calibrated and stable radiometer with very low noise, rivaling that of much larger and more expensive operational instruments.**

Reference Sensor	87 GHz	164 GHz	174 GHz	178 GHz	181 GHz
GPM GMI	-0.59	-0.27	0.80	0.22	N/A
MetOp-A MHS	-0.19	-1.14	0.93	-0.16	-0.44
MetOp-B MHS	-0.21	-1.13	1.04	-0.34	-0.75
NOAA-19 MHS	-0.38	-2.10	-0.16	-0.64	-0.82
Mean Difference	**-0.33**	**-1.23**	**0.63**	**-0.26**	**-0.68**
Standard Dev.	**0.16**	**0.65**	**0.48**	**0.31**	**0.16**

Summary

- TEMPEST-D mission has demonstrated potential for a train of 6U CubeSats with TEMPEST instruments spaced 3-4 minutes apart to perform first *global temporally-resolved measurements of cloud and precipitation processes*.
- Reduced the risk, cost and development time for future science missions using TEMPEST CubeSats.
- Demonstrated very well-calibrated and stable radiometer on a 6U CubeSat.
- Raised TRL of the low-noise, low-mass, low-power TEMPEST mm-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 180 days to date.
- Demonstrated cross-calibration of TEMPEST radiometers with GPM Microwave Imager and MHS on NOAA and EUMETSAT with 1 K or better accuracy and ~0.5 K or better precision.
- Demonstrated rapid development of a 6U CubeSat for Earth science measurements; 2.5 years from project start to delivery for launch integration.


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