# Temporal Experiment for Storms and Tropical Systems Technology Demonstration (TEMPEST-D) to Enable Temporally-Resolved Observations of Clouds and Precipitation on a Global Basis using 6U-Class Satellite Constellations

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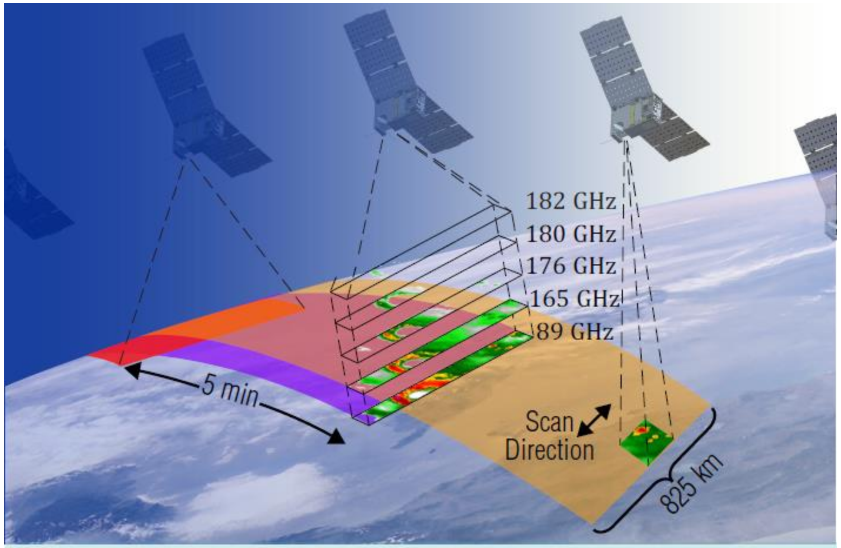
# Temporal Experiment for Storms and Tropical Systems (TEMPEST)

**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?*
  - Provides global, *temporally-resolved* observations of cloud and precipitation *processes* using a 6U-Class satellite constellation
  - Constrains weather and climate models using millimeter-wave radiometer observations
- TEMPEST-D technology demonstration began in August 2015 as a partnership among CSU, JPL and BCT.
  - Delivered 6U flight system with integrated payload to NanoRacks for launch integration on March 22, 2018.
- NASA CubeSat Launch Initiative (CSLI)
- Launched by Orbital ATK on CRS-9 from NASA Wallops to ISS on May 21, 2018
- Planned deployment into orbit by NanoRacks from JEM in July/August 2018



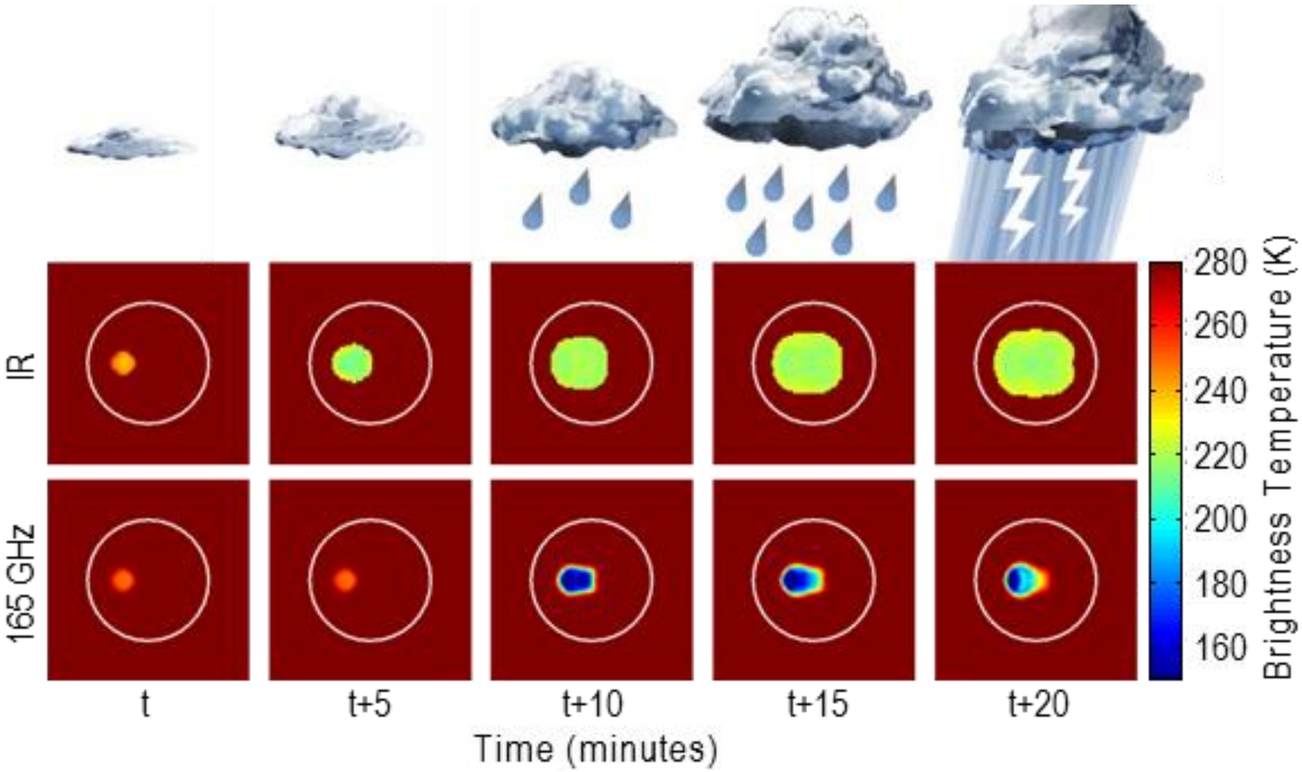

5 identical 6U small sats, each with an identical 5-channel radiometer, flying 5 minutes apart

# Observations of Transition from Clouds to Precipitation

Temporal evolution of convective system

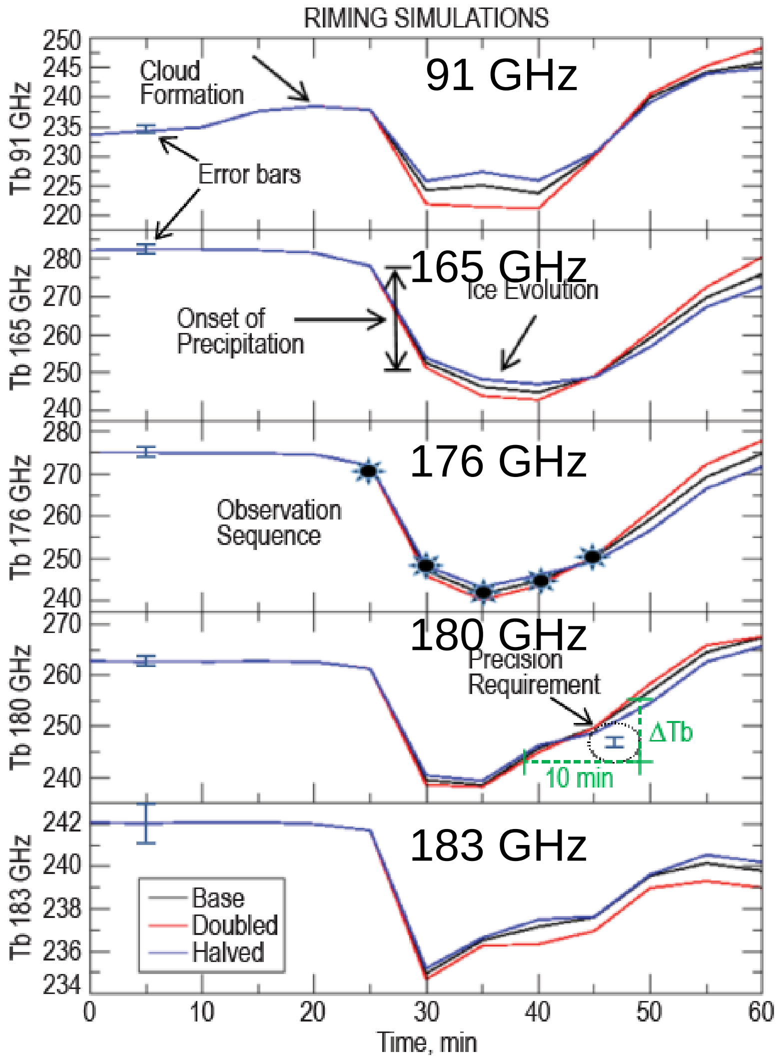
Infrared Brightness Temperature

Millimeter-wave Brightness Temperature, both from model



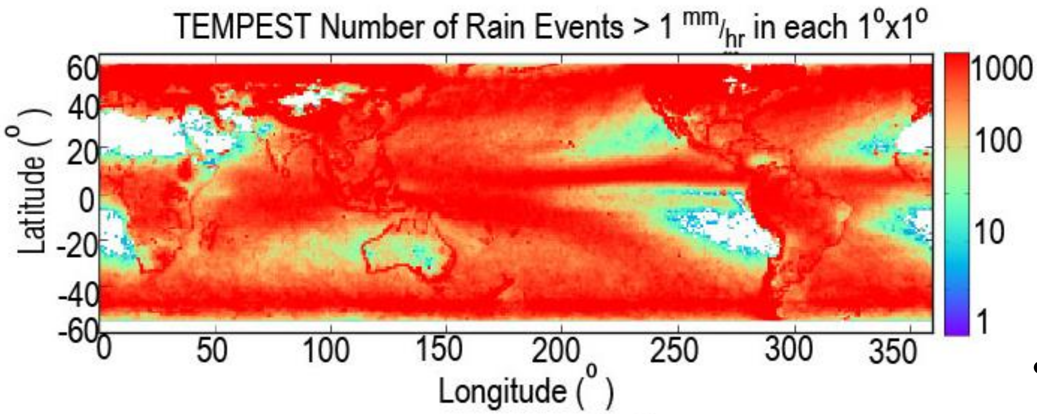

- Infrared brightness temperatures (middle row, available from GEO) show cloud top temperatures, locations and morphology.
- Onset of precipitation clearly detected at millimeter-wave frequencies on TEMPEST constellation, including 165 GHz (bottom row).
- TEMPEST minimum spatial resolution of 25 km is shown (circles).

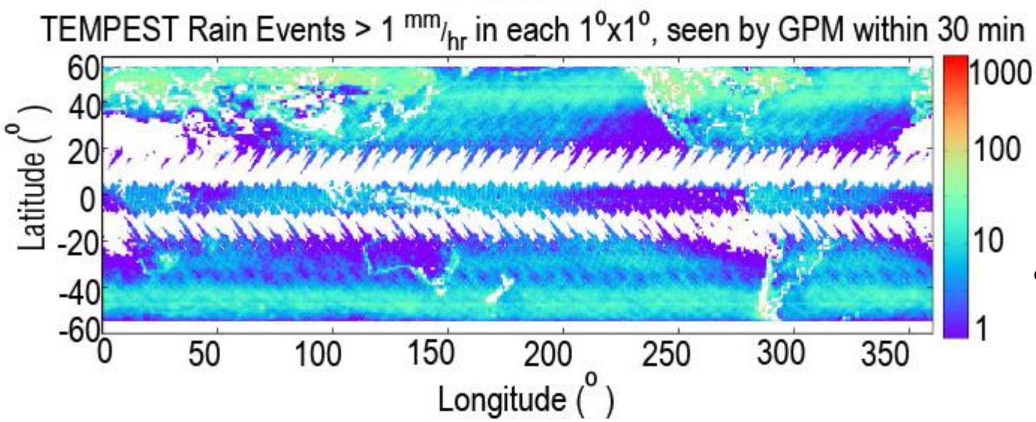
# Temporal Development of Ice in Cloud-Scale Models




- Modeled brightness temperatures at the five TEMPEST frequencies with 25-km spatial resolution
- Simulations compare different rates of supercooled water droplets collecting on ice crystals (riming efficiency).
- Rate varies from baseline (black) to twice (red) and half (blue).
- Measurable difference between curves is 4 K or greater in 5 minutes at onset of ice formation. Instrument precision requirement is 1 K in 5 minutes.
- Ice remaining in clouds after precipitation has substantial effects on climate. Residual ice can be compared to W-band radar observations from NASA's CloudSat or ESA's EarthCARE.

# Global Time-Resolved Observations of Cloud & Precipitation Processes




- TEMPEST mission observations will be complementary to NASA CYGNSS and NASA TROPICS Earth Venture missions.

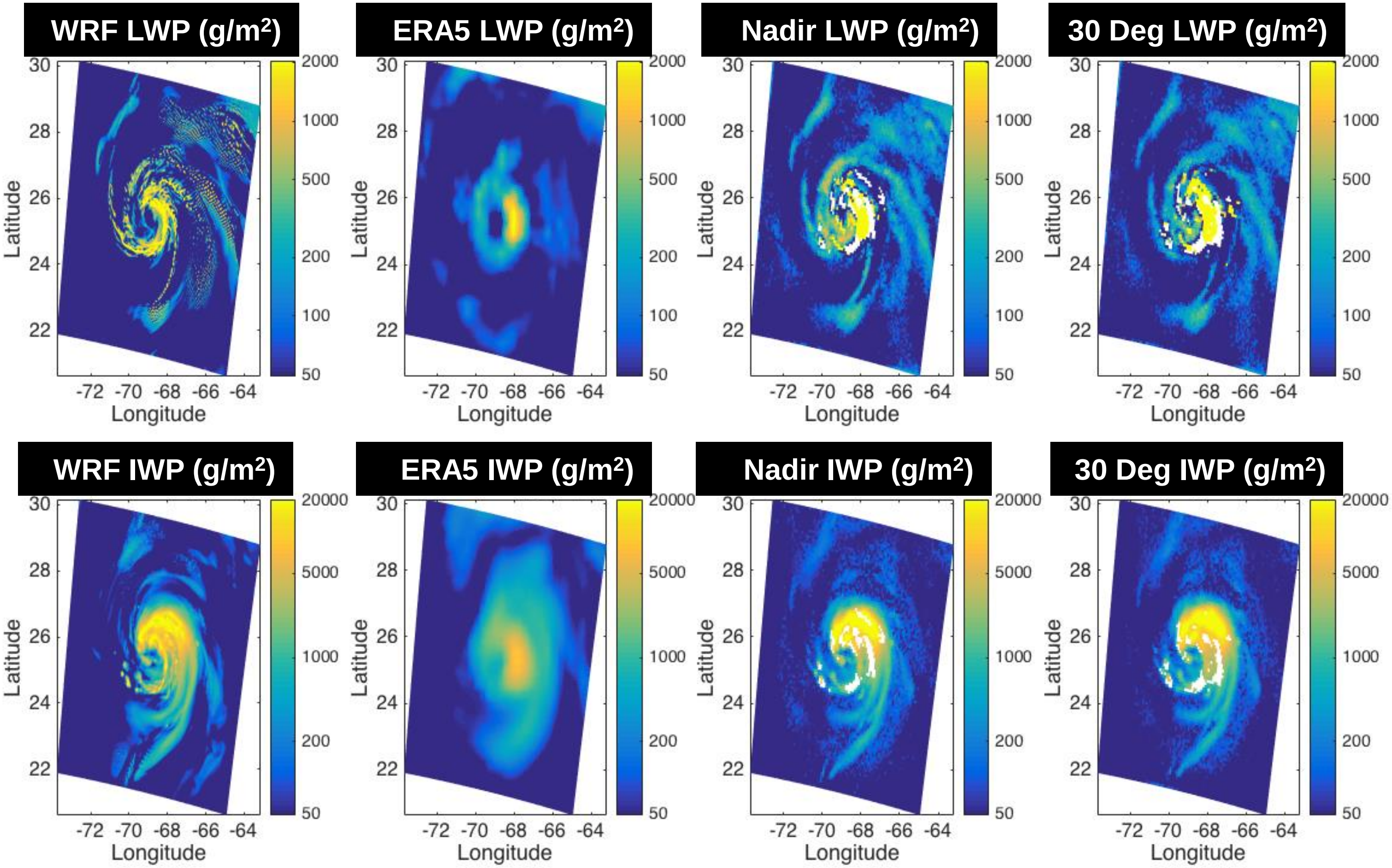
- During a future one-year mission, TEMPEST constellation could make more than 3,000,000 time-resolved observations of precipitation (> 1 mm/hr), including 100,000+ deep-convection events
- Could perform more than 50,000 precipitation observations coincident (within 30 minutes) with NASA/JAXA Global Precipitation Mission (GPM) core satellite
- Assumes nominal TEMPEST orbit for deployment from ISS at 400-km altitude and 51.6° inclination.
- Precipitation estimates from AMSR-E satellite radiometer data with oceanic observations only.

# Simulated Observations of TEMPEST Constellation over Hurricane Gonzalo

**"Truth"** **A-priori** **Retrievals**

**Cloud Liquid**

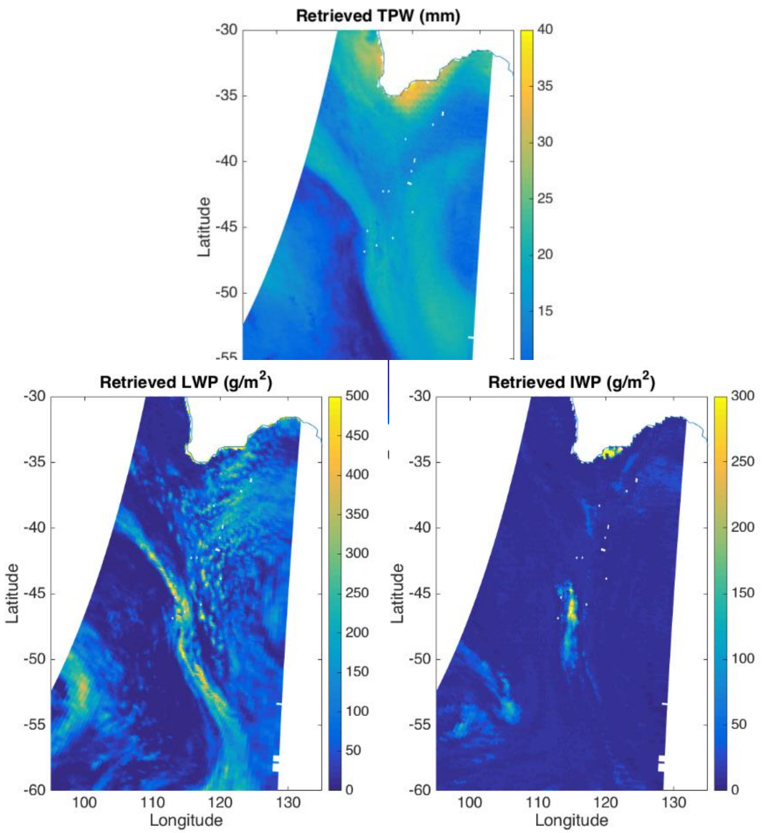
**Cloud Ice**




From WRF model of Hurricane Gonzalo in Oct. 2014

# CSU 1D-Var Retrieval for TEMPEST-D and Cross-Calibration with MHS

- Builds on CSU 1D-Var (Duncan and Kummerow, 2016); observed brightness temperatures balanced against a-priori knowledge to find most likely state vector
- Retrieves water vapor profile (3 EOFs) and cloud liquid water path (LWP), with option to retrieve cloud ice water path (IWP)
- View-angle-dependent measurement error covariance matrix ($\mathbf{S_y}$) greatly reduces biases near the edge of the swath
- Applicable to both TEMPEST-D risk reduction and improved TEMPEST-D vs. MHS single and double difference validation activities.




1D-Var retrieval of total precipitable water, liquid water path, and ice water path from the Microwave Humidity Sounder (MHS)

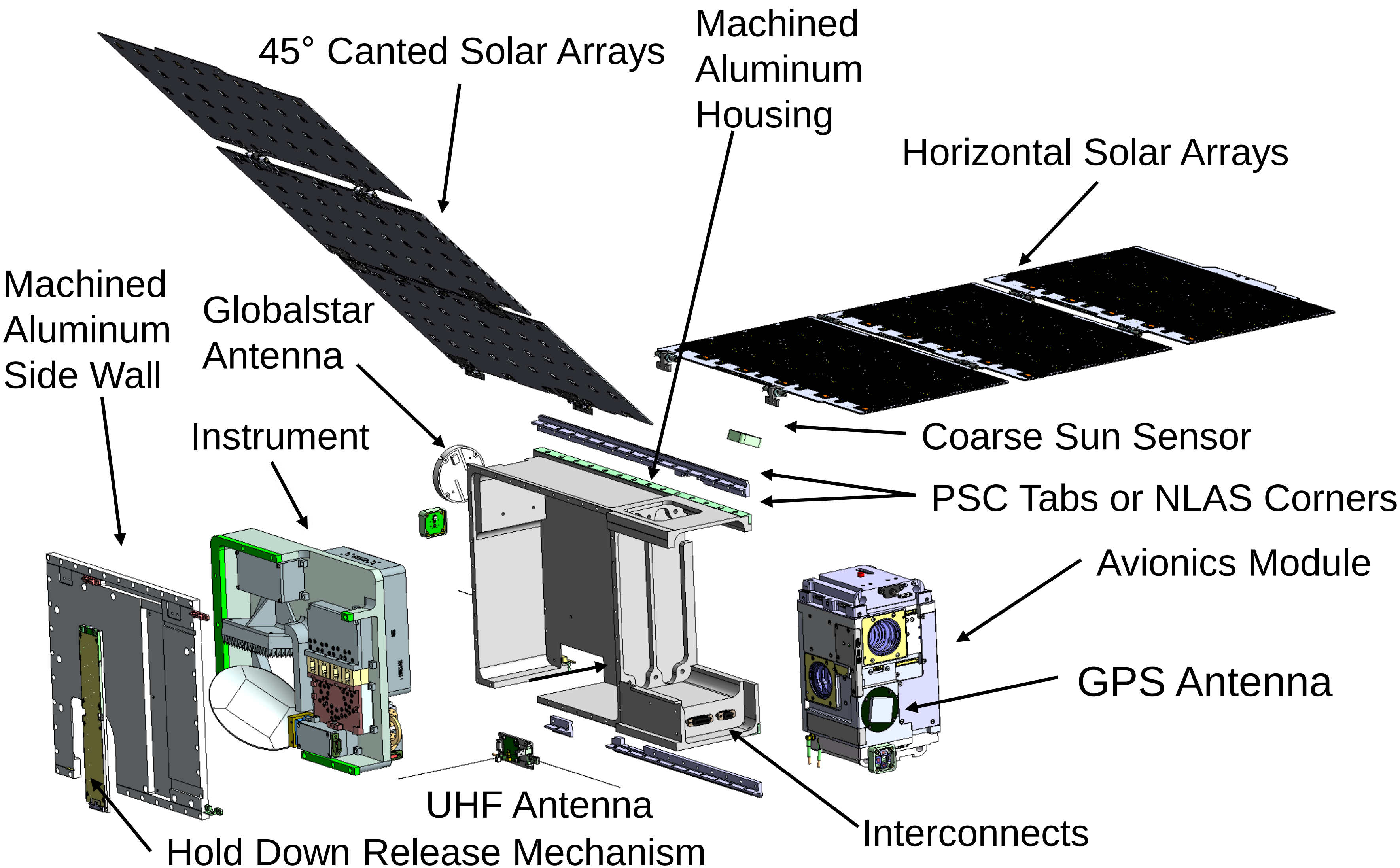
# TEMPEST-D Demonstration: Motivation and Objectives

- Demonstrate capability of 6U CubeSats to contribute to NASA Earth Science measurements in a 90-day technology demonstration mission
- Reduce **risk**, cost and development time for future measurements of Earth science processes using CubeSat constellations
- Raise the technology readiness level (TRL) of the TEMPEST mm-wave radiometer instrument from 5 to 9 (scanning reflector to 7)
- Provides the first in-space demonstration of a millimeter-wave radiometer based on an InP HEMT low-noise amplifier front-end (LNA) for Earth Science measurements.

**Success Criteria:**

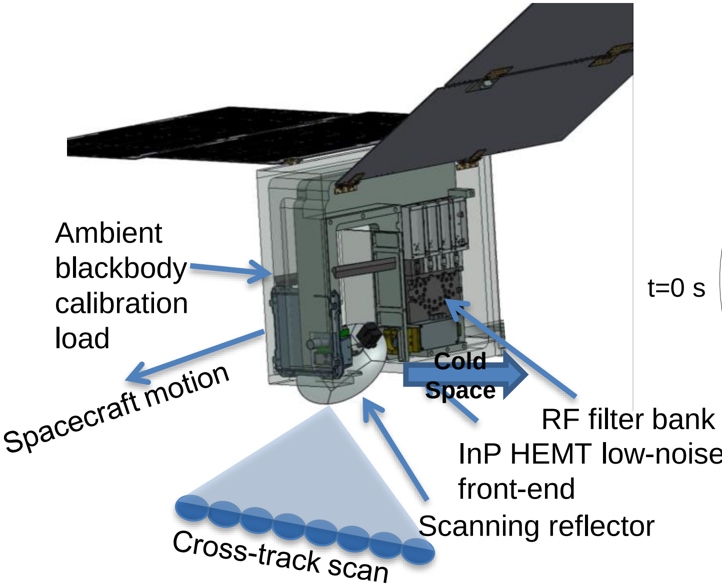
- Demonstrate feasibility of differential drag maneuvers to achieve required time separation of 6U-Class satellites in same orbital plane
- Demonstrate cross-calibration between TEMPEST mm-wave radiometers and NASA/JAXA Global Precipitation Mission Microwave Imager and/or Microwave Humidity Sounder (MHS, on two NOAA satellites and two ESA/EUMETSAT satellites) with 2 K precision and 4 K accuracy.

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

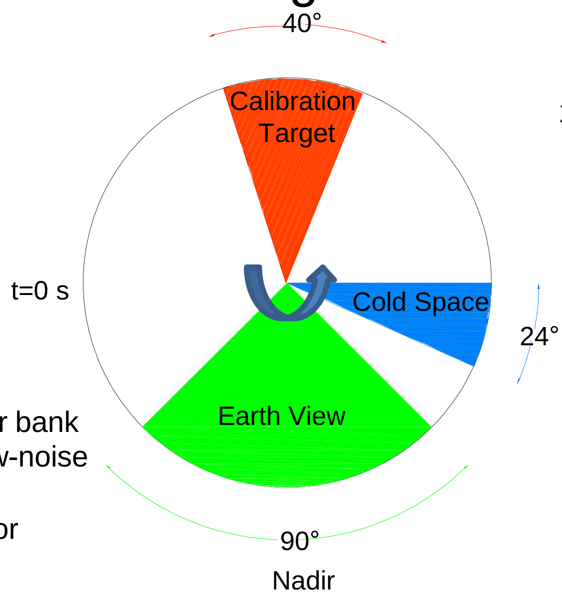


# TEMPEST-D Instrument: Radiometer Calibration

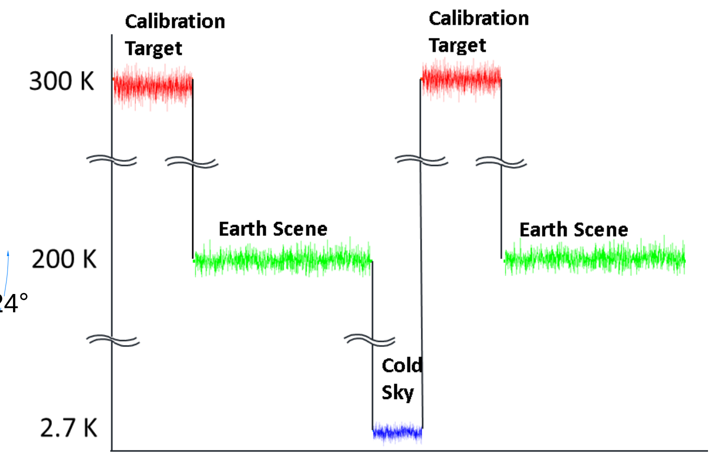
TEMPEST-D Instrument




Observing Profile

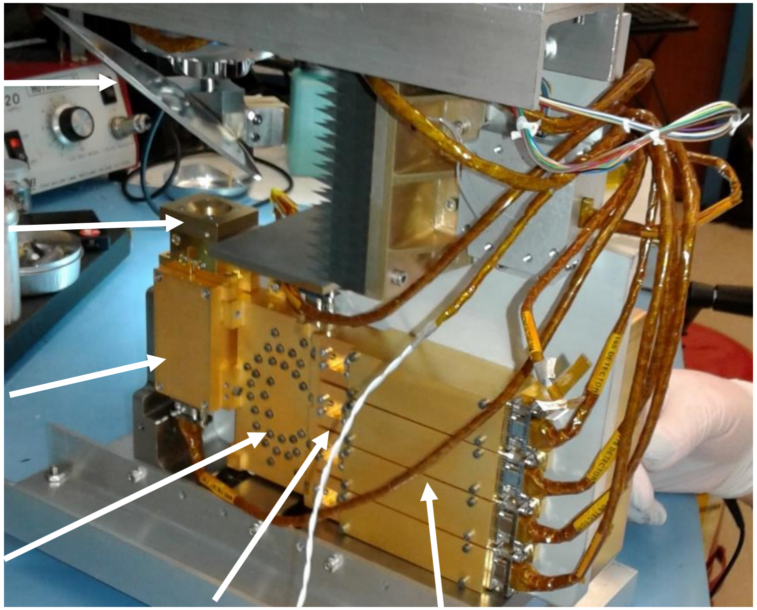


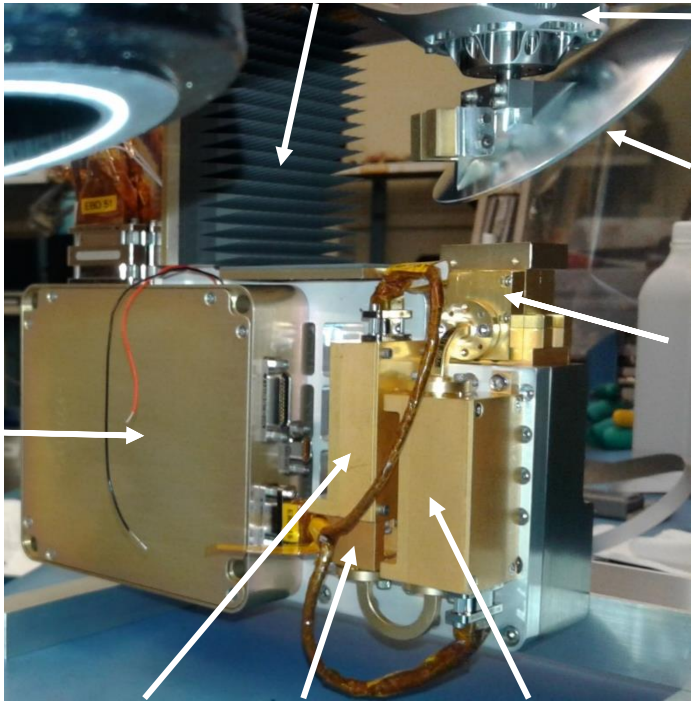

Time Series of Output Data



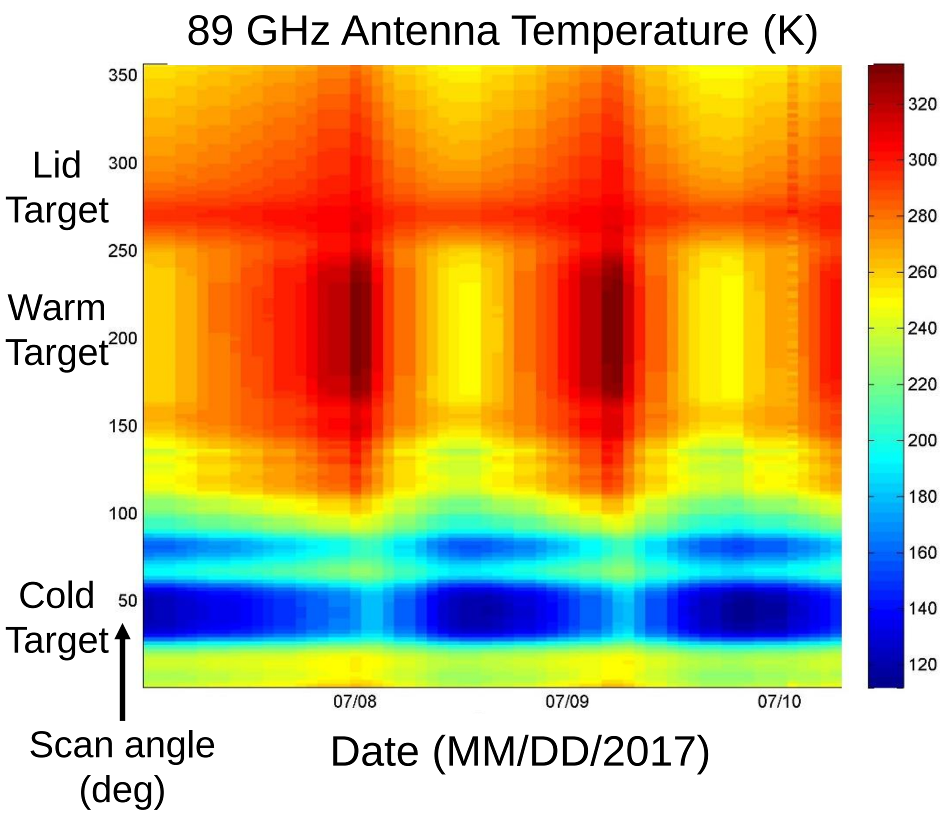

- Five-frequency millimeter-wave radiometer measures Earth scene over ±45° nadir angles, for an 825-km swath width from a nominal orbit altitude of 400 km. Spatial resolution ranges from 13 to 25 km for 89 to 182 GHz.
- TEMPEST-D performs two-point end-to-end calibration every 2 sec. by measuring cosmic microwave background at 2.73 K ("cold sky") and ambient blackbody calibration target each revolution (scanning at 30 RPM).

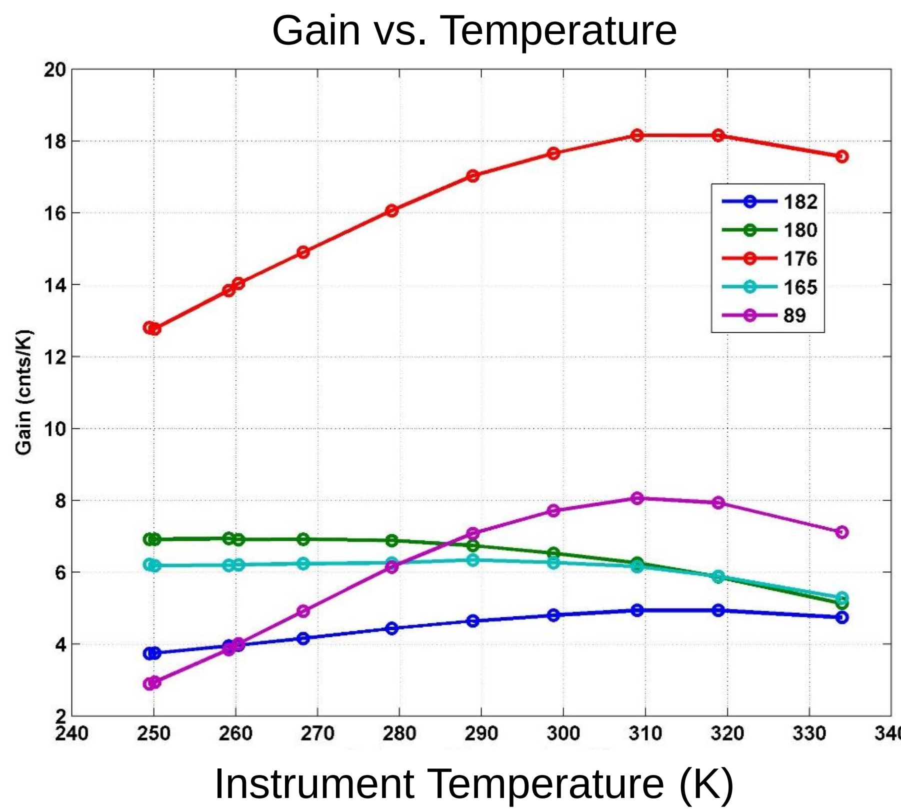
# Flight Model Radiometer Instrument Bench-top Integration at JPL



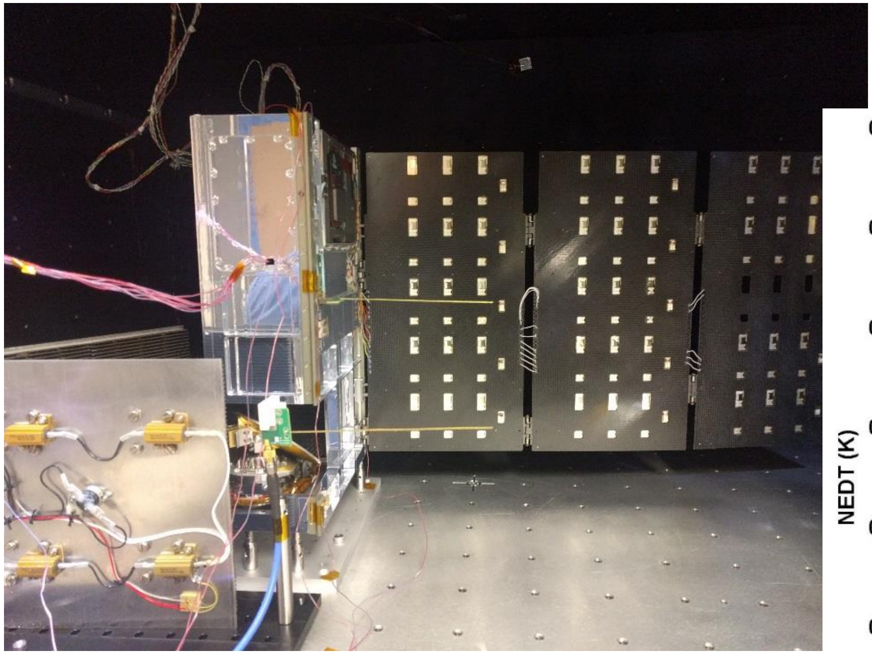
# Thermal Vacuum Testing Results for Flight Instrument (Jul. 2017)



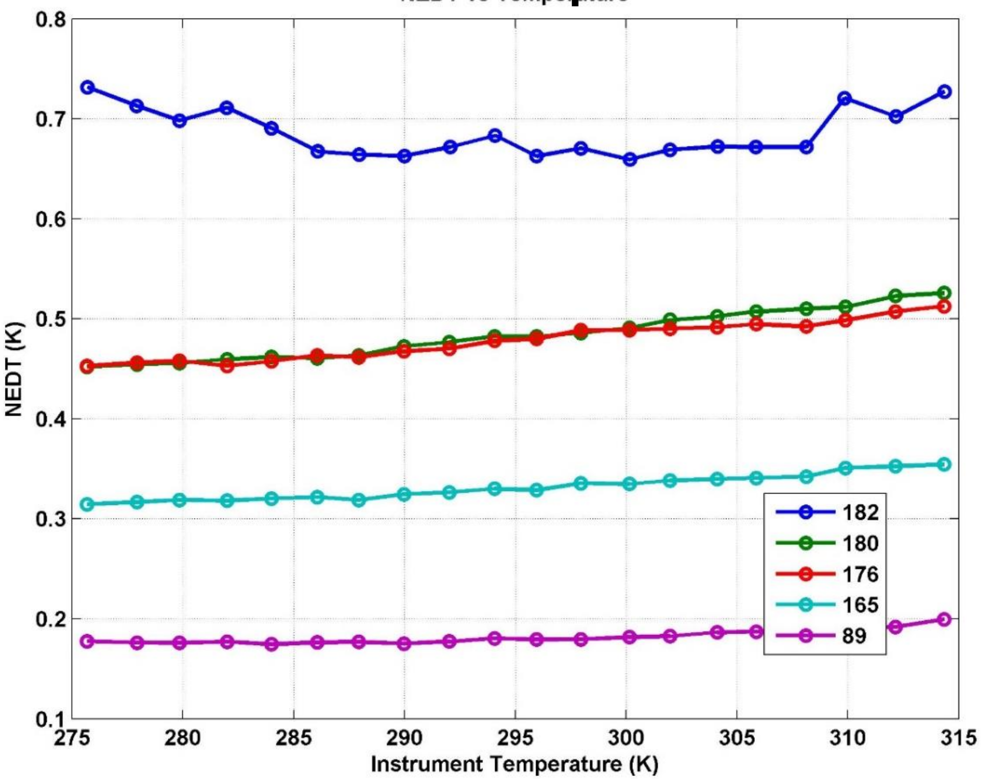




Gain measured while viewing blackbody calibration target at chamber temperature varying from -25°C to +60°C.

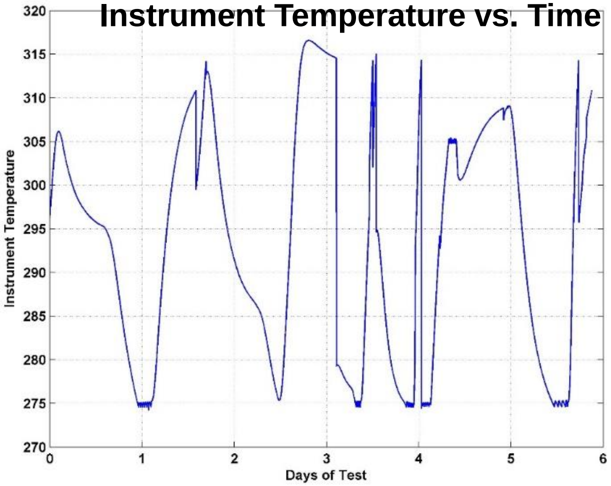
# Instrument Performance during Spacecraft TVac Testing (Jan. 2018)



**Radiometric Resolution vs. Instrument Temperature**




**Instrument Temperature vs. Time**




Measured radiometric resolution values meet total noise requirements of 1.4 K for all five millimeter-wave radiometer channels.

# Radiometer Instrument Technical Resources Summary

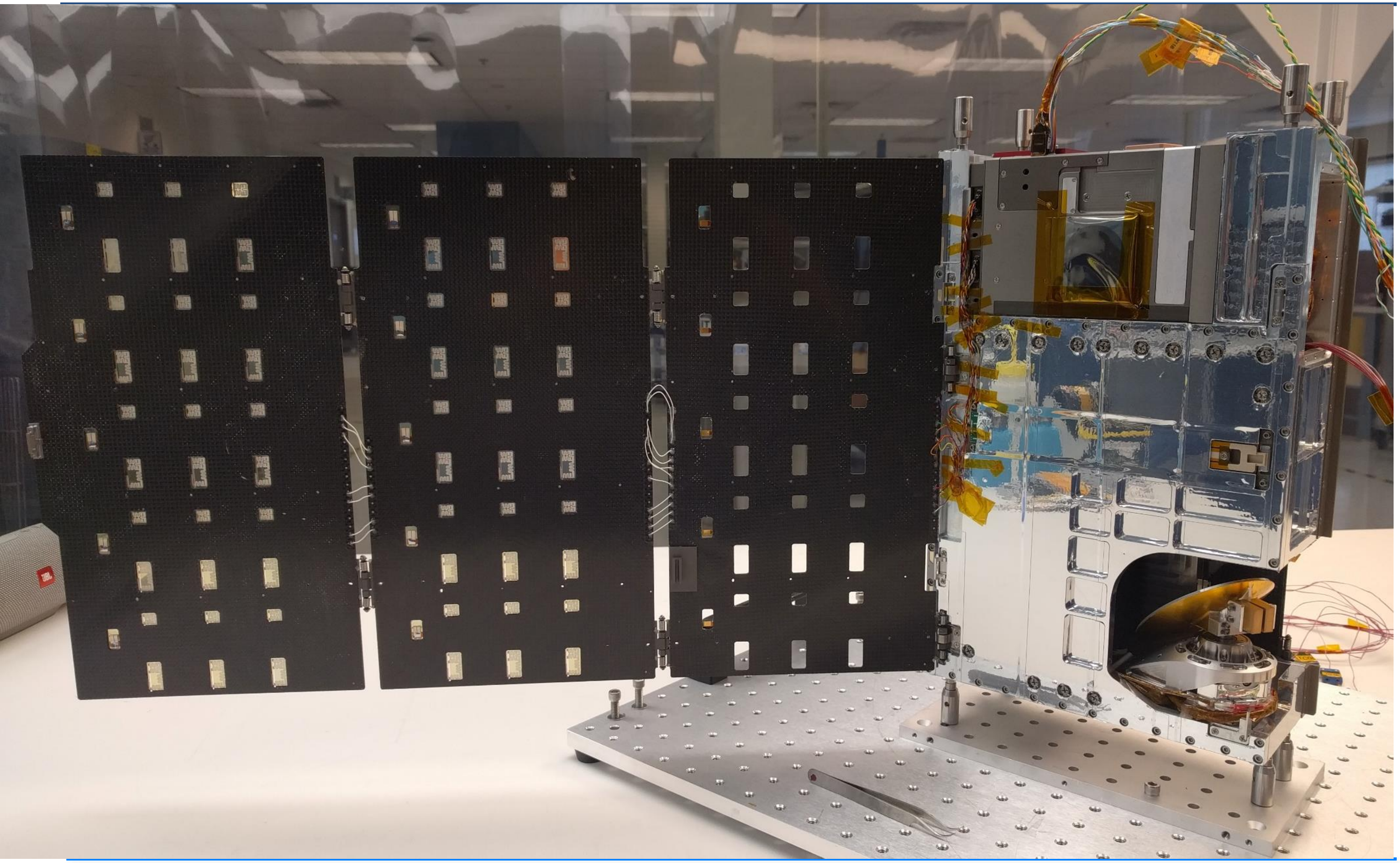
| Resource | CBE | Allocation | Margin (Actual) |
|---|---|---|---|
| Radiometer Mass (kg)* | 3.75 | 4.0 | 6.25% |
| Radiometer Power (W) | 6.0 | 6.5 | 8% |
| Radiometer Data Rate (Kbps)** | 10.3 | 12.3 | 16% |
| Radiometer Precision (K) | 0.4-0.95 | 1.4 | 71-32% |
| Radiometer Accuracy (K) | 3.5 | 4 | 13% |

$$MARGIN = 100 \times \frac{Allocation - CBE}{Allocation}$$

*Change due to titanium standoff replacement with aluminum
**Includes spacecraft state-of-health telemetry

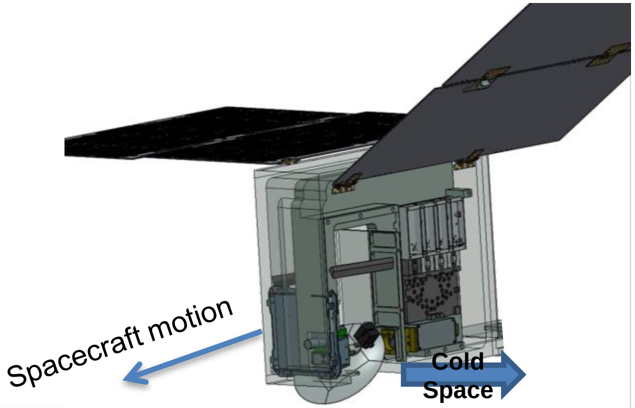
All excess margin can now be released to the spacecraft.

# TEMPEST-D Flight Unit Integrated at BCT (Feb. 2018)



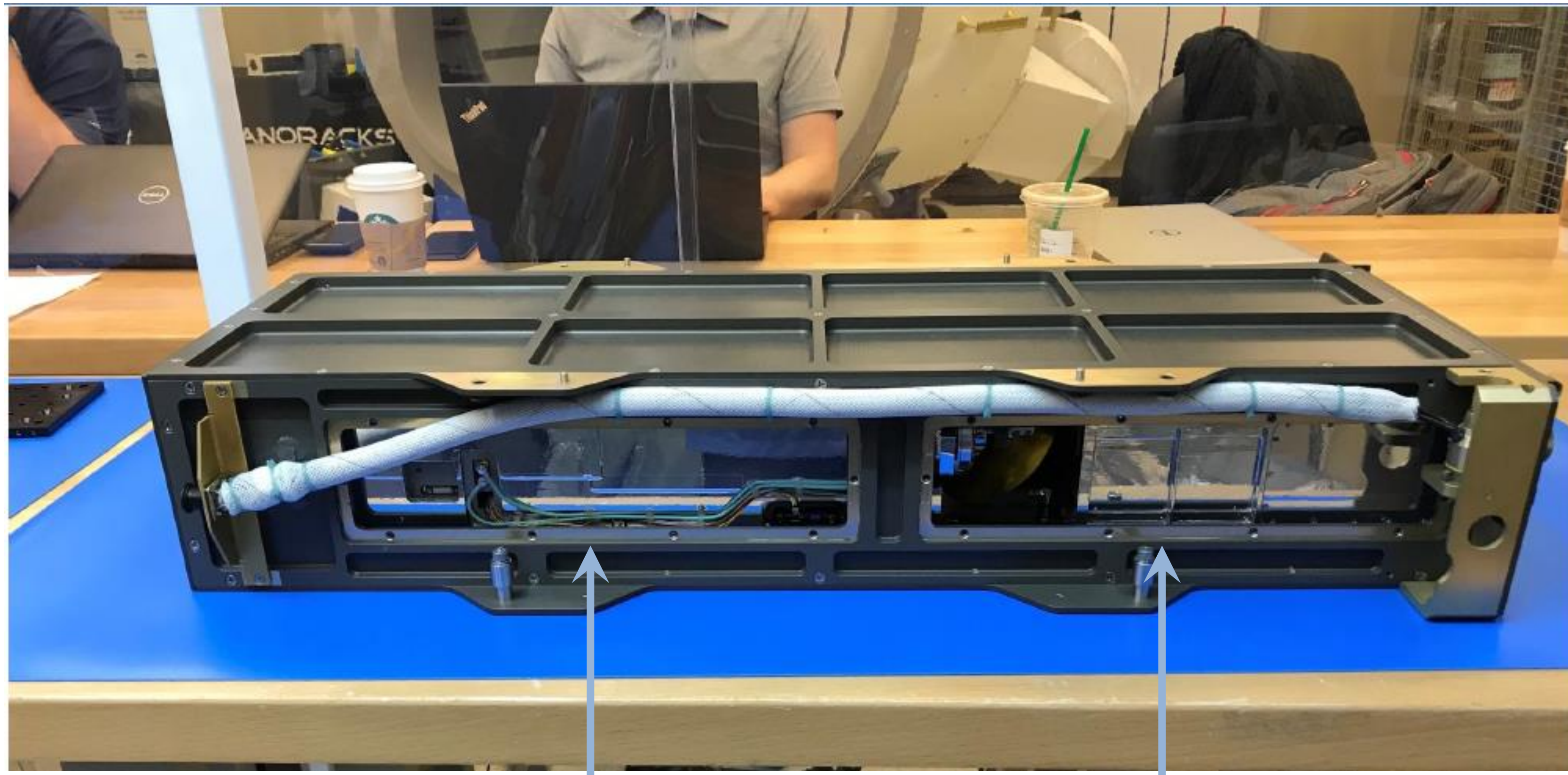
# TEMPEST-D Mission: Recent Milestones

- Ground compatibility testing completed at NASA Wallops on Feb. 16, 2018
- Workmanship vibration penalty testing completed on Feb 22, 2018.
- Thermal balance penalty testing completed on Mar. 2, 2018.
- FCC granted radio communication license on Mar. 8, 2018
  - Primary Comms: Cadet-U to NASA Wallops, UHF ~450 MHz Uplink and ~470 MHz Downlink
  - Secondary Comms: S-band Globalstar to MEO: ~1.6 GHz
- Successfully integrated into NanoRacks 6U Deployer along with CubeRRT on Mar. 22, 2018.
- Launched to ISS on OA-9 on May 21, 2018




NASA Wallops 18-m dish

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




**CubeRRT** **TEMPEST-D**

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


Photo Credit: NASA

# Orbital ATK Cygnus Arrived at ISS on May 24, 2018

Photo Credit: NASA

# Summary

- TEMPEST-D mission to demonstrate capability of 6U CubeSats to perform global temporally-resolved observations of cloud and precipitation *processes*
- Reduces risk, cost and development time for future CubeSat constellation missions to perform repeat-pass radiometry to measure temporal signatures of atmospheric processes
- Provides first in-space technology demonstration of a millimeter-wave radiometer based on an InP HEMT low-noise amplifier front-end for Earth Science measurements
- Demonstrates feasibility of differential drag maneuvers to achieve required time separation of 6U CubeSats in the same orbital plane
- Demonstrates cross-calibration of TEMPEST radiometers with NASA/JAXA GPM Microwave Imager and/or MHS with 2 K precision and 4 K accuracy
- Demonstrates capability for rapid development of CubeSats for Earth science, about 2.5 years from project start to delivery for launch integration
- Launched on Orbital ATK CRS-9 from NASA Wallops to ISS on May 21, 2018
- Planned for deployment into orbit from ISS by NanoRacks in July/Aug. 2018


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