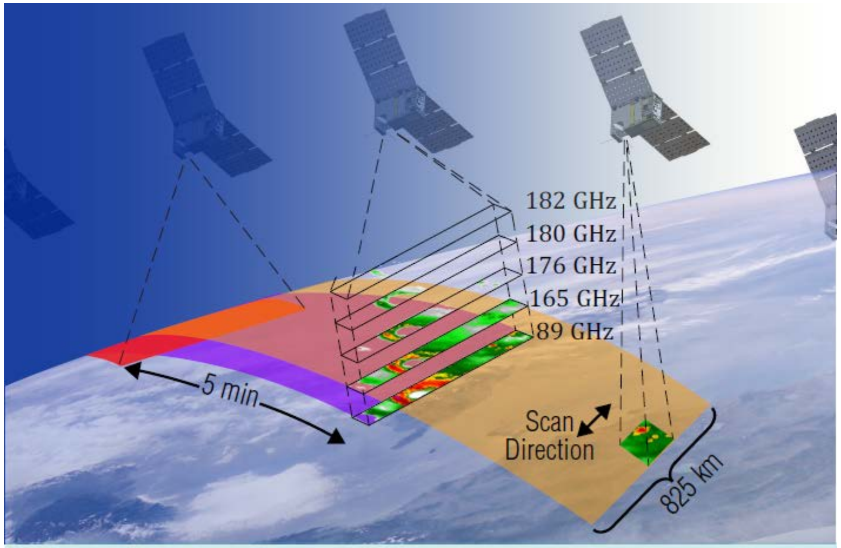
Temporal Experiment for Storms and Tropical Systems Technology Demonstration (TEMPEST-D) Mission: Enabling Time-Resolved Cloud and Precipitation Observations from 6U-Class Satellite Constellations

Steven C. Reising[1], Todd C. Gaier[2], Christian D. Kummerow[1], Sharmila Padmanabhan[2], Boon H. Lim[2], Cate Heneghan[2], Wesley Berg[1], V. Chandrasekar[1], Jonathan P. Olson[1], Shannon T. Brown[2], John Carvo[3] and Matt Pallas[3]

[1]Colorado State University, Fort Collins, CO
[2]NASA Caltech/Jet Propulsion Laboratory, Pasadena, CA
[3]Blue Canyon Technologies, Boulder, CO

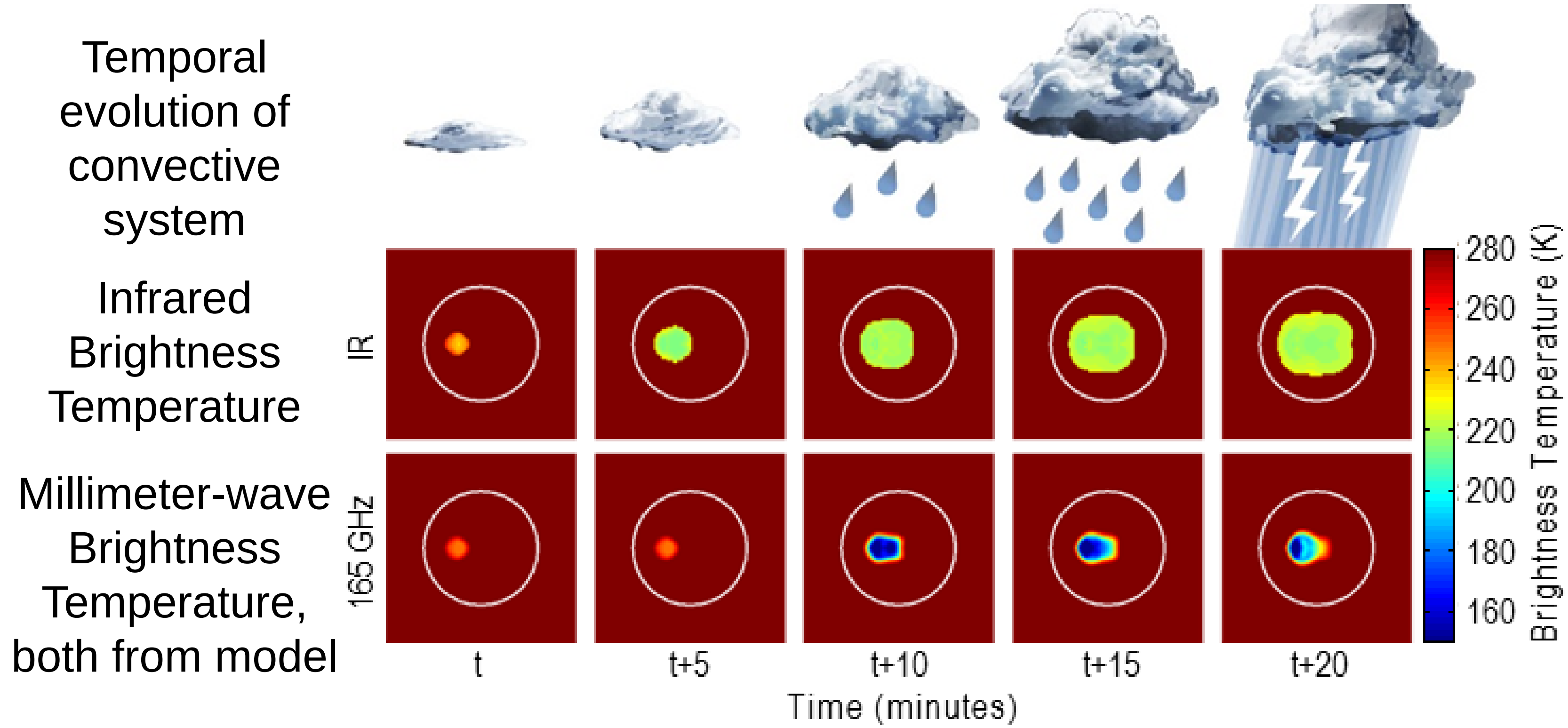
Temporal Experiment for Storms and Tropical Systems (TEMPEST)

- TEMPEST was proposed to NASA Earth Venture Instrument-2 in Nov. 2013.
  - Low-risk, high-margin approach to use 6U-Class satellites (6U CubeSats) for repeat-pass millimeter-wave radiometry
  - First global temporally-resolved observations of cloud and precipitation processes to improve weather and climate models
  - Selected by Earth Venture for in-space technology demonstration managed by NASA Earth Science Technology Office (ESTO).
- TEMPEST-D started in Aug. 2015 as a partnership among CSU, JPL and BCT, with 2.5-year development cycle.
  - Deliver one complete flight system with integrated payload to NanoRacks for launch integration by Feb. 1, 2018.
- Manifested by NASA CSLI for launch on OA-9 to ISS, planned for Mar. 14, 2018
  - Commercial resupply service to ISS on Cygnus Antares II for deployment via NanoRacks within several months



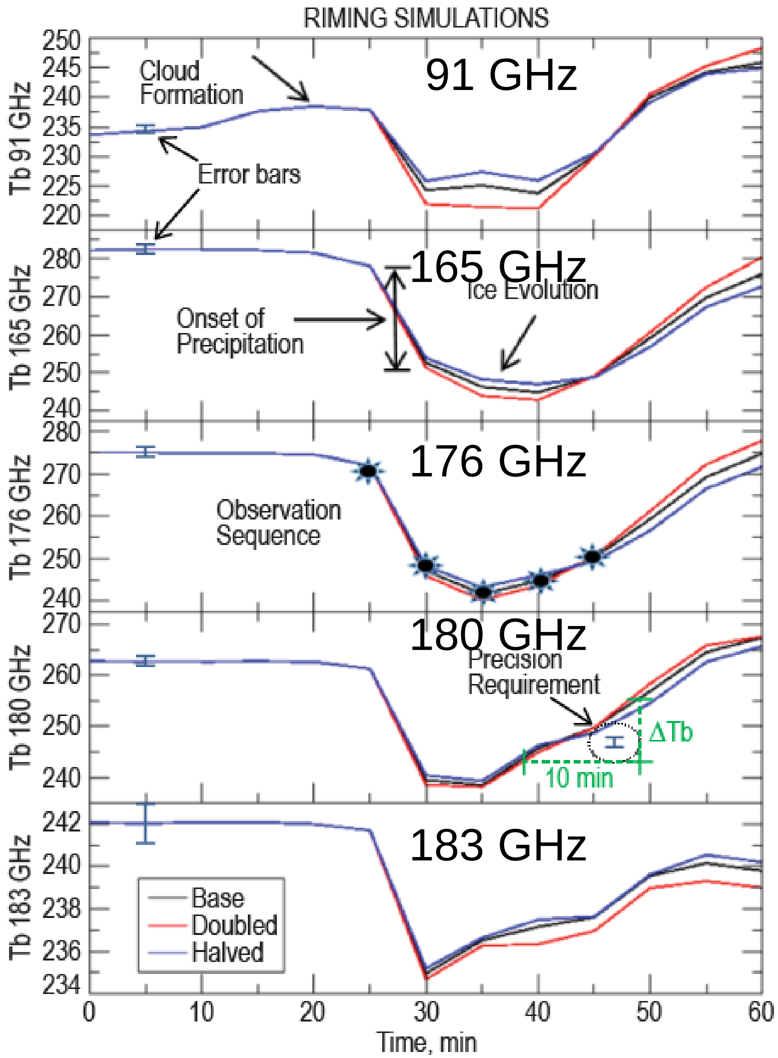
5 identical 6U small sats, each with an identical 5-channel radiometer, flying 5 minutes apart

Observations of Transition from Clouds to Precipitation



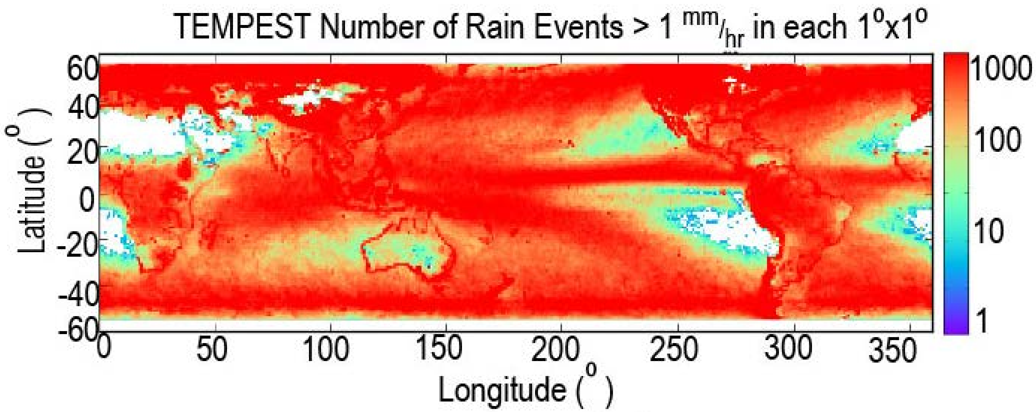
- Infrared brightness temperatures (middle row, available from GEO) show cloud top temperatures, locations and morphology.
- Onset of precipitation clearly detected at millimeter-wave frequencies on TEMPEST constellation, including 165 GHz (bottom row).
- TEMPEST minimum spatial resolution of 25 km is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

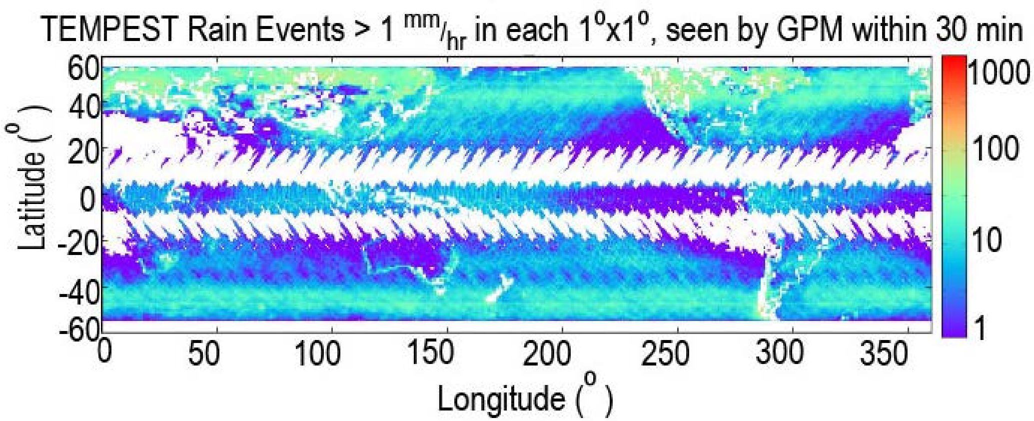
Temporal Development of Ice in Cloud-Scale Models



- 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.

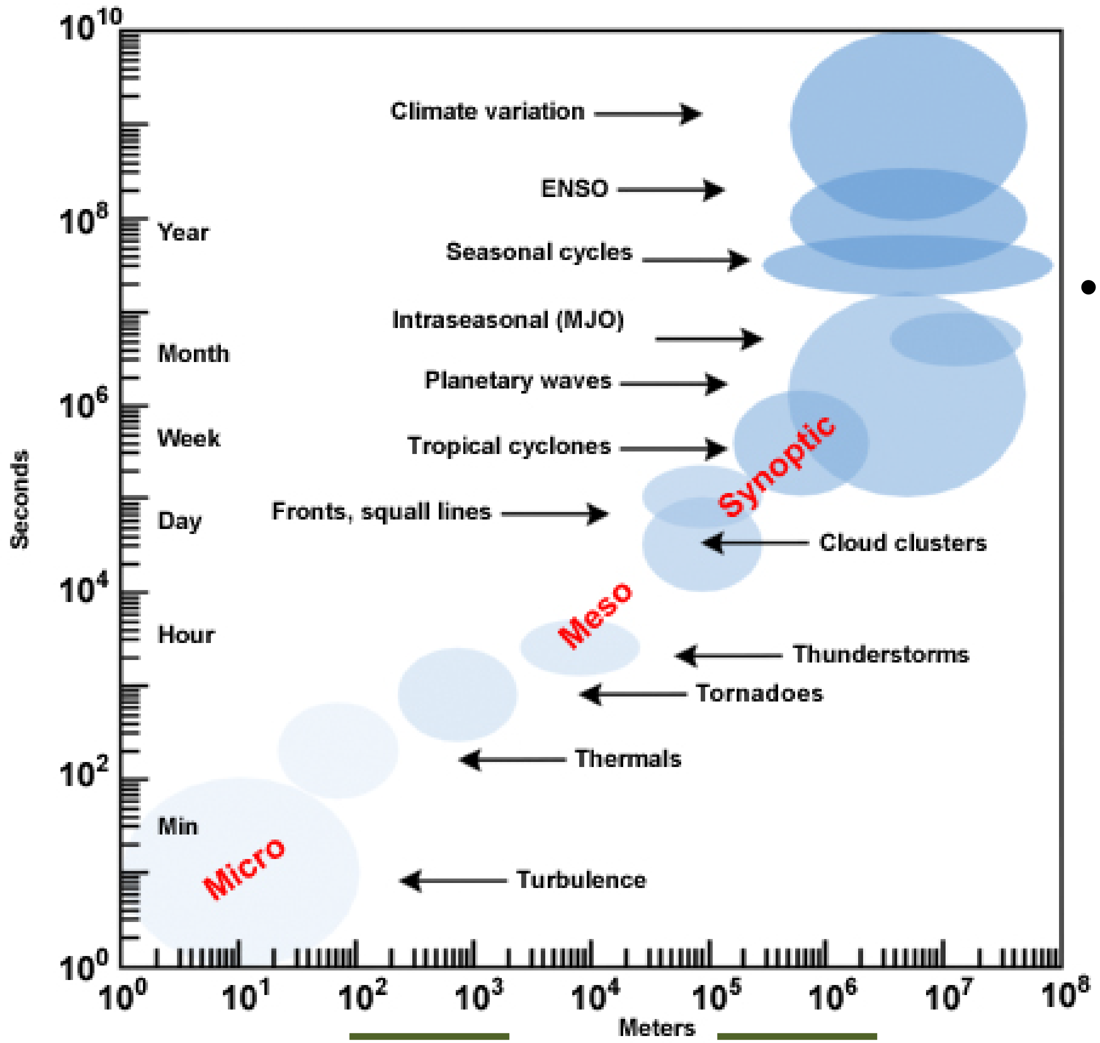
Global Time-Resolved Observations of Clouds and Precipitation





- 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's Global Precipitation Mission (GPM)
- 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.

Spatio-Temporal Scales Observed by Proposed TEMPEST Mission



TEMPEST-D TEMPEST-D + Polar-Orbiting Sats in LEO

- TEMPEST enables temporal sampling on the time scale of tens of minutes, corresponding to meteorological structures with spatial scales on the order of hundreds of m to a few km.

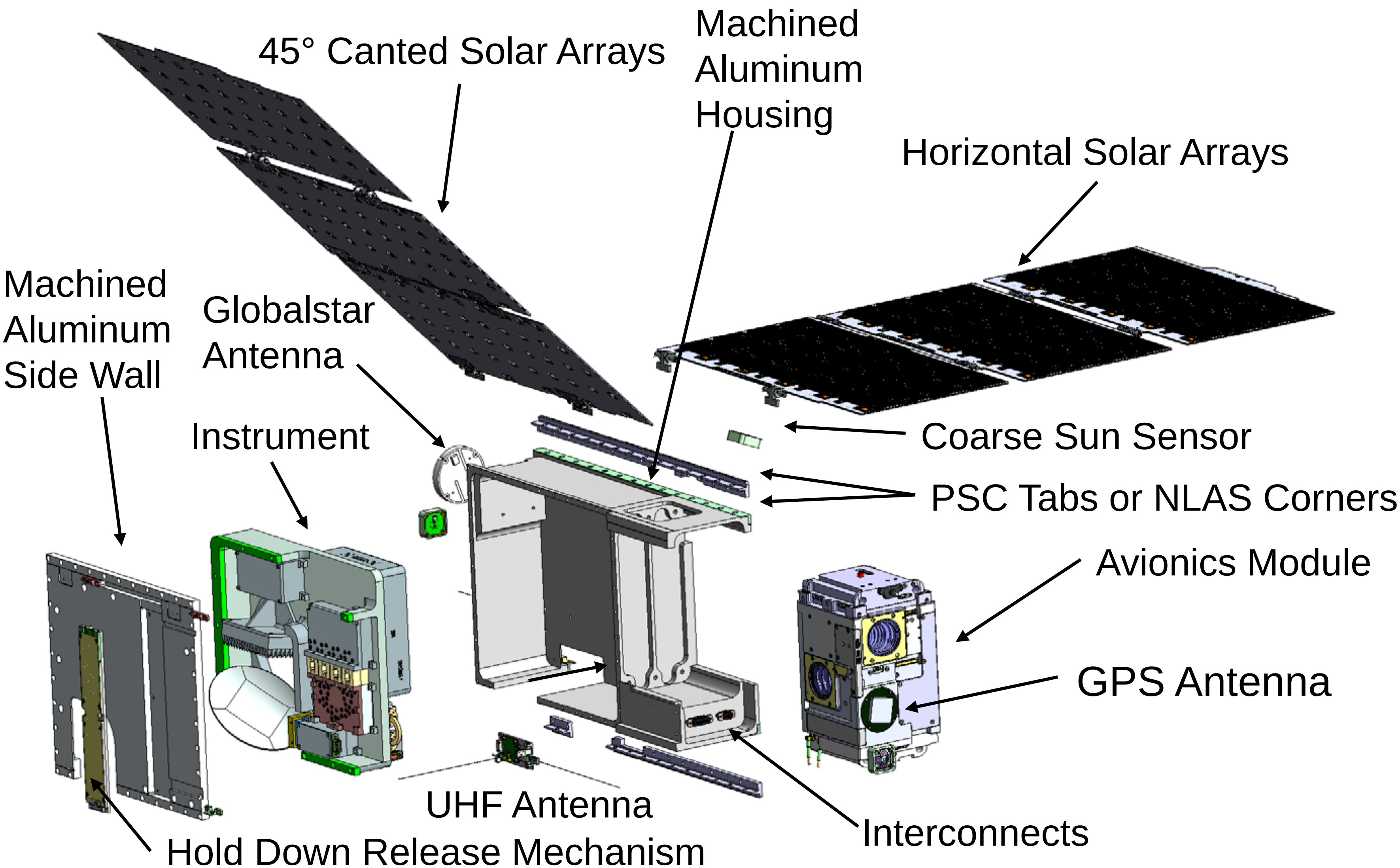
TEMPEST-D Demonstration: Motivation and Objectives

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

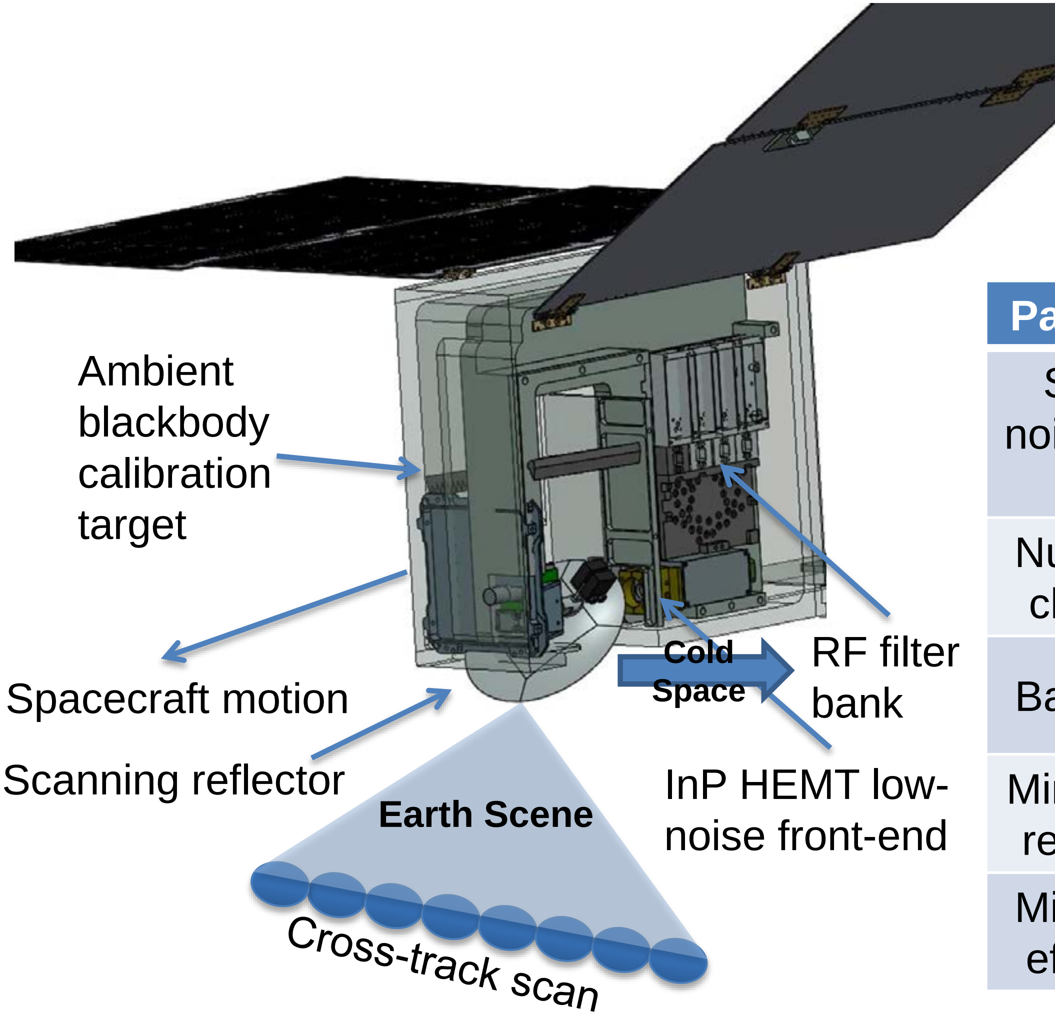
Success Criteria:

- 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



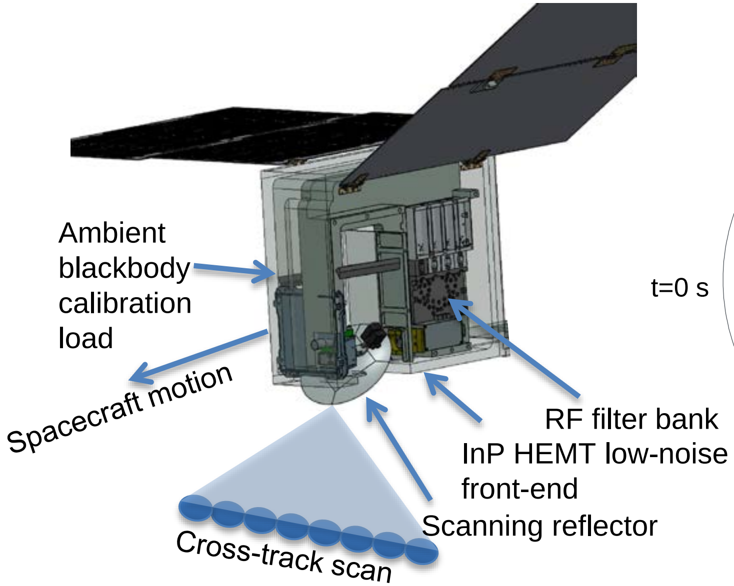
TEMPEST-D Millimeter-Wave Radiometer for 6U-Class Satellite



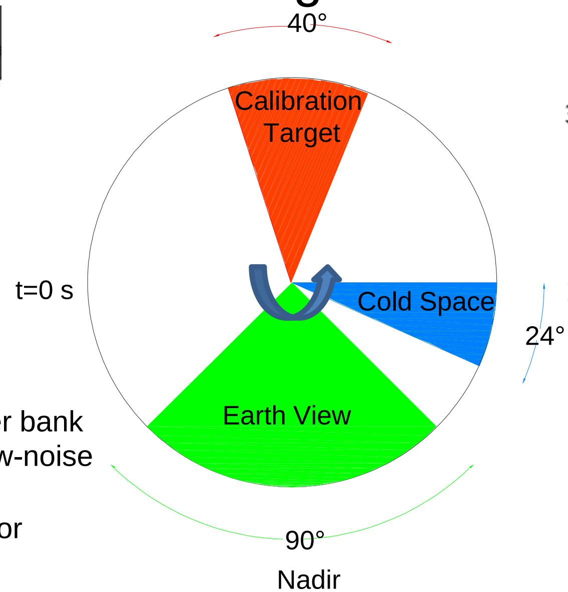
Parameter	Specification	
System noise temp.	< 800 K at 89 GHz < 1300 K at 165, 176, 180 and 182 GHz	
Number of channels	5	
Bandwidth	4 GHz at 89 and 165 GHz 2 GHz at 176, 180 & 182 GHz	
Min. spatial resolution	13 km at 182 GHz	25 km at 89 GHz
Min. beam efficiency	> 90%	> 90%

TEMPEST-D Instrument: Radiometer Calibration

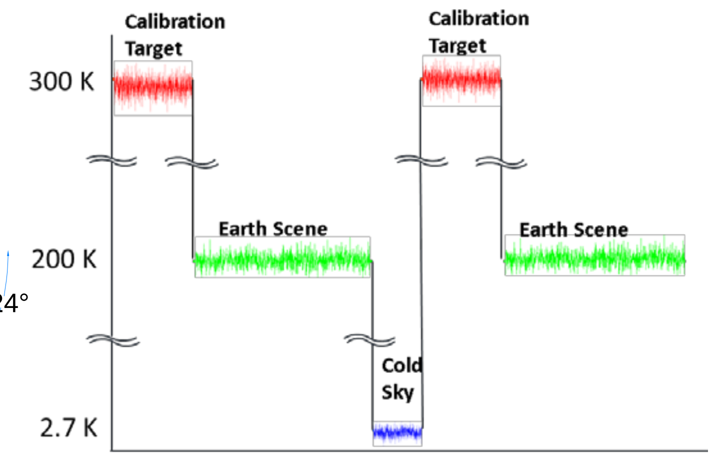
TEMPEST-D Instrument



Observing Profile



Time Series of Output Data



- Five-frequency millimeter-wave radiometer measures Earth scene over ±45° nadir angles, providing an 825-km swath width from a nominal orbit altitude of 400 km. Each pixel is sampled for 5 ms.
- Space view observes cosmic microwave background at 2.73 K ("cold sky"). Ambient Blackbody calibration target is measured each revolution to perform two-point external calibration every 2 sec. (scanning at 30 RPM).

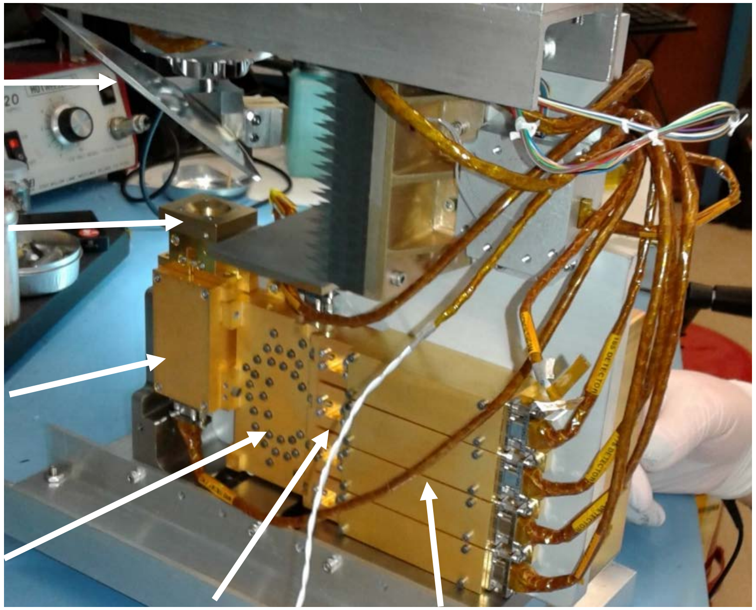
Flight Model Radiometer Instrument Bench-top Integration at JPL

Scanning Reflector

Dual-Frequency Feed horn

165-182 GHz Radiometer Front-end

165-182 GHz Power Divider



165-182 GHz Filter Bank

165-182 GHz Detectors

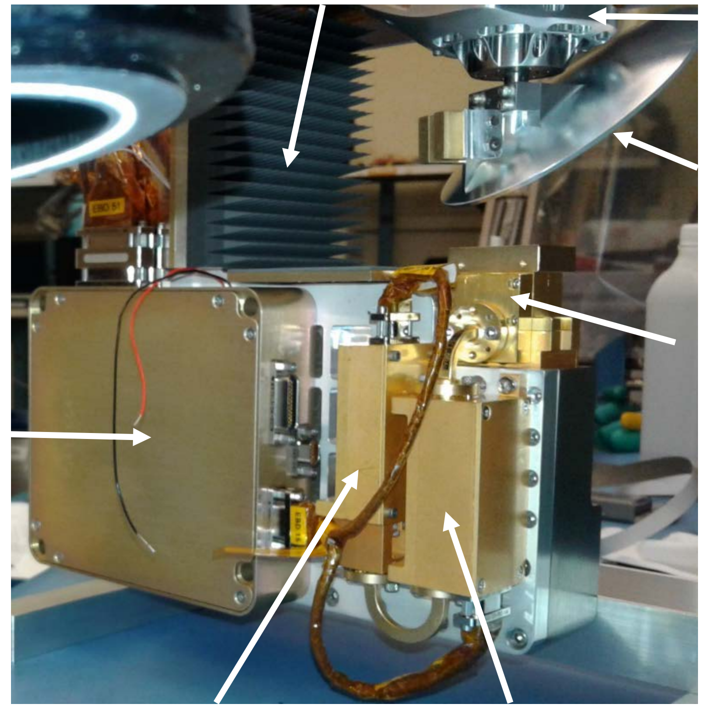
Ambient Calibration Target

Scanning Motor

Scanning Reflector

Dual-Frequency Feed horn

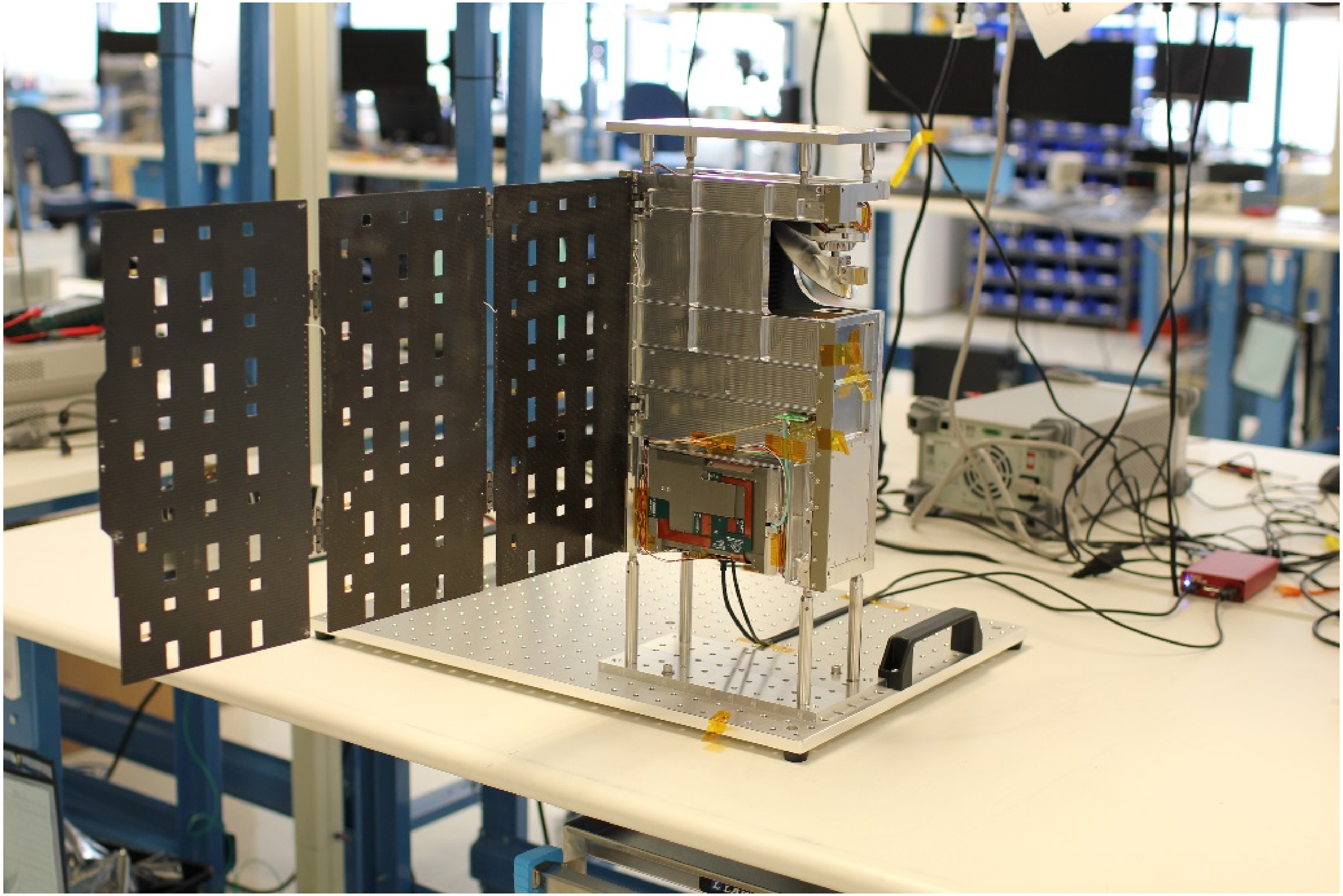
Command & Data Handling and Power Distribution Subsystem



89 GHz Detector

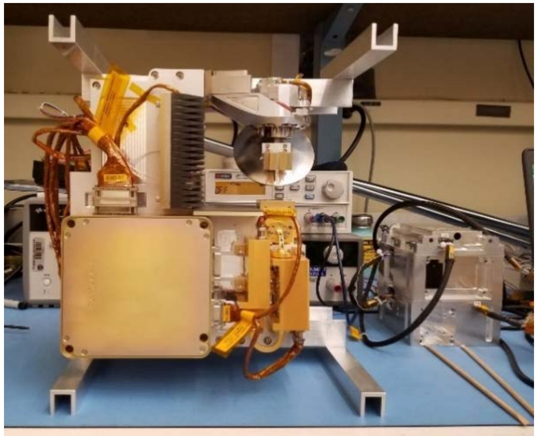
89 GHz Radiometer Front-end

Spacecraft Bus Integrated with Spare Instrument at BCT

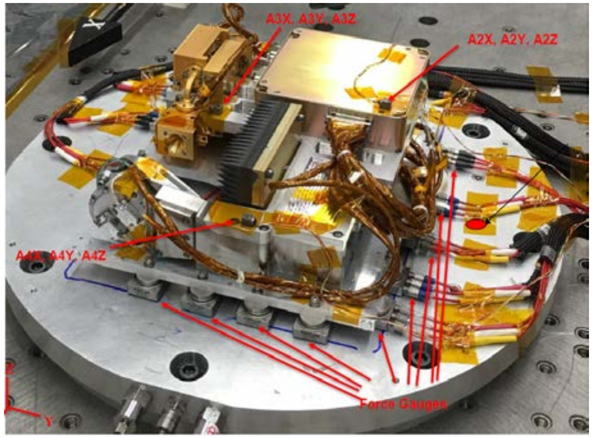


TEMPEST-D Instrument Status

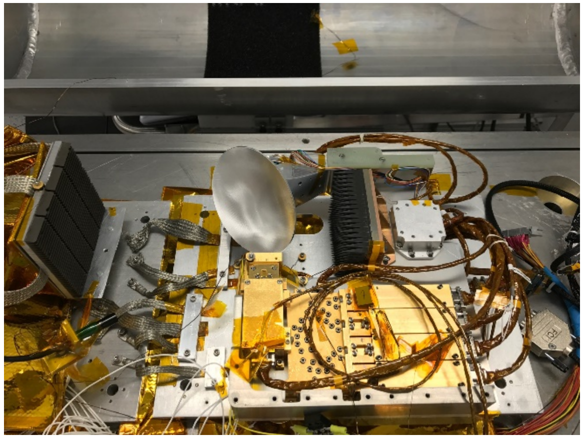
- **Flight spare:** Successfully completed EMI/EMC self-compatibility testing with spacecraft bus. (April 2017)
- **Flight instrument:**
  - Completed end-to-end receiver bandpass and linearity measurements successfully. (June 2017)
  - Integrated and vibration testing successfully completed. (June 2017)
  - 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)



Instrument Assembly



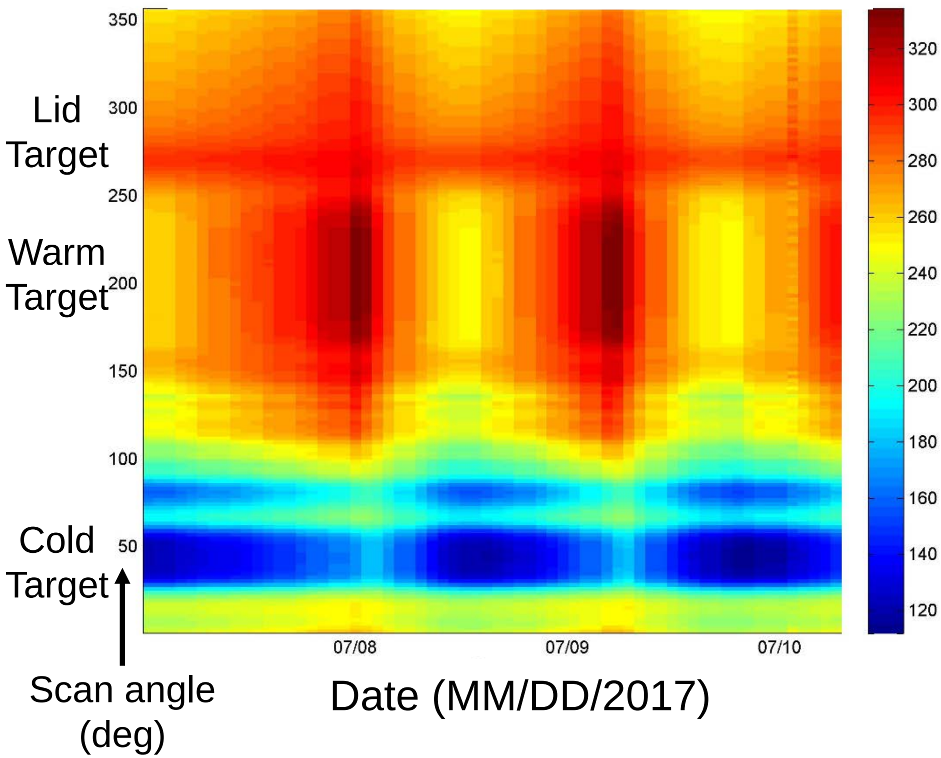
Vibration Testing



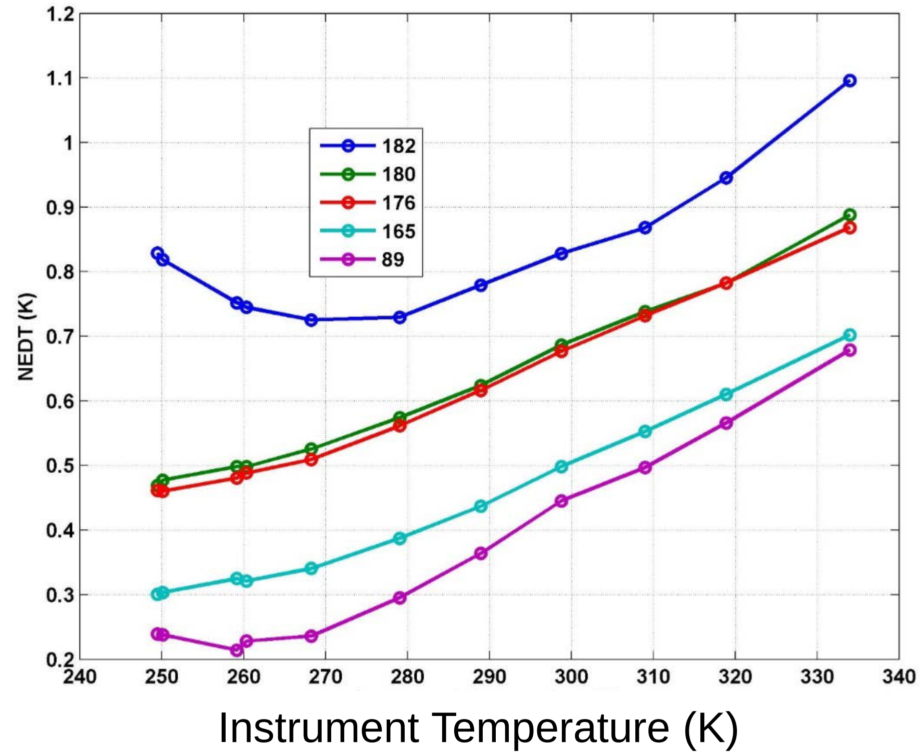
TVAC Testing

TVAC Testing Results for Flight Instrument

89 GHz Antenna Temperature (K)



NEDT vs. Temperature for 5 channels



NEDT is measured on warm target, which varies with chamber temperature.

Summary

- TEMPEST-D mission to demonstrate capability of 6U-Class satellites to perform global observations of clouds and precipitation processes
- Reduces risk, cost and development time for repeat-pass radiometry to measure temporal signatures of precipitation using small satellite constellations
- Provides first in-space technology demonstration of a millimeter-wave radiometer based with an InP HEMT low-noise amplifier front-end for Earth Science measurements
- Raises the TRL of the TEMPEST mm-wave radiometer instrument from 6 to 9 (scanning reflector to 7)
- Demonstrates the feasibility of differential drag maneuvers to achieve required time separation of 6U-Class satellites 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
- Features rapid development cycle of 2.5 years from project start to delivery to NanoRacks for integration on Feb. 1, 2018.
- Launch expected on Cygnus Antares II from Wallops to ISS on Mar. 14, 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.