NASA Earth Science Technology Forum (ESTF 2017)
June 13-15, 2017 Caltech, Pasadena, CA

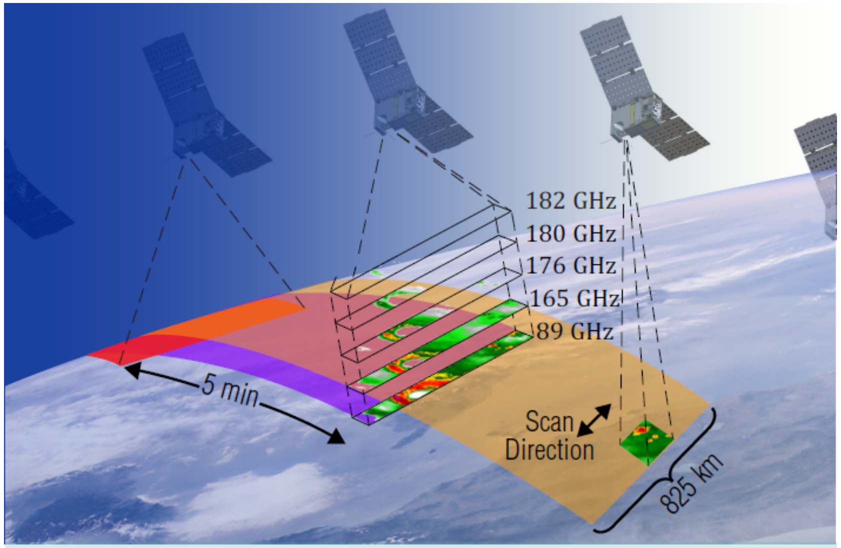
Enabling Temporally-Resolved Measurements of Clouds and Precipitation from 6U-Class Satellite Constellations: Temporal Experiment for Storms and Tropical Systems Technology Demonstration (TEMPEST-D) Mission

Steven C. Reising[1], Todd C. Gaier[2], Christian D. Kummerow[1], Sharmila Padmanabhan[2], Boon H. Lim[2], Cate Heneghan[2], V. Chandrasekar[1], Wesley Berg[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

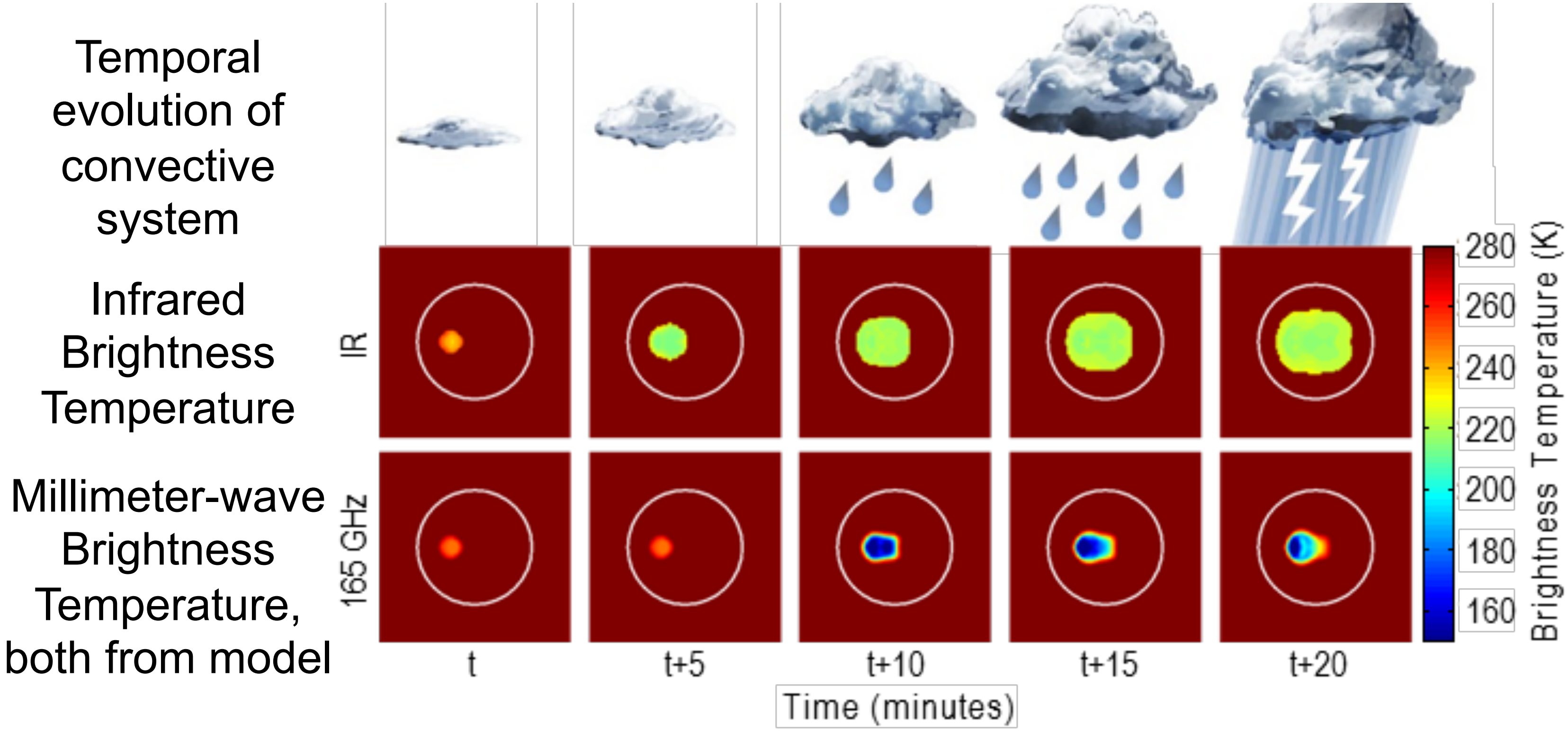
Temporal Experiment for Storms and Tropical Systems (TEMPEST)

- TEMPEST proposed to NASA Earth Venture Instrument-2 in Nov. 2013
  - Low-risk, high-margin approach to use 6U-Class satellites 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 project started in Aug. 2015, with a 2-year development cycle.
  - Deliver one complete flight system with integrated payload for launch integration in early autumn of 2017.
- Manifested by NASA CSLI for launch on ELaNa XXIII in Q2 of CY2018.
  - Commercial resupply service to ISS for deployment by NanoRacks several months after launch.



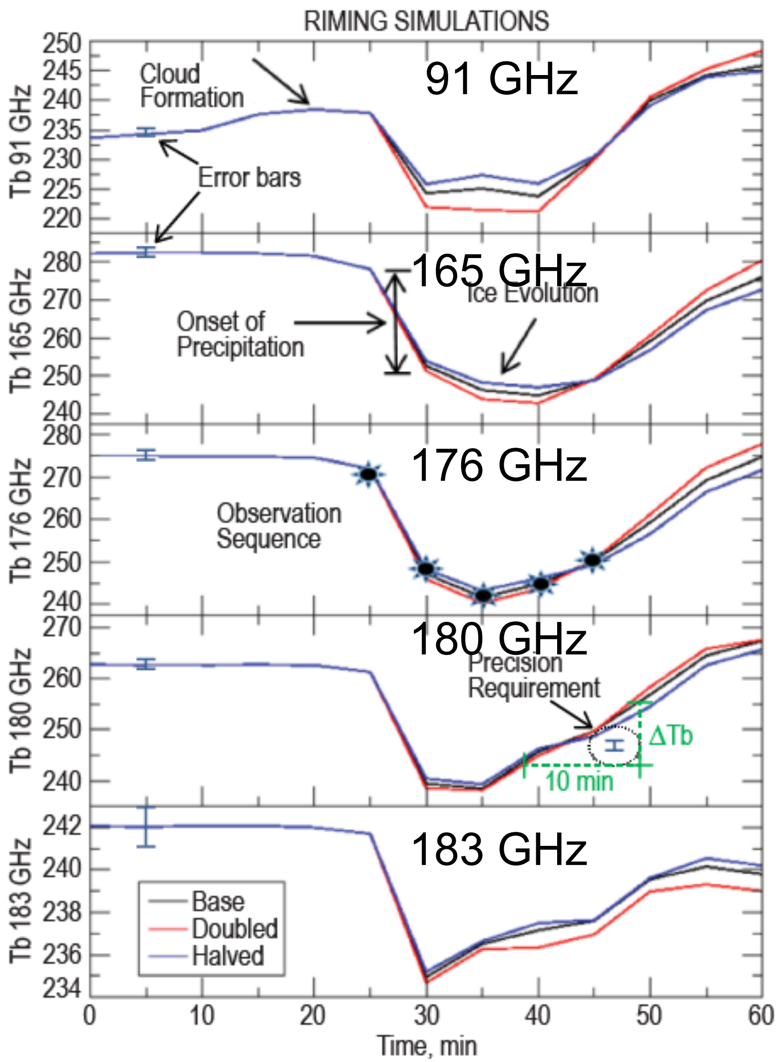
5 identical 6U small sats, each with an identical 5-channel radiometer, flying 5 minutes apart

Observations of Transition from Clouds to Precipitation



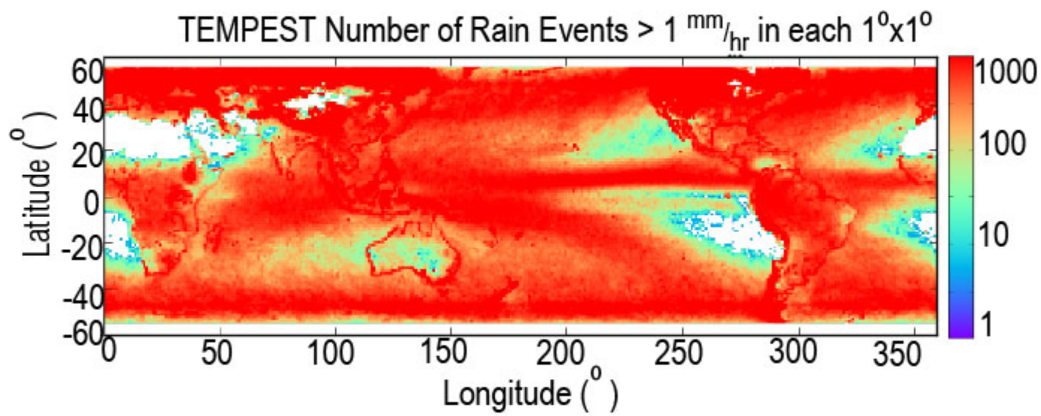
- Infrared brightness temperatures (middle row, available from GEO) show cloud top temperatures, locations and morphology.
- Onset of precipitation clearly detected at millimeter-wave frequencies on TEMPEST constellation, including 165 GHz (bottom row).
- TEMPEST minimum spatial resolution of 25 km is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

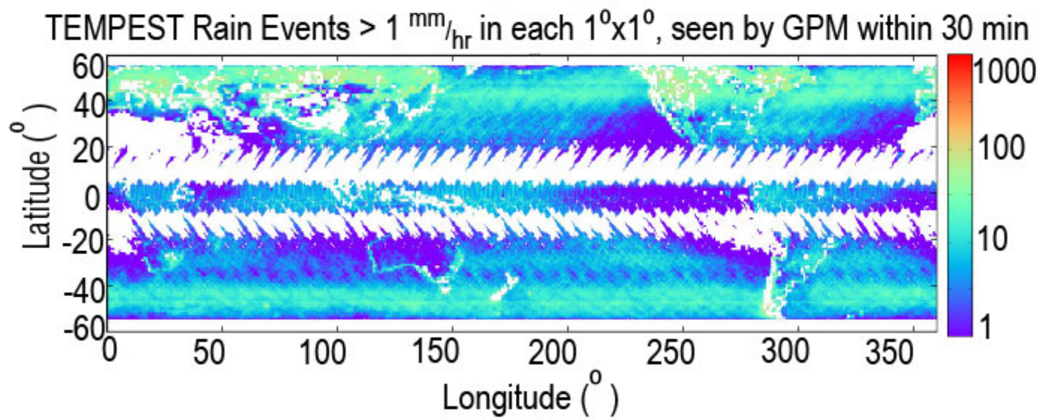
Temporal Development of Ice in Cloud-Scale Models



- 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 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.

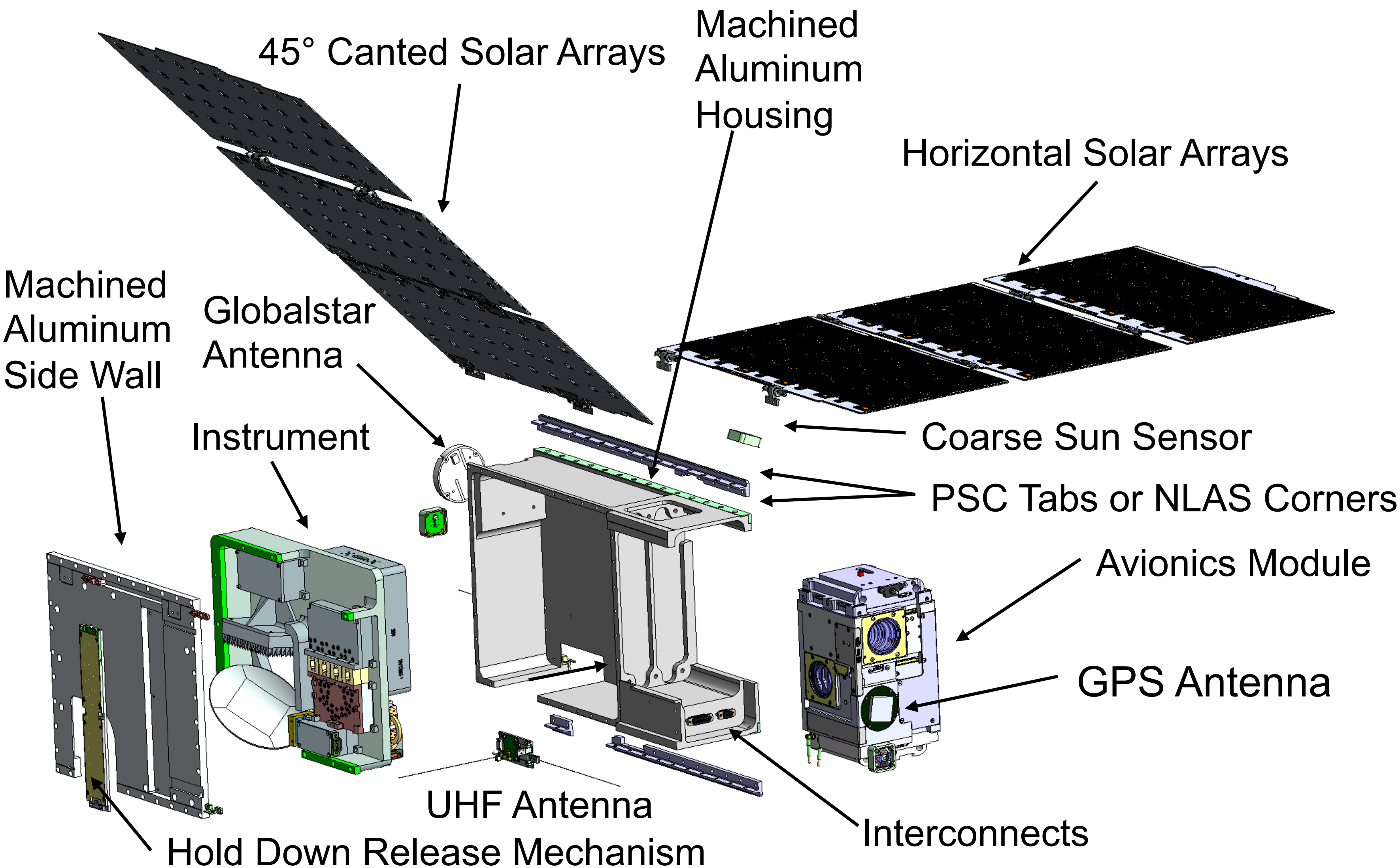
TEMPEST-D Demonstration: Motivation and Objectives

- 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 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 based on an InP HEMT low-noise amplifier front-end (LNA) for Earth Science measurements.

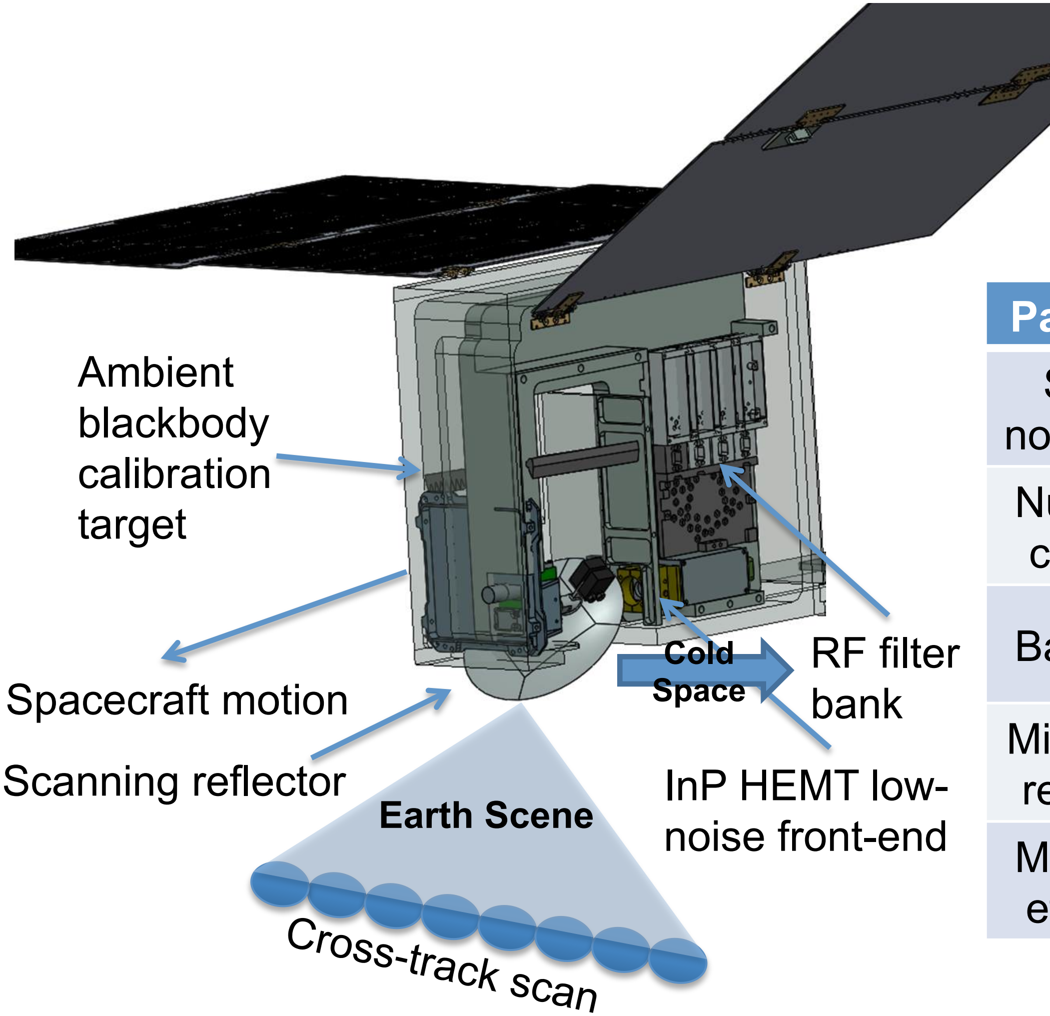
Success Criteria:

- 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 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



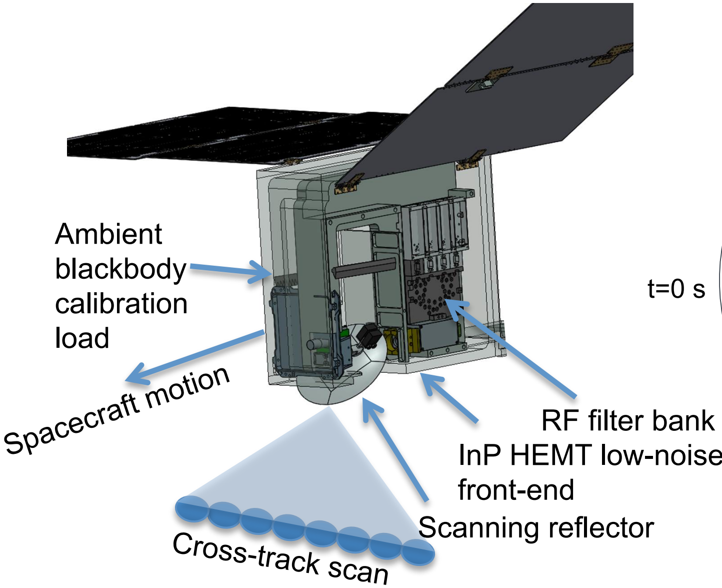
TEMPEST-D Millimeter-Wave Radiometer for 6U-Class Satellite



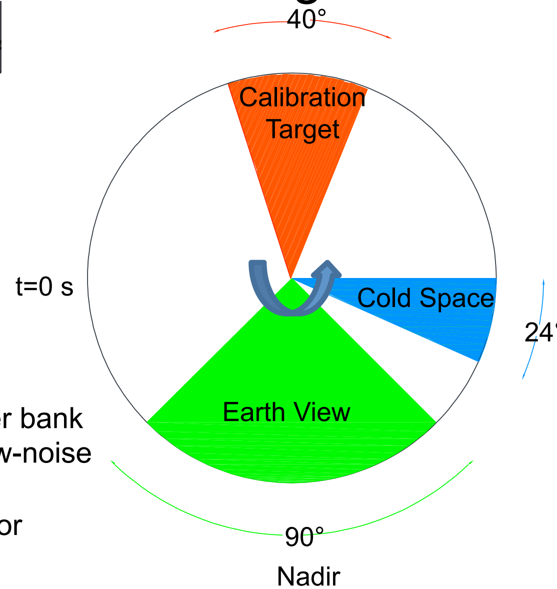
Parameter	Specification	
System noise temp.	< 600 K for 89, 165 & 176 GHz < 750 K for 180 and 182 GHz	
Number of channels	5	
Bandwidth	4 GHz at 89 and 165 GHz 2 GHz at 176, 180 & 182 GHz	
Min. spatial resolution	13 km at 182 GHz	25 km at 89 GHz
Min. beam efficiency	> 90%	> 90%

TEMPEST-D Instrument: Radiometer Calibration

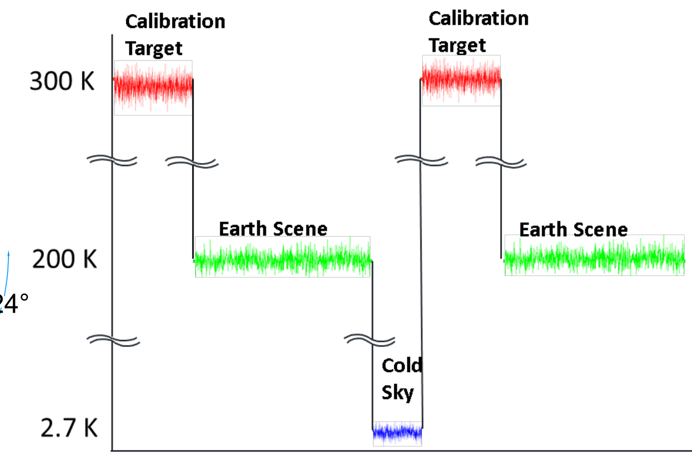
TEMPEST-D Instrument



Observing Profile

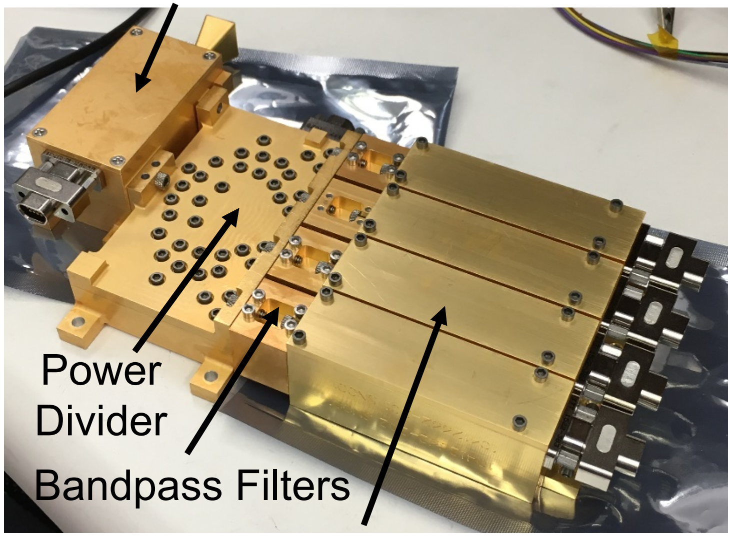


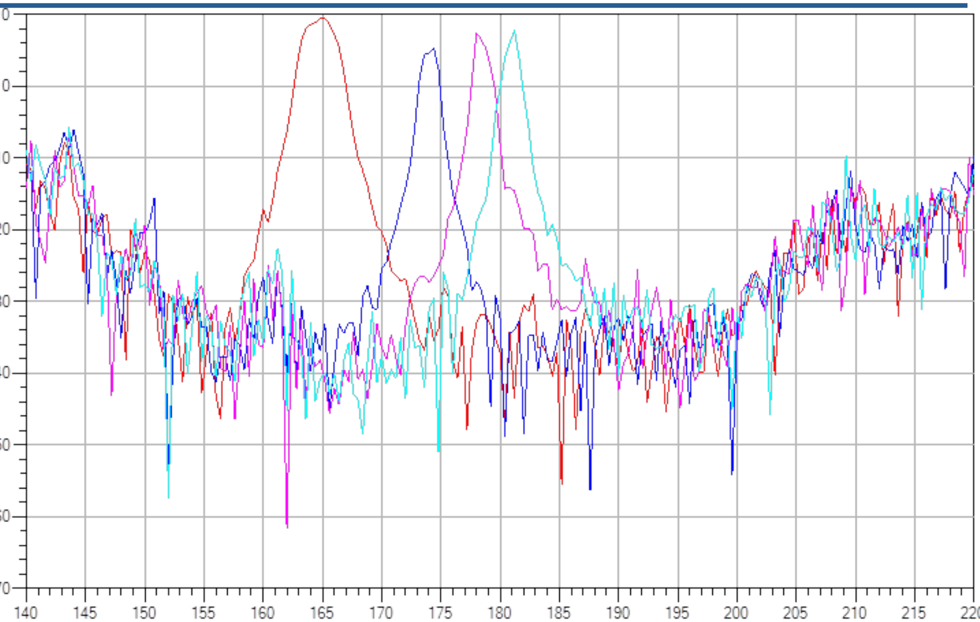
Time Series of Output Data



- 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).

Frequency Response of Flight Model Millimeter-wave Bandpass Filters

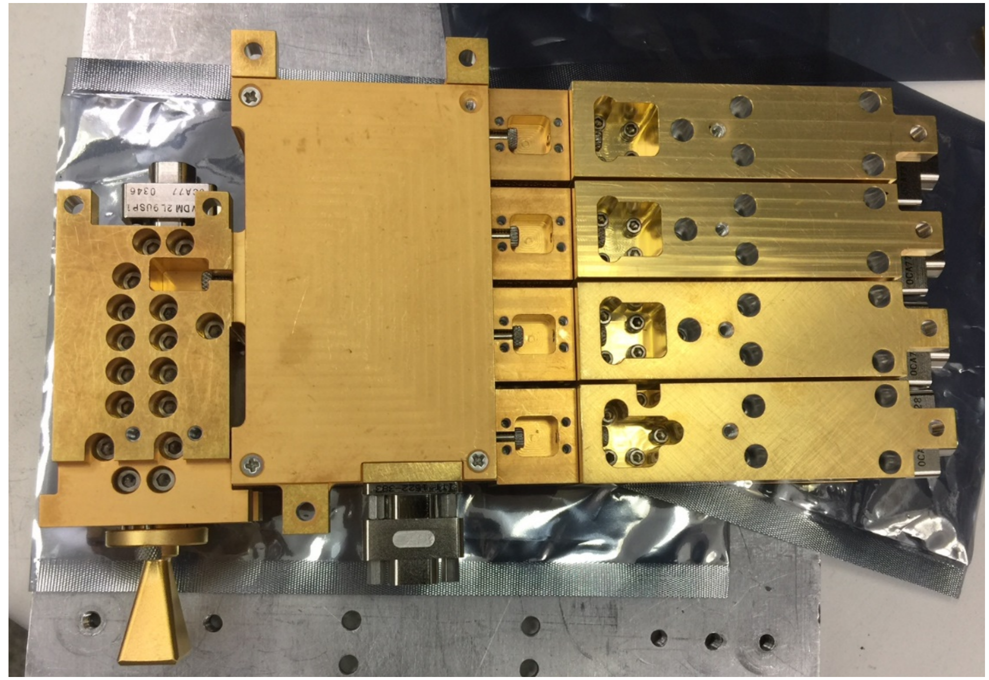




Center Frequency Requirement (GHz)	Center Frequency Measurement (GHz)	Noise Bandwidth Requirement (GHz)	Noise Bandwidth Measurement (GHz)
165 ± 2	163.9	3 ± 1	4.071
176 ± 2	175.2	2 ± 0.5	1.901
180 ± 2	178.3	2 ± 0.5	1.986
182 ± 2	181.1	2 ± 0.5	1.908

End-to-End Testing of Flight Model Radiometer Receivers

89-GHz Receiver under test



165-GHz to 182-GHz Receiver under test

Frequency (GHz)	Receiver Noise Temperature Requirement (K)	Receiver Noise Temperature Measurement (K) (CBE / FM-2)
89	812	420
165	1340	416
174	1110	550
178	1110	580
181	1110	690

Receiver noise temperatures were measured using ambient load and LN_2 (Y-factor method) with a standard-gain horn. All receiver noise temperatures meet requirements with large margins.

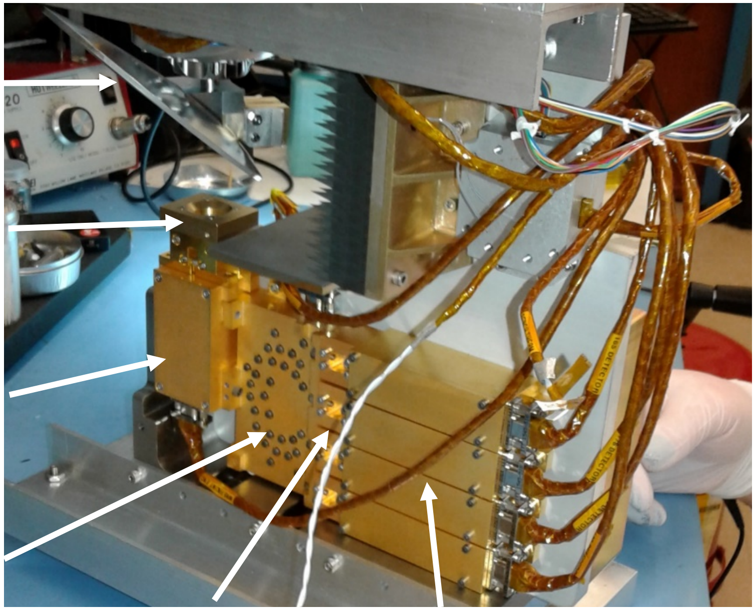
Flight Model Radiometer Instrument Bench-top Integration at JPL

Scanning Reflector

Dual-Frequency Feed horn

165-182 GHz Radiometer Front-end

165-182 GHz Power Divider

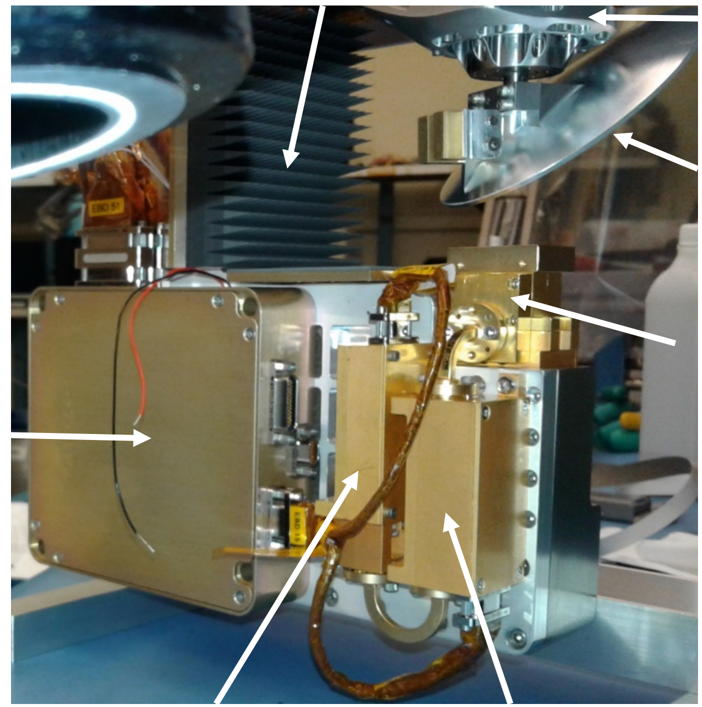


165-182 GHz Filter Bank

165-182 GHz Detectors

Command & Data Handling and Power Distribution Subsystem

Ambient Calibration Target



Scanning Motor

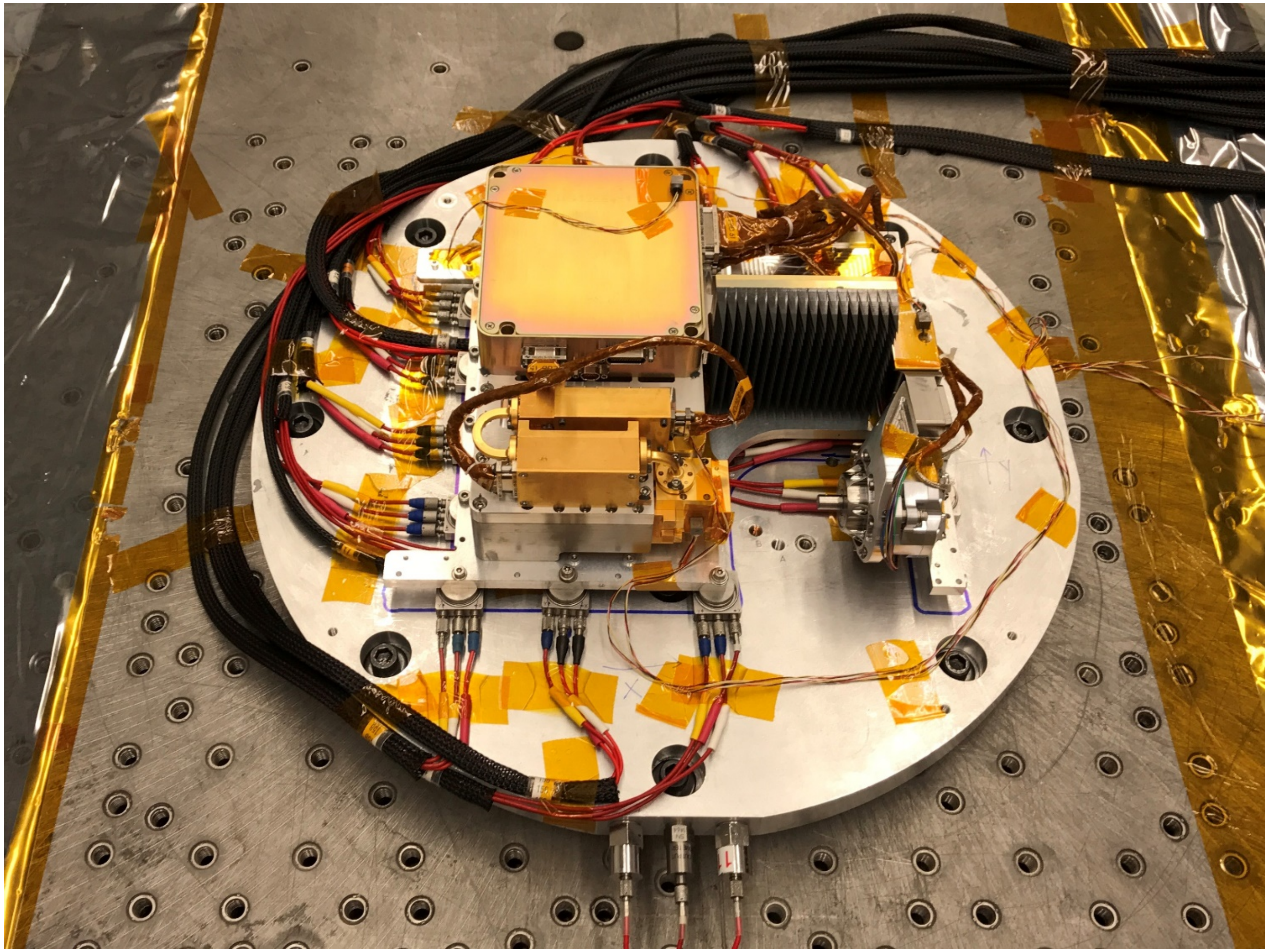
Scanning Reflector

Dual-Frequency Feed horn

89 GHz Detector

89 GHz Radiometer Front-end

Vibration Testing of Flight Model Radiometer Instrument at JPL



TEMPEST-D flight model (FM1) tested to GEVS levels at JPL last week.

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 on 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 MHS with 2 K precision and 4 K accuracy
- Features rapid development cycle of two years from project start to delivery for NanoRacks integration in autumn 2017 and launch to ISS in Q2/CY2018.