Temporal Experiment for Storms and Tropical Systems Technology Demonstration (TEMPEST-D)

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³University of Wisconsin, Madison, WI, ⁴University of Michigan, Ann Arbor, MI, ⁵City College of New York, CUNY, New York, NY,
⁶University of Maryland, College Park, MD, ⁷NOAA, College Park, MD
• TEMPEST-D provides first in-space technology demonstration of a millimeter-wave radiometer (90-183 GHz) based on InP HEMT low-noise amplifier front-end aboard a 6U-Class satellite.

• TEMPEST-D raises the instrument TRL from 5 to 7.

• TEMPEST-D is a partnership among CSU, JPL and spacecraft provider (TBD with process in place to determine)

• Managed by NASA ESTO with funding from Earth System Science Pathfinder in Earth Science Division

• Start in July 2015 for three-year technology demonstration task
TEMPEST-D Scientific Motivation and Objectives

- Demonstrate capability of U-Class Satellites to provide suitable measurements to advance NASA’s Earth Science Goals
- Reduce cost, risk and development time of future constellations of NASA’s small satellites to perform Earth Science measurements
- Demonstrate drag-adjusting altitude maneuvers required to provide time separation to a U-Class constellation with common deployment
- Demonstrate precision intercalibration with existing conically-scanning satellite radiometers with similar frequencies within 1-2 K

6U-Class satellite with millimeter-wave radiometer instrument
Reference: Global Precipitation Mission Microwave Imager

- GPM Microwave Imager is a conically-scanning radiometer measuring at 10, 18, 23, 36, 89, 166, 176, and 180 GHz

Online at www.spaceflight101.com

Reference: Sampling/Coverage of GPM Constellation
TEMPEST-D Instrument Design

Five-frequency millimeter-wave radiometer at 91, 165, 176, 180 and 183 GHz
- MMIC-based
- Cross-track scanning
- Self-calibrating
TEMPEST-D Radiometer Calibration

TEMPEST-D Instrument

- Five-frequency millimeter-wave radiometer measures Earth scene over ±45° incidence angles from nadir.
- This provides an 825-km swath width from a nominal altitude of 400 km.
- Each pixel is sampled for 5 ms.
- Space view observes cold sky, i.e. cosmic microwave background at 2.7 K.
- Ambient calibration target provides the second measurement for two-point calibration to determine instrument gain and offset.

Observing Profile

Time Series of Output Data

300 K
200 K
2.7 K
24° 24° 40°
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
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<tbody>
<tr>
<td>System noise temperature</td>
<td>&lt; 600 K</td>
</tr>
<tr>
<td>Number of channels</td>
<td>5</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>4 GHz at 91 and 166 GHz; 2 GHz at 173, 180 and 183 GHz</td>
</tr>
<tr>
<td>Minimum spatial resolution</td>
<td>13 km at 183 GHz</td>
</tr>
<tr>
<td>Minimum beam efficiency</td>
<td>&gt; 90%</td>
</tr>
<tr>
<td>Mass</td>
<td>&lt; 3 kg</td>
</tr>
<tr>
<td>Power</td>
<td>&lt; 8 W</td>
</tr>
<tr>
<td>Volume</td>
<td>3U</td>
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<tr>
<td>Precision (Stability)</td>
<td>0.5 K (CBE)</td>
</tr>
<tr>
<td>Accuracy (Calibration)</td>
<td>1 K (CBE)</td>
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</table>
Enabling Technology: 35-nm InP HEMT Low-Noise Amplifiers

- 35-nm InP HEMT process
- Record low noise temperature of 300 - 350 K from 140 - 190 GHz (at room temperature)
- Chip area of 900 x 560 µm²
- Three-stage design with separate gate bias for the first stage to optimize low-noise performance
- The LNA was mounted in optimized WR-08 and WR-05 waveguide housings for testing over a broad bandwidth.

Microwave Atmospheric Sounder on CubeSat (MASC)

- Prototype millimeter-wave sounding radiometer for 6U CubeSat; JPL R&TD led by Sharmila Padmanabhan.
- Instrument occupies 3U of a 6U CubeSat, with mass of 3 kg and power consumption of 6.5 W.
- Temperature and water vapor profiling using 4 channels each near absorption lines at 118.75 GHz and 183.31 GHz oxygen and water vapor absorption lines, respectively.
- Receiver noise temperatures were measured using standard gain horns.
- Heritage from NASA ESTO-funded ACT, IIP and AITT programs as well as JPL RACE CubeSat mission.
TEMPEST-D Selected in Feb. 2015 by NASA CubeSat Launch Initiative

- TEMPEST-D was selected by NASA CSLI (ELaNa) in Feb. 2015
- Assigned priority #7 of 14 (based on predicted launch readiness, launch priority orbital requirements, etc.

From https://www.nasa.gov/directorates/heo/home/CSLI_selections.html#2015

<table>
<thead>
<tr>
<th>CSLI Rank</th>
<th>Short Name</th>
<th>Project</th>
<th>Organization</th>
<th>POC</th>
<th>Cube Size</th>
<th>Status</th>
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<tbody>
<tr>
<td>1</td>
<td>OPEN</td>
<td>OPEN: Open Prototype for Educational NanoSats</td>
<td>University of North Dakota</td>
<td>Ronald Marsh</td>
<td>1U</td>
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<td>2</td>
<td>RadSat</td>
<td>RadiSat: Satellite Demonstration of a Radiation Tolerant System</td>
<td>Montana State University</td>
<td>Dr. Brock LaMeres</td>
<td>3U</td>
<td>In Work</td>
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<td>ALBus</td>
<td>Advanced Electrical Bus (ALBus)</td>
<td>NASA Glenn Research Center</td>
<td>Katie Shaw</td>
<td>3U</td>
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<td>MITEE</td>
<td>MITEE: Miniature Tether Electrodynamics Experiment</td>
<td>University of Michigan</td>
<td>Dr. Brian Gilchrist</td>
<td>3U</td>
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<td>KickSat-2</td>
<td>KickSat-2: A Technology Demonstration Mission for the Sprite ChipSat</td>
<td>Cornell University Manchester</td>
<td>Zachary</td>
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<td>TBEx</td>
<td>TBEx – The Tandem Beacon Experiment</td>
<td>The University of Michigan</td>
<td>Dr. James Cutler</td>
<td>3U</td>
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<td>7</td>
<td>TEMPEST-D</td>
<td>TEMPEST-D: Temporal Experiment for Storms and Tropical Systems - Demonstrator</td>
<td>Colorado State University</td>
<td>Dr. Steven Reising</td>
<td>6U</td>
<td>In Work</td>
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### TEMPEST-D Key Roles

<table>
<thead>
<tr>
<th>Name</th>
<th>Role</th>
<th>Institution</th>
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</thead>
<tbody>
<tr>
<td>Steven Reising</td>
<td>Principal Investigator</td>
<td>Colorado State University (CSU)</td>
</tr>
<tr>
<td>Todd Gaier</td>
<td>JPL Lead Co-I</td>
<td>Jet Propulsion Laboratory (JPL)</td>
</tr>
<tr>
<td>Ron Steinkraus</td>
<td>Project Manager; Spacecraft and Mission Operations</td>
<td>JPL</td>
</tr>
<tr>
<td>V. Chandrasekar</td>
<td>CSU Co-I; Validation / Engineering Interface</td>
<td>CSU</td>
</tr>
<tr>
<td>Sharmila Padmanabhan</td>
<td>Instrument Engineer</td>
<td>JPL</td>
</tr>
<tr>
<td>Boon Lim</td>
<td>Systems Engineer</td>
<td>JPL</td>
</tr>
<tr>
<td>Christian Kummerow</td>
<td>Validation Lead</td>
<td>CSU</td>
</tr>
<tr>
<td>Ted Sweetser</td>
<td>Orbital Architecture</td>
<td>JPL</td>
</tr>
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</table>
TEMPEST-D Schedule

- July 2015: Project Start
- Nov. 2016: Deliver radiometer instrument for integration & test
- Dec. 2016: Complete 6U-Class satellite bus
- July 2017: Deliver TEMPEST-D spacecraft to launch provider
- After launch: 3 months of operations; 3 months analysis & validation
- Jun. 2018: Project Completion
Temporal Experiment for Storms and Tropical Systems (TEMPEST)

**BENEFITS AND STRENGTHS**

- First global observations of time evolution of precipitation
- Low-cost approach and rapid development using 6U CubeSats
- Unique data sets to improve weather and climate prediction models

**IMPORTANCE TO NASA**

- Constrain climate models through improved understanding of cloud processes, transition from clouds to precipitation and impact on Earth’s energy balance
- Characterize temporal variability of precipitation globally to improve understanding of water cycle
Infrared brightness temperatures (GEO) show only cold cloud top temperatures.

Transition from clouds to precipitation is clearly detected at millimeter-wave frequencies on TEMPEST constellation, including 165 GHz.

TEMPEST spatial resolution of 25 km at lowest frequency is shown (circles).
Sensitivity of Climate Model Predictions to Onset of Precipitation

[Adapted from Golaz et al., GRL, 2013; Suzuki et al., GRL, 2013]

- Global climate model temperature anomaly projections for onset of precipitation at cloud droplet sizes of 6 µm (red), 8 µm (green) and 11 µm (blue).
- TEMPEST constellation could provide the first global sample of the onset of precipitation, constraining climate prediction models.
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).
- 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. Precision requirement is 1 K in 5 minutes.
- Ice remaining in clouds after precipitation can have significant effects on climate system. Residual ice can be compared to W-band radar observations from CloudSat or ESA’s EarthCARE.
Global Observations of Temporal Evolution of Precipitation

• In a potential one-year mission, TEMPEST constellation could make more than 3,000,000 temporal observations of precipitation (> 1 mm/hr), including 100,000+ deep-convection events.

• Could perform more than 50,000 coincident precipitation observations within 30 minutes of NASA’s Global Precipitation Mission (GPM) for a nominal TEMPEST orbit for ISS launch at 400-km altitude and 51° inclination.

• Precipitation estimates from AMSR-E satellite radiometer data with oceanic observations only.
TEMPEST 6U-Class Satellites and Passive Constellation Maneuvers

KEY FLIGHT CHARACTERISTICS

- 5 identical 6U CubeSats
  
  **Attitude:**
  - 3-axis stabilization
  - 0.13° (1σ) control
  - 0.15° (1σ) knowledge

- **Mass:**
  - 5.8 kg (Margin: 38%)

- **Power:**
  - 13 W (Margin: 23%)
  - Peak Power: 65 W EOL

- **Communications:**
  - 1 Mbps S-band (Margin: 22%)

- Orbital characteristic (CSLI compatible)
  - Altitude: 390 – 450 km
  - Inclination: 50° – 65°

- Temporal spacing strategy
  - Drag-adjusting attitude maneuvers used to achieve temporal separation between CubeSats
Summary

- TEMPEST-D provides first in-space technology demonstration of a 90-183 GHz millimeter-wave radiometer based on InP HEMT low-noise amplifier front-end aboard a 6U-Class satellite
- TEMPEST-D raises the instrument TRL from 5 to 7.
- TEMPEST-D partners are CSU, JPL and spacecraft provider (TBD).
- To demonstrate capability of U-Class Satellites to provide suitable measurements to advance NASA’s Earth Science Goals
- To reduce cost, risk and development time of future constellations of NASA’s small satellites to perform Earth Science measurements
- To demonstrate drag-adjusting altitude maneuvers required for time separation for U-Class constellation with common deployment
- To provide precision intercalibration with existing conically-scanning Earth-viewing radiometers with similar frequencies to within 1-2 K
- Start in July 2015 for launch by Jan. 2018; 3 months of operations