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

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Temporal Experiment for Storms and Tropical Systems (TEMPEST)

• TEMPEST was proposed to NASA for Earth Venture Instrument-2 as a low-risk, high-margin approach toward the use of 6U-Class satellites for repeat-pass radiometry to measure temporal signatures of precipitation.

• TEMPEST was selected by Earth Ventures for in-space technology demonstration and is managed by NASA’s Earth Science Technology Office (ESTO).

• TEMPEST-D demonstration began in August 2015, with a 2-year development cycle. The complete satellite will be ready for delivery to the launch provider in July 2017.

• Manifested by NASA CSLI on ELaNa XXIII for launch to ISS in the first half of 2018 for deployment into orbit within ~3 months after launch.
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-Class satellites
- 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 mission 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 substantial effects on climate system. Residual ice can be compared to W-band radar observations from CloudSat and ESA’s EarthCARE.
Left: Rapid revisits of a small convective system observed with the JPL HAMSR instrument on the ER-2 high-altitude aircraft during an atmospheric river event (CalWater-2) on Feb. 5, 2015. Right: Time series of five observations over 30 minutes of two convective cells within this warm system. For the cell labeled “b”, the cloud is observed while forming precipitation and then disappears. The larger core labeled “a” is observed while growing. These data clearly demonstrate the ability of millimeter-wave temporal observations to gain information on cloud processes.
Global Observations of Temporal Evolution of Precipitation

- During a future 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 a nominal 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 Motivation and Objectives

- Demonstrate capability of 6U-Class satellites to perform 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)
- Collaborative, experienced team among CSU (Validation), JPL (Instrument) and Blue Canyon Technologies (BCT, Spacecraft & Operations)
TEMPEST-D In-Space Technology Demonstration

- 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 the feasibility of differential drag maneuvers to achieve required time separation of 6U-Class satellites in the same orbital plane
  - Demonstrate cross-calibration between TEMPEST mm-wave radiometers and NASA GPM GMI and/or MHS on NOAA and ESA/EUMETSAT satellites with 2 K precision and 4 K accuracy.
TEMPEST-D Instrument Design and Configuration

Five-frequency millimeter-wave radiometer at 89, 165, 176, 180 and 182 GHz
- MMIC-based
- Cross-track scanning
- Self-calibrating (290 K and cold sky)

Ambient blackbody calibration load
RF filter bank
InP HEMT low-noise front-end

Spacecraft motion
Scanning reflector
Earth Scene
Cross-track scan

V
Five-frequency millimeter-wave radiometer measures Earth scene over ±45° nadir angles, providing an 825-km swath width from a 400-km altitude orbit. Each pixel is sampled for 5 ms.

Space view observes cosmic microwave background at 2.73 K (“cold sky”). Blackbody calibration target (at 290 K) is measured each revolution to perform two-point external calibration every 2 sec. (scanning at 30 RPM).
## TEMPEST-D Instrument Requirements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>System noise temperature</td>
<td>&lt; 600 K for 89, 165 and 176 GHz&lt;br&gt; &lt; 750 K for 180 and 182 GHz</td>
</tr>
<tr>
<td>Number of channels</td>
<td>5</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>4 GHz at 89 GHz and 165 GHz&lt;br&gt; and 2 GHz at 176, 180 and 182 GHz</td>
</tr>
<tr>
<td>Minimum spatial resolution</td>
<td>13 km at 182 GHz&lt;br&gt; 25 km at 89 GHz</td>
</tr>
<tr>
<td>Minimum beam efficiency</td>
<td>&gt; 90%</td>
</tr>
</tbody>
</table>
# TEMPEST-D Technical Resource Summary

<table>
<thead>
<tr>
<th>Resource</th>
<th>Current Best Estimate (CBE)</th>
<th>Allocation</th>
<th>Margin (Actual)</th>
<th>Margin Required (CDR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiometer Mass (kg)</td>
<td>2.8</td>
<td>4</td>
<td>30%</td>
<td>10%</td>
</tr>
<tr>
<td>Radiometer Power (W)</td>
<td>5.35</td>
<td>6.5</td>
<td>18%</td>
<td>15%</td>
</tr>
<tr>
<td>Radiometer Data Rate (Kbps)</td>
<td>9.7</td>
<td>12.3</td>
<td>21%</td>
<td>20%</td>
</tr>
<tr>
<td>Radiometer Precision (K)</td>
<td>0.72</td>
<td>1.4</td>
<td>49%</td>
<td>10%</td>
</tr>
<tr>
<td>Radiometer Accuracy (K)</td>
<td>3.5*</td>
<td>4</td>
<td>13%</td>
<td>10%</td>
</tr>
</tbody>
</table>

\[
MARGIN = 100 \times \frac{Allocation - CBE}{Allocation}
\]

*Estimate of maximum uncertainty based on pre-launch antenna pattern measurements. Data from on-orbit cold-space calibration maneuvers will be used to correct/refine the pre-launch corrections.*
JPL’s Microwave Atmospheric Sounder on CubeSat (MASC)

MASC measures at 118 GHz +1, +2, +7, +8 GHz for temperature and 183 GHz -1, -2, -7, -8 GHz for water vapor profiling. MASC was deployed on NASA DC-8 during PECAN (Great Plains) in July ‘15 and OLYMPEX (Washington) in Nov-Dec ‘15.

MASC packaged inside unpressurized DC-3 housing.

Thermal vacuum testing of MASC completed in Sep. 2015.

Image Courtesy of Dr. Simone Tanelli, JPL.
TEMPEST-D Low-Power Direct Detection mm-Wave Radiometer

<table>
<thead>
<tr>
<th>Direct Detection</th>
<th>Voltage (V)</th>
<th>Current (A)</th>
<th>CBE Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spin Mechanism</td>
<td>15/-5/5</td>
<td>0.03/0.06/0.09</td>
<td>1.55</td>
</tr>
<tr>
<td>RF-Front End 89 GHz</td>
<td>5</td>
<td>0.120</td>
<td>0.60</td>
</tr>
<tr>
<td>RF-Front End 182 GHz</td>
<td>5</td>
<td>0.15</td>
<td>0.75</td>
</tr>
<tr>
<td>Back-end 89 GHz (includes video board)</td>
<td>+15/-15</td>
<td>0.01</td>
<td>0.15</td>
</tr>
<tr>
<td>Back-end 182 GHz (includes video board)</td>
<td>+15/-15</td>
<td>0.06</td>
<td>0.90</td>
</tr>
<tr>
<td>FPGA + ADC</td>
<td>5</td>
<td>0.25</td>
<td>1.40</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>5.35</td>
</tr>
</tbody>
</table>
TEMPEST-D Prototype Bandpass Filters Measured at 165-182 GHz

- Measured center frequencies and bandwidths are well within error allocations.

<table>
<thead>
<tr>
<th>Performance (in GHz)</th>
<th>Requirement (in GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth-165</td>
<td>3.9</td>
</tr>
<tr>
<td>Bandwidth-176</td>
<td>2.232</td>
</tr>
<tr>
<td>Bandwidth-180</td>
<td>1.848</td>
</tr>
<tr>
<td>Bandwidth-182</td>
<td>1.989</td>
</tr>
<tr>
<td>Center freq-165</td>
<td>164.1</td>
</tr>
<tr>
<td>Center freq-176</td>
<td>174.4</td>
</tr>
<tr>
<td>Center freq-180</td>
<td>180.0</td>
</tr>
<tr>
<td>Center freq-182</td>
<td>181.9</td>
</tr>
</tbody>
</table>
Summary

- TEMPEST-D was selected for 90-day technology demonstration of capability of 6U-Class satellite constellations for NASA Earth Science
- Reduce risk, cost and development time for repeat-pass radiometry to measure temporal signatures of precipitation using small satellite constellations
- Provide first in-space technology demonstration of a millimeter-wave radiometer based on an InP HEMT low-noise amplifier front-end for Earth Science measurements
- Raise the TRL of the TEMPEST mm-wave radiometer instrument from 6 to 9 (scanning reflector to 7)
- Demonstrate the feasibility of differential drag maneuvers to achieve required time separation of 6U-Class satellites in the same orbital plane
- Demonstrate cross-calibration of TEMPEST mm-wave radiometers with GPM GMI and/or MHS with 2 K precision and 4 K accuracy.
- Rapid development cycle of two years from start of project to delivery for launch integration in Jul. 2017 for launch to ISS in early 2018
Thank you for your attention!
Mille grazie!
Backup Slides
TEMPEST-D Instrument: Initial Design

Five-frequency millimeter-wave radiometer at 91, 165, 176, 180 and 183 GHz
- MMIC-based
- Cross-track scanning
- Self-calibrating
TEMPEST-D Millimeter-Wave Direct-Detection Receiver

- Prototypes have been machined, assembled and tested successfully with healthy margins on error allocations.
JPL’s High-Altitude MMIC Sounding Radiometer (HAMSR)

HAMSR measures 50-58 GHz, 118 GHz and 183 GHz bands [Brown et al., *IEEE TGRS*, 2011].