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

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Comparison Between On-orbit Passive Microwave Sensors

Sensor A

Sensor B

87 GHz Brightness Temperature (K)

190 200 210 220 230 240 250 260 270 280 290
Sensor B
NOAA Advanced Technology Microwave Sounder (ATMS)
75 kg, 100 W, $$$$
TEMPEST addresses 2017 National Academies Earth Science Decadal Survey:

- **Why do convective storms, heavy precipitation, and clouds occur exactly when and where they do?** (“Most Important” Science Question W-4)
  - Providing global, *temporally-resolved observations of cloud and precipitation processes* using a train of 6U CubeSats with millimeter-wave radiometers
  - Sampling rapid changes in convective clouds and surrounding water vapor environment every 3-4 minutes for up to 30 minutes.

- TEMPEST-D, a NASA Earth Venture Tech Demo mission, delivered a 6U CubeSat with radiometer instrument to launch provider 2.5 years after project start.
  - Launch provided by CSLI on ELaNa 23
  - Launched by Orbital ATK on CRS-9 from NASA Wallops to ISS on May 21, 2018
  - Deployed into orbit from ISS by NanoRacks on July 13, 2018
TEMPEST CubeSat Train

Uniquely samples developing convection over 3-30 minute time scales
TEMPEST-D 6U-Class Spacecraft
XB1 Bus from Blue Canyon Tech.

- 45° Canted Solar Arrays
- Machined Aluminum Housing
- Horizontal Solar Arrays
- Globalstar Antenna
- Instrument
- Machined Aluminum Side Wall
- Hold Down Release Mechanism
- UHF Antenna
- Coarse Sun Sensor
- PSC Tabs or NLAS Corners
- Avionics Module
- GPS Antenna
- Interconnects
TEMPEST-D Instrument Performs End-to-End Radiometric Calibration

TEMPEST-D Instrument

- Observing Profile
- Brightness Temp. Time Series

Five-frequency millimeter-wave radiometer measures Earth scene up to ±60° nadir angles, for an 1550-km swath width from a initial orbit altitude of 400 km. Spatial resolution ranges from 13 km at 181 GHz to 25 km at 87 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).
NGC / JPL 35-nm InP HEMT
Low-Noise Amplifiers (LNAs)

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

Flight Model Radiometer Instrument
Built and Integrated at JPL

164-181 GHz Detectors

164-181 GHz Filter Bank

Scan Mechanism Controller
Scanning Reflector
Scanning Motor

164-181 GHz Power Divider
164-181 GHz Radiometer Front-end

87 GHz Radiometer Front-end
87 GHz BP Filter

Dual-Frequency Feed horn

Command & Data Handling and Power Distribution Subsystem

Ambient Calibration Target
TEMPEST-D Instrument Performance: Pre-Launch and On-Orbit

**Radiometric Resolution vs. Instrument Temperature**

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Pre-launch NEdT (K)</th>
<th>On-orbit NEdT (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>87</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>164</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>174</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>178</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>181</td>
<td>0.7</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Measured radiometric resolution (NEdT) with 5-ms integration time, both pre-launch and on-orbit, easily meet total noise requirements of 1.4 K for all five millimeter-wave radiometer channels.
Launched by Orbital ATK from NASA Wallops to ISS on May 21, 2018

Photo Credit: NASA
TEMPEST-D, a NASA Earth Venture Tech Demo mission, delivered a completed 6U CubeSat with radiometer instrument to launch provider 2.5 years after project start.
TEMPEST-D First Few Full Orbits on Sept. 11, 2018

TEMPEST-D 87 GHz Brightness Temperature (K)

Some gaps from incomplete or corrupted downlinked packets

87 GHz window channel sensitive to water vapor, clouds and precipitation.
TEMPEST-D Captured Three Hurricanes on Sept. 11, 2018

TEMPEST-D 164 GHz
Brightness Temperature (K)

Florence

Isaac

Helene
TEMPEST-D
HURRICANE DORIAN
10-DAY TRACK
Demonstrating capability of heterogeneous small satellite constellations
• September 28, 2018, TEMPEST-D and RainCube overflew Typhoon Trami < 5 minutes apart

• TEMPEST-D + RainCube + CYGNSS winds

• Typhoon Trami observed shortly after it had weakened from Cat 5 to Cat 2
TEMPEST-D Brightness Temperatures at 87 GHz on October 26, 2019

87 GHz Brightness Temp.

T_B (K)

190 200 210 220 230 240 250 260 270 280 290
TEMPEST-D Brightness Temperatures at 87 GHz on November 11, 2019

87 GHz Brightness Temp.
TEMPEST-D Brightness Temperatures at 164-181 GHz on October 26, 2019

164 GHz Brightness Temp.

174 GHz Brightness Temp.

178 GHz Brightness Temp.

181 GHz Brightness Temp.

TB (K)
TEMPEST-D Brightness Temperatures at 164-181 GHz on November 11, 2019

164 GHz Brightness Temp.

174 GHz Brightness Temp.

178 GHz Brightness Temp.

181 GHz Brightness Temp.

T_B (K)
TEMPEST-D Brightness Temperatures at 87 GHz on May 12-19, 2019

One Week of TEMPEST-D Data
TEMPEST-D demonstrates improved receiver performance over the current generation of NOAA operational sensors.

Radiometer Noise

- Extremely low-noise due to new InP HEMT amplifier technology
- Stable over mission to date

<table>
<thead>
<tr>
<th>NEDT @ $T_A = 300K$</th>
<th>TEMPEST-D$^1$</th>
<th>NPP ATMS$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>18 ms Integration Time &amp; ATMS Bandwidths</td>
<td></td>
<td></td>
</tr>
<tr>
<td>87 GHz</td>
<td>0.13 K</td>
<td>0.29 K</td>
</tr>
<tr>
<td>164 GHz</td>
<td>0.25 K</td>
<td>0.46 K</td>
</tr>
<tr>
<td>174 GHz</td>
<td>0.2 K</td>
<td>0.38 K</td>
</tr>
<tr>
<td>178 GHz</td>
<td>0.25 K</td>
<td>0.54 K</td>
</tr>
<tr>
<td>181 GHz</td>
<td>0.7 K</td>
<td>0.73 K</td>
</tr>
</tbody>
</table>

$^1$ Equivalent NEDT for ATMS bandwidth/integration time

$^2$ Kim et al., 2014
Cross-Calibration of TEMPEST-D with NASA, NOAA & EUMETSAT Sensors

- Double difference technique developed for GPM used to evaluate TEMPEST-D calibration compared to reference sensors; maps other sensors’ observations to TEMPEST frequencies and view angles
- TEMPEST calibration within 1.3 K of reference sensors, meeting accuracy requirement of 4 K.
- TEMPEST stability within 0.7 K of reference sensors, meeting precision requirement of 2 K.
- Model uncertainty contributes to larger differences for 164 GHz channel
- Results indicate TEMPEST-D a very well calibrated and stable radiometer with very low noise, rivaling that of much larger operational instruments.

Calibration Differences in Kelvin (Reference – TEMPEST-D)

<table>
<thead>
<tr>
<th>Reference Sensor</th>
<th>87 GHz</th>
<th>164 GHz</th>
<th>174 GHz</th>
<th>178 GHz</th>
<th>181 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPM GMI</td>
<td>-0.56</td>
<td>-0.30</td>
<td>0.81</td>
<td>0.19</td>
<td>N/A</td>
</tr>
<tr>
<td>MetOp-A MHS</td>
<td>-0.33</td>
<td>-1.12</td>
<td>0.96</td>
<td>-0.17</td>
<td>-0.47</td>
</tr>
<tr>
<td>MetOp-B MHS</td>
<td>-0.33</td>
<td>-1.23</td>
<td>0.94</td>
<td>-0.43</td>
<td>-0.84</td>
</tr>
<tr>
<td>NOAA-19 MHS</td>
<td>-0.39</td>
<td>-2.07</td>
<td>-0.12</td>
<td>-0.61</td>
<td>-0.82</td>
</tr>
<tr>
<td><strong>Mean Difference</strong></td>
<td><strong>-0.39</strong></td>
<td><strong>-1.25</strong></td>
<td><strong>0.61</strong></td>
<td><strong>-0.29</strong></td>
<td><strong>-0.72</strong></td>
</tr>
<tr>
<td><strong>Standard Deviation</strong></td>
<td><strong>0.09</strong></td>
<td><strong>0.63</strong></td>
<td><strong>0.45</strong></td>
<td><strong>0.30</strong></td>
<td><strong>0.17</strong></td>
</tr>
</tbody>
</table>

Mean calibration differences between TEMPEST-D and four reference sensors based on 21 days of data. Dashed lines indicate corresponding mean scene brightness temperature.
TEMPEST-D Stability with Instrument Temperature over 1 Year of Operations

- Mean calibration differences between TEMPEST-D and four reference sensors as a function of instrument temperature over a full year of on-orbit operations.

- Solid lines show calibration difference (K, left axis). Dashed lines show the number of observations in the 2-degree interval (right axis).

- All five channels exhibit consistent calibration differences across the full range of observed instrument temperatures, showing no evidence of calibration errors associated with changes in instrument temperature.
TEMPEST-D 360° Pitch Maneuver for Antenna Pattern Correction

- 360° pitch maneuver performed to characterize antenna pattern correction over scan
- Scan dependent biases < 0.5 K for all channels prior to antenna pattern correction
Near-coincident observations with MHS on MetOp-B on Dec. 9, 2018 at 11:24 UTC

The two instruments and retrieval algorithms agree on the main features of the water vapor field, with no sharp gradients between the two swaths

They also agree well on the location of liquid phase clouds to the south of Japan, as well as the existence of ice particles to the north of Papua New Guinea
Along-Track Scanning using a Passive Microwave Sounder on a 6U CubeSat

- Cross-track scanning, typical for microwave sounders, provides a wide swath.
- Along-track scanning experiment provides a narrow swath, but any footprint on Earth’s surface is observed many times.
- For clear skies, evaluate consistency of the retrieved products.
- For convective activity, investigate effects of different slant path geometries.
Along-Track Scanning: Atmospheric Parameter Retrieval Results

Results suggest that the uncertainty/noise inherent in making measurements with different slant paths is small compared to spatial variability, particularly in cloud liquid water.
Thank you for your kind attention. Thanks to the NASA Earth Venture Tech Program for their support. Thanks to the NASA Earth Science Technology Office for program management.

Data are publicly available at tempest.colostate.edu
Backup Slides
Southeastern U.S. Precipitation: Comparison with Ground Radar Rainfall

TEMPEST-D observations from Jan. 29, 2019 over a southeastern U.S. winter storm, with ground-based weather radar rainfall estimates shown in the lower-right panel. Circles show the area covered by each ground-based radar.
TEMPEST-D and ATMS NPP data are statistically equivalent on all observed spatial scales.