Early Results and Potential Earth Science Applications: Temporal Experiment for Storms and Tropical Systems Technology Demonstration (TEMPEST-D) 6U CubeSat Mission

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Thanks to NASA Wallops for providing ground station communications support.
Comparison Between On-orbit Passive Microwave Sensors

Sensor A

Sensor B

Oct. 16, 2018
12 UTC
Southern Ocean

87 GHz Brightness Temperature (K)
Comparison Between On-orbit Passive Microwave Sensors

Sensor A

Sensor B

87 GHz Brightness Temperature (K)

11-Dec-2018
Sensor B
NOAA Advanced Technology Microwave Sounder (ATMS)
75 kg, 100 W, $$$$ 

Sensor A
TEMPEST-D
3.8 kg, 6.5 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?
  - 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
  - Demonstrated 7 months of mission lifetime to date since commissioning.
TEMPEST-D Instrument Performs End-to-End Radiometric Calibration

TEMPEST-D Instrument

- Command & Data Handling electronics
- Scan mechanism
- Direction of satellite motion
- Antenna reflector

Observing Profile

- 30°
- Up to 120° Nadir

Time Series of Output Data

- 174 GHz On-Orbit Calibrated Scan Data
- Calibration Target

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).
TEMPEST-D Spacecraft Integrated at BCT in Feb. 2018
Launched on NASA ELaNa 23 by Orbital ATK to ISS on May 21, 2018

Photo Credit: NASA
TEMPEST-D and CubeRRT Deployed by NanoRacks on July 13, 2018
TEMPEST-D First Full Orbit 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 Hurricane Florence in its first full-swath orbit on Sept. 11, 2018

The 164 GHz color image shows the convection and intense rain bands around the inner core through the ice scattering signature. The greyscale image shows geostationary visible signature.
On 28 Sept. 2018, TEMPEST-D and RainCube overflew Typhoon Trami < 5 minutes apart.

RainCube nadir Ka-band reflectivity shown overlaid on TEMPEST-D 164 GHz brightness temperature illustrating complementary nature of these sensors and potential for constellation use to observe precipitation.

Trami observed shortly after it had weakened from Cat 5 to Cat 2.
TEMPEST-D Sounding Channels provide 4 levels of vertical resolution to “slice” precipitation and compare with RainCube profile.

Similar asymmetry observed in depth of eyewall convection between TEMPEST-D and RainCube (strongest on west side and to the south).
TEMPEST-D Brightness Temperatures at 164-181 GHz on Dec. 9, 2018

TEMPEST-D 164 GHz

TEMPEST-D 174 GHz

TEMPEST-D 178 GHz

TEMPEST-D 181 GHz

$T_B$ (K)
TEMPEST-D Brightness Temperatures at 87 GHz from Dec. 8 to 14, 2018

12/08/2018

200 220 240 260 280
Validation of TEMPEST-D Data using 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 contributing to larger differences for 164 GHz channel.
- Results indicate TEMPEST-D is a very well-calibrated radiometer, indistinguishable from operational-class imaging radiometers.

Mean calibration differences between TEMPEST-D and four reference sensors based on 18 days of data. Dashed lines indicate corresponding mean scene brightness temperature.

<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>-0.60</td>
<td>-0.33</td>
<td>0.81</td>
<td>0.13</td>
<td>N/A</td>
</tr>
<tr>
<td>MetOp-A MHS</td>
<td>-0.22</td>
<td>-1.16</td>
<td>0.93</td>
<td>-0.17</td>
<td>-0.48</td>
</tr>
<tr>
<td>MetOp-B MHS</td>
<td>-0.25</td>
<td>-1.19</td>
<td>1.02</td>
<td>-0.36</td>
<td>-0.79</td>
</tr>
<tr>
<td>NOAA-19 MHS</td>
<td>-0.37</td>
<td>-2.16</td>
<td>-0.21</td>
<td>-0.68</td>
<td>-0.84</td>
</tr>
<tr>
<td><strong>Mean Difference</strong></td>
<td><strong>-0.35</strong></td>
<td><strong>-1.26</strong></td>
<td><strong>0.61</strong></td>
<td><strong>-0.29</strong></td>
<td><strong>-0.71</strong></td>
</tr>
<tr>
<td><strong>Standard Deviation</strong></td>
<td><strong>0.15</strong></td>
<td><strong>0.65</strong></td>
<td><strong>0.49</strong></td>
<td><strong>0.29</strong></td>
<td><strong>0.16</strong></td>
</tr>
</tbody>
</table>
TEMPEST-D Met Mission Success Criteria in First 90 Days

- Demonstrate that TEMPEST-D radiometers remain cross-calibrated with at least one other orbiting radiometer with inter-satellite precision of 2 K and accuracy of 4 K
  - Measured calibration stability within 0.7 K and accuracy within 1.3 K of reference sensors ✓
- Demonstrate the feasibility of orbital drag maneuvers to control 6U CubeSat satellite altitude to 100 m or better, to show ability to achieve relative positioning in an orbiting train
  - Showed that TEMPEST-D altitude can be controlled to 50 m or better using attitude control relative to CubeRRT ✓
- Demonstrate orbital operations for more 90 days after spacecraft and instrument commissioning
  - Demonstrated mission operations since commissioning for more than 7 months to date ✓
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**
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 using a 6U CubeSat: Preliminary Results

- Performed along-track scanning at 92-degree yaw attitude for more than 12 hours on each of Jan. 29 and 30, 2019.
- Repeated experiment for more than 16 hours on Apr. 8, 2019.

- Retrieved Total Water Vapor (TPW) is stable with Earth incidence angle (EIA), for a short period (above).
- Retrieved TPW is stable over 24 hours (right). EIA bias is still under study.
TEMPEST-D Mission Summary

• TEMPEST-D, a NASA Earth Venture Tech Demonstration mission, met its success criteria within the first 90 days of operations.

• Demonstrated potential for a train of identical TEMPEST 6U CubeSats to perform *first temporal* global measurements of clouds and precipitation at 3-4 minute spacing for up to 30 minutes.

• Demonstrated mission operations since spacecraft commissioning for more than 7 months to date

• Demonstrated that quality of TEMPEST-D data is indistinguishable from that acquired by well-established operational radiometers, even though the 6U CubeSat is a fraction of the size and costs significantly less.

• Demonstrated cross-calibration of TEMPEST radiometers with NASA, NOAA and EUMETSAT reference sensors with accuracy of 1.3 K or better and stability of 0.7 K or better.

• Demonstrated rapid development of a 6U CubeSat for Earth Science technology demonstration, 2.5 years from project start to launch delivery.
Thank you for your kind attention. Thanks to the NASA Earth Venture Program and CSLI for their support. Thanks to the NASA Earth Science Technology Office for program management.