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

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ABSTRACT

The Temporal Experiment for Storms and Tropical Systems Technology Demonstration (TEMPEST-D) mission is to demonstrate the capability of 6U-Class satellite constellations to perform repeat-pass radiometry to measure clouds and precipitation with high temporal resolution on a global basis. The TEMPEST mission concept is to improve understanding of clouds and precipitation by providing critical information on their time evolution in different climatic regimes. Measuring at five frequencies from 89 to 182 GHz, TEMPEST-D millimeter-wave radiometers are capable of penetrating into the cloud to observe changes as precipitation begins or ice accumulates inside the storm. The TEMPEST-D flight model radiometer instrument has been completed, passed functional testing, vibration testing and self-compatibility testing with the XB1 spacecraft bus. The next steps for the TEMPEST-D millimeter-wave radiometer are thermal vacuum testing and antenna pattern measurements. The complete TEMPEST-D flight system will be delivered to NanoRacks for launch integration in the autumn of 2017, in preparation for launch to the ISS in the second quarter of 2018, with deployment shortly thereafter into a nominal orbit at 400-km altitude and 51.6° inclination.

INTRODUCTION

Over the past 5-10 years, small and nano-satellites known as CubeSats (a.k.a. U-Class satellites) have increased in capability and reliability due to the increasing maturity of industry partners providing standardized spacecraft, payload integration, launch and operations. What started as an educational standard to broaden access to space has become increasingly attractive to industry for Earth imaging, and to government and universities to accomplish in-space technology demonstration and global science observations. In particular, CubeSats have recently begun to enhance the science measurement capabilities[1] of national and international space agencies, including NASA, ESA, and many others. Efforts in this area have focused on developing and exploiting the unique advantages that CubeSats bring to bear to accomplish the goals of Earth observation and remote sensing. These include rapid development cycles with the potential for incorporating the latest technological developments, lower mission costs enabled by reduced overhead by allowing reasonable risks deemed not acceptable for larger missions, and lower cost access to space as secondary payloads on launches of opportunity.

In particular, CubeSats can provide enhanced capabilities for microwave and millimeter-wave remote sensing for Earth observations, focused on rapid refresh times that are generally unavailable from low Earth orbit by using CubeSat constellations. In particular, CubeSats have the potential to improve remote sensing of clouds and precipitation, including tropical storms, hurricanes, cyclones and typhoons. Visible and infrared measurements of clouds are operationally available from geostationary orbit with rapid refresh times. However, due to the large absorption of infrared and visible wavelengths within clouds, these images are sensitive to the cloud-top temperature but do not penetrate significantly below the cloud tops[2]. In contrast, passive millimeter-wave measurements penetrate deep into the cloud to observe changes as precipitation begins or ice accumulates inside the cloud[3,4]. A constellation of 6U-Class satellites, each with an identical millimeter-wave radiometer instrument, can provide global observations of the transition from non-precipitating to precipitating clouds with high temporal resolution, as described by Reising *et al.*[5].

TEMPEST TECHNOLOGY DEMONSTRATION MISSION

The Temporal Experiment for Storms and Tropical Systems (TEMPEST) mission, as proposed to the NASA Earth Venture Instrument-2 program in November 2013, consists of a constellation of five identical 6U-Class satellites, each carrying a five-frequency millimeter-wave radiometer and flying five minutes apart in the same orbital plane. When deployed from the International Space Station (ISS) into a nominal orbit at 400-km altitude and 51.6° inclination, such a one-year constellation mission could observe more than 3,000,000 time-resolved observations of precipitation, including at least 100,000 deep-convection events. In addition, more than 50,000 of the 3,000,000 observed events would be coincident with the NASA/JAXA Global Precipitation Mission's (GPM) core satellite, providing substantial additional information from both the Global Microwave Imager (GMI) radiometer and the Dual-frequency Precipitation Radar (DPR).

TEMPEST was selected by NASA Earth Venture in July 2014 to perform in-space technology demonstration managed by the NASA Earth Science Technology Office (ESTO). The TEMPEST-D (Demonstration) project commenced in August 2015, with a two-year development cycle, to deliver one complete 6U flight system with integrated payload for launch integration at NanoRacks in the autumn of 2017. The TEMPEST-D project will also produce one complete flight system spare to reduce launch risk. TEMPEST-D is conducted by a highly collaborative experienced team led by Colorado State University, responsible for overall project leadership and radiometer data validation; NASA/Caltech Jet Propulsion Laboratory, providing the radiometer instrument payload and radiometer calibration; and Blue Canyon Technologies Inc., responsible for the spacecraft bus, payload integration into the flight system, as well as launch support and flight operations.

TEMPEST-D has been manifested by NASA's CubeSat Launch Initiative[6] on Educational Launch of Nanosatellites (ELaNa) XXIII, currently planned for launch to the ISS in the second quarter of calendar year 2018. The ELaNa XXIII launch will be operated by an ISS Commercial Resupply Service (CRS) provider (TBD), such as SpaceX or Orbital ATK. Within a few months after they arrive at ISS, TEMPEST-D and other U-Class satellites will be deployed into orbit via a NanoRacks CubeSat Deployer[7] attached to the robot arm connected to the Japanese Experiment Module on the ISS.

TEMPEST-D Goals and Success Criteria

TEMPEST-D is intended to reduce the risk, cost and development time for 6U-Class satellite constellations to perform Earth observations with rapid refresh times. Secondly, the TEMPEST-D project is to increase the Technology Readiness Level (TRL) of the millimeter-wave radiometer instrument from 6 to 9. Finally, TEMPEST-D is to provide the first in-space demonstration of a millimeter-wave radiometer based on an InP HEMT low-noise amplifier (LNA) front end for Earth Science observations.

The TEMPEST-D mission success criteria for a 90-day mission after on-orbit commissioning are as follows: (1) to demonstrate feasibility of differential drag measurements required to achieve the desired time separation of 6U-Class satellites deployed together in the same orbital plane, and (2) to demonstrate cross-calibration with 2 K precision and 4 K accuracy between TEMPEST-D millimeter-wave radiometers and the NASA/JAXA GPM/GMI or the Microwave Humidity Sounder currently in orbit on two NOAA satellites and two ESA/EUMETSAT satellites.

TEMPEST-D MM-WAVE RADIOMETER PAYLOAD

The TEMPEST-D millimeter-wave radiometer performs continuous measurements at five frequencies, 89, 165, 176, 180 and 182 GHz. The five-frequency radiometer is based on the direct-detection architecture, in which the RF input to the feed horn is amplified, bandlimited, and detected using Schottky diode detectors[8]. The use of direct-detection receivers based on InP HEMT MMIC LNA front ends substantially reduces the mass, volume and power requirements of these radiometers[9]. Input signals are bandlimited using waveguide-based bandpass filters to meet the radiometer bandwidth requirements of 4±1 GHz at center frequencies of 89 and 165 GHz, as well as 2±0.5 GHz at 176, 180 and 182 GHz center frequencies.

The TEMPEST-D radiometer performs cross-track scanning, measuring the Earth scene between -45° and

+45° nadir angles, providing an 825-km wide swath from a 400-km nominal orbit altitude. Each radiometer pixel is sampled for 5 ms. The radiometer performs end-to-end calibration during each rotation of the scanning reflector. The radiometer observes both cosmic background radiation at 2.7 K and an ambient blackbody calibration target (at approximately 300 K) every 2 seconds, for a scan rate of 30 RPM. A schematic representation of the TEMPEST-D observing profile over a 360° reflector scan and the resulting output data time series are shown in Figure 1.

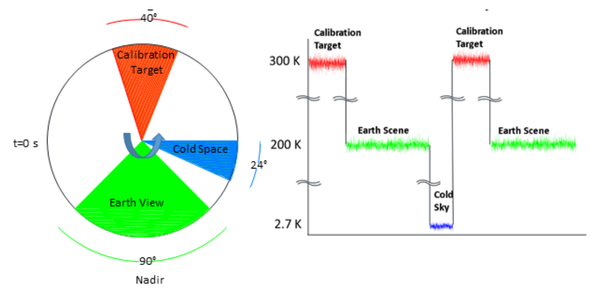

Figure 1: Schematic representation of TEMPEST-D observing profile (left) and output data time series (right) for each reflector scan

The TEMPEST-D flight model radiometer instruments (two copies, FM1 and FM2) have been designed, fabricated and integrated at JPL. Figure 2 shows the TEMPEST-D instrument, including scanning reflector (top left), dual-frequency feed horn originally developed under a NASA ESTO Advanced Component Technology (ACT-08) program (center left) and the four radiometer channels from 165 to 182 GHz, including front-ends, power divider, bandpass filter bank and detectors. Measurements of the receiver bandpass and linearity of each of the five frequency channels have been performed at JPL.

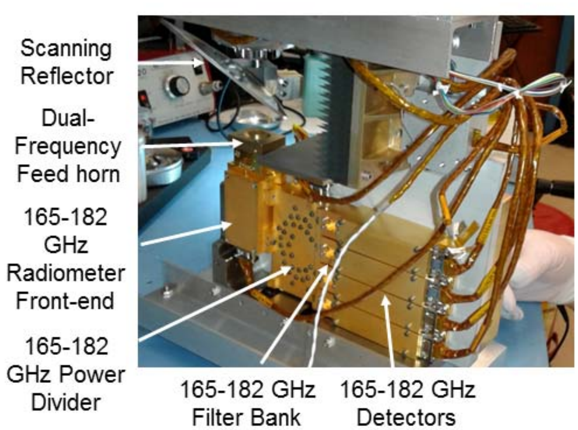

Figure 2: TEMPEST-D flight model radiometer instrument ready for delivery at JPL

Both TEMPEST-D flight model instruments have been integrated with the XB1 6U spacecraft avionics and bus at BCT, as shown in Figure 3. The TEMPEST-D flight model radiometer and spacecraft bus have passed electromagnetic self-compatibility tests in an anechoic chamber designed for EMI testing.

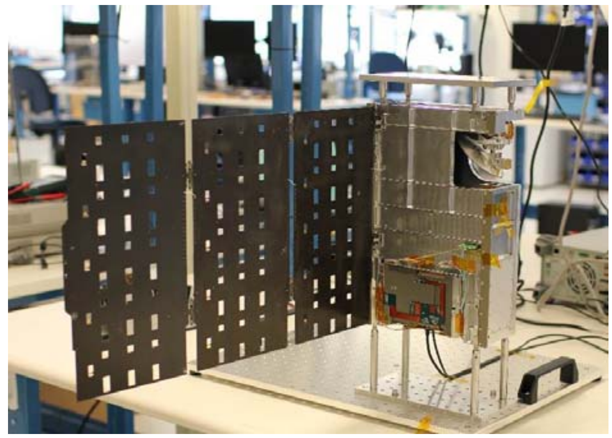

Figure 3: TEMPEST-D flight model radiometer instrument and XB1 spacecraft bus for self-compatibility testing at BCT

The TEMPEST-D flight model radiometer instrument has passed vibration testing to General Environmental Verification Standard (GEVS) levels at JPL. Figure 4 shows the TEMPEST-D flight model instrument in the configuration for vibration testing. The receiver characteristics have been measured and compared for both pre- and post-vibration testing. The next steps for the flight model radiometer instrument are thermal vacuum (TVAC) testing and antenna radiation pattern testing at JPL.

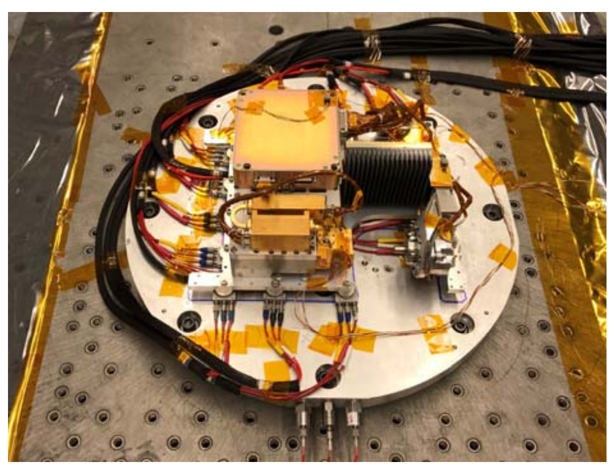

Figure 4: TEMPEST-D flight model radiometer instrument in vibration testing configuration at JPL

SUMMARY

The Temporal Experiment for Storms and Tropical Systems Technology Demonstration (TEMPEST-D) mission is under development to demonstrate the capability of 6U-Class satellite constellations to perform global observations of clouds and their transition to precipitation. This will reduce the risk, cost and development time for repeat-pass radiometry to measure clouds and precipitation with high temporal resolution. TEMPEST-D is to provide the first in-space technology demonstration of a millimeter-wave radiometer based on an InP HEMT LNA-based front-end for Earth Science measurements. In addition, the TEMPEST-D mission is to raise the TRL of the millimeter-wave radiometer instrument from 6 to 9.

The TEMPEST-D instrument is a millimeter-wave, self-calibrating radiometer measuring at five frequencies from 89 to 182 GHz. Two copies of the flight model radiometer instrument have been produced at JPL. The receiver channels have been characterized in terms of bandpass response and linearity. The TEMPEST-D radiometer instrument has passed vibration testing to GEVS levels at JPL. The flight model radiometer has been integrated into the XB1 6U spacecraft bus at BCT and has successfully passed electromagnetic self-compatibility testing.

The TEMPEST-D flight system will be ready for delivery to NanoRacks in the autumn of 2017 for launch integration. TEMPEST-D has been manifested for launch on NASA CSLI's ELaNa XXIII to the ISS in the second quarter of 2018. TEMPEST-D is expected to be deployed within a few months via the NanoRacks CubeSat Deployer into a nominal orbit of 400-km altitude and 51.6° inclination. The TEMPEST-D mission is for 90 days after on-orbit commissioning to demonstrate cross-calibration with existing millimeter-wave radiometers, GPM/GMI or MHS. Differential drag maneuvers will be demonstrated to achieve required time separation of members of a 6U-Class satellite constellation performing repeat-pass radiometry in a single orbital plane.

Acknowledgments

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References

1. Committee on Achieving Science Goals with CubeSats, "Achieving Science with CubeSats: Thinking Inside the Box," The National Academies, Washington DC, 130 pp., 2016.
2. Takahashi, H., and Z. J. Luo, "Characterizing tropical overshooting convection from joint analysis of CloudSat and geostationary satellite observations," *J. Geophys. Res.*, vol. 119, pp. 112-121, 2014.
3. Spencer, R. W., H. M. Goodman, and R. E. Hood, "Precipitation retrieval over land and ocean with the SSM/I: Identification and characteristics of the scattering signal," *J. Atmos. Oceanic Technol.*, vol. 6, pp. 254-273, 1989.
4. Mohr, K. I., and E. J. Zipser, "Defining mesoscale convective systems by their 85-GHz ice scattering signatures," *Bull. Amer. Meteor. Soc.*, vol. 77, pp. 1179–1189, 1996.
5. Reising, S. C., T. C. Gaier, C. D. Kummerow, V. Chandrasekar, S. T. Brown, S. Padmanabhan, B. H. Lim, S. C. van den Heever, T. S. L'Ecuyer, C. S. Ruf, Z. S. Haddad, Z. J. Luo, S. J. Munchak, G. Berg, T. Koch and S. A. Boukabara, "Overview of Temporal Experiment for Storms and Tropical Systems (TEMPEST) CubeSat Constellation Mission," *2015 IEEE MTT-S International Microwave Symposium Digest*, Phoenix, Arizona, May 2015, pp. 1-4.
6. Reising, S. C., P. Kangaslahti, S. T. Brown, NASA CubeSat Launch Initiative, Online at: https://www.nasa.gov/content/about-cubesat-launch-initiative. Last viewed on June 22, 2017.
7. NASA International Space Station: NanoRacks CubeSat Deployer. Online at: https://www.nasa.gov/mission_pages/station/research/experiments/1350.html. Last viewed on June 22, 2017.
8. D. E. Dawson, A. L. Lee, D. P. Albers, O. Montes, T. C. Gaier, D. J. Hoppe, and B. Khayatian, "InP HEMT low-noise amplifier-based millimeter-wave radiometers from 90 to 180 GHz with internal calibration for remote sensing of atmospheric wet-path delay," *2012 IEEE MTT-S International Microwave Symposium Digest*, Montreal, Quebec, Canada, June 2012, pp. 1-3.
9. Kangaslahti, P., E. Schlecht, J. Jiang, W. R. Deal, A. Zamora, K. Leong, S. C. Reising, X. Bosch and M. Ogut, "CubeSat Scale Receivers for Measurement of Ice in Clouds," *Proc. 14th Specialist Meeting on Microwave Radiometry and Remote Sensing of the Environment (MicroRad 2016)*, Espoo, Finland, April 2016, pp. 42-47.