# Atmospheric Science Achievements and Perspectives from a 3-Year CubeSat Mission: Temporal Experiment for Storms and Tropical Systems – Demonstration (TEMPEST-D)

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## ABSTRACT

Temporal Experiment for Storms and Tropical Systems – Demonstration (TEMPEST-D) is a nearly 3-year NASA mission to demonstrate global observations from a multi-frequency microwave sensor deployed on a 6U CubeSat platform. The TEMPEST constellation was originally proposed in 2013 to perform high temporal resolution observations of rapidly evolving storms using a constellation of five identical 6U CubeSats in a single orbital plane. To demonstrate necessary capability to successfully operate the TEMPEST constellation, NASA's Earth Venture Technology program funded the production, deployment and operation of a TEMPEST-D, a multi-frequency microwave radiometer on a 6U CubeSat, which was successfully delivered for launch less than 2 years after PDR. TEMPEST-D was launched to ISS on May 21, 2018 and deployed into orbit on July 13, 2018. TEMPEST-D performed the first global Earth observations from a multi-frequency microwave radiometer on a CubeSat. The TEMPEST-D mission substantially exceeded expectations in terms of data quality, stability, consistency and mission duration. TEMPEST-D data were validated using the double-difference technique for cross-calibration with scientific and operational microwave sensors observing at similar frequencies, including 4 MHS sensors on NOAA-19, MetOp-A, -B and -C, as well as GPM/GMI. These validation results showed that TEMPEST had comparable or better performance to much larger operational sensors in terms of calibration accuracy, precision and stability throughout the nearly 3-year mission. TEMPEST-D performed detailed observations of the microphysics of hurricanes, typhoons and tropical cyclones during three consecutive hurricane seasons. After accomplishing all of its success criteria within the first 90 days of operations, TEMPEST-D continued to produce high-quality atmospheric science data for nearly three years, until it re-entered the Earth's atmosphere on June 21, 2021.

## 1 INTRODUCTION

The Temporal Experiment for Storms and Tropical Systems – Demonstration (TEMPEST-D) mission is a NASA SMD/ESD Earth Venture Technology Demonstration mission operating a single 6U CubeSat to demonstrate technology necessary for a CubeSat constellation to observe temporal changes in convective storms and the surrounding water vapor environment. The TEMPEST-D mission focuses on demonstration of the ability to perform global observations from a passive microwave/millimeter-wave sounder/imager deployed on a 6U CubeSat. The TEMPEST mission was originally proposed to NASA's Earth Venture Instrument-2 in November 2013 as a constellation of five identical 6U CubeSats with multi-frequency passive microwave sensors in a single orbital plane. Such a CubeSat constellation mission would provide 7-minute temporal sampling of rapidly-developing convective activity over a nearly 30-minute period [1]. To demonstrate the necessary technology and capability for TEMPEST constellation operation, NASA's Earth Venture Technology program funded the TEMPEST-D mission to build, deploy and operate a multi-frequency microwave radiometer on a single 6U CubeSat [2]. The TEMPEST-D mission is a collaboration led by Colorado State University, responsible for the science and leading the validation, NASA/Jet Propulsion Laboratory (JPL), responsible for the design, production and testing of the microwave instrument (payload) as well as its calibration, and Blue Canyon Technologies (BCT), providing the XB1 spacecraft as well as payload integration to the spacecraft, flight qualification, and on-orbit operations throughout the mission.

## 2 TEMPEST-D CUBESAT MISSION

The TEMPEST-D Team successfully delivered the TEMPEST-D 6U CubeSat for launch integration in March 2018, less than 2 years after the preliminary design review (PDR) for the project. Launch of the TEMPEST-D CubeSat was provided by NASA's CubeSat Launch Initiative on Orbital ATK's commercial resupply mission (CRS-9), that was launched from NASA Wallops to the International Space Station (ISS) on May 21, 2018. The TEMPEST-D CubeSat was deployed into low Earth orbit on July 13, 2018, nearly simultaneously with CubeRRT [3], and within several hours of RainCube [4]. A photo of both TEMPEST-D and CubeRRT on-orbit shortly after deployment is shown in Figure 1. TEMPEST-D was deployed into an initial orbit with 405-km altitude and 51.6° inclination. TEMPEST-D performed its first full-swath on-orbit observations on September 11, 2018. In just the first few orbits, TEMPEST-D performed well-calibrated observations of Hurricanes Florence, Helene and Isaac over the Atlantic Ocean.

Figure 1. Photograph of TEMPEST-D (right) and CubeRRT (left) shortly after deployment from the ISS on July 13, 2018. Credit: NASA.

NASA Wallops Flight Facility (WFF) provided satellite-to-ground communications throughout the mission using their 18-m UHF antenna and ground station. During the period from October 8, 2020 to March 21, 2021, the 18-m dish antenna at WFF was unexpectedly offline for maintenance. During this period, BCT commanded the TEMPEST-D spacecraft periodically using a backup UHF antenna from their facilities in Boulder, Colorado. These 10 ground contacts allowed TEMPEST-D to recover from sun pointing (default reset state after watchdog timeout) and move to fine reference pointing, thereby maintaining low-drag orientation and substantially extending the lifetime of the mission until WFF antenna operation was restored after nearly 6 months of downtime. When TEMPEST-D resumed operations in March 2021, it continued to produce the same quality of data as 6 months before.

After accomplishing all of its success criteria within the first 90 days of operations, TEMPEST-D continued to produce high-quality atmospheric science data nearly continuously for almost three years, until it re-entered the Earth's atmosphere on June 21, 2021. TEMPEST-D calibrated, geolocated brightness temperature measurements are publicly available at tempest.colostate.edu/data. These data have been downloaded by 57 user groups in 13 countries on 5 continents.

## 3 TEMPEST-D MILLIMETER-WAVE RADIOMETER INSTRUMENT

The TEMPEST-D instrument is a cross-track scanning millimeter-wave sounding radiometer with five frequency channels centered at 87, 164, 174, 178 and 181 GHz. The TEMPEST-D radiometer provides nadir footprint sizes ranging from 25 km at 87 GHz to 13 km at 181 GHz, from a nominal 400-km orbit. The TEMPEST-D instrument is the first on-orbit microwave radiometer to use the InP HEMT low-noise amplifier (LNA) based direct-detection receivers for Earth-viewing remote sensing. The instrument occupies 4U (about 22 x 20 x 10 cm) of volume inside a 6U or larger CubeSat, has 3.8 kg mass, consumes only 6.5 W of power and operates at nearly 100% duty cycle. Similar to operational microwave sounders in low-Earth orbit (LEO), TEMPEST-D observes the Earth scene up to ±60º nadir angles. TEMPEST-D performs end-to-end calibration every 2 seconds by measuring both cosmic microwave background at 2.73 K ("cold sky") and an ambient blackbody calibration target each revolution (scanning at 30 RPM). When operating at 100% duty cycle, the aggregate output data rate for the TEMPEST-D radiometer, is less than 12 kilobits/s, including housekeeping data. Padmanabhan *et al.* [5] provided a detailed description of the TEMPEST-D radiometer instrument and its testing, flight qualification and pre-launch characterization.

## 4 TEMPEST-D ON-ORBIT PERFORMANCE

TEMPEST-D performed the first global Earth observations from a multi-frequency microwave radiometer on a CubeSat. The TEMPEST-D mission substantially exceeded expectations of data quality, stability, consistency and mission duration. TEMPEST-D performed global passive microwave observations of the microphysics of hurricanes, typhoons and tropical cyclones from a CubeSat for 3 consecutive hurricane seasons (2018-2020). As part of its Level-1 success criteria for technology validation, TEMPEST-D demonstrated orbital drag maneuvers (scheduled attitude changes) to control 6U CubeSat altitude to 50 m or better, relative to CubeRRT that was deployed nearly simultaneously, as shown in Figure 1.

TEMPEST-D passive microwave brightness temperature data were validated by Berg *et al.* [6] using the double-difference technique for inter-calibration with existing scientific and operational microwave/millimeter-wave sensors operating at similar frequencies on traditional, much larger satellites. These include the Global Precipitation Mission Microwave Imager (GPM/GMI) and the 4 copies of the Microwave Humidity Sensor (MHS) on NOAA-19, as well as ESA/EUMETSAT MetOp-A, -B and -C. TEMPEST-D validation was performed using 50 days of data over a 13-month period from October 2018 to November 2019 [6]. Results showed that TEMPEST-D has comparable or better performance than much larger, more expensive satellite sensors in terms of instrument noise, calibration accuracy, precision and stability throughout the nearly 3-year mission. In terms of Earth science technology, TEMPEST-D provided the first on-orbit demonstration of long-term reliability as well as state-of-the art 1/f-noise performance of new InP HEMT amplifier technology developed jointly by JPL and Northrop Grumman Corporation [7].

## 5 TEMPEST-D ATMOSPHERIC SCIENCE ACCOMPLISHMENTS

Schulte *et al.* [8] used the Colorado State University (CSU) One-Dimensional Variational (1DVAR) retrieval algorithm to retrieve total precipitable water (TPW), cloud liquid water path (LWP), and cloud ice water path (IWP) from brightness temperature observations by TEMPEST-D and Microwave Humidity Sounder (MHS). These retrievals demonstrated similar performance by TEMPEST-D to the larger and more expensive MHS on ESA/EUMETSAT MetOp satellites.

Chandrasekar *et al.* [9] cross-validated TEMPEST-D passive microwave brightness temperature observations over precipitation systems using nearly simultaneous reflectivity observations by RainCube, the first weather radar on a CubeSat. Results of this validation showed very good qualitative agreement and quantitatively high correlation between the two datasets using complementary microwave remote sensing modalities. Radhakrishnan *et al.* [10, 11] implemented artificial neural networks to estimate surface rainfall from TEMPEST-D brightness temperature (TB) observations over ground weather radar networks. They showed that the rainfall estimated from TEMPEST-D observations matches that of ground radar products in terms of location and intensity. Finally, Goncharenko *et al.* [12] analyzed the performance of CubeSat constellations of radiometers to improve temporal resolution of both microwave temperature and humidity sounding as well as observations of rapidly-changing storms from low Earth orbit (LEO). The authors concluded that the deployment and operation of CubeSat constellations could provide the capability to dramatically reduce average revisit times for both weather forecasting and convective storm observations on a global basis. The aforementioned scientific studies demonstrate that TEMPEST-D substantially exceeded expectations and provided high scientific output for a modest investment by NASA's Earth Venture Technology Program.

## 6 TEMPEST-D FOLLOW-ON AND FUTURE MISSIONS

The accuracy, precision and stability of TEMPEST-D microwave radiometer on a 6U CubeSat demonstrated throughout the three-year mission open a myriad of possibilities for Earth observation and science missions on small satellites to enable rapid temporal observations of cloud and precipitation processes. During the development of the TEMPEST-D mission, a nearly identical microwave sensor, TEMPEST-D2, was produced alongside the original to reduce risk from the original manifest for launch. In 2021, TEMPEST-D2 was delivered to the U.S. Space Force for integration with the Compact Ocean Wind Vector Radiometer (COWVR), previously developed by NASA/JPL. On December 21, 2021, COWVR and TEMPEST-D2 were launched from KSC as part of the Space Test Program (STP-H8) mission for at least 3 years of Earth observations aboard the ISS. Both COWVR and TEMPEST-D2 microwave radiometers were successfully deployed on ISS on January 7-8, 2022. They have operated nearly continuously since that date. As such, these two passive microwave sensors provide a unique, synergistic opportunity for coordinated global observations of the Earth's oceans and atmosphere using complementary small satellite instruments. Finally, the demonstrated complementary passive/active microwave observations of TEMPEST-D and RainCube over storm systems was an important contributor to NASA's selection in November 2021 of the Investigation of Convective Updrafts (INCUS), as Earth Venture Mission-3, to be launched in 2026. INCUS is led by Colorado State University, in partnership with NASA's Jet Propulsion Laboratory and Blue Canyon Technologies. The INCUS constellation consists of three small satellites, each including an augmented version of the RainCube radar, as well as one TEMPEST-based microwave radiometer.

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