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Remote Sensing of Clouds and Precipitation Processes using Small Satellite Constellations: Perspectives from the 3-Year TEMPEST-D On-orbit Demonstration and Follow-on Missions

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The Temporal Experiment for Storms and Tropical Systems – Demonstration (TEMPEST-D) mission demonstrated the first global observations from a multi-frequency microwave radiometer on a CubeSat. Initially intended for three months of operations, the TEMPEST-D CubeSat was deployed from the ISS in July 2018 and continued performing nearly continuous atmospheric observations for three years until it re-entered the Earth's atmosphere in June 2021. This NASA Earth Venture Technology mission exceeded expectations in scientific data quality, instrument calibration, radiometer stability, and mission duration. TEMPEST-D brightness temperatures were validated using the double-difference technique for comparison with scientific and operational microwave sensors. Satellite microwave radiometers for comparison included GPM/GMI and four MHS sensors on NOAA and ESA/EUMETSAT satellites. These sensors operate at similar frequencies to TEMPEST-D, which observes at 87 GHz for total precipitable water, and at 164, 174, 178 and 181 GHz for water vapor sounding, cloud water and precipitation retrievals. During its nearly 3-year mission, TEMPEST-D was demonstrated to have performance comparable to or better than much larger, conventional operational sensors, in terms of calibration accuracy, precision, stability and instrument noise.

TEMPEST-D performed observations of hurricanes, typhoons and tropical cyclones during three consecutive hurricane seasons, in many cases nearly doubling the number of observations from GPM/GMI alone. Nearly simultaneous observations by TEMPEST-D and JPL's RainCube weather radar demonstrated a high degree of correlation between complementary passive and active microwave measurements of convective storms and tropical cyclones from the two CubeSats. TEMPEST-D periodically performed along-track scanning measurements, providing the first space-borne demonstration of "hyperspectral" microwave sounding observations to retrieve the height of the planetary boundary layer with high precision.

The highly successful, stable operation of the TEMPEST-D instrument on a 6U CubeSat for nearly three years paves the way for future opportunities to enhance microwave sounding and imaging of water vapor, clouds and precipitation. When the TEMPEST-D instrument was produced, a nearly identical TEMPEST sensor was built side-by-side for risk reduction. The other TEMPEST sensor was delivered to the U.S. Space Force and integrated with NASA/JPL's Compact Ocean Wind Vector Radiometer (COWVR). On December 21, 2021, COWVR and TEMPEST were launched from KSC as part of STP-H8 for 3 years of operations on the ISS. Since January 7, 2022, COWVR and TEMPEST-H8 have been performing complementary observations of the atmosphere and oceans. The air-sea interface & atmospheric profile (ASAP) Science Working Group has been formed at NASA/JPL to maximize scientific benefit from COWVR and TEMPEST-H8 observations.

Atmospheric inversion techniques have been developed to retrieve water vapor altitude profiles, as well as single-layer cloud liquid water and cloud ice water, from TEMPEST brightness temperature measurements, using ECMWF Reanalysis v5 (ERA5) data as an initial guess. These TEMPEST-D retrievals are being enhanced through the inclusion of geostationary infrared data from GOES-16 ABI channels, increasing the number of levels of water vapor retrieval and reducing retrieval error, particularly in the upper troposphere. In addition, quantitative precipitation estimates from TEMPEST-D on-orbit observations have been produced using a machine-learning approach. Precipitation retrievals over land-falling hurricanes, tropical cyclones and continental storms demonstrated very good agreement with multiradar/multisensor system (MRMS) quantitative precipitation estimates (QPE). These QPE retrievals are being expanded from CONUS-only to a global basis using the GPM IMERG precipitation dataset. Similar techniques are being applied to TEMPEST-H8 observations from the ISS to provide retrievals of water vapor profiles, cloud liquid water, cloud ice water, and precipitation.