Overview of Temporal Experiment for Storms and Tropical Systems (TEMPEST) CubeSat Constellation Mission

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***Abstract* — The proposed Temporal Experiment for Storms and Tropical Systems (TEMPEST) satellite mission addresses key science needs related to cloud and precipitation processes using a constellation of five CubeSats with identical five-frequency millimeter-wave radiometers spaced 5-10 minutes apart in orbit. This CubeSat constellation will directly observe the time evolution of clouds to study the conditions that control the transition of clouds to precipitation. The TEMPEST millimeter-wave radiometers will penetrate into the cloud to directly observe changes as the cloud begins to precipitate or ice accumulates inside the storm. TEMPEST provides observations at five millimeter-wave frequencies from 90 to 183 GHz using a single compact instrument that is well suited for a 6U CubeSat architecture and fits well within the NASA CubeSat Launch Initiative capabilities.**

***Index Terms* — high electron mobility transistors (HEMTs), indium phosphide (InP), low-noise amplifiers, monolithic millimeter-wave integrated circuits (MMICs), radiometers.**

I. Introduction

Knowledge of clouds, cloud processes and precipitation is essential to our understanding of climate and climate change [1]. Uncertainties in the representation of key processes that govern the formation and dissipation of clouds and, in turn, control the global water and energy budgets lead to substantially different predictions of future climate in current models [2, 3]. Over the past decade and a half, we have gained a better understanding of these parameters from focused Earth science observational satellite missions, including the NASA/JAXA Tropical Rainfall Measurement Mission (TRMM) and NASA's CloudSat/CALIPSO, as well as a host of suborbital experiments. The NASA/JAXA Global Precipitation Measurement (GPM) mission core satellite [4] that was successfully launched into orbit on February 28, 2014, substantially adds to this body of knowledge by providing precipitation observations of both liquid and solid hydrometeors having both higher latitude coverage and better sensitivity than TRMM has. While such large satellite missions as these, including international collaboration, were designed to provide comprehensive data on clouds and precipitation, each provides only a snapshot in time of each cloud's development. On the other hand, processes that control the development of cloud systems and the transition to precipitation occur primarily on time scales of the order of 5–30 minutes that are not generally observable from low Earth-orbiting satellites, including the ones described above, due to their repeat-pass times of many hours to days.

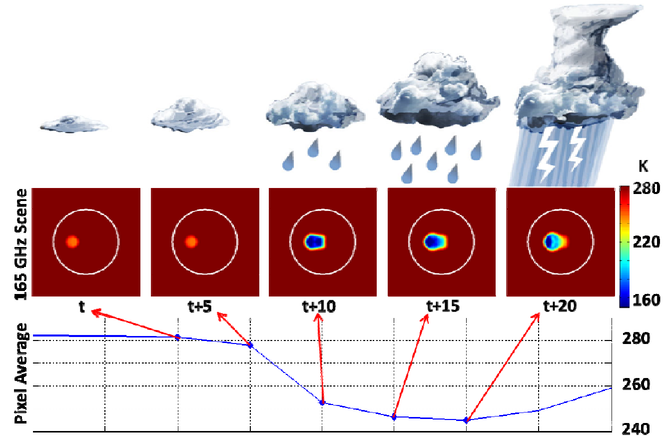

Fig. 1. The transition from clouds to precipitation is apparent at the millimeter-wave frequencies observed by TEMPEST, as is evident in the decrease in observed brightness temperatures. The top row depicts the time evolution of a convective system. The middle and bottom rows depict the evolution of millimeter-wave brightness temperatures at 165 GHz during the temporal development of the convective system. The circle with 25-km diameter shows the expected spatial resolution of TEMPEST. Infrared wavelengths are sensitive only to the cloud-top temperature. In contrast, millimeter-wave frequencies, including 165 GHz, penetrate into the clouds and detect the transition to precipitation.

II. TEMPEST Mission

The proposed TEMPEST mission will provide the first temporal observations of cloud and precipitation processes on a global scale. These observations are important to understand the linkages in and between Earth's water and energy balance, as well as to improve understanding of cloud model microphysical processes that are vital to climate change prediction.

Figure 1 illustrates the TEMPEST observational concept with five successive measurements at five-minute intervals over a cloud transitioning from non-precipitating to precipitating. The change is evident in the significant decrease in 165 GHz brightness temperature. This change is not observable in infrared measurements, which are currently available over large regions of the Earth at high temporal resolution from geostationary satellites, since the infrared measurement is sensitive only to the cloud top temperature and is unable to penetrate into clouds [5]. In contrast, millimeter-wave frequencies penetrate into the cloud to directly observe changes as the cloud begins to precipitate or as ice accumulates inside the storm (e.g., [6, 7]).

By measuring the evolution of clouds from the moment of the onset of precipitation, TEMPEST improves our understanding of cloud processes and helps to constrain one of the largest sources of uncertainty in climate models to address important science needs related to cloud and precipitation processes. Cloud processes are most critical in the development of climate models that will soon run at scales that explicitly resolve clouds and precipitation (e.g. [8, 9]). Therefore, the TEMPEST mission focuses directly on examining, validating and improving the parameterizations currently used in cloud scale models.

III. MILLIMETER-WAVE RADIOMETER INSTRUMENT DESIGN

TEMPEST uses a constellation of five CubeSats to provide temporal information on cloud and precipitation processes not available from any previous or existing spaceborne instruments. Each CubeSat contains a single instrument, an identical five-frequency millimeter-wave radiometer at 91, 165, 176, 180, and 183 GHz. The direct-detection architecture of the radiometer reduces its power consumption and eliminates the need for a local oscillator, reducing complexity. The post-detection electronics are based on Jason-1 through Jason-3 heritage adapted to the CubeSat form factor [10].

Figure 2 shows the physical design of the TEMPEST instrument which fits in a volume smaller than a standard 3U CubeSat (30 cm x 10 cm x 10 cm), although different in form factor. TEMPEST millimeter-wave radiometers view the Earth scene over the 825 km wide swath at the nominal 400-km altitude, and the scanning reflector provides two-point calibration each rotation using two known temperatures of an internal microwave blackbody absorber and the cosmic microwave background. This is a similar reflector scanning and calibration methodology, albeit in a much smaller form factor, to that used on the NOAA Advanced Technology Microwave Sounder (ATMS) [11] and on the Global Hawk unattended aerial vehicle (UAV) using the High Altitude MMIC Sounding Radiometer (HAMSR) [12].

The TEMPEST millimeter-wave radiometer design is based on recent technology developments using new 35-nm indium phosphide (InP) high-electron mobility transistor (HEMT)

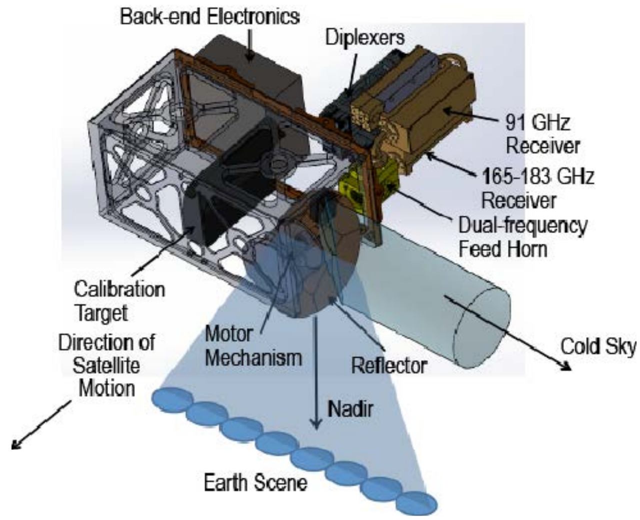

Fig. 2. The TEMPEST millimeter-wave radiometer instrument scans at 30 rpm to view the Earth scene across an 825-km swath.

low- noise amplifiers (LNAs) operating in a number of frequency bands from 90 to 183 GHz [13, 14]. These LNAs have been measured in a packaged MMIC-based receiver to have a noise temperature of 200 K and gain of 13-15 dB at 90 GHz as well as a noise temperature of 325-350 K and a gain of 16-18 dB at 165 to 183 GHz. These measurements were performed at room temperature in packaged waveguide modules [15, 16]. Each low-noise amplifier consumes 30 mW of power, and the technology has been tested across a wide range of temperatures and in vacuum [17].

The 91 GHz receiver is based on the 90-GHz receiver channel of the High-frequency Airborne Microwave and Millimeter-wave Radiometer (HAMMR), shown in Figure 3 [14]. The bandwidth is defined using low insertion loss microstrip coupled line filters on quartz substrates. The amplified 91 GHz signal is detected by a COTS zero-bias gallium arsenide (GaAs) detector diode, which has nonlinearity of better than 1%.

The TEMPEST receiver for the 165 to 183 GHz channels is nearly identical to that used by the Radiometer Atmospheric CubeSat Experiment (RACE), shown in Figure 3 [18]. The TEMPEST receivers have a noise temperature less than 500 K

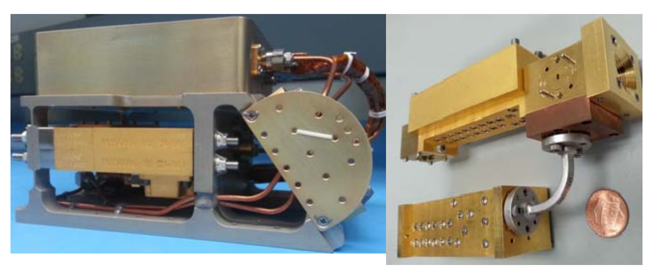

Fig. 3. RACE radiometer (left) and HAMMR radiometer (right) provide instrument heritage for TEMPEST radiometer design.

(4.3 dB) and a NEΔT of less than 0.25 K. The most challenging TEMPEST radiometer bandwidth of 2 GHz, or

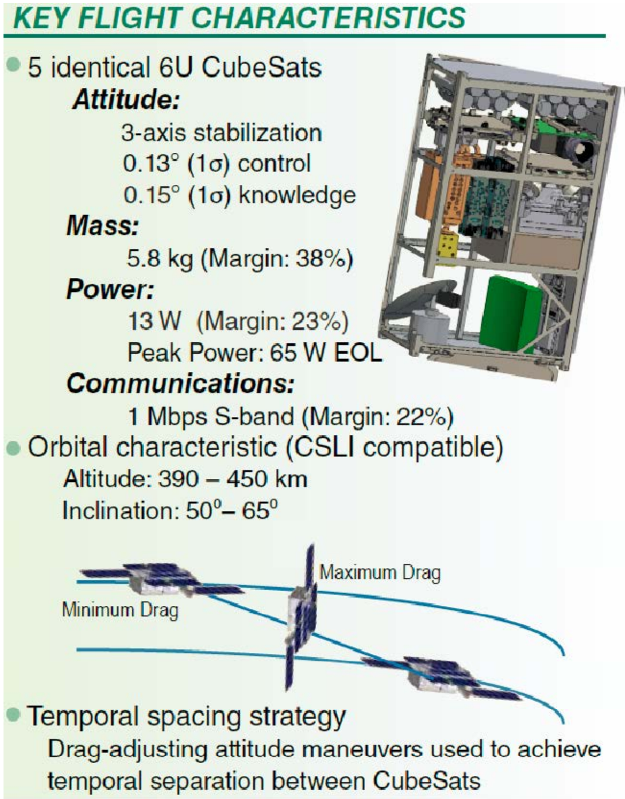

Fig. 4. TEMPEST flight system and 6U CubeSat characteristics

1%, at 180 and 183 GHz was already demonstrated using waveguide filters for RACE. RACE was manifested in the Orbital Sciences' ISS resupply mission that was lost during an explosion shortly after launch on October 28, 2014.

IV. TEMPEST Flight System

The TEMPEST mission is a constellation of five identical 6U CubeSats (30 x 20 x 10 cm, 8 kg), as shown in Figure 4. The CubeSats are deployed from a single launch vehicle, ensuring that all five are in the same orbit. Temporal spacing of five to ten minutes between successive spacecraft is established using a series of drag-adjusting attitude maneuvers. Mass, power and communications requirements are all met with margins of 22% to 38%, as shown in Figure 4.

V. Conclusion

The proposed TEMPEST mission will provide the first global observations of the time evolution of precipitation. Using a constellation of five CubeSats with identical five-frequency millimeter-wave radiometers launched together and spaced apart in orbit by five to ten minutes, TEMPEST addresses important science needs related to cloud and precipitation processes. TEMPEST measures at five millimeter-wave radiometer frequencies from 91 to 183 GHz based on recently-developed 35-nm gate length InP HEMT MMIC low-noise amplifiers. The cross-track scanning radiometer is calibrated each scan using internal and external loads. The compact radiometer is ideally suited to a 6U CubeSat architecture without sacrificing performance.

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