

On-Orbit Results from the NASA Time-Resolved Observations of Precipitation structure and Storm Intensity with a Constellation of Smallsats (TROPICS) Mission

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ABSTRACT

The NASA TROPICS Earth Venture (EVI-3) CubeSat constellation mission will provide nearly all-weather observations of 3-D temperature and humidity, as well as cloud ice and precipitation horizontal structure, at high temporal resolution to conduct high-value science investigations of tropical cyclones. TROPICS will provide rapid-refresh microwave measurements (median refresh rate better than 60 minutes for the baseline mission) over the tropics that can be used to observe the thermodynamics of the troposphere and precipitation structure for storm systems at the mesoscale and synoptic scale over the entire storm lifecycle. The TROPICS constellation mission comprises four 3U CubeSats (5.4 kg each) in two low-Earth orbital planes. Each CubeSat contains a Blue Canyon Technologies bus and a high-performance radiometer payload to provide temperature profiles using seven channels near the 118.75 GHz oxygen absorption line, water vapor profiles using three channels near the 183 GHz water vapor absorption line, imagery in a single channel near 90 GHz for precipitation measurements (when combined with higher resolution water vapor channels), and a single channel at 205 GHz that is more sensitive to precipitation-sized ice particles. TROPICS spatial resolution and measurement sensitivity is comparable with current state-of-the-art observing platforms. Two dedicated launches (two spacecraft per launch) for the TROPICS constellation mission on Rocket Lab Electron vehicles occurred in 2023 (May 8 and May 26) to place the spacecraft in 32.75-degree inclined orbits at 550 km altitude. Data will be downlinked to the ground via the KSAT-Lite ground network. NASA's Earth System Science Pathfinder (ESSP) Program Office approved the separate TROPICS Pathfinder mission, which launched on June 30, 2021, in advance of the TROPICS constellation mission as a technology demonstration and risk reduction effort. The TROPICS Pathfinder mission has provided an opportunity to checkout and optimize all mission elements prior to the primary constellation mission and is still operating nominally.

OVERVIEW OF THE TROPICS SPACECRAFT

The 5.4 kg TROPICS flight 3U spacecraft is shown in Fig. 1. The spacecraft bus was developed by Blue Canyon Technologies, and the payload was developed

by MIT Lincoln Laboratory. Spacecraft dimensions are approximately 10 x 10 x 36 cm. A full-duplex S-band Innoflight SCR-100 radio is used to downlink data to the ground, where it is processed and relayed to the NASA

GES DISC for download. DC power consumption for the radiometer payload and scanning assembly is less than 5 W, permitting 100% duty cycle operation. Dual star trackers provide excellent attitude knowledge, enabling the geolocation uncertainty better than 1/20 of a footprint.

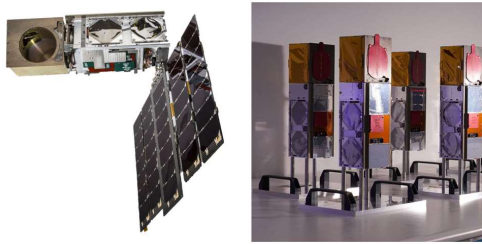


Figure 1. TROPICS satellite (left), showing the rotating payload connected to the satellite bus via a rotary joint. Also shown in the image on the left is the articulating solar array, which rotates (as does the satellite bus) to track the sun to maximize power output. The four satellites that will comprise the constellation are shown on the right. (Photo credit: Blue Canyon Technologies)

DESCRIPTION OF THE TROPICS RADIOMETER INSTRUMENT

The radiometer payload provides observations in 12 channels spanning approximately 90 to 206 GHz. 81 footprints are measured in a swath subtending ± 60 degrees from nadir across the satellite track as the payload rotates at 30 RPM. Given the Pathfinder orbit altitude of approximately 530 km, this results in a swath width of almost 2000 km. The Pathfinder was launched into a sun synchronous orbit with local time of the descending node of approximately 2:00pm. The calibration of the radiometer is achieved by: 1) injecting noise (generated by a weakly coupled noise diode) into the radiometer front end, and 2) measuring the cold cosmic background radiation. These calibrations are performed once per payload scan (every 2 seconds). The TROPICS radiometer payload is shown in Fig. 2. Key components are highlighted, and spectral/spatial properties are given. The spatial resolution of each channel (at nadir) is given in Fig. 2 for the nominal constellation orbital altitude of 550 km (slightly higher than the Pathfinder orbit of 530 km). The constellation orbits will not be sun synchronous, instead, there will be three, equally-spaced (in RAAN) orbits, each with inclination of 30° . Each constellation orbit will contain two satellites. The G-band (180-206 GHz) channels exhibit a noise-equivalent delta temperature (NEDT) of 0.4-0.6 K, and the 90-120 GHz channels exhibit an NEDT of 0.6-1.0 K. The NEDT values are generally stable over time, even over frequent radiometer downtime early in the mission when the spacecraft was being

commissioned and updated. Radiometer uptime is now routinely 100%, with only infrequent restarts due to radiation single event effects. For example, the radiometer operated 100% of the time in February, 2022 with zero downtime, and this is representative of current performance. Radiometric calibration accuracies, determined by comparing to GEOS-5 atmospheric fields, is also quite good, with deviations less than 1 K for all non-surface-impacted channels and all instrument temperatures. The temperature sounding channels show accuracies of better than 0.6 K, with negligible residual calibration drift over the course of the mission. Scan biases are less than 1 K within scan angles of $\pm 45^\circ$. Geolocation accuracies have been determined to be better than 1/20th of a footprint diameter for all channels by comparing a large number of coastline crossings.

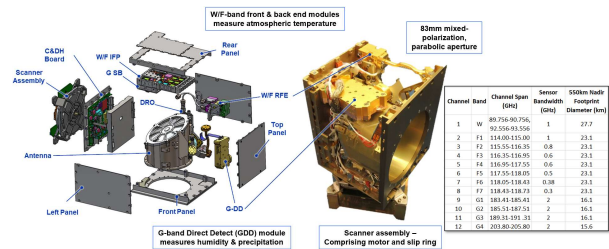


Figure 2. Overview and characteristics of the TROPICS radiometer payload.

OVERVIEW OF THE TROPICS GROUND SEGMENT

Mission data flow is shown in Fig. 3. Data is first downlinked over an S-band link to ground stations operated by Kongsberg Satellite Services (KSAT). Hartebeesthoek, South Africa is the primary ground station for the constellation satellites, and the Pathfinder satellite uses Svalbaard as its ground station location. Blue Canyon Technologies operates the Mission Operations Center (MOC), MIT Lincoln Laboratory operates the Science and Payload Operations Center (SPOC), and the University of Wisconsin creates the geophysical data products at the Data Processing Center (DPC).

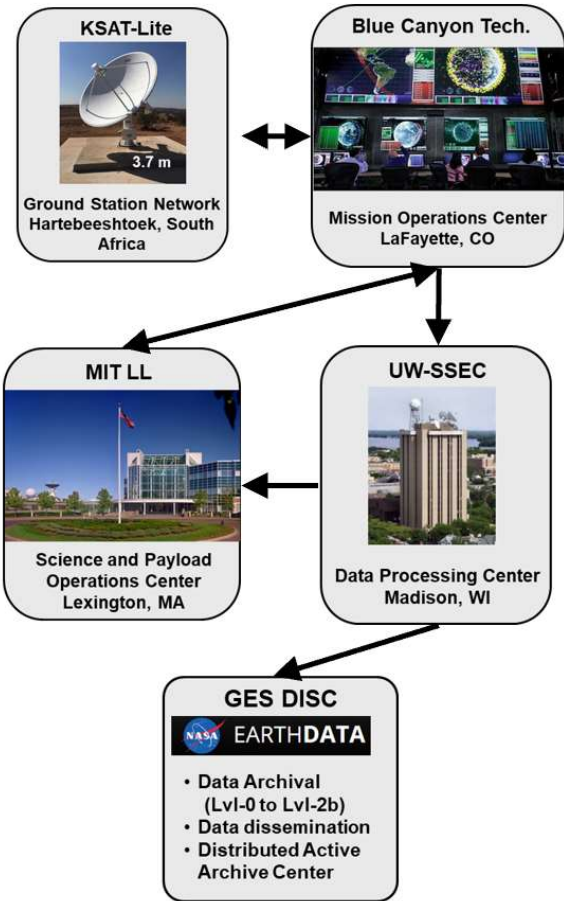


Figure 3. TROPICS mission data flows down from the spacecraft to KSAT-Lite ground stations, through BCT mission operations, to data processing at U. Wisconsin-Madison, and finally out to the generally public through the NASA GES-DISC.

TROPICS PATHFINDER ON-ORBIT COMMISSIONING RESULTS

The TROPICS Pathfinder satellite has been operating almost continuously for the last eleven months and has collected many extraordinary images of tropical cyclones. Of particular interest is imagery collected by the 205 GHz channel, the first of its kind on a spaceborne cross-track sounder. For example, Super Typhoon Mindulle was observed by the TROPICS Pathfinder on Sep 26, 2021, as shown in Fig. 4. Very clear and distinct storm structure is revealed by the TROPICS Pathfinder observations at 205 GHz, including rain bands and eyewall. Another example is Cyclone Mocha, shown in Fig. 5 as observed by TROPICS Pathfinder at 205 GHz. Again, detailed storm structure is revealed in these images, showing a relatively large, clear eye and spiral rain band structure. Finally, Fig. 6 shows Cyclone Mawar observed on May 23, 2023.

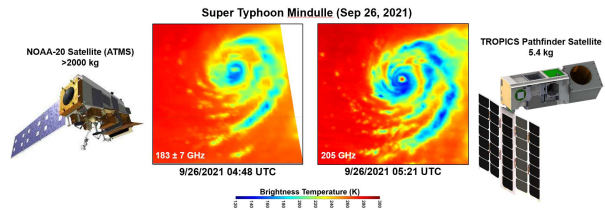


Figure 4. Super Typhoon Mindulle as observed by the Advanced Technology Microwave Sounder (ATMS) on the NOAA-20 satellite and by the TROPICS Pathfinder satellite on Sep 26, 2021.

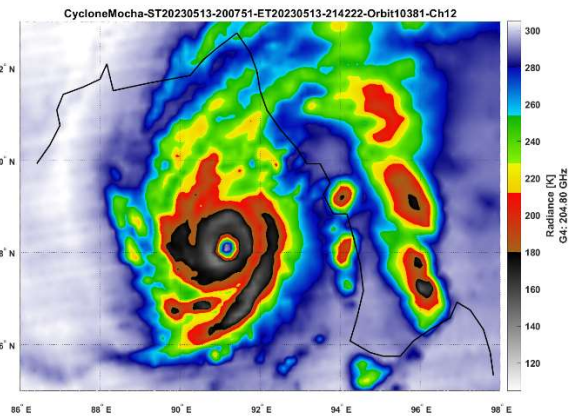


Figure 5. Cyclone Mocha as observed by the TROPICS Pathfinder at 205 GHz on May 13, 2022. The colorbar indicates the brightness temperature in units of Kelvins.

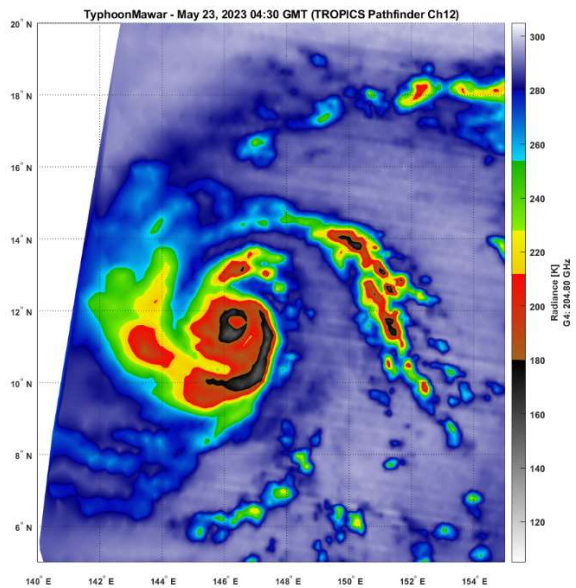


Figure 6. Cyclone Mawar as observed by the TROPICS Pathfinder at 205 GHz on May 23, 2023 (4:30 UTC).

SUMMARY AND LOOK AHEAD TO THE CONSTELLATION MISSION

The TROPICS Pathfinder precursor mission has demonstrated exceptional capabilities of the radiometers that are now flying as part of the four-satellite TROPICS constellation. Spacecraft performance and reliability has been demonstrated, as has radiometer calibration, stability, and geolocation. All aspects of the ground and data processing elements are fully checked out and ready for implementation as part of the constellation mission.

The four constellation vehicles have been placed into two separate orbital planes in May 2023 by Rocket Lab Electron vehicles (see Fig. 7). The orbit altitude is approximately 550 km and the inclination is 32.75 degrees. The two orbital planes are approximately equally space in Right Ascension of the Ascending Node (RAAN). The spacecraft bus checkout for all four spacecraft is complete and payload commissioning is now in progress with expected readiness for 2023 Atlantic hurricane season.



Figure 7. Photo of the May 26 launch of two TROPICS constellation spacecraft from Mahia, New Zealand aboard a Rocket Lab Electron launch vehicle.

We expect the new, high-revisit capabilities of TROPICS with performance demonstrated by Pathfinder will provide invaluable information to better understand and predict severe storms, and many similar systems are expected to be developed and deployed to further extend and improve the record of small-satellite microwave sounding, started by the launch of the MicroMAS-2 mission in January 2018. These new observations will complement and augment the planned operational enterprise of microwave observations by NOAA, EUMETSAT, and others.

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