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The NASA TROPICS CubeSat Constellation Mission: Overview and Science Objectives

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ABSTRACT

The Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS) mission was selected by NASA in 2016 as part of the Earth Venture–Instrument (EVI-3) program. The overarching goal for TROPICS is to 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 passive 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. TROPICS comprises a constellation of at least six CubeSats with cross-track scanning microwave radiometers in three low-Earth orbital planes (two satellites per plane). The mission is on-track to deliver flight-ready hardware in 2019. The System Requirement Review and Mission Definition Review have been completed, and the Preliminary Design Review is scheduled for late 2017.

INTRODUCTION

The TROPICS mission will implement a spaceborne earth observation system designed to collect measurements over the tropical latitudes to observe the thermodynamics and precipitation structures of Tropical Cyclones (TCs) over much of the storm systems' lifecycles. The measurements will provide nearly all-weather observations of 3D temperature and humidity, as well as cloud ice, precipitation horizontal structure and instantaneous surface rain rates. These measurements and the increased temporal resolution provided by the CubeSat constellation, are needed to better understand the TC lifecycles and the environmental factors that affect the intensification of TCs. The TROPICS CubeSats will be launched on NASA provided expendable launch vehicles as either the primary or secondary payload to form a multi-plane constellation capable of providing median observation revisit rates necessary to fulfill all threshold science requirements.

The TROPICS core instrument is a cross-track scanning passive microwave spectrometer that provides measurements of upwelling thermal emission and scattering of the earth's atmosphere. Measurements are taken in 12 channels near atmospheric absorption features due to oxygen and water vapor. Processing of the raw radiance values measured by the spectrometer yields atmospheric temperature, moisture, rain rates, and other information relevant to precipitation structure and storm intensity. Instrumentation needed to make these measurements has been used in space for decades, and ultra-compact instrumentation for CubeSat implementation is now available with high technology readiness level.

The scientific goal of TROPICS is to provide nearly all-weather observations of 3D temperature and humidity, as well as cloud ice and precipitation horizontal structure, at high temporal resolution [compared to current passive microwave (PMW) measurements] to conduct high-value science investigations of TCs. Critical science questions to be addressed include:

1. What are the relationships between upper-level warm-core evolution and storm intensity and structure change?
2. What is the role of rapidly evolving storm structure in TC formation and intensity change?
3. How does environmental moisture impact TC structure, size, and intensity?
4. Can TC intensity forecasts be improved through utilization of rapid-update microwave information?

The TROPICS science program is directly relevant to three of the six NASA Earth Science Focus Areas: Weather, Water and Energy Cycle, and Climate Variability and Change. TROPICS addresses goals and objectives from the 2014 NASA Strategic Plan including advancing the understanding of Earth and developing technologies to improve the quality of life on our home planet (strategic goal 2) and advancing knowledge of Earth as a system to meet the challenges of environmental change and to improve life on our planet (objective 2.2). Furthermore, the TROPICS measurements intersect with the 2014 NASA Science Plan, including improving the capability to predict weather and extreme weather events, and furthering the use of Earth system science research to inform decisions and provide benefits to society. Finally, the TROPICS mission directly addresses the need for rapid-update observations with cloud-penetrating capability, cited in the National Research Council (NRC) recommendation to fly the PATH decadal survey mission to improve understanding of fundamental severe storm thermodynamic processes.

SCIENCE OBJECTIVES

The fundamental physical parameters required to address the TROPICS science objectives are 3D atmospheric temperature and humidity, storm intensity, and horizontal precipitation structure. These parameters have a long heritage of being derived from spaceborne PMW imagery and sounding channels (e.g., AMSU, ATMS, SSMIS). Practical considerations of antenna and instrument size and mass for a CubeSat system guide the selection of PMW channels for TROPICS.

Temperature and moisture profiles are retrievable from seven channels near 118 GHz and three near 183 GHz, respectively. Precipitation structure is obtained from a combination of 90 GHz, 206 GHz, and the temperature and moisture channels, with horizontal resolution matching that of the moisture data due to the high sensitivity to precipitation hydrometeors at 183 GHz. The 206-GHz channel will be sensitive to smaller ice particles than the 90-GHz channel and will generally produce a stronger signal. These observables link back to science requirements and to the primary sensor requirements (horizontal and vertical resolution and sensitivity).

The key linkages between the primary TROPICS observables and science objectives are summarized below.

Objective 1: “Relate precipitation structure evolution, including the diurnal cycle, to the evolution of the upper-level warm core and associated intensity changes.” Temperature sounding performance of 2 K RMS up to 50 hPa (approximately 20 km altitude) provided by TROPICS allows sensing of upper tropospheric TC warm cores, important since a fully resolvable TC warm core is desired for objective estimates of storm intensity (see Figure 1). The ATMS temperature sounding requirement drives the TROPICS sensor sensitivity requirement to approximately 0.5 K at the native sensor horizontal resolution, as determined using simulations of temperature profile retrieval performance with the TROPICS bands. Techniques developed to estimate the intensity of TCs from microwave sounder information have greatly aided TC satellite analysts and warning centers around the globe.

These techniques measure the upper-level warm-core anomaly and relate it to TC intensity assuming hydrostatic principles and statistical relationships. The upper-level thermal anomalies associated with the TC warm core are computed from brightness temperature (T_B) fields for selected microwave channels. To compute the local anomaly, a core radiance value is taken from the warmest pixel near the TC center. Environmental values are selected from a filtered pattern surrounding the TC and averaged. The resulting T_B anomalies are then correlated with coincident in-situ aircraft intensity data to develop regression equations.

Objective 2: “Relate the occurence of intense precipitation cores (convective bursts) to storm intensity evolution.” High-frequency PMW observations provide a wealth of information on scattering by precipitation-sized ice particles. The novel 206 GHz channel will be particularly sensitive to ice particle scattering and will provide an opportunity to better identify and map convective precipitation. All TROPICS channels together provide some information on vertical structure and will allow the derivation of proxies for intensity of precipitation in TCs. These methodologies will be modified to the combination of 90, 118, 183, and 206 GHz to arrive at brightness temperature depressions and differential scattering parameters between different channels with different gas absorption strength. Scattering signatures will be tied back to hydrometeor content and height of the scattering layer using a set of high-resolution simulations of tropical storms derived from the state-of-the-art 3D modeling system.

Objective 3: “Relate retrieved environmental moisture measurements to coincident measures of storm structure (including size) and intensity.” A major unknown is whether dry air acts to potentially weaken TCs through modification of precipitation structure or overall convective activity. TROPICS will provide coupled measurements of the more slowly varying environmental humidity profiles around a TC, and heretofore unresolvable short-term variations in vortex-scale horizontal precipitation structure over the lifetime of storms that will enhance our ability to determine the extent of environmental humidity control on TC precipitation and intensity.

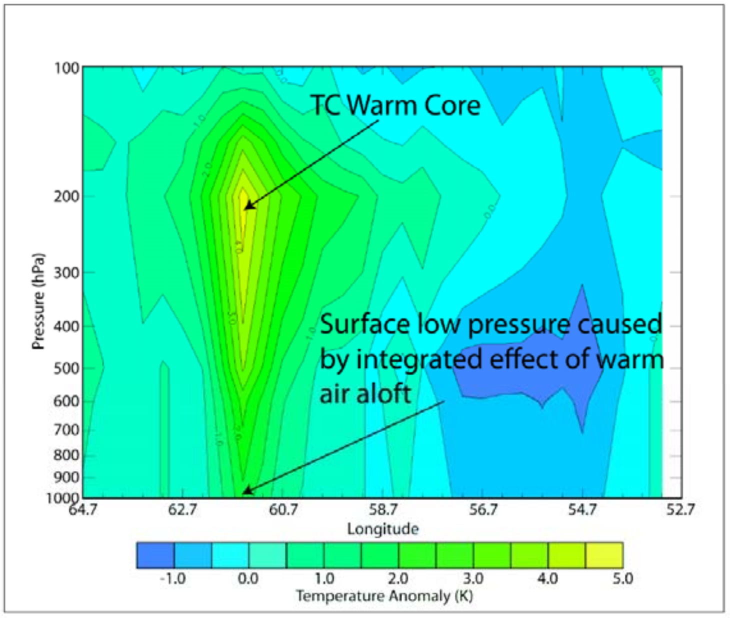

Fig. 1. Microwave sounders are capable of measuring the warm-core thermal anomaly above TC centers [the example vertical cross section above was derived from AMSU during Hurricane Edouard (2014)]. Storm intensity estimates are obtained in relation to the strength of the warm core using either measured brightness temperatures or retrieved thermal anomalies.

TECHNICAL APPROACH

TROPICS comprises a constellation of identical 3U CubeSats, each hosting a passive microwave spectrometer payload. The CubeSat constellation members will be flown in a circular low-earth orbit in equally spaced orbital planes, with multiple satellites randomly spaced within a plane. The orbit inclination will be roughly 30 degrees. The constellation will allow for rapid-revisit sampling of vertical temperature and moisture profiles of TCs. Each CubeSat will record the raw passive microwave data and relay the raw data to the ground, where the data will be processed to produce the temperature and moisture profiles. Key components of the mission are described below.

Space Vehicles

Each member of the TROPICS constellation is an identical 3U CubeSat consisting of a spectrometer payload integrated onto a commercially-procured bus. The spectrometer payload consists of a rotating passive RF antenna measuring spectral radiance as it rotates about the CubeSat velocity vector. The payload is based upon a similar design previously flown by MIT LL on the MicroMAS-2 mission. However, a significant amount of redesign has been required to meet TROPICS performance and mission reliability requirements. The redesign includes:

1. Antenna modification to optimize ground profile while minimizing side lobes
2. Noise reduction in analog front end
3. Higher-dynamic-range analog-to-digital converter
4. Modifications to spectrometer channel center frequencies and bandwidths
5. Higher-reliability control electronics
6. Higher-reliability and lower-power scanner assembly

A notional SV including the bus and payload is shown in Figure 2. The MicroMAS-2 bus does not have sufficient pointing accuracy or power generation capability to meet the TROPICS mission requirements. The TROPICS bus will match much of the functionality of the MicroMAS-2 bus, but will take advantage of recent advances in CubeSat bus technology and reliability.

Ground Stations

The TROPICS 3U CubeSats will interface with a ground station network to allow for satellite command and control and downlink of bus and payload telemetry for each CubeSat in the constellation. The baseline plan calls for use of the NASA Near Earth Network for communications.

Data Processing

MIT LL will interact with the mission operations provider to acquire the down-linked raw science data

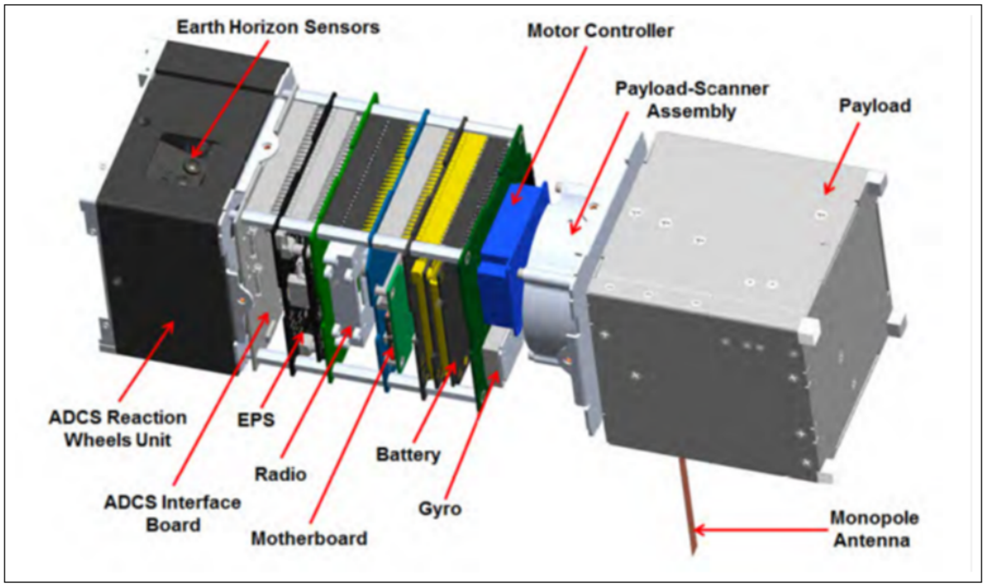

Fig. 2. MicroMas-2 Space Vehicle (without solar panels)

and format it into data products that can be shared with the data processing center at the University of Wisconsin. The data products will be made available to the data processing center via a secured connection. The data will be stored at MIT LL in a SQL database on a MIT LL computer system that includes disk redundancy and data backups. The entire mission data set will be stored at MIT LL for the duration of the TROPICS project. The key elements of the TROPICS mission are shown in Figure 3.

CONCLUSIONS

TROPICS will be the first demonstration that science payloads on low-cost CubeSats can push the frontiers of spaceborne monitoring of the Earth to enable system science and will fill gaps in our knowledge of the short time scale--hourly and less--evolution of tropical cyclones, where current capabilities are an order of magnitude slower. The TROPICS mission will implement a spaceborne earth observation mission designed to collect measurements over the tropical latitudes to observe the thermodynamics and precipitation structures of TCs over much of the storm lifecycle. The measurements will provide nearly all-weather observations of 3D temperature and humidity, as well as cloud ice and precipitation horizontal structure. These measurements and the increased temporal resolution provided by the CubeSat constellation, are needed to better understand the TC lifecycles and the environmental factors that affect the intensification of TCs.

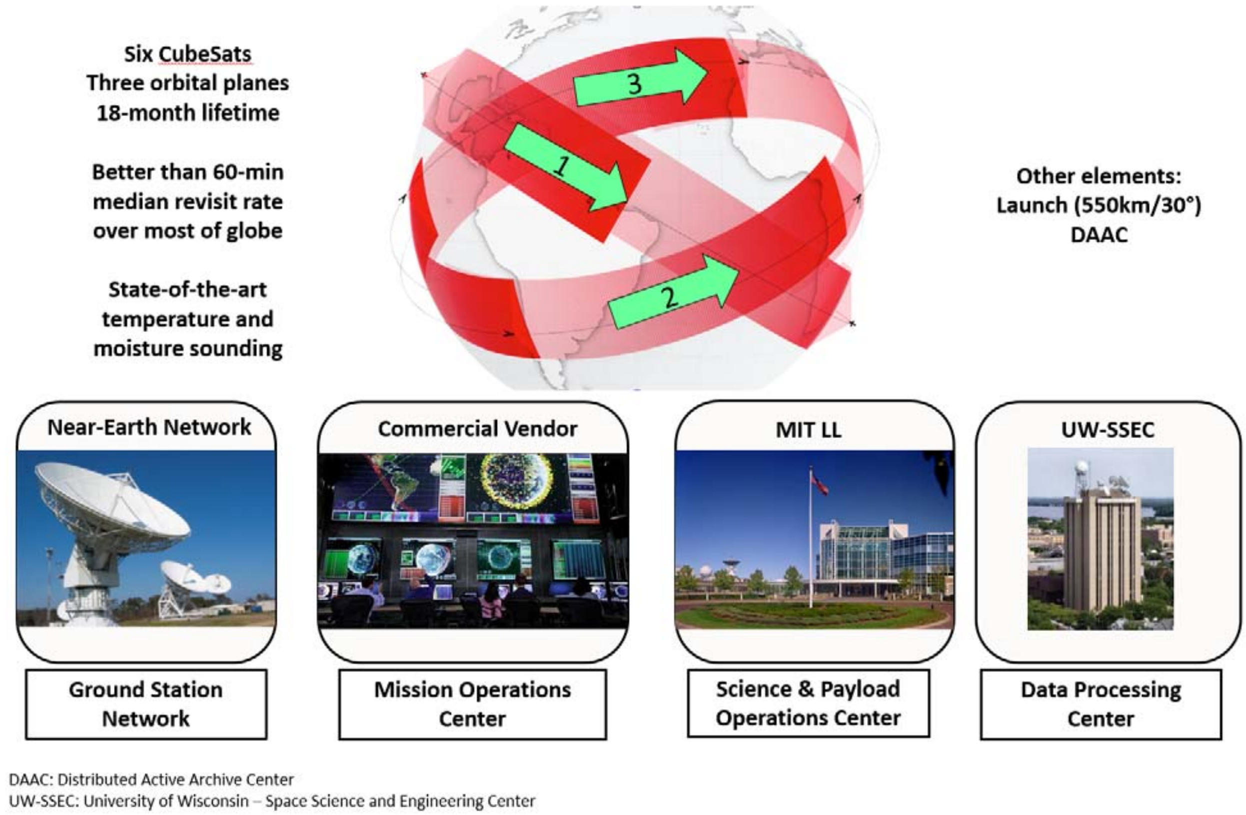

Fig. 3. Overview of the TROPICS mission elements.

REFERENCES

1. Blackwell, William, et al. "Nanosatellites for earth environmental monitoring: The MicroMAS project." *12th Specialist Meeting on Microwave Radiometry and Remote Sensing of the Environment (MicroRad)*. IEEE, 2012.

2. Blackwell, William J., (2017). "New Small Satellite Capabilities for Microwave Atmospheric Remote Sensing." *Seventh Conference on Transition of Research to Operations.* Seattle, Washington: American Metorological Society.

3. NASA Science Mission Directorate. (2012). *ESTO :: ROSES 2012 InVEST Selections*. Retrieved from nasa.gov: https://esto.nasa.gov/files/solicitations/INVEST_12/ROSES2012_InVEST_awards.html

4. Blackwell, William J. "Millimeter-wave receivers for low-cost CubeSat platforms." *Microwave Symposium (IMS), 2015 IEEE MTT-S International*. IEEE, 2015.

5. Blackwell, W., and K. Cahoy. "Small Satellite Constellations for Data Driven Atmospheric Remote Sensing." *Dynamic Data-Driven Environmental Systems Science*. Springer International Publishing, 2015. 3-9.

6. Cahoy, Kerri, et al. "Development of the Microwave Radiometer Technology Acceleration (MiRaTA) CubeSat for all-weather atmospheric sounding." *Geoscience and Remote Sensing Symposium (IGARSS), IEEE International*. IEEE, 2015.

7. National Academies of Sciences, Engineering, and Medicine. 2016. *Achieving Science with CubeSats: Thinking Inside the Box*. Washington, DC: The National Academies Press.

8. Blackwell, W. J., & Pereira, J. (2016). "New Small Satellite Capabilities for Microwave Atmospheric Remote Sensing: The Earth Observing Nanosatellite-Microwave (EON-MW)." *Sixth Conference on Transition of Research to*

Operations. New Orleans, Louisiana: American Metorological Society.

9. NASA. 2016. *NASA Selects Instruments to Study Air Pollution, Tropical Cyclones*. Retrieved from NASA.gov: https://www.nasa.gov/press-release/nasa-selects-instruments-to-study-air-pollution-tropical-cyclones

10. Blackwell, W. J., Braun, S. A., Bennartz, R., Velden, C. S., DeMaria, M., Atlas, R., . . . Rogers, a. R. (2017). The TROPICS Smallsat Tropical Cyclone Mission: High Temporal Resolution Microwave Imagery As Part of NASA's Third Earth Venture-Instrument (EVI-3) Program. *21st Conference on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface.* American Meteorological Society.

11. Hoffman, R. N., and R. Atlas, 2016: Future observing system simulation experiments. *Bull. Amer. Meteor. Soc.*, 97, 1601–1616.

12. Boukabara, S.-A., Garrett, K., & Kumar, K. (July 2016). "Assessment of Potential Gaps in the Satellite Observing System Coverage." *Monthly Weather Review*, 2548-2563.

13. Blackwell, William J. "The MicroMAS and MiRaTA CubeSat atmospheric profiling missions." *Microwave Symposium (IMS), 2015 IEEE MTT-S International*. IEEE, 2015.

14. Blackwell, W., & Pereira, J. (2015). "New Small Satellite Capabilities for Microwave Atmoshperic Remote Sensing: The Earth Observing Nanosatellite-Microwave." *29th AIAA/USU Conference on Small Satellites.* Logan, Utah: AIAA/USU.

15. Marinan, Anne D., et al. "Assessment of Radiometer Calibration with GPS Radio Occultation for the MiRaTA CubeSat Mission." *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 9.12 (2016): 5703-5714.

16. Ruan, Weitong, et al. "A Probabilistic Analysis of Positional Errors on Satellite Remote Sensing Data Using Scattered Interpolation." *IEEE Geoscience and Remote Sensing Letters* (2017).

17. Poghosyan, Armen, and Alessandro Golkar. "CubeSat evolution: Analyzing CubeSat capabilities for conducting science missions." *Progress in Aerospace Sciences* 88 (2017): 59-83.

18. Boukabara, S.-A., Moradi, I., Atlas, R., Casey, S. P., Cucurull, L., Hoffman, R., . . . Zhou, Y. (2016). Community Global Observing System Simulation Experiment (OSSE) Package. *Journal of Atmospheric and Oceanic Technology*, 1759-1777.