New Capabilities for All-Weather Microwave Atmospheric Sensing Using CubeSats and Constellations

W. Blackwell, K. Clark, D. Cousins, D. Crompton, A. Cunningham, M. Diliberto,
L. Fuhrman, R. Leslie, I. Osaretin, and S. Michael
MIT Lincoln Laboratory
WJB@LL.MIT.EDU

ABSTRACT

Three MIT Lincoln Laboratory nanosatellite missions flying microwave radiometers for high-resolution atmospheric sensing are in varying stages of development. Microwave instrumentation is particularly well suited for implementation on a very small satellite, as the sensor requirements for power, pointing, and spatial resolution (aperture size) can be accommodated by a nanosatellite platform. The Microsized Microwave Atmospheric Satellite Version 2a (MicroMAS-2a), launched on January 11, 2018 and has demonstrated temperature sounding using channels near 118 GHz and humidity sounding using channels near 183 GHz. A second MicroMAS-2 flight unit (MicroMAS-2b) will be launched in Fall 2018 as part of ELANA-XX. 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 microwave measurements (median refresh rate of approximately 40 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 six CubeSats in three low-Earth orbital planes. Each CubeSat will host a high performance radiometer 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 206 GHz that is more sensitive to precipitation-sized ice particles. TROPICS flight hardware development is on track for a 2019 delivery. Finally, the Earth Observing Nanosatellite-Microwave (EON-MW) mission is being formulated by MIT Lincoln Laboratory for NOAA as part of the Polar Follow-On (PFO) Program's 2017 budget request. PFO plans to extend JPSS for two more missions and provides a means to mitigate the risk of a gap in continuity of weather observations. The PFO request aims to achieve robustness in the polar satellite system to ensure continuity of NOAA's polar-orbiting weather observations. The baseline EON-MW design accommodates a scanning 22-channel, high-resolution microwave spectrometer on a 12U CubeSat platform to provide data continuity with the existing AMSU and ATMS microwave sounding systems. EON-MW will nominally be launched into a sun-synchronous orbit for a two to three year mitigation mission in 2021 that will also demonstrate advanced miniaturized microwave sounder technology that expands on the capabilities developed for MicroMAS-2 and TROPICS.

MICROMAS-2 Mission Overview

The MicroMAS-2a CubeSat is a 3U scanning CubeSat with a dual spinner payload that was launched on January 11th, 2018. MicroMAS-2b is scheduled for launch in the Fall of 2018. MicroMAS-2a/b are follow-on missions to the MicroMAS-1 mission that launched in 2014 and deployed from the International Space Station in 2015, and they carry an improved 10-channel radiometer that measures water vapor at 89 and 207 GHz; temperature, pressure, and precipitation at 118 GHz; and humidity and precipitation at 183 GHz. Figure 1 shows the MicroMAS-2a satellite.

Figure 1: The MicroMAS-2a satellite is 4.5 kg and 34 x 10 x 10 cm^3

MicroMAS-2a provided the first ever CubeSat microwave radiometer cross-track sounding data (NASA GSFC IceCube provided imagery in a single channel near 883 GHz). An initial analysis comparing MicroMAS-2a to ATMS over the same location is shown below in Figure 2 for W-band. The ATMS data is masked in order to provide a better comparison to the MicroMAS-2a data. The location of the imagery is an ice sheet over Alaska that is breaking up into the ocean. The comparison between MicroMAS-2a data takes place over seven hours apart; thus, it provides a qualitative analysis but radiance validation needs to be completed in order to provide a quantitative analysis of the CubeSat data.

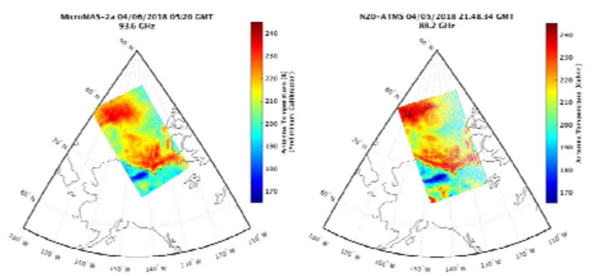

Figure 2: MicroMAS-2a on-orbit data (left) compared to NOAA-20 ATMS data (right) observed approximately seven hours earlier.

TROPICS MISSION OVERVIEW

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.

TROPICS 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).

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.

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.

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.

TROPICS MISSION IMPLEMENTATION

TROPICS comprises a constellation of six 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 bus provided by Blue Canyon Technologies (BCT). 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, but has been updated to provided improved performance and reliability.

Ground Stations

The TROPICS 3U CubeSats will interface with the KSAT-lite ground station network to allow for satellite command and control and downlink of bus and payload telemetry for each CubeSat in the constellation.

Data Processing

Mission operations will be provided by BCT, and MIT LL will interact with the BCT to acquire the down-linked raw science data 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 the NASA Goddard Earth Sciences Data and Information Services Center (GES DISC).

TROPICS SUMMARY

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.

EON-MW Mission Overview

The Earth Observing Nanosatellite-Microwave (EON-MW) mission is being formulated by MIT Lincoln Laboratory for NOAA as part of the Polar Follow-On (PFO) Program's 2017 budget request. PFO plans to extend JPSS for two more missions and provides a means to mitigate the risk of a gap in continuity of weather observations. The PFO request aims to achieve robustness in the polar satellite system to ensure continuity of NOAA's polar-orbiting weather observations. The baseline EON-MW design accommodates a scanning 22-channel, high-resolution microwave spectrometer on a 12U CubeSat platform to provide data continuity with the existing AMSU and ATMS microwave sounding systems. EON-MW will nominally be launched into a sun-synchronous orbit for a two to three year mitigation mission in 2021 that will also demonstrate advanced miniaturized microwave sounder technology that expands on the capabilities developed for TROPICS, MicroMAS-2, and MiRaTA.

Key EON-MW planned features include a pair of compact single-reflector radiometers that permit the entire microwave sounding payload to be developed with a total mass of approximately 4 kg while maximizing antenna aperture for optimal spatial resolution. The spacecraft bus is approximately 16 kg, and the entire satellite (prior to solar array deployment) measures approximately 22x22x34 cm. Communications to ground are planned with a space-qualified X-band transceiver and a ground station to be nominally located at a high latitude. Average power consumption of the satellite is approximately 50 W. This presentation will provide an overview of the EON-MW mission, discuss key satellite and payload subsystems, describe risk reduction and mission planning, and present key attributes of the ground and data segments.

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