Lessons Learned from the NASA TROPICS CubeSat Constellation Mission

Andrew Cunningham
William Blackwell, Michael DiLiberto, Shawn Donnelly, Stephen Gillmer, R. Vincent Leslie, Joelle Prince, and Nicholas Zorn

LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

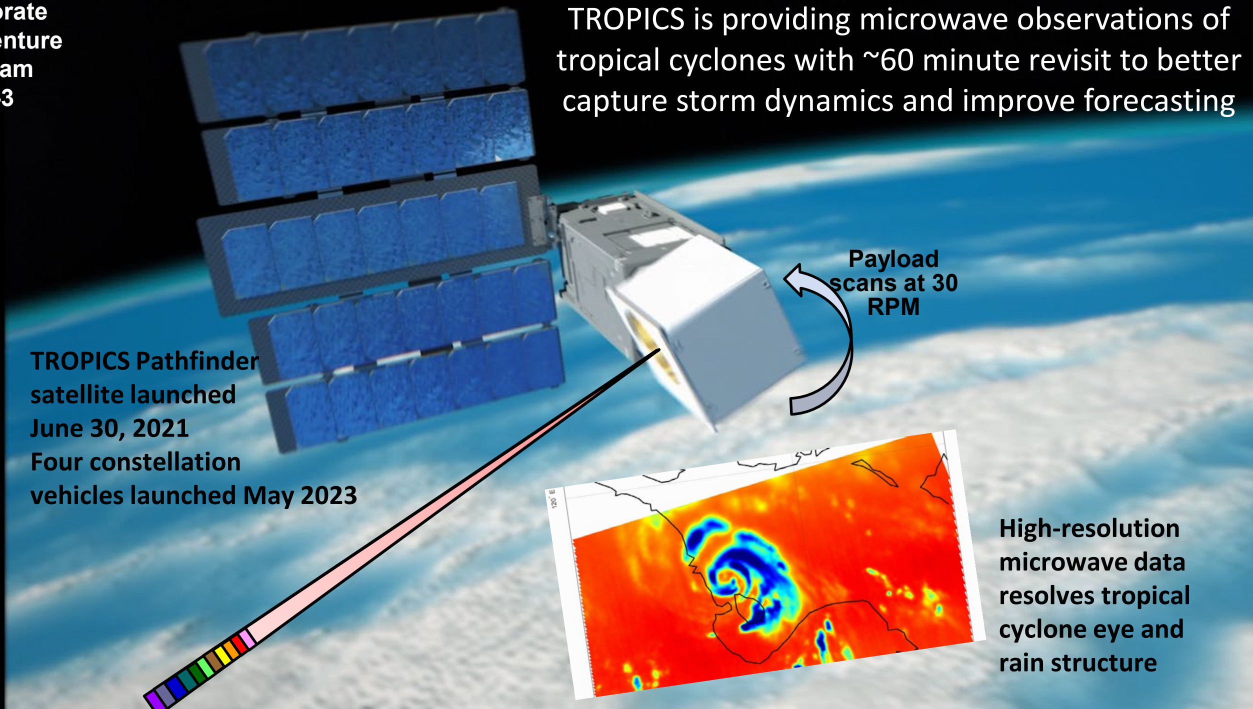
- **TROPICS Mission Background**
- TROPICS Lessons Learned
  - Requirements
  - Prototyping Firmware and Software
  - Overcoming GPS Failure
  - Auto-resume
  - Slip Ring
- Summary

TROPICS: Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats

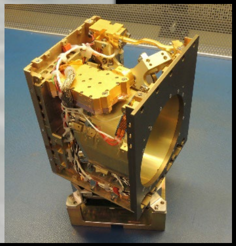
William J. Blackwell (MIT LL), Principal Investigator   Scott A. Braun (NASA GSFC), Project Scientist

Science Mission Directorate
Earth Venture Program
EVI-3

TROPICS is providing microwave observations of tropical cyclones with ~60 minute revisit to better capture storm dynamics and improve forecasting

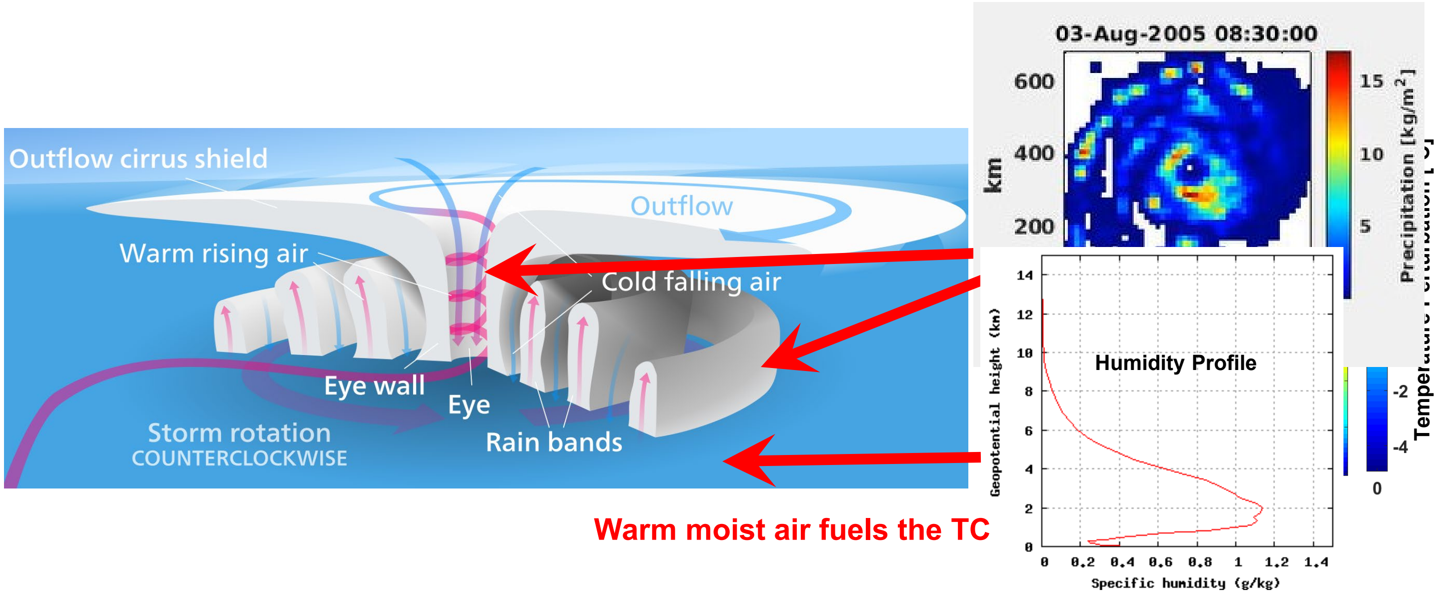


Constellation of Four 3U CubeSats
MIT LL payload; BCT bus; KSAT downlink



TROPICS Microwave Sounder
12 channels (90-205 GHz)
Temperature, Moisture, Rain Rate

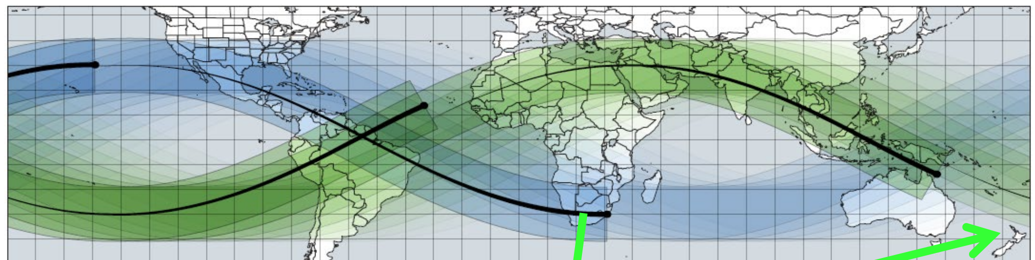
NASA TROPICS Mission to Study Tropical Cyclones



Need to measure 4-D temperature, humidity and precipitation to better understand hurricane science and therefore improve the forecast models

TROPICS Mission Overview

Two orbital planes (33° inclination at 550 km altitude) with two Cubesats in each is providing ~60 minute median revisit rate



- **Launched by Rocket Lab on May 8 & 26, 2023 from Mahia, NZ into two orbital planes**
- **Mission has four CubeSats with year-long science operations**
- **Mission has been extended through 2026!**
- **Data latency ~60 minutes**

GES DISC

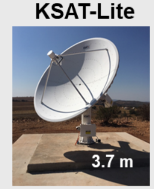
EARTHDATA

- Data Archival (Lvl-0 to Lvl-2b)
- Data dissemination
- Distributed Active Archive Center

UW-SSEC

Data Processing Center
Madison, WI

KSAT-Lite



Ground Station Network
Hartebeeshtoek, South Africa

Blue Canyon Tech.

Mission Operations Center
LaFayette, CO

MIT LL

Science and Payload Operations Center
Lexington, MA

NEW GROUND STATION ONLINE IN DUBAI (ATLAS Space)

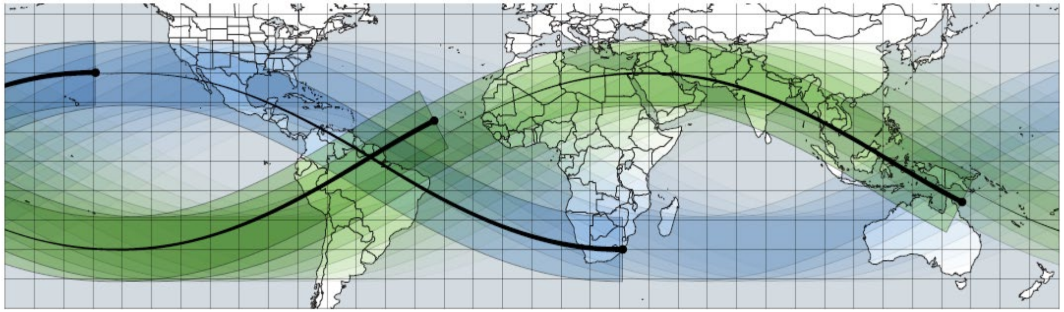
Backup Ground Stations: Mauritius, West Australia, & Puertollano

CubeSat Overview & Status

- **TROPICS-01 (Pathfinder)** Deorbited
  - **Aug. 2021 to Dec. 2023**
- **TROPICS-03 Active**
  - **Started 15-Jun-2023**
- **TROPICS-05 Active**
  - **Started 15-Jun-2023**
- **TROPICS-06 Active**
  - **Started 15-Jun-2023**
- **TROPICS-07 Inactive**
  - **15-Jun-2023 to 31-Jul-2023**

Median revisit rate is 70-90 minutes with three satellites

Orbit Parameter	Pathfinder	Constellation Launch #1	Constellation Launch #2	Constellation Launch #3
SV ID	1	2 & 4	5 & 6	3 & 7
Altitude (km)	528.8 – 544.2	N/A	540-553	540-553
Inclination (deg.)	97.51	N/A	32.74	32.74
Longitude of the ascending node (deg.) on 6Jun2023 for constellation	330.29	N/A	TROPICS-05 353.2 TROPICS-06 352.6	TROPICS-03 162.9 TROPICS-07 162.8
Launch date/time yyyy-mm-dd HH:MM:SS.SSS	2021-06-30 T19:31:00.178Z	June 12, 2022	2023-05-08 T01:00:00Z	2023-05-26 T03:46:00Z
NORAD ID	TROPICS PATHFINDER 48901	N/A	TROPICS-05 56442 TROPICS-06 56444	TROPICS-03 56753 TROPICS-07 56754

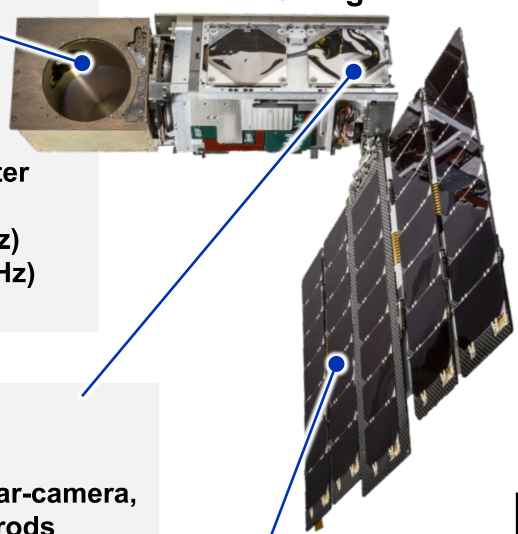


TROPICS Satellite Overview

1U Payload
- Rotating microwave radiometer
- Scanner assembly
- 83 mm aperture
- Noise-diode / deep space calibration

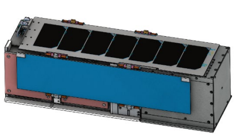
Ultra-compact W / F / G radiometer
- W-band 92 GHz
- F-band 7 chan. (114-119 GHz)
- G-band 4 chan. (183 & 204 GHz)

3U CubeSat
10 cm x 10 cm x 36 cm
5.4 kg

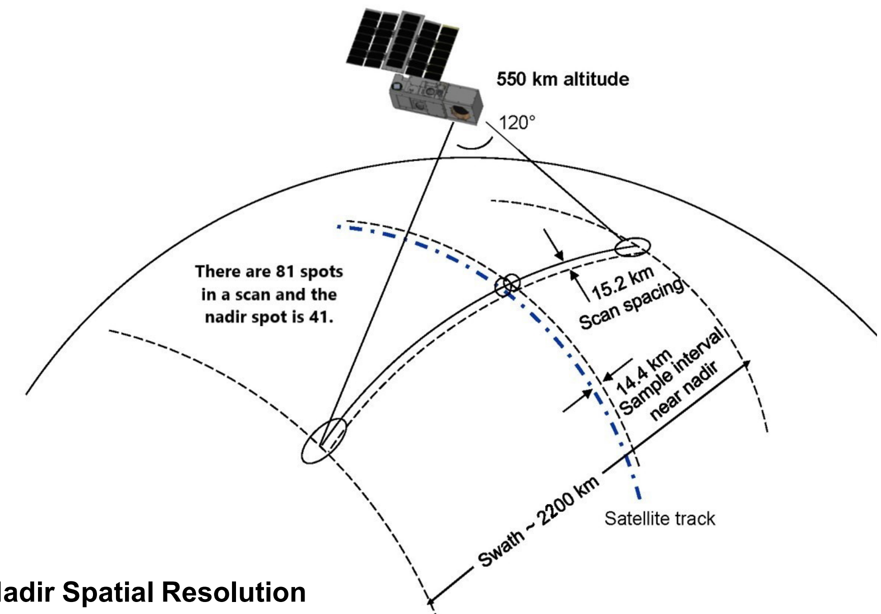


2U Bus: BCT XB-1
- S-band radio
- ADCS: sun sensor(s), star-camera, reaction wheels, torque rods

Deployed Articulating 5-panel solar array



Stowed

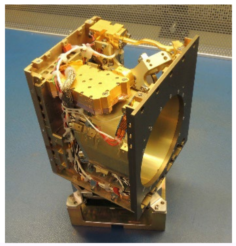


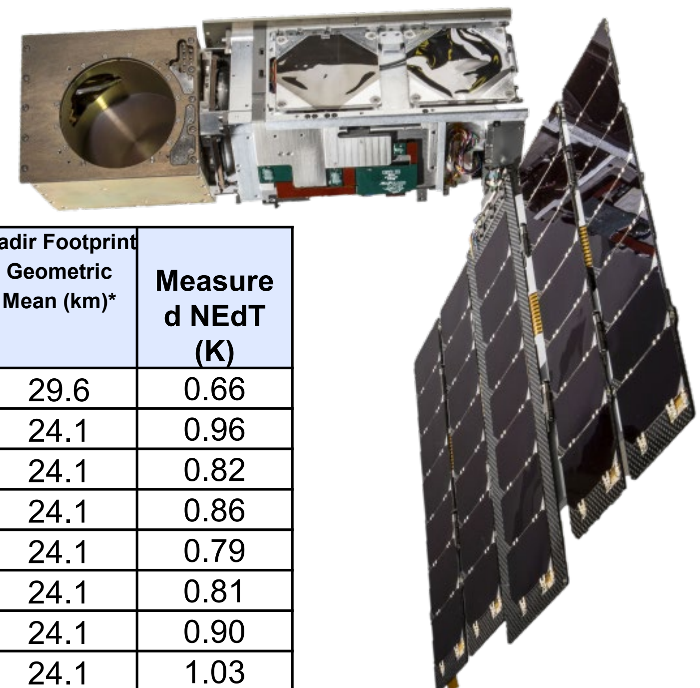
Nadir Spatial Resolution

Direction	W-band (Ch. 1)	F-band (Ch. 2-8)	G-band (Ch. 9-12)
Down-track	27.2 km	23.0 km	14.4 km
Cross-track	28.9 km	25.2 km	17.9 km

TROPICS Payload Overview

Payload power: 3W
Mass: ~1kg

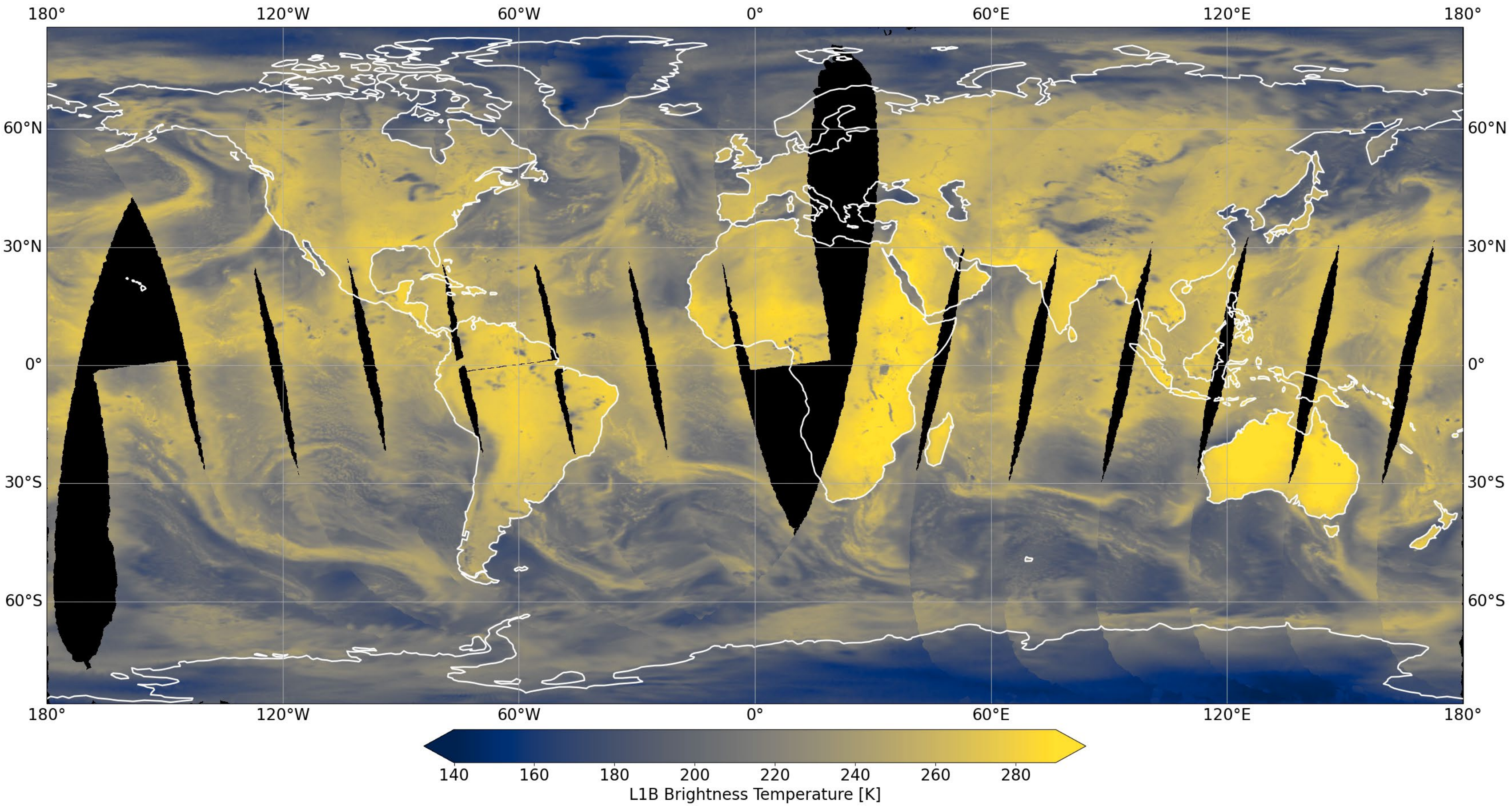




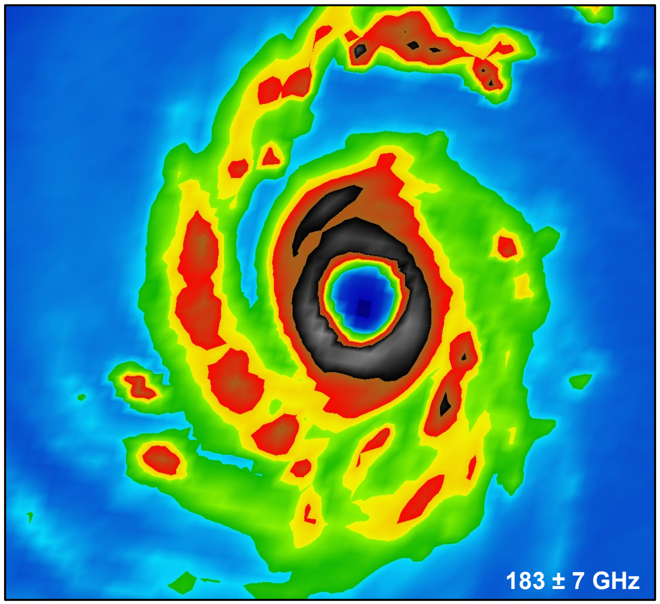
TMS Channel	Central frequency	ATMS Channel	MHS Channel	*MWHS-2 Channel*
1	91.655±1.4 GHz	88.2 GHz	89.0 GHz	*89.0 GHz*
2	114.50 GHz	-	-	*118.75±5.0*
3	115.95 GHz	-	-	*118.75±3.0*
4	116.65 GHz	-	-	*118.75±2.5*
5	117.25 GHz	-	-	*118.75±1.1*
6	117.80 GHz	-	-	*118.75±0.8*
7	118.24 GHz	-	-	*118.75±0.3*
8	118.58 GHz	-	-	*118.75±0.2*
9	184.41 GHz	183.31±1.0	183.31±1.0	*183±1.0*
10	186.51 GHz	183.31±3.0	183.31±3.0	*183±3.0*
11	190.31 GHz	183.31±7.0	190.31	*183±7.0*
12	204.8 GHz	-	-	-

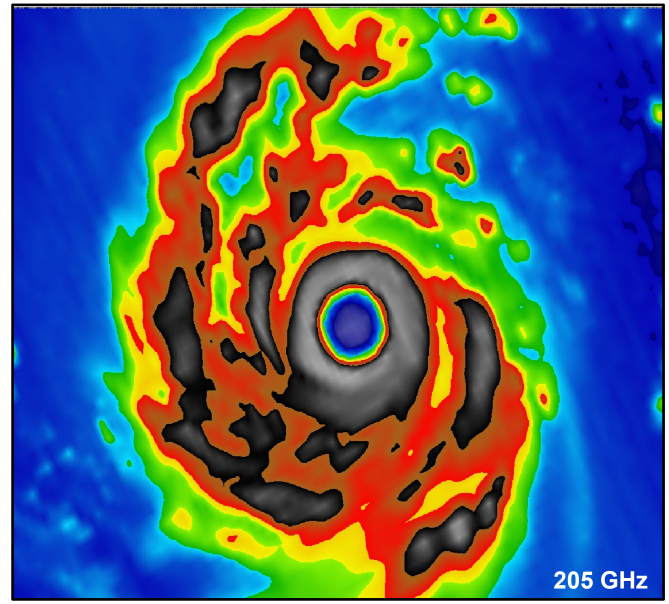
Beamwidth (degrees) Down/Cross	Nadir Footprint Geometric Mean (km)*	Measured NEdT (K)
3.0/3.17	29.6	0.66
2.4/2.62	24.1	0.96
2.4/2.62	24.1	0.82
2.4/2.62	24.1	0.86
2.4/2.62	24.1	0.79
2.4/2.62	24.1	0.81
2.4/2.62	24.1	0.90
2.4/2.62	24.1	1.03
1.5/1.87	16.9	0.58
1.5/1.87	16.9	0.55
1.5/1.87	16.9	0.53
1.35/1.76	15.2	0.52

TROPICS Pathfinder W-band Data Over 18 Months (Real-time * 300,000)



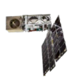
TROPICS Reveals New Storm Structure Details Relative to Current Operational Sounder (ATMS)





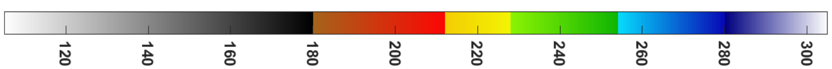
NOAA-20

Kong-Rey
Oct 29, 2024



TROPICS-3
(enlarged by ~50X)

TROPICS obs of Kong-Rey warm core anomaly (13 K) was the largest ever for a microwave sounder!



- TROPICS Mission Background
- **TROPICS Lessons Learned**
  - **Requirements**
  - **Prototyping Firmware and Software**
  - **Overcoming GPS Failure**
  - **Auto-resume**
  - **Slip Ring**
- Summary

TROPICS Requirements Overview

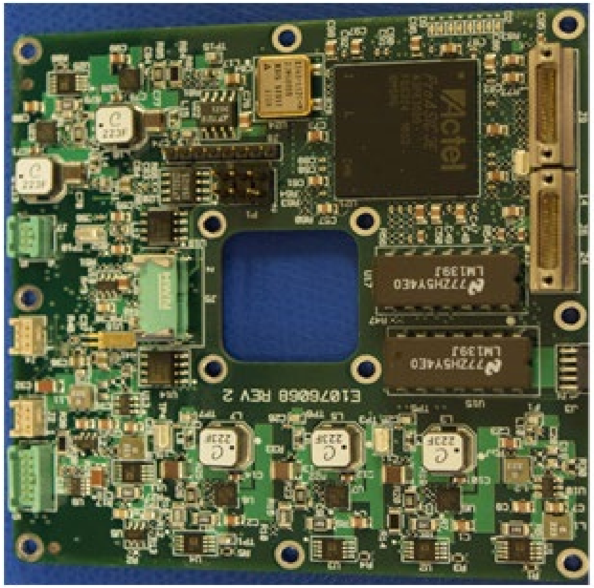
- **TROPICS a NASA Class D mission**
  - **Cost Capped**
- **Tailored Requirements critical to mission success**
  - **Two day meeting meeting with NASA program management, technical assurance, and mission assurance**
  - **Not feasible to follow classic NASA space mission requirements and procedures for component selection and testing**
    - **Procured commercial bus**

      Requirement flow down not practical
    - **Key Microwave RF components did not have space heritage or testing**

      Program schedule and cost constraints did not allow qualifying components

Bhaset PCB

- **3U cubesat with a ~ 1U payload not conducive to traditional flatpack packing**
- **ProAsic3 FPGA plastic BGA package significantly smaller than the ceramic column grid array**
- **Use of automotive grade plastic components with some heritage and radiation testing**

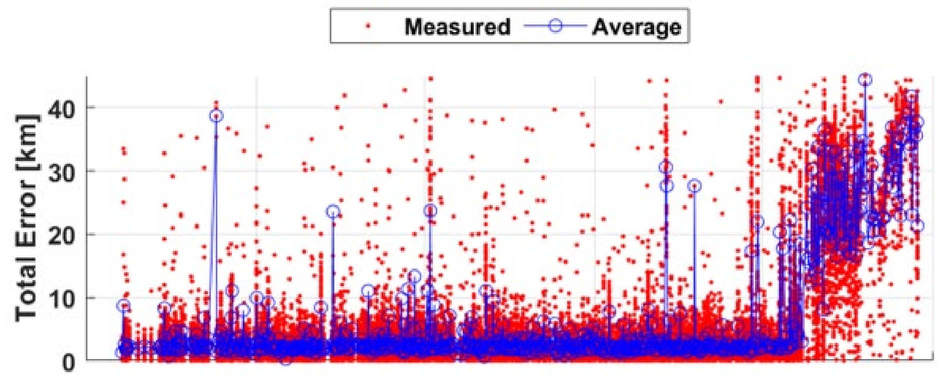


PROTOTYPE SOFTWARE/FIRMWARE FOR COMPONENT TESTING EARLY

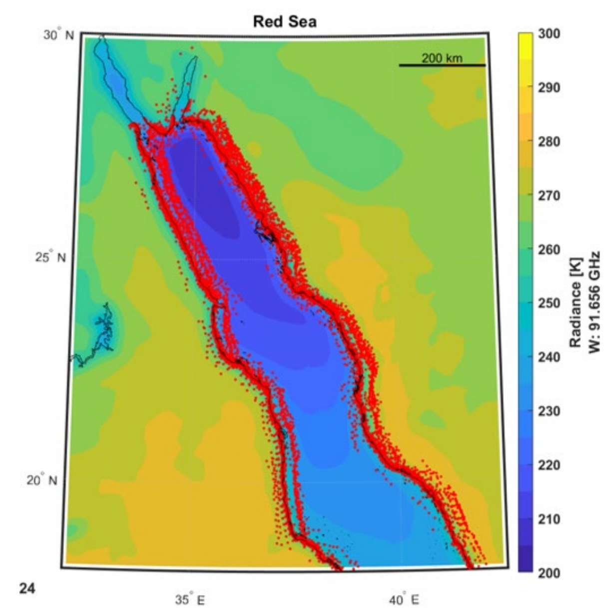
- Firmware and software developed early and used in component and board testing
- RF vendor provided prototype electronics to test their components
  - Used same firmware and software used in flight system
  - Updated when flight code updated
- Bus vendor provided payload simulator
  - Same hardware and electrical interface as flight payload
  - Same firmware and software
    - Updated when flight code updated
- Issues identified early in the development and build cycle
- Provided confidence when flight units assembled and tested

OVERCOMING GLOBAL POSITONING SYSTEM (GPS) FAILURE

- **Position accuracy necessary for knowing where the atmospheric measurements with respect to other sensor data**
- **GPS failure was planned for and analyzed during development**
  - **Updating the Two Line Element (TLE) during ground contacts**
  - **Results degraded but adequate performance**
  - **Further investigation in improving the accuracy of the TLE updates**
    - **Compensating for command propagation**



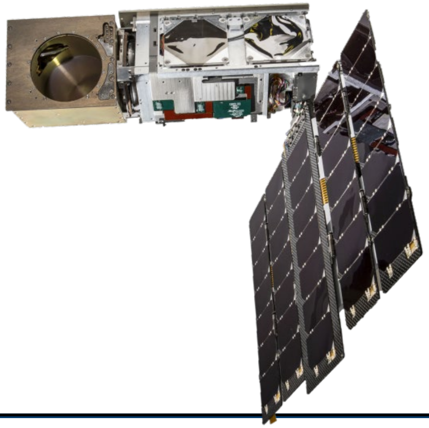
TROPICS Pathfinder Geo-location ThroughGPS Failure



Geo-Location Red Sea Overlay

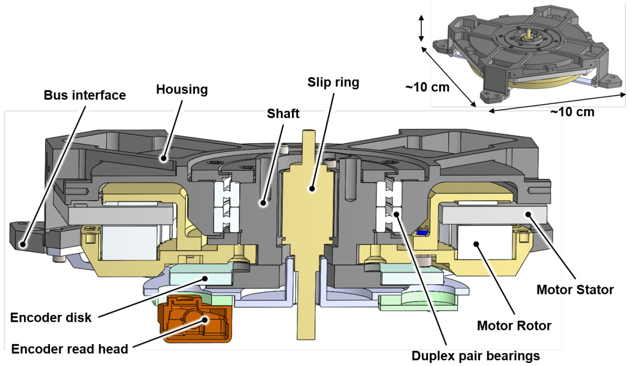
AUTO RESUME

- **Revisit rate of the TROPICS constellation is a key mission requirement**
- **Anomaly recovery time a key component of the revisit**
- **At the beginning of operations after constellation launch the timeline for anomaly recovery was two ground contacts which was 6-8 hours worst case and 90 minutes best case**
- **Blue Canyon Technology (Raytheon) and MITLL developed macro scripts that ran on the bus to recover from an anomaly in ~15 minutes, significantly improving the revisit rate**



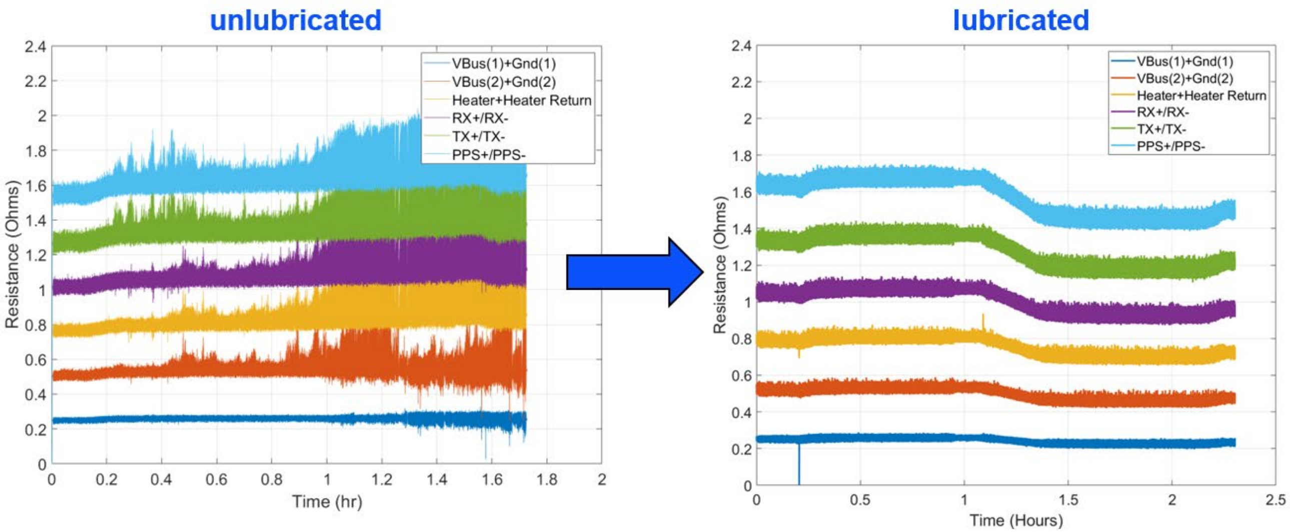
SLIP RING

- **Slip ring for rotating TROPIC payload selected due to heritage**
  - **Original design wind turbines**
  - **Modifed for space mission with 10 hours operation at 6 RPM**
  - **Life tested for MicroMas (precursor to TROPICS) with 50 million cycles**
- **First sign of problems with TROPICS SN1 payload in TVAC**
  - **CRC errors over serial communication for command and data from payload**
  - **Testing showed transient discontinuities while rotating**
  - **Over constraining wires and misalignment ruled out**
- **Slip ring test results differed at MITLL and Vendor**
  - **Major difference was humidity during testing**
  - **Stick slip identified as a potential cause**



Stick Slip

- Stick-slip is an undesired, jerky, and pulsating slip of two objects moving against each other.
- This causes the resistance to vary significantly. High humidity can alleviate stick-slip with the humidity acting as a lubricant.
- This phenomena is discussed in great detail in two papers by M. Antler and R. Hayes.



Slip Ring Lubrication

Slip Ring Flight Units

- MITLL fabricated an alignment fixture and worked with vendor to align, lubricate, and assembled flight slip rings from the best slip ring parts
- Slip rings were tested over temperature in a dry nitrogen environment for 24 hours while monitoring resistance
- Slip rings were disassembled and inspected for wear and debris
  - If minimal units were reassembled and integrated in the payload
- An accelerated life test of one slip ring was started and run during the storage period before a launch was procured
  - Slip ring accumulated the equivalent of three years on orbit by increasing the speed in dry nitrogen environment
  - Some increase in resistance was seen
    - Resistance decreased if slip ring was run in opposite direction for a short duration (5 minutes)

Slip Ring On Orbit

- TROPICS constellation launched May 2023
  - Payload operation started in June
  - No CRC errors observed for a few months
  - July CRC errors seen in two payloads
    - One payload responded well to spinning backwards as a mitigation
    - The other continued to degrade
  - TROPICS Pathfinder launched in 2022
    - Performed well without CRC errors for two years
    - CRC errors observed for the first time in Fall 2023
    - A few weeks later an anomaly occurred that affected the SADA drive, star tracker, and payload communication
    - These all had a bus FPGA I/O bank in common
    - Failure attributed to excessive slip ring debris shorting the 12V bus voltage to the serial communication lines

      Radiation damage other possibility but not as likely

Slip Ring Lessons Learned

1. Heritage is not enough for selecting a component. Determining how the heritage mission application to the current mission and the heritage qualification testing is critical. Specify, analyze, and test the component to current mission requirements.
2. This is a moving part and the screening needed to be part of the test strategy before assembly.
3. The possibility of a short needed to be identified earlier and considered when selecting the wiring. The 12V supply then could be separated from the serial line by grounds.

- TROPICS Mission Background
- TROPICS Lessons Learned
  - Requirements
  - Prototyping Firmware and Software
  - Overcoming GPS Failure
  - Auto-resume
  - Slip Ring
- **Summary**

SUMMARY

- Agreeing on requirements is key to successful missionand program objectives. It can also help with relationships with sponsors, vendors and support organizations especially if what you are doing requires doing things differently.
- Integrating firmware and software with relevant hardware smooths integration and test later.
- Contingency planning can speed recovery to operation
- Using mission operations to optimize mission uptime
- The lesson of the Slip Ring is universal for all space acquisitions, trust but verify vendor's workmanship. Heritage isnice but it is not sufficient. Oversight of a critical component is necessary.

Acknowledgements

- The authors would like to acknowledge and thank the many people who made TROPICS mission happen, including (but not limited to) the NASA Earth Science Division, coworkers at MITLL, and Blue Canyon Technologies.