Lessons Learned from the NASA TROPICS CubeSat Constellation Mission

Andrew Cunningham, William Blackwell, Michael DiLiberto, Shawn Donnelly, Stephen Gillmer, R. Vincent Leslie, Glenn Perras, Joelle Prince, and Nicholas Zorn
MIT Lincoln Laboratory
244 Wood St
Lexington MA 02420
781-981-2747
cunninghama@ll.mit.edu

Abstract—**The NASA TROPICS CubeSat constellation mission is currently providing wide-swath microwave observations of tropical cyclones in twelve channels spanning 90-205 GHz at unprecedented revisit rates to improve our basic scientific understanding of how storms form and evolve and to improve our ability to forecast storm track and intensity. Four satellites were successfully placed into orbit on Rocket Lab Electron launch vehicles on May 8 and May 26 (NZST) 2023 – two satellites were deployed in each launch, resulting in two equally-spaced 33-degree inclined orbital planes at 550-km altitude. In advance of the constellation mission, the TROPICS engineering qualification unit was launched as part the Transporter-2 rideshare mission on a SpaceX Falcon 9 launch vehicle into a sun-synchronous orbit at 530-km altitude. This TROPICS "Pathfinder" satellite operated successfully for 2.5 years and has provided a vast data record to validate and optimize all the aspects of the TROPICS constellation mission, including the flight segment, ground segment, and science data segment. These five satellites have demonstrated the first ever microwave data record provided with better than 60-minute median revisit rate, and these observations have been downlinked to users with latencies of approximately 45 minutes on average, permitting the use of these data by operational forecasting centers. The mission has utilized a wide array of commercial products and services, from cubesat buses, command and control, ground stations, and launch to implement the mission at much lower costs than traditional, operational weather satellite systems. Many technical innovations combined with a new paradigm for high-performance earth observation have come with many challenges, obstacles, and setbacks over the course of mission planning, development, implementation, and operation. In this paper, we describe many of these problems in some detail and present observations, lessons learned, and a look at how the solutions that were conceived to overcome the issues could be used to improve future missions in a wide variety of application areas.**

979-8-3503-5597-0/25/$31.00 ©2025 IEEE

1. TROPICS Constellation Overview

The TROPICS mission provides rapid-revisit microwave sounding observations that are used to better characterize the environment and precipitation structure of tropical cyclones, leading to improved forecasts of track and intensity. The primary elements of the constellation mission are summarized in Figure 1. Ground stations for the TROPICS mission are provided by Kongsberg Satellite Services (KSAT) and Atlas Space Operations. The TROPICS payload is a twelve-channel microwave radiometer that measures the brightness temperature of earth's atmosphere and surface. By choosing specific frequencies for the radiometer channels that are sited near atmospheric absorption lines at 118.75 and 183.31 GHz, a vertical profile of air temperature and moisture is measured. The radiometer scans the earth once every two seconds, and the forward motion of the satellite advances each of these "scan lines" by approximately one footprint thus providing a three dimensional profile of the atmosphere. The radiometer data is processed on the ground into various geophysical products used in a variety of tropical storm research areas. Figure 2 shows the absorption spectrum of the atmosphere, and Figure 3 shows the radiometer channel characteristics. The scan pattern is shown in Figure 4. The scan produces 101 measured points per revolution with 81 radiometer measurements on the ground, 10 measurements of the reference noise diode, and 10 measurements of deep space. The measurements of the noise diode and deep space provide a per scan calibration of the earth measurements. Post-launch calibration validation activities confirmed that all radiance (Level 1) and geophysical (Level 2) products are meeting baseline mission requirements.

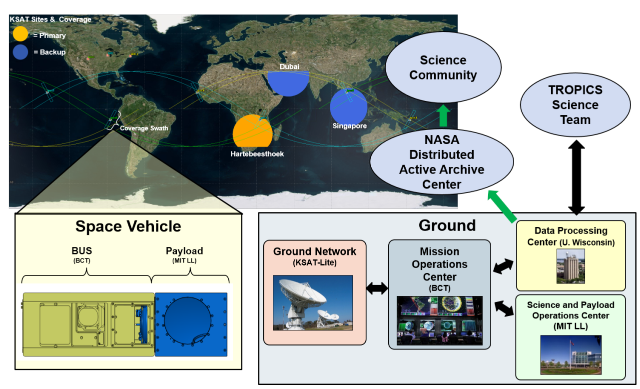

Figure 1. **Primary elements of the TROPICS mission**

The bus was manufactured by Blue Canyon Technologies of Boulder, CO. The avionics chassis houses the main controller, power board, battery, torque rods, magnetometers, GPS receiver, two star trackers, inertial measurement unit,

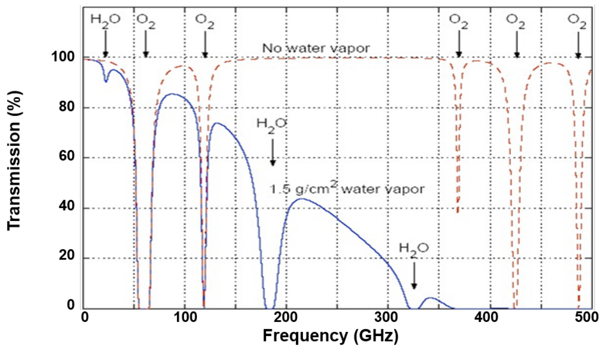

Figure 2. Simulated atmospheric absorption spectrum for a model atmosphere

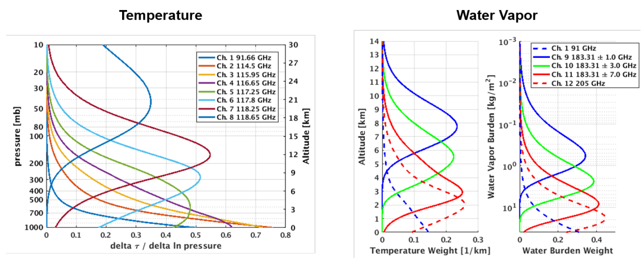

Figure 3. TROPICS temperature and moisture weighting functions, showing the sensitivity of each radiometer channel to various altitudes of the atmosphere

and two reaction wheels. A larger third reaction wheel is in the Solar Array Drive Assembly (SADA) Housing Assembly and counteracts the motion of the payload scanner. Also in the SADA housing assembly is the Innoflight SCR- 100 S-band radio and the stepper motor which drives the articulated solar panels. An exploded view of the space vehicle is shown in Figure 5 and the model of the TROPICS space vehicle shown in Figure 7 along with a model of the radiometer, Figure 6.

Six TROPICS flight vehicles were assembled along with a qualification unit and completed by January of 2020 and ready for launch. A photograph of the six flight vehicles is shown in Figure 8. The NASA launch procurement was delayed, and the six flight vehicles were stored safely for over a year, from June 2020 to August of 2021. The six flight vehicles were removed from storage, calibration verified, and BCT updated and regression tested the flight software. Due to the delay in the TROPICS flight vehicle launch, the qualification vehicle was refit and launched into a sun synchronous orbit aboard the SpaceX Transporter-2 mission as a pathfinder mission[1].

On June 12th, 2022 Astra attempted to launch two TROPICS flight vehicles. Due to an in-flight anomaly, the second stage failed to deploy the vehicles in the expected orbit and the vehicles were lost[2], [3].

In May of 2023 Rocket Labs successfully launched the remaining four TROPICS space vehicles with two launches to phase the constellation. A photo of the first launch is shown in Figure 9.

The pathfinder vehicle operated for almost three years and smoothed the way for the TROPICS mission. The pathfinder re-entered the atmosphere in July 2024.

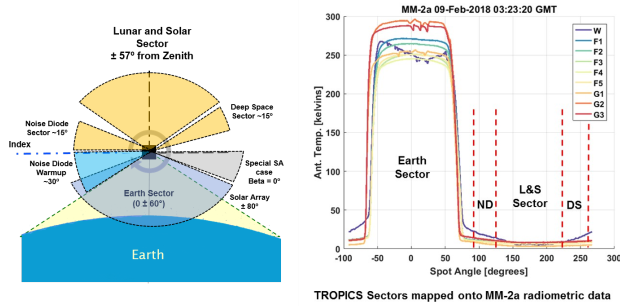

Figure 4. TROPICS scan pattern, showing the earth and calibration sectors. Also shown for reference are hemispherical views taken on-orbit by the MicroMAS-2 sounder CubeSat in 2018.

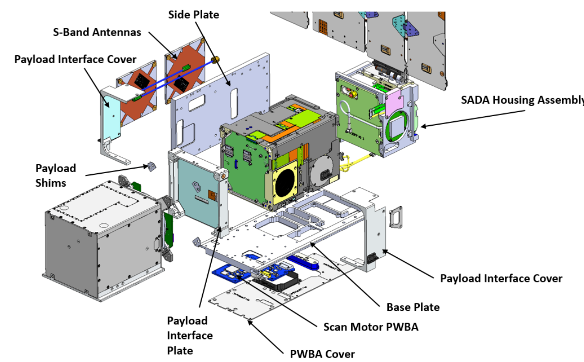

Figure 5. TROPICS Space Vehicle (SV) Exploded View

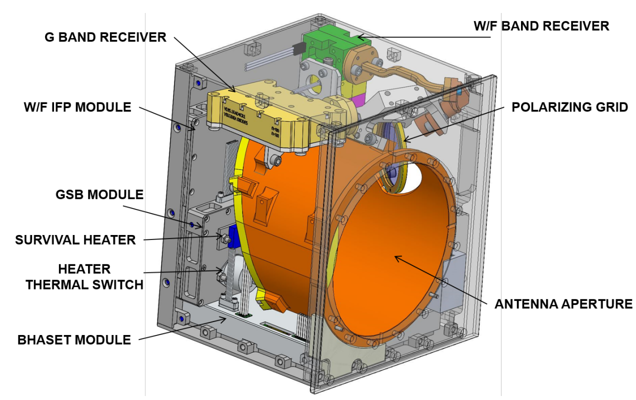

Figure 6. Key TROPICS Radiometer Features

This paper focuses on the lessons in operating the TROPICS constellation.

2. Requirements Tailoring

TROPICS was a relatively early commercial small satellite constellation mission for NASA and MIT Lincoln Laboratory (MITLL). The mission objectives along with the smaller, better, faster, cheaper posture for the mission. The "NASA Class D" risk posture made it evident that to be successful that in addition to changing what we did we would have to change

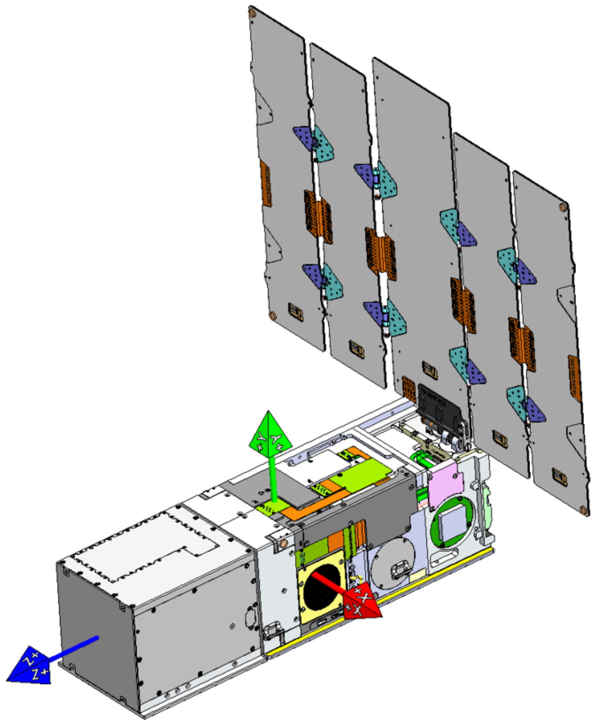

Figure 7. **Space Vehicle Model**

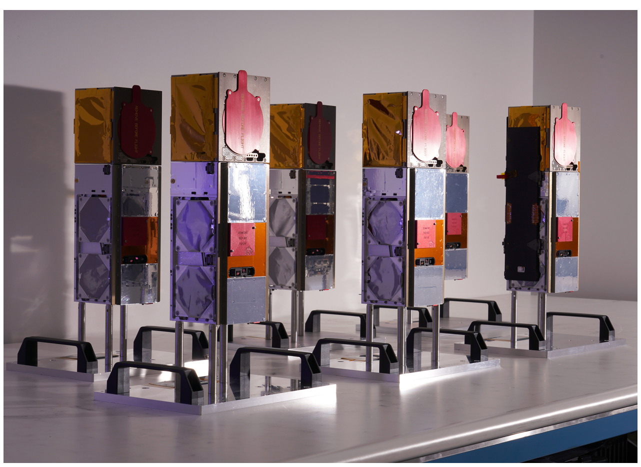

Figure 8. **TROPICS Flight Vehicles**

how we did it. A two day meeting was held with NASA program management, technical assurance and mission assurance to review potentially applicable NASA documents and tailor them to meet the needs to the program. The meeting focused on how TROPICS would execute requirements verification, major program milestone and reviews, component testing, and mission assurance to maintain quality and balance risk. The discussion, agreements and documentation from that meeting proved invaluable throughout the project, in reducing time and costs in component selection, bus vendor selection, and major program reviews while maintaining the quality needed to meet all our goals.

A few examples: Many of the critical RF components of the radiometer did not have space heritage counterparts, and cost limitations prohibited a comprehensive qualification campaign for these components. The size limitations in a

Figure 9. **Rocket Lab TROPICS first launch May 7, 2023**

3U cubesat prevented the use of flatpack components. The ProAsic3 Field Programmable Gate Array (FPGA) was used in a previous design at MITLL which used a ceramic column grid array package with an area of 529 mm^2 which is significantly larger than the plastic ball grid array which is 169 mm^2, 68% smaller. A comparison is shown in Figure 13. TROPICS avoided the schedule and cost of EE-INST-002 up-screening for automotive grade components, relying on published radiation testing for selected components. The tailoring was crucial to vendor selection and management, allowing MITLL to review and , select vendors products and procedures without flowing NASA requirements directly. This was especially useful in the selection of a bus vendor. Lastly, the requirements tailoring worked well within the team but having the tailoring agreement document was critical to getting and maintaining understanding with support organizations, staff and and management outside of the team.

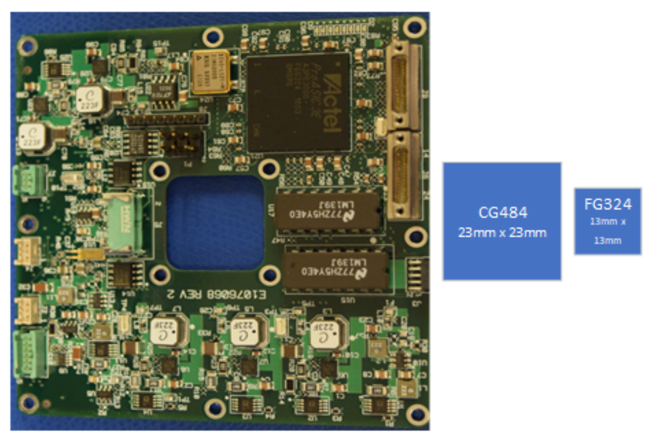

Figure 10. **Bhaset PCB and FPGA Package Size Comparison**

3. PROTOTYPE SOFTWARE/FIRMWARE FOR COMPONENT TESTING EARLY

Another significant lesson from the TROPICS mission was the value of using flight-like firmware and software early in the development process. This practice allows for the identification and resolution of bugs and issues at the earliest stages, thereby reducing the cost and complexity of fixes later in the development or test cycles. MITLL discovered and resolved firmware, software, component, and other bugs and issues by using early firmware and software during prototype and unit testing.

The RF vendor was provided test hardware by MITLL to test components in a flight like manner prior to shipping them, allowing for the screening of the components prior to integration and avoided finding issues at higher assembly levels where diagnosis and fix takes additional time and money.

Early payload simulators were assembled to provide identical hardware and software interfaces. These payload simulators were used for testing the test set ups at MITLL and used at the bus vendor BCT to test the payload interfaces.

By using flight firmware and software early on in TROPICS many issues were found and resolved before flight unit testing and integration with the bus saving time and money. One example everyone runs into is the TX and RX lines are crossed. This was found before the cables were fabricated.

4. Overcoming GPS failure

The TROPICS mission data required continuous accurate position knowledge to geo-locate the radiometer data on the earth. The possibility of a GPS receiver failing was considered and mitigation planned for. The mitigation analysis considered uploading a TLE during ground contacts and how the position knowledge degrades between ground contacts. The analysis showed that uploading a TLE was adequate for useful data for the TROPICS mission.

The Pathfinder GPS failed after two years on orbit in August of 2023 and the contingency plan of uploading TLE's was implemented. The data from the GPS failure and the TLE implementation was post processed and included in the plot in Figure 11. The plot shows the GPS accuracy before the failure and the TLE accuracy after the GPS failure. Figure 12 shows the land-sea boundary of the Red Sea from Pathfinder. Data geolocation certainly degraded, but the measurements were still useful and satisfied requirements for most science products.

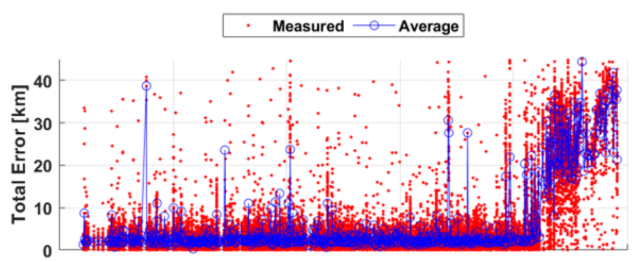

Figure 11. **TROPICS Pathfinder Geo-location Through GPS Failure**

Contingency planning was extremely effective providing a quick response to a GPS failure and maintaining the usefulness of the TROPICS data.

5. Auto Resume

A critical aspect of the TROPICS mission is the median revisit rate, how many times the TROPICS Constellation images a tropical storm during the storm's lifetime. The standard mission operations procedure for recovering a satellite after an anomaly is recovering the bus to fine reference point (LVLH) on the first contact and commanding the payload to operational mode on the second ground contact. Best case the time when a satellite is not operational is 90 minutes if the anomaly happened right before a scheduled ground contact. Worst case is 6-8 hours if the anomaly occurred during gaps in ground contacts and results in many missed opportunities to gather radiometer data over a tropical storm. The BCT and MITLL TROPICS mission operations team developed a macro script which autonomously recovered the satellite into fine reference point and payload into operational mode. The loss of radiometer data is now on the order of 15 minutes.

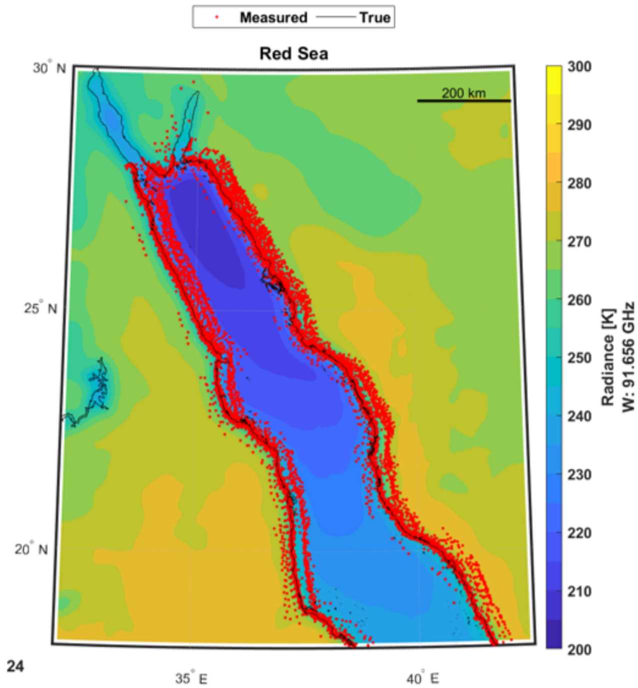

Figure 12. **Geo-Location Red Sea Overlay**

6. Slip Ring

The slip ring selected for TROPICS previously flew on a radiation belt storm probe (THEMIS 2007). The THEMIS requirement was for the slip ring to operate 10 hours at 6 RPM. The slip ring design was originally designed for use in wind turbines and need to be modified and qualified for use in space. It was next flown on a MIT cubesat (MICROMAS) in 2015. The slip ring underwent a life test of 50 Million cycles in air at room temperature. The slip ring was very attractive for TROPICS due to the small size and familiarity with the MICROMAS mission. In hindsight heritage was not enough for selecting this critical component.

The slip rings were assembled in the TROPICS payload simulator and the TROPICS qualification payload without issue. However, during the Thermal Vacuum testing (TVAC) calibration of the first flight payload Cyclical Redundancy Check (CRC) errors were detected over the Universal Asynchronous Receiver Transmitter (UART). Signal integrity issues were verified with an oscilloscope while monitoring the serial lines of the rotating the payload. These observations indicated a discontinuity likely occuring in the slip ring. The payload was removed and disassembled to gain access to the slip ring. The first theory was that over constraining of the wire bundles in and out of the slip ring could cause misalignment of the brushes to the shaft. After modifications to assure careful routing of the wires to avoid misalignment the CRC issues remained.

One interesting result of the investigation was that the resistance was measured while slip ring was rotating over temperature at MITLL and then at the vendor with very different results. The resistance was very noisy and exceeded the requirements at MITLL and met requirements at the vendor's facility. The data was reviewed and the major difference was environmental. The humidity at MITLL during the test was low, $< 20\%$, and much higher at the vendor's facility, $> 80\%$. This lead the investigation to possible stick-slip behavior of the slip ring. Stick-slip is an undesired, jerky, and pulsating slip of two objects moving against each other. This causes the resistance to vary significantly. High humdity 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. [4] [5]

The TROPICS team consulted NASA expert on tribology who had experience with slip rings used on the International Space Station (ISS) for the articulating solar panels. The slip rings as built were not lubricated and had issues serious enough that an astronaut lubricated them during a space walk. The recommendation to lubricate led to an experiment comparing the slip ring resistance with and without lubrication shown in Figure 13.

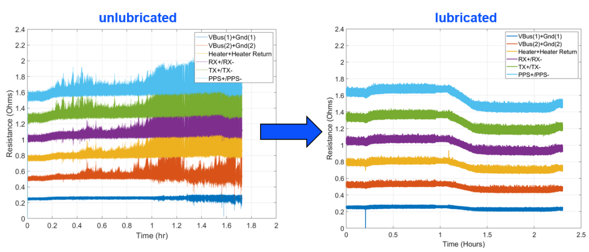

Figure 13. **Slip Ring Lubrication**

MITLL fabricated a alignment fixture and with the vendor selected the best of the brushes and shafts from the fabricated flight units build a set of slip rings with lubrication that would be adequate for flight payloads.

The slip rings were run in and tested over temperature while monitoring the resistance. After a 24 hour run in the slip ring was taken apart and checked for debris. If minimal debris was seen the slip rings were cleaned and reassembled. The unit was then operated over temperature and resistance monitored during the test. If the slip ring passed it was acceptable for a flight payload.

All six flight payloads were assembled with the reworked slip rings. No further CRC errors were detected during payload and flight vehicle testing.

MTILL started an accelerated slip ring life test that ran during storage of the flight space vehicles and accumulated over three years operation. This was done by accelerating the speed of the slip ring rotation and in a dry nitrogen environment. During the test some increase in resistance was seen but if the slip ring was run the opposite rotation direction then the resistance decreased. This was seen as a possible mitigation if CRC errors were seen on orbit after launch.

In May of 2023 four TROPICS space vehicles on orbit. After a couple weeks of bus commissioning the payloads were operated. All looked good for the first few month with no CRC errors. However in July, some CRC errors were seen on two of the payloads. For one, spinning the payload backwards has been a successful mitigation strategy and it has been operating successfully ever since. The other unit continued to worsen and the payload is currently not operational.

The Pathfinder unit that was launched a year before the TROPICS constellation operated without any CRC errors for over two years. In the late fall of 2023 a few CRC errors were detected. A few weeks later there was anomaly on the space vehicle that caused the malfunction of SADA drive, the star tracker, and the payload. It was initially attributed to radiation single events since the event happened during high solar activity. After a close look the damage could also be attributed to excessive slip ring debris causing a short across 12V bus voltage and the serial line. This voltage transient would cause damage to the payload LVDS receivers and the bus's FPGA I/O bank which interfaces to the payload, star tracker, and SADA drive. This failure is more likely than three separate destructive Single Event Latchup (SEL) events simultaneously.

The lessons learned from the TROPICS slip rings:

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.

7. Summary

The TROPICS constellation has four satellites on orbit with three operating and gathering data. The original constellation was six satellites with four needed to meet the mission baseline requirements for storm revisit rate (60 minute median revisit rate). Unfortunately, two satellites were lost in a failed launch. For the first Atlantic storm season Pathfinder provided additional data.

- Agreeing on requirements is key to successful mission and 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 is nice but it is not sufficient. Oversight of a critical component is necessary.

8. Acknowledgments

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.

REFERENCES

[1] Cunningham, A ; Zorn, N *Launch, Commissioning, and First-Light Observations for the NASA TROPICS Pathfinder Satellite* (IEEE Aerospace Conference 2023)

[2] Foust, J *Astra launch of NASA TROPICS cubesats fails*(Space News June, 12, 2022) https://spacenews.com/astra-launch-of-nasa-tropics-cubesats-fails/)

[3] Foust, J *Astra identifies cause of last failed Rocket 3.3 launch*(Space News March, 3, 2023, https://spacenews.com/astra-identifies-cause-of-last-failed-rocket-3-3-launch/)

[4] Antler, M, *Wear, Friction, and Electrical Noise Phenomena in Severe Sliding Systems* ASLE Transactions, Vol. 5, 1962

[5] Hayes, R, et al,*Electrical Noise Performance of Gold-on-Gold Slip Rings* Proc. Aerospace Mechanisms Symp., 2016

BIOGRAPHY

Andrew Cunningham *received a B.S. in Electrical Engineering from University of Michigan, Ann Arbor, MI, and M.S. in Electrical Engineering from Northeastern University, Boston, MA. He has been with MIT Lincoln Laboratory for 16 years. He was a lead engineer on several space imaging projects involving Lincoln CCD's. Previously he worked at Adaptive Optics Associates for 17 years in Cambridge, MA, and Raytheon Corporation for 3 years.*

William J. Blackwell *(Fellow, IEEE) received the Sc.D. degree in electrical engineering and computer science from MIT, Cambridge, MA, USA, in 2002. He is a Laboratory Fellow at MIT Lincoln Laboratory, Lexington, MA and currently serves as the Principal Investigator for the NASA TROPICS Earth Venture mission. His research involves environmental monitoring using ground, air, and space-based sensors.*