The CubeSat Radiometer Radio Frequency Interference Technology Validation (CubeRRT) mission: objectives, accomplishments, and lessons learned

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Community of Practice Webinar Series

Overview

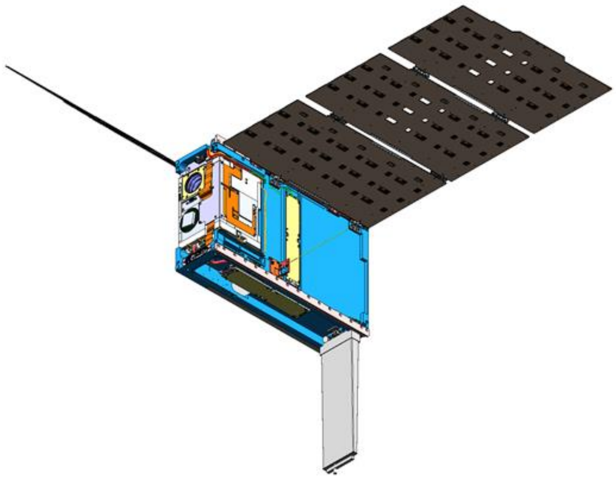
- Introduction to the CubeRRT mission
- Description of the RFI problem for passive microwave remote sensing
- Overview of the CubeRRT mission objectives
- Description of the CubeRRT design, integration, and testing phases
- Summary of launch, deployment, and operations
- Lessons learned
- Conclusions

CubeRRT Introduction

CubeRRT Overview

- CubeRRT: CubeSat Radiometer Radio Frequency Interference (RFI) Technology Validation mission
  - Funded by NASA's In-space Validation of Earth Science Technologies (InVEST-15) program

- 6U CubeSat to demonstrate spaceborne RFI detection and mitigation technology
  - Address data processing needs of future satellite-based microwave radiometer systems



CubeRRT Timeline

- Project initiated on January 4, 2016
- CDR on February 7, 2017
- Delivery of integrated spacecraft to Nanoracks on March 22, 2018
- Launched on May 21, 2018 (OA-9 / ELaNa 23 ISS resupply)
- Deployment from ISS on July 13, 2018
- “First light” data acquired on September 5, 2018
- Re-entry on November 26, 2020

CubeRRT Team

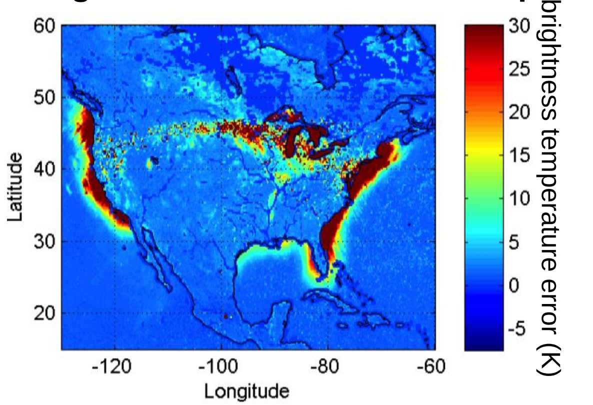
- The Ohio State University
  - Prof. Joel Johnson, PI
  - Chris Ball, PM
- Goddard Space Flight Center
  - Lead: Jeff Piepmeier
- Jet Propulsion Lab
  - Lead: Sid Misra
- Blue Canyon Technologies
  - Lead: Doug Laczkowski

Motivation – RFI Problem

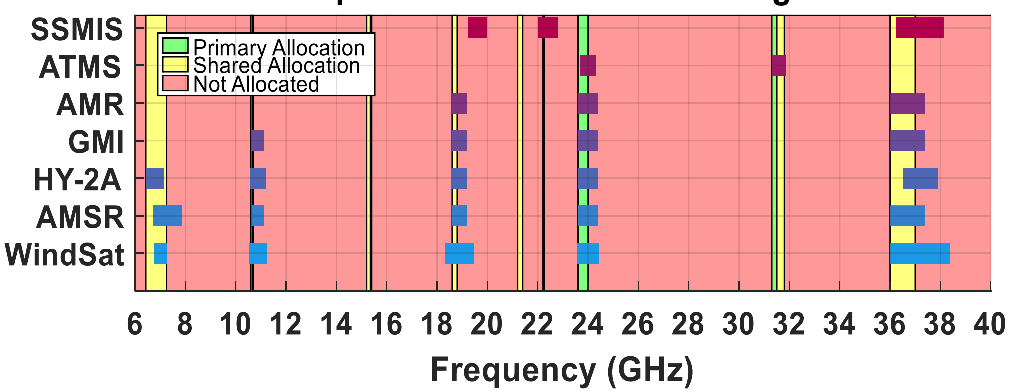
RFI Problem for Microwave Radiometry

- Microwave radiometers observe the naturally generated microwave thermal emission from Earth
  - Extensive use in atmospheric sensing (e.g., EOS)
  - Soil moisture, ice coverage/depth, ocean salinity, etc.
- Man-made transmissions cause radio-frequency interference (RFI) in microwave radiometers
  - Radiometers attempt to avoid RFI by operating in frequency bands where transmission is prohibited (“Science Bands”)
  - This is not always possible or effective

GMI Image at 18.7 GHz with RFI ‘hot spots’



Spectrum Allocation and Usage



RFI Problem for Microwave Radiometry

- RFI problem challenging for future radiometer systems
  - Increasing use of multiple channels
  - Bandwidth within each channel is increasing
  - Data volumes will grow beyond capacity to downlink
- On-board RFI mitigation is needed for future spaceborne radiometers

	SMAP	Future
Number of bands	1	6 or more
Bandwidth	20 MHz	100’s of MHz in each channel
RFI Processing on ground?	Yes (small downlink volume)	Not possible (downlink volume too large)
RFI Processing on-board spacecraft?	No; not necessary	Yes; only way to address RFI for future systems

CubeRRT Mission

- Technology validation mission
- Mature RFI mitigation technology from TRL 5 to TRL 7
- Demonstrate digital processor to detect and filter RFI
  - Pulsed and continuous sinusoidal RFI
  - Downlink raw and RFI-mitigated data
  - Compare on-orbit RFI flags with reconstruction on ground
- Meet baseline mission requirement
  - At least 100 hours of spaceborne operation
  - 10 hours in each of 10 pre-defined frequency bands

Center Frequencies (MHz)

6800	23800
10400	31400
18700	34000
19400	36500
22200	37500

Mission Properties

Frequency	6 to 40 GHz Tunable, 1 GHz instantaneous
Polarization	Circular polarization
Observation angle/Orbit (ISS launch)	0° Earth Incidence Angle 400 km altitude, 51.6° orbit inclination
Spatial Resolution	80 km (40 GHz) to 240 km (6 GHz)
Integration time	100 msec
Ant Gain/ Beamwidth	12dBi/30° (6 GHz), 21 dBi/10° (40 GHz)
Interference Mitigation	On-board Nyquist sampling of 1 GHz spectrum; On-board real-time Kurtosis and Cross-Frequency Detection Downlink of frequency resolved power and kurtosis in 128 channels to verify on-board performance
Calibration	Internal: Reference load and Noise diode sources External: Cold sky and Ocean measurements
Noise equiv dT	0.8 K in 100 msec (each of 128 channels in 1 GHz)
Average Payload Data Rate	9.375 kpbs (including 25% duty cycle) ~102 MB per day,~ 37 GB over 1 year mission life
Downlink	135 MB per daily ground contact [6 minute contact with 3 Mbps UHF cadet Radio] 32% margin over payload data

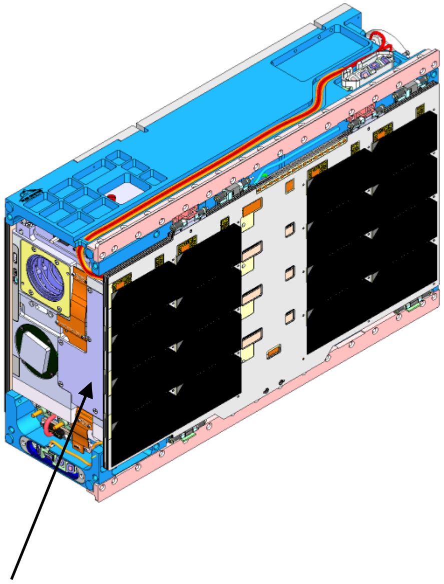
Spacecraft and Payload – Design, Integration, Test

THE OHIO STATE UNIVERSITY

Spacecraft Design

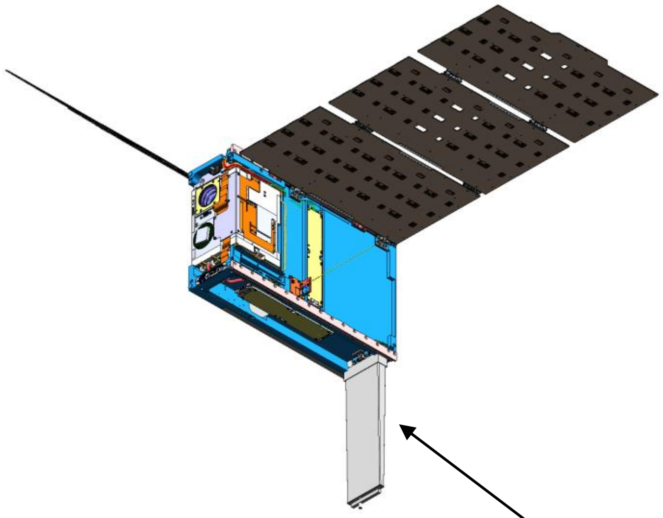
- Antennas and solar panels deploy from stowed position post-deployment
- Operates in a nadir viewing configuration
- Designed for yaw steering, which maximizes solar panel view of sun while taking radiometry measurements

Post-deploy stowed



XB1 Control Unit

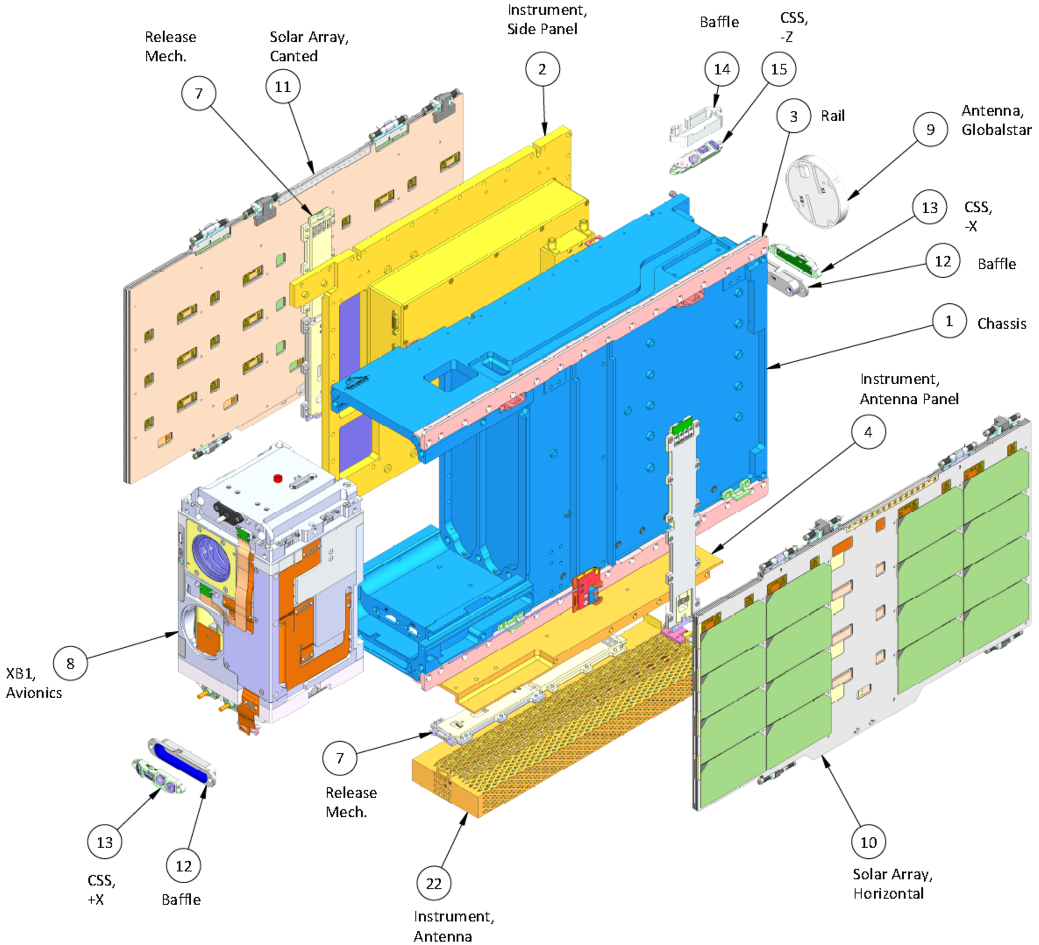
Payload antennas deploy toward nadir



Antenna
Deployed position

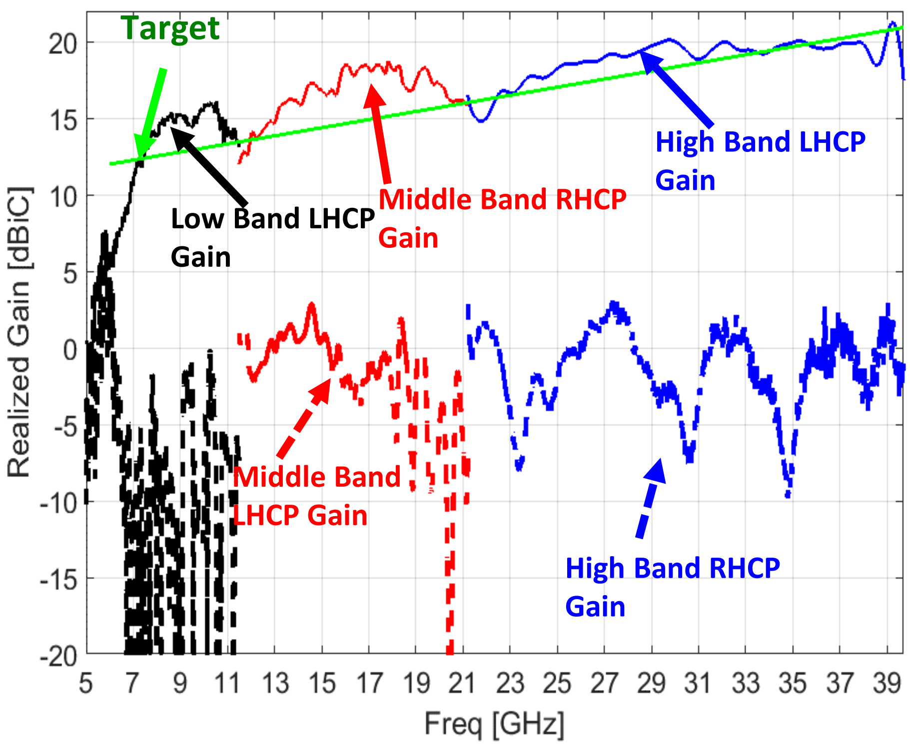
CubeSat System Overview

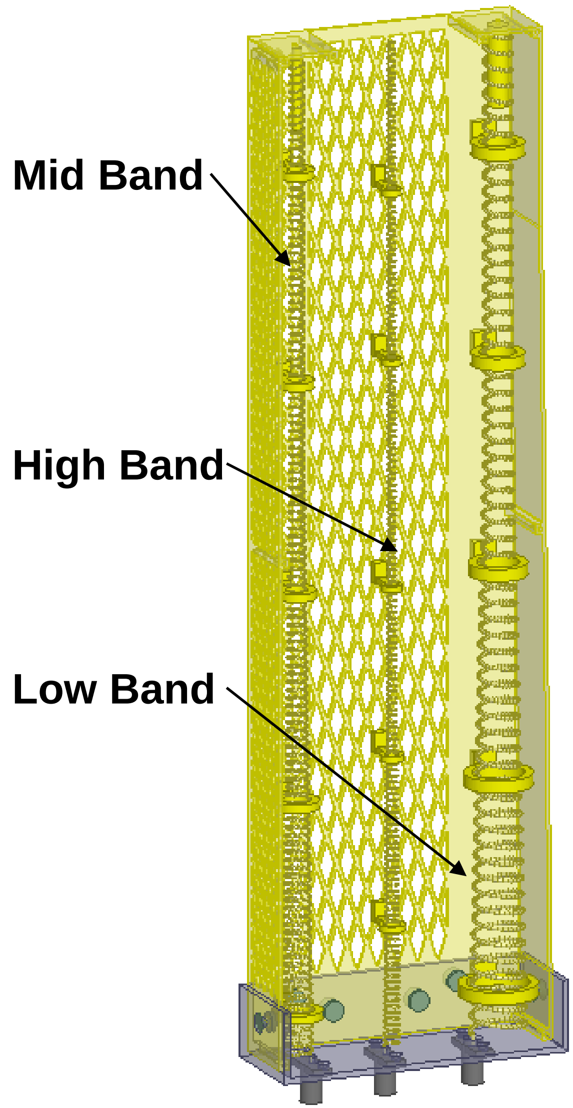
- Blue Canyon Technologies delivered 6U spacecraft bus
- BCT's XB1 unit provides flight computer, attitude control, navigation information, and communications
- Bus provides isolated power to payload radiometer to prevent ground loops
- Two contacts per weekday planned using WFF ground station
  - Primary: UHF Cadet radio
  - Backup: Globalstar satellite network



Payload Instrument – RF Antennas

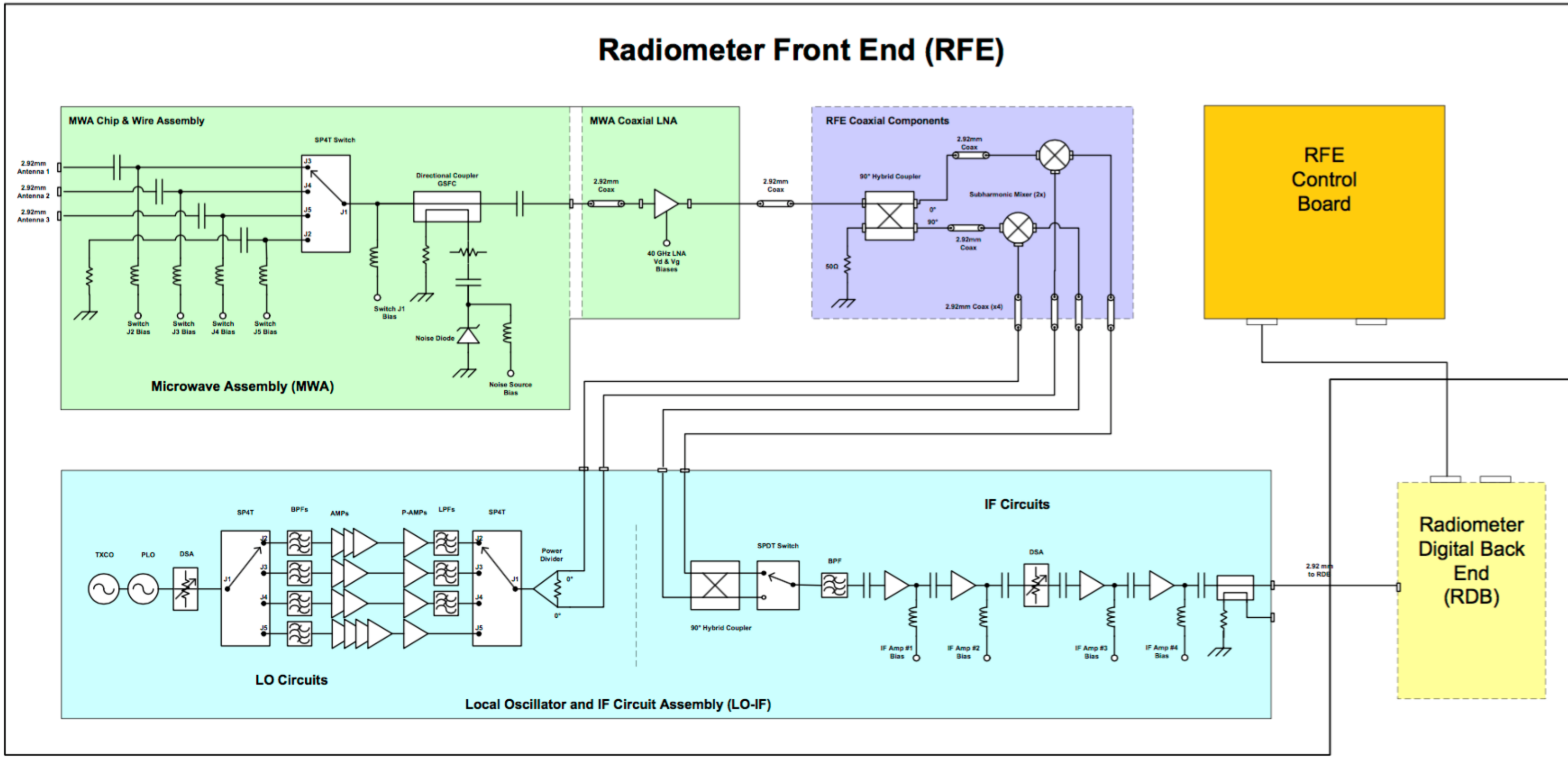
- Developed by Ohio State University
- Three tapered helical antenna elements to allow coverage of 6-40 GHz
- Radome included for mechanical support and to improve tuning; optimized for each antenna element





Payload Instrument – Radiometer Front-End

- Developed by NASA Goddard Space Flight Center
- Major subsystems
  - Microwave Assembly (MWA)
  - Local Oscillator and IF Circuit Assembly (LO-IF)



Payload Instrument – Digital Back-End

- Developed by NASA JPL
- ADC samples RFE's IF output at 2 GSPS
- RFI detection and mitigation performed using a combination of firmware (Zynq FPGA fabric) and software (Zynq embedded ARM processor)
  - Provides options in trading off power consumption versus flexibility and processor speed
- Multiple algorithms offer better performance for differing RFI types

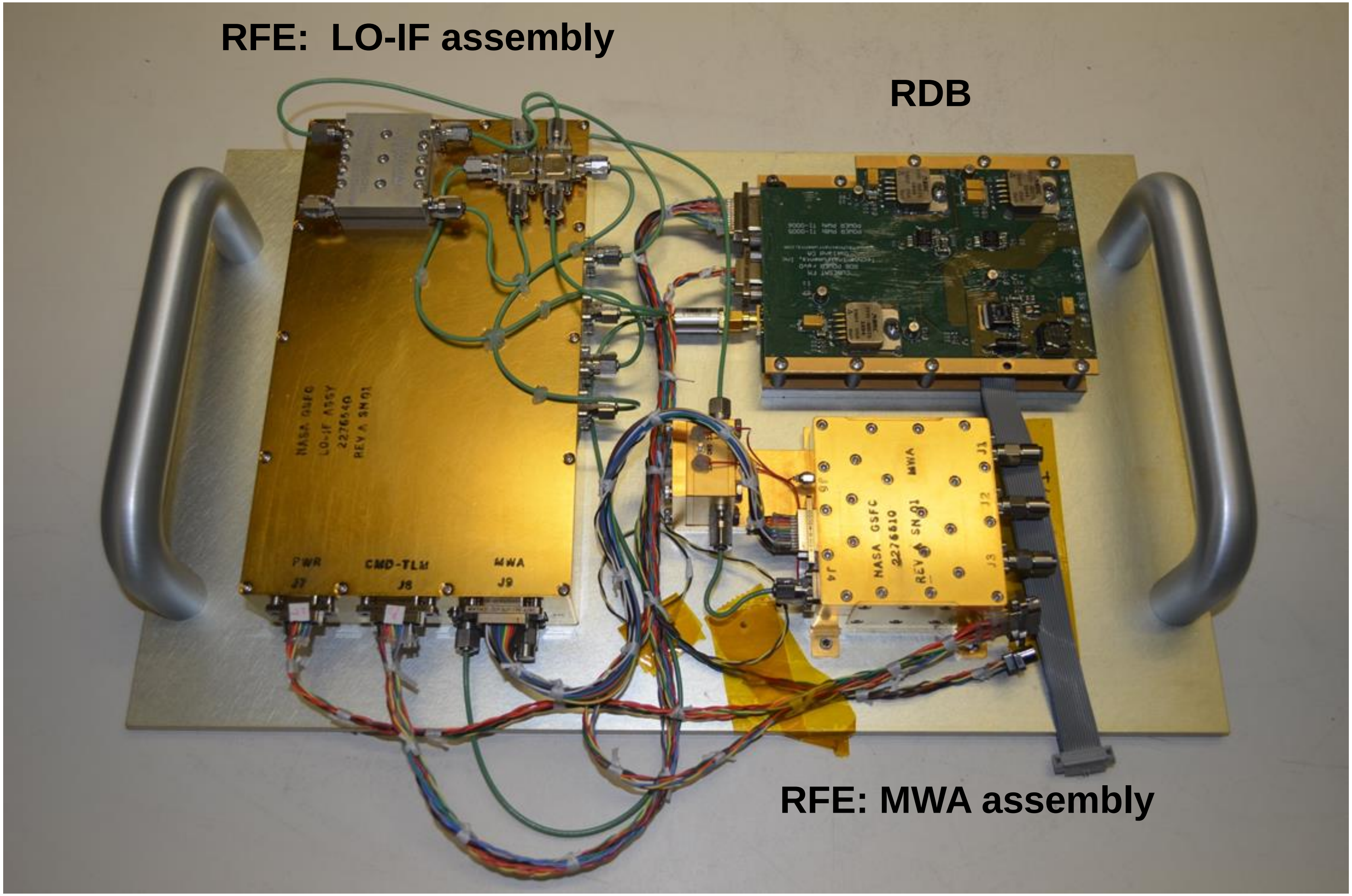
Cross Frequency (128ch/100ms)	CW, narrowband signals
Kurtosis (128ch/100ms)	Pulsed-type/low-level RFI

- Cross-frequency "flattens" data on board to improve sensitivity
  - Uses antenna/reference data to remove majority of passband shape prior to detection
  - Also includes additional on board frequency dependent table to "flatten" even further

Key Design Accomplishments

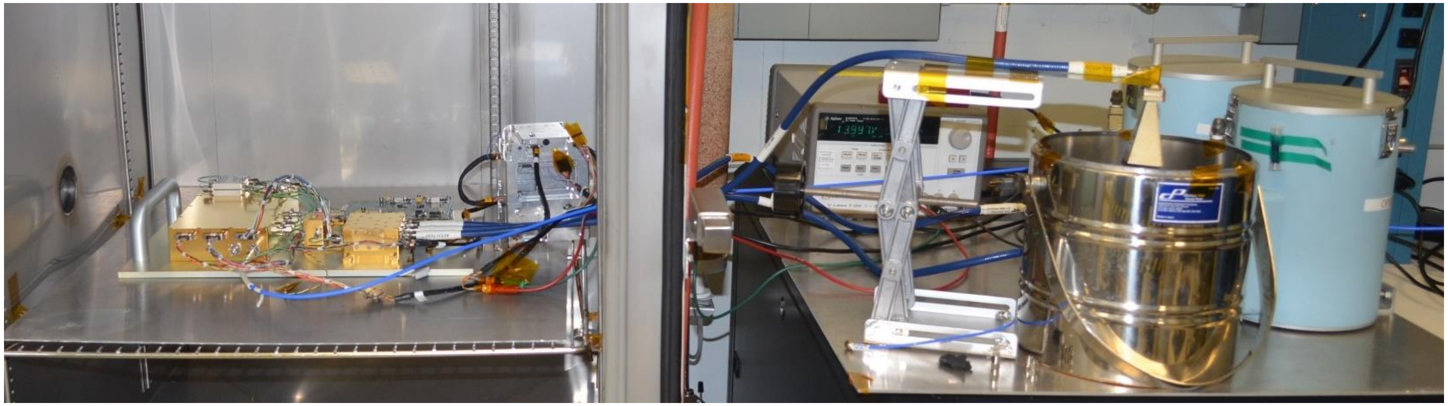
- RF antenna subsystem
  - Tapered helical antenna structures enable wideband performance in small form factor
  - Suitable for many future smallsat missions
- RFE subsystem
  - Unique design to enable wideband radiometry within tight SWaP constraints
  - NEDT < 1K up to 10 GHz, < 3K up to 30 GHz
  - RFE team awarded a patent in May 2020
- RDB subsystem
  - Packaging RFI processing capability into 0.25U, 170 g mass, <10 W power consumption represents a major enabling capability for future radiometer missions
  - New processing capabilities such as passband “flattening” provide significant RFI mitigation performance enhancement

Payload Integration



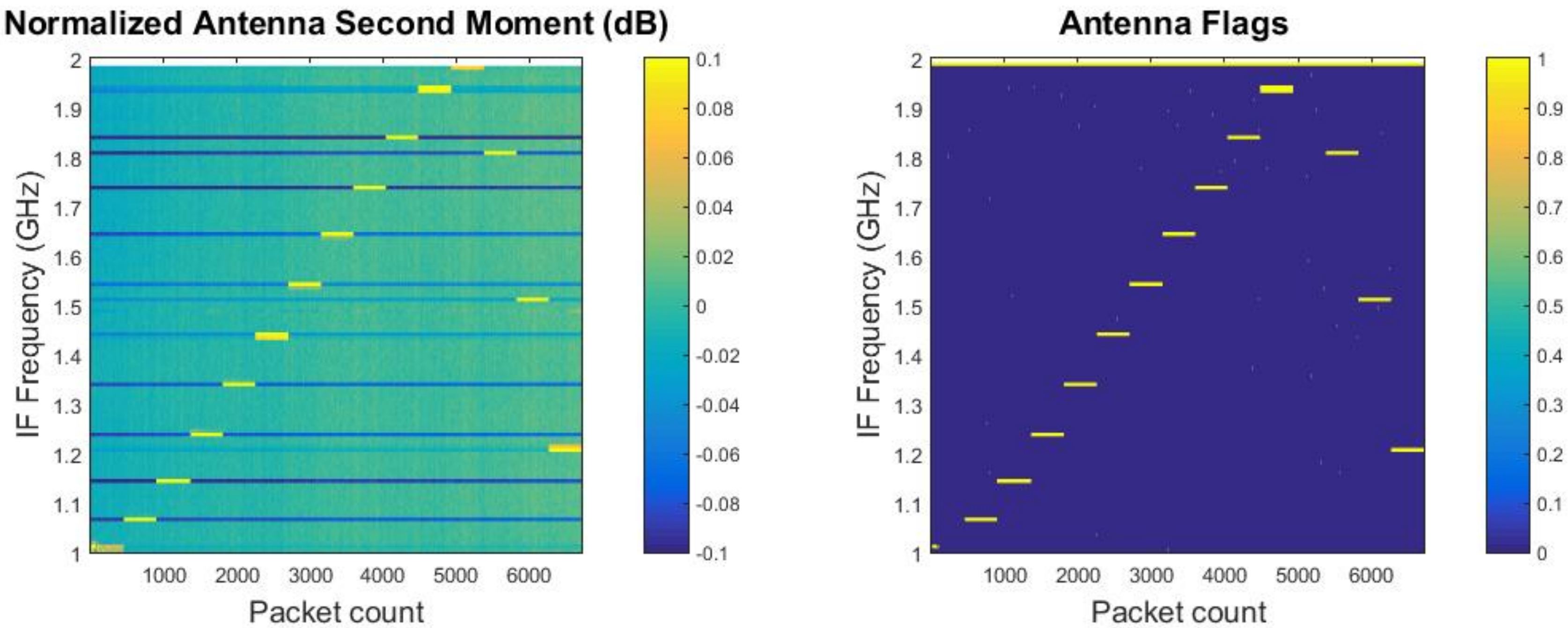
Payload Testing

- Flight model testing for the integrated CubeRRT payload occurred in October 2017 at GSFC
- Testing highlights include:
  - End-to-end radiometry measurements through integrated payload
  - Passband flattening implementation and optimization
  - Successful RFI detection and mitigation using injected and radiated signals
  - Thermal cycle testing



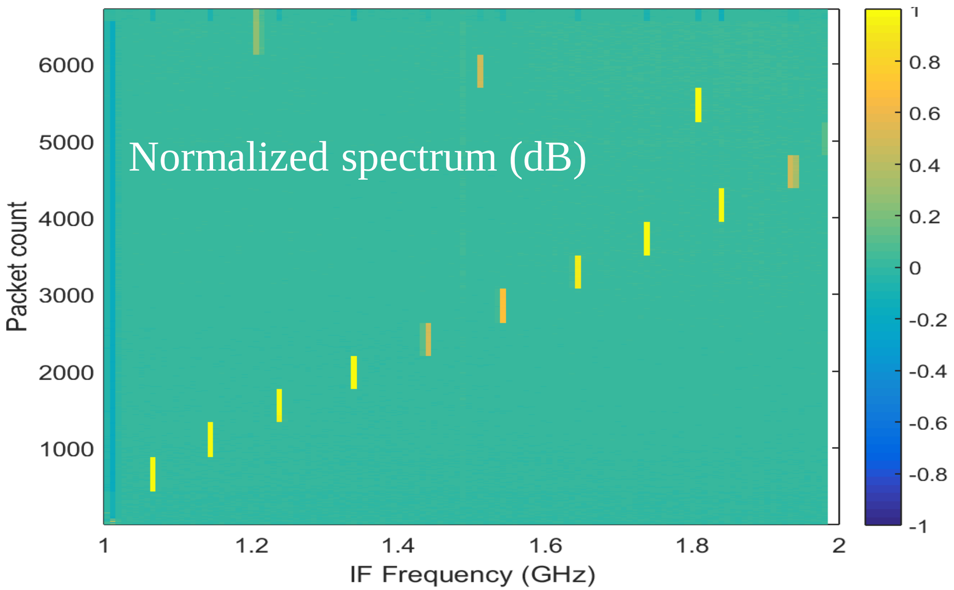
Payload FM Testing: RFI Detection

- Tested the ability to detect injected RFI
- Radiometer was tuned to a fixed frequency, with RFI injected and stepped across passband
- RFI was correctly flagged for the antenna measurements

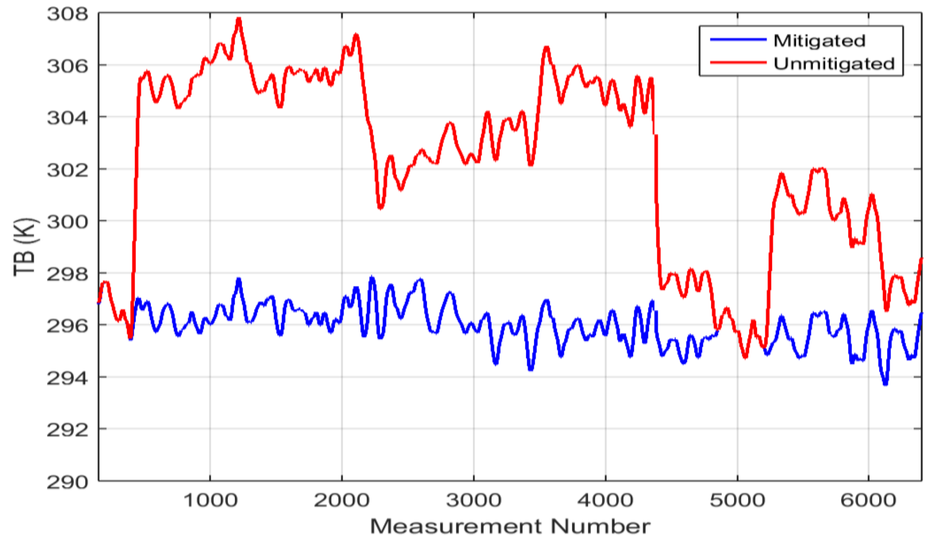


RFI Detection Performance Tests

- Example injecting sinusoidal RFI at differing frequencies into 9.9-10.9 GHz measurements
- RFI source power kept constant, but contribution modulated by passband shape of radiometer
- CubeRRT reports 128 point spectra versus time, but also removes corrupted RFI and reports mitigated and unmitigated total power

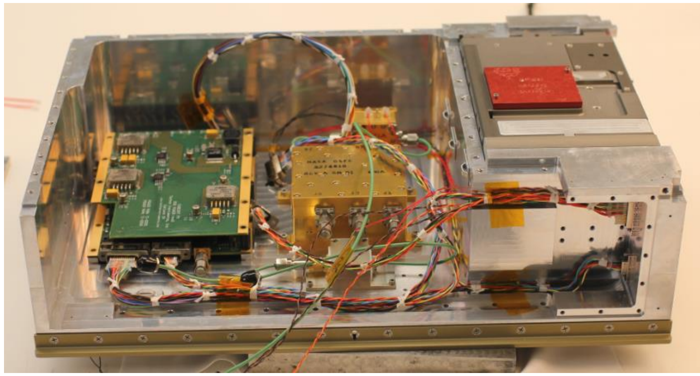


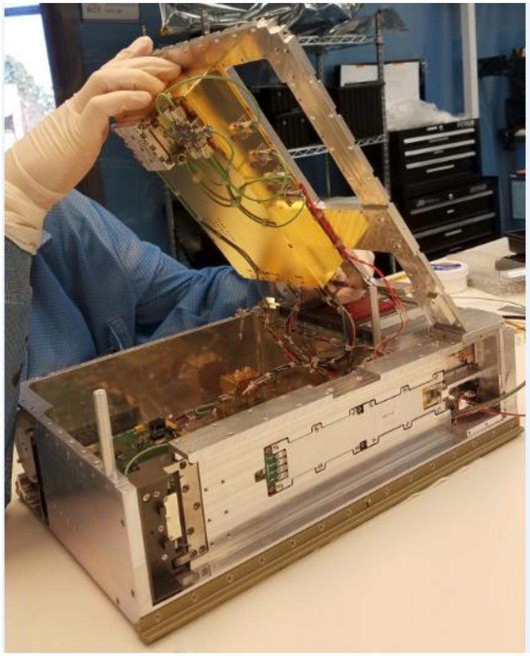
- Injected RFI contribution in this example varies from ~ 2K to ~ 10K depending on location in passband
- CubeRRT mitigates RFI down to ~ 2 NEDT level
  - Plot to right is averaged over multiple measurements to make RFI contributions clearer

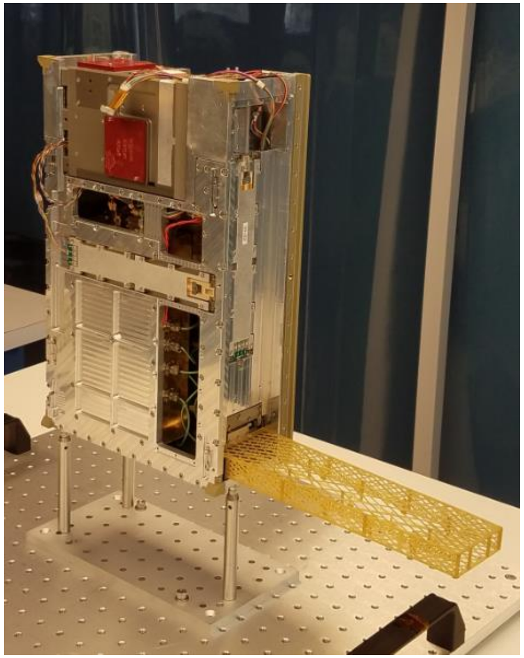


Payload-Spacecraft Integration

- RFE/RDB delivered to Blue Canyon Technologies and integrated into spacecraft November 2017

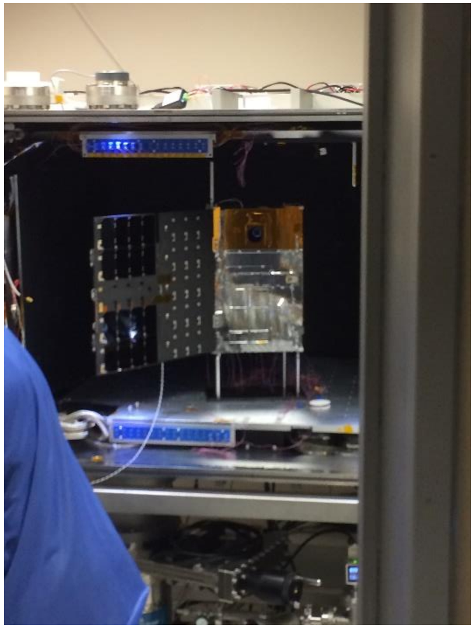


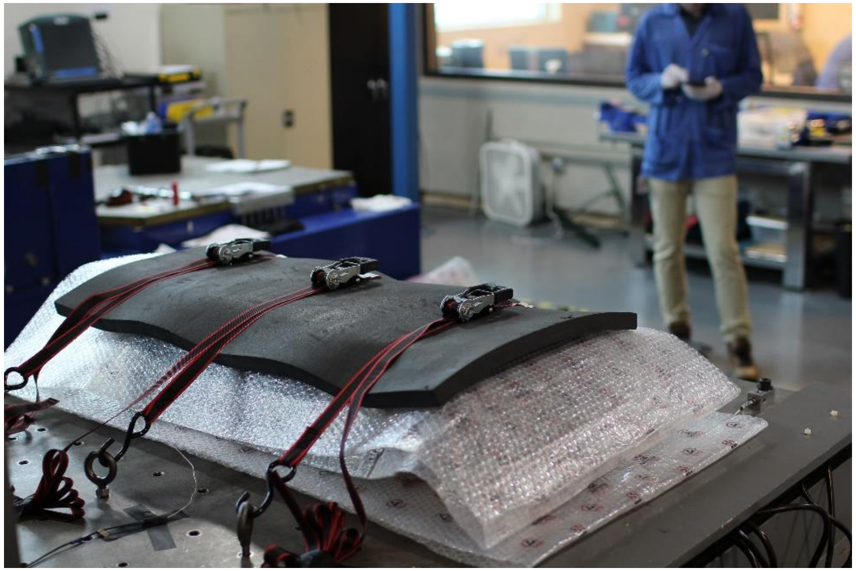




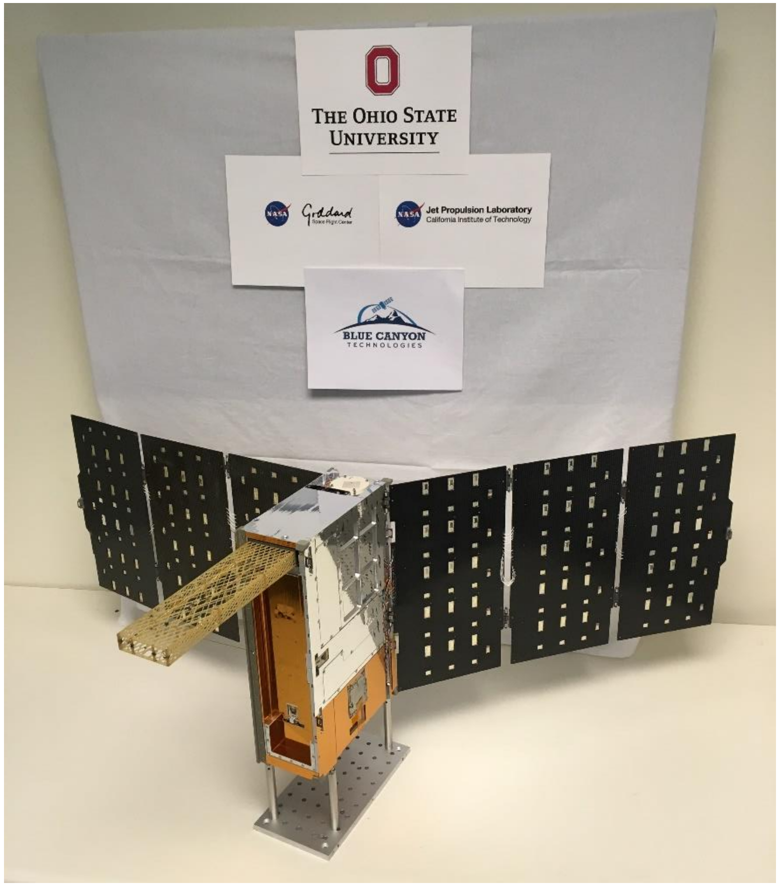
Integrated Spacecraft Testing

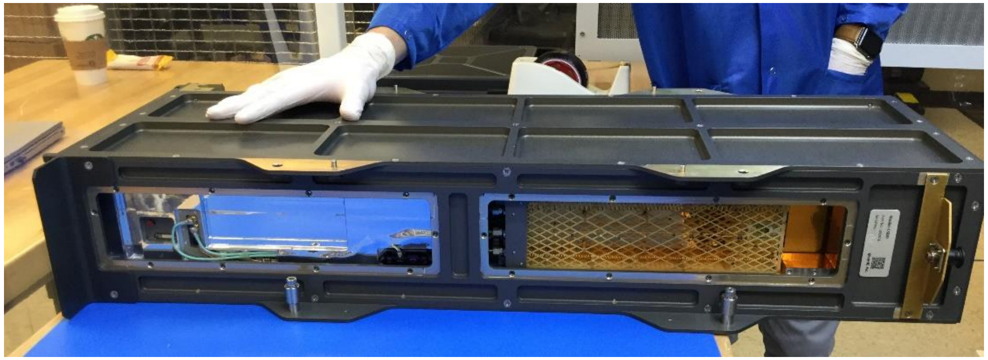
- Testing Jan-Feb 2018 included:
  - Self-compatibility
  - Environmental
    - Random vibration
    - Thermal vacuum
  - Day-in-the-Life





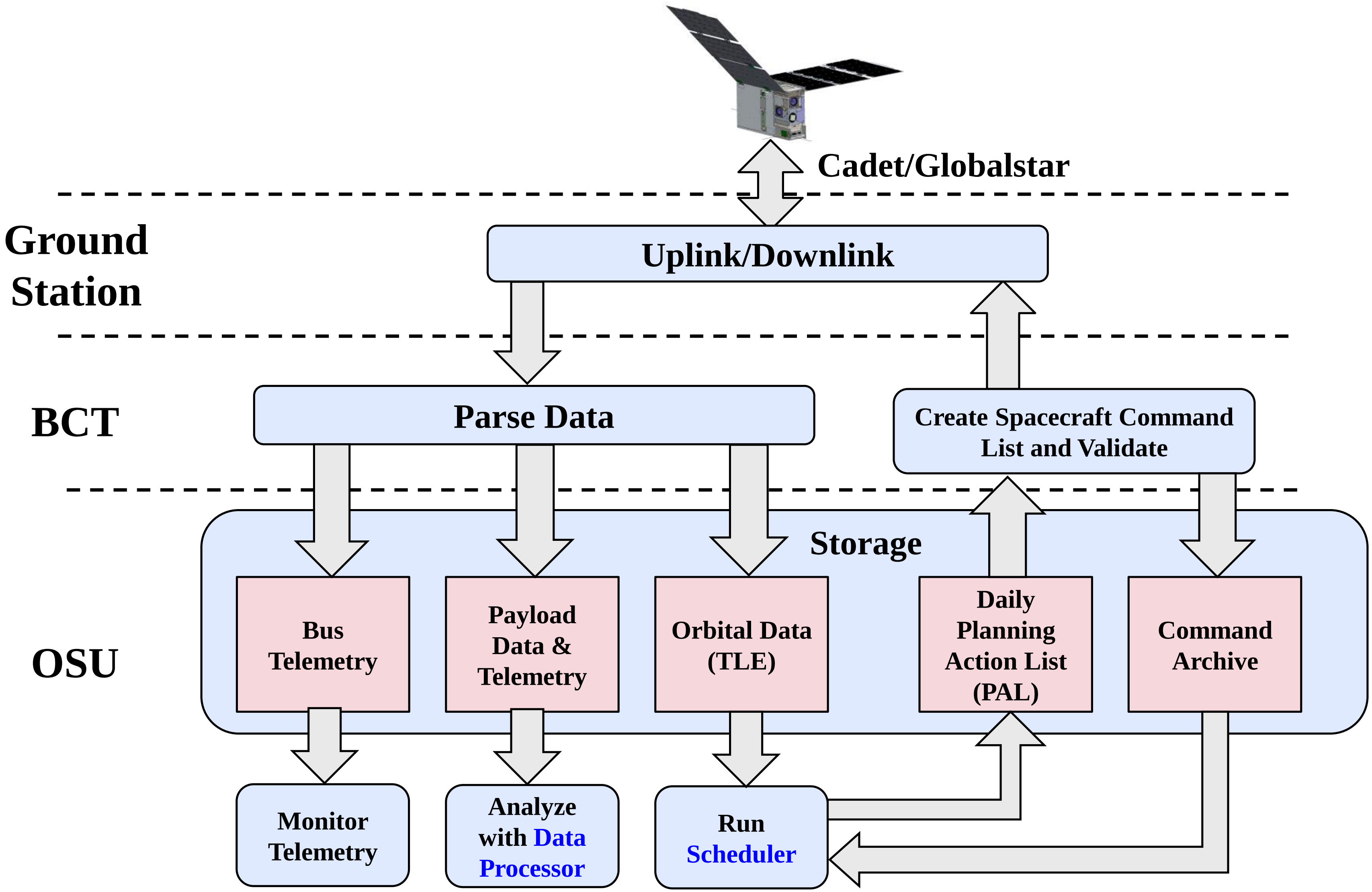
Payload-Spacecraft Integration



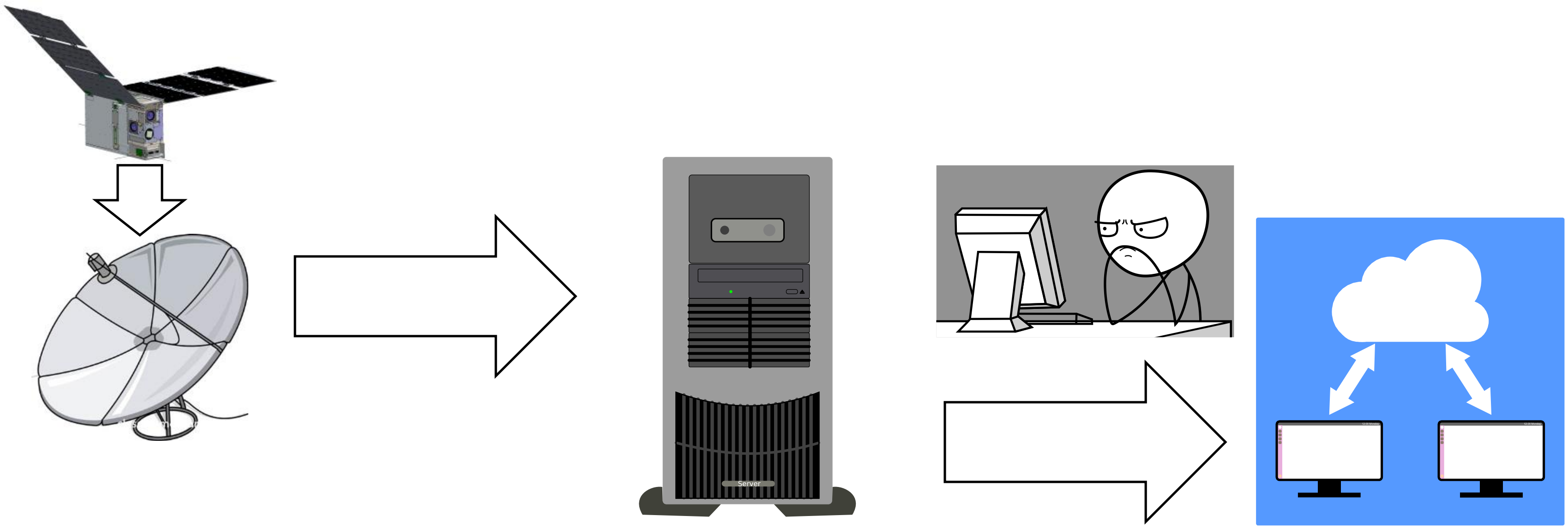


Operations Planning

Standard Operations Flow



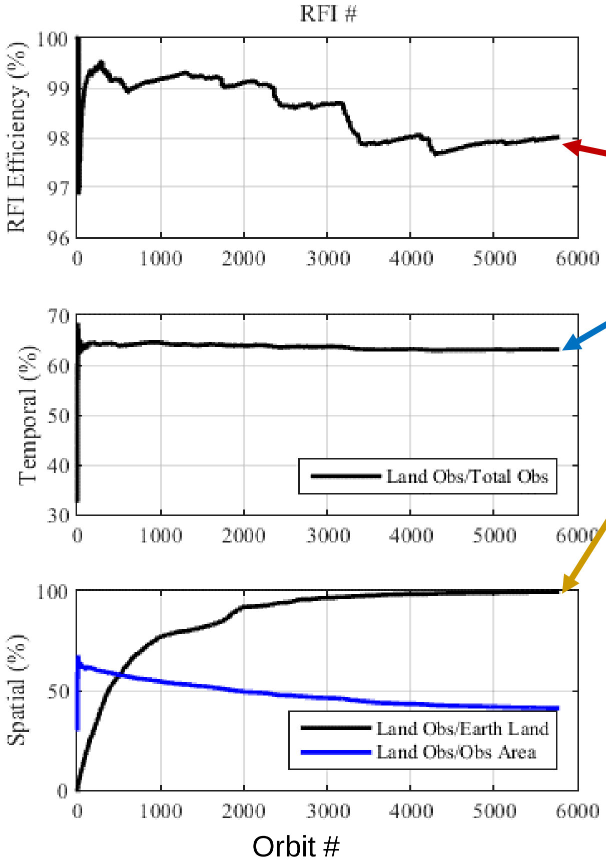
Data Processor Flow Diagram



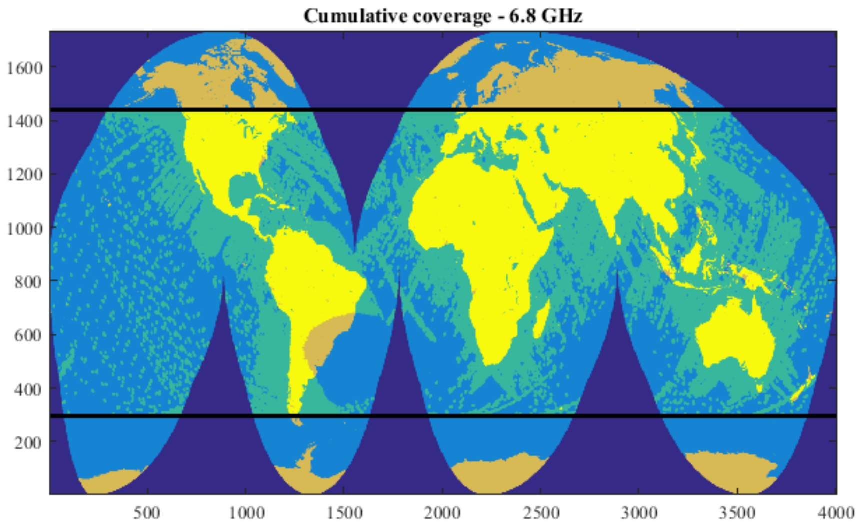
Level 0	1A Processor	Level 1A	1B Processor	Level 1B
Raw downlinked data, pushed by BCT to SFTP server	Extract payload data and desired telemetry to Level 1A	Relevant CubeRRT data in HDF5 format	Calibrate brightness, geolocate data, analyze RFI	Final data product located at SFTP/web

Operations Planning Tool

- CubeRRT serves as a case study for optimizing operations in the presence of power resource limitations
- Typical duty cycle ~30% with fully functioning payload
- Significant effort to plan payload ops to maximize RFI measurements

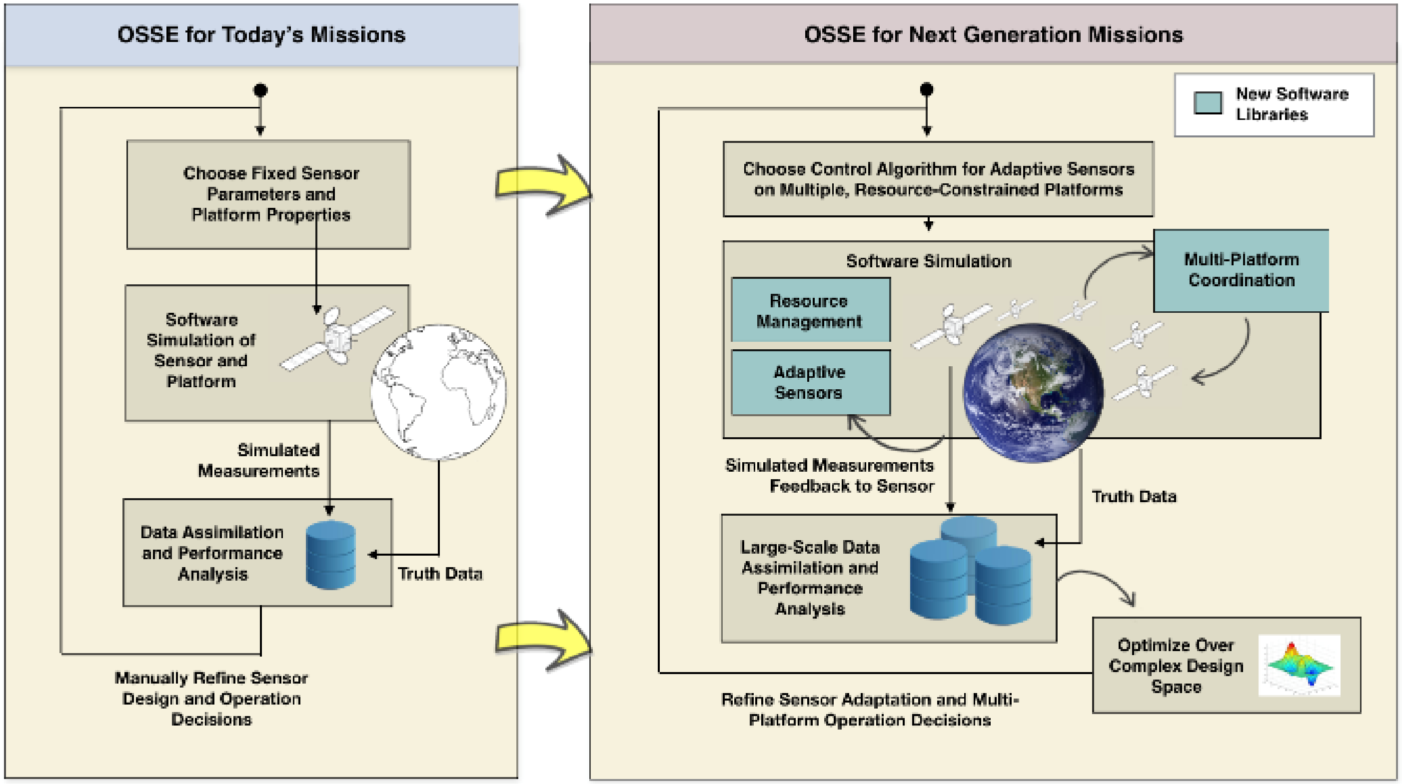


- Average RFI efficiency of 98%
- 65% of total observation time over land
- Over 99% of land observed at each frequency



Lessons Learned – Resource Constrained Ops

- Next-gen smallsat missions require sophisticated mission planning tools
- Simulation Toolset for Adaptive Remote Sensing (STARS) – AIST-17

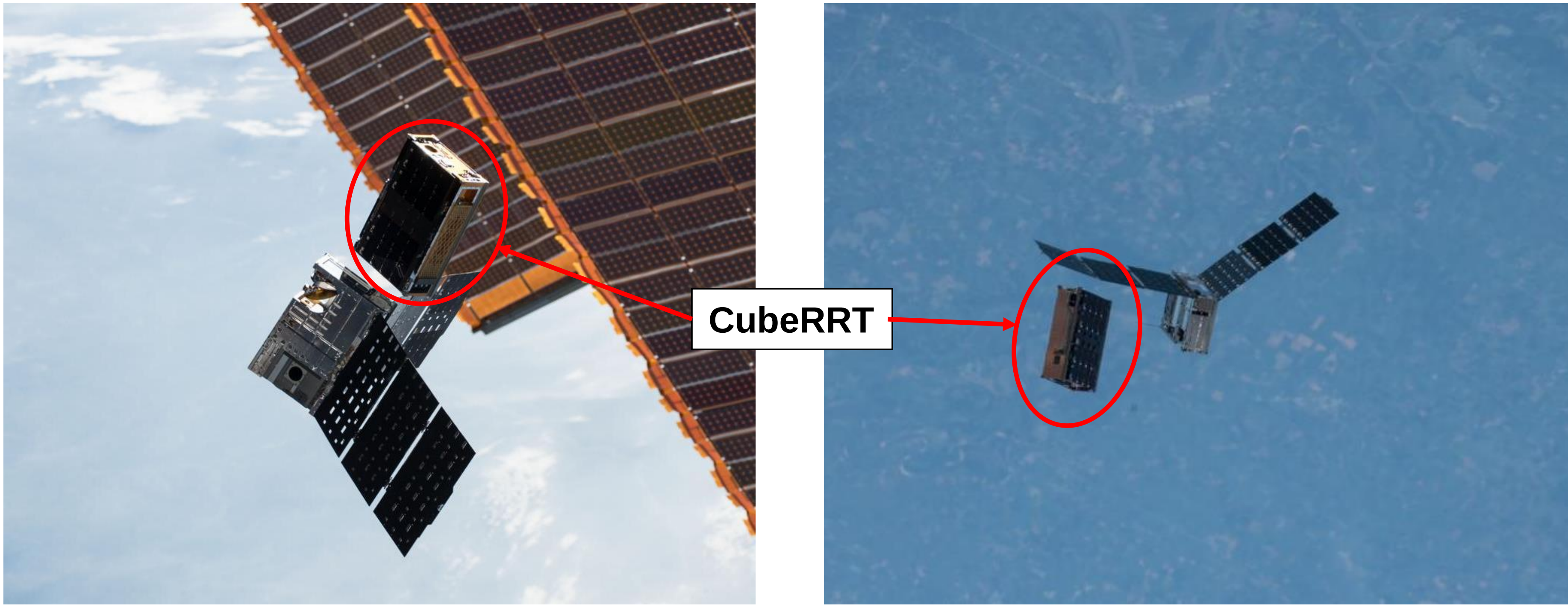


OSSE's for NASA's future multi-platform, resource-constrained adaptive sensor instruments will need to leverage software libraries that are specifically designed to address these complex systems

Launch, Deployment, Operations, & Lessons Learned

OA-9 Launch (May 21, 2018 4:44am)

ISS Deployment (July 13, 12:35pm GMT)



- CubeRRT deployed with TEMPEST-D
- Successful sun pointing immediately after deployment
- Commissioning activities commenced immediately

Establishing Ground Communications

- Leveraged WFF's UHF ground station
- Experienced a variety of hardware and software issues that impeded ground comms
- Able to check state of health via Globalstar
- Established reliable low data rate comms by 8/20 (500 kbps)
- Established full data rate (3 Mbps) by 8/23

Ground Comms Lessons Learned

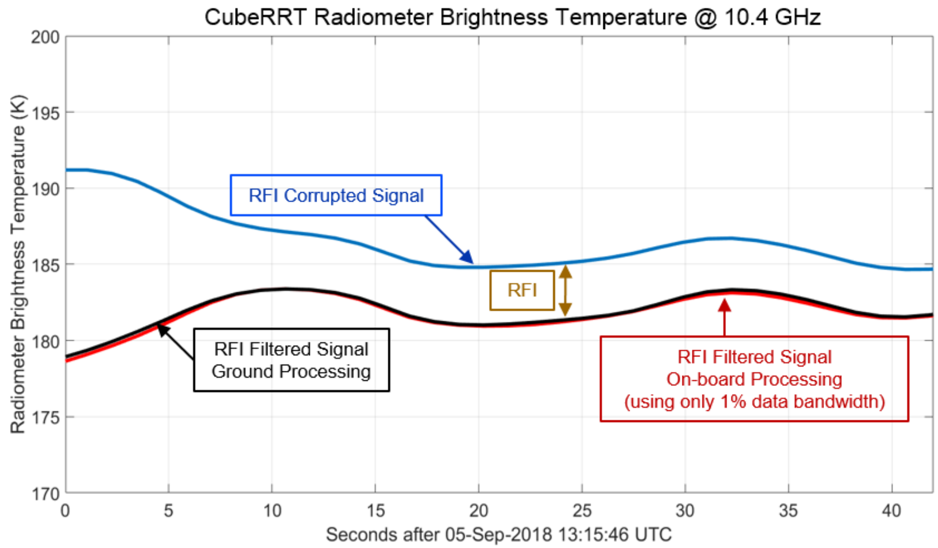
- Use of a single ground station resulted in various communications issues throughout the mission
  - Hardware issues degraded signal reception
  - Regular maintenance would occasionally cause loss of data
  - Multiple ground stations would provide redundancy and mitigate data loss if one experiences a problem – however higher cost
  - Multiple stations also allows more contacts per week and minimizes conflicts with nearby CubeSats
- Newer CubeSat radios and ground stations enable more use of S or X band comms
  - ESTO has since discouraged use of UHF radios
  - Higher frequencies support higher data rates
- Use of Globalstar as a backup to receive state of health and other key data was critical during comms blackouts

Commissioning

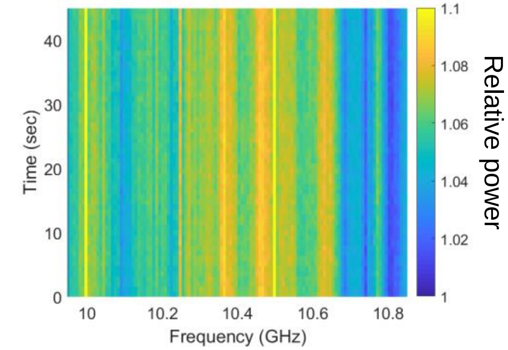
- Spacecraft commissioning (8/23-30)
  - Acquired initial state of health telemetry
  - Updated fault protection checks
  - Uploaded ephemeris data
  - Conducted additional communications checks
  - Calibrated star trackers
- Payload commissioning (8/29-9/8)
  - Conducted payload measurements with antenna stowed
  - Deployed antenna
  - Collected first light (9/5)
  - Continued payload tests until RFE anomaly

First Light (Sept 5, 2018)

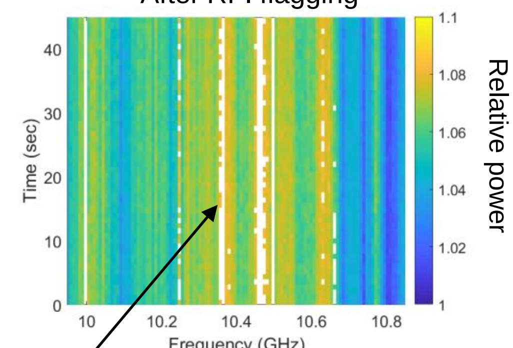
10 minute data collect over Pacific ocean
9/5/18
13:15-13:25Z



128 frequency channel spectrum used onboard



After RFI flagging

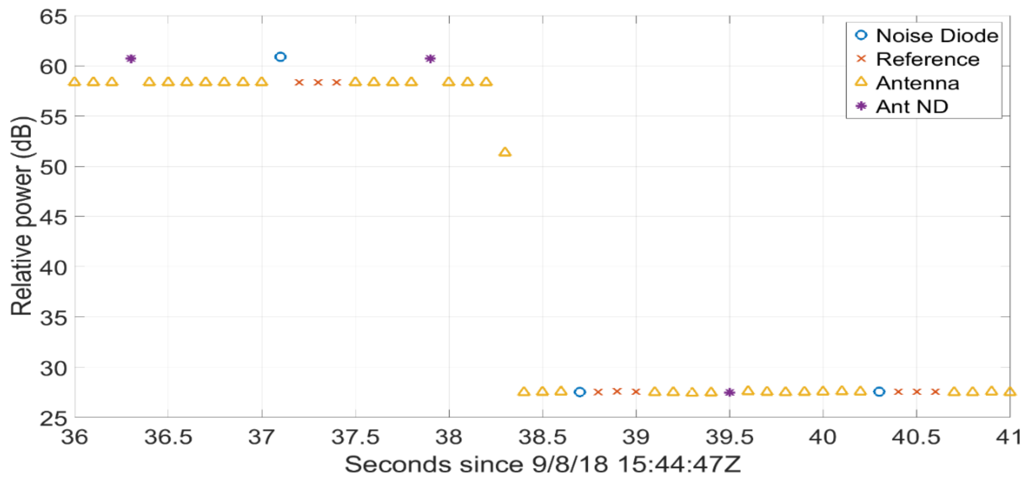


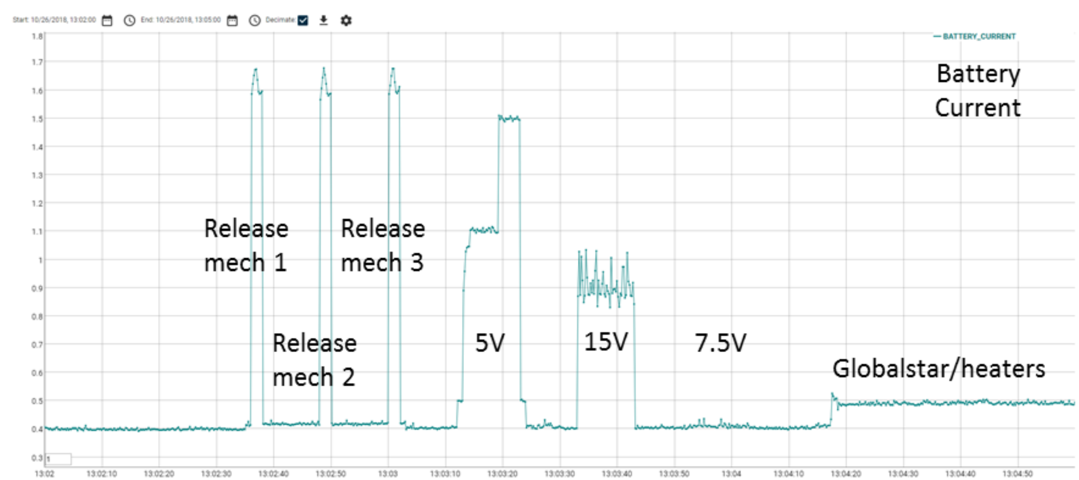
White areas mark RFI removed

Smoothed CubeRRT radiometer brightness temperatures demonstrate on-board RFI filtering: original RFI corrupted signal (blue) corrected on-orbit to RFI filtered signal (red) that is validated with ground processed data (black). On-board filtering ***requires 99% less data to be downlinked.***

RFE Anomaly

- Payload radiometer experienced anomalous shut down during a 10-minute collect on Sept 8
- Subsequent telemetry data indicated loss of +7.5V DC power to radiometer front end (RFE)
- Numerous attempts to recover RFE operation, including “phoenix maneuver”
- No recovery of RFE subsystem





RFE Anomaly – Lessons Learend

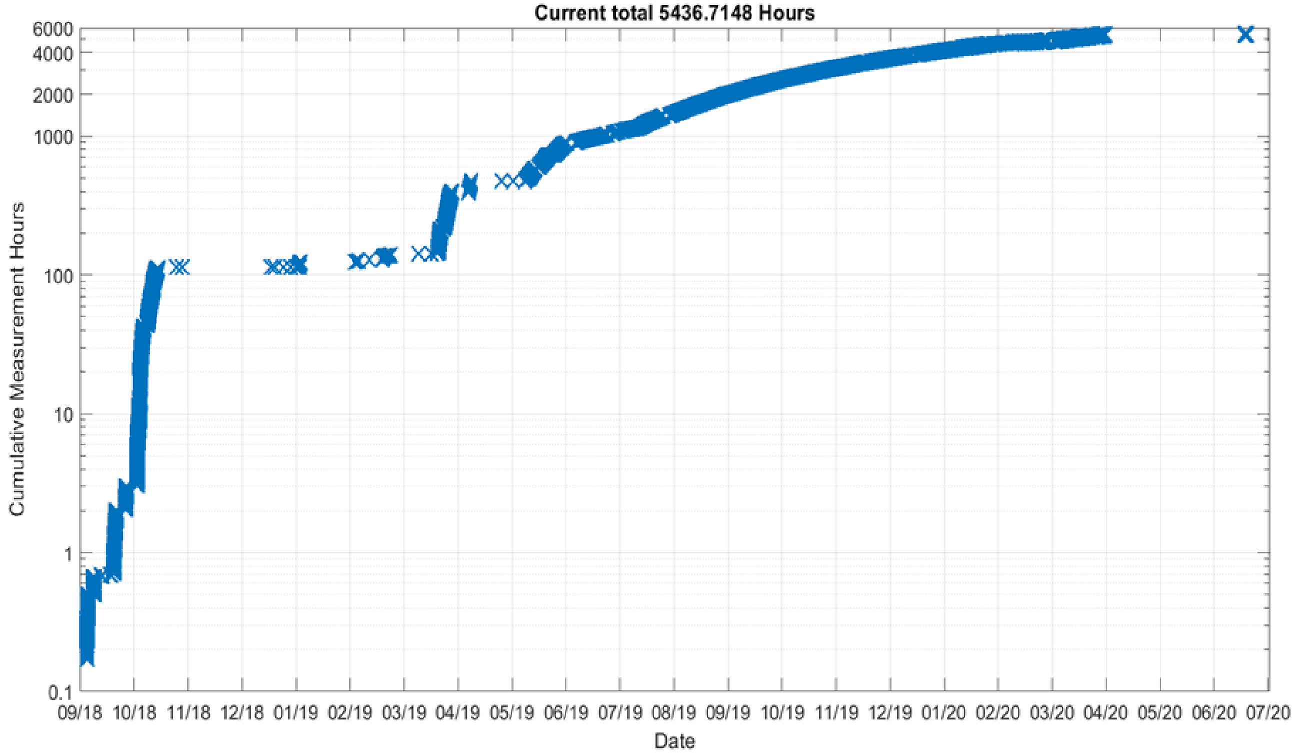
- Despite extensive root cause analysis, loss of 7.5V bias, and thus RFE, was never determined
  - Power converter on isolated power expansion board
  - Wiring harness from spacecraft to payload
  - Series resistor on RFE
- Payload operation was successfully tested in TVAC for more than 100 hours, no evidence to suggest failure risk
  - Some rework occurred to account for increased 7.5V current draw
  - Reworks occurred on compressed schedule, but no evidence of issues
- Future designs for similar power converters should include option to disconnect converter input supply to enable direct reset of any converter latchups
  - Phoenix maneuver was attempted to reset entire spacecraft – at great risk
- Additional peer-review of possible single point of failure mechanisms is warranted

On-Orbit Issues – Loss of Radio Contact

- Loss of radio contact
  - CubeRRT lost contact with WFF ground station on Oct 29
    - Uploading new commands to diagnose RFE anomaly
  - Contact restored Dec 12
  - Root cause – flight software error caused continual resets, loss of attitude control
  - Bus reset from radiation event triggered reboot on uncorrupted redundant image
  - FSW bug fixed and operations resumed
- Lessons learned
  - Use of mission-specific command verification tools (even for very minor changes)
  - Verification of future commands on ground-based test hardware prior to uplink
  - Future missions could implement fault protection check to prevent continuous reboot cycle
  - Develop troubleshooting scripts prior to launch

RDB-Only Operations

- Obtained over 5000 hours of RDB-only operation
- Mitigated “self-RFI” generated by the payload
- Met primary mission objectives to elevate TRL of RDB



RDB-Only – Lessons Learned

- RDB is the key technology validated by the CubeRRT mission
- RDB performed spectacularly in near continuous operation for thousands of hours
  - No degradation of performance
  - No unexpected interruptions, resets, latchups
- Specifically, COTS Xilinx Zynq 7100 (dual-core ARM processor and FPGA firmware fabric) has been demonstrated in a space environment
- RFI mitigation process has been validated and shown to drastically decrease data downlink volume for implementation on future missions

Conclusions

TRL Assessment

The CubeRRT project matured digital backend processing system and RFI mitigation technique from TRL 5 to 7

Technology/Measurement Technique	Heritage	Entry TRL	Planned Exit TRL	Success Criteria
On-board wideband RFI mitigation technique	SMAP radiometer backend, PALS flights	5	7	Successful flight validation
Wideband digital backend for RFI mitigation	Previous FPGA based RFI-processors; PALS airborne flights; Current spaceborne development for MarCO, Lunar Flashlight and NEAScout	5	6	Demonstration in thermal vacuum
			7	Successful flight validation

Summary

- CubeRRT mission validated critical RFI detection and mitigation technologies for future Earth observing microwave radiometers operating at 6-40 GHz
- This technology is already being incorporated in proposals for next generation microwave radiometry missions
- The CubeRRT satellite was successfully designed, assembled, tested, launched, deployed, and commissioned
- Despite several challenges, on-orbit operations were able to demonstrate over 5000 hours of RDB operation without a single failure, elevating TRL of the technology to 7

Key Accomplishment – CubeRRT Beer!

SPACE-GRANT - CUBERRT

Availability Retired

Flavor Profile Clean/Crisp

Style IPA

Style Name Extra Pale Ale

ABV 6.20%

Hops Cashmere, Nelson Sauvin, Falconer's Flight

Malt Caramel Vienne 20L, Craft Master Blend (Silo), Swaen Vienna, Wheat Malt

Crushability

Three Words , ,

First Brewed 2018-04-30

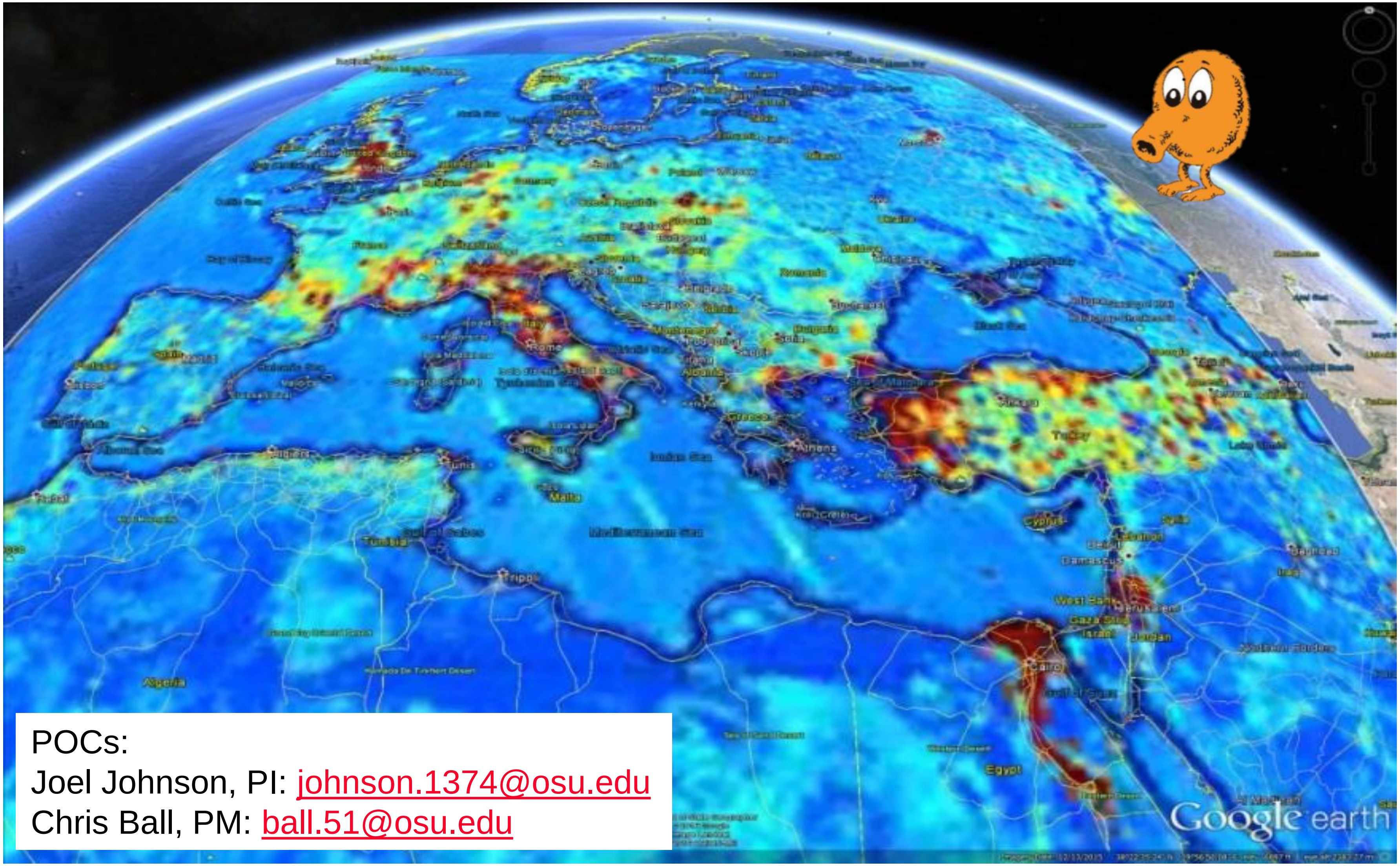
Last Brewed 2018-04-30

AVAILABILITY MONTHS

Jan	Feb	Mar	Apr	May	Jun
Jul	Aug	Sep	Oct	Nov	Dec

Meet CubeRRT, the first satellite designed, engineered, and built at Ohio State's ElectroScience Laboratory. Developed in collaboration with NASA's Jet Propulsion Laboratory and the Goddard Space Flight Center, CubeRRT's work in orbit will demonstrate technology that will support future missions for agriculture and climate science. To celebrate its launch from Wallops Flight Facility in Virginia, we just brewed up this special Space-Grant Series beer. CubeRRT, the beer, is a super limited, launch-ready Extra Pale featuring Falconer's Flight, Cashmere, and Nelson Sauvin hops. 10,9,8,7...

Questions?



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