The CubeSat Radiometer RFI Technology Validation (CubeRRT) Mission: Instrument Pre-Launch Testing and Project Status

The Ohio State University

S. Misra, R. Bendig, C. Felten, S. Brown, R. Jarnot
NASA JPL

J. Kocz
California Institute of Technology

NASA GSFC

D. Laczkowski, M. Pallas, E. Krauss
Blue Canyon Technologies

Small Sat 2018
Logan, UT
CubeRRT Overview

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

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

• Launched on May 21, 2018 (OA-9 / ELaNa 23 ISS resupply)

• Deployed from ISS on July 13, 2018
RFI Problem for Microwave Radiometry

- Microwave radiometers observe the naturally generated microwave thermal emission from Earth for use in a variety of science applications.
- Man-made transmissions cause radio-frequency interference (RFI).
- Radiometers attempt to avoid RFI by operating in frequency bands where transmission is prohibited, but this is not always possible or effective.

RFI problem is even more challenging for future radiometer systems.

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

• Technology validation mission
  – Designed for 1 year of operation
  – Mature RFI mitigation technology from TRL 5 to TRL 7

• Demonstrate digital processor to detect and filter RFI
  – Mitigate pulsed and continuous sinusoidal RFI
  – Downlink raw and RFI-mitigated data
  – Compare reported RFI flags with reconstruction on ground

• Meet baseline mission requirement
  – Provide radiometry data from at least 100 hours of spaceborne operation
  – 10 hours in each of 10 pre-defined frequency bands

<table>
<thead>
<tr>
<th>Mission Properties</th>
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<tr>
<td>Frequency</td>
</tr>
<tr>
<td>Polarization</td>
</tr>
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</table>
| 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 |
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
- Radiometer payload
  - RF antennas
  - Radiometer front-end
  - Radiometer digital back-end
Spacecraft Deployment

- 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

![Spacecraft Deployment Diagram]

Post-deploy stowed

Payload antennas deploy toward nadir

XB1 Control Unit

Antenna
Deployed position
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
RFI Mitigation Performance Tests

- Injected RFI contribution varied from ~ 2K to ~ 10K depending on location in passband
- CubeRRT mitigates RFI down to ~ 2 NEDT level
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
• Delivery to Nanoracks Mar 2018 for launch prep
Payload-Spacecraft Integration
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
- Preliminary Globalstar telemetry data indicate power positive, temperatures within expected ranges
- Currently establishing UHF Cadet contacts with WFF ground station
Next Step: Operations

- Two contacts per weekday via Wallops Ground Station
- Measure during passes over likely RFI locations (land)
  - Observe RFI ~14 seconds per location
    - Antenna has spot size ~80 km at 40 GHz, ~240 km at 6 GHz
- Manage battery depth-of-discharge
  - Up to 33% duty cycle (~30 minutes out of a ~90 minute orbit)
- Option 1: Use location to power on
  - On-board event checks to detect when entering a power-on region
  - Command generated to power on for pre-defined length of time
- Option 2: Plan weekly schedule of payload on/off times
  - Scheduler tool used to predict satellite location and power status
  - Commands uploaded periodically to satellite
  - On-board timed command table
- Baseline mission objectives (10 hours of operation in all 10 frequency bands) achieved within first 14 to 21 days
Conclusions and Lessons Learned

- CubeRRT will validate RFI detection and mitigation technologies for future Earth observing microwave radiometers operating 6-40 GHz
  - Currently on-orbit, commissioning phase to begin shortly
  - Approximately one year of operations
  - Processed data will be publicly available through OSU
- Accelerated development timeline worked, but benefitted greatly from NASA space system expertise
- Would benefit from more testing and ops planning involving ground station
- Additional exploration of comms options to better enable downlink of data volume
- Simulation tools to optimize duty cycle important for meeting mission objectives
- CubeRRT beer is very tasty
Questions?

POCs:
Joel Johnson, PI: johnson.1374@osu.edu
Chris Ball, PM: ball.51@osu.edu
BACK UP SLIDES
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

*Graph showing realized gain over frequency.*
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

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<tr>
<th>Method</th>
<th>RFI Type</th>
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<tr>
<td>Cross Frequency</td>
<td>CW, narrowband signals</td>
</tr>
<tr>
<td>Kurtosis</td>
<td>Pulsed-type/low-level RFI</td>
</tr>
</tbody>
</table>

• 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
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

Normalized spectrum (dB)
Sample Instrument Performance Data

- Radiometric Sensitivity (NEDT):
  - < 1K for f< 10 GHz
  - ~ 1-3K for 10<f<35GHz
  - ~ 3-30K for f> 35 GHz
- Coarse sensitivity for f> 35 GHz will allow only large RFI sources O(~20-100K) to be observed
- Real-time RFI detection and removal can still be shown
Data Processor Flow Diagram

<table>
<thead>
<tr>
<th>Level 0</th>
<th>1A Processor</th>
<th>Level 1A</th>
<th>1B Processor</th>
<th>Level 1B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw downlinked data, pushed by BCT to SFTP server</td>
<td>Extract payload data and desired telemetry to Level 1A</td>
<td>Relevant CubeRRT data in HDF5 format</td>
<td>Calibrate brightness, geolocate data, analyze RFI</td>
<td>Final data product located at SFTP/web</td>
</tr>
</tbody>
</table>
CONOPS: 1 Year Results

• 1 year of operation operating 30 min/orbit and frequency switching every 10s results in:

  • Baseline mission objectives (10 hours of operation in all 10 frequency bands) achieved within first 14 days

  Average RFI efficiency of 98%

  65% of total observation time over land

  Over 99% of land observed at each frequency
Standard Operations Flow

**Ground Station**

- **BCT**
  - Parse Data
  - Bus Telemetry
  - Payload Data & Telemetry
  - Orbital Data (TLE)

- **OSU**
  - Monitor Telemetry
  - Analyze with Data Processor
  - Run Scheduler
  - Daily Planning Action List (PAL)
  - Command Archive

**Uplink/Downlink**

**Cadet/Globalstar**