Radiometer Payload for the **TEMP**oral **E**xperiment for **S**torms and **T**ropical systems Demonstration Mission (TEMPEST-D)

Venture EVI-2

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Instrument Requirements and Challenges

- The TEMPEST-D radiometer instrument has been designed to perform high-precision radiometric measurements under mass, volume and power constraints – all within a tightly cost-capped environment.
- Approach:
  - Operate in millimeter-wave bands to reduce aperture requirements, while maintaining observational capability to further cloud and precipitation science
  - Utilize MMIC technology to reduce size, mass and power without compromising performance
  - Calibrate using proven internal and external reference target techniques
  - Utilize lower-power direct detection instead of heterodyne architecture
  - Leverage existing high TRL technologies wherever possible to reduce risk
    - Scanning mechanism from BCT reaction wheel motors
    - Calibrator from Zax Millimeter-Wave Corp. (AMSU/ATMS/MLS heritage)
    - Bias and readout circuits from SWOT/Sentinel-6

Instrument Mass and Power

Resource	CBE	Allocation	Margin (Actual)
Radiometer Mass (kg)*	4.1	4.1	0%
Radiometer Power (W)	6.0	6.5	8%
Radiometer Data Rate (Kbps)**	10.3	12.3	16%
Radiometer Precision (K)	0.4-0.95	1.4	71-32%
Radiometer Accuracy (K)	3.5	4	13%

$$MARGIN = 100 \times \frac{Allocation - CBE}{Allocation}$$

*Includes the instrument mounting plate
**Includes spacecraft state-of-health telemetry

All excess margin has been released to the spacecraft.

Key Radiometer Level 3 Requirements

<table>
<tr><th>Title</th><th>Shall Statement</th><th>L1 Parents</th><th>Verification Approach</th></tr>
<tr><td>Measurement</td><td>The Radiometer shall have at least 5 channels at distinct sideband frequencies between 89 and 183 GHz with center frequencies and bandwidth as defined in table below.
<table>
<tr><th>Center Frequency (GHz)</th><th>Bandwidth (GHz)</th></tr>
<tr><td>89 ± 2</td><td>4 ± 2</td></tr>
<tr><td>165 ± 2</td><td>3 ± 1</td></tr>
<tr><td>176 ± 2</td><td>2 ± 0.5</td></tr>
<tr><td>180 ± 2</td><td>2 ± 0.5</td></tr>
<tr><td>182 ± 2</td><td>2 ± 0.5</td></tr>
</table></td><td>L1- 3.1.3.</td><td>VNA Test</td></tr>
<tr><td>Precision</td><td>The Radiometer shall meet the error allocations listed in the table below.
<table>
<tr><th>Error Allocation</th><th>89 GHz</th><th>176 GHz</th></tr>
<tr><td>Measurement noise (NEΔT, 1/f, 2 Instruments)</td><td>0.48 K</td><td>0.61 K</td></tr>
<tr><td>Residual antenna temperature error</td><td>0.1 K</td><td>0.1 K</td></tr>
<tr><td>Residual brightness temperature calibration</td><td>0.15 K</td><td>0.15 K</td></tr>
<tr><td>RSS total error allocation</td><td>0.51 K</td><td>0.64 K</td></tr>
<tr><td>Flowed down from Science Requirement</td><td>1.4 K</td><td>1.4 K</td></tr>
</table></td><td>L1- 3.1.3
This assumes 1.4 K instrument error for the two instruments being compared.</td><td>Radiometric hot-cold test</td></tr>
<tr><td>Accuracy</td><td>The Radiometer shall meet the error allocations listed in the table below.
<table>
<tr><th>Error Allocation</th><th>89 GHz</th><th>176 GHz</th></tr>
<tr><td>Measurement noise:
Radiometric resolution (NEΔT)*
Residual 1/f noise</td><td>
0.3 K
0.15 K</td><td>
0.4 K
0.15K</td></tr>
<tr><td>Antenna temp calibration error</td><td>0.15 K</td><td>0.18 K</td></tr>
<tr><td>Brightness temp calibration error</td><td>0.15 K</td><td>0.15 K</td></tr>
<tr><td>Prelaunch calibration bias</td><td>3 K</td><td>3 K</td></tr>
<tr><td>RSS total Instrument error</td><td>3.03 K</td><td>3.04 K</td></tr>
<tr><td>From Science Requirement</td><td>4 K</td><td>4 K</td></tr>
</table></td><td>L1- 3.1.4</td><td>Radiometric hot-cold test thermal vacuum</td></tr>
</table>

Measurement Noise Performance Flowdown

Measurement Noise Error Allocations

Error Component`	89 GHz	176 GHz
Noise on scene measurement at 5 ms for T_B = 150 K	0.25	0.4
Noise from calibration measurements	0.15	0.25
System drift over averaging window	0.15	0.25
System Margin	0.35	0.3
Measurement Noise	0.48 K	0.6 K

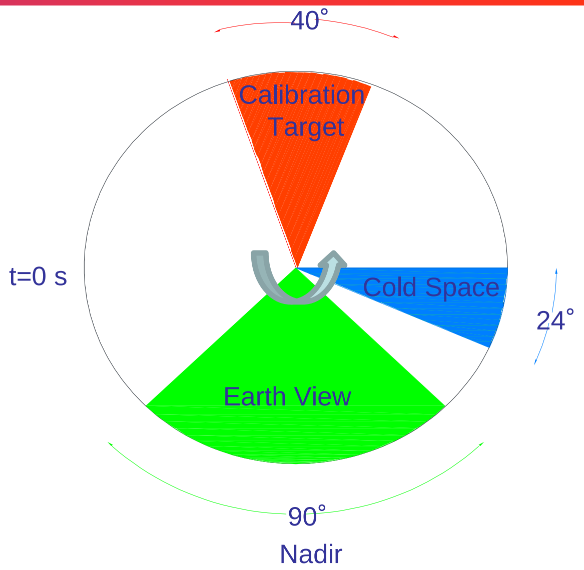
- Sub-system allocations managed through detailed spreadsheets
- Measurement noise error budget verified through end-to-end instrument simulation
  - Counts → TB

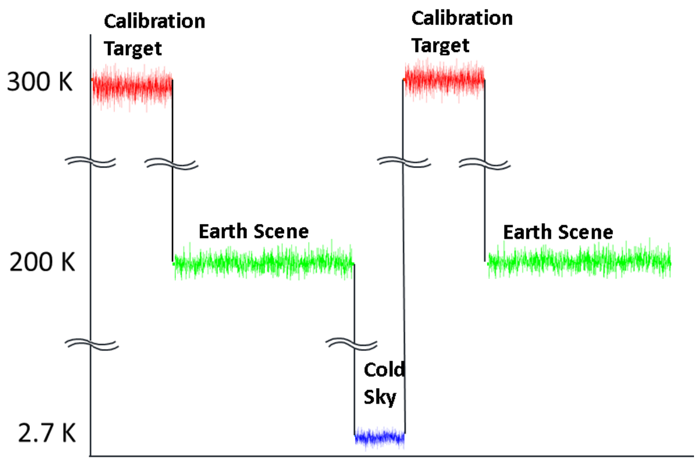
Sub-system Allocations	89 GHz	176 GHz	Compliance
Receiver Noise Figure (dB)	5.8 dB	7.5 dB	C
Front end loss (dB)	< 0.5 dB	< 0.5 dB	C
Ohmic Loss (dB)	< 1 dB	< 1 dB	C
ADC resolution (bits)	15	15	C
Gain (dB/C) Temperature Coefficient	0.1 dB/C	0.1 dB/C	C
Inherent stability (1/f)	0.1 K	0.1 K	C

C= Compliant

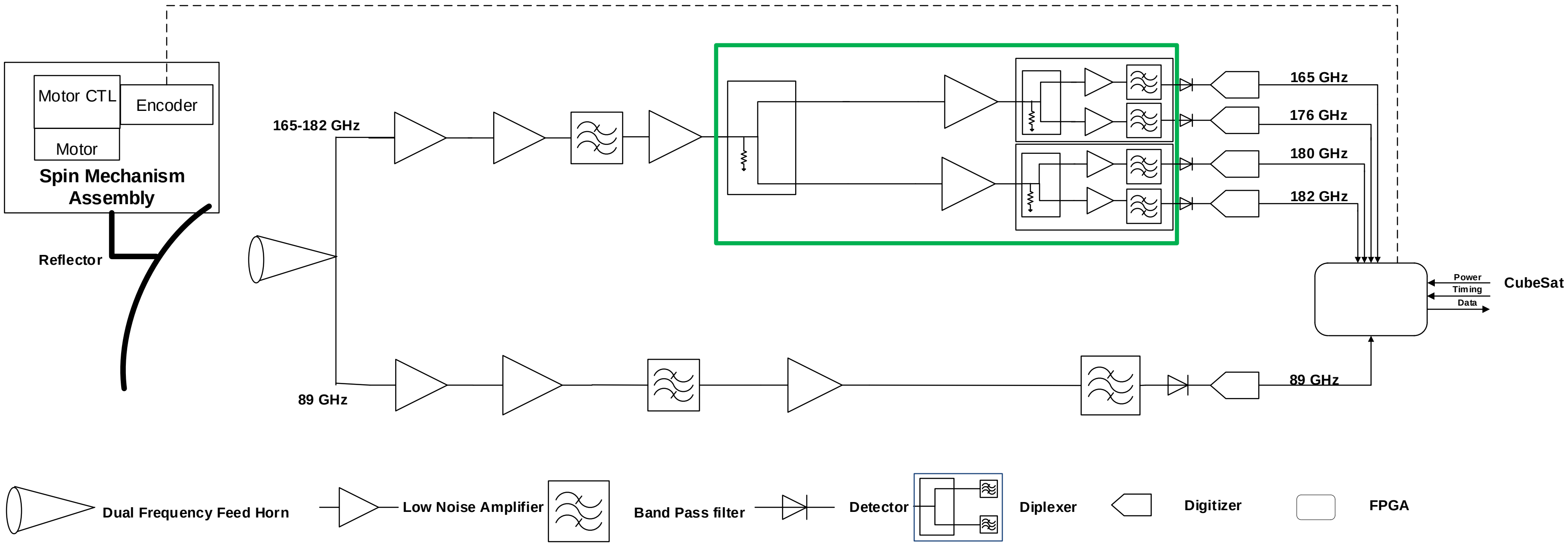
Instrument Requirements

Parameter	Specification	
System noise temperature	< 800 K @ 89 GHz <1300 K @ 165-183 GHz	
Number of channels	5	
Bandwidth	~4 GHz at 89 GHz and 165 GHz ~2 GHz at 176, 180 and 182 GHz	
Minimum spatial resolution	13 km at 183 GHz	25 km at 90 GHz
Minimum beam efficiency	> 90%	> 90%





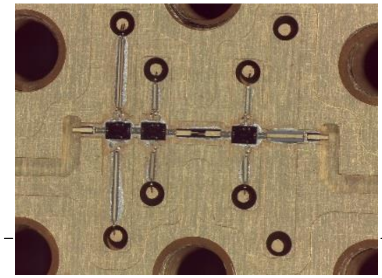
Block Diagram: Direct-Detection Approach

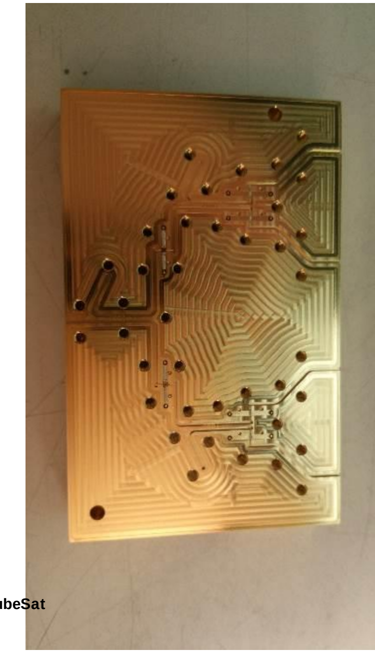


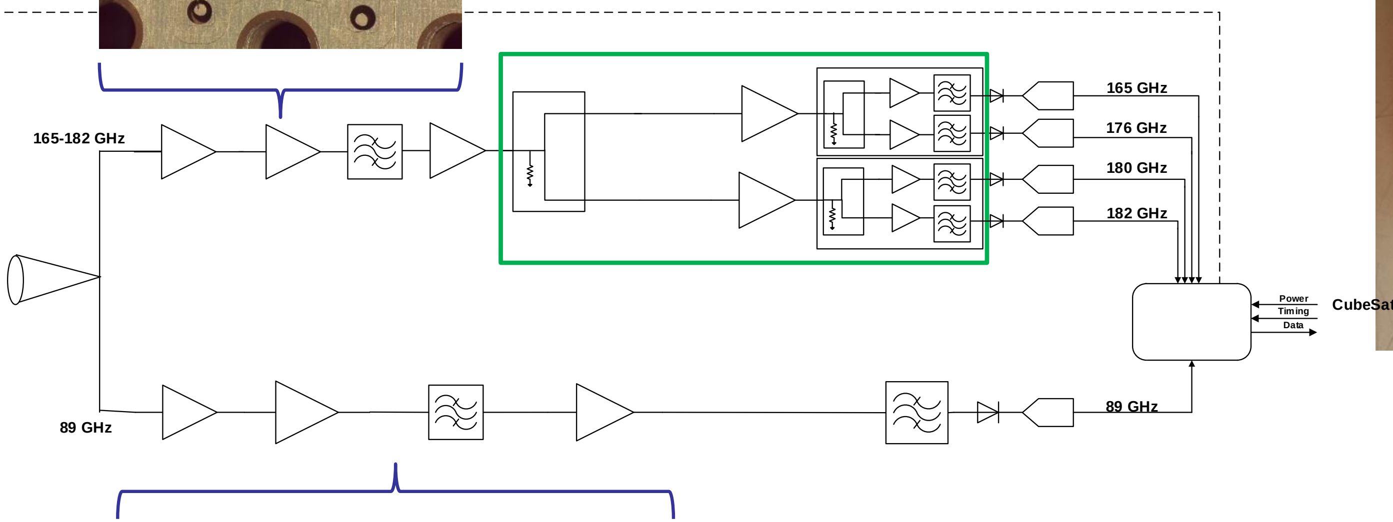
Direct Detection	Voltage (V)	Current (A)	CBE Power (W) Direct-Detection
Spin Mechanism	8	0.09	0.72
RF-Front End 89 GHz	5	0.1	0.5
RF-Front End 182 GHz	5	0.15	0.75
Back-end 89 GHz (includes video board)	5	0.025	0.125
Back-end 182 GHz (includes video board)	5	0.1	0.5
FPGA + ADC	5	0.25	1.25
Total			**3.8**

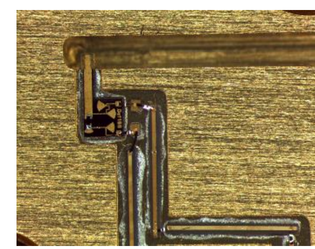
RF Front-End
Direct-Detection Approach

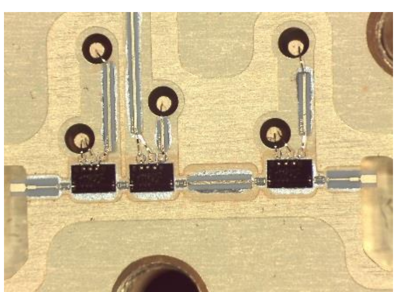
- Prototypes and complete receiver have been tested.



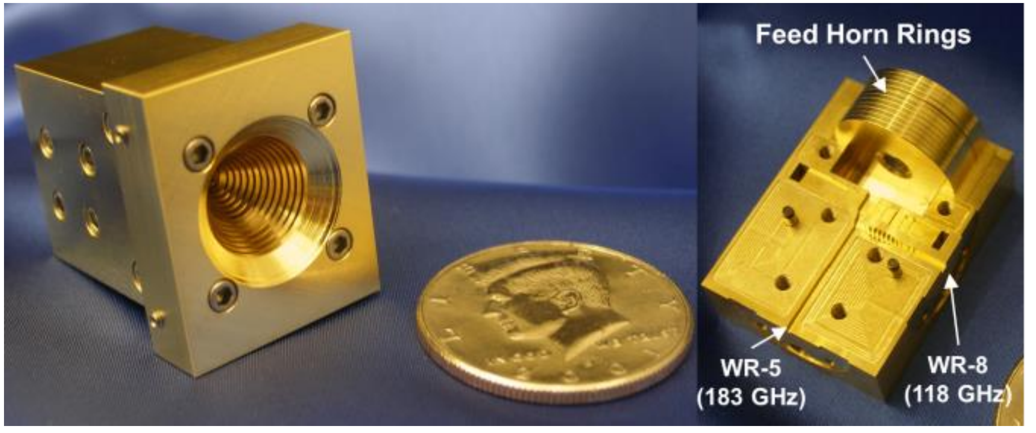


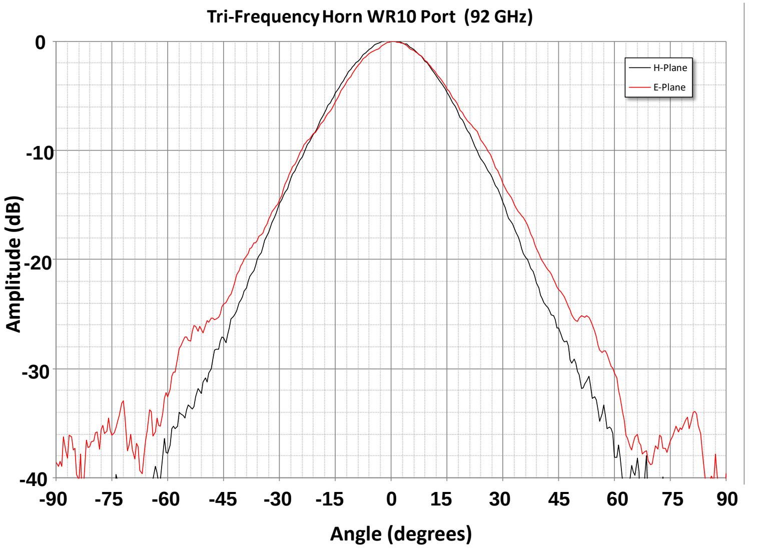


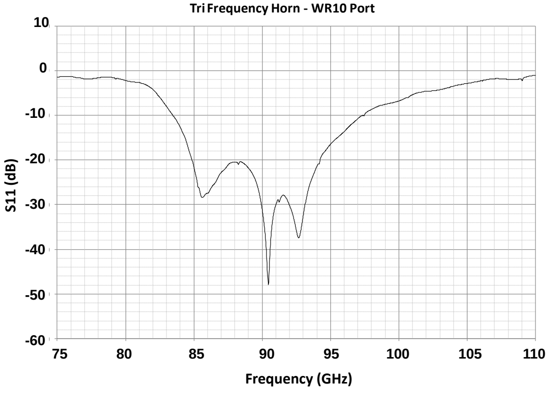


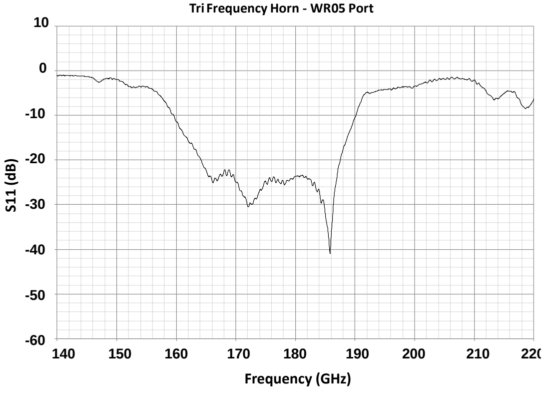


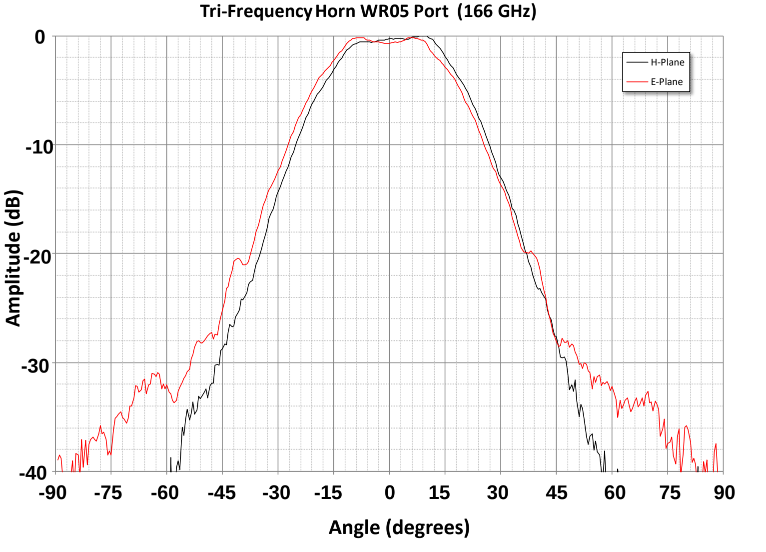
Feed Horn: Measured Patterns



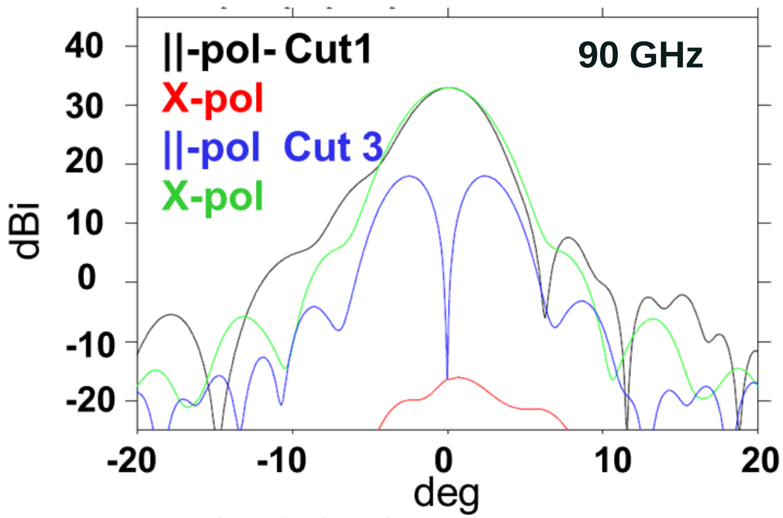


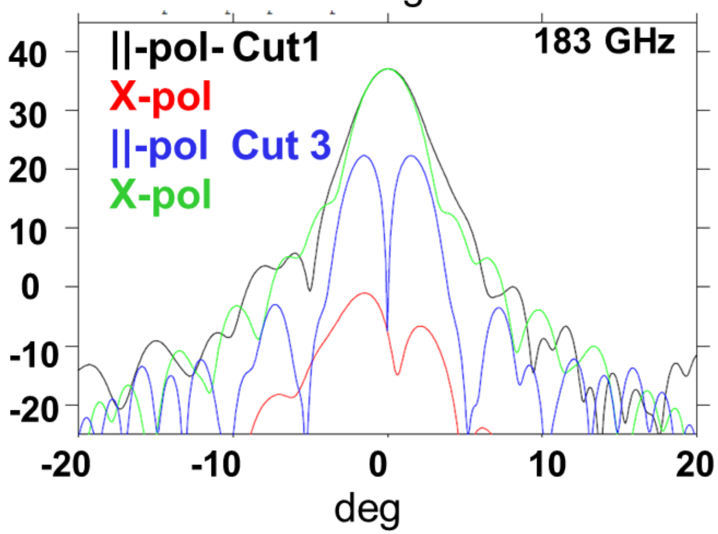






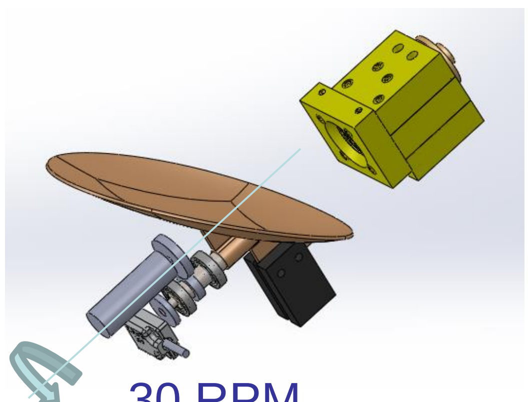
Optics Design

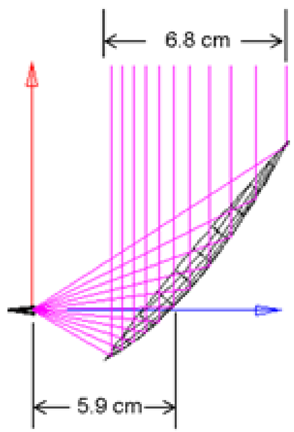




Frequency (GHz)	HPBW degrees	Beam Efficiency
90	3.6	92%
183	1.8	91%

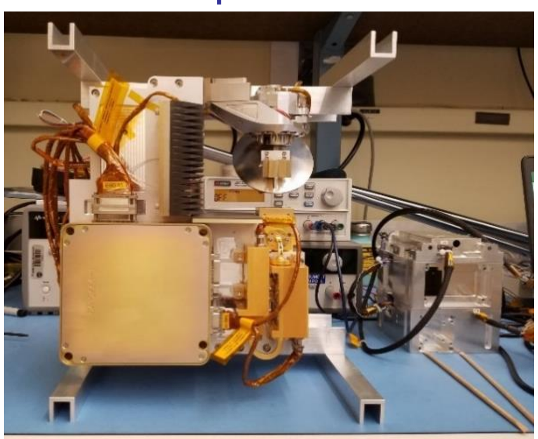
- Offset paraboloid reflector is used to feed the single corrugated tri-frequency horn designed and retuned for 90 GHz and 183 GHz

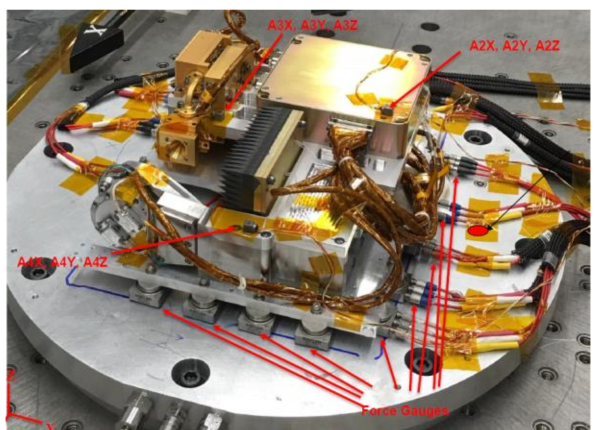




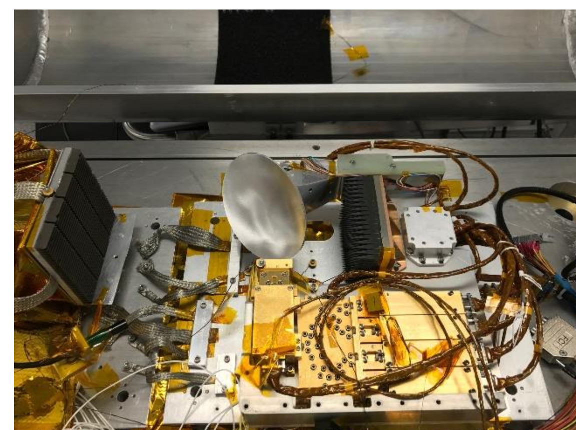
Instrument Status

- Flight spare successfully completed EMI self-compatibility testing with spacecraft bus on Apr. 21-30, 2017.
- Flight instrument end-to-end receiver bandpass and linearity measurements completed on Jun. 1-3, 2017.
- Flight instrument successfully integrated, PWA conformal coated and completed vibration testing on Jun. 8, 2017
- Flight instrument successfully completed thermal vacuum testing on Jul. 5-8, 2017.
- Flight unit and spare unit antenna pattern validation measurements to be performed on Jul. 12-15, 2017.


Instrument assembly

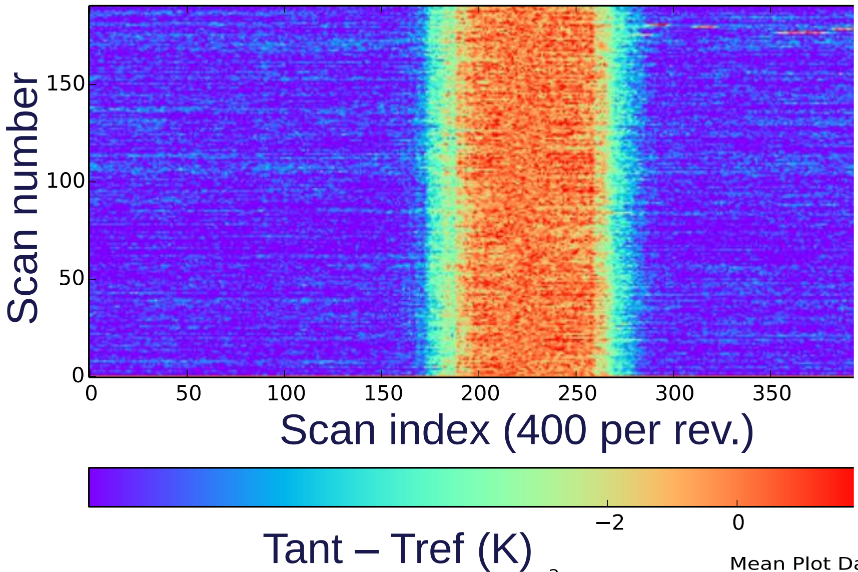


Vibration testing

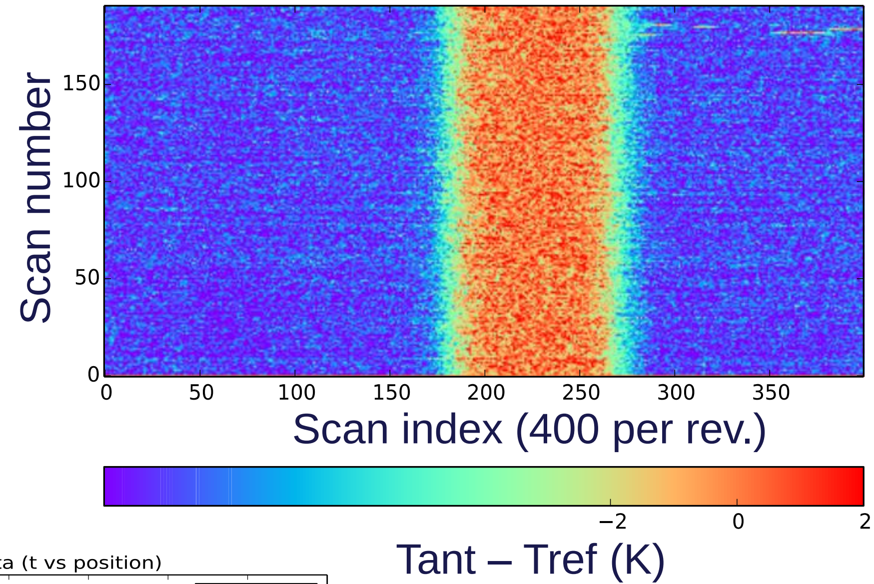

TVAC testing

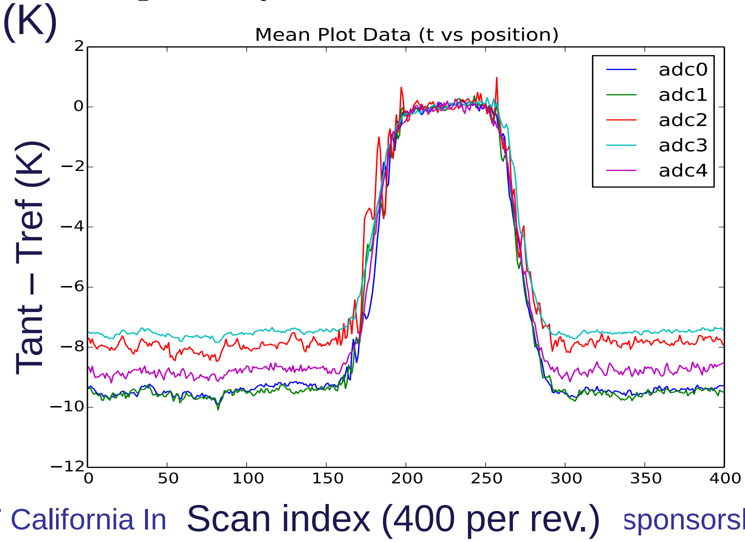
Testing Results: EMI Self-Compatibility Tests

180 GHz Radiometer Data

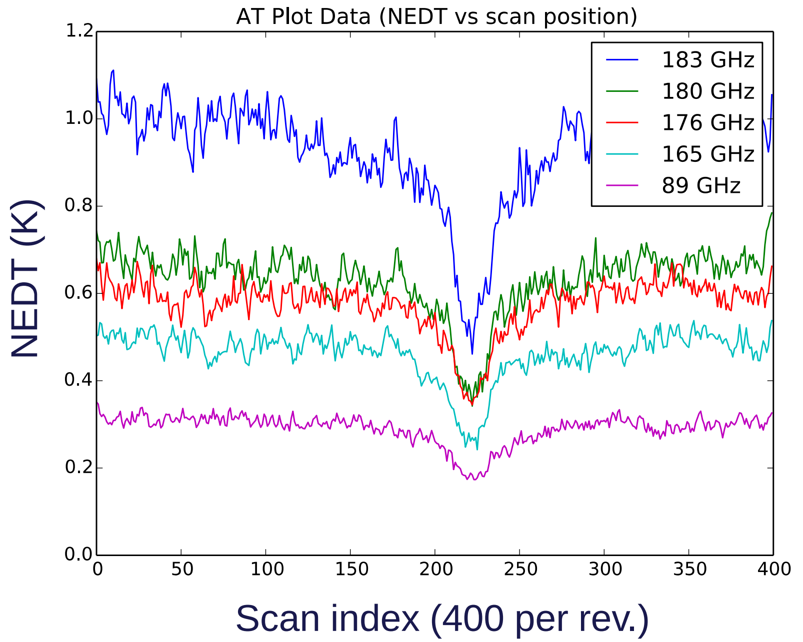


89 GHz Radiometer Data





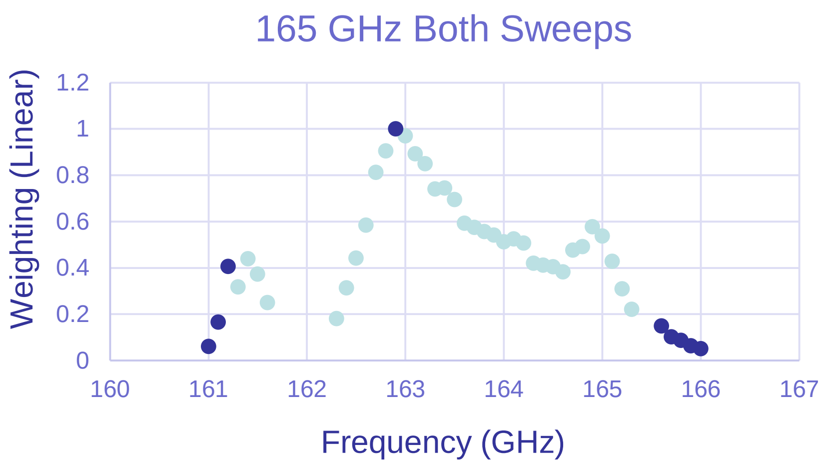
Testing Results: Post-EMI Self-Compatibility Tests

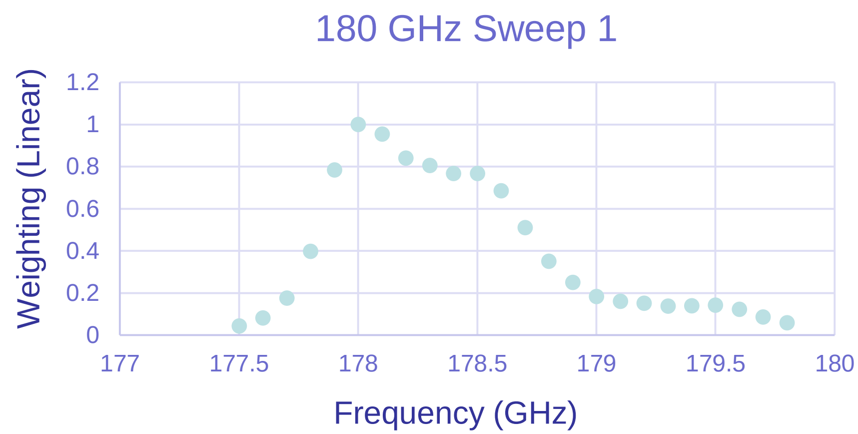


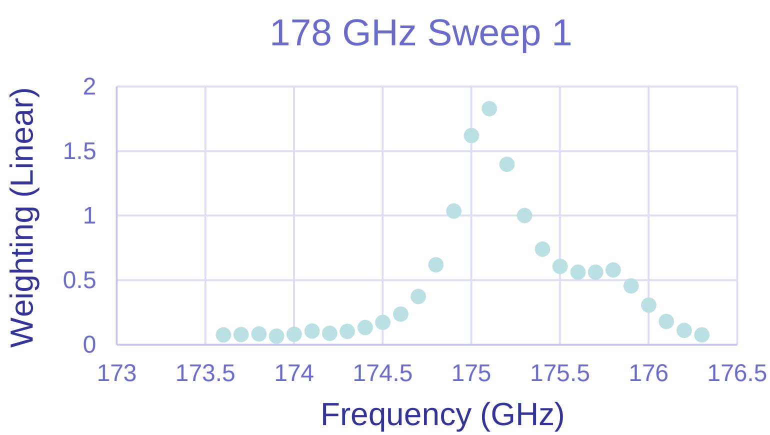
Frequency (GHz)	NEDT (K)	Total Noise Requirement (K)
89	0.3	1.4
164	0.5	1.4
175	0.6	1.4
178	0.7	1.4
181	0.9	1.4

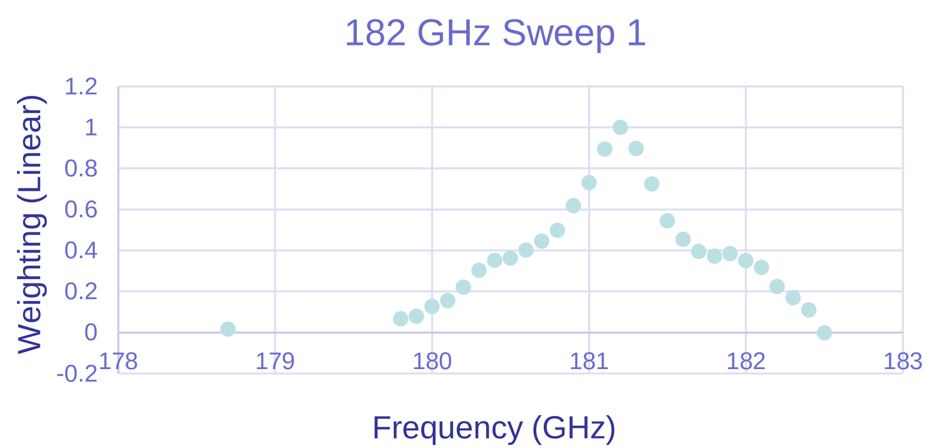
Measured NEDT values meet total noise requirements for all five millimeter-wave radiometer channels.

Testing Results: End-to-End Receiver Bandpass Responses



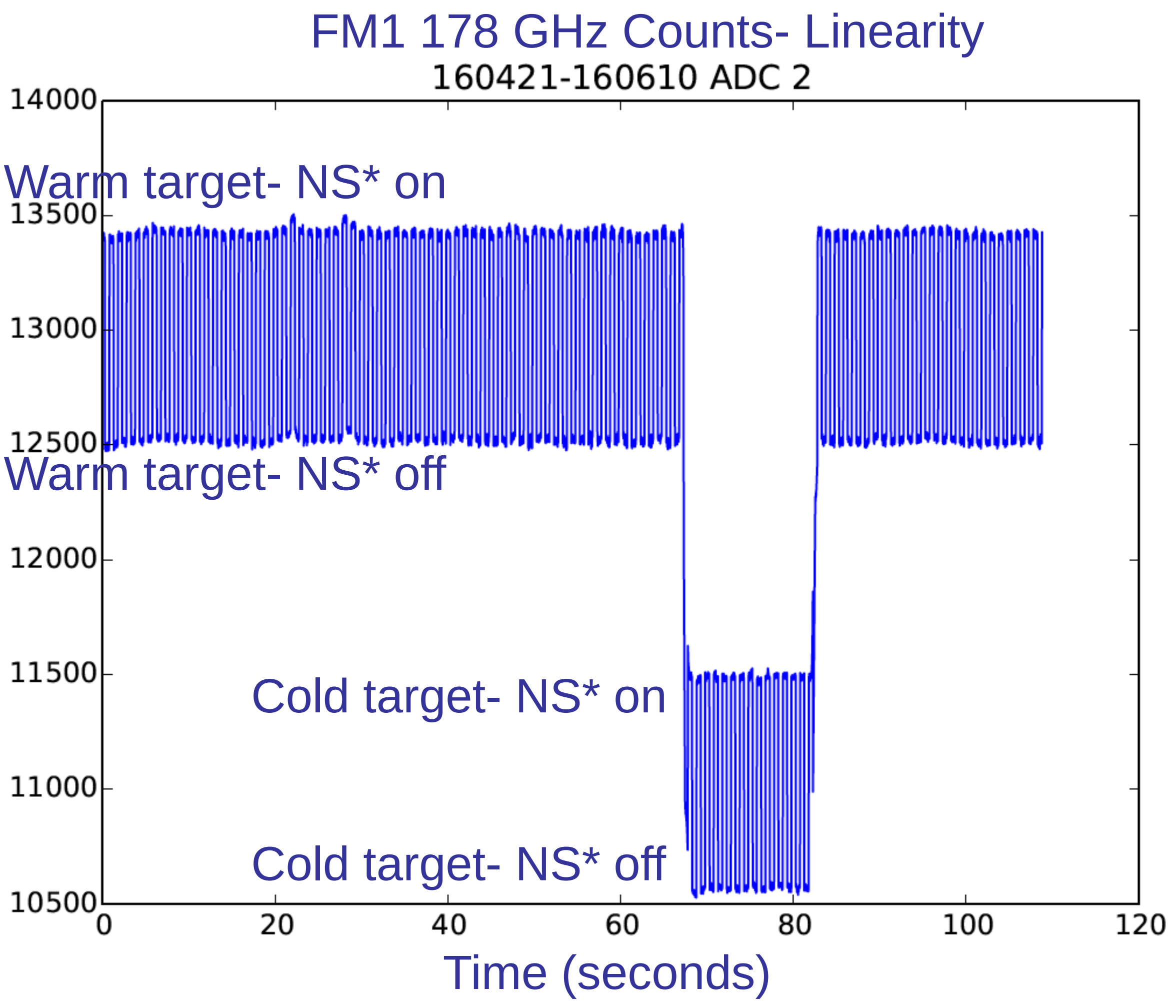






Measured end-to-end receiver bandpass responses will be used as input to validation algorithms.

Testing Results: Linearity of Flight Model and Flight Spare



Flight Model (FM1) QL Results:

182 GHz max non-linearity = 2.67%
180 GHz max non-linearity = 2.93%
178 GHz max non-linearity = 2.04%
165 GHz max non-linearity = 2.90%

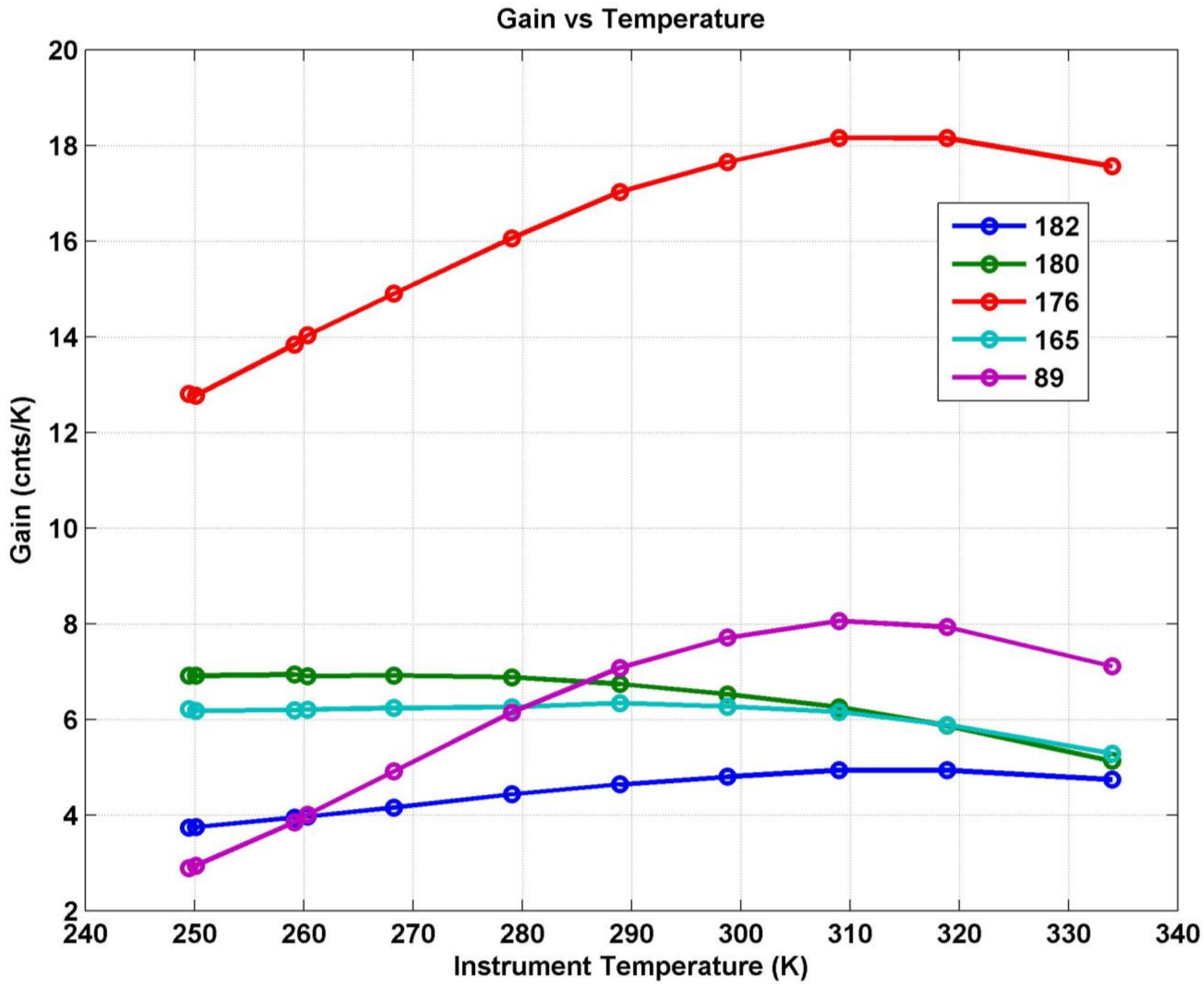
Flight Spare (FM2) QL Results:

182 GHz max non-linearity = 2.81%
180 GHz max non-linearity = 2.69%
178 GHz max non-linearity = 2.73%
165 GHz max non-linearity = 4.88%

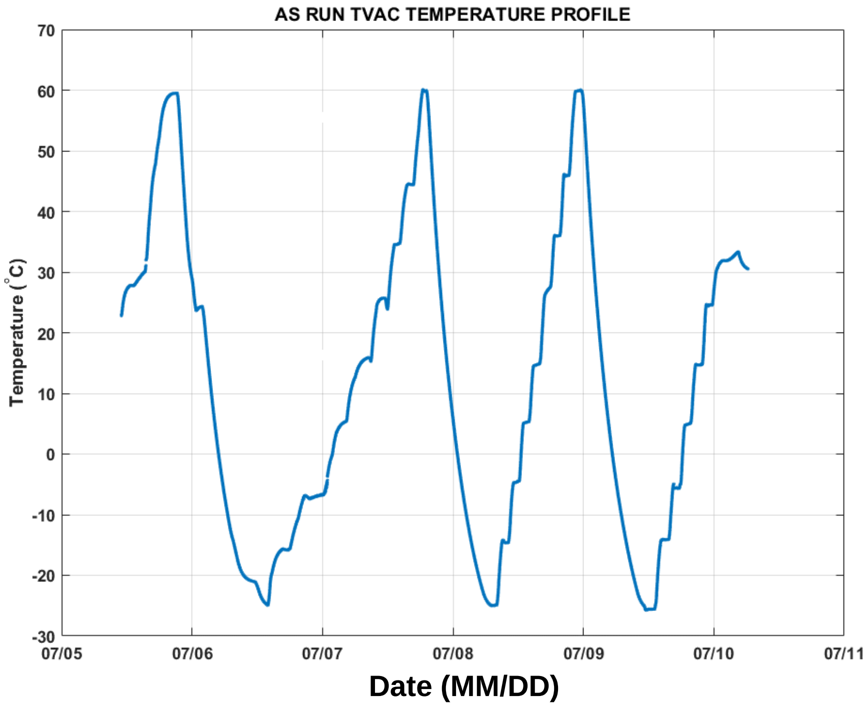
A more complete linearity test was performed, but the results have not yet been analyzed.

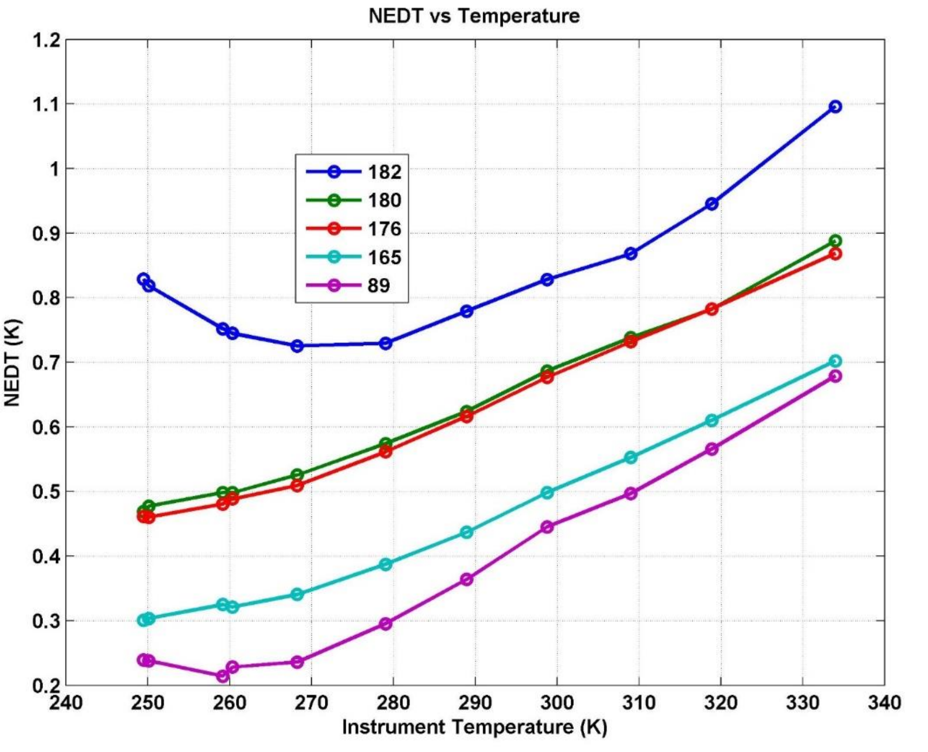
*NS = noise source

TVAC Results for Flight Model: Gain vs. Temperature



TVAC Results for Flight Model: NEDT vs. Temperature





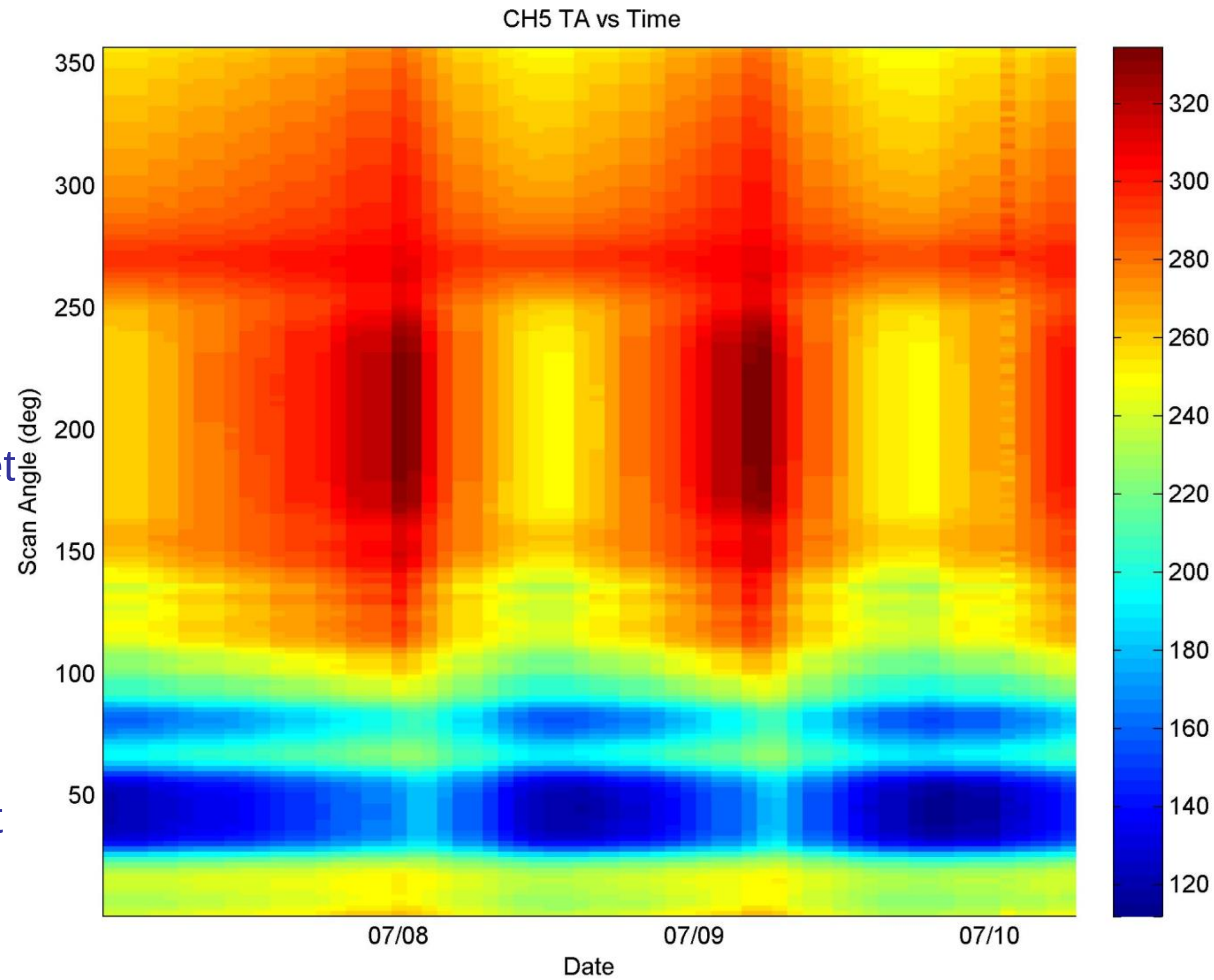
NEDT Measured on cold target, which varies with temperature

TVAC Results for Flight Model: 89 GHz Chamber Imagery

Lid Target

Warm Target

Cold Target



Summary

- We have developed and tested a compact millimeter-wave radiometer to perform precision measurements of upwelling brightness temperatures from clouds and precipitation.
- The radiometer instrument performance meets or exceed specifications.
- The Flight Instrument has been delivered to BCT for Spacecraft I&T.
- The Flight Spare Instrument will be delivered to BCT for spare Spacecraft I&T by the end of September.