Temporal Experiment for Storms and Tropical Systems – Technology Demonstration (TEMPEST-D): Risk Reduction for Constellations of 6U-Class Satellites

Steven C. Reising[1], Todd C. Gaier[2], Christian D. Kummerow[1], V. Chandrasekar[1], Sharmila Padmanabhan[2], Boon H. Lim[2], Cate Heneghan[2], Jon Olson[1], Shannon T. Brown[2], Tooraj Kia[2], Christopher S. Ruf[3], Susan C. Van den Heever[1], Tristan S. L'Ecuyer[4], Zhengzhao Johnny Luo[5], S. Joseph Munchak[6], Ziad S. Haddad[2], and Sid-Ahmed Boukabara[7]

[1]Colorado State University, Fort Collins, CO
[2]NASA Caltech/Jet Propulsion Laboratory, Pasadena, CA
[3]University of Michigan, Ann Arbor, MI; [4]University of Wisconsin, Madison, WI
[5]City College of New York, NY
[6]NASA Goddard Space Flight Center, Greenbelt, MD
[7]NOAA NESDIS, College Park, MD

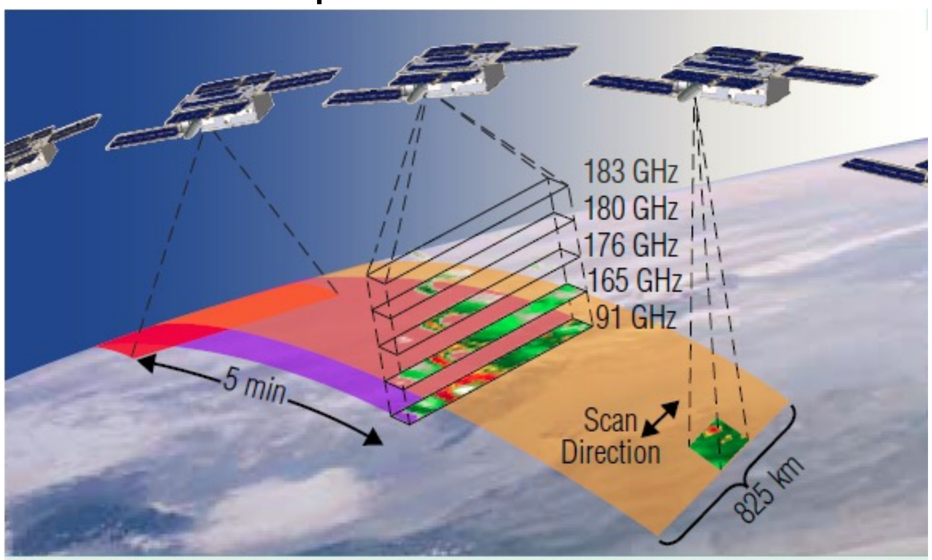
TEMPEST-D Background

- TEMPEST was proposed to NASA under the Earth Ventures Instrument-2 call.
- It proposed a low-risk, high-margin approach toward the use of CubeSats for repeat-pass radiometry to measure temporal signatures of precipitation.
- TEMPEST was selected to receive technology demonstration funding under the program.
- TEMPEST-D (Demonstration) began in August 2015
- To be ready for delivery for launch in August 2017

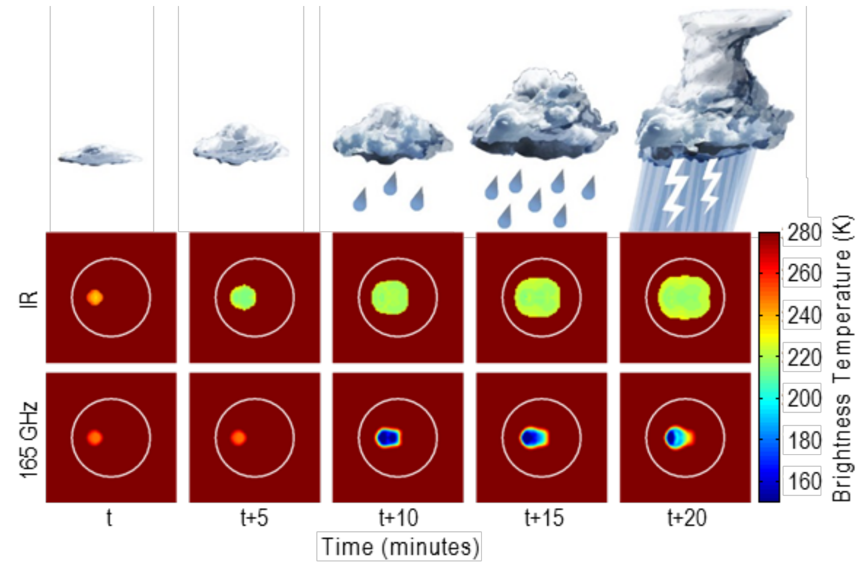
Temporal Experiment for Storms and Tropical Systems (TEMPEST)

BENEFITS AND STRENGTHS

- First global observations of time evolution of precipitation
- Low-cost approach and rapid development using 6U-Class satellites
- Unique data sets to improve weather and climate prediction models



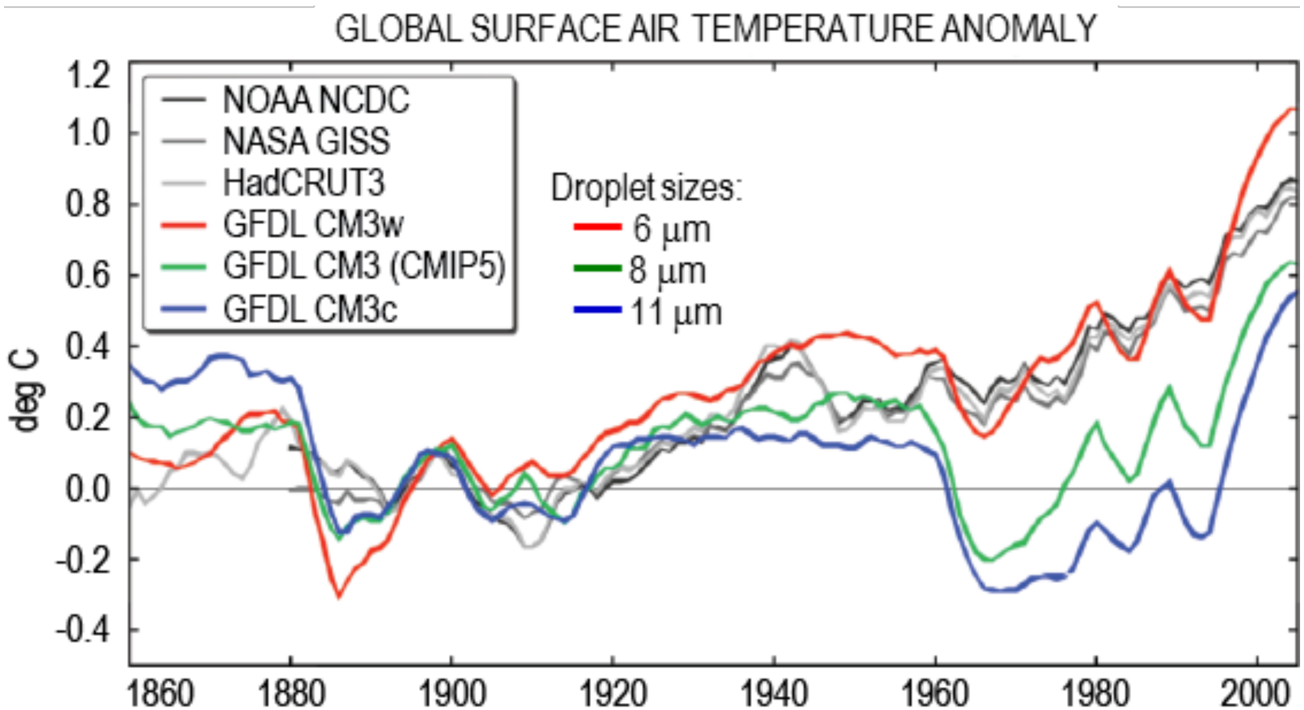
5 identical 6U CubeSats, each with an identical 5-channel radiometer, flying 5 minutes apart



IMPORTANCE TO NASA

- Constrain climate models through improved understanding of cloud processes, transition from clouds to precipitation and impact on Earth's energy balance
- Characterize temporal variability of precipitation globally to improve understanding of water cycle

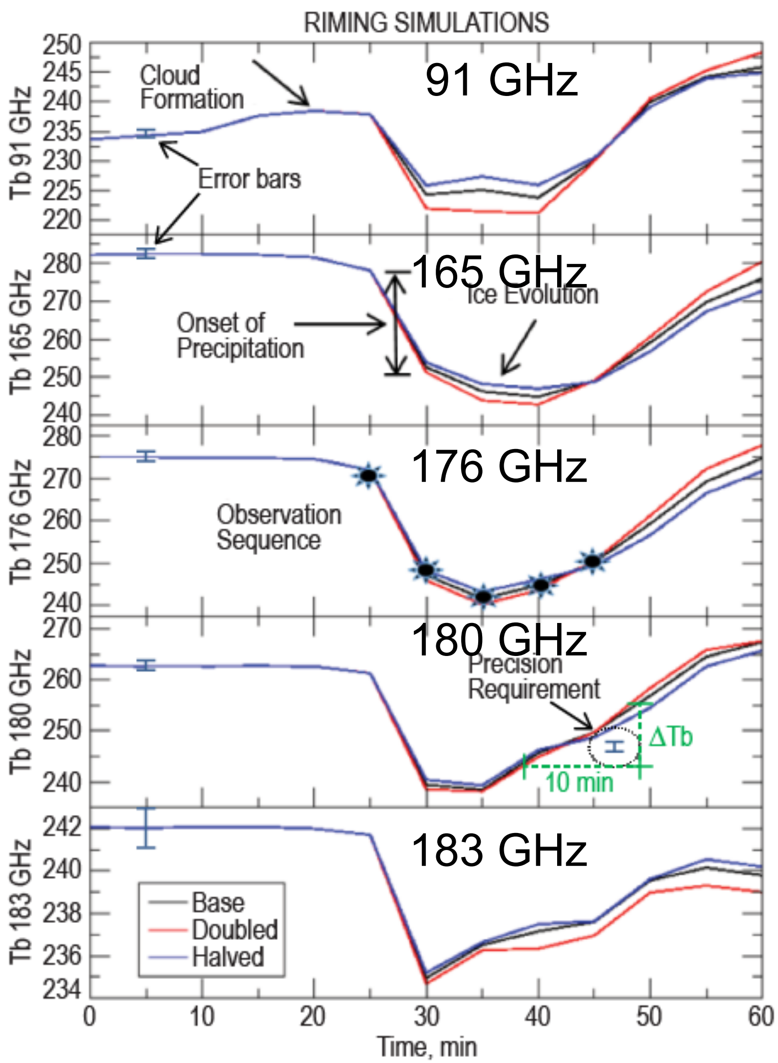
Sensitivity of Climate Model Predictions to Onset of Precipitation



[Adapted from Golaz et al., *GRL*, 2013; Suzuki et al., *GRL*, 2013]

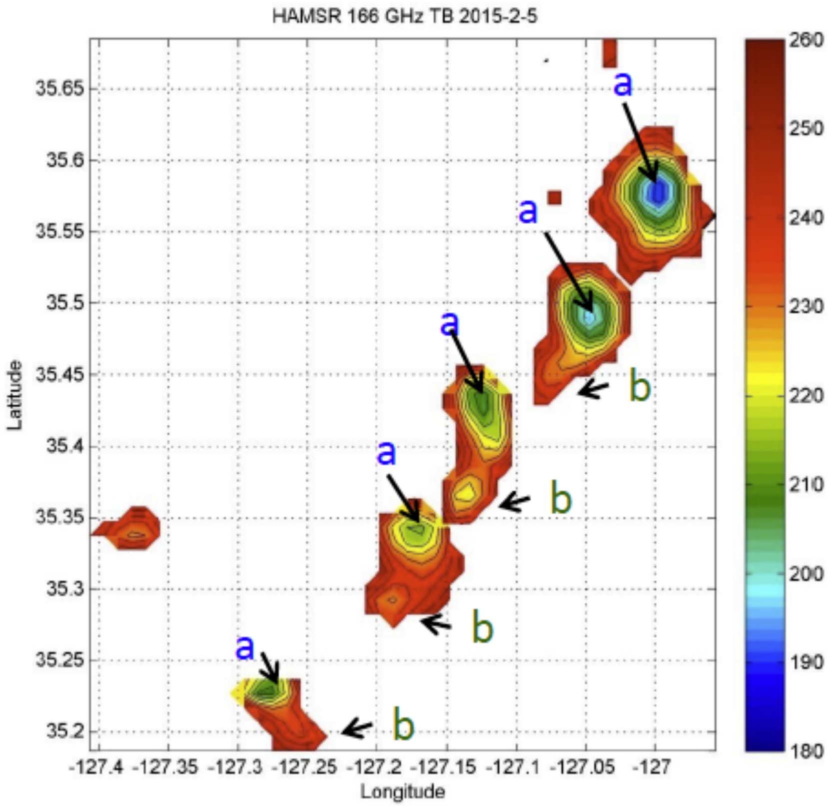
- Global climate model temperature anomaly projections for onset of precipitation at cloud droplet sizes of 6 μm (red), 8 μm (green) and 11 μm (blue).
- TEMPEST constellation could provide the first global sample of the onset of precipitation, constraining climate prediction models.

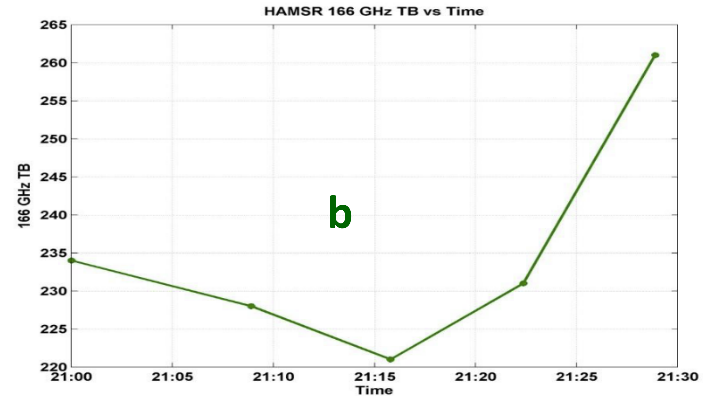
Temporal Development of Ice in Cloud-Scale Models

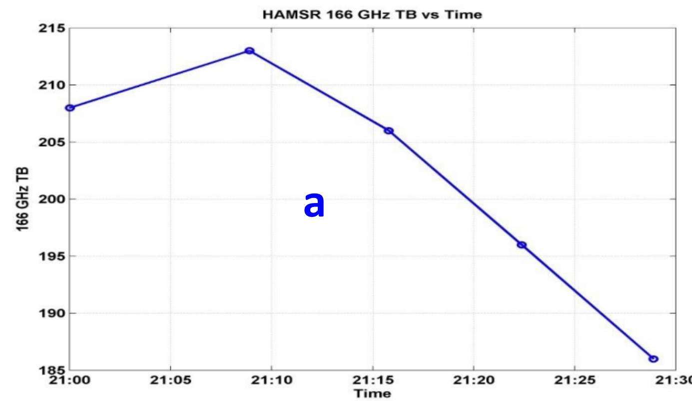


- Modeled brightness temperatures at the five TEMPEST frequencies with 25-km spatial resolution
- Simulations compare different rates of supercooled water droplets collecting on ice crystals (riming efficiency).
- Efficiency (rate) varies from baseline (black) to twice (red) and half (blue).
- Measurable difference between curves is 4 K or greater in 5 minutes at onset of ice formation. Precision requirement is 1 K in 5 minutes.
- Ice remaining in clouds after precipitation can have substantial effects on climate system. Residual ice can be compared to W-band radar observations from CloudSat or ESA's EarthCARE.

JPL's High Altitude MMIC Sounding Radiometer: CalWater-2 Repeat-pass Measurements (Brown et al., 2015)

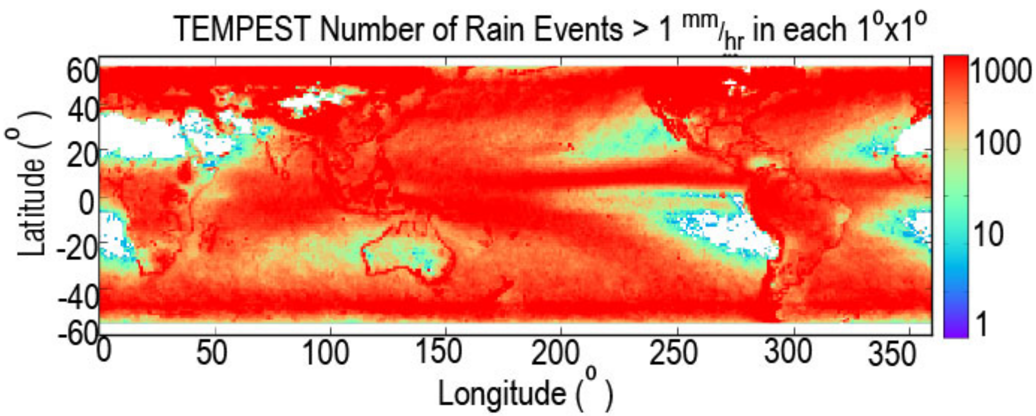


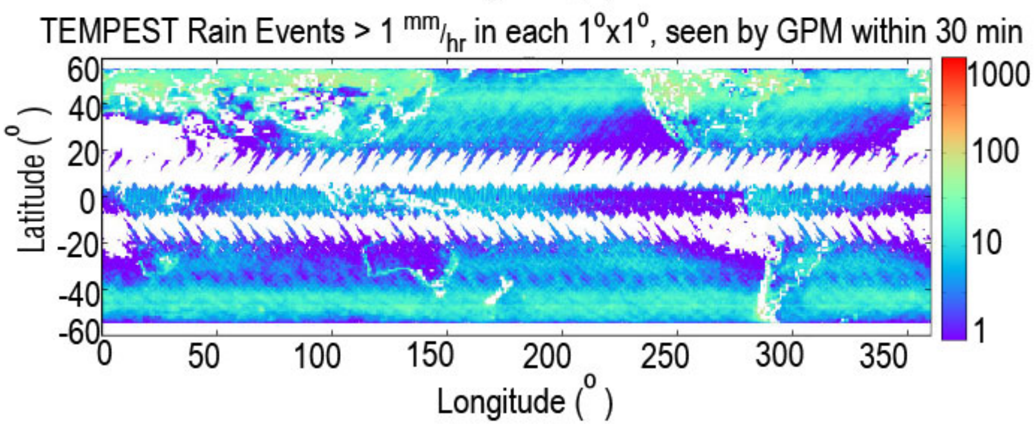




Left: Rapid revisits of a small convective system observed with the JPL HAMSR instrument on the ER-2 high-altitude aircraft during an atmospheric river event (CalWater-2) on Feb. 5, 2015. Right: Time series of five observations over 30 minutes of two convective cells within this *warm system*. For the cell labeled "b", the cloud is observed while forming precipitation and then disappears. The larger core labeled "a" is observed while growing. These data clearly demonstrate the ability of millimeter-wave temporal observations to gain information on the dynamics of cloud systems.

Global Observations of Temporal Evolution of Precipitation

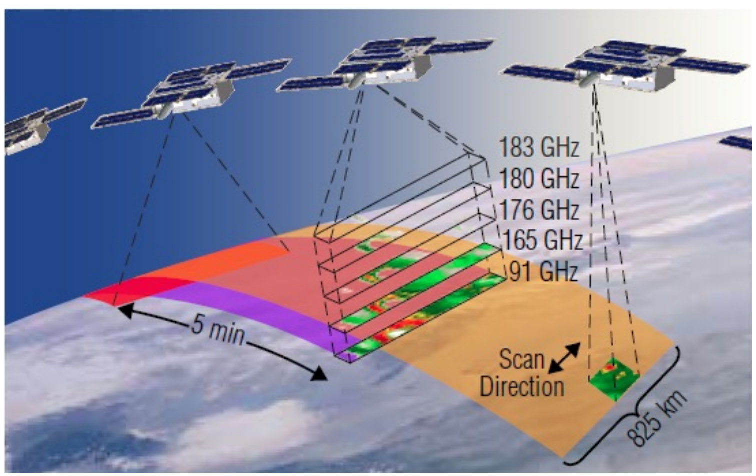




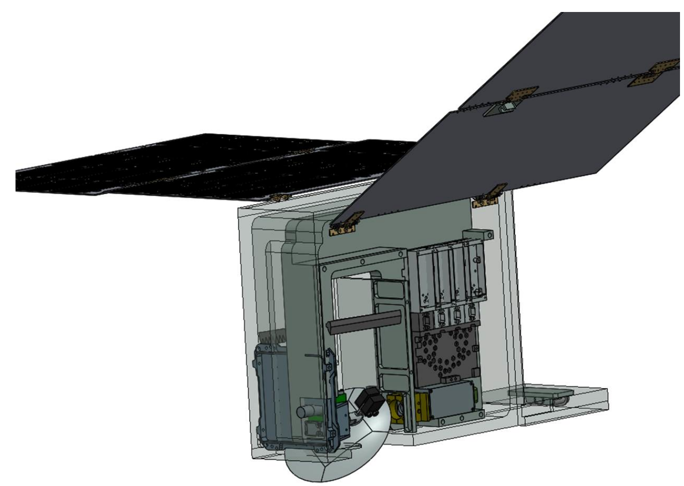
- In a future one-year mission, TEMPEST constellation could make more than 3,000,000 temporal observations of precipitation (> 1 mm/hr), including 100,000+ deep-convection events
- Could perform more than 50,000 coincident precipitation observations within 30 minutes of NASA's Global Precipitation Mission (GPM) for a nominal TEMPEST orbit for ISS launch at 400-km altitude and 51° inclination.
- Precipitation estimates from AMSR-E satellite radiometer data with oceanic observations only.

TEMPEST-D Motivation and Objectives

- Demonstrate technology for 6U-Class nanosatellites to advance NASA's Earth Science Goals
- Reduce cost, **risk** and development time for future constellations of small satellites to perform Earth Science measurements
- Demonstrate the feasibility of orbital drag maneuvers to achieve time separation of U-Class constellations in **the same orbital plane**
- Demonstrate precision intercalibration of millimeter-wave radiometers with other space-borne assets, e.g. NASA GPM Microwave Imager (GMI) and Microwave Humidity Sensor (MHS) on NOAA & ESA/EUMETSAT satellites.

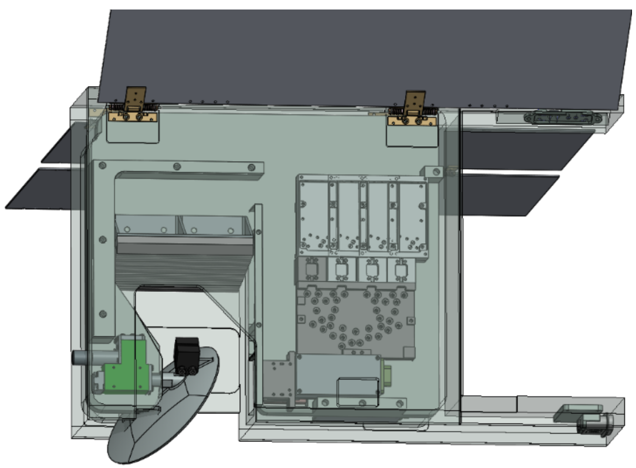


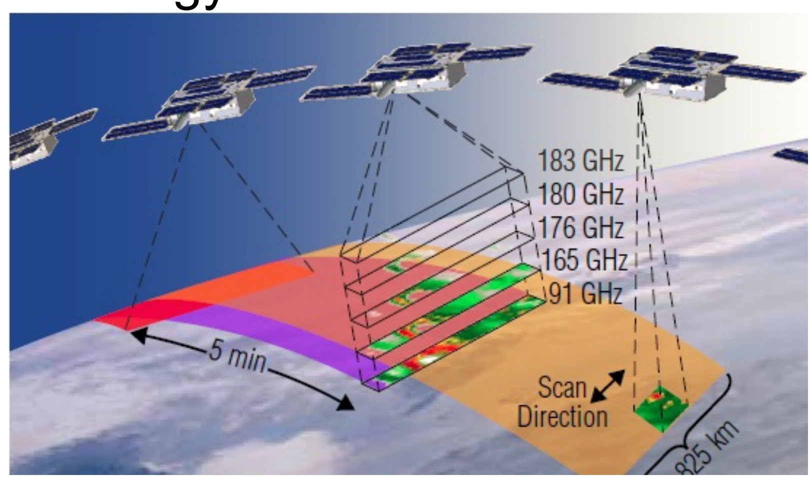
6U-Class satellite with millimeter-wave radiometer instrument



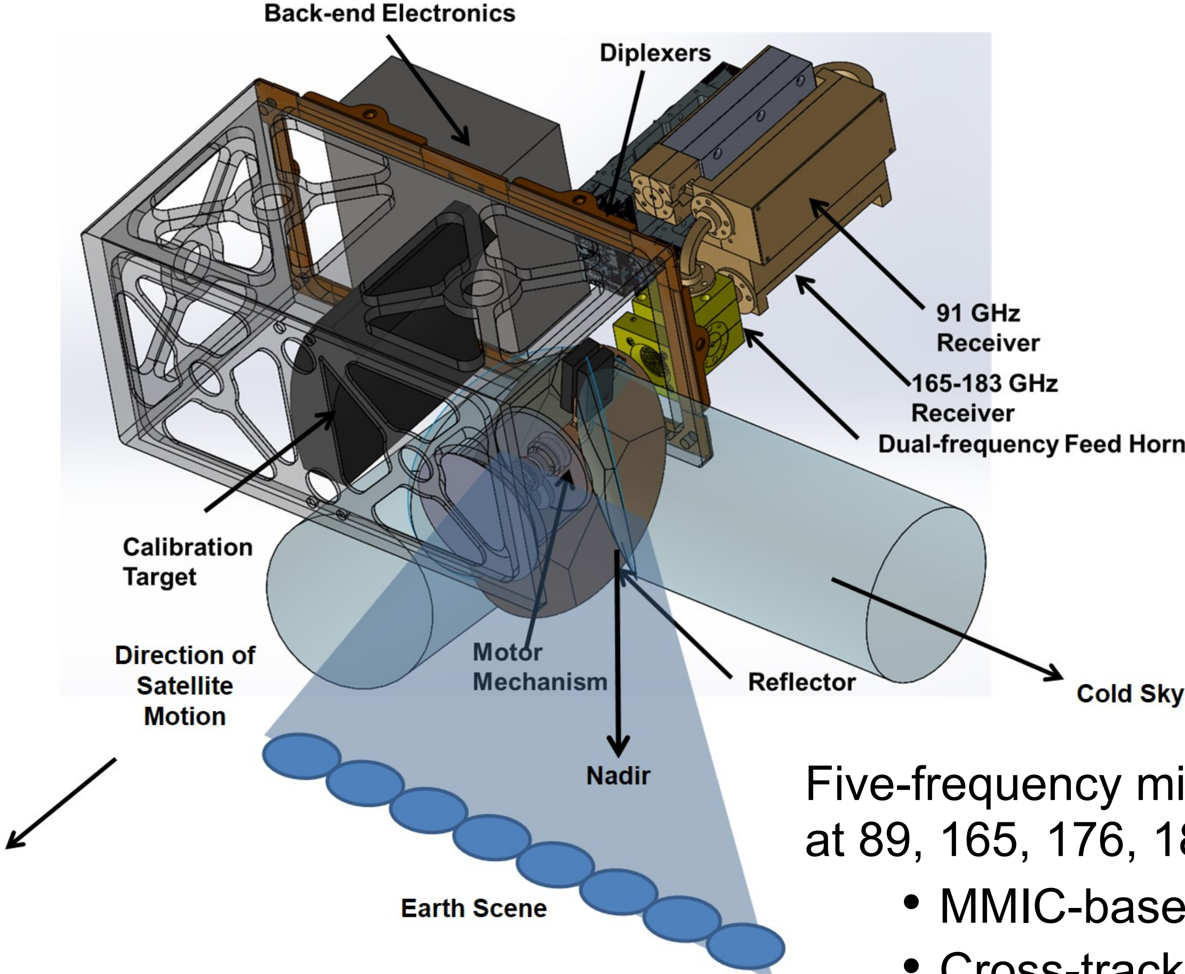
TEMPEST-D In-Space Technology Demonstration

- TEMPEST-D provides the first in-space technology demonstration of a millimeter-wave radiometer (89-182 GHz) based on an InP HEMT low-noise amplifier front-end in a 6U-Class nanosatellite.
- TEMPEST-D team is a partnership among CSU, JPL and Blue Canyon Technologies.
- TEMPEST-D raises the TRL of the radiometer instrument from 6 to 7.
- Selected by NASA CubeSat Launch Initiative (CSLI) in Feb. 2015
- Manifested for launch on Firefly Systems Alpha (VCLS) in Mar. 2018
- 3 months of on-orbit operations for technology demonstration





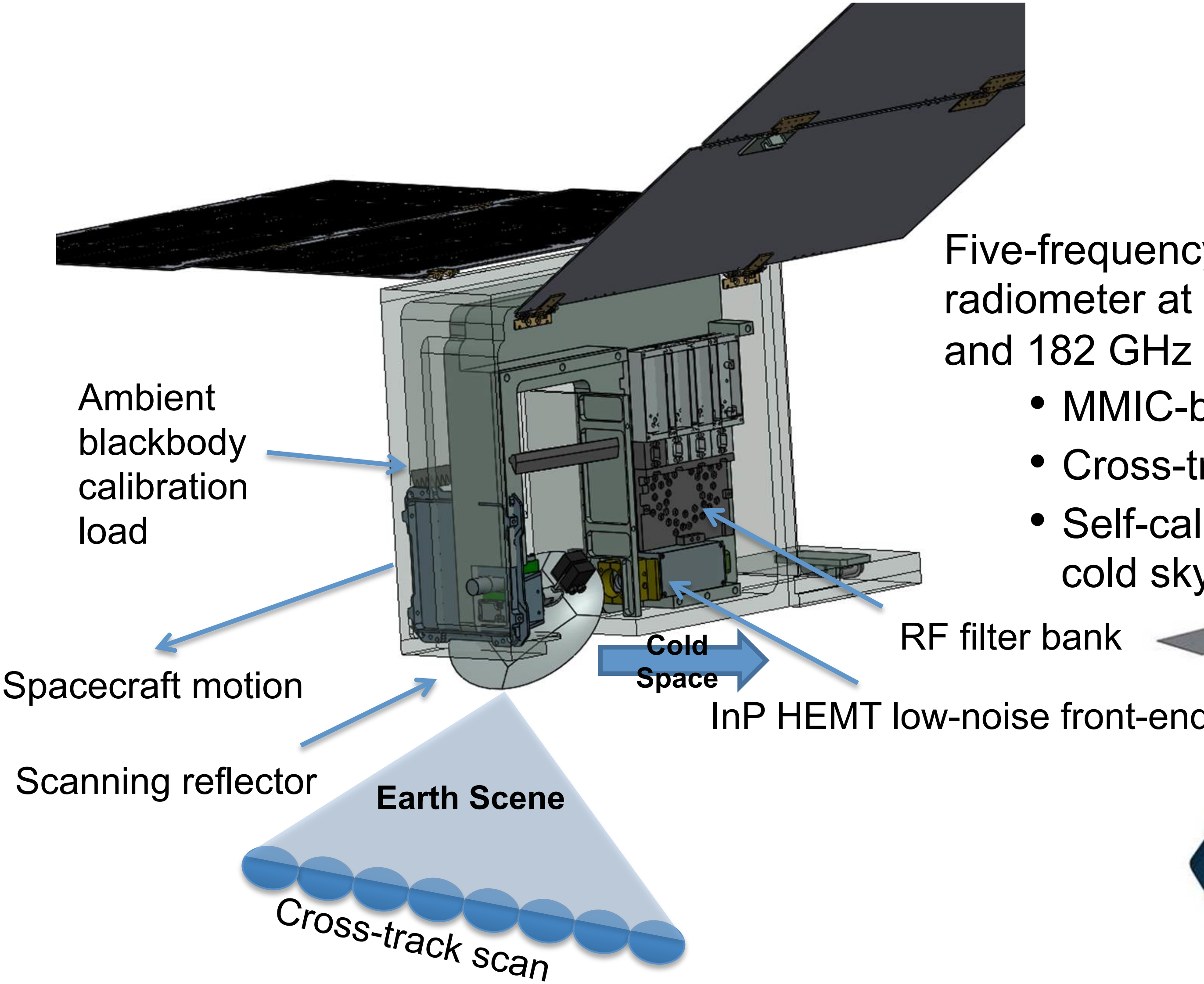
TEMPEST-D Instrument: Initial Design



Five-frequency millimeter-wave radiometer at 89, 165, 176, 180 and 182 GHz

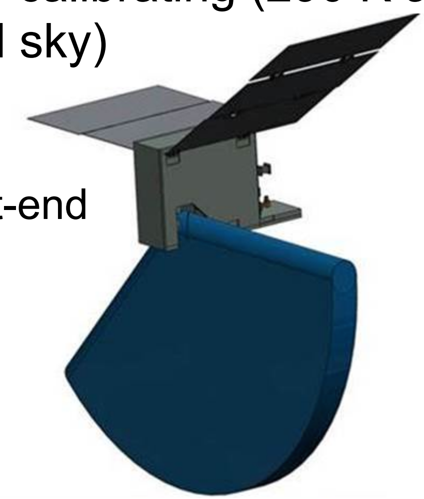
- MMIC-based
- Cross-track scanning
- Self-calibrating

TEMPEST-D Instrument Design: Mature Configuration



Five-frequency millimeter-wave radiometer at 89, 165, 176, 180 and 182 GHz

- MMIC-based
- Cross-track scanning
- Self-calibrating (290 K and cold sky)



TEMPEST-D Instrument Requirements

Parameter	Specification	
System noise temperature	< 600 K	
Number of channels	5	
Bandwidth	~4 GHz at 89 GHz and 165 GHz and ~2 GHz at 176, 180 and 182 GHz	
Minimum spatial resolution	13 km at 182 GHz	25 km at 89 GHz
Minimum beam efficiency	> 90%	> 90%

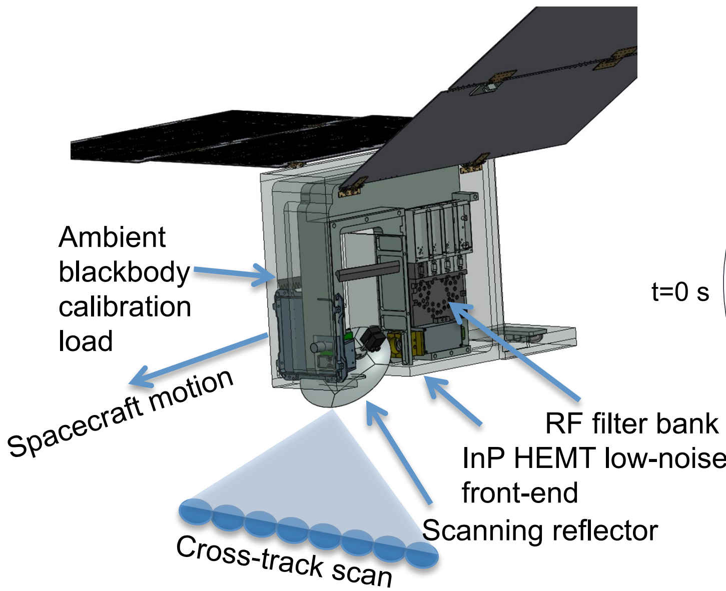
Technical Resources Summary

Resource	Current Best Estimate (CBE)	Allocation	Margin (Actual)	Margin Required (by CDR)
Radiometer Mass (kg)	1.6	3	60%	20%
Radiometer Power (W)	3.8	6.5	42%	20%
Radiometer Data Rate (Kbps)	8	10	20%	20%
Radiometer Precision (K)	0.65	1.4	54%	20%
Radiometer Accuracy (K)	3	4	25%	20%

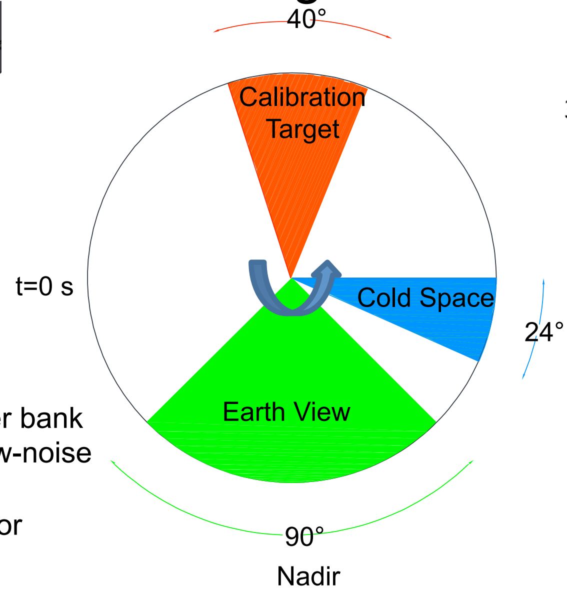
$$MARGIN = 100 \times \frac{Allocation - CBE}{Allocation}$$

TEMPEST-D Radiometer Calibration

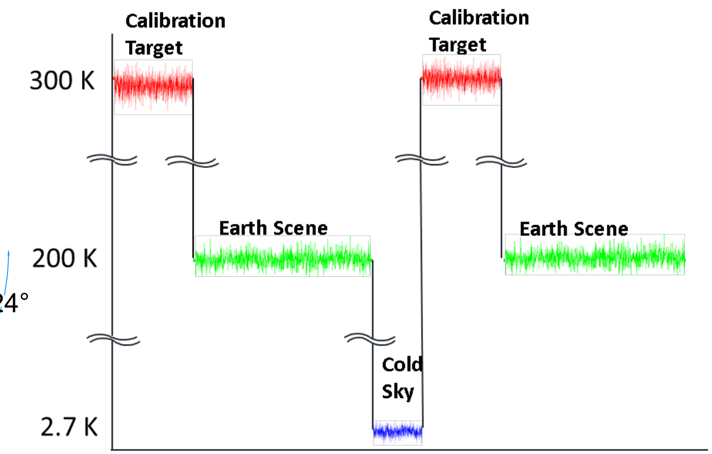
TEMPEST-D Instrument



Observing Profile

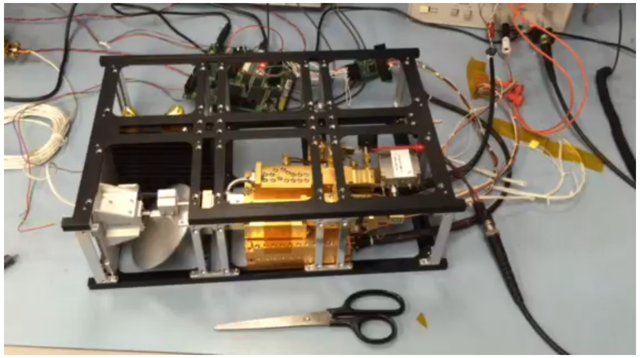


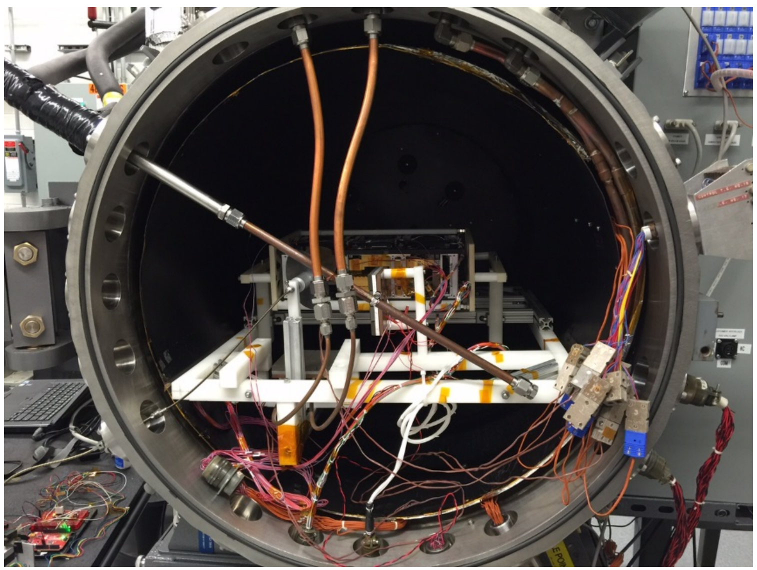
Time Series of Output Data



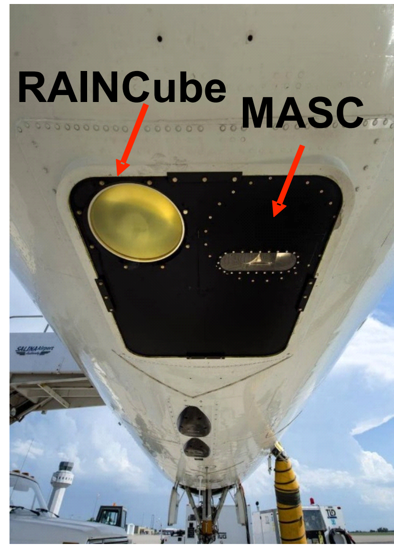
- Five-frequency millimeter-wave radiometer measures Earth scene over ±45° nadir angles, providing an 825-km swath width from a nominal altitude of 400 km. Each pixel is sampled for 5 ms.
- Space view observes cosmic microwave background at 2.73 K ("cold sky"). Blackbody calibration target (at 290 K) is measured each revolution to perform two-point external calibration every 2 sec. (scanning at 30 RPM).

Microwave Atmospheric Sounder on CubeSat (MASC at JPL)





Thermal vacuum testing of MASC completed in Sep. 2015.



MASC was deployed on the NASA DC-8 during PECAN campaign in July 2015 and OLYMPEX campaign from Nov. 2015 to Jan. 2016.

MASC (unpressurized) packaged inside the housing.

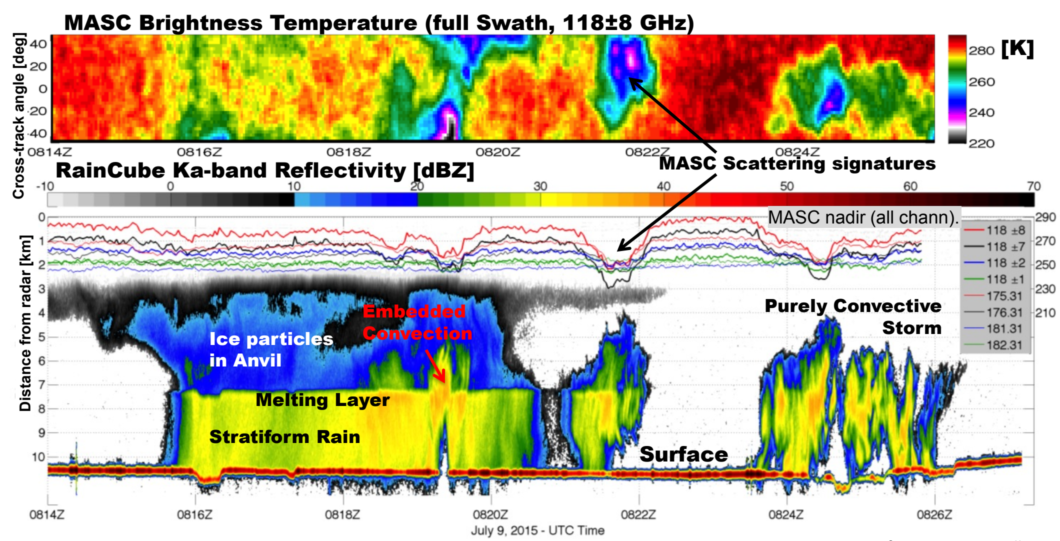
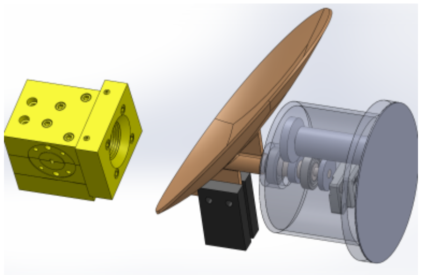


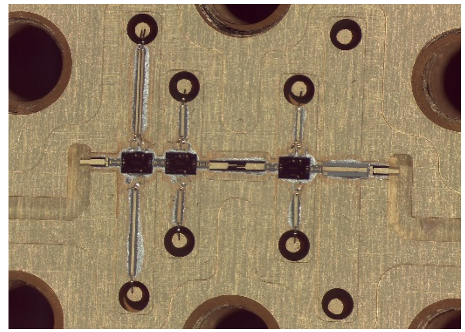
Image Courtesy of Dr. Simone Tanelli, JPL.

MASC Instrument Architecture and Hardware Heritage

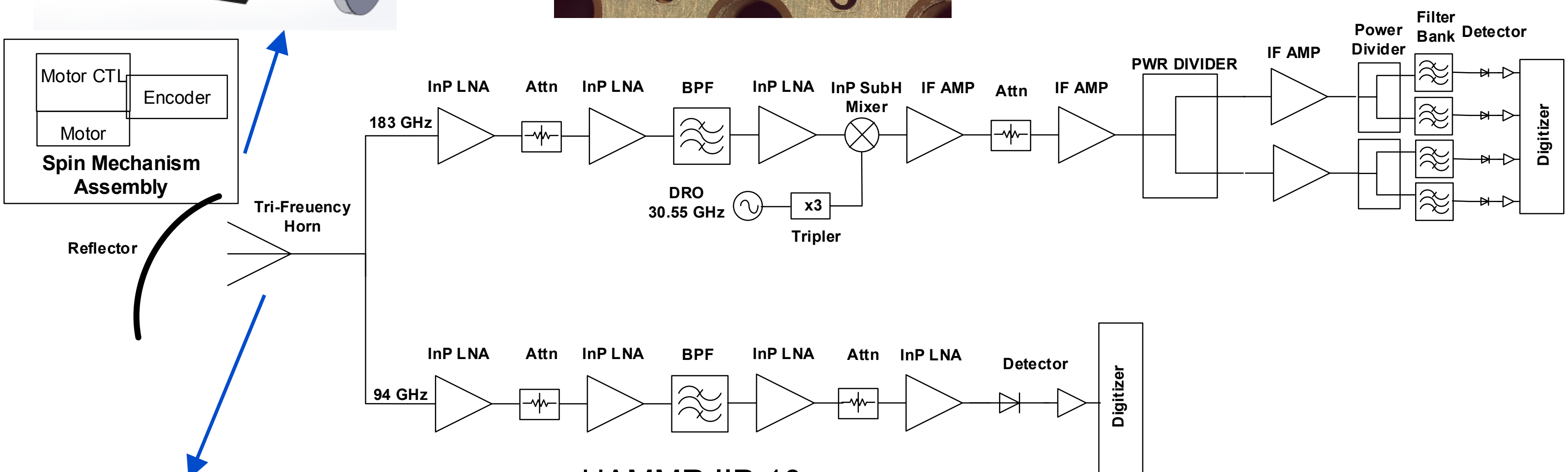
JPL R&TD Offset Paraboloid Reflector design



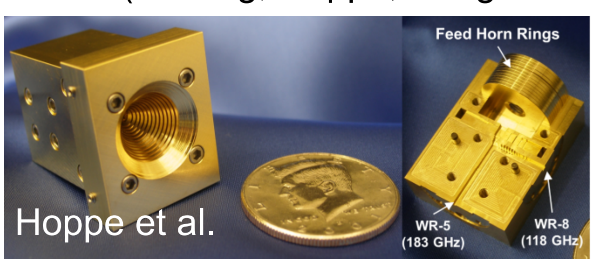
MASC 183 GHz front-end



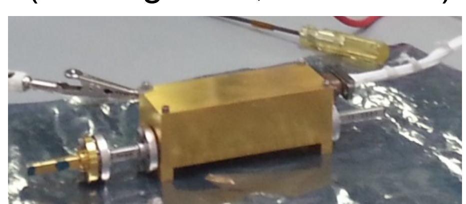
RACE Digitizer



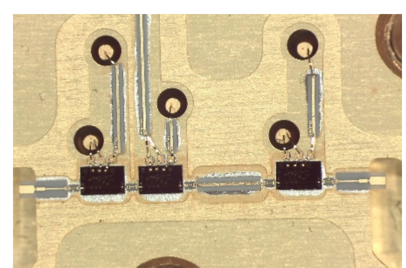
ACT-08 (Reising, Hoppe, Kangaslahti)



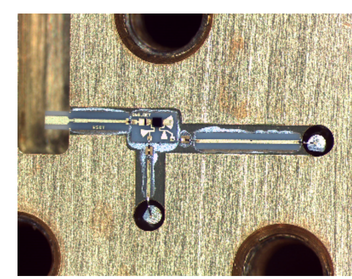
HAMMR IIP-10 (Reising et al.; CSU+JPL)



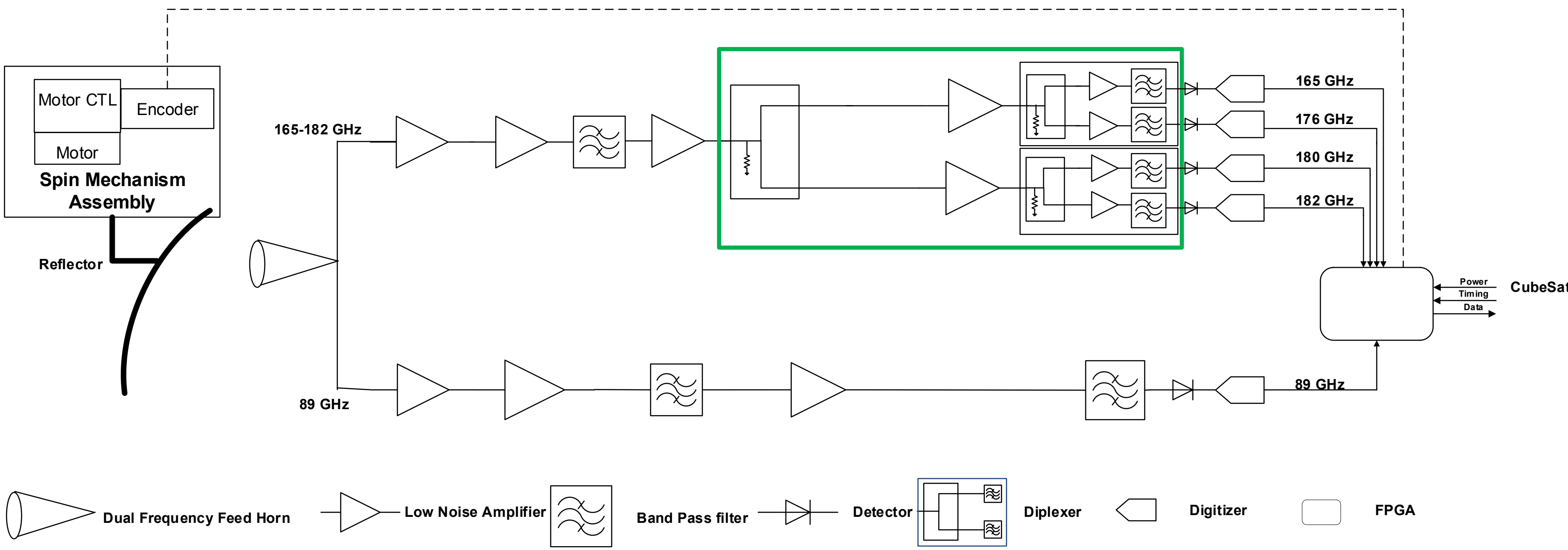
MASC 118 GHz front-end



IIP 90 GHz Detector

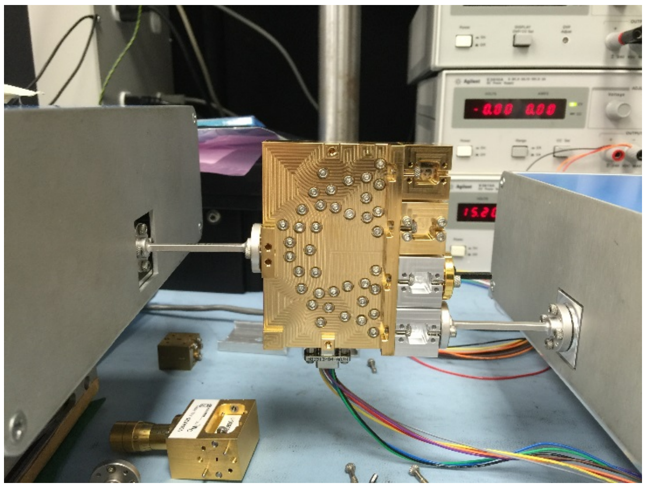


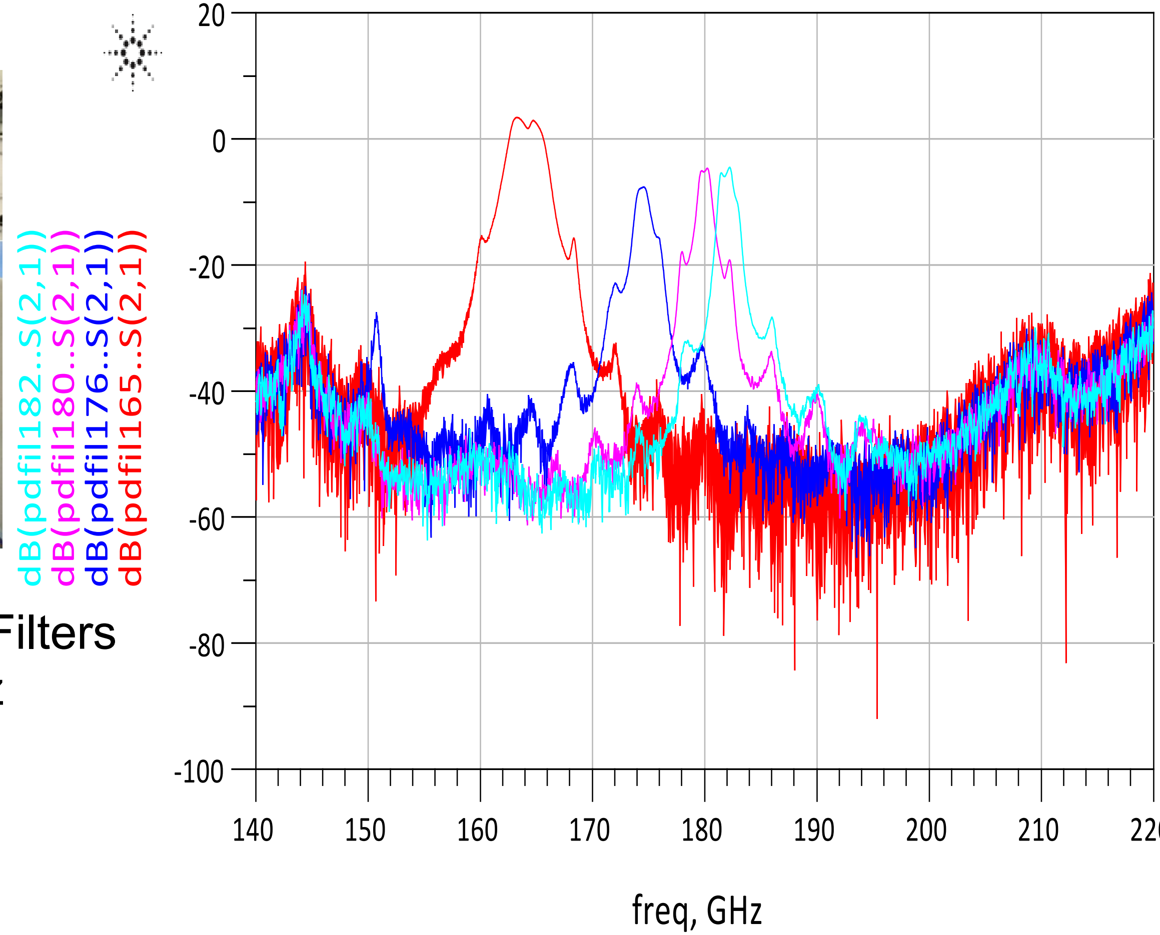
Block Diagram: Direct-Detection Approach



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**

Prototype Power Divider: Preliminary Data





Waveguide-based Bandpass Filters at 165, 176, 180 and 182 GHz

NB1	NB2	NB3	NB4	fc1	fc2	fc3	fc4
3.911	2.320	1.848	1.989	1.641E11	1.744E11	1.800E11	1.819E11

TEMPEST-D Summary

- Provides first in-space technology demonstration of a mm-wave (89-182 GHz) radiometer based on an InP HEMT low-noise amplifier front-end aboard a 6U-Class satellite
- Raises the TRL of the radiometer instrument from 6 to 7.
- To demonstrate capability of U-Class Satellites to advance NASA's Earth Science Goals
- To reduce cost, risk and development time for future constellations of small satellites to perform NASA Earth Science measurements
- To demonstrate the feasibility of orbital drag maneuvers to achieve time separation of U-Class constellations in the same orbital plane
- To demonstrate precision intercalibration of millimeter-wave radiometers (2 K or better) with existing space-borne assets, such as GMI and MHS
- Started in Aug. 2015; ready for delivery for launch in Aug. 2017
- 3 months of on-orbit operations for technology demonstration
- Prototyping has begun; measured results are expected soon