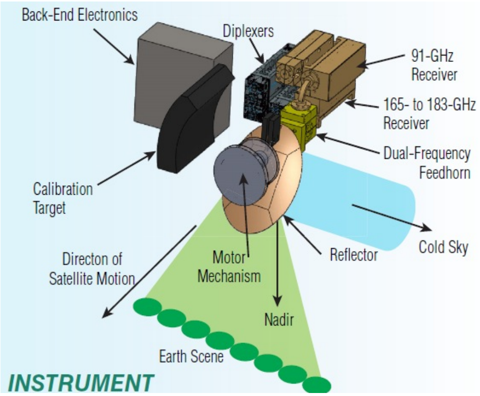
Temporal Experiment for Storms and Tropical Systems Technology Demonstration (TEMPEST-D)

Steven C. Reising[1], Todd C. Gaier[2], Christian D. Kummerow[1], V. Chandrasekar[1], Shannon T. Brown[2], Sharmila Padmanabhan[2], Boon H. Lim[2], Susan C. van den Heever[3], Tristan S. L'Ecuyer[3], Christopher S. Ruf[4], Ziad S. Haddad[2], Z. Johnny Luo[5], S. Joseph Munchak[6], Timothy C. Koch[2], and Sid A. Boukabara[7]

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

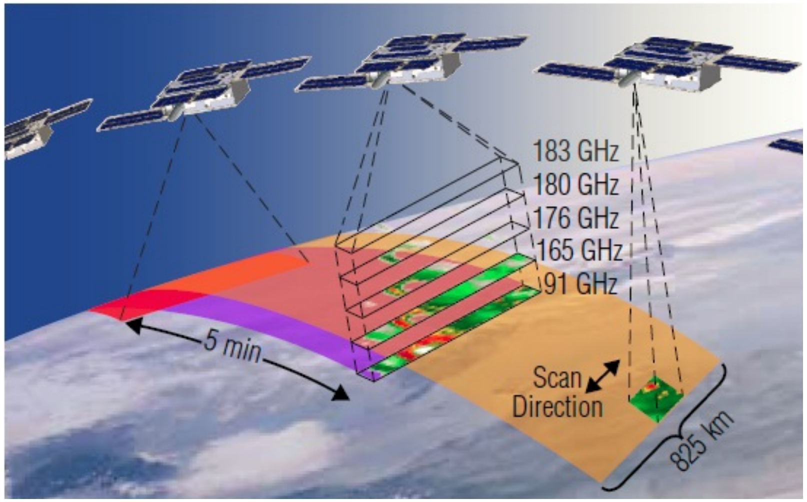
TEMPEST In-Space Technology Demonstration

- TEMPEST-D provides first in-space technology demonstration of a millimeter-wave radiometer (90-183 GHz) based on InP HEMT low-noise amplifier front-end aboard a 6U-Class satellite.
- TEMPEST-D raises the instrument TRL from 5 to 7.
- TEMPEST-D is a partnership among CSU, JPL and spacecraft provider (TBD with process in place to determine)
- Managed by NASA ESTO with funding from Earth System Science Pathfinder in Earth Science Division
- Start in July 2015 for three-year technology demonstration task

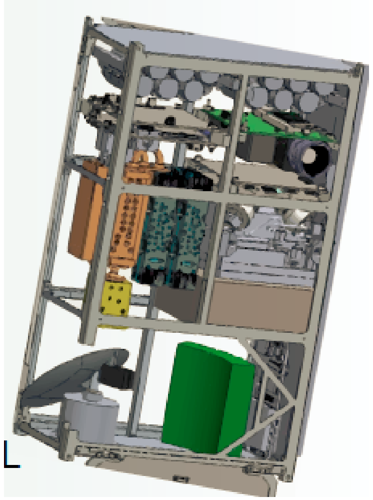


TEMPEST-D Scientific Motivation and Objectives

- Demonstrate capability of U-Class Satellites to provide suitable measurements to advance NASA's Earth Science Goals
- Reduce cost, risk and development time of future constellations of NASA's small satellites to perform Earth Science measurements
- Demonstrate drag-adjusting altitude maneuvers required to provide time separation to a U-Class constellation with common deployment
- Demonstrate precision intercalibration with existing conically-scanning satellite radiometers with similar frequencies within 1-2 K

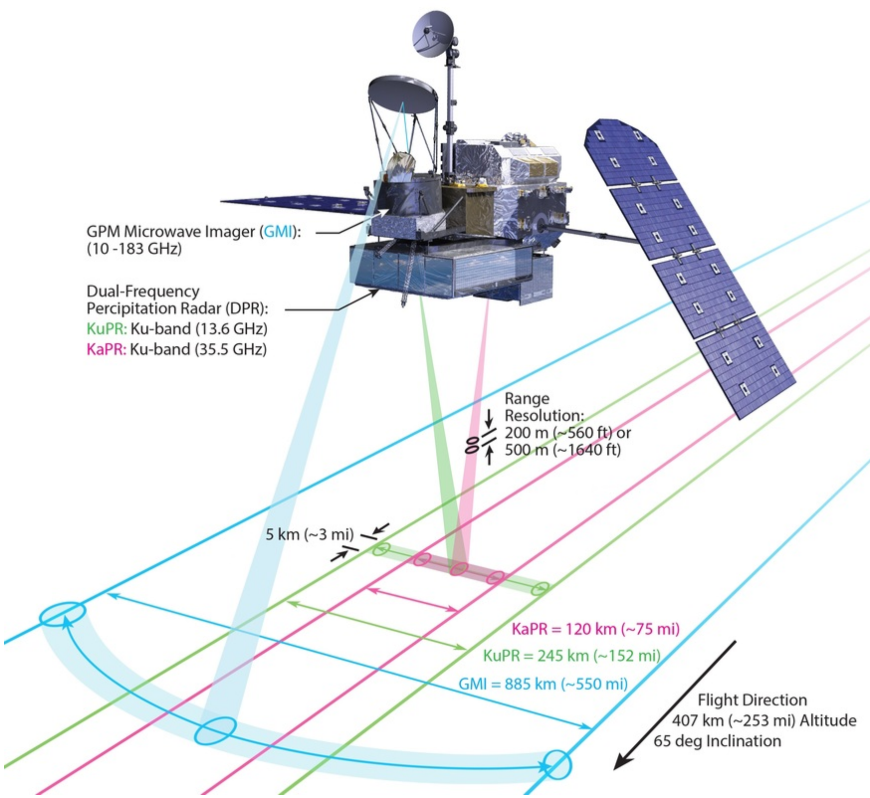


6U-Class satellite with millimeter-wave radiometer instrument



Reference: Global Precipitation Mission Microwave Imager

- Global Precipitation Mission launched Feb. 27, 2014.
- GPM Microwave Imager is a conically-scanning radiometer measuring at 10, 18, 23, 36, 89, 166, 176, and 180 GHz



Online at www.spaceflight101.com

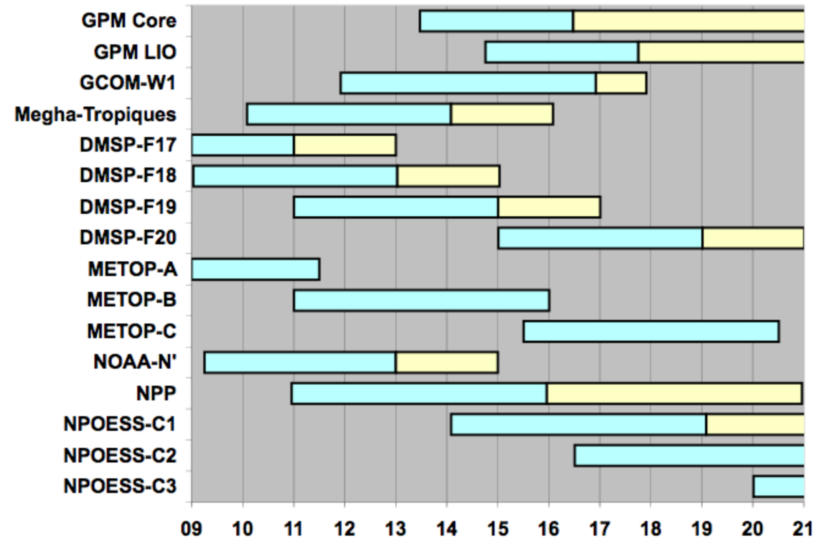
TABLE I
GMI PERFORMANCE REQUIREMENTS

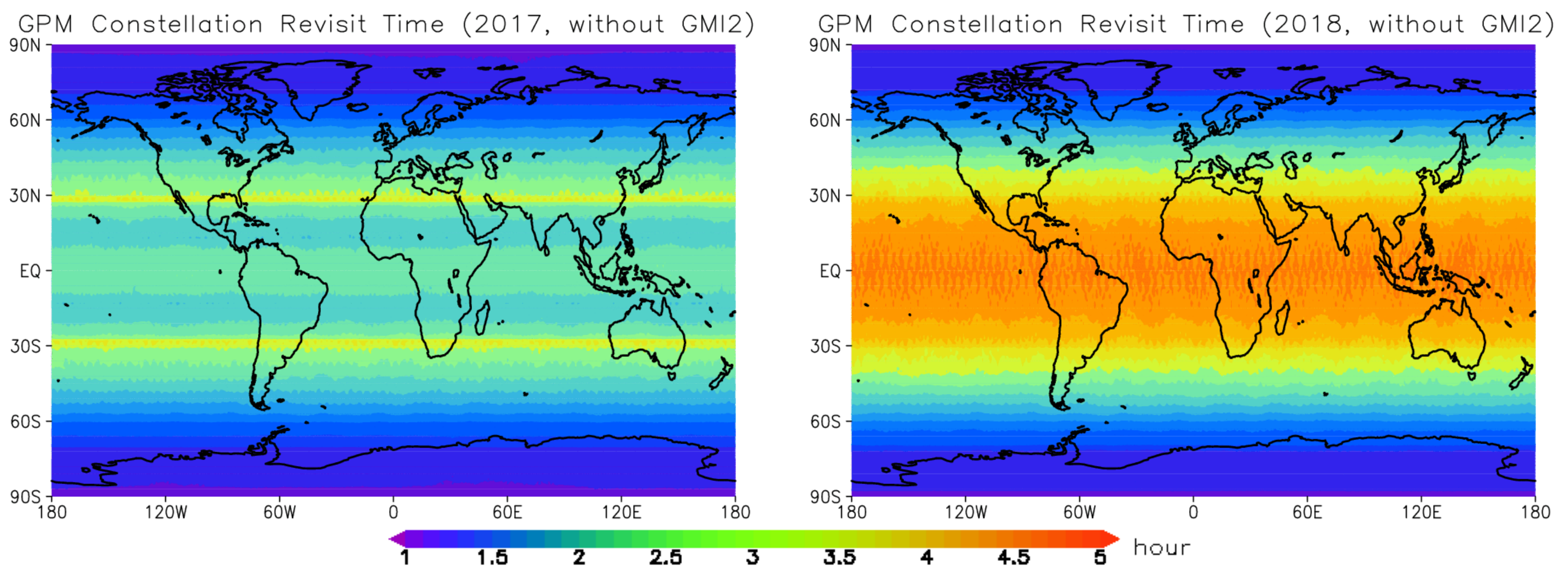
Ch	Center freq (GHz)	Pol	Freq stability (MHz)	Bandwidth (MHz)	Sampling interval (ms)	NEDT (K) **
1	10.65	V	10	<100	3.6	<0.96
2	10.65	H	10	<100	3.6	<0.96
3	18.7	V	20	<200	3.6	<0.84
4	18.7	H	20	<200	3.6	<0.84
5	23.8	V	20	<400	3.6	<1.05
6	36.64*	V	50	<1000	3.6	<0.65
7	36.64*	H	50	<1000	3.6	<0.65
8	89	V	200	<6000	3.6	<0.57
9	89	H	200	<6000	3.6	<0.57
10	166	V	200	<4000	3.6	<1.5
11	166	H	200	<4000	3.6	<1.5
12	183.31 ± 3	V	200	<2000	3.6	<1.5
13	183.31 ± 7	V	200	<2000	3.6	<1.5

Calibration uncertainty	<1.35K (Ch 1–9); <1.5K (Ch 10–13)
Calibration stability	<0.5K (All Ch's)
Dynamic range	3 to 340K (All Ch's)
Nonlinearity	<0.5K (All Ch's)

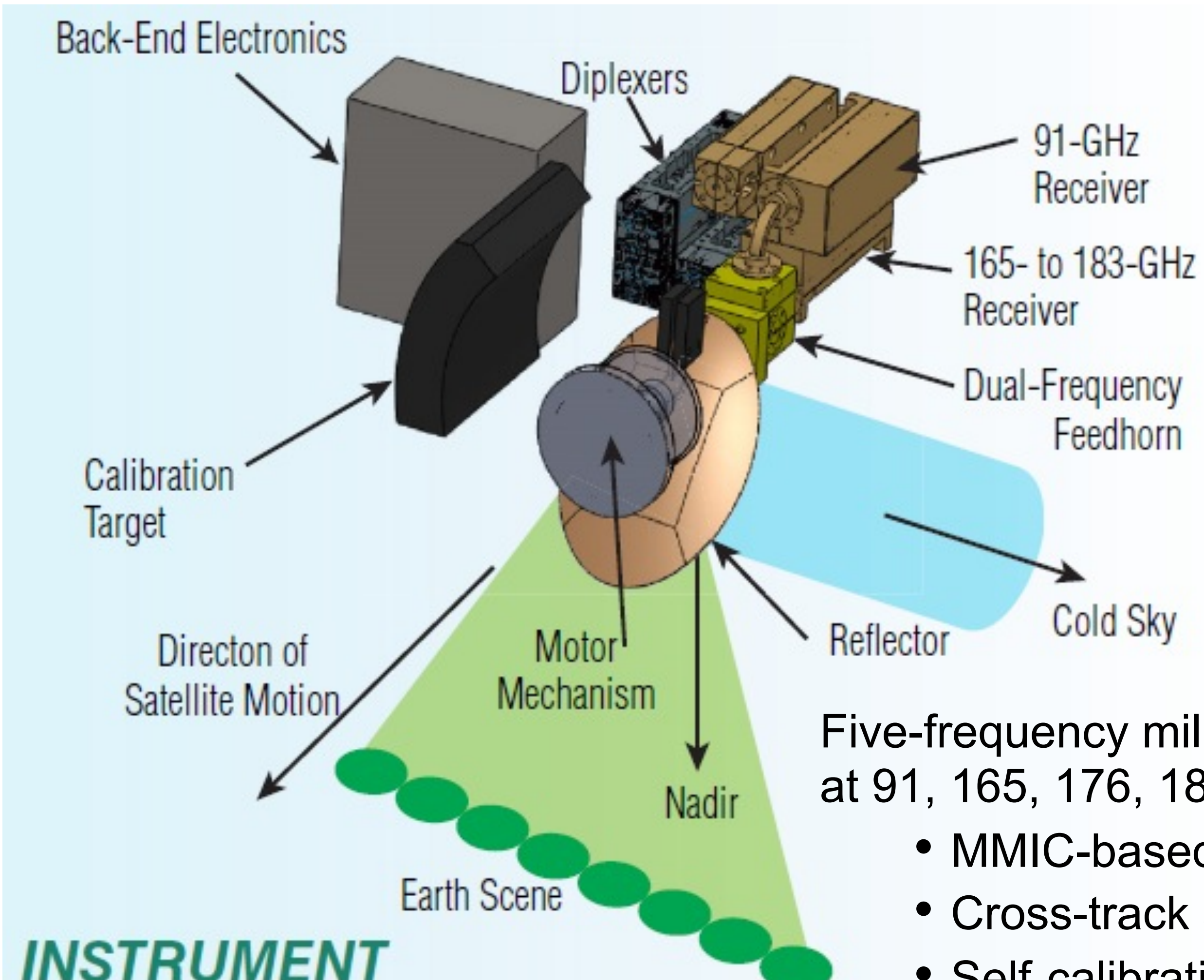
Draper et al., *IEEE J-STARS*, in press, 2015.

Reference: Sampling/Coverage of GPM Constellation





TEMPEST-D Instrument Design

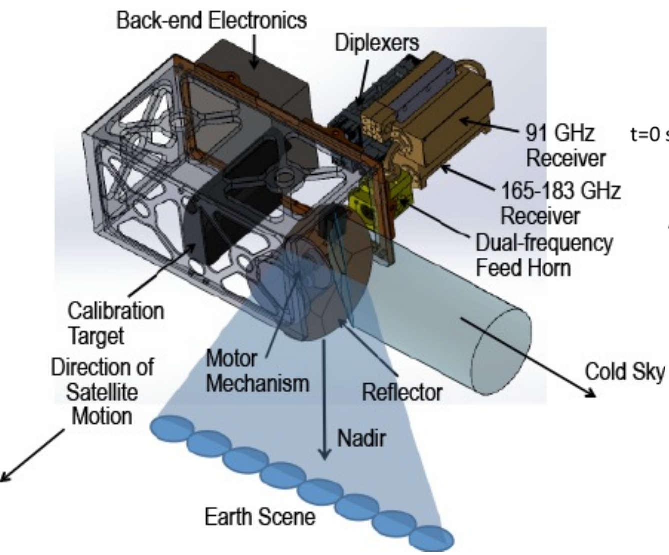


Five-frequency millimeter-wave radiometer at 91, 165, 176, 180 and 183 GHz

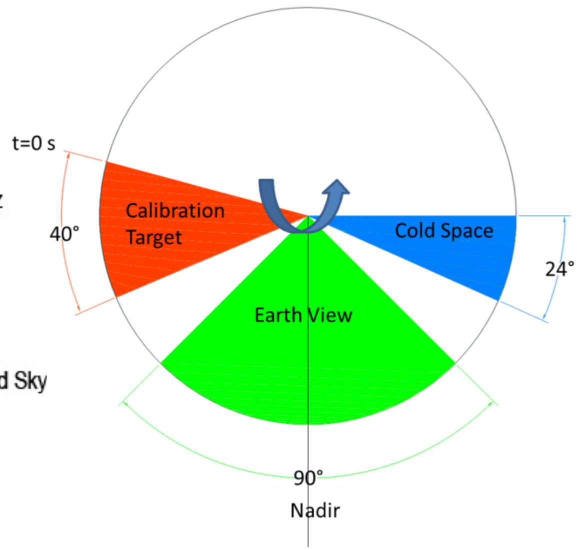
- MMIC-based
- Cross-track scanning
- Self-calibrating

TEMPEST-D Radiometer Calibration

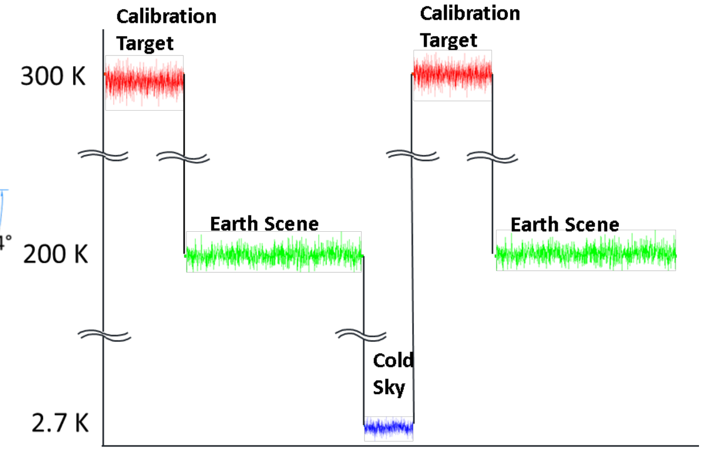
TEMPEST-D Instrument



Observing Profile



Time Series of Output Data

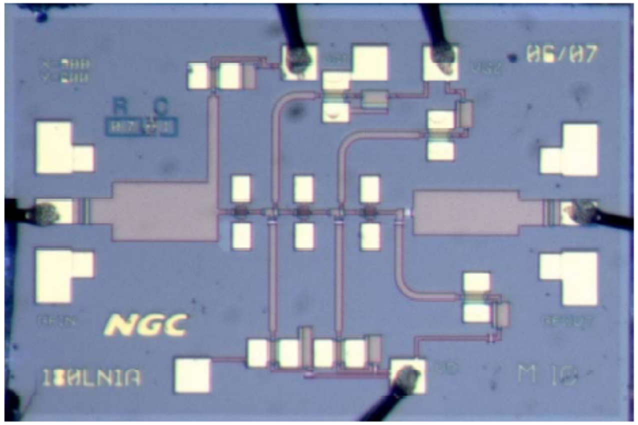


- Five-frequency millimeter-wave radiometer measures Earth scene over ±45° incidence angles from nadir.
- This provides an 825-km swath width from a nominal altitude of 400 km.
- Each pixel is sampled for 5 ms.
- Space view observes cold sky, i.e. cosmic microwave background at 2.7 K.
- Ambient calibration target provides the second measurement for two-point calibration to determine instrument gain and offset.

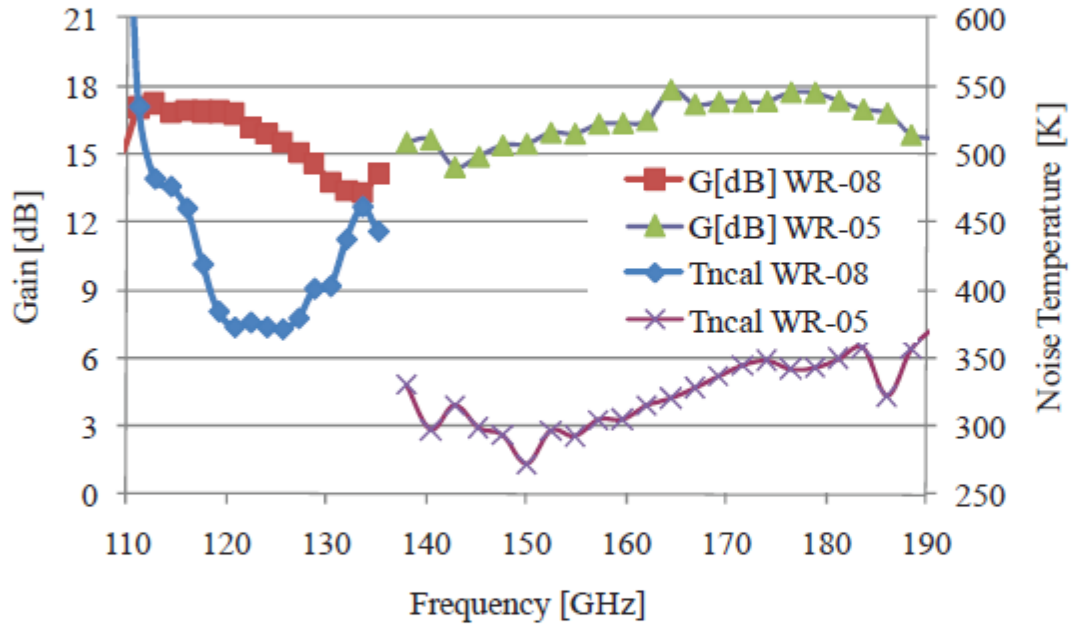
TEMPEST-D Instrument Specifications

Parameter	Specification	
System noise temperature	< 600 K	
Number of channels	5	
Bandwidth	4 GHz at 91 and 166 GHz; 2 GHz at 173, 180 and 183 GHz	
Minimum spatial resolution	13 km at 183 GHz	24 km at 91 GHz
Minimum beam efficiency	> 90%	> 90%
Mass	< 3 kg	
Power	< 8 W	
Volume	**3U**	
Precision (Stability)	0.5 K (CBE)	
Accuracy (Calibration)	1 K (CBE)	

Enabling Technology: 35-nm InP HEMT Low-Noise Amplifiers

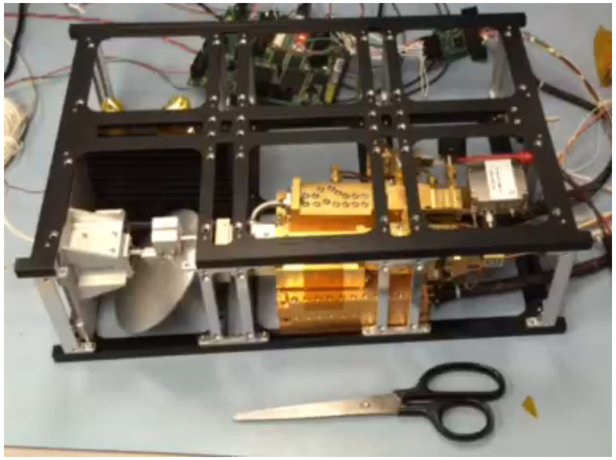


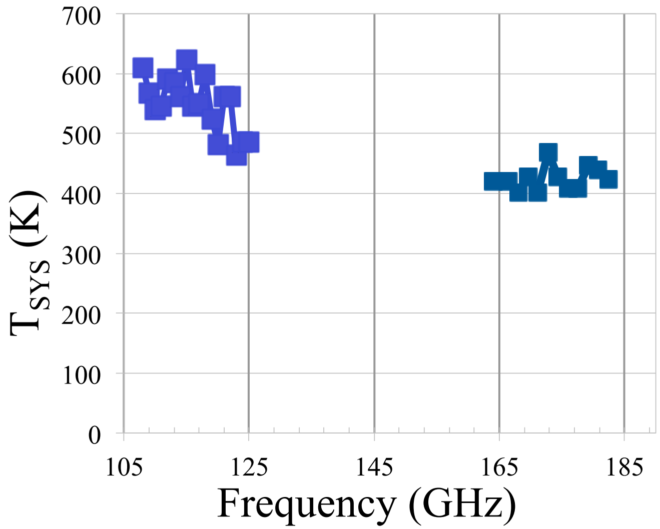
From Kangaslahti et al.,
Proc. Int'l Microwave Symp. 2012



- 35-nm InP HEMT process
- Record low noise temperature of 300 - 350 K from 140 - 190 GHz (at room temperature)
- Chip area of 900 x 560 μm^2
- Three-stage design with separate gate bias for the first stage to optimize low-noise performance
- The LNA was mounted in optimized WR-08 and WR-05 waveguide housings for testing over a broad bandwidth.

Microwave Atmospheric Sounder on CubeSat (MASC)

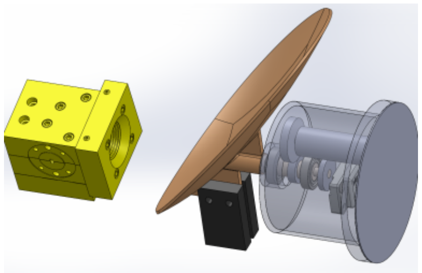




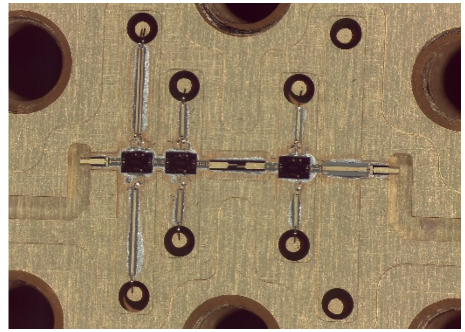
- Prototype millimeter-wave sounding radiometer for 6U CubeSat; JPL R&TD led by Sharmila Padmanabhan
- Instrument occupies 3U of a 6U CubeSat, with mass of 3 kg and power consumption of 6.5 W
- Temperature and water vapor profiling using 4 channels each near absorption lines at 118.75 GHz and 183.31 GHz oxygen and water vapor absorption lines, respectively
- Receiver noise temperatures were measured using standard gain horns.
- Heritage from NASA ESTO-funded ACT, IIP and AITT programs as well as JPL RACE CubeSat mission.

MASC Instrument Architecture and Hardware Heritage

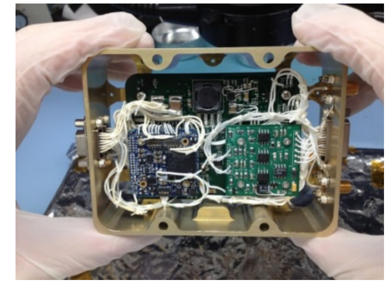
JPL R&TD Offset Paraboloid Reflector design

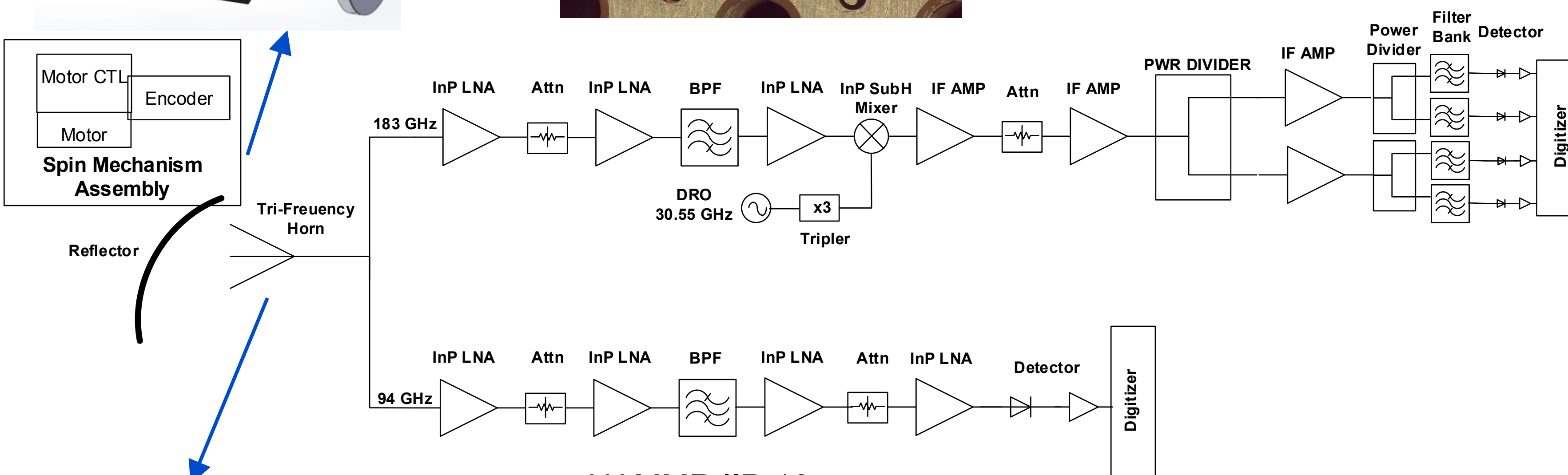


MASC 183 GHz front-end

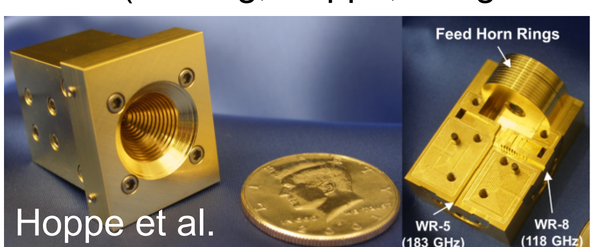


RACE Digitizer

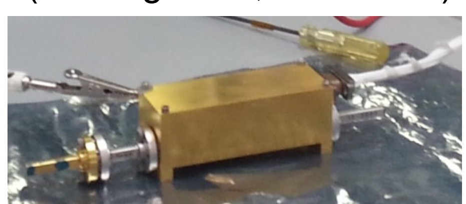




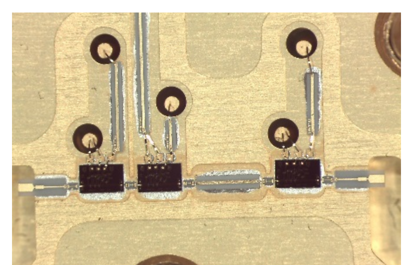
ACT-08 (Reising, Hoppe, Kangaslahti)



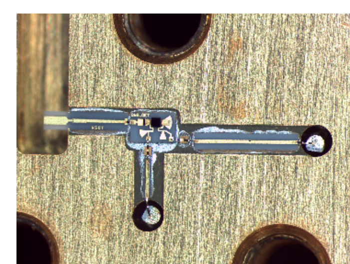
HAMMR IIP-10 (Reising et al.; CSU+JPL)



MASC 118 GHz front-end



IIP 90 GHz Detector



TEMPEST-D Selected in Feb. 2015 by NASA CubeSat Launch Initiative

- TEMPEST-D was selected by NASA CSLI (ELaNa) in Feb. 2015
- Assigned priority #7 of 14 (based on predicted launch readiness, launch priority orbital requirements, etc.

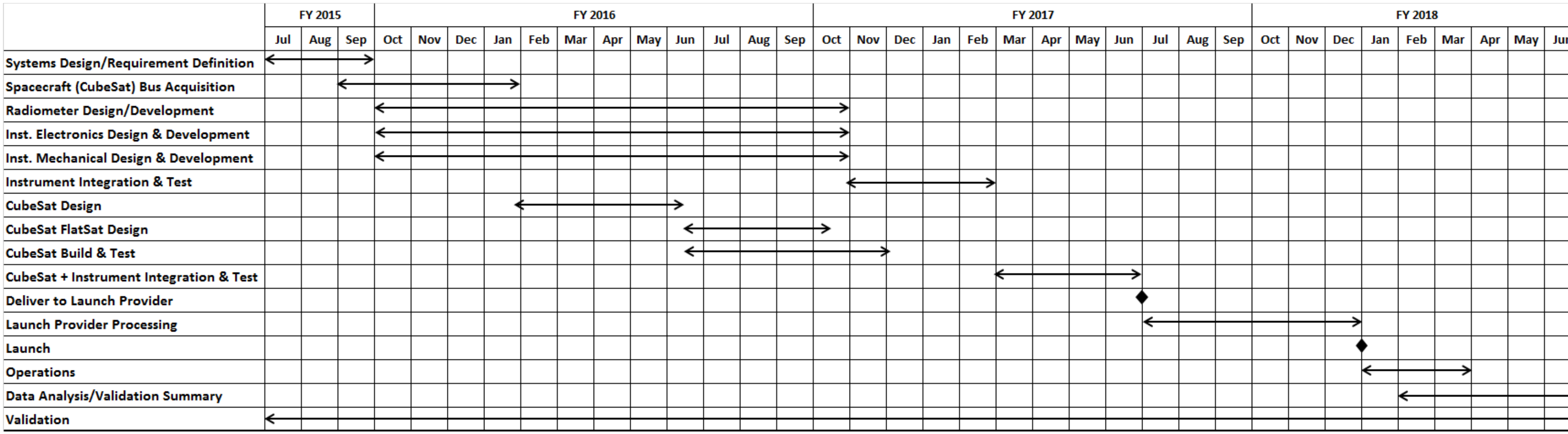
February 2015 Selection						
CSLI Rank	Short Name	Project	Organization	POC	Cube Size	Status
1	OPEN	OPEN: Open Prototype for Educational NanoSats	University of North Dakota	Ronald Marsh	1U	In Work
2	RadSat	RadSat: Satellite Demonstration of a Radiation Tolerant System	Montana State University	Dr. Brock LaMeres	3U	In Work
3	ALBus	Advanced ELectrical Bus (ALBus)	NASA Glenn Research Center	Katie Shaw	3U	In Work
4	MiTEE	MiTEE: Miniature Tether Electrodynamics Experiment	University of Michigan	Dr. Brian Gilchrist	3U	In Work
5	KickSat-2	KickSat-2: A Technology Demonstration Mission for the Sprite ChipSat	Cornell University	Zachary Manchester	3U	In Work
6	TBEx	TBEx – The Tandem Beacon Experiment	The University of Michigan	Dr. James Cutler	3U	In Work
7	TEMPEST-D	TEMPEST-D: Temporal Experiment for Storms and Tropical Systems - Demonstrator	Colorado State University	Dr. Steven Reising	6U	In Work

From https://www.nasa.gov/directorates/heo/home/CSLI_selections.html#2015

TEMPEST-D Key Roles

Name	Role	Institution
Steven Reising	Principal Investigator	Colorado State University (CSU)
Todd Gaier	JPL Lead Co-I	Jet Propulsion Laboratory (JPL)
Ron Steinkraus	Project Manager; Spacecraft and Mission Operations	JPL
V. Chandrasekar	CSU Co-I; Validation / Engineering Interface	CSU
Sharmila Padmanabhan	Instrument Engineer	JPL
Boon Lim	Systems Engineer	JPL
Christian Kummerow	Validation Lead	CSU
Ted Sweetser	Orbital Architecture	JPL

TEMPEST-D Schedule

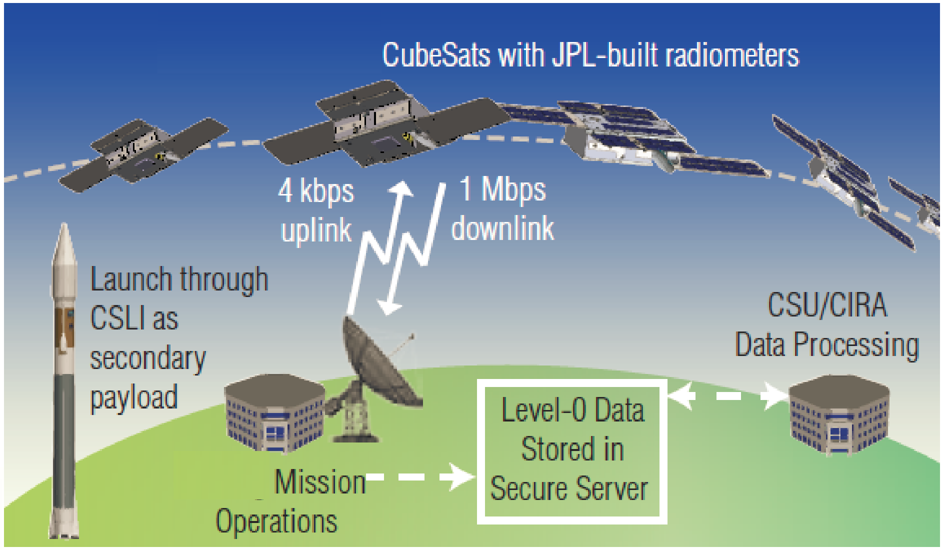


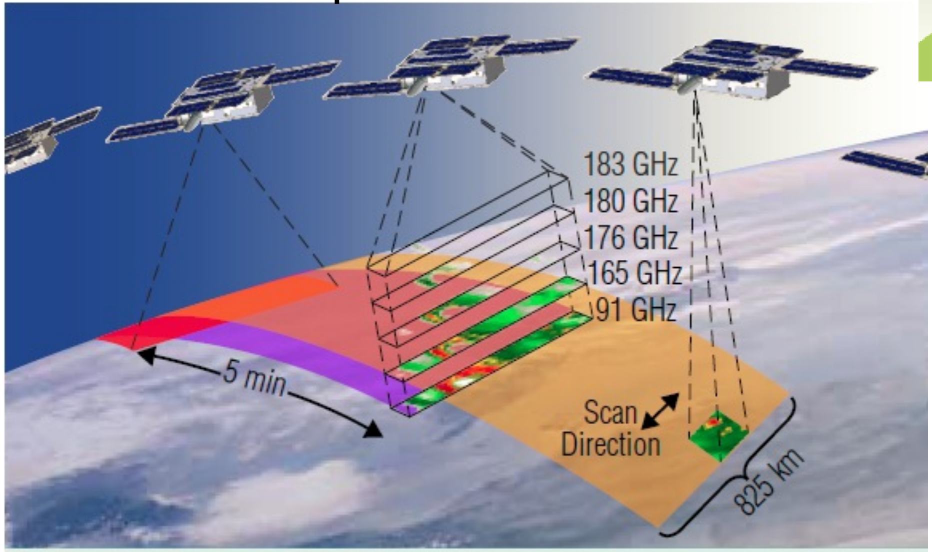
- July 2015: Project Start
- Nov. 2016: Deliver radiometer instrument for integration & test
- Dec. 2016: Complete 6U-Class satellite bus
- July 2017: Deliver TEMPEST-D spacecraft to launch provider
- July 2017 to Jan. 2018: 6-month window for launch availability
- After launch: 3 months of operations; 3 months analysis & validation
- Jun. 2018: Project Completion

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 CubeSats
- 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

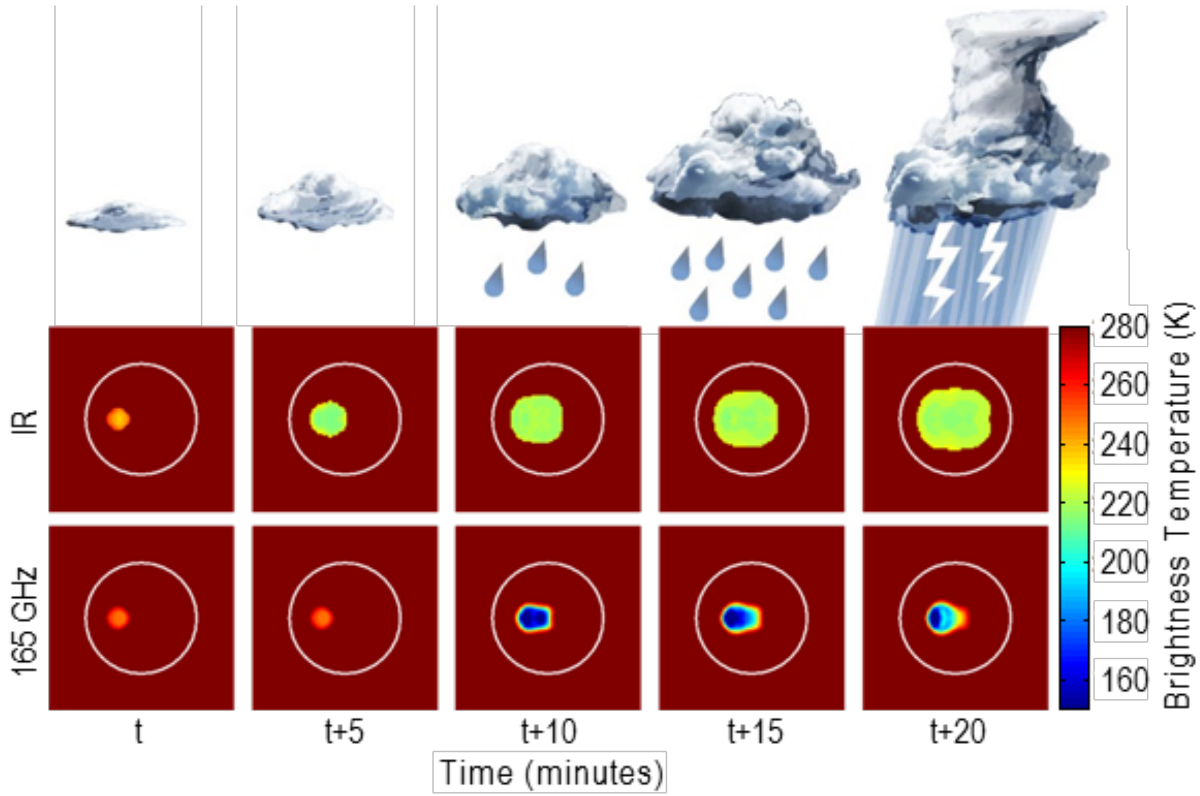
- Constrain climate models through improved understanding of cloud processes, transition from clouds to precipitation and impact on Earth's energy balance
- Characterize temporal variability of precipitation globally to improve understanding of water cycle

Future Vision: Observation of Transition from Clouds to Precipitation

Temporal evolution of convective system

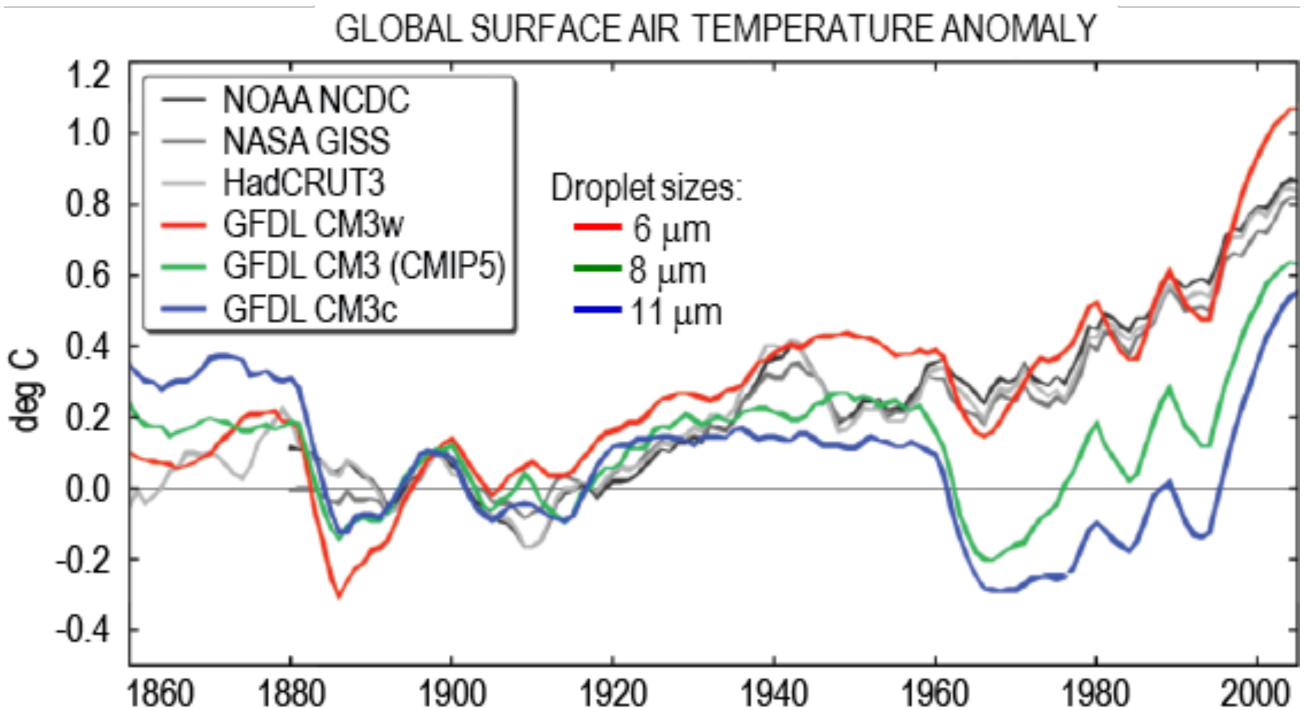
Infrared Brightness Temperature

Millimeter-wave Brightness Temperature, both from model



- Infrared brightness temperatures (GEO) show only cold cloud top temperatures.
- Transition from clouds to precipitation is clearly detected at millimeter-wave frequencies on TEMPEST constellation, including 165 GHz.
- TEMPEST spatial resolution of 25 km at lowest frequency is shown (circles).

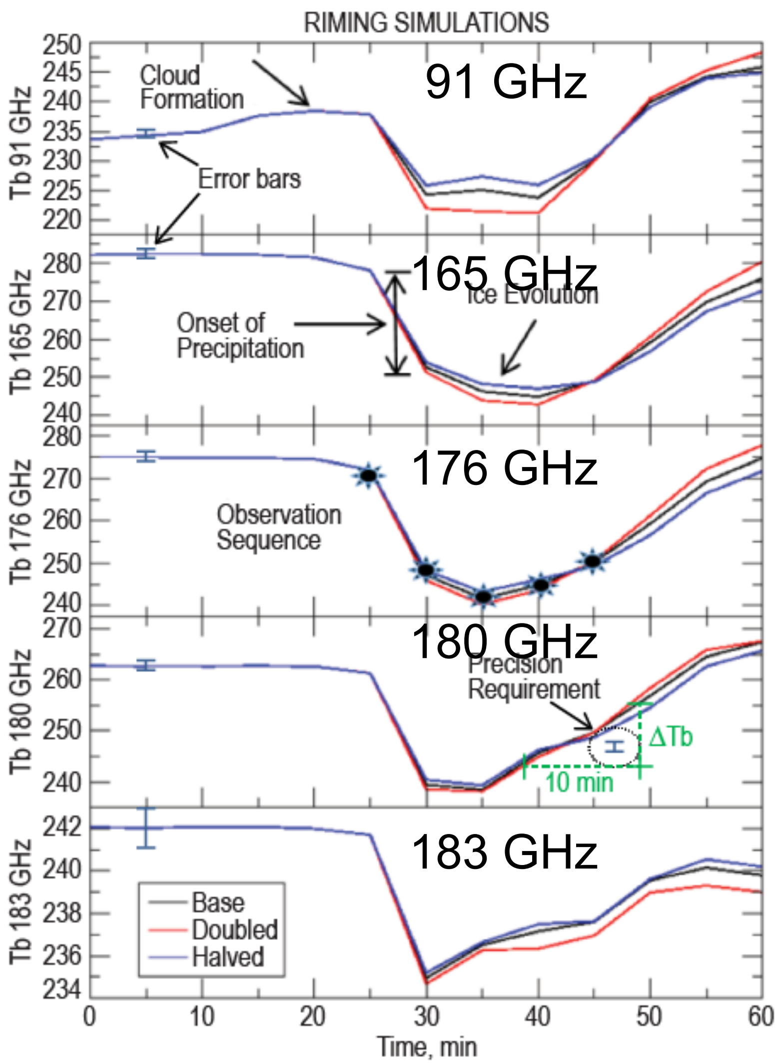
Sensitivity of Climate Model Predictions to Onset of Precipitation



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

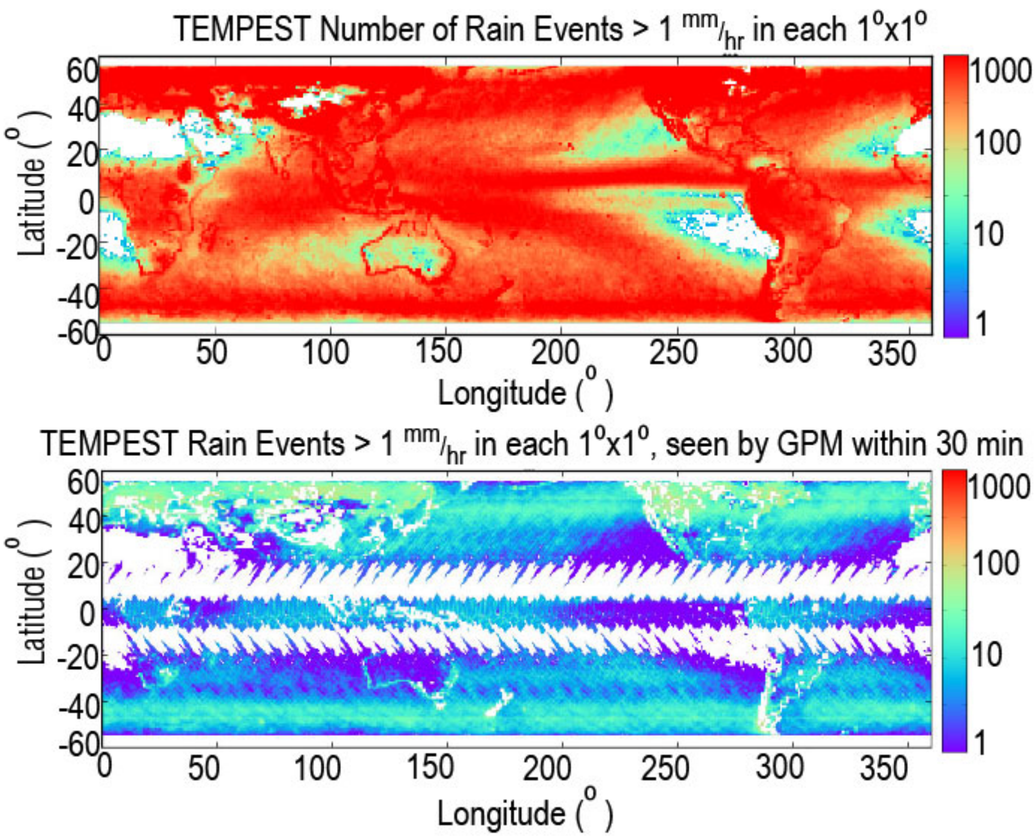
- Global climate model temperature anomaly projections for onset of precipitation at cloud droplet sizes of 6 µm (red), 8 µm (green) and 11 µm (blue).
- TEMPEST constellation could provide the first global sample of the onset of precipitation, constraining climate prediction models.

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 significant effects on climate system. Residual ice can be compared to W-band radar observations from CloudSat or ESA's EarthCARE.

Global Observations of Temporal Evolution of Precipitation



- In a potential 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 6U-Class Satellites and Passive Constellation Maneuvers

KEY FLIGHT CHARACTERISTICS

- 5 identical 6U CubeSats

  Attitude:

  3-axis stabilization
  0.13° (1σ) control
  0.15° (1σ) knowledge

  Mass:

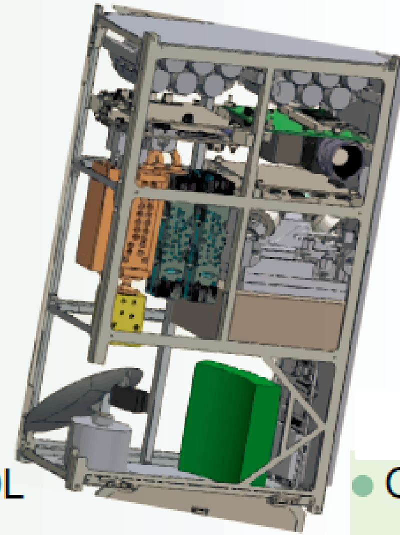
  5.8 kg (Margin: 38%)

  Power:

  13 W (Margin: 23%)
  Peak Power: 65 W EOL

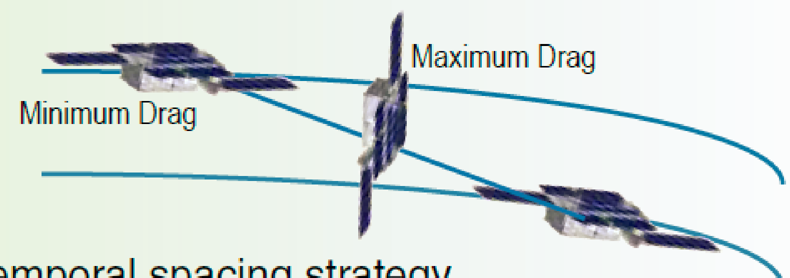
  Communications:

  1 Mbps S-band (Margin: 22%)



- Orbital characteristic (CSLI compatible)

  Altitude: 390 – 450 km
  Inclination: 50°– 65°



- Temporal spacing strategy

  Drag-adjusting attitude maneuvers used to achieve temporal separation between CubeSats

Summary

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- TEMPEST-D raises the instrument TRL from 5 to 7.
- TEMPEST-D partners are CSU, JPL and spacecraft provider (TBD).
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- To reduce cost, risk and development time of future constellations of NASA's small satellites to perform Earth Science measurements
- To demonstrate drag-adjusting altitude maneuvers required for time separation for U-Class constellation with common deployment
- To provide precision intercalibration with existing conically-scanning Earth-viewing radiometers with similar frequencies to within 1-2 K
- Start in July 2015 for launch by Jan. 2018; 3 months of operations