Temporal Experiment for Storms and Tropical Systems Demonstration (TEMPEST-D): Global Atmospheric Science Observations from a CubeSat

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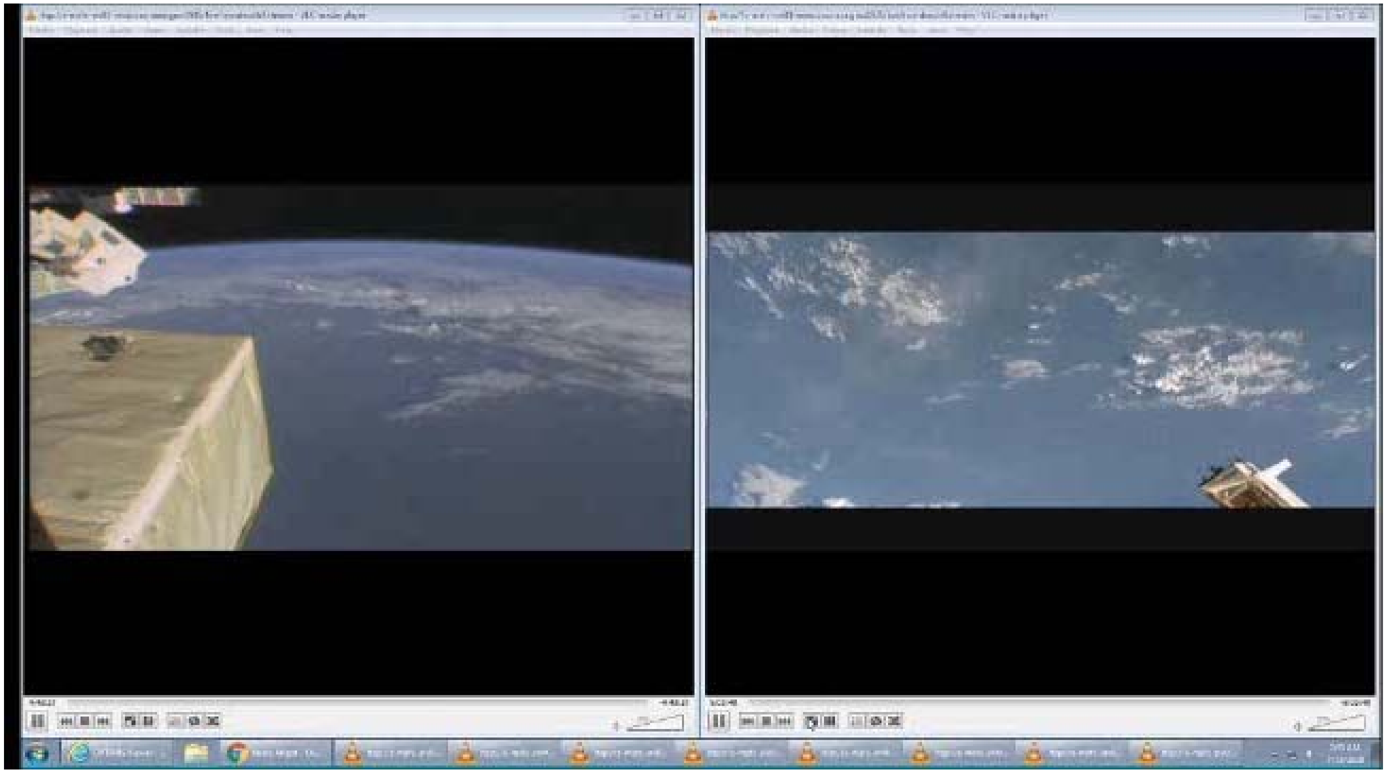
[2]NASA Caltech/Jet Propulsion Laboratory, Pasadena, CA
[3]Blue Canyon Technologies, Boulder, CO

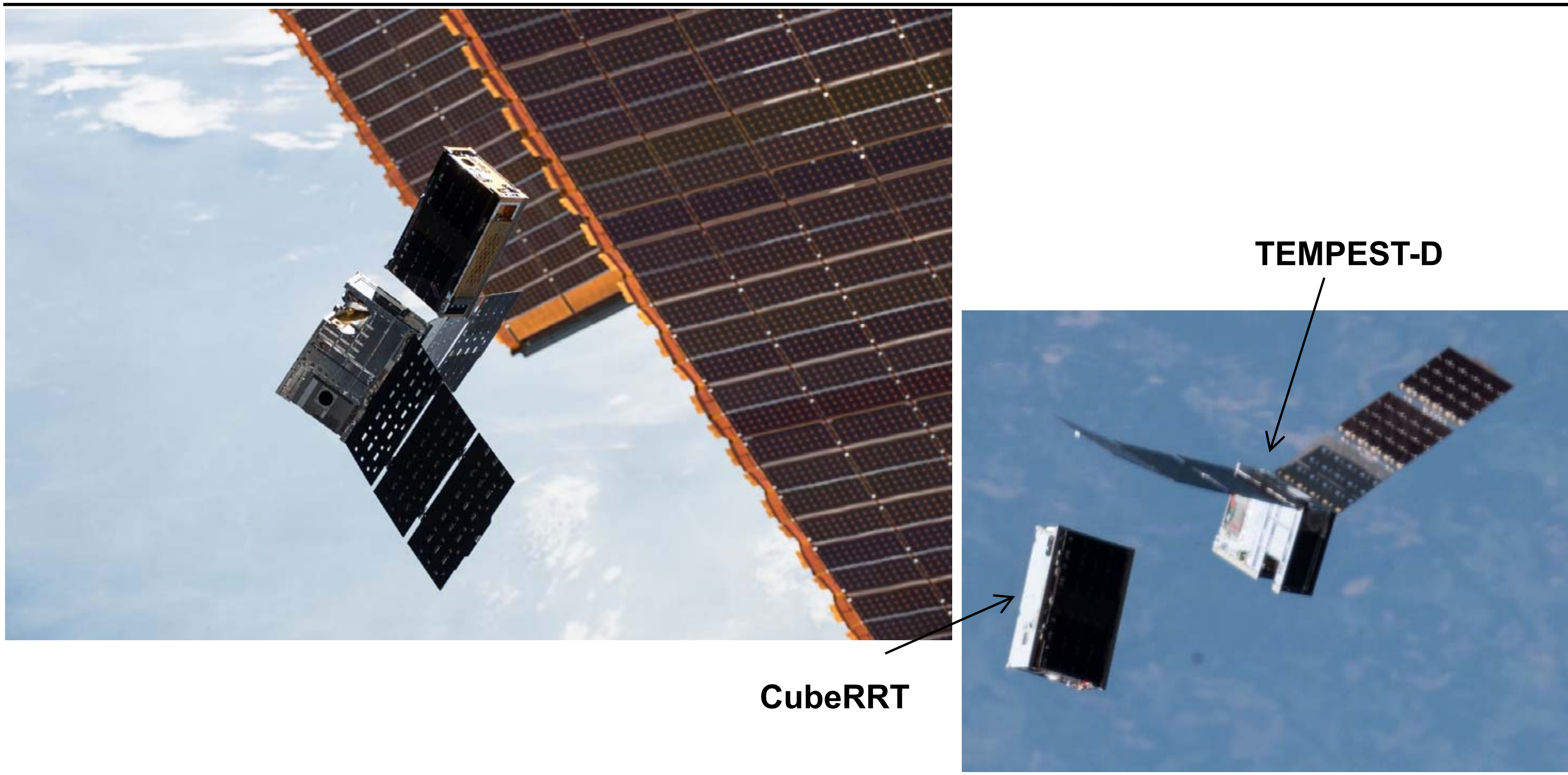
Thanks to NASA Wallops for providing UHF ground communications!

TEMPEST-D and CubeRRT Deployment into Orbit from ISS



Recorded on ISS on July 13, 2018   Credit: NASA

TEMPEST-D and CubeRRT, Shortly After Deployment on July 13, 2018

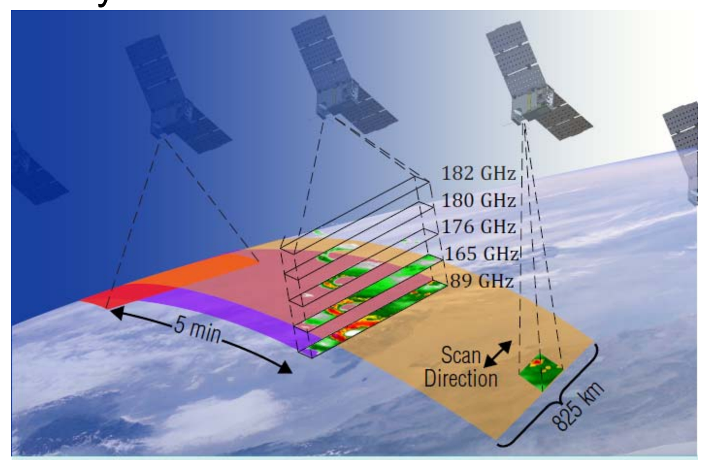


Temporal Experiment for Storms and Tropical Systems (TEMPEST)

TEMPEST addresses 2017 National Academies Earth Science Decadal Survey:

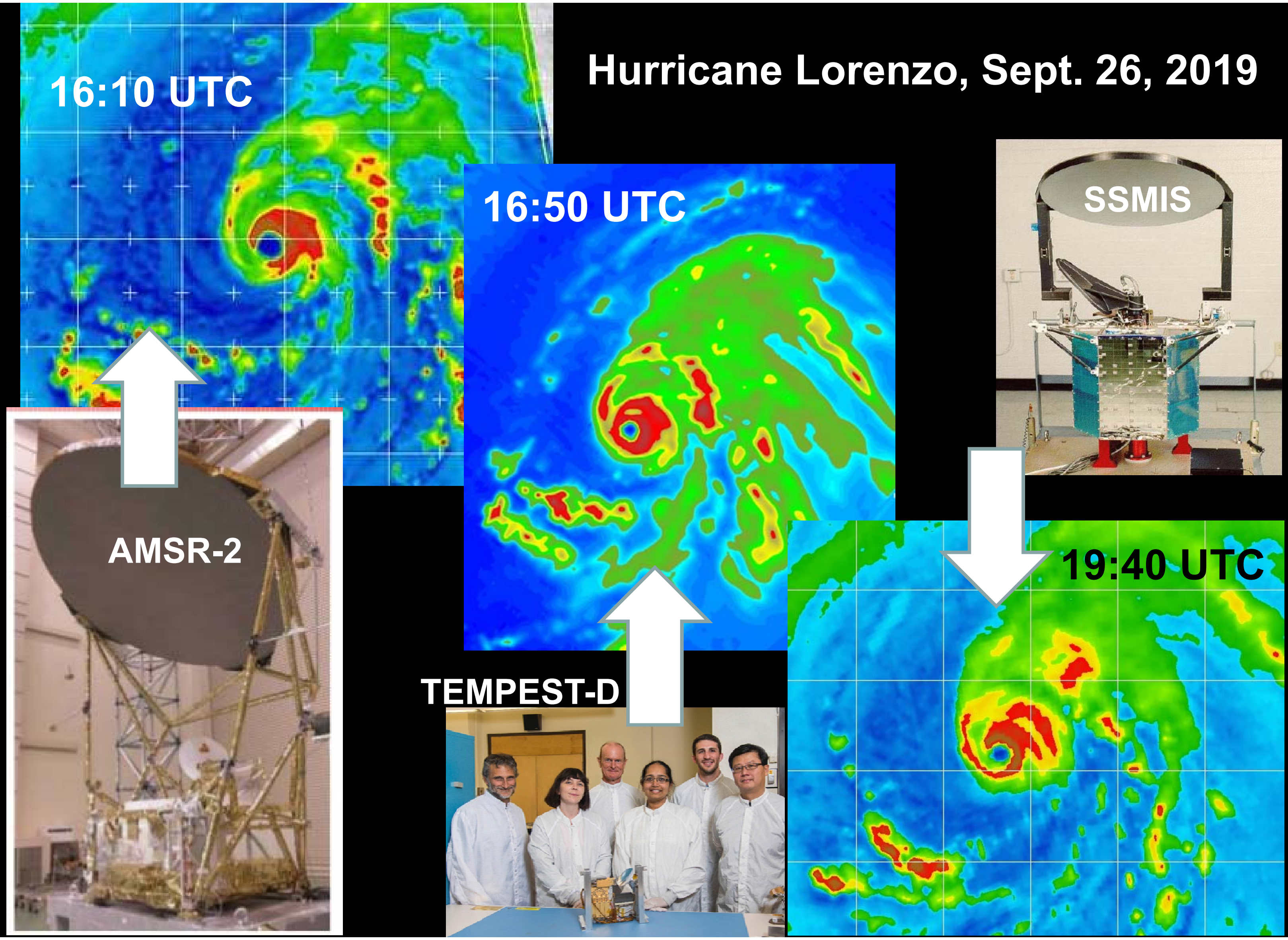
- *Why do convective storms, heavy precipitation, and clouds occur exactly when and where they do?* (Most Important Science Question W-4)
- Proposed to NASA EVI-2 in 2013 as a constellation of 5 identical 6U CubeSats to provide *temporally-resolved observations of rapidly-evolving storms* every 5 minutes for up to 30 minutes.
- Chosen as NASA Earth Venture Technology Demonstration mission and delivered a 6U CubeSat with multi-channel millimeter-wave radiometer for launch less than 2 years after PDR.

- Launched by Orbital ATK from NASA Wallops to ISS on May 21, 2018.
- Deployed into orbit by Nanoracks on July 13, 2018.



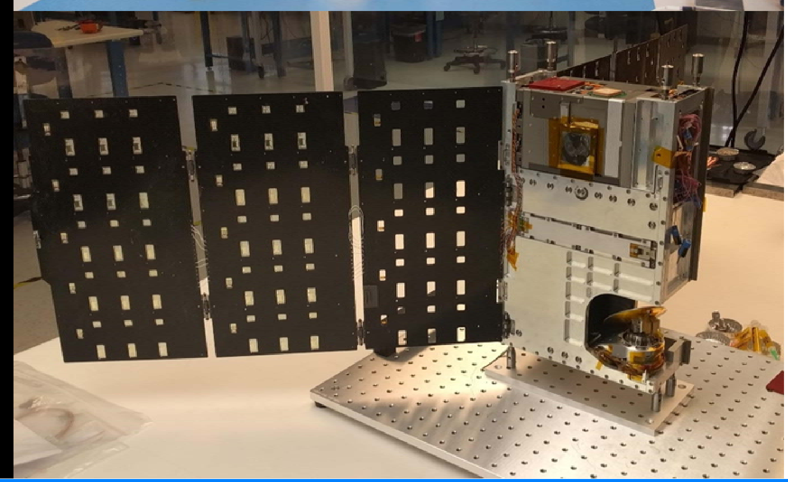
5 identical 6U small sats, each with an identical 5-channel radiometer, flying 5 minutes apart

Hurricane Lorenzo, Sept. 26, 2019



NOAA Advanced Technology Microwave Sounder (ATMS)
75 kg, 100 W, **$$$$**

TEMPEST-D
3.8 kg, 6.5 W, $



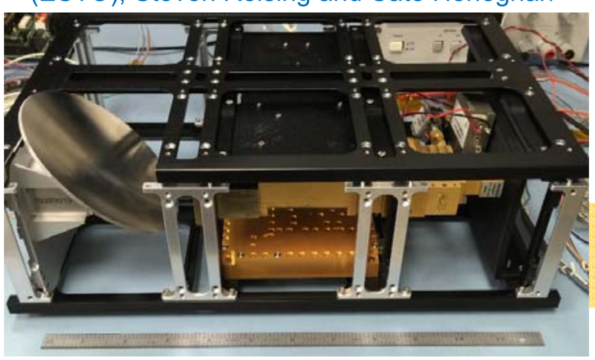
TEMPEST-D Team and Heritage Reflect Over a Decade of Investment in Earth Science Technology Development

TEMPEST-D Team (L to R): Rudy Bendig, Mary Soria, Sharmila Padmanabhan, Ann Batchelor, Bob Bauer (ESTO), Steven Reising and Cate Heneghan

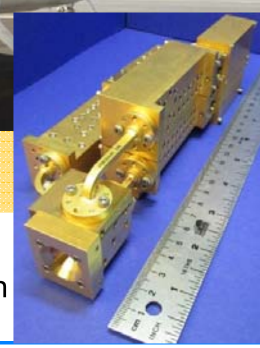
Sustained investment by JPL and ESTO led to TEMPEST proposal to NASA EVI-2 in 2013 (CSU/JPL)

NASA SMD/ESD created Earth Venture Tech Program in 2014

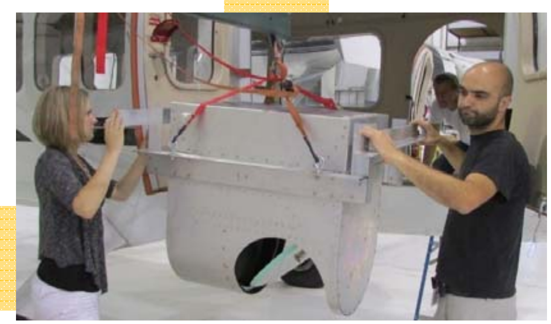
TEMPEST-D Instrument Team (L to R): Todd Gaier, Heather Lim, Alan Tanner, Sharmila Padmanabhan, Rudy Bendig and Boon Lim



Microwave Atmospheric Sounder on CubeSat (MASC, JPL R&TD)

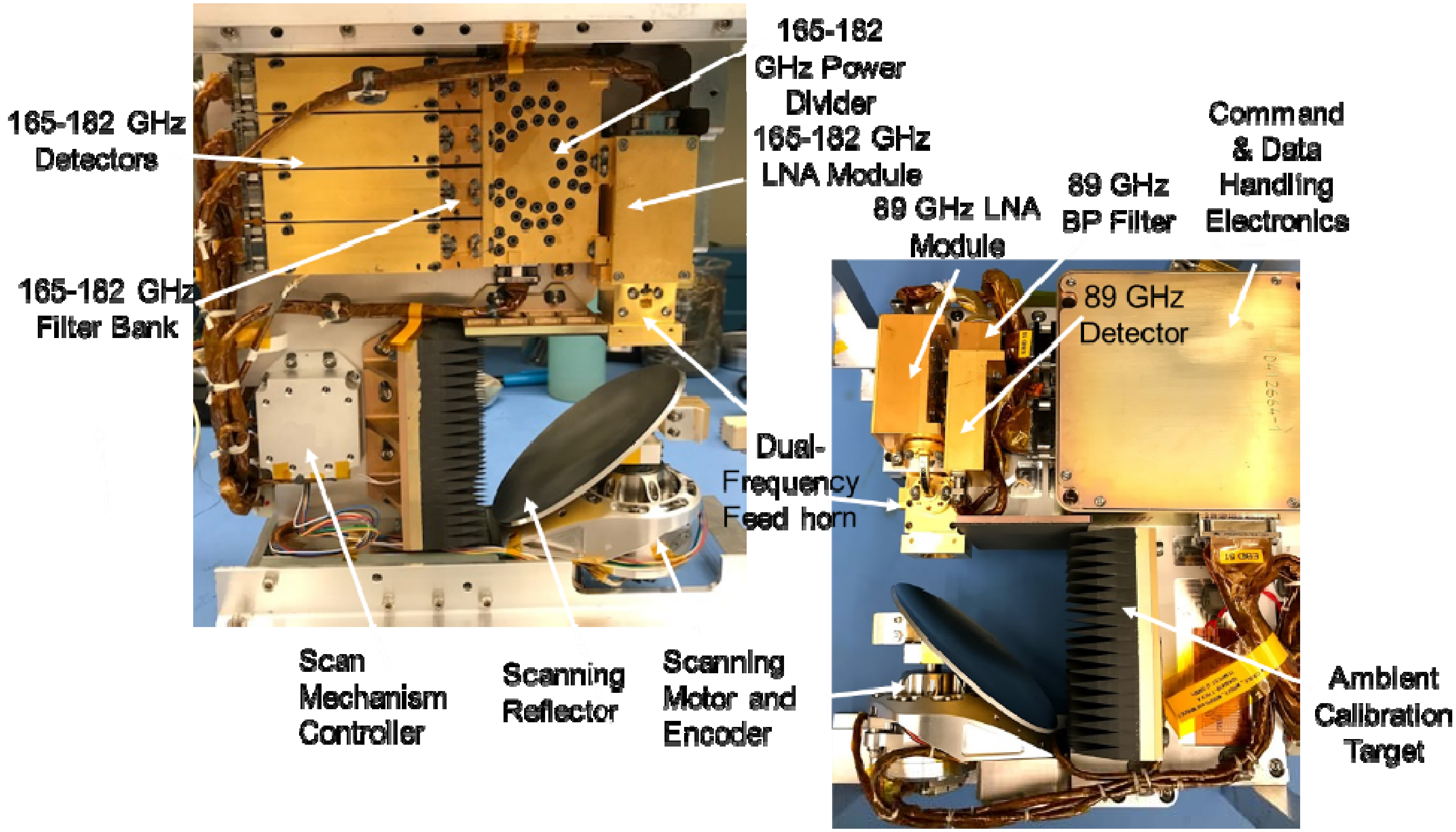


Also led to HRMR on Sentinel-6 Michael Freilich



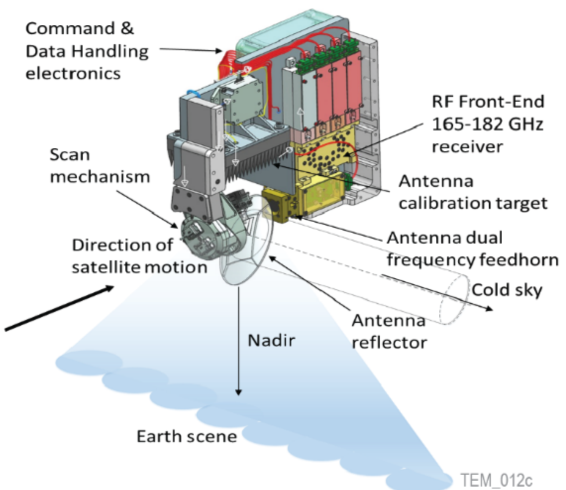
High-frequency Airborne Microwave and Millimeter-wave Radiometer (HAMMR IIP, NASA ESTO, CSU/JPL)

TEMPEST-D Flight Model Radiometer Instrument: Built and Integrated at JPL

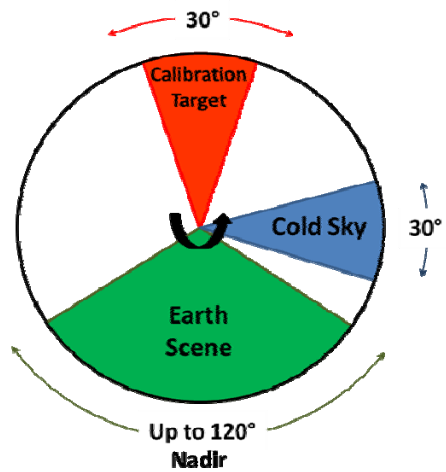


TEMPEST-D Instrument Performs On-Orbit, End-to-End Radiometric Calibration

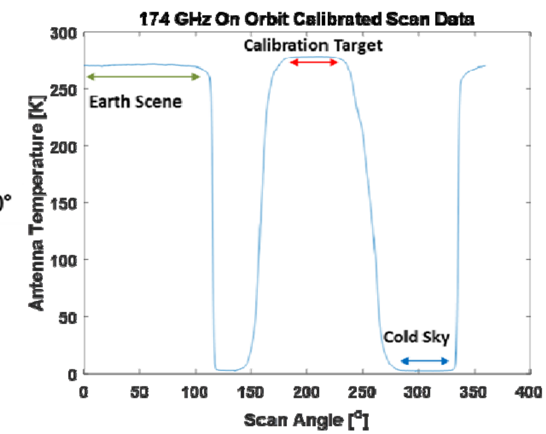
TEMPEST-D Instrument



Observing Profile

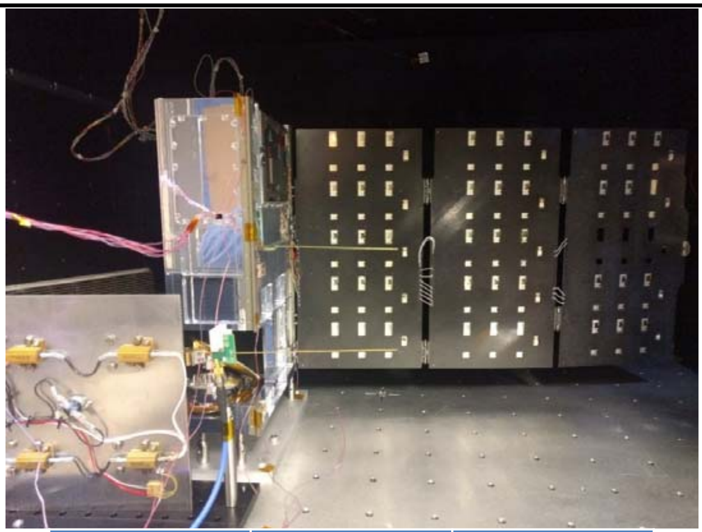


Brightness Temp. Time Series



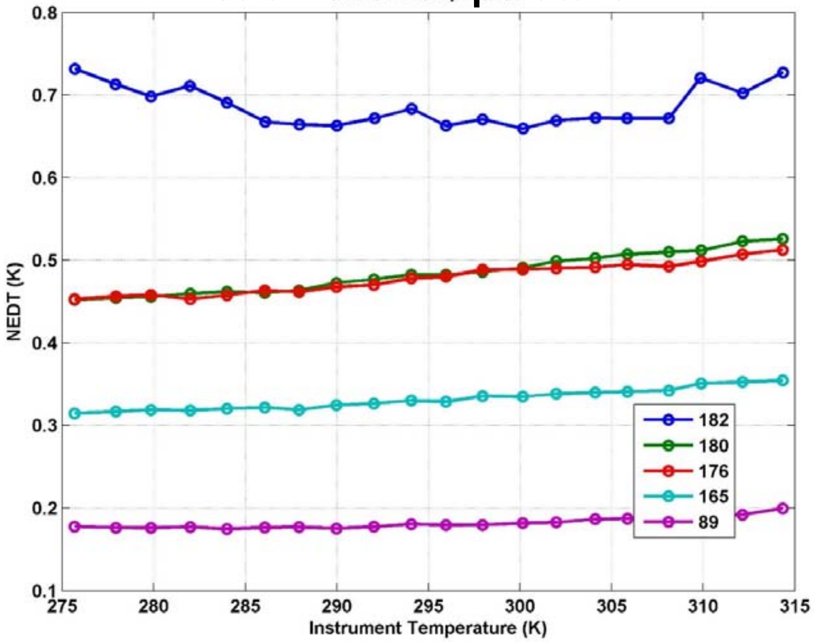
- Five-frequency millimeter-wave radiometer measures Earth scene up to ±60° nadir angles, for a 1550-km swath width from a initial orbit altitude of 400 km. Horizontal resolution ranges from 12.5 km at 181 GHz to 25 km at 87 GHz.
- TEMPEST-D performs two-point end-to-end calibration every 2 sec. by measuring cosmic microwave background at 2.73 K (“cold sky”) and ambient blackbody calibration target each revolution (scanning at 30 RPM).

TEMPEST-D Radiometric Instrument Performance: Pre-Launch and On-Orbit



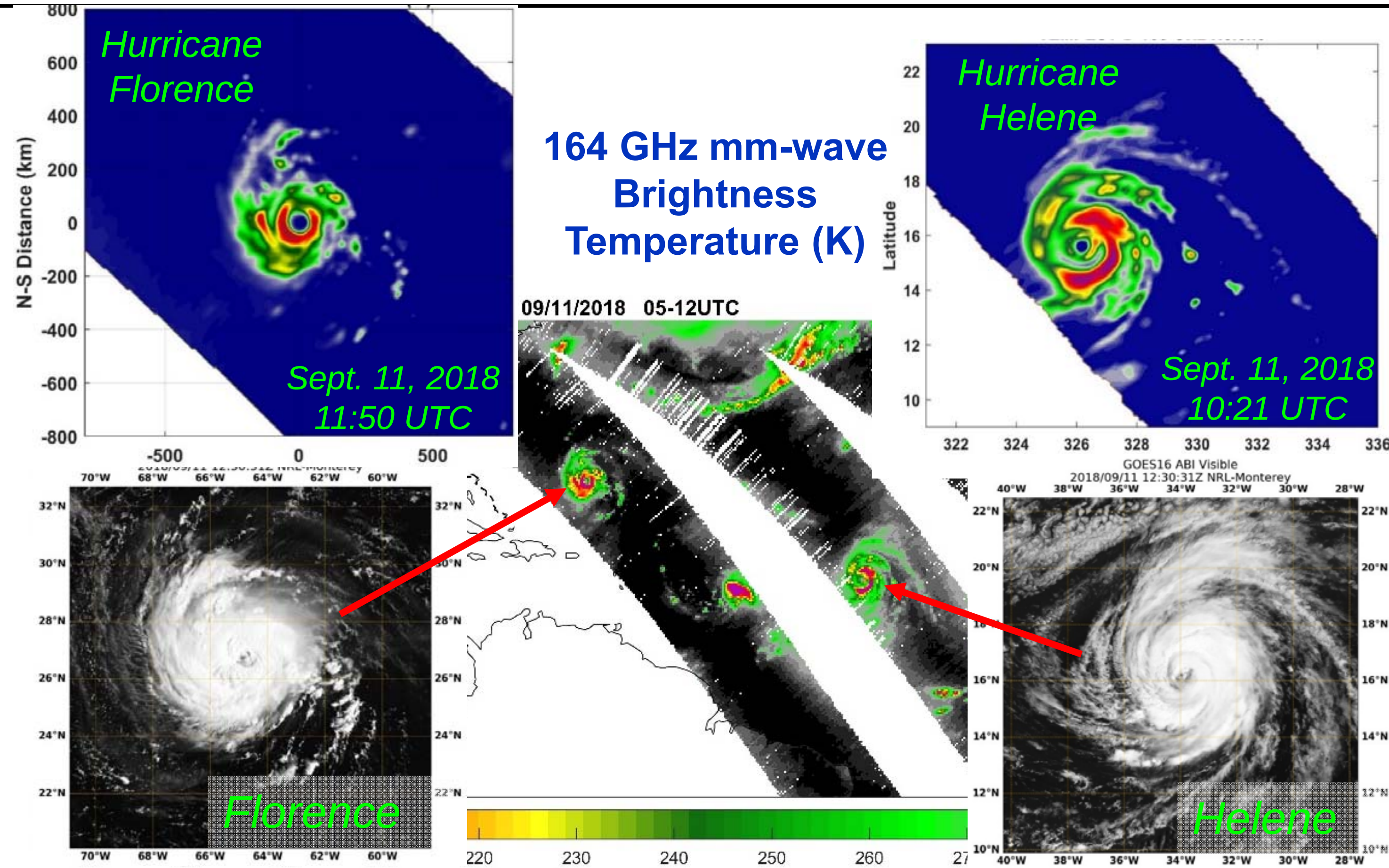
Frequency (GHz)	Pre-launch NEdT (K)	On-orbit NEdT (K)
87	**0.2**	**0.2**
164	**0.3**	**0.3**
174	**0.5**	**0.5**
178	**0.5**	**0.5**
181	**0.7**	**0.7**

Radiometric Resolution vs. Instrument Temperature

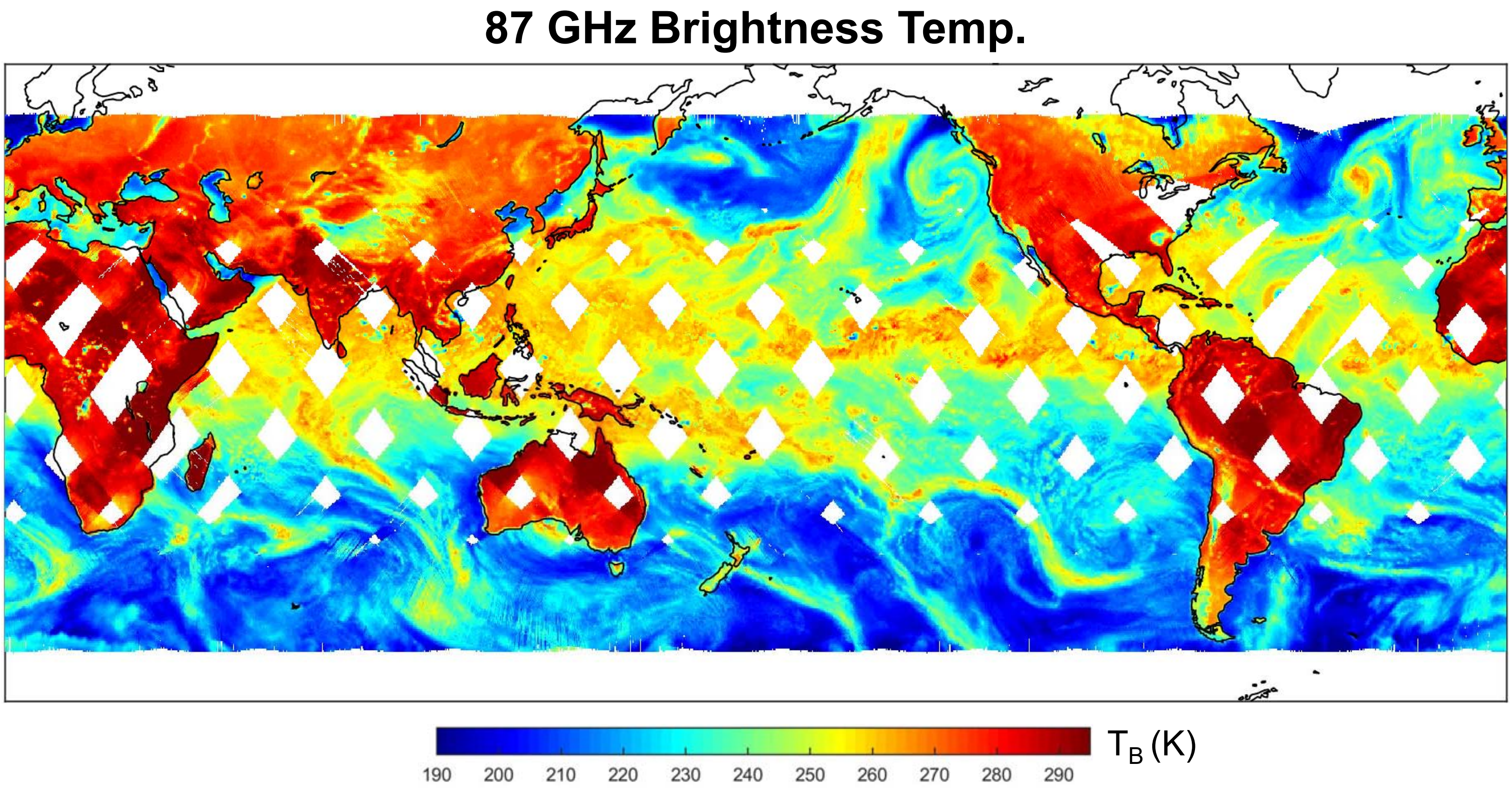


Measured radiometric resolution (NEdT) with **5-ms integration time,** both pre-launch and on-orbit, easily meet total noise requirements of 1.4 K for all five millimeter-wave radiometer channels.

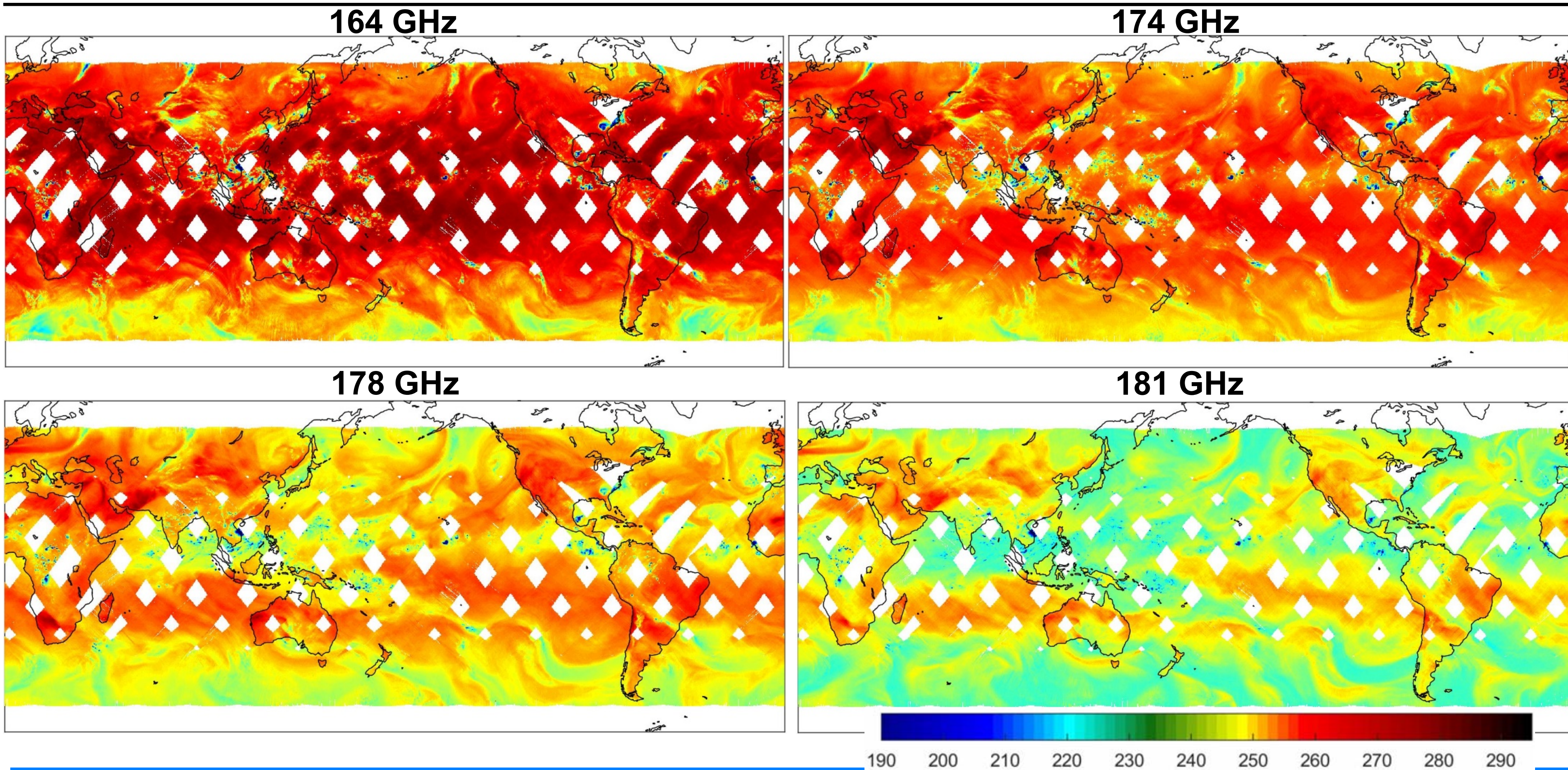
TEMPEST-D Mission: Hurricane Observations during First Full Orbits of Data: Sept. 11, 2018



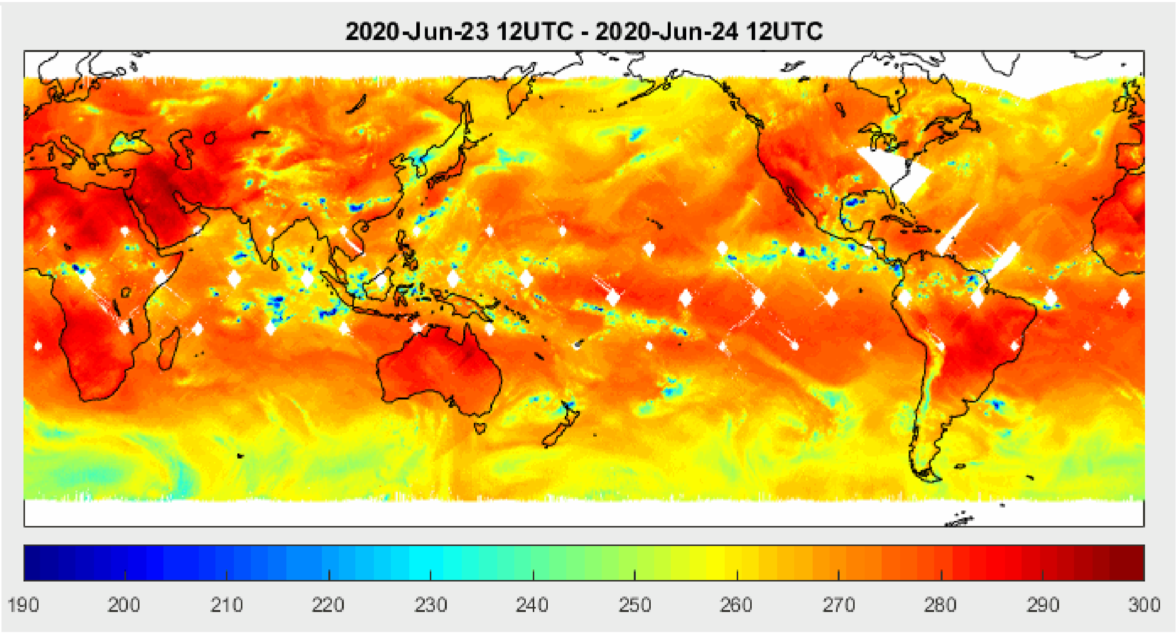
TEMPEST-D Brightness Temperatures at 87 GHz on September 17, 2020



TEMPEST-D Brightness Temperatures at 164-181 GHz on September 17, 2020



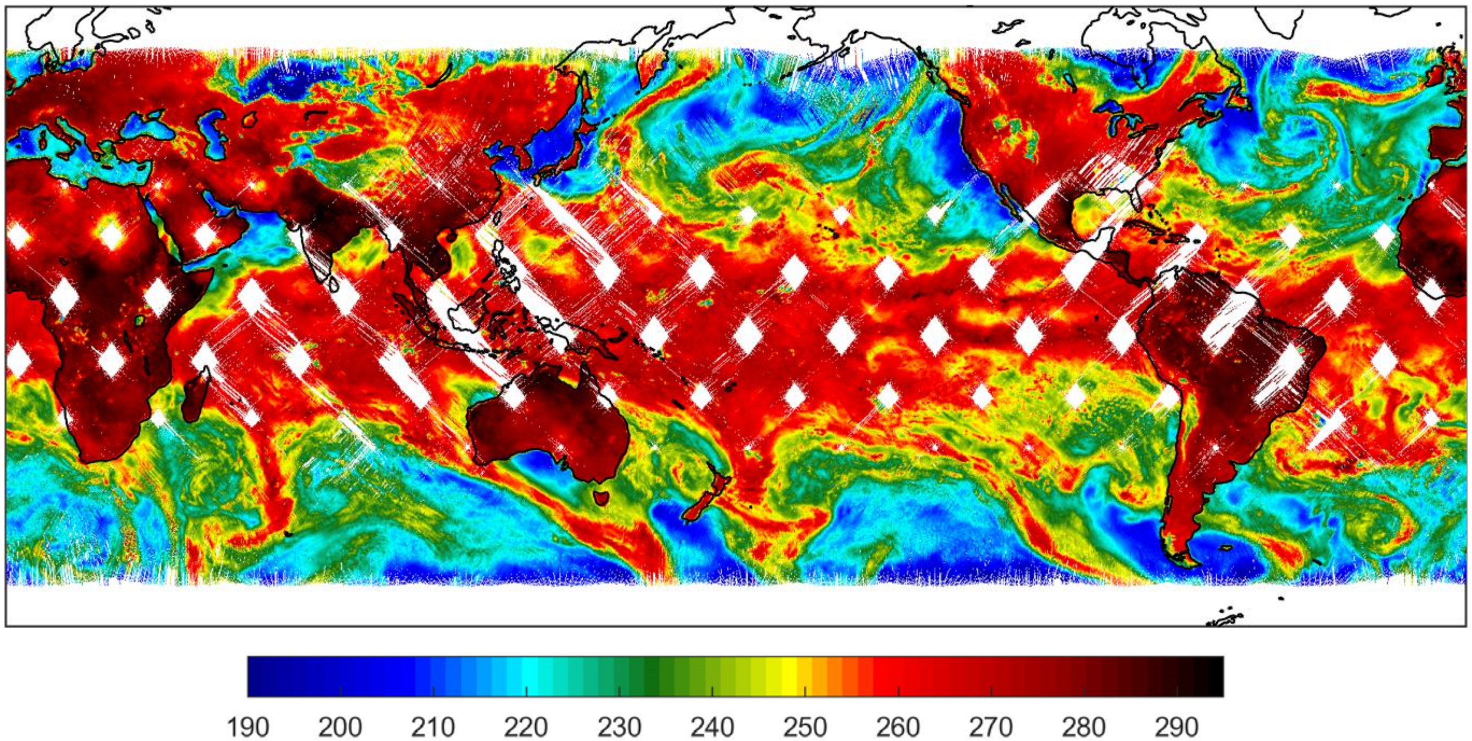
TEMPEST-D Brightness Temperatures at 174 GHz on June 23 to July 3, 2020



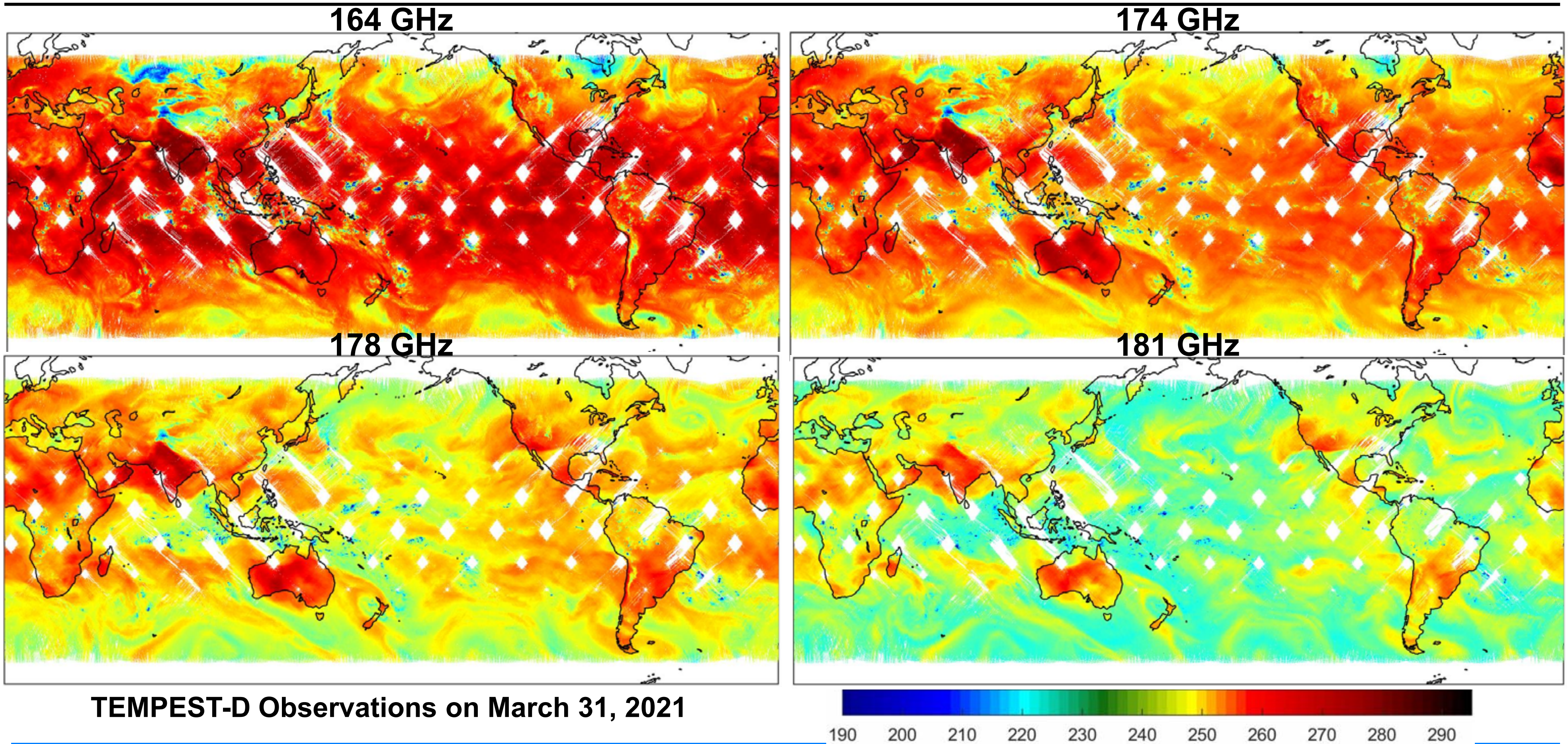
TEMPEST-D Venture Tech Mission: Global Atmospheric Observations for Nearly 3 Years on Orbit

- TEMPEST-D multi-channel mm-wave radiometer was in hibernation on orbit for 6 months due to downtime at NASA Wallops for repair of the UHF antenna system.
- These global Earth observations from the TEMPEST-D CubeSat were made only 9 hours after the instrument was turned on.
- TEMPEST-D instrument performance after 6 months of hibernation in space is the same as before.

TEMPEST-D 87 GHz Brightness Temperatures (K) Observed on March 31, 2021

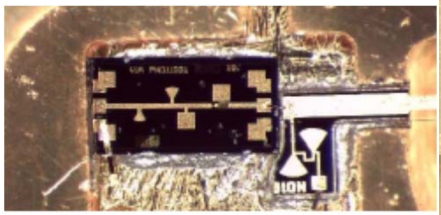


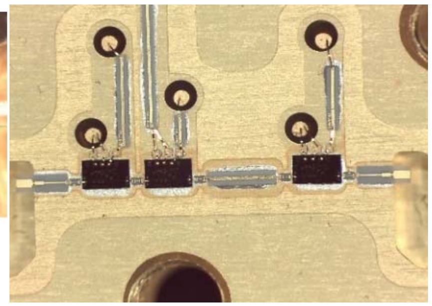
TEMPEST-D Venture Tech Mission: Global Atmospheric Observations for Nearly 3 Years on Orbit



TEMPEST-D Observations on March 31, 2021

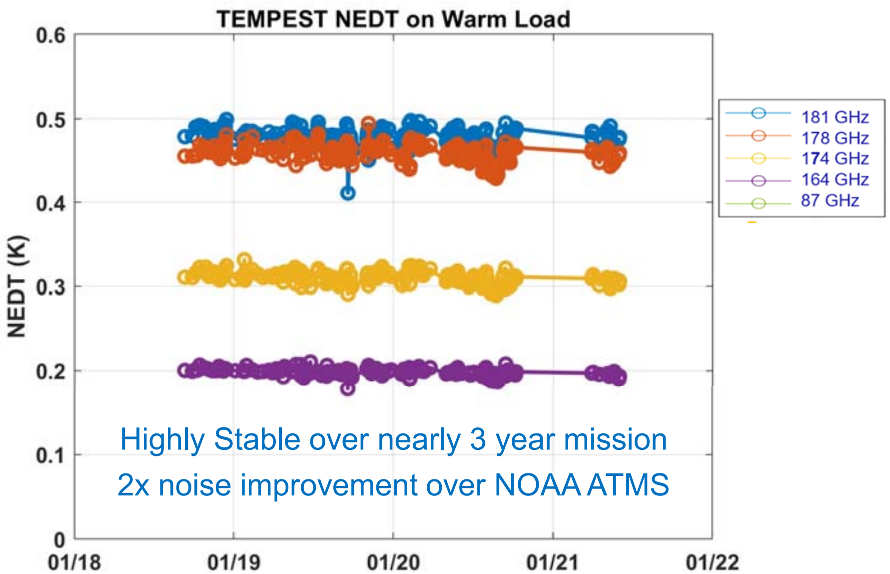
TEMPEST-D Mission: Well-Calibrated Atmospheric Science Data for Nearly 3 Years On Orbit





On-orbit demonstration of new InP HEMT Low Noise Amplifier Technology (NGC/JPL)

Padmanabhan et al., *TGRS*, 2021.

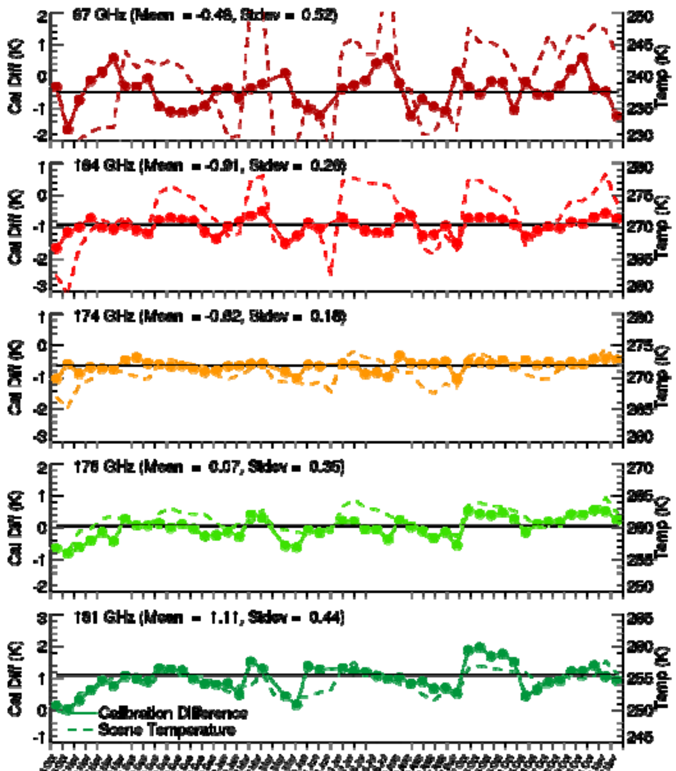


- On-orbit trending during extended mission reduces risk for future operational microwave sensors on CubeSats or SmallSats
- Radiometer accuracy, precision and stability all rock solid throughout nearly 3-year TEMPEST-D mission
- TEMPEST-D demonstrates improved receiver performance over the current generation of NOAA operational sensors

NEDT @ T_A = 300K 18 ms Integration Time & ATMS Bandwidths	TEMPEST-D[1]	NPP ATMS[2]
87 GHz	0.13 K	0.29 K
164 GHz	0.25 K	0.46 K
174 GHz	0.2 K	0.38 K
178 GHz	0.25 K	0.54 K
181 GHz	0.7 K	0.73 K

[1] Equivalent NEDT for ATMS bandwidth/integration time
[2] Kim, E., et al., *JGR*, 2014.

TEMPEST-D Sensor Cross-Calibration Over First 14 Months of Operations



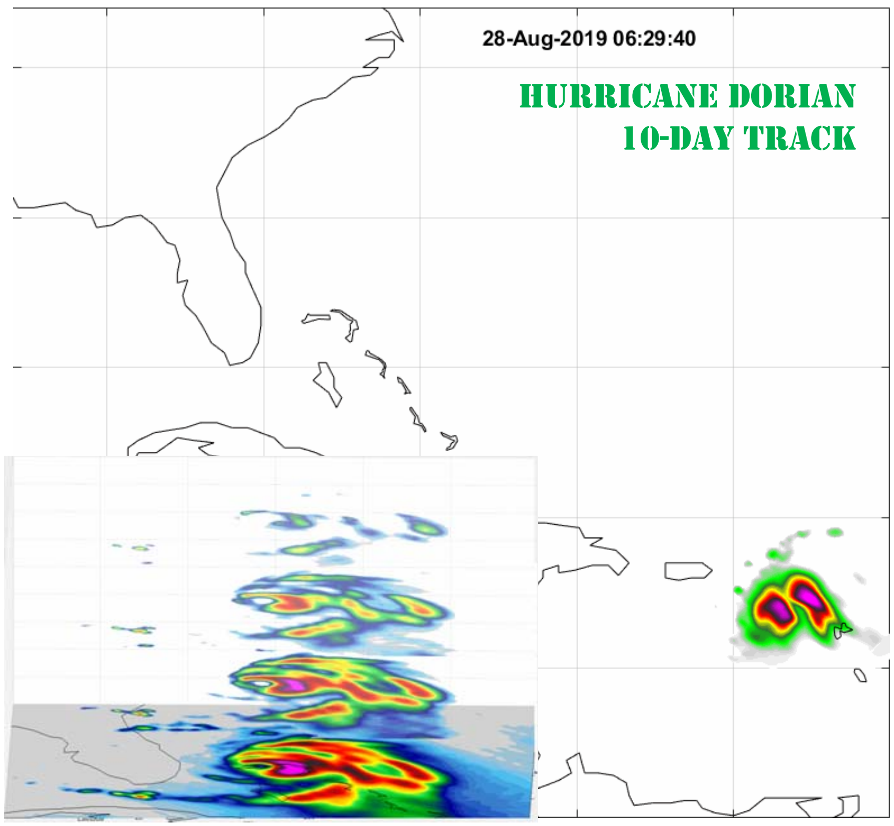
Mean calibration differences between TEMPEST-D and four reference sensors based on 50 days of data over a 13-month period. Dashed lines indicate corresponding mean scene brightness temperatures. From Berg et al., *IEEE TGRS*, 2021.

- Double difference technique developed for GPM used to validate TEMPEST-D data compared to GMI and 4 MHS sensors on NOAA and EUMETSAT satellites
- TEMPEST absolute calibration accuracy within 1 K of reference sensors, well within 4 K accuracy requirement.
- TEMPEST calibration precision (std. dev.) within 0.6 K of reference sensors, well within 2 K precision requirement.
- **Results demonstrate that TEMPEST-D is a very well calibrated and stable radiometer with very low noise, rivaling that of much larger operational instruments.**

Calibration Differences in Kelvin (Reference – TEMPEST-D)

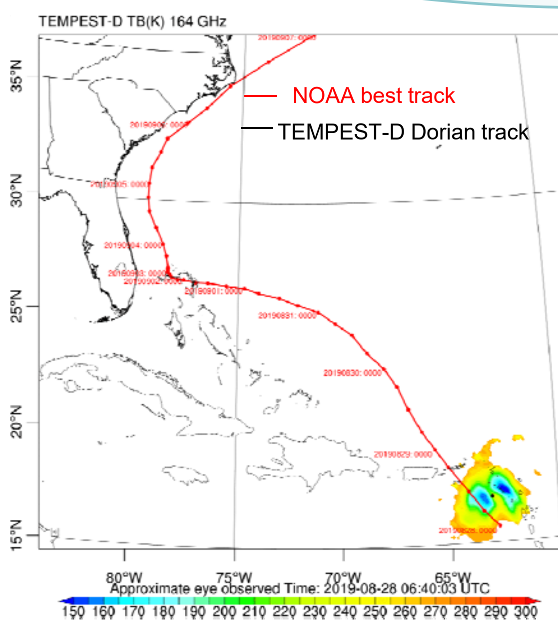
Reference Sensor	87 GHz	164 GHz	174 GHz	178 GHz	181 GHz
GPM GMI	-0.58	-0.40	-0.55	0.37	N/A
METOP-A MHS	-0.39	-0.92	-0.36	0.13	1.42
METOP-B MHS	-0.37	-1.25	-0.81	-0.29	1.21
METOP-C MHS	-0.35	-1.34	-0.68	-0.30	1.14
NOAA-19 MHS	-0.43	-1.89	-0.77	-0.34	0.34
Mean (MHS only)	-0.39	-1.43	-0.69	-0.23	0.93
Mean (MHS + GMI)	**-0.48**	**-0.91**	**-0.62**	**0.07**	**0.93**
Standard Deviation	**0.12**	**0.51**	**0.21**	**0.39**	**0.41**

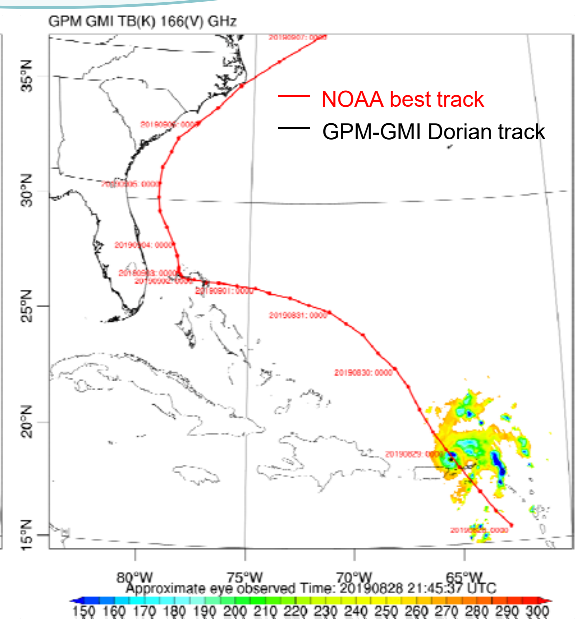
TEMPEST-D Mission: Observations of Hurricanes, Tropical Cyclones and Convective Systems for 3 Years



Calibrated TEMPEST-D data are publicly available!

https://tempest.colostate.edu/data





Public Distribution of TEMPEST-D Data

TEMPEST-D calibrated data are publicly available (after user registration) at https://tempest.colostate.edu/data. Users from 57 institutions in 13 countries on 5 continents have downloaded TEMPEST-D calibrated data, as listed below.

Institution	Country
Aerospace Corporation	USA
Aerospace Info Research Institute	China
Atmospheric & Environmental Research	USA
Andrew Seidl	USA
Bergen Technical Schools	USA
Carr Astro	USA
CFA Melbourne	Australia
CGM	USA
Chengdu University	China
CNES	France
CNR Institute of Atmos. Sci. & Climate	Italy
Colorado State University	USA
Deep Inc.	USA
Dominion Energy	USA
Georgetown University	USA
Global Science and Technology	USA
Hancock Whitney Bank	USA
Harp Technologies Ltd.	Finland
Indian Institute of Technology Bombay	India

Institution	Country
Indian Institute of Tropical Meteorology	India
ISRO Satellite Centre (ISAC)	India
Japan Meteorological Agency	Japan
Johns Hopkins University	USA
Karlsruhe Institute of Technology	Germany
Kellogg Brown & Root	USA
Manheim Township School District	USA
Massachusetts Institute of Technology	USA
Météo-France	France
Mississippi State University	USA
Morgan State University	USA
NASA/Caltech Jet Propulsion Laboratory	USA
NASA/Earth Science Technology Office	USA
NASA/Goddard Space Flight Center	USA
NASA/Langley Space Flight Center	USA
NASA/Marshall Space Flight Center	USA
Nanjing University/NUIST	China
National Meteorological Service	Argentina
National Space Science Center	China

Institution	Country
National Technical University of Athens	Greece
Naval Research Laboratory	USA
NOAA CIRA	USA
NOAA Headquarters	USA
NOAA Hurricane Research Division	USA
NOAA/NESDIS/STAR	USA
Olin College	USA
Orbital Micro Systems	USA
Politecnico di Milano	Italy
Texas A&M University	USA
Turkish Meteorological Service	Turkey
UCAR	USA
University of California Los Angeles	USA
University of Colorado	USA
University of Leicester	UK
University of Maryland	USA
University of Miami	USA
University of Oklahoma	USA
Virginia Tech	USA

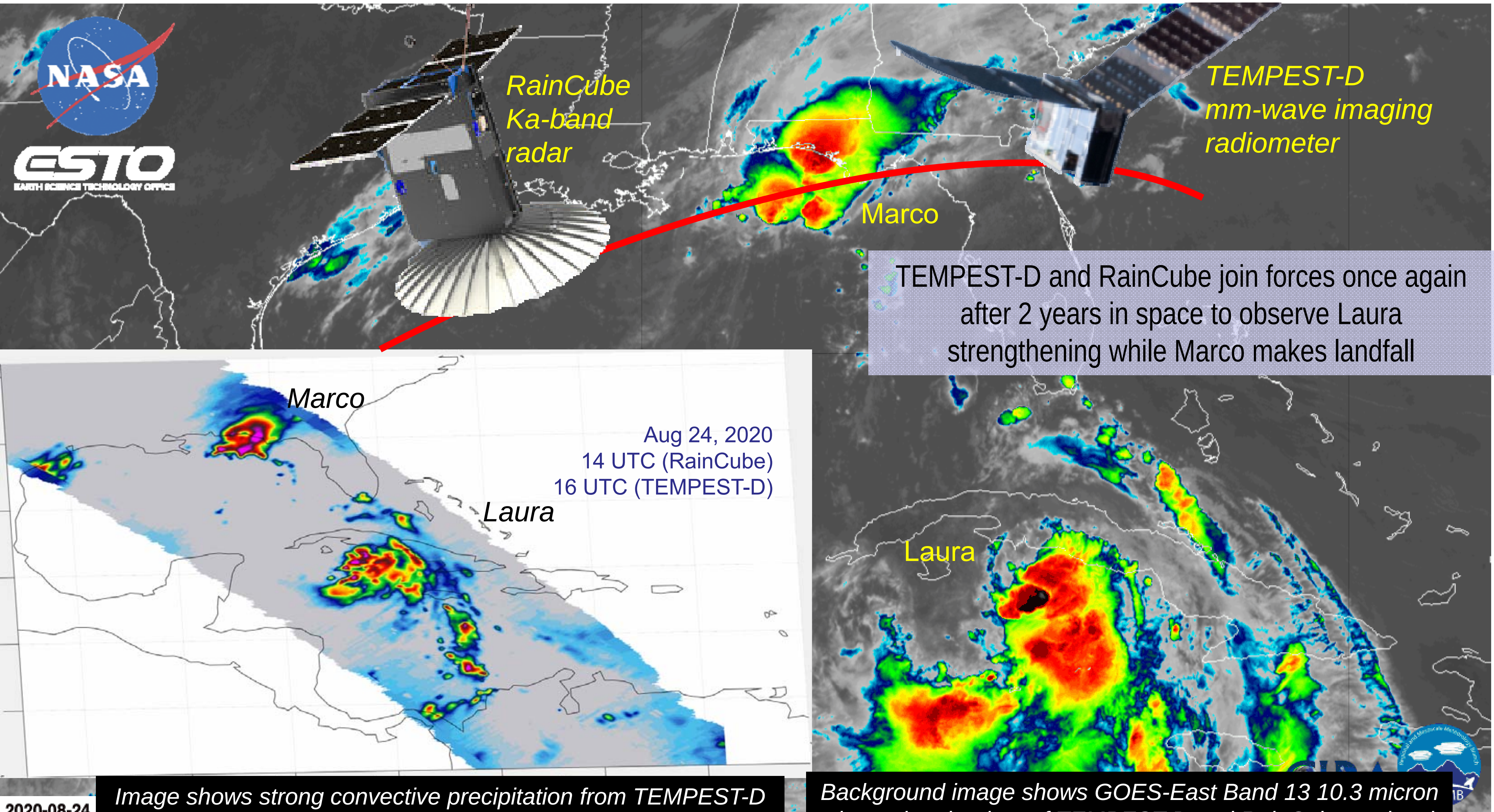
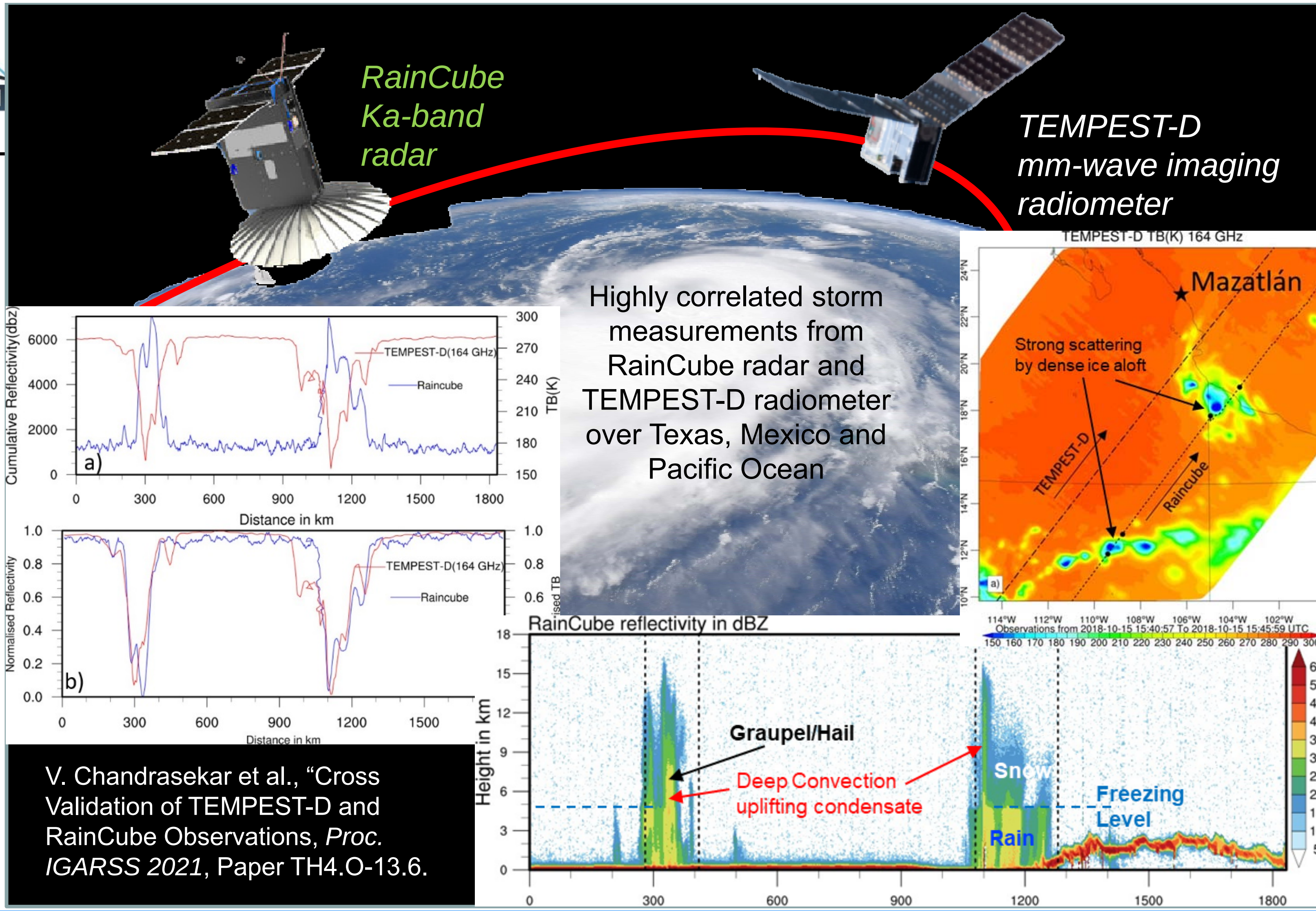


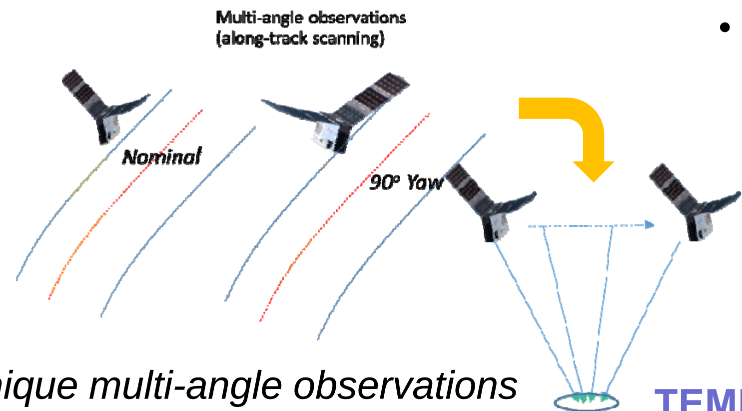
Image shows strong convective precipitation from TEMPEST-D combined with vertical precipitation structure from RainCube

Background image shows GOES-East Band 13 10.3 micron channel at the time of TEMPEST-D and RainCube retrieval

Correlation coefficient between TEMPEST-D TB and RainCube Reflectivity: > 0.90

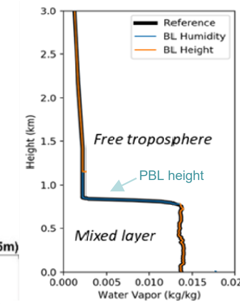


Unique Observations Demonstrated by TEMPEST-D

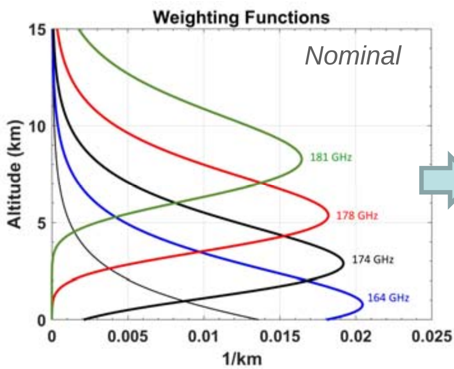


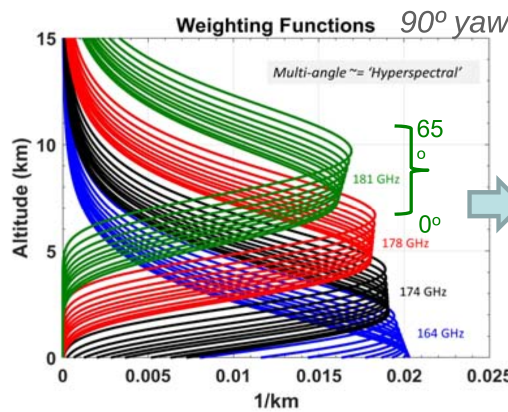
Unique multi-angle observations accomplished by flying TEMPEST-D yawed by 90º

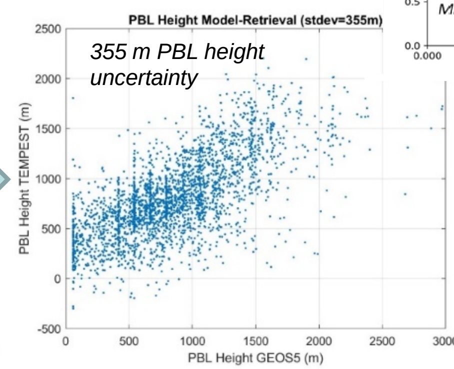
- Multi-angle sounding improves vertical sampling through troposphere, analogous to a "hyperspectral" sounder
  - A promising application is improving measurement capability in planetary boundary layer (PBL)
  - Also enables uncertainty quantification for time resolved measurement concepts



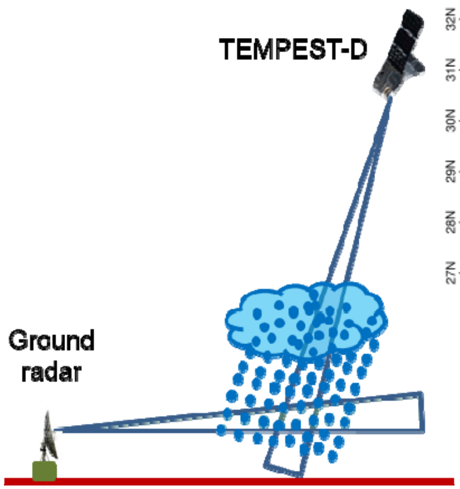
TEMPEST-D allows testing these new concepts with satellite data for the first time

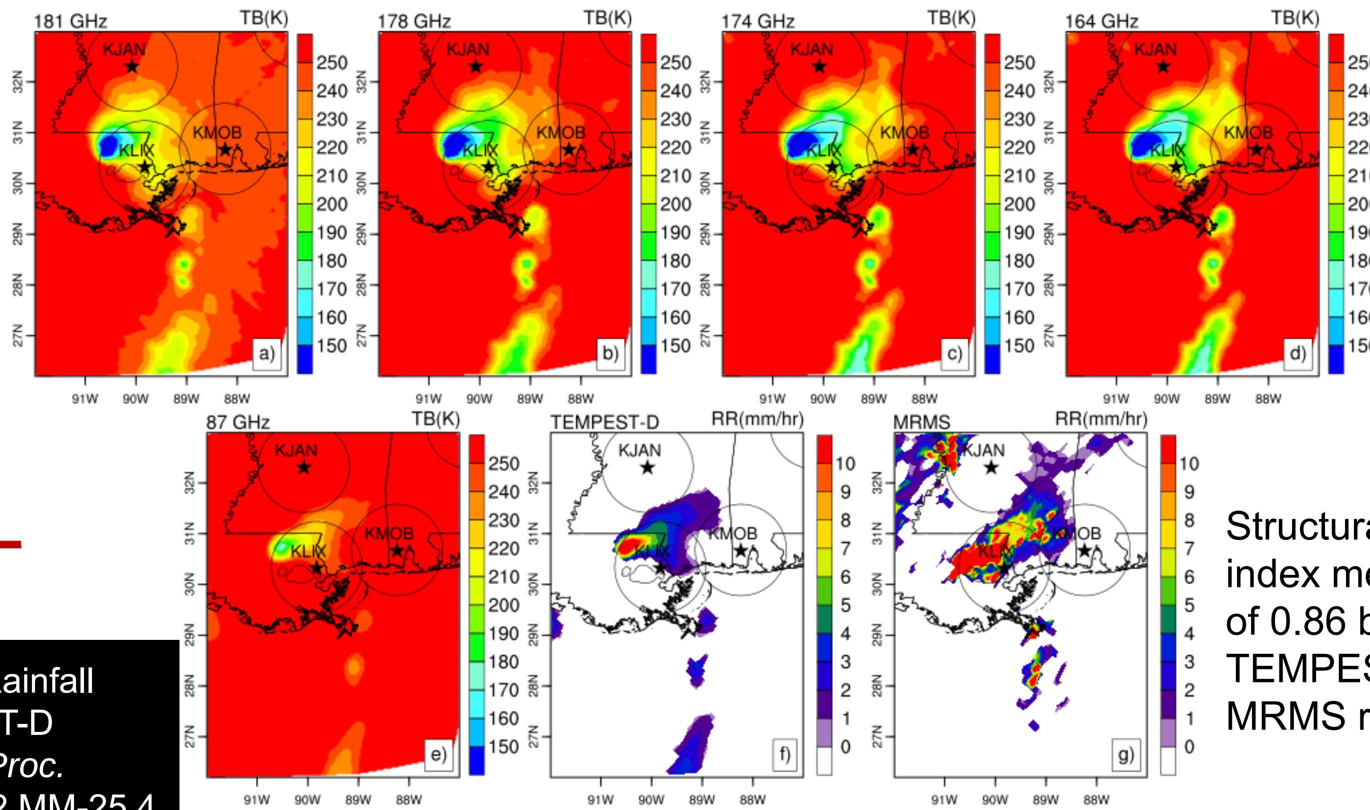






TEMPEST-D Derived Rainfall Estimates over Tropical Storm Olga Landfall near New Orleans, Oct. 26, 2019





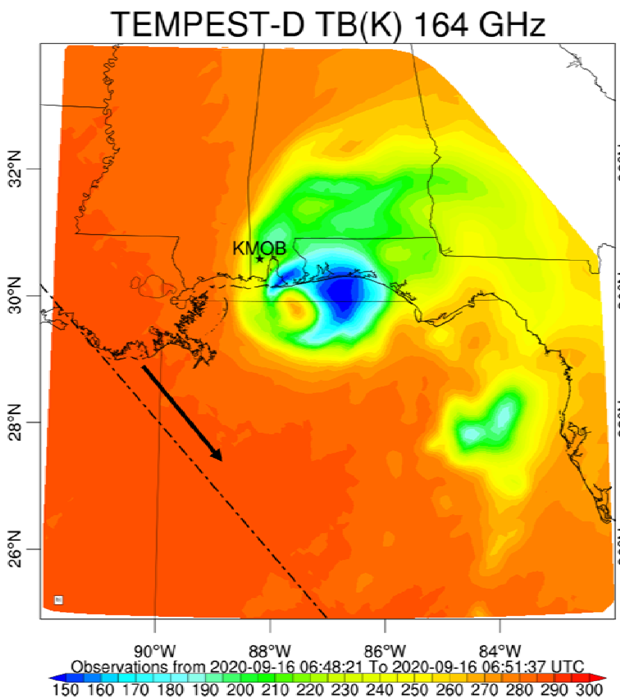
(a to e) TEMPEST-D TB data, (f) TEMPEST-D rain rate, and (g) NWS MRMS rain rate.

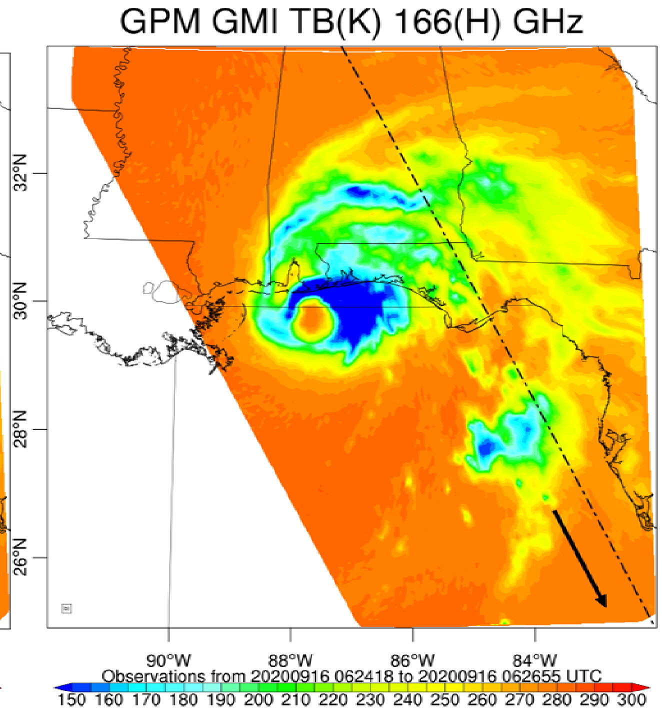
Structural similarity index measure (SSIM) of 0.86 between TEMPEST-D and MRMS rainfall

V. Chandrasekar et al., “Rainfall Estimation from TEMPEST-D CubeSat Observations,” *Proc. IGARSS 2021*, Paper TH2.MM-25.4

Comparison of TEMPEST-D and GPM-GMI Observations over Hurricane Sally

September 16, 2020 at 06:50 UTC (TEMPEST-D)

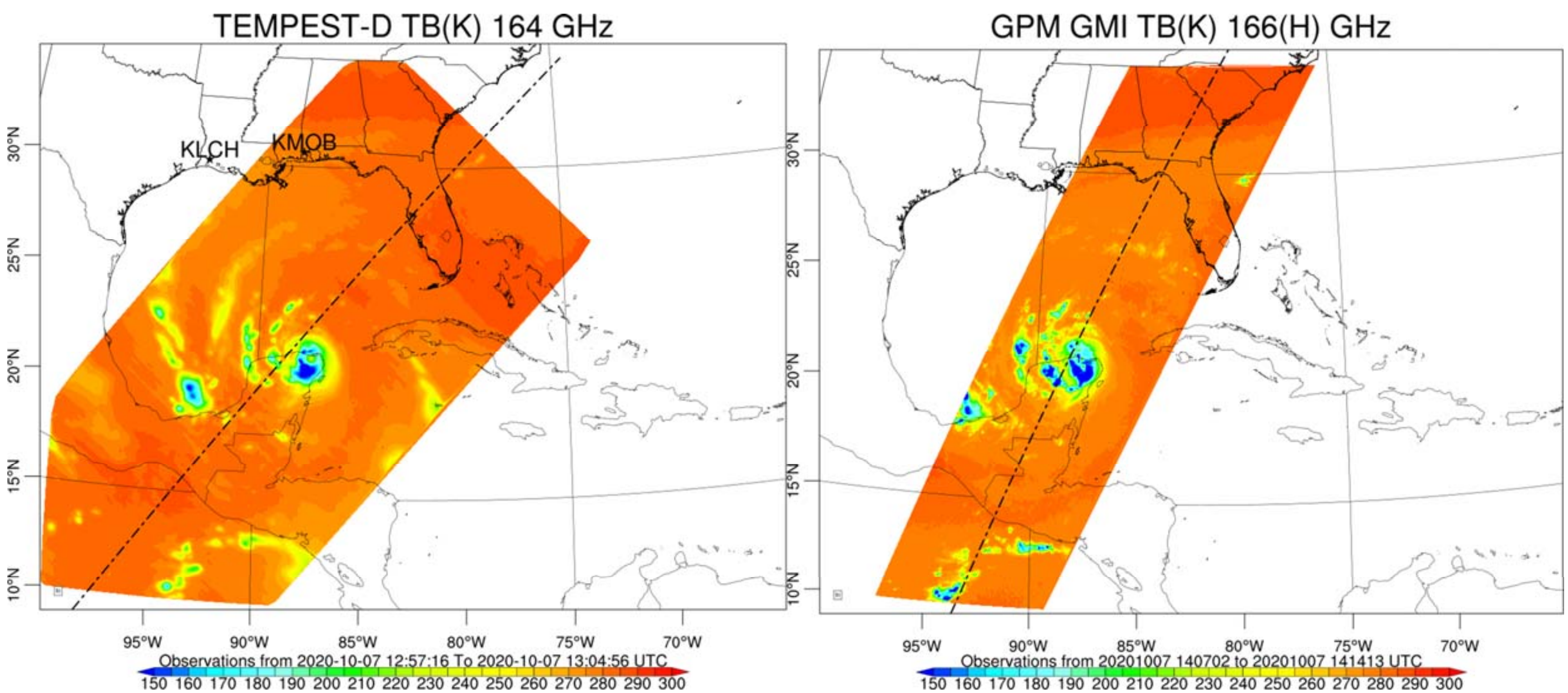




- TEMPEST-D observed Hurricane Sally **25 minutes after** GPM.

Comparison of TEMPEST-D and GPM-GMI Observations over Hurricane Delta

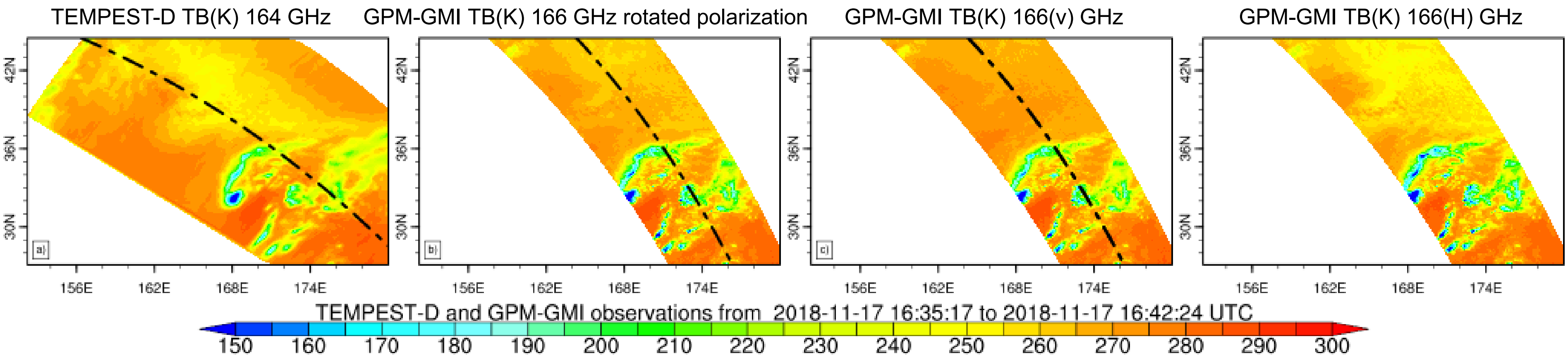
October 7, 2020 at 13:00 UTC (TEMPEST-D)



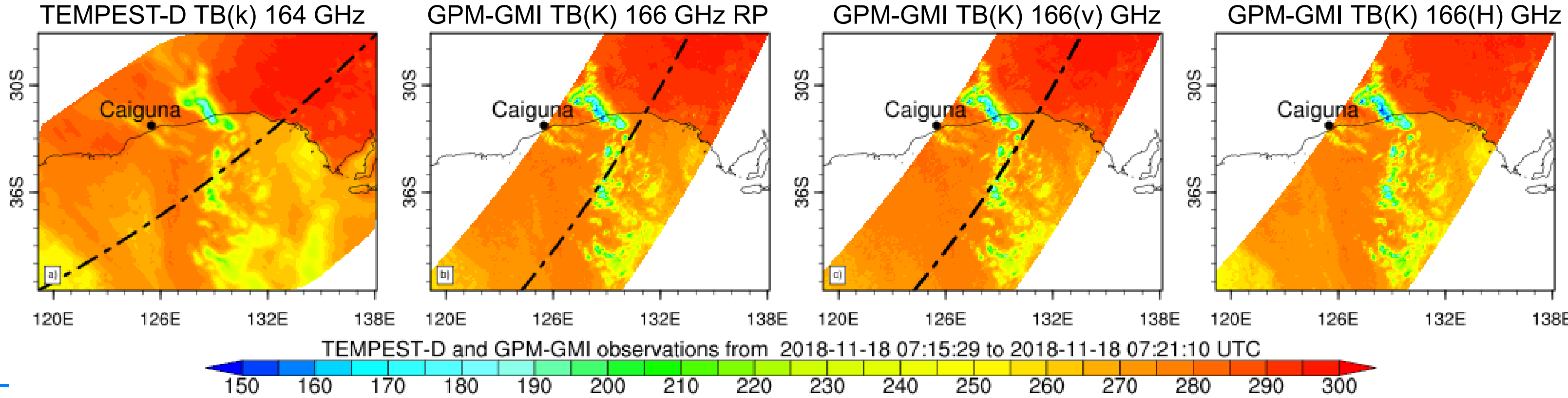
- TEMPEST-D observed Hurricane Delta **70 minutes before** GPM.

Comparison of Near-Simultaneous Measurements of Precipitation by TEMPEST-D and GPM-GMI

TEMPEST-D and GPM-GMI Precipitation Observations over the North Pacific Ocean on November 17, 2018

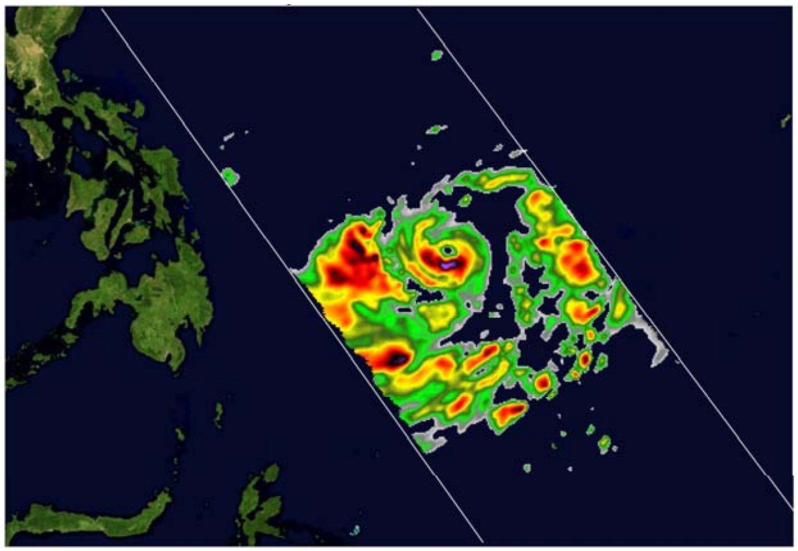


TEMPEST-D and GPM-GMI Precipitation Observations over The Great Australian Bight on November 18, 2018



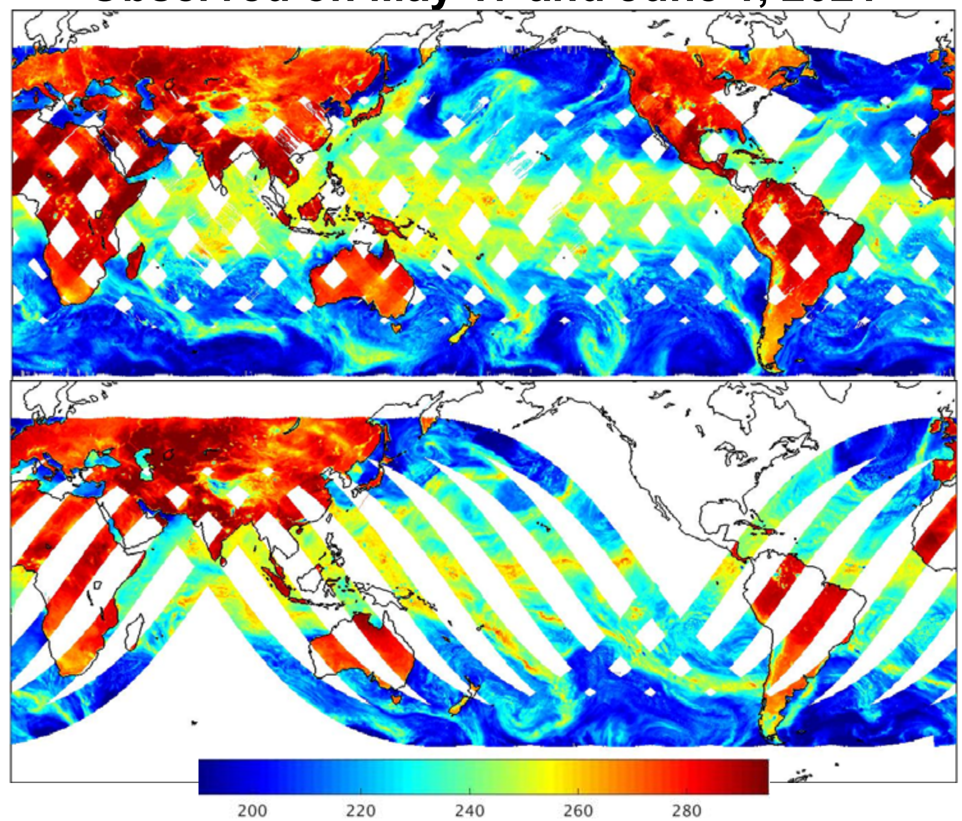
TEMPEST-D Observations after Nearly Three Years on Orbit

TEMPEST-D Observations of Typhoon Surigae on April 16, 2021

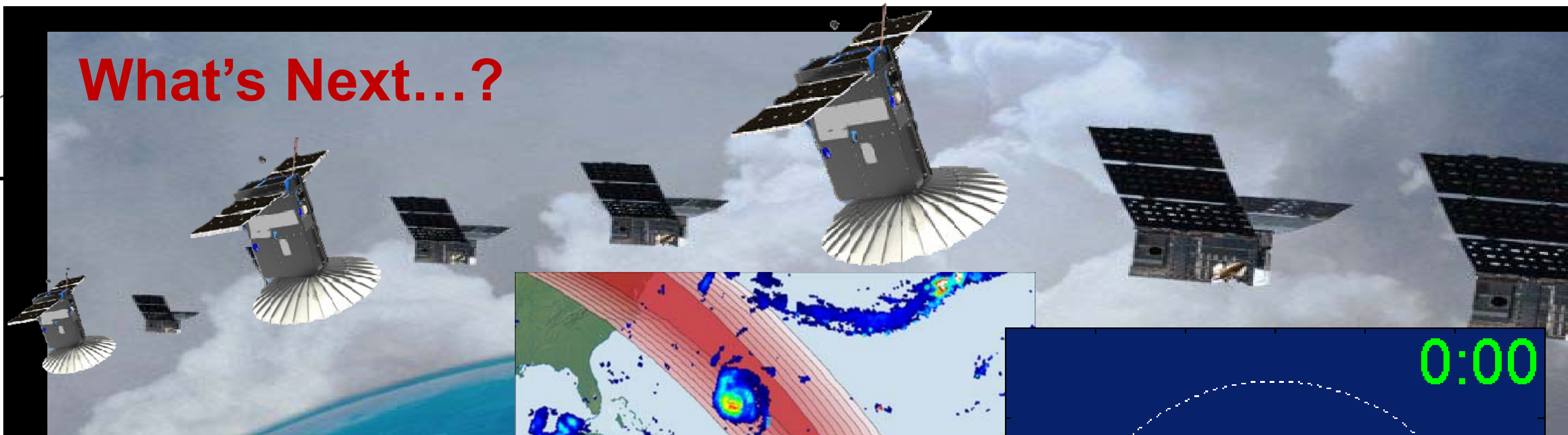


TEMPEST-D remote-sensing observations of Typhoon Surigae, strongest N. Hemisphere tropical cyclone (TC) to occur before May. TEMPEST-D observed precipitation bands around the eye east of the Philippines, with strongest areas of precipitation shown in yellow and red.

TEMPEST-D 87 GHz Brightness Temperatures (K) Observed on May 17 and June 1, 2021

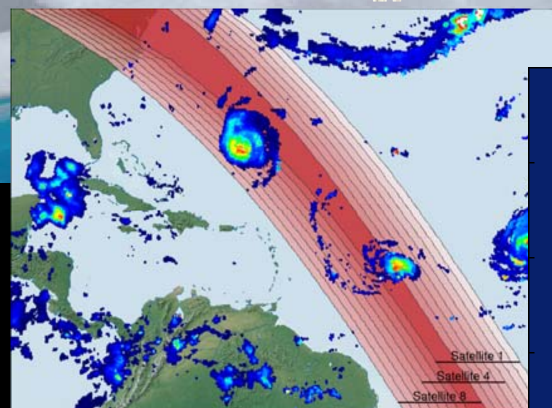


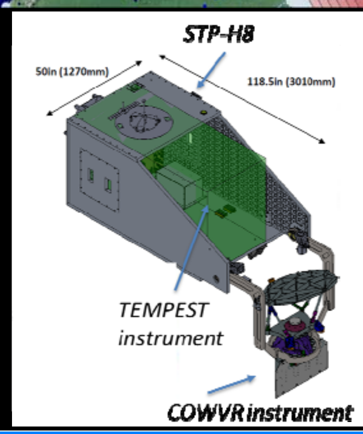
What's Next…?

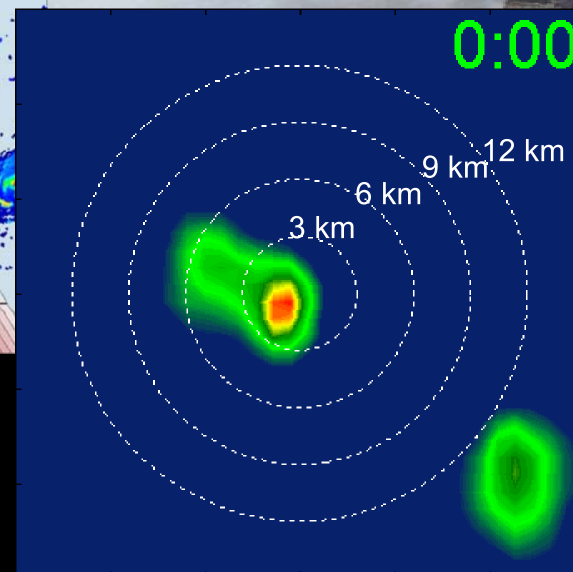


TEMPEST-D mission success enables new science mission concepts with heterogeneous sensors

- Constellations for rapid revisit time
- Combined complementary measurements with heterogeneous sensors
- Available for future EV-M and EV-I opportunities

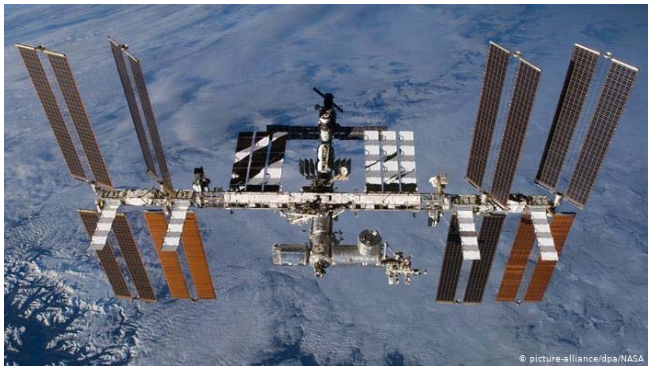


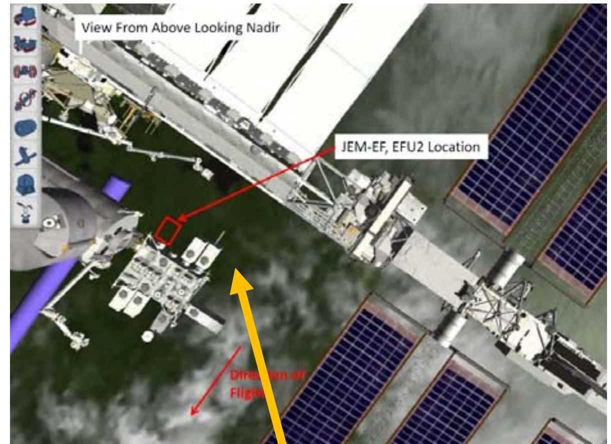




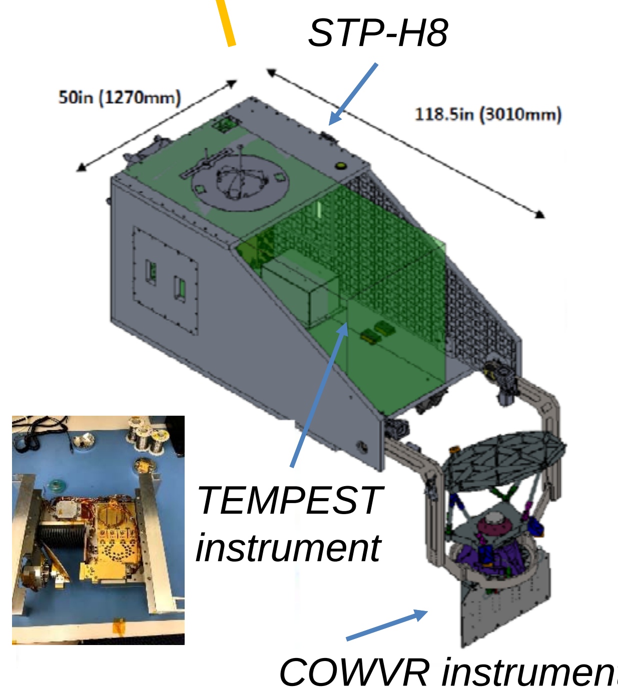
TEMPEST-D2 will be deployed on ISS for 3 years in Dec. 2021, enabled by the success of the TEMPEST-D CubeSat mission!

STP-H8 Mission

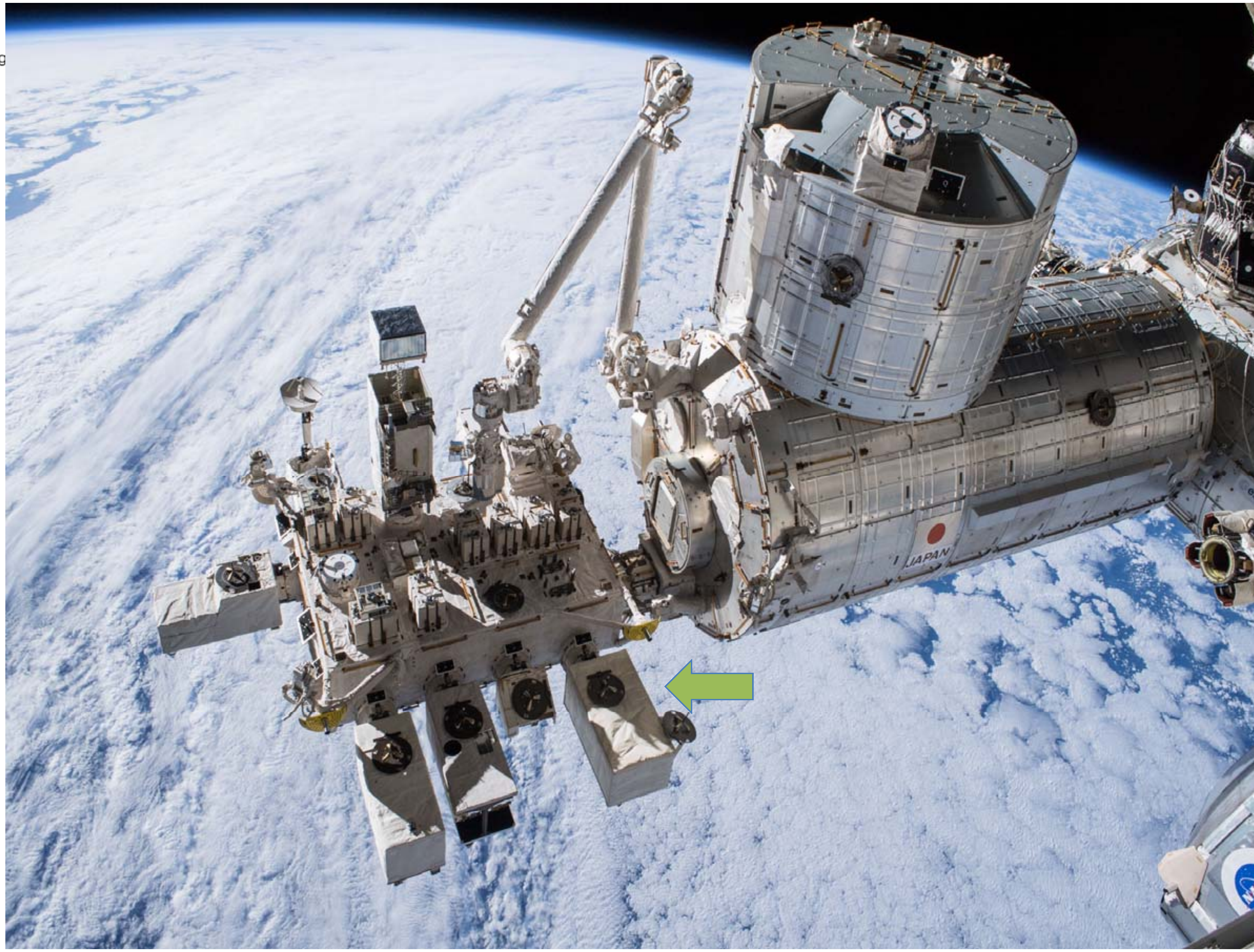




- **Space Force mission to demonstrate new low-cost microwave sensor technologies for weather**
  - **COWVR: measures ocean surface wind vector**
  - **NASA provided TEMPEST-D2: measures water vapor, precipitation**
- **Deployment to ISS (JEM-EF module)**
- **DoD Space Test Program--Houston team is performing Mission Manager role**
- **Manifested for launch on December 21, 2021**
- **Operations: 3 years**
- **Science data processing at JPL**
- **Data will be distributed via PO.DAAC**



Jet Propulsion Laboratory
California Institute of Technolog

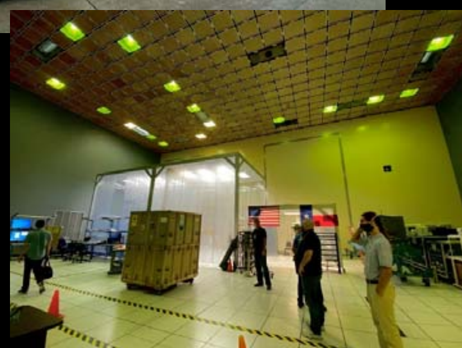


COWVR & TEMPEST-D2 on ISS Products

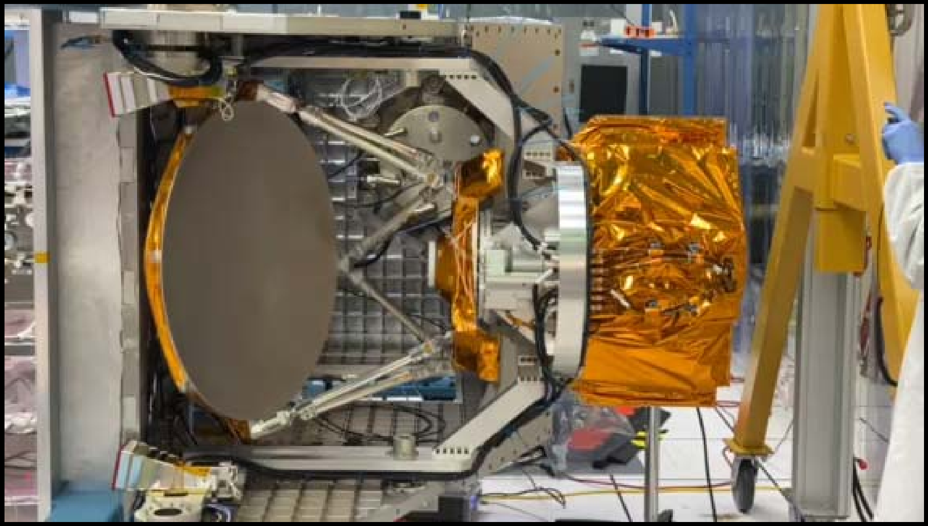
Variable	Spatial Resolution	Expected Uncertainty			Data producer
Wind vector	30 km	WS<6	6<WS<12	WS>12	JPL
		38°	16°	8°	
		1m/s	1m/s	1m/s	
Precipitable Water Vapor	30 km	<0.3 cm			JPL
Cloud Liquid Water	30 km	0.05 mm			JPL
Precipitation Rate	15 km				CSU/JPL[1]
Ice Water Path	15 km	<50% for IWP>200g/m^2			CSU[1]
Water Vapor Profile	15 km	15%			CSU[1]
Brightness Temperature	13-30 km	< 0.3K			JPL

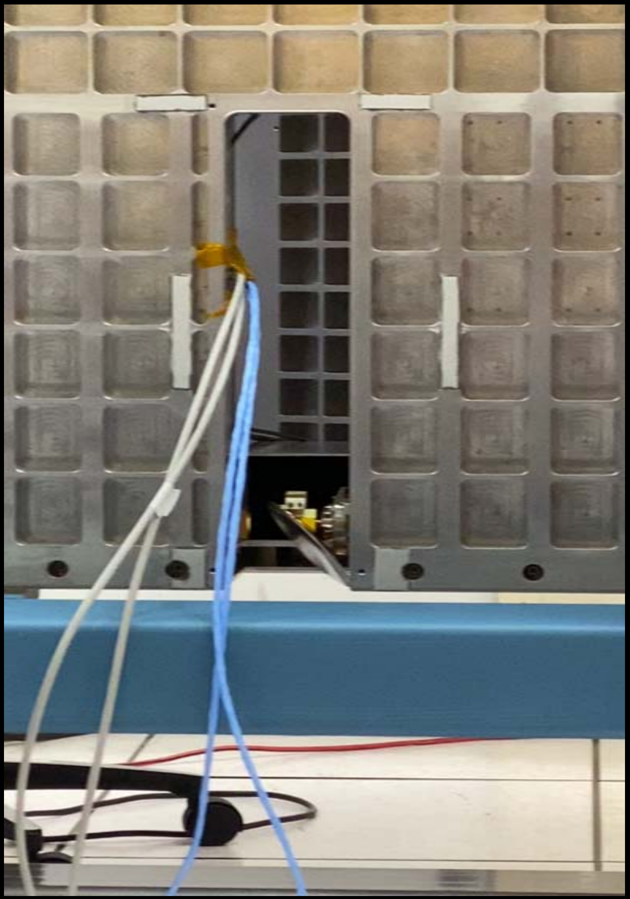
[1]NASA funded development



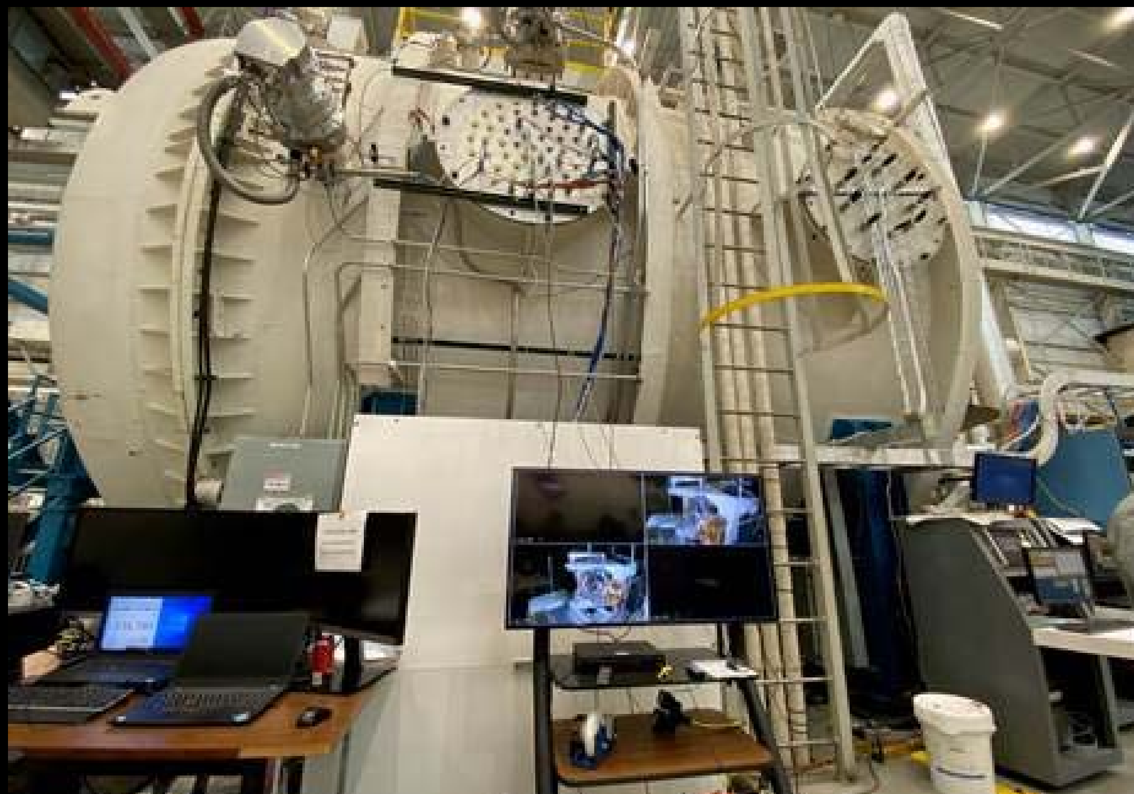



- COWVR successfully delivered to NASA Johnson Space Center on July 9, 2020 for integration with STP-H8
- Post-ship performance and functional testing nominal

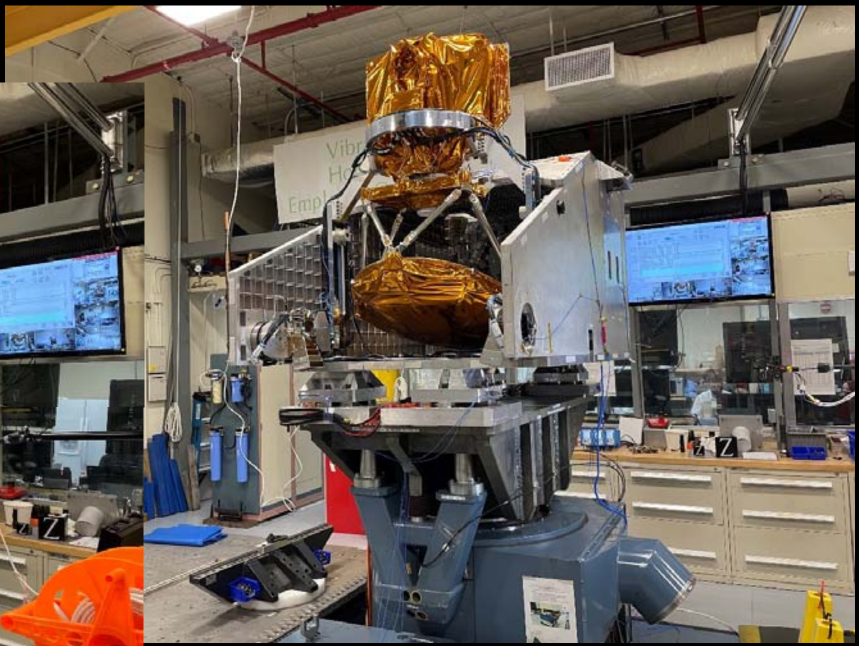




Electrical and Mechanical Integration in May 2021



Thermal Vacuum
Testing in July 2021
at MSFC

Vibration Testing in
August 2021 at KSC

Next Steps: COWVR and TEMPEST-D2 on ISS

- Manifested for launch on SpaceX CRS-24 on Dec. 21, 2021 at Kennedy Space Center
  - Once on station, STP-H8 will be moved by robotic arm to JEM-EF module within a few days

- Check-out period after launch to methodically verify sensor health and validate processing software and data interfaces

NEWS | November 5, 2021

NASA Selects New Mission to Study Storms, Impacts on Climate Models

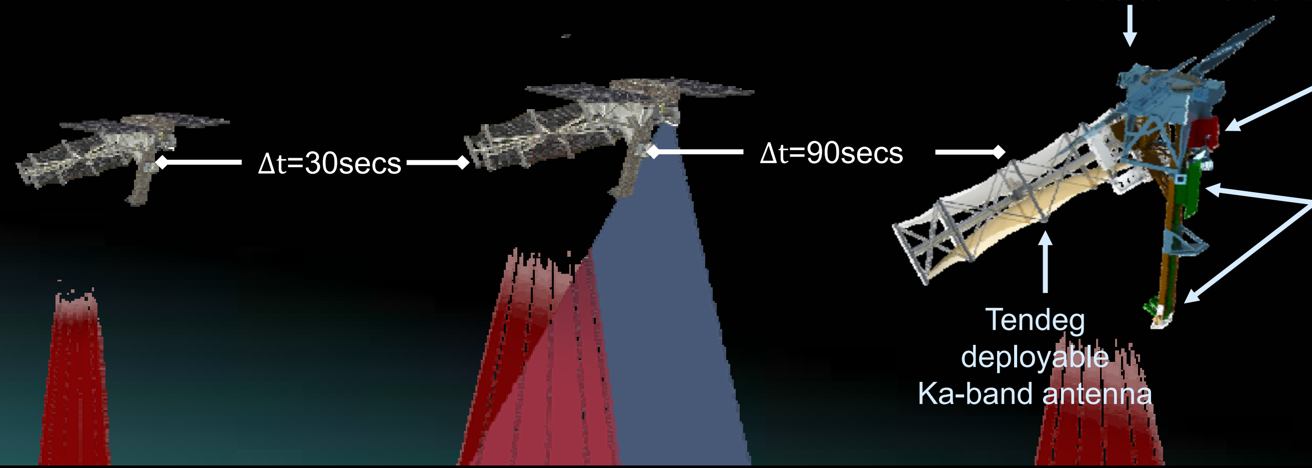
Towering cumulonimbus thunderstorm clouds are seen in this photo taken Aug. 15, 2014, looking east toward the Atlantic Ocean from the Space Launch Complex 37 area at Cape Canaveral Air Force Station (now Cape Canaveral Space Force Station) in Florida. NASA has selected a new Earth science mission called Investigation of Convective Updrafts (INCUS) that will study the behavior of tropical storms and thunderstorms, including their impacts on weather and climate models. Credit: NASA/Jim Grossmann

In Brief:

Called INCUS, it aims to directly address why convective storms, heavy precipitation, and clouds occur exactly when and where they form.

NASA has selected a new Earth science mission that will study the behavior of tropical storms and thunderstorms, including their impacts on weather and climate models. The mission will be a collection of three SmallSats, flying in tight coordination, called Investigation of Convective Updrafts (INCUS), and is expected to launch in 2027 as part of NASA's Earth Venture Program.

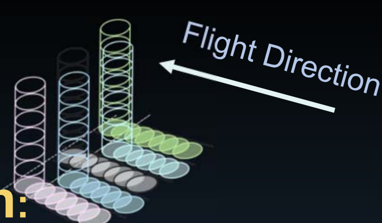
INCUS Investigation of Convective Updrafts



PI: Susan van den Heever, CSU
Deputy PI: Ziad Haddad, JPL
Project Scientist: Simone Tanelli, JPL

Mission Management & Participating Organizations

CSU: PI Org, Science Data Processing
JPL: Instruments & Mission Management
Tendeg: Deployable Antennas
BCT: Spacecraft, Mission Ops
CCNY, GSFC, MSFC, NOAA, SBU, TAMU: Science Co-Is

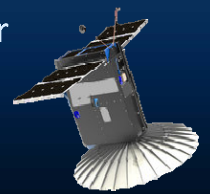


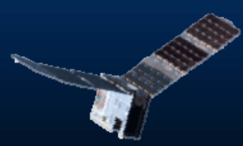
The INCUS Baseline Mission:

- Flies 3 SmallSats carrying RainCube-like radars with cross-track scanning capabilities and a TEMPEST-D-like radiometer
- Applies a novel time-differencing (Δt) approach
- Provides the first ever tropics-wide measurements of convective mass flux

Selected for NASA Earth Venture Mission (EVM-3) on Nov. 5, 2021

RainCube Ka-band radar + TEMPEST-D mm-wave radiometer





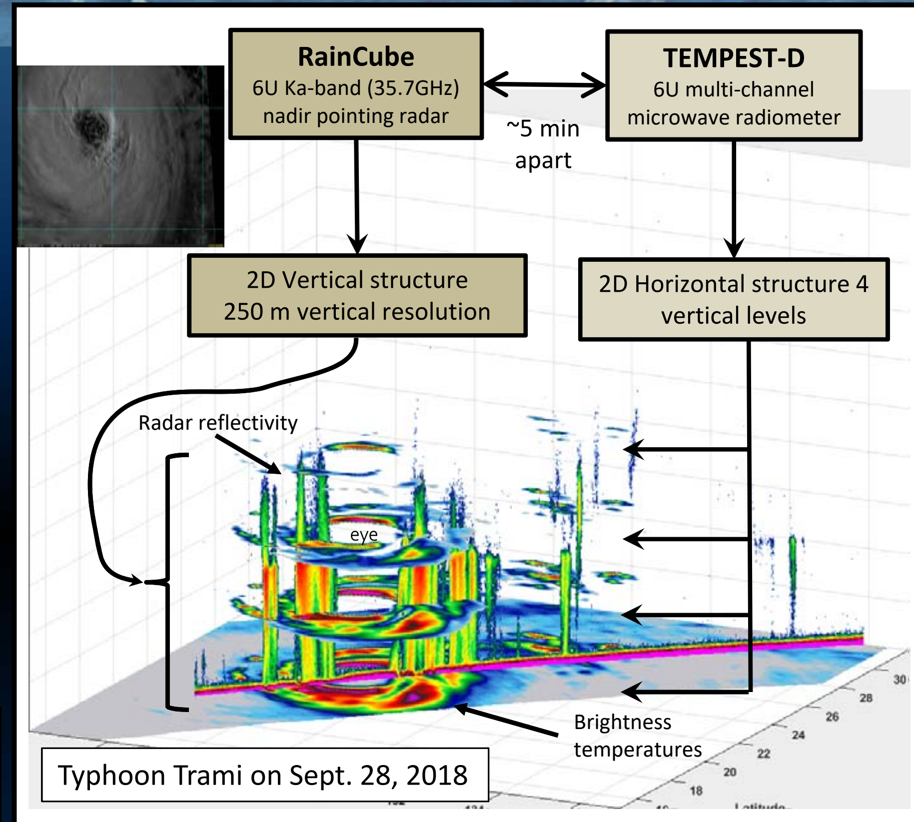
INCUS

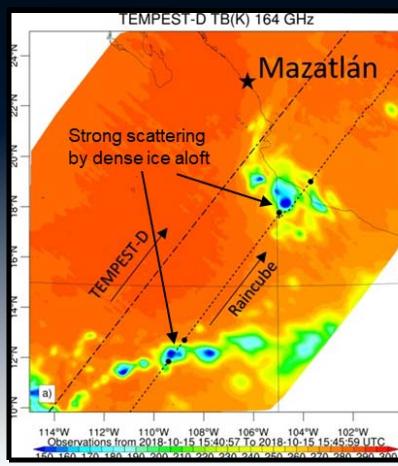
INCUS draws on the strengths of BOTH RainCube and TEMPEST-D to provide unprecedented vertical and horizontal views of storm structure and processes.

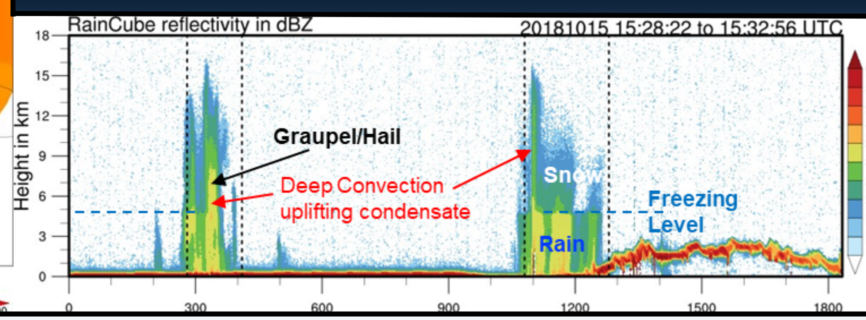
Figures and animations by Simone Tanelli, Shannon Brown and Steve Reising

(Right) On September 28, 2018, TEMPEST-D and RainCube overflew Typhoon Trami < 5 minutes apart

(Bottom) Correlated storm measurements from RainCube radar and TEMPEST-D radiometer over Texas, Mexico and Pacific Ocean



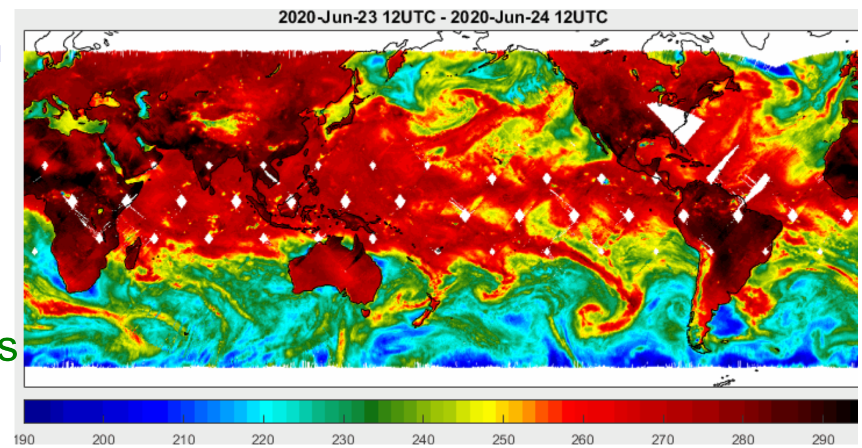




TEMPEST-D Mission: Lessons Learned

- Issue #1: On-board GPS did not achieve lock on orbit (similar to HaloSat & CubeRRT)
- Solution #1: Geolocation to a few km accomplished by aligning TEMPEST-D brightness temperature discontinuities to land/water boundaries.
  - Same technique used to validate radiometer geolocation on traditional satellites

- Issue #2: Single ground UHF antenna & ground system for communications with limited data downlink
- Resolution #2a: Acquired TEMPEST-D radiometer data at 100% duty cycle. Prioritized data downlinked based on science value.
- Resolution #2b: Downlinked tropical cyclone (hurricanes & typhoons) images with minimum latency (<1 day)

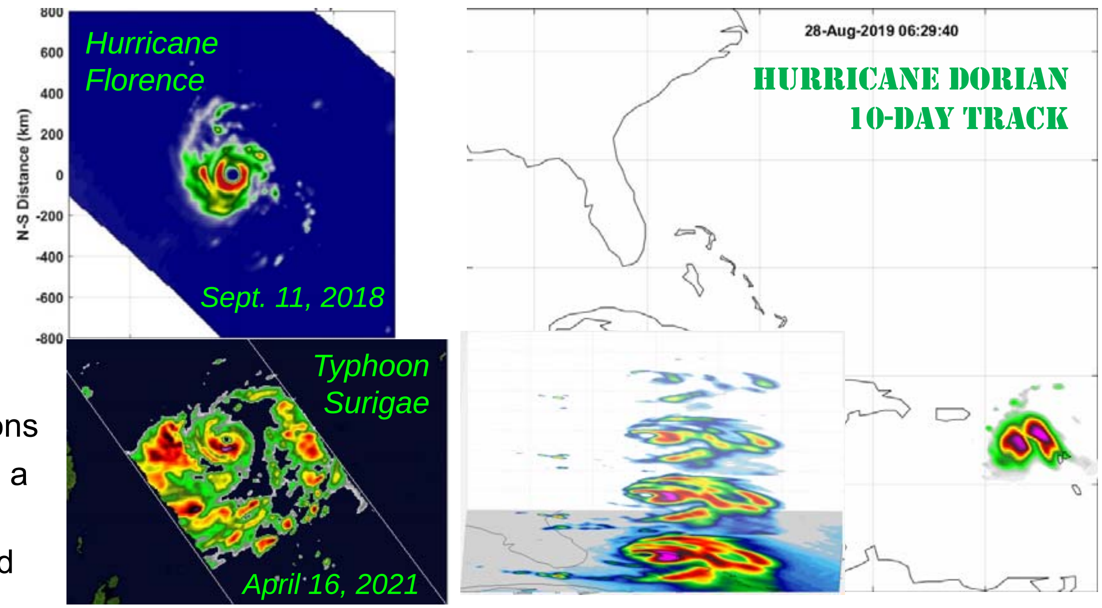


- Big Picture: Both of these issues based on c. 2017 CubeSat technology have since been resolved. Current S-band/X-band communications (e.g. TROPICS) have overcome limitations imposed by UHF.

TEMPEST-D Mission Accomplishments: 6U CubeSat with Nearly 3 Years on Orbit

Technology Demonstration Accomplishments:

- First global Earth observations from a multi-frequency microwave radiometer on a CubeSat
- Performed continuous passive microwave observations from a CubeSat in LEO for nearly 3 years
- Demonstrated instrument performance equivalent to operational microwave sounders, i.e. radiometer calibration accuracy, precision and stability
- Performed altitude control of a CubeSat necessary to form a constellation from a single orbital deployment



Earth Science Accomplishments:

- Performed passive microwave observations of hurricanes, typhoons and TCs from a CubeSat for 3 consecutive seasons
- Demonstrated first quantitative precipitation estimates from a CubeSat radiometer
- TEMPEST-D and RainCube demonstrated highly-correlated passive and active microwave storm observations from CubeSats
- First space-borne use of “hyperspectral” microwave sounding observations to retrieve planetary boundary layer (PBL) height

TEMPEST-D data publicly available at tempest.colostate.edu/data

TEMPEST-D data have been downloaded by 57 user groups in 13 countries on 5 continents.

TEMPEST-D CubeSat Microwave Sounder: Peer-Reviewed Publications

Peer-Reviewed Journal Papers:

1. Goncharenko, Y. V., S. C. Reising, F. Iturbide-Sanchez and V. Chandrasekar, “Design and Analysis of CubeSat Microwave Radiometer Constellations to Observe Temporal Variability of the Atmosphere,” *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, early release online, Nov. 2021, doi: 10.1109/JSTARS.2021.3128069.
2. Padmanabhan, S., T. C. Gaier, A. B. Tanner, S. T. Brown, B. H. Lim, S. C. Reising, R. Stachnik, R. Bendig and R. Cofield (2021) “TEMPEST-D Radiometer: Instrument Description and Prelaunch Calibration,” *IEEE Transactions on Geoscience and Remote Sensing*, vol. 59, no. 12, pp. 10213-10226, Dec. 2021, doi:10.1109/TGRS.2020.3041455.
3. Berg, W., S. T. Brown, B. H. Lim, S. C. Reising, Y. Goncharenko, C. D. Kummerow, T. C. Gaier and S. Padmanabhan (2021) “Calibration and Validation of the TEMPEST-D CubeSat Radiometer,” *IEEE Transactions on Geoscience and Remote Sensing*, vol. 59, no. 6, pp. 4904-4914, Jun. 2021, doi:10.1109/TGRS.2020.3018999.
4. Schulte, R. M., C. D. Kummerow, W. Berg, S. C. Reising, S. T. Brown, T. C. Gaier, B. H. Lim and S. Padmanabhan (2020) “A Passive Microwave Retrieval Algorithm with Minimal View Angle Bias: Application to the TEMPEST-D CubeSat Mission,” *Journal of Atmospheric and Oceanic Technology*, Feb. 2020, doi:10.1175/JTECH-D-19-0163.1.

TEMPEST-D CubeSat Microwave Sounder: Peer-Reviewed Publications

Selected Peer-Reviewed Conference Publications:

1. Chandrasekar, V., C. Radhakrishnan, S. C. Reising, W. Berg, S. T. Brown, S. Tanelli, O. O. Sy and G. F. Sacco, "Cross Validation of TEMPEST-D and RainCube Observations," Under review for: *Proc. 2021 IEEE International Geoscience and Remote Sensing Symposium (IGARSS 2021)*, Brussels, Belgium, Jul. 2021.
2. Chandrasekar, V., C. Radhakrishnan, W. Berg and S. C. Reising, "Rainfall Estimation from TEMPEST-D CubeSat Observations, Under review for: *Proc. 2021 IEEE International Geoscience and Remote Sensing Symposium (IGARSS 2021)*, Brussels, Belgium, Jul. 2021.
3. Berg, W., C. Kummerow, S. Reising, V. Chandrasekar, R. Schulte, Y. Goncharenko, B. Kilmer, S. Brown, B. Lim, S. Padmanabhan and T. Gaier, "Demonstrating the Viability of the TEMPEST-D CubeSat Radiometer for Science Applications, In: *Proc. 2019 IEEE International Geoscience and Remote Sensing Symposium (IGARSS 2019)*, Yokohama, Japan, Jul. 2019, doi: 10.1109/IGARSS.2019.8897881.

TEMPEST-D CubeSat Microwave Sounder: Peer-Reviewed Publications

Selected Peer-Reviewed Conference Publications (cont.):

4. Reising, S. C., T. C. Gaier, S. Padmanabhan, B. H. Lim, C. Heneghan, C. D. Kummerow, W. Berg, V. Chandrasekar, C. Radhakrishnan, S. T. Brown, J. Carvo and M. Pallas, “An Earth Venture In-Space Technology Demonstration Mission for Temporal Experiment for Storms and Tropical Systems (TEMPEST),” In: *Proc. 2018 IEEE International Geoscience and Remote Sensing Symposium (IGARSS 2018)*, Valencia, Spain, Jul. 2018, pp. 6301-6303.
5. Padmanabhan, S., T. C. Gaier, B. H. Lim, R. Stachnik, A. Tanner, S. Brown, S. C. Reising, W. Berg, C. D. Kummerow and V. Chandrasekar, “Radiometer for the Temporal Experiment for Storms and Tropical systems Demonstration Mission,” In: *Proc. 2018 IEEE International Geoscience and Remote Sensing Symposium (IGARSS 2018)*, Valencia, Spain, Jul. 2018, pp. 2001-2003.
6. Reising, S. C., T. C. Gaier, C. D. Kummerow, S. Padmanabhan, B. H. Lim, C. Heneghan, V. Chandrasekar, W. Berg, J. P. Olson, S. T. Brown, J. Carvo, and M. Pallas, “Temporal Experiment for Storms and Tropical Systems Technology Demonstration (TEMPEST-D) Mission: Enabling Time-Resolved Cloud and Precipitation Observations from 6U-Class Satellite Constellations,” In: *Proc. 31st AIAA/USU Conference on Small Satellites*, Logan, Utah, Aug. 2017, SSC17-III-01.

TEMPEST-D Venture Tech CubeSat Mission Providing Global Microwave Observations for Nearly Three Years

- TEMPEST-D, a NASA Earth Venture Tech Demo mission, met all of its Level 1 requirements within the first 90 days of operations and continued for nearly 3 years.
- Demonstrated rapid development cycle with delivery of CubeSat with multi-frequency millimeter-wave radiometer within 2 years after PDR.
- TEMPEST-D has significantly **exceeded requirements for calibration** accuracy and precision, with performance **comparable to much larger operational satellites**.
- TEMPEST-D radiometer instrument was **highly stable** over the nearly 3-year mission, with no evidence of calibration errors due to on-orbit temperature.
- Demonstrated infusion of NASA ESTO-funded technology developed over more than a decade from TRL 2 (ACT-08) to TEMPEST-D tech demo/science mission at TRL 9.
- Highly-correlated complementary measurements with RainCube enable new science mission concepts for the future.
- TEMPEST-D2 instrument to be deployed on ISS (STP-H8) in Dec. 2021 for 3 years.
- Future constellations have the potential to provide rapid revisit time to observe variability not only of temperature and water vapor but also rapidly-evolving storms.