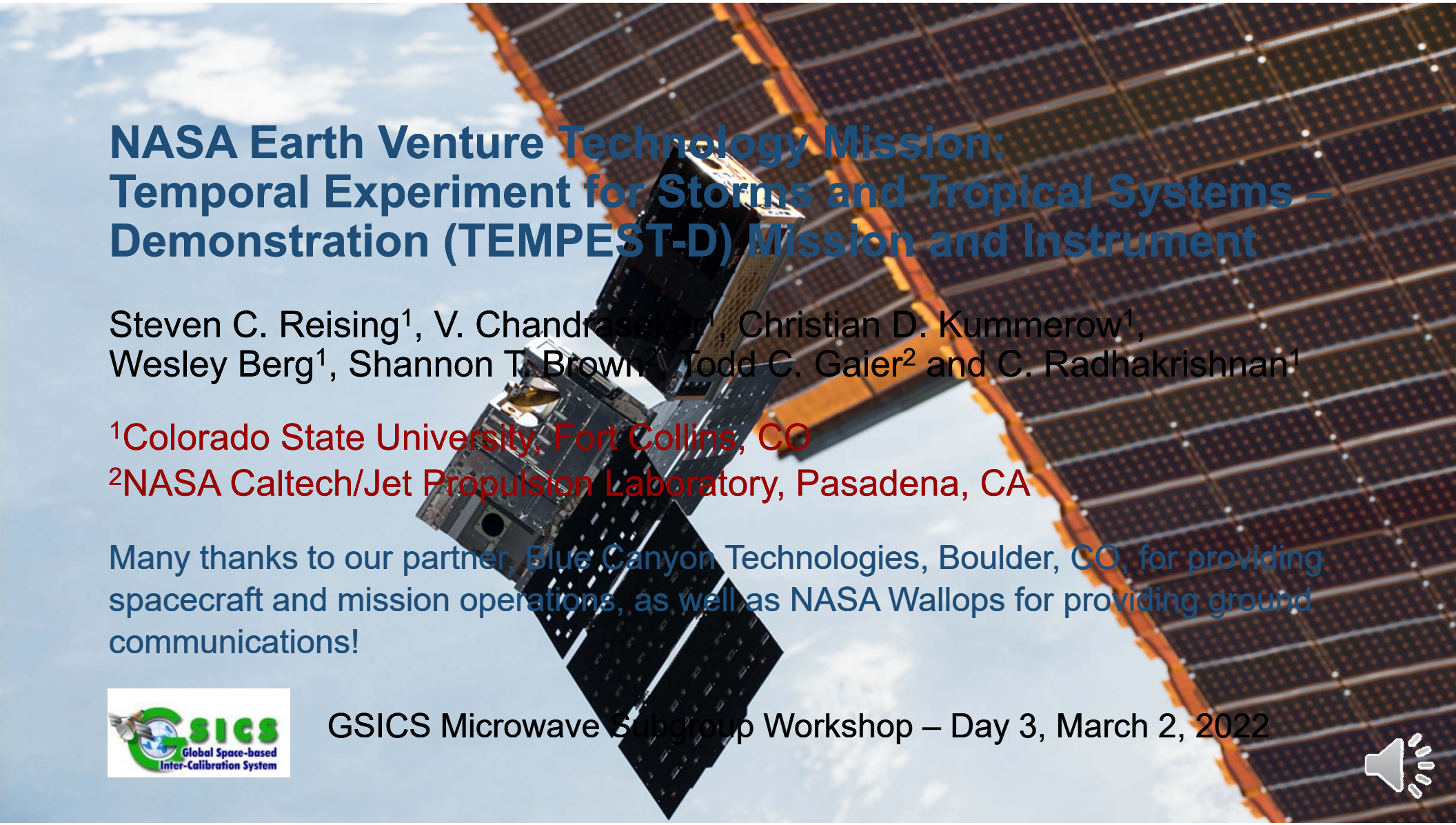


# NASA Earth Venture Technology Mission: Temporal Experiment for Storms and Tropical Systems – Demonstration (TEMPEST-D) Mission and Instrument

Steven C. Reising[1], V. Chandrasekar[1], Christian D. Kummerow[1], Wesley Berg[1], Shannon T. Brown[2], Todd C. Gaier[2] and C. Radhakrishnan[1]

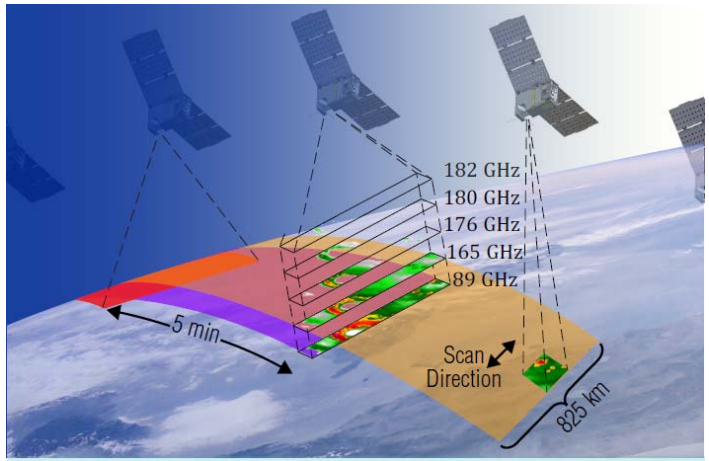
[1]Colorado State University, Fort Collins, CO
[2]NASA Caltech/Jet Propulsion Laboratory, Pasadena, CA

Many thanks to our partner, Blue Canyon Technologies, Boulder, CO, for providing spacecraft and mission operations, as well as NASA Wallops for providing ground communications!

GSICS Microwave Subgroup Workshop – Day 3, March 2, 2022

# Temporal Experiment for Storms and Tropical Systems (TEMPEST)

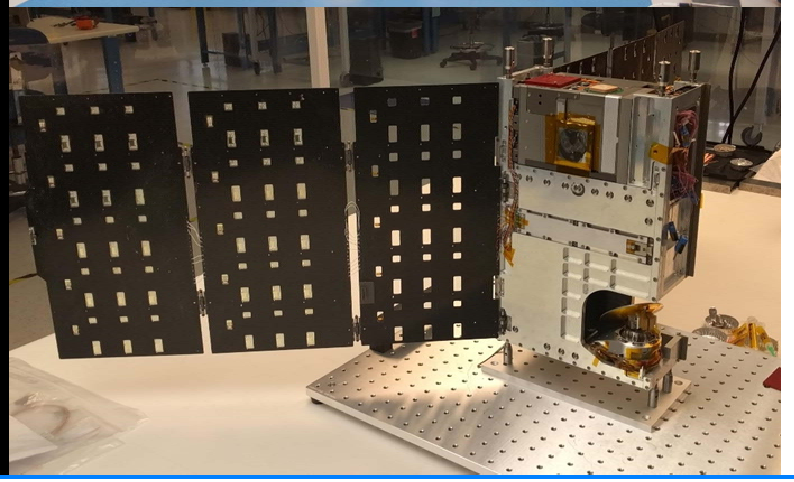
- TEMPEST addresses 2017 National Academies Earth Science Decadal Survey: *Why do convective storms, heavy precipitation, and clouds occur exactly when and where they do?* (Most Important Science Question W-4)
- Proposed to NASA Earth Venture Instrument-2 in 2013 as a constellation of 5 identical 6U CubeSats to provide *temporally-resolved observations of rapidly-evolving storms* every ~5 minutes
- Selected as NASA Earth Venture Technology Demonstration mission to deploy a single 6U CubeSat with multi-channel millimeter-wave radiometer; started in August 2015.
- NASA selected TROPICS CubeSat constellation for Earth Venture Instrument-3 in March 2016.
- TEMPEST-D technology demonstration mission delivered 6U CubeSat in under 2 years; deployed into orbit in July 2018
- TEMPEST-D planned for 3-month mission; greatly exceeded expectations by providing atmospheric data for nearly 3 years!
- TEMPEST-D2 launched on Dec. 21, 2021 for 3 years on ISS!
- Success of TEMPEST-D and RainCube essential in selection of INCUS as Earth Venture Mission to be launched in 2027!



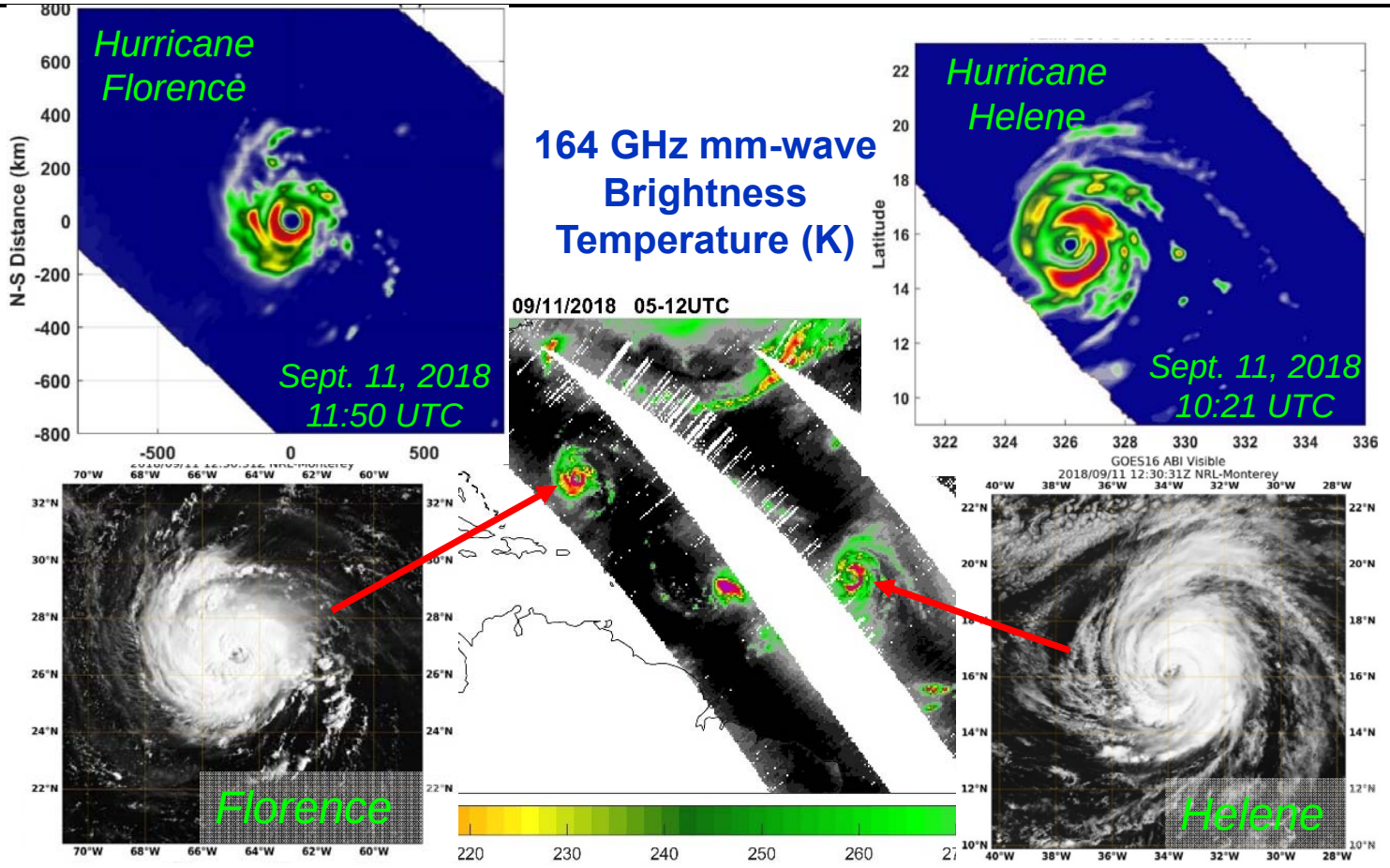

5 identical 6U small sats, each with an identical 5-channel radiometer, flying 5 minutes apart

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


**TEMPEST-D**
3.8 kg, 6.5 W, $

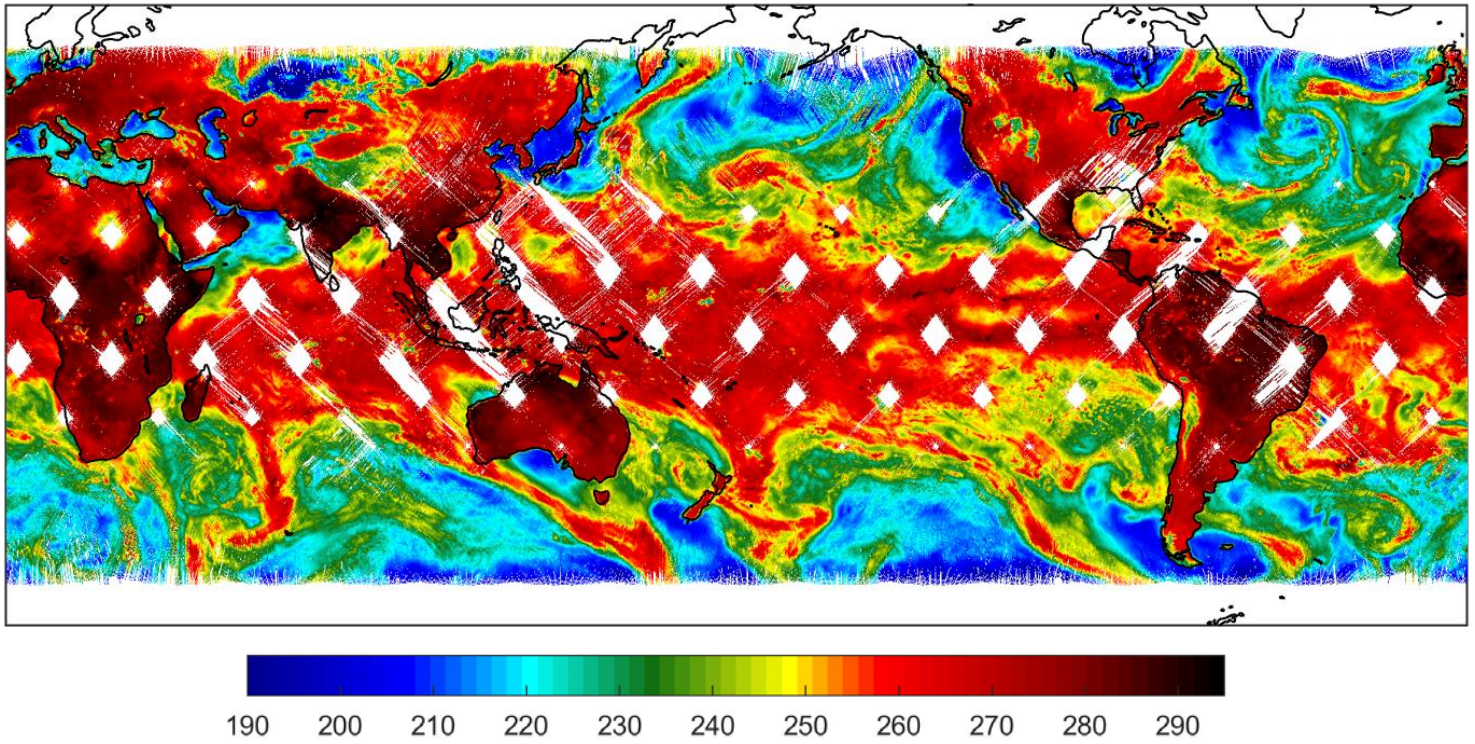


# TEMPEST-D Mission: Hurricane Observations during First Full Orbits of Data: Sept. 11, 2018

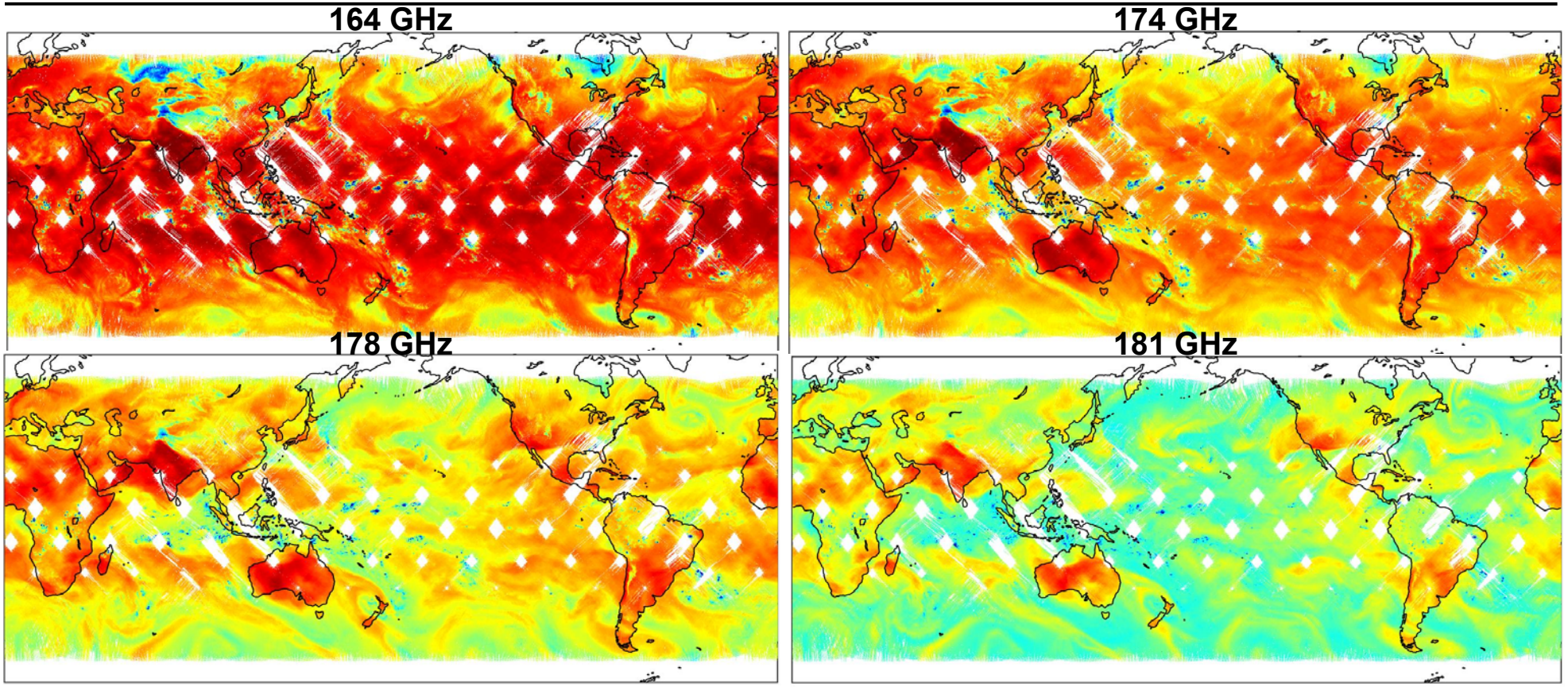


# TEMPEST-D Venture Tech Mission: Global Atmospheric Observations for Nearly 3 Years on Orbit

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



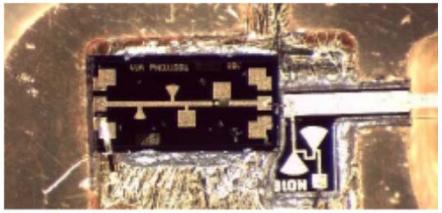
# TEMPEST-D Venture Tech Mission: Global Atmospheric Observations for Nearly 3 Years on Orbit

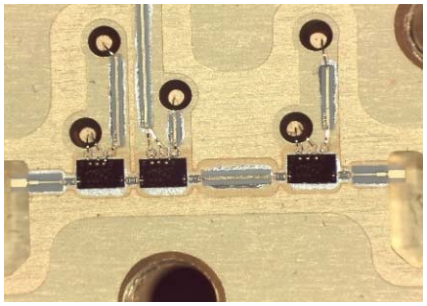



**TEMPEST-D Observations on March 31, 2021**

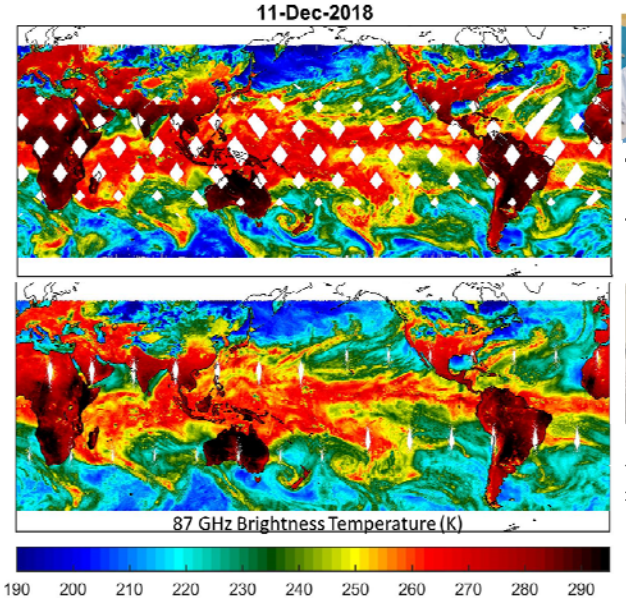
# TEMPEST-D Mission: Well-Calibrated Atmospheric Science Data for Nearly 3 Years On Orbit

*On-orbit demonstration of new InP HEMT Low Noise Amplifier Technology (NG)*





*Padmanabhan et al., TGRS, 2021.*

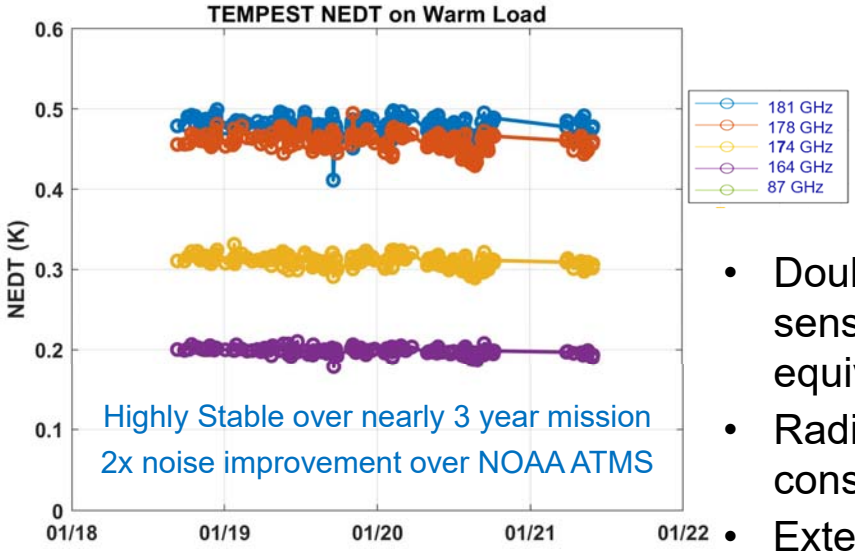



TEMPEST-D

*3.8kg, 6.5W, $*

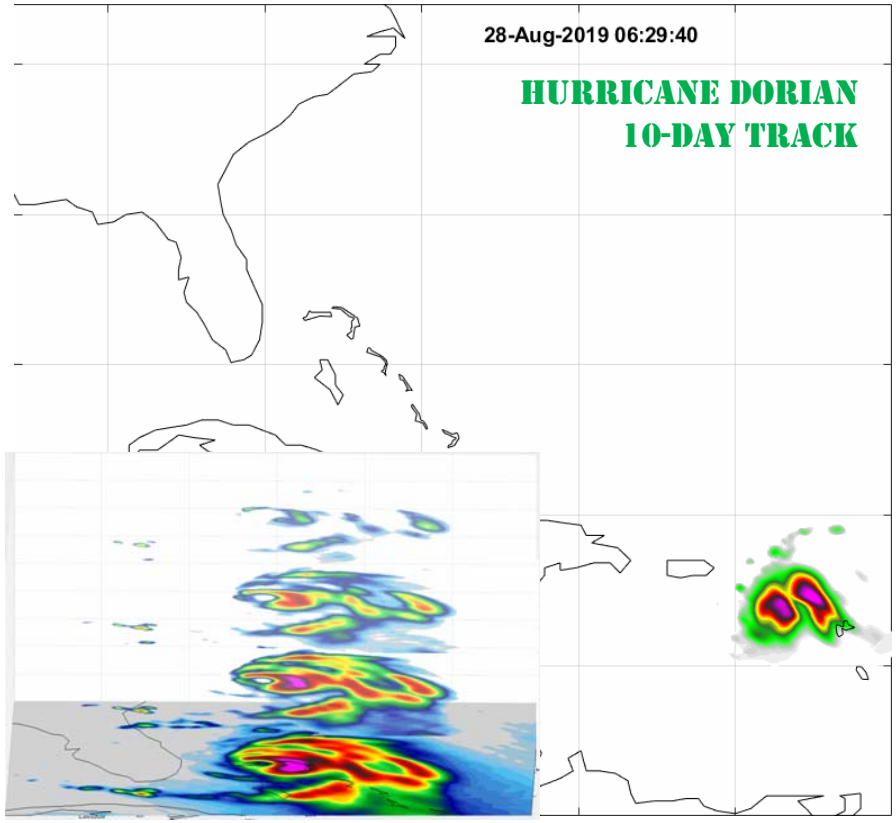
NOAA Advanced Technology Microwave Sounder (ATMS)

*75kg, 100W, $$$$*




- Double-difference inter-calibration with GPM/GMI and 4 MHS sensors (NOAA / MetOp) demonstrated TEMPEST-D calibration equivalent to operational sensors (*Berg et al., TGRS, 2021*)
- Radiometer accuracy, precision and stability all highly consistent throughout nearly 3-year TEMPEST-D mission
- Extended operations provided risk reduction for future missions

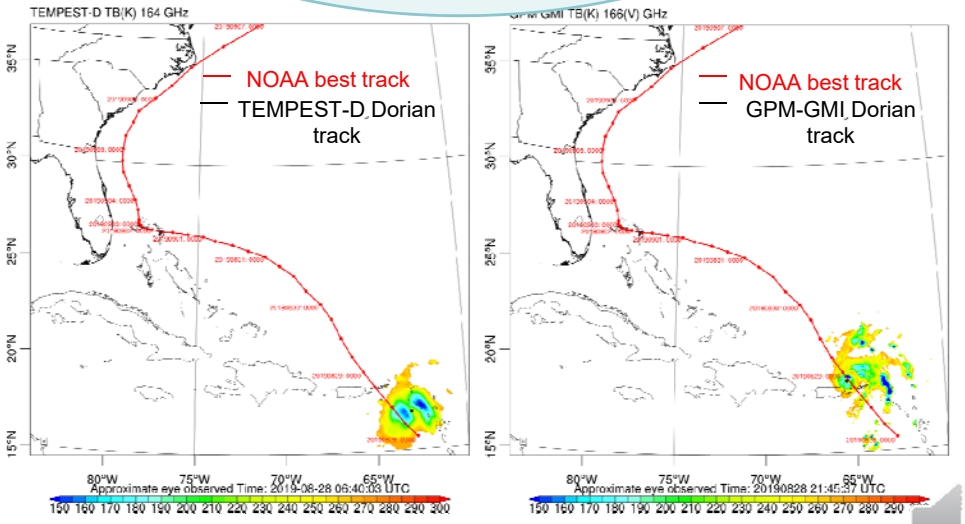
# TEMPEST-D Mission: Observations of Hurricanes, Tropical Cyclones and Convective Systems for 3 Years

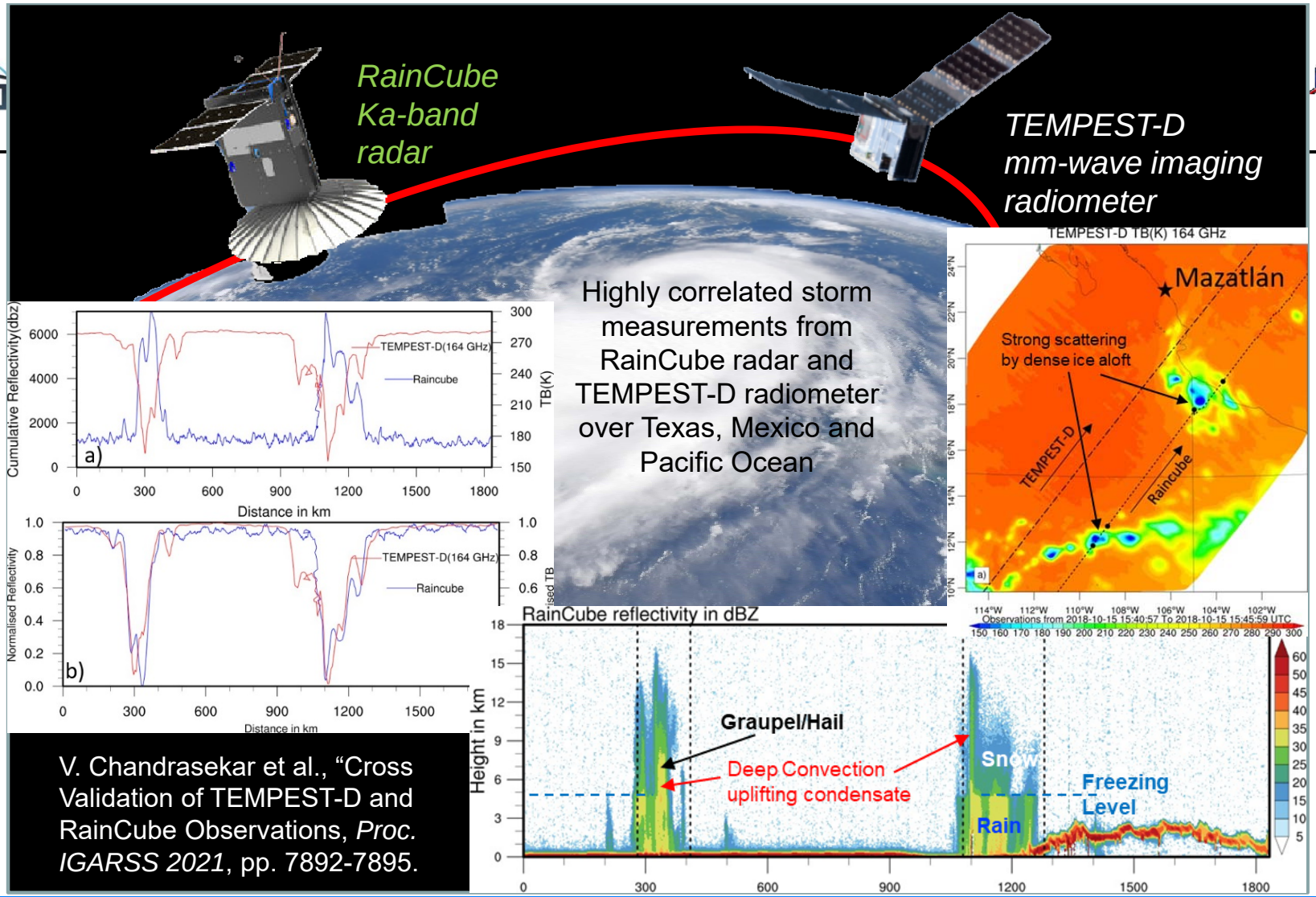



Calibrated TEMPEST-D data are publicly available!

https://tempest.colostate.edu/data

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

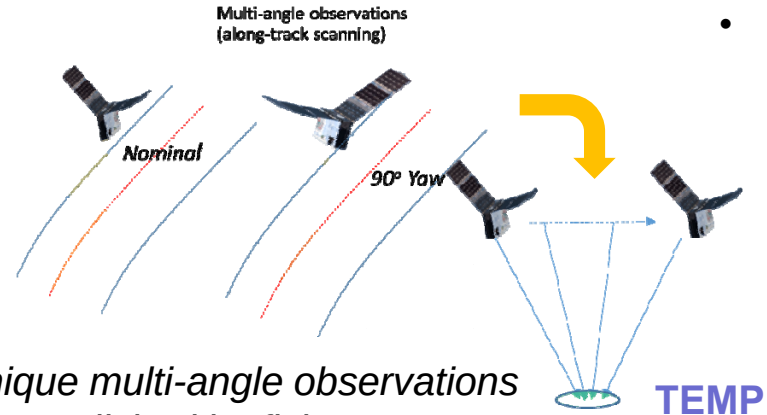





Correlation coefficient between TEMPEST-D TB and RainCube Reflectivity: > 0.90

V. Chandrasekar et al., "Cross Validation of TEMPEST-D and RainCube Observations, *Proc. IGARSS 2021*, pp. 7892-7895.

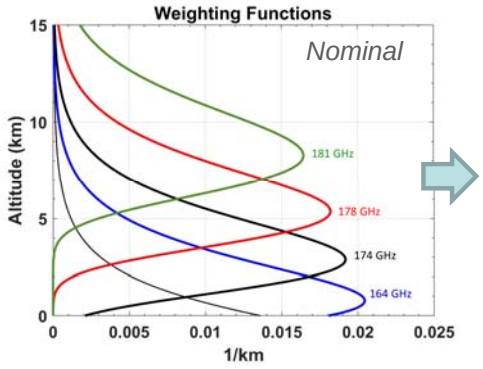
# Unique Observations Demonstrated by TEMPEST-D

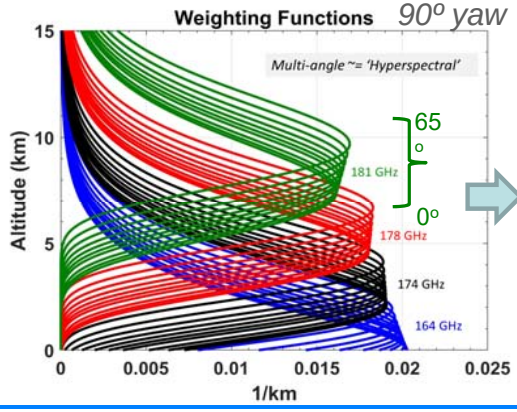


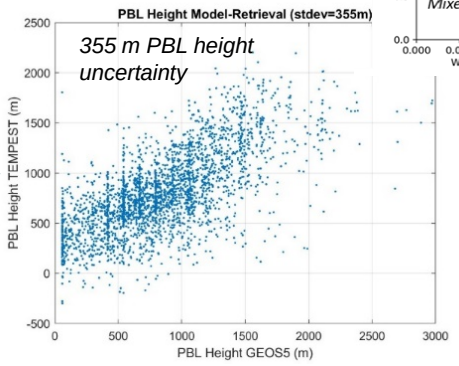

*Unique multi-angle observations accomplished by flying TEMPEST-D yawed by 90º*

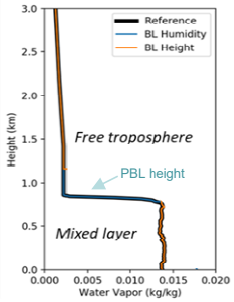
- Multi-angle sounding improves vertical sampling through troposphere, analogous to a "hyperspectral" sounder
  - A promising application is improving measurement capability in planetary boundary layer (PBL)
  - Also enables uncertainty quantification for time resolved measurement concepts

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

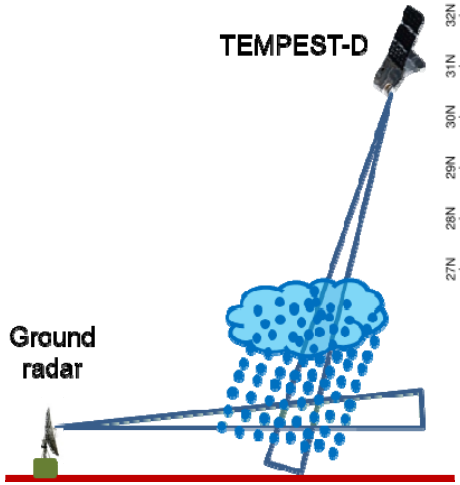


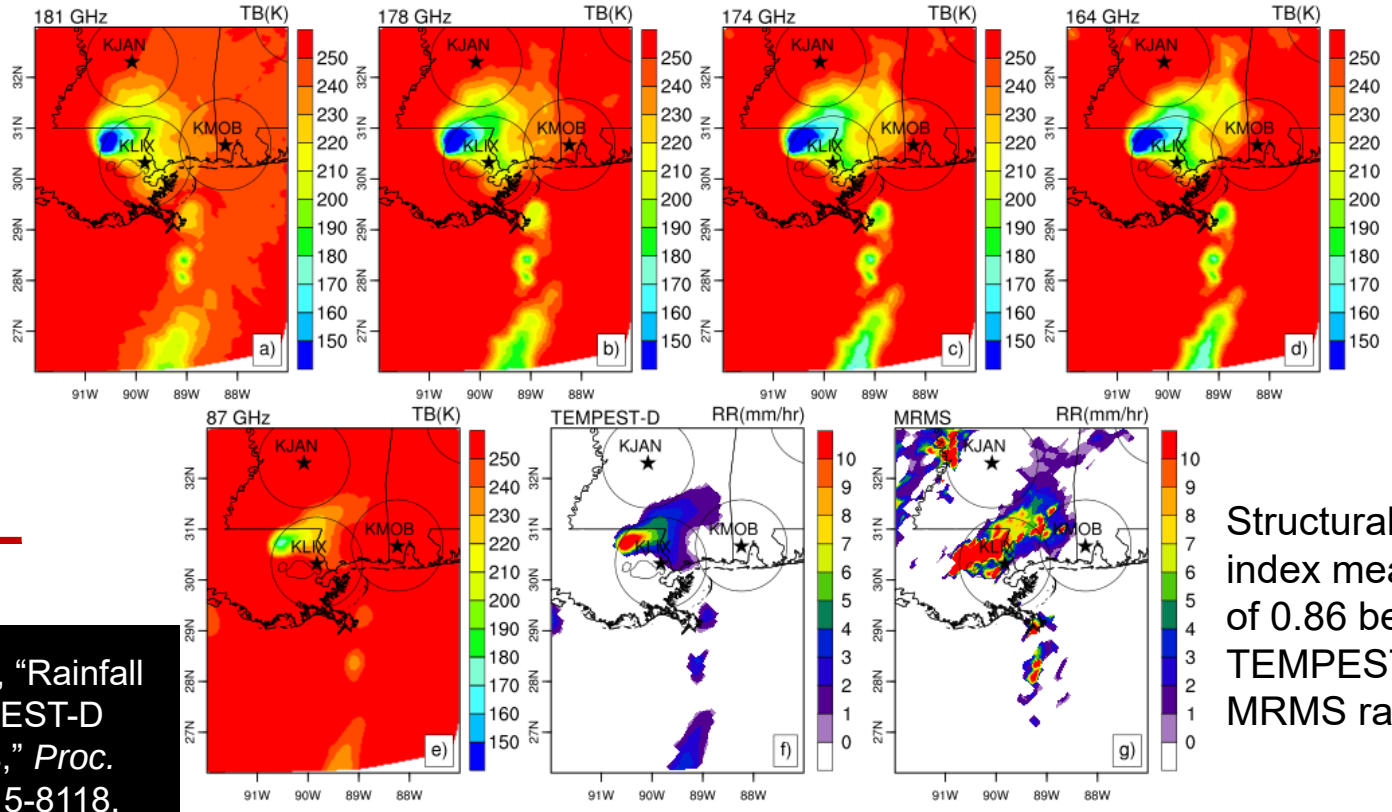



# TEMPEST-D Derived Rainfall Estimates over Tropical Storm Olga Landfall near New Orleans, Oct. 26, 2019



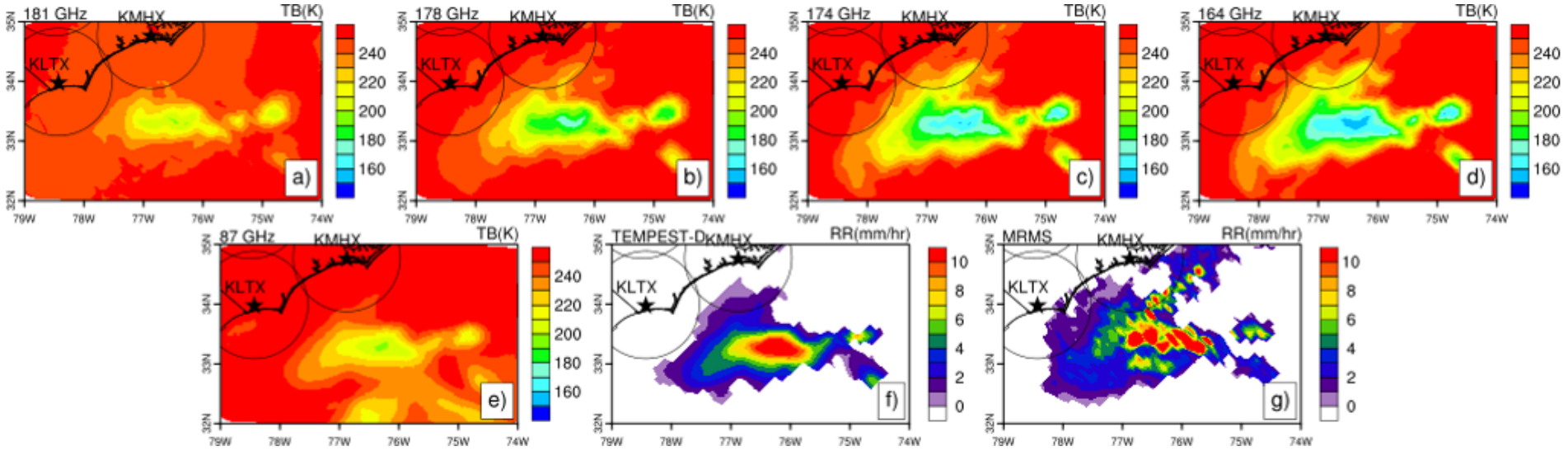




V. Chandrasekar et al., "Rainfall Estimation from TEMPEST-D CubeSat Observations," *Proc. IGARSS 2021*, pp. 8115-8118.

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

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

# TEMPEST-D Retrieved Rainfall for Continental Storm over Fort Campbell, KY on October 7, 2019



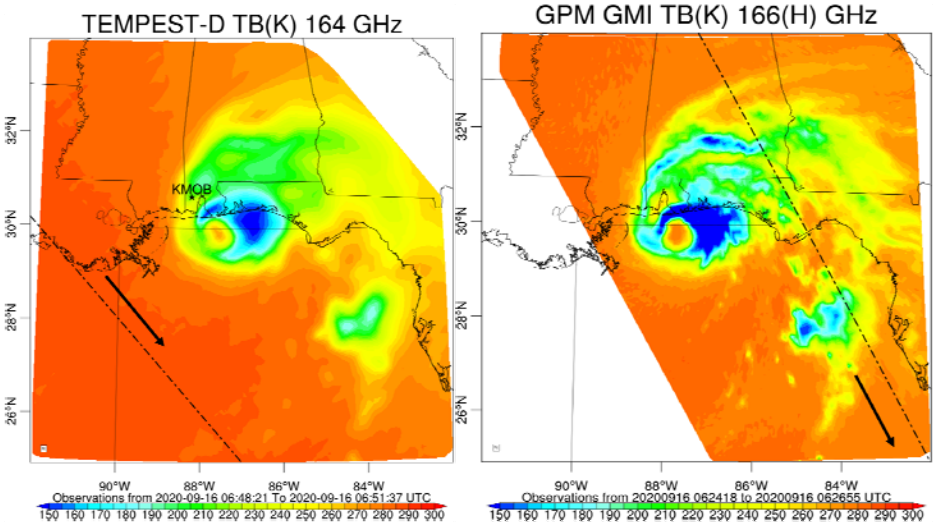

(a to e) TEMPEST-D observations, (f) TEMPEST-D rain rate, and (g) MRMS rain rate.

V. Chandrasekar et al., "Rainfall Estimation from TEMPEST-D CubeSat Observations," *Proc. IGARSS 2021*, pp. 8115-8118.

**Structural Similarity Index Measure (SSIM) of 0.72**

# Comparison of TEMPEST-D and GPM-GMI Observations of Hurricanes Sally and Delta

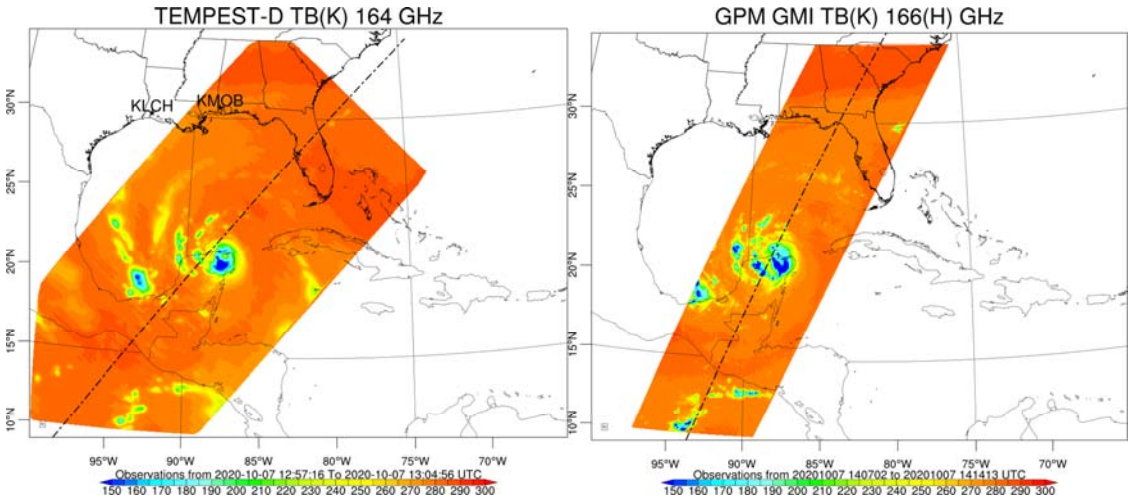
## Hurricane Sally on September 16, 2020




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

C. Radhakrishnan et al., "Cross-Validation of TEMPEST-D and GPM/GMI Observations over Precipitating Systems," *IGARSS 2022, in review.*

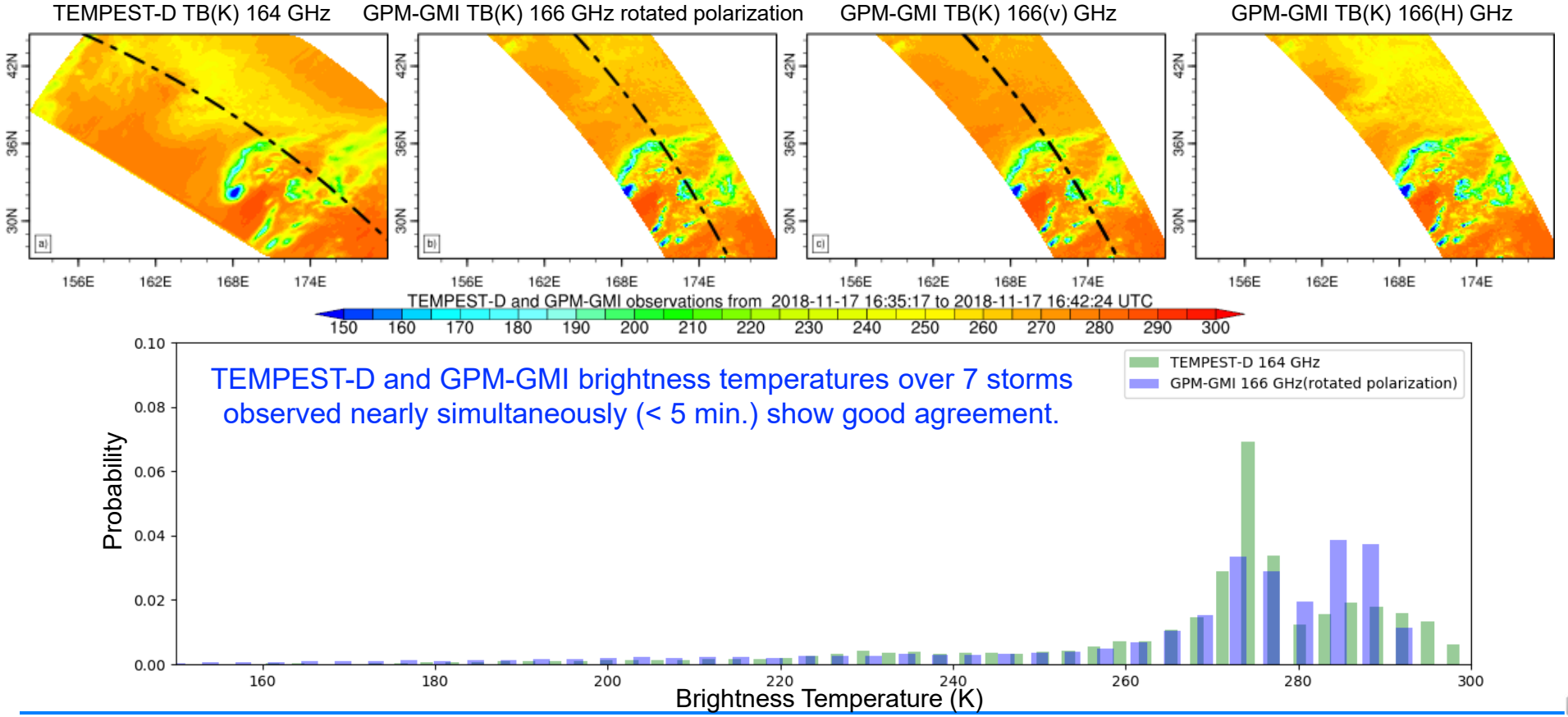
## Hurricane Delta on October 7, 2020




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

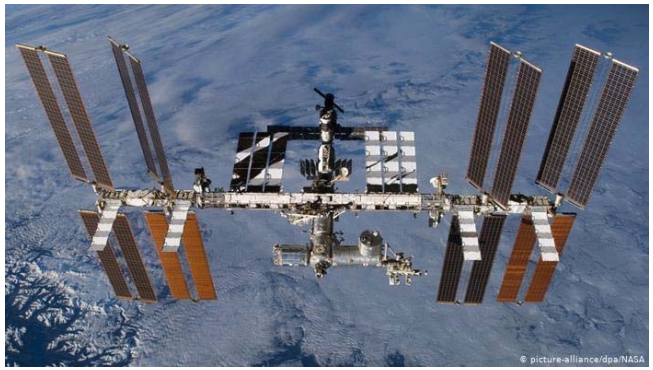
# Comparison of Near-Simultaneous Measurements of Precipitation by TEMPEST-D and GPM-GMI

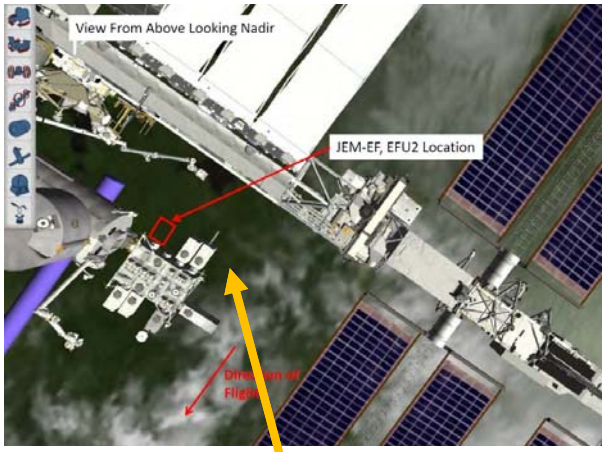
## TEMPEST-D and GPM-GMI Precipitation Observations over the North Pacific Ocean on November 17, 2018



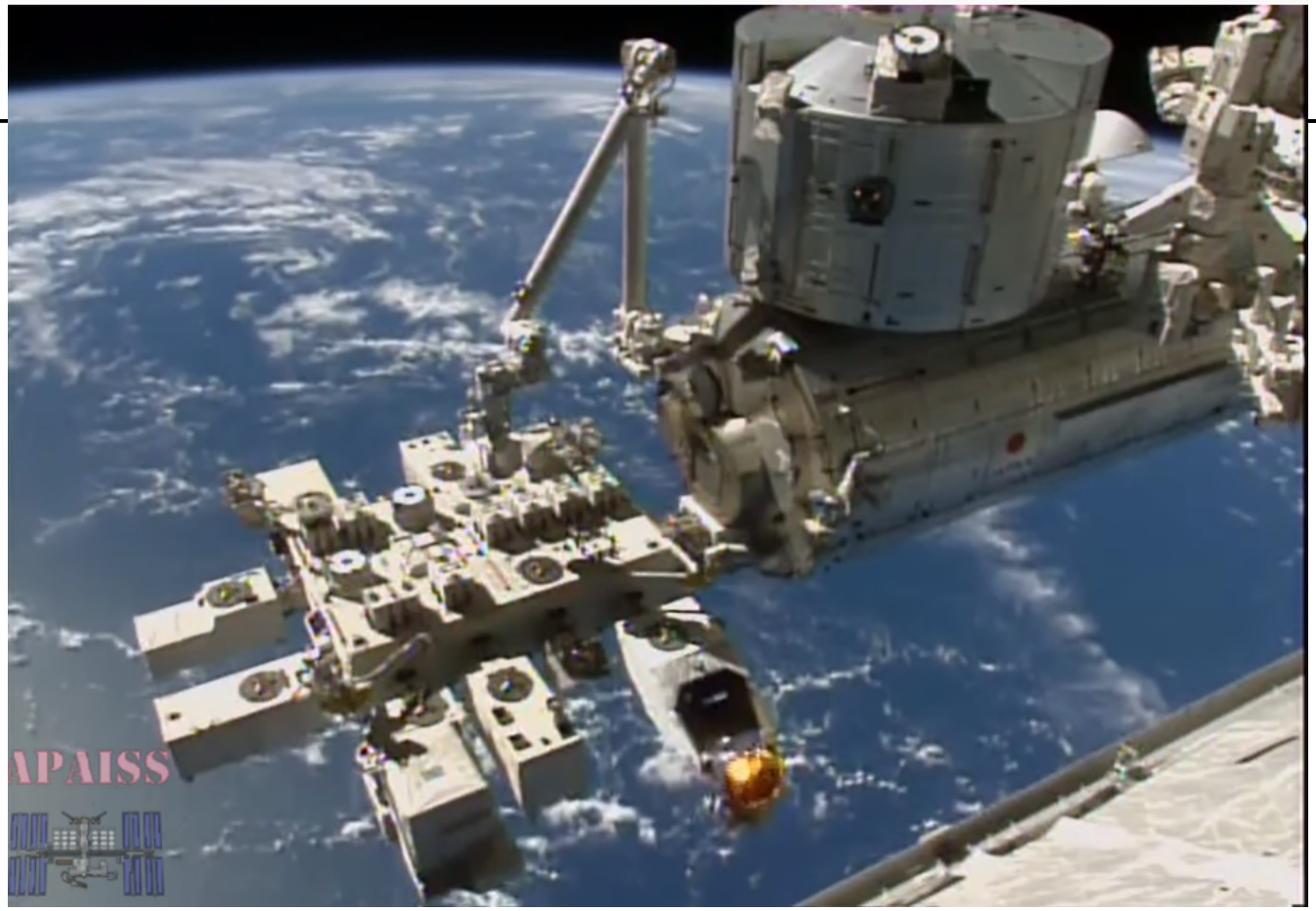
Jet Propulsion Laboratory
California Institute of Technology

# STP-H8 Mission



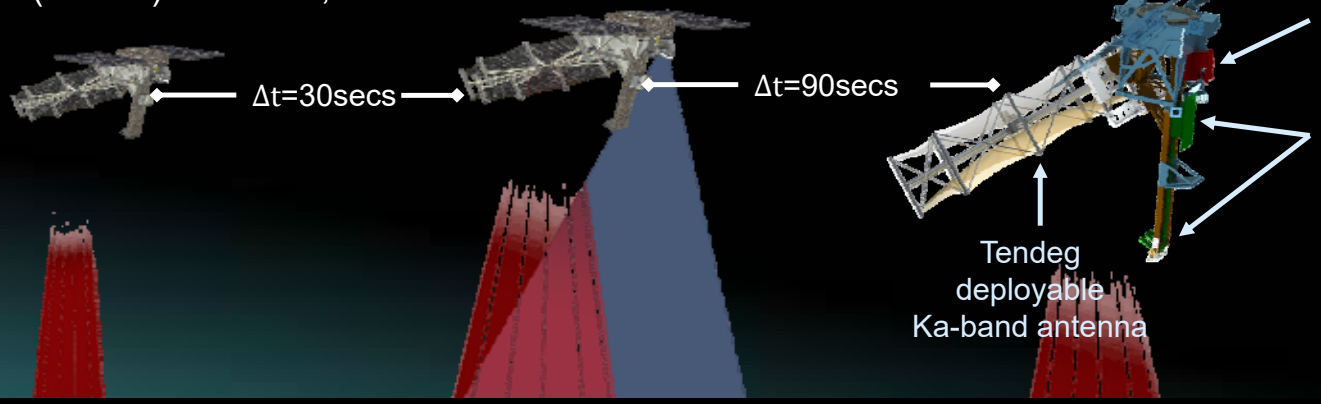

- **Space Force mission to demonstrate new low-cost microwave sensor technologies for weather**
  - **COWVR measures ocean surface wind vector**
  - **NASA provided TEMPEST-D2: measures water vapor, precipitation**
- **Deployment to ISS (JEM-EF module)**
- **DoD Space Test Program--Houston team is performing Mission Manager role**
- **Lauched on SpaceX CRS-24 on Dec. 21, 2021**
- **Operations for at least 3 years**
- **Science data processing at JPL and CSU**




COWVR and TEMPEST were deployed via robot arm on ISS on January 8, 2022.
See ISS fan's YouTube video at https://www.youtube.com/watch?v=rHbGfAtrHCQ

# INCUS Investigation of Convective Updrafts

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





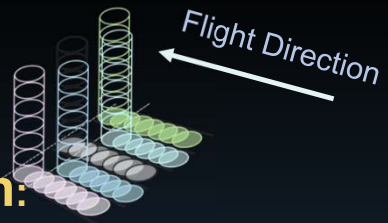


**PI:** Susan van den Heever, CSU
**Deputy PI:** Ziad Haddad, JPL
**Project Scientist:** Simone Tanelli, JPL

**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

Colorado State University
NASA Jet Propulsion Laboratory California Institute of Technology




## 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 ($\Delta t$) approach
- Provides the first ever tropics-wide measurements of convective mass flux

# TEMPEST-D Demonstration to Enable Temporal Observations of Cloud and Precipitation Processes

- TEMPEST-D NASA Earth Venture Technology Demonstration mission deployed and operated the first multi-frequency microwave radiometer to perform global observations from a CubeSat.
- TEMPEST-D was originally planned as a 3-month technology demonstration mission. It greatly exceeded expectations by performing global atmospheric observations for nearly 3 years.
- Double-difference inter-calibration with scientific and operational sensors operating at similar frequencies demonstrated that the TEMPEST-D instrument on a CubeSat has similar accuracy, precision and stability to traditional satellite missions.
- TEMPEST-D2 and COWVR were successfully deployed during STP-H8 on January 8, 2022 for 3 years of operations on ISS.
- Near-real time data products expected to be made available from these oceanic and atmospheric microwave sensors on ISS.
- Success of TEMPEST-D and RainCube essential in selection of INCUS as Earth Venture Mission (EVM-3) to be launched in 2027.