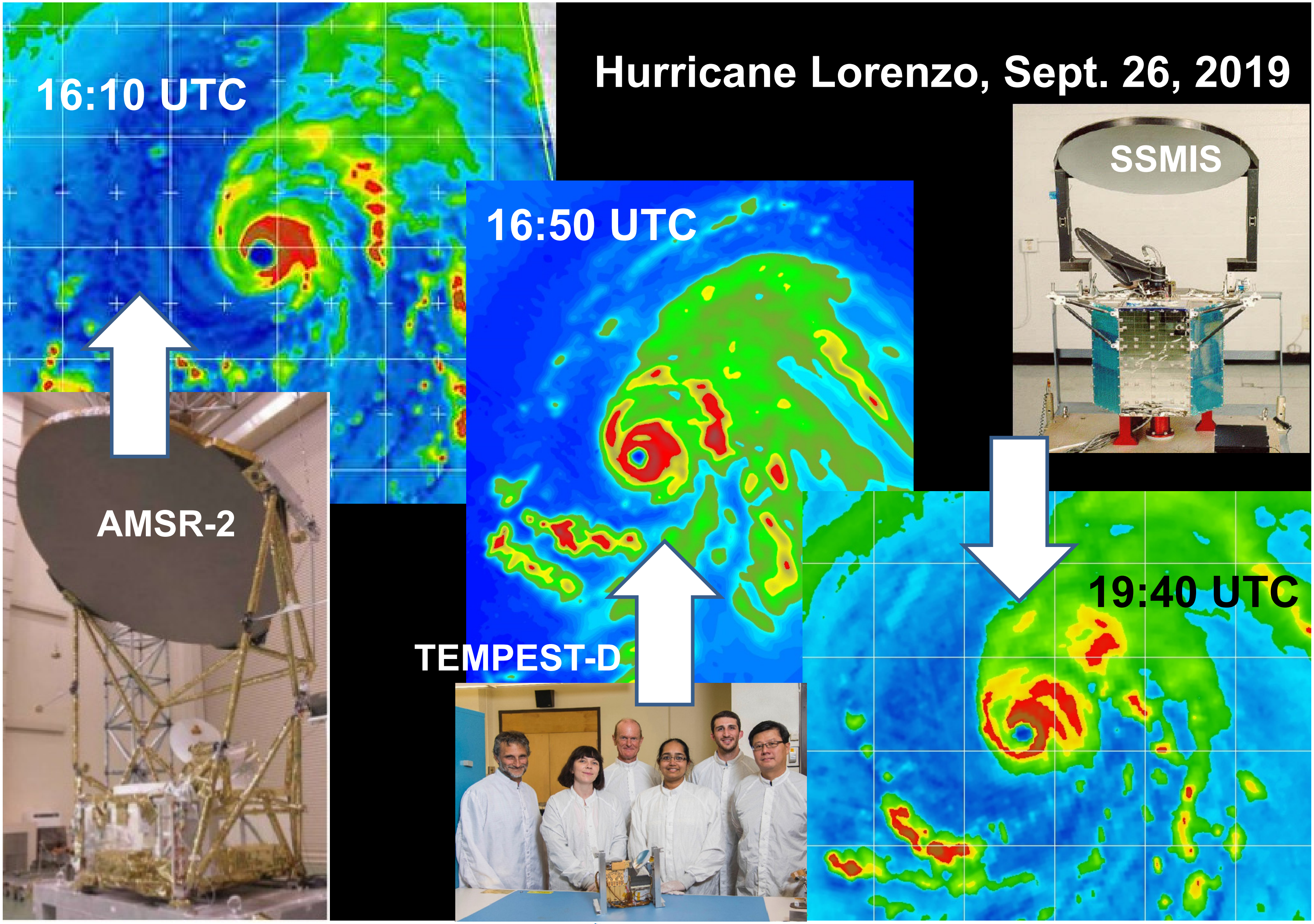
European Geosciences Union
General Assembly 2020 (Online)

Calibration and Validation of TEMPEST-D Microwave Atmospheric Sounder on a CubeSat for Applications in Weather Prediction and Climate Monitoring

Steven C. Reising[1], Shannon T. Brown[2], Todd C. Gaier[2], Wesley Berg[1], Christian D. Kummerow[1], Sharmila Padmanabhan[2], Boon H. Lim[2], V. Chandrasekar[1], Cate Heneghan[2], Richard Schulte[1], Yuriy Goncharenko[1], C. Radhakrishnan[1], Matthew Pallas[3], Doug Laczkowski[3], Austin Bullard[3] and Nancy Gaytan[3]

[1]Colorado State University, Fort Collins, CO
[2]NASA Caltech/Jet Propulsion Laboratory, Pasadena, CA
[3]Blue Canyon Technologies, Boulder, CO

Thanks to NASA Wallops for providing ground station communications support.


Hurricane Lorenzo, Sept. 26, 2019
16:10 UTC
AMSR-2
16:50 UTC
TEMPEST-D
SSMIS
19:40 UTC

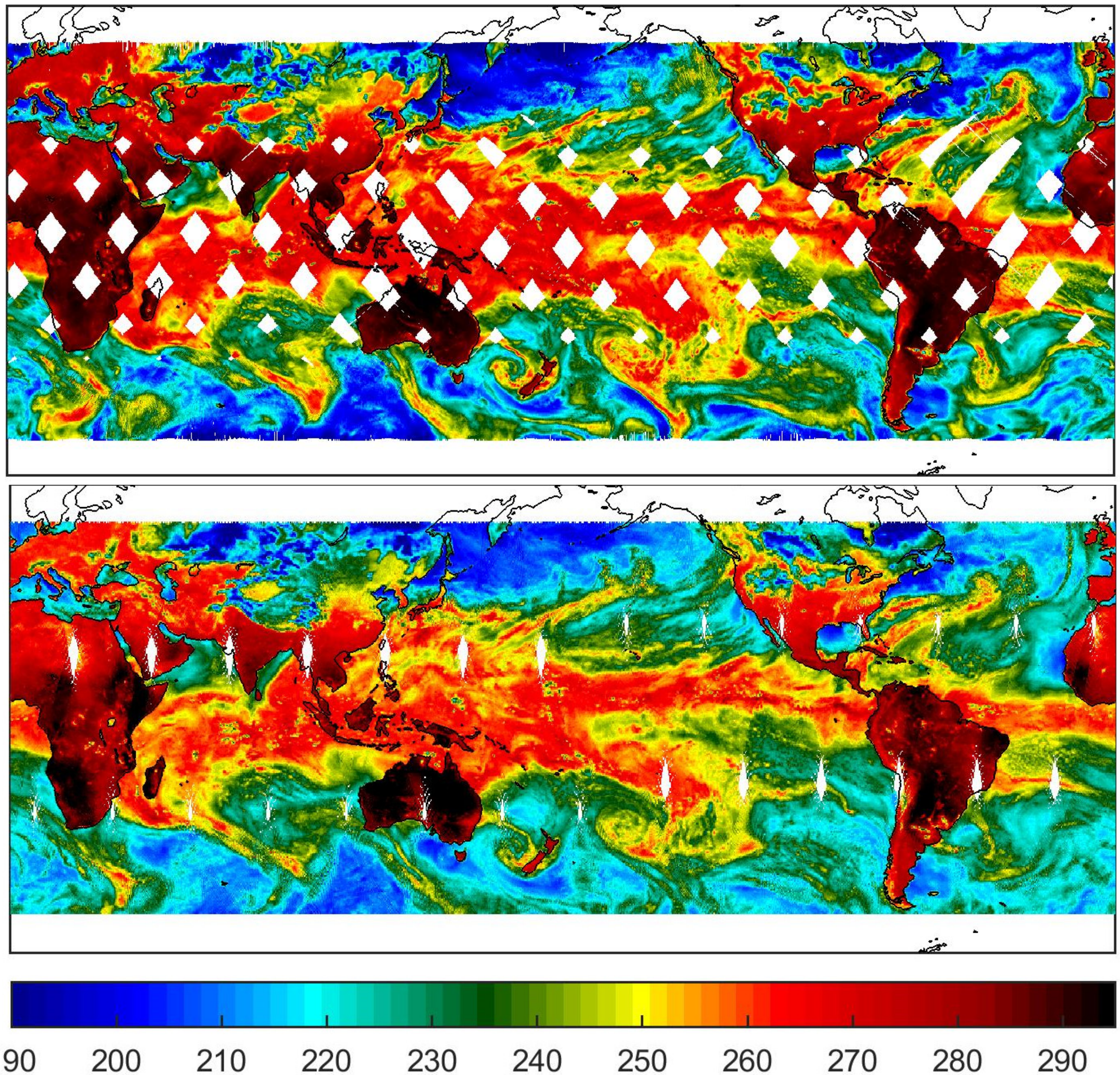
Comparison Between On-orbit Passive Microwave Sensors

December 11, 2018

Sensor A

Sensor B

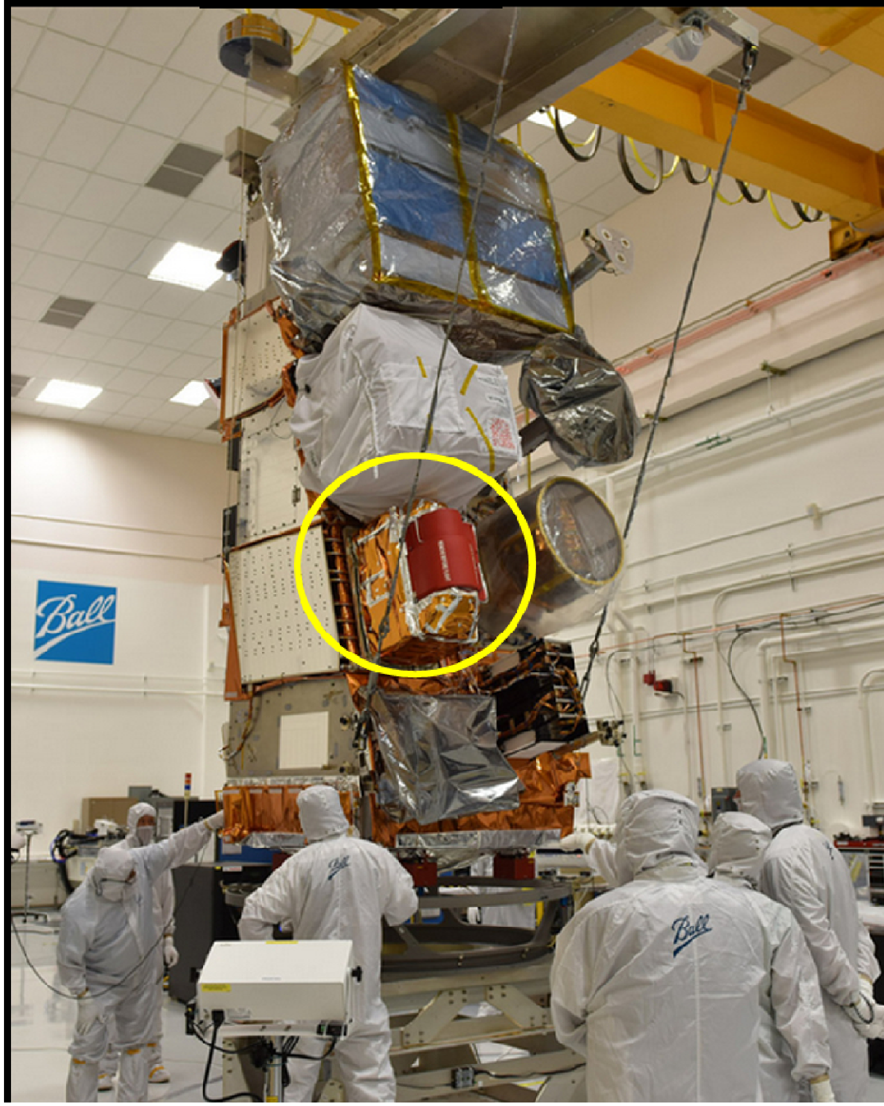
87 GHz Brightness Temperature (K)



Sensor B

NOAA Advanced Technology Microwave Sounder (ATMS)

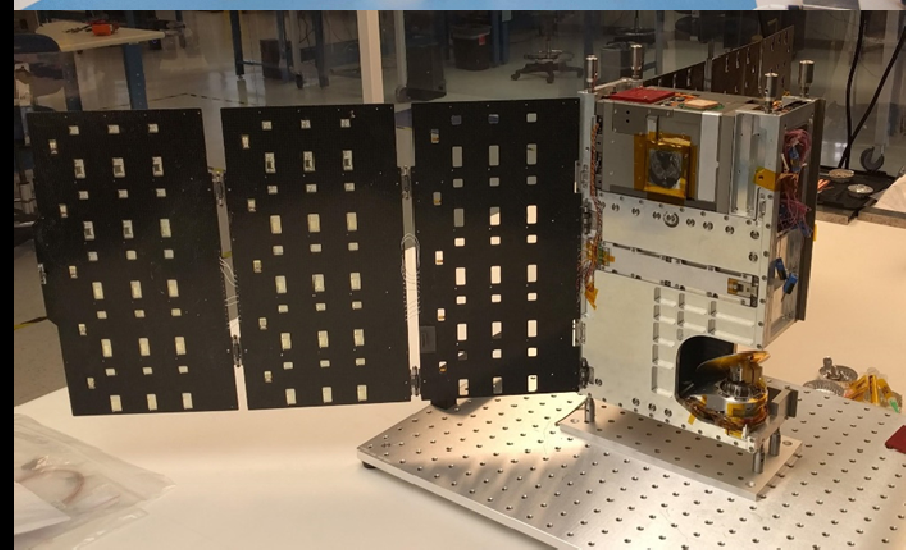
75 kg, 100 W, **$$$$**



Sensor A

TEMPEST-D

3.8 kg, 6.5 W, $

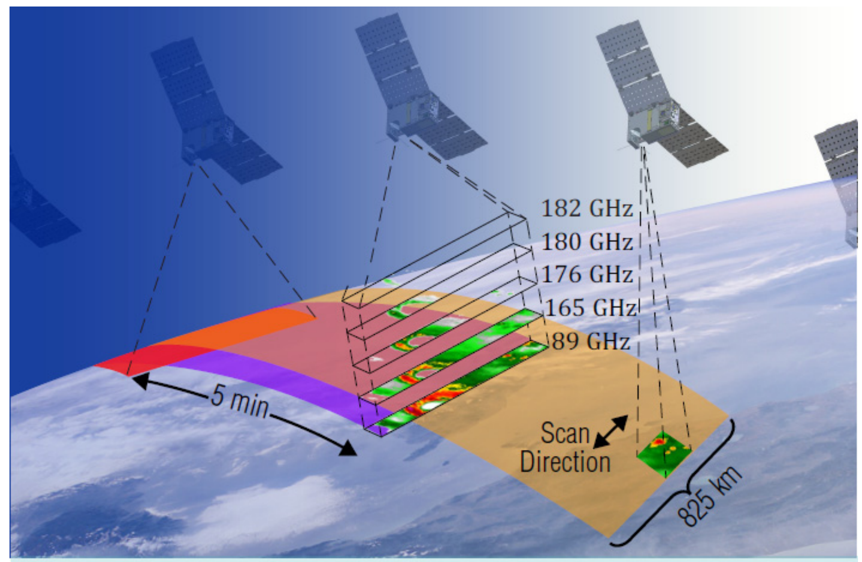


Temporal Experiment for Storms and Tropical Systems (TEMPEST)

TEMPEST addresses 2017 National Academies Earth Science Decadal Survey:

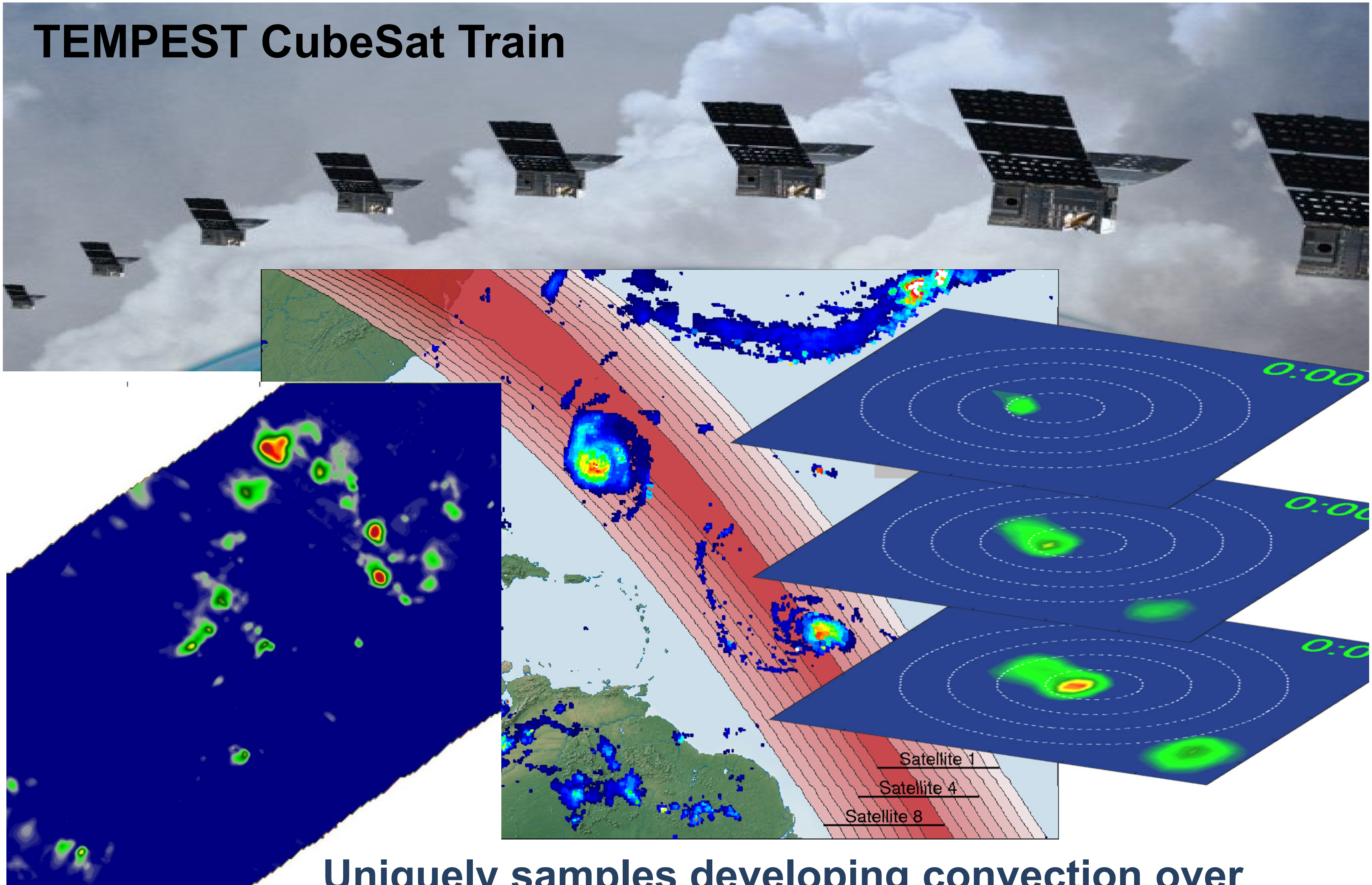
- *Why do convective storms, heavy precipitation, and clouds occur exactly when and where they do?* ("Most Important" Science Question W-4)
  - Providing global, *temporally-resolved observations of cloud and precipitation processes* using a train of 6U CubeSats with millimeter-wave radiometers
  - Sampling rapid changes in convective clouds and surrounding water vapor environment every 3-4 minutes for up to 30 minutes.

- TEMPEST-D, a NASA Earth Venture Tech Demo mission, delivered a 6U CubeSat with radiometer instrument to launch provider 2.5 years after project start.
- Launch provided by CSLI on ELaNa 23
- Launched by Orbital ATK on CRS-9 from NASA Wallops to ISS on May 21, 2018
- Deployed into orbit from ISS by Nanoracks on July 13, 2018.



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

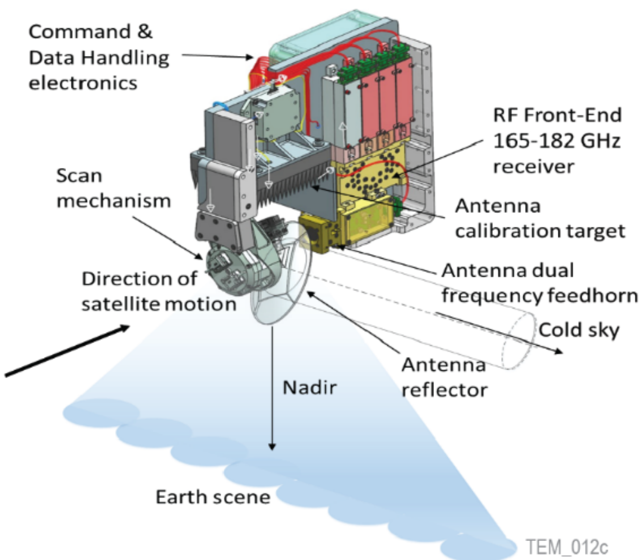
TEMPEST CubeSat Train



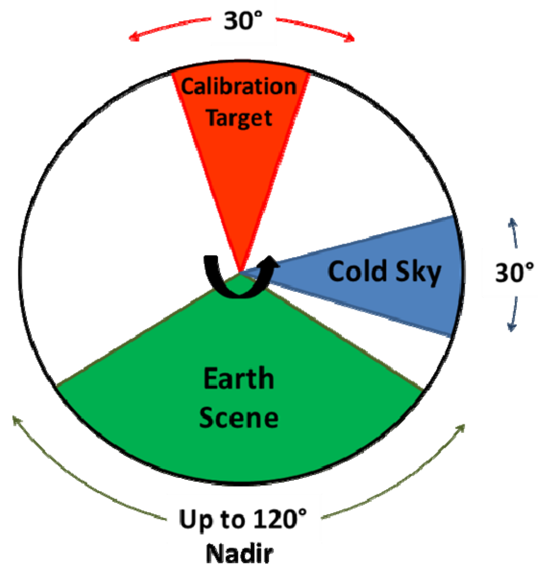
Uniquely samples developing convection over 3-30 minute time scales

TEMPEST-D Instrument Performs End-to-End Radiometric Calibration

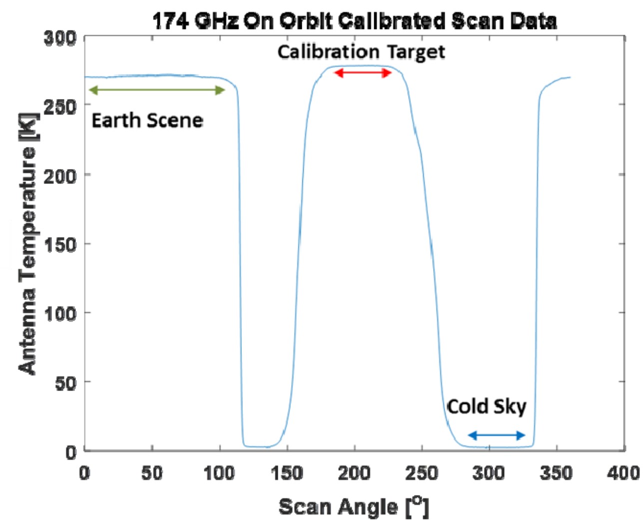
TEMPEST-D Instrument



Observing Profile

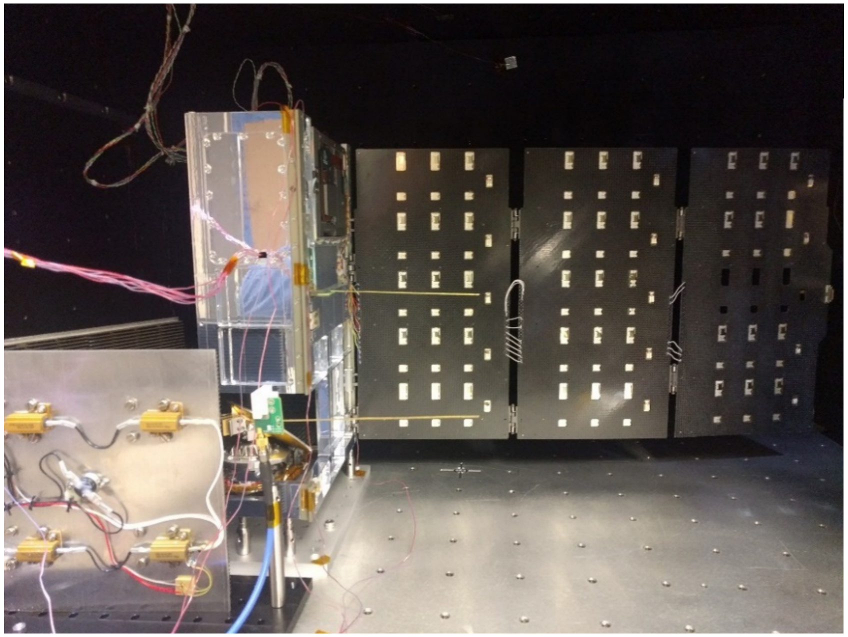


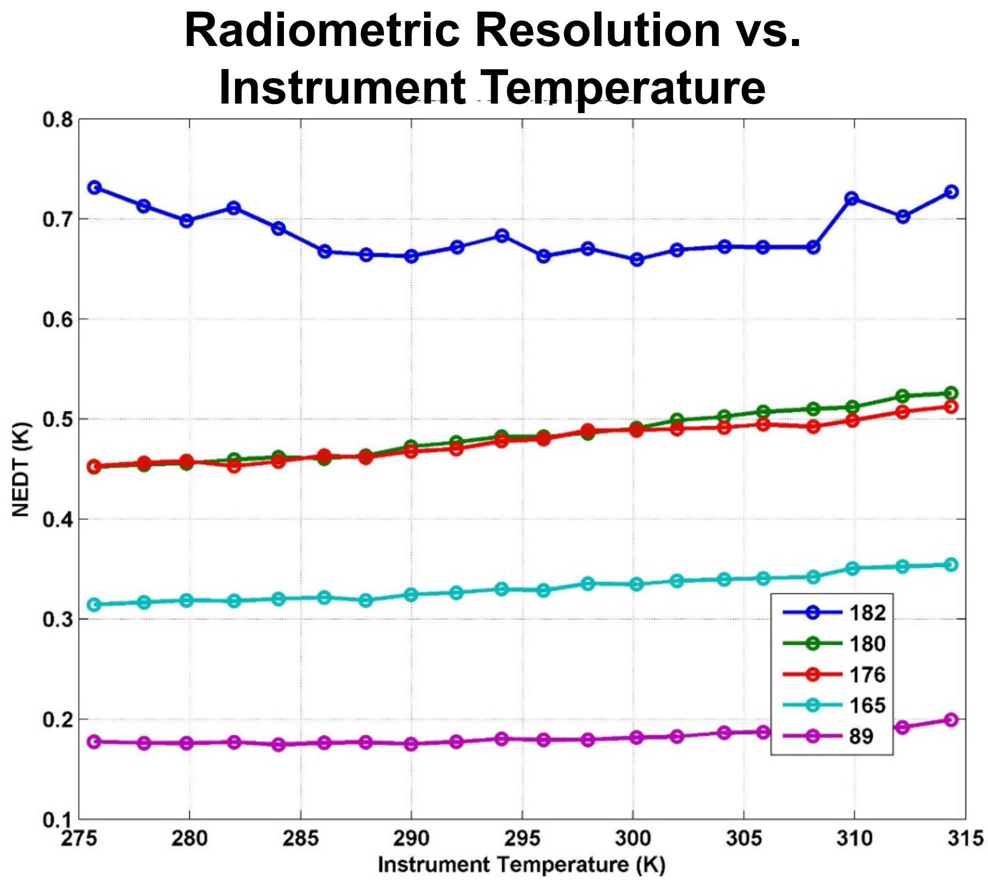
Brightness Temp. Time Series



- Five-frequency millimeter-wave radiometer measures Earth scene up to ±60° nadir angles, for an 1550-km swath width from a initial orbit altitude of 400 km. Spatial resolution ranges from 13 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 Instrument Performance: Pre-Launch and On-Orbit

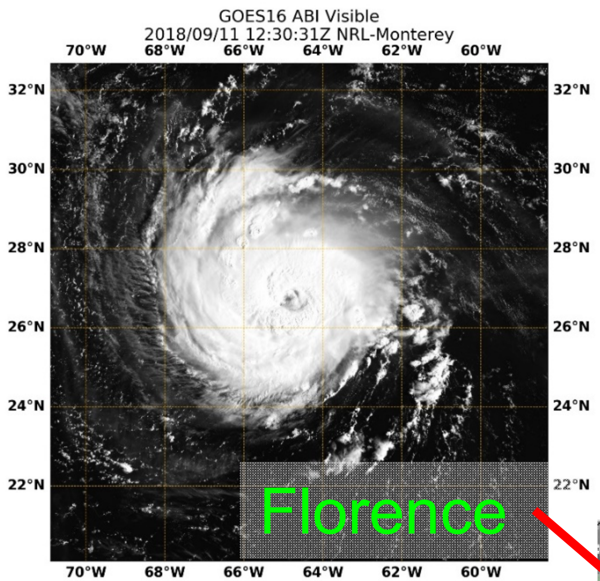




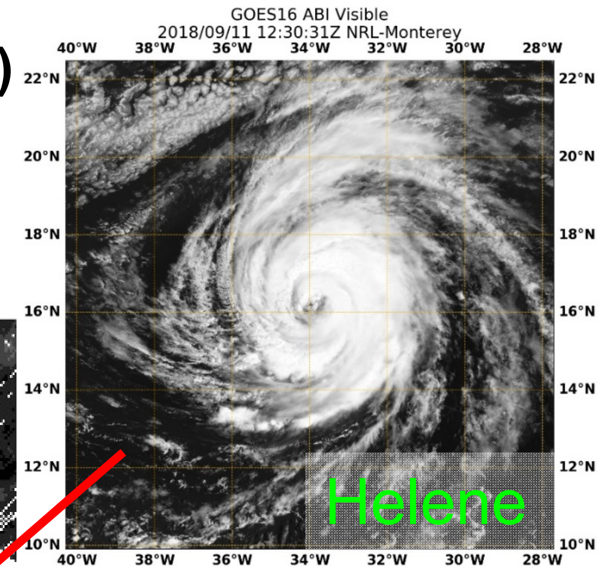
Frequency (GHz)	Pre-launch NEdT (K)	On-orbit NEdT (K)
87	**0.2**	**0.2**
164	**0.3**	**0.3**
174	**0.5**	**0.5**
178	**0.5**	**0.5**
181	**0.7**	**0.7**

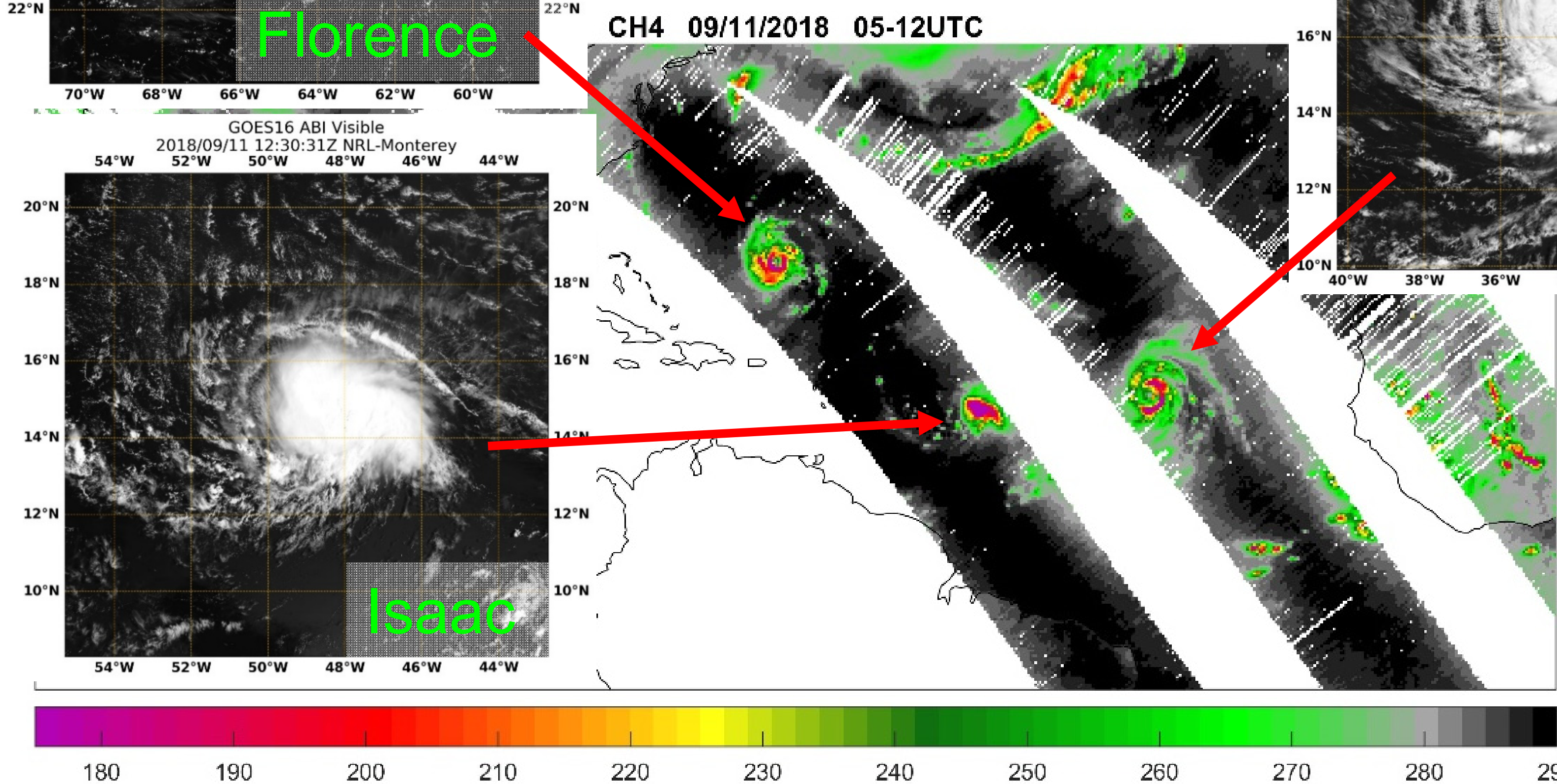
Measured radiometric resolution (NEdT) with **5-ms integration time,** both pre-launch and on-orbit, easily meet total noise requirements of 1.4 K for all five millimeter-wave radiometer channels.

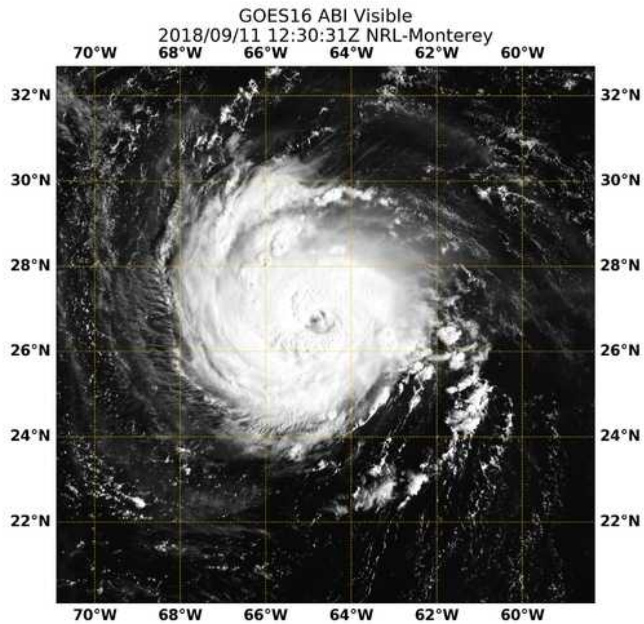
TEMPEST-D Data: First Full Orbits on Sept. 11, 2018

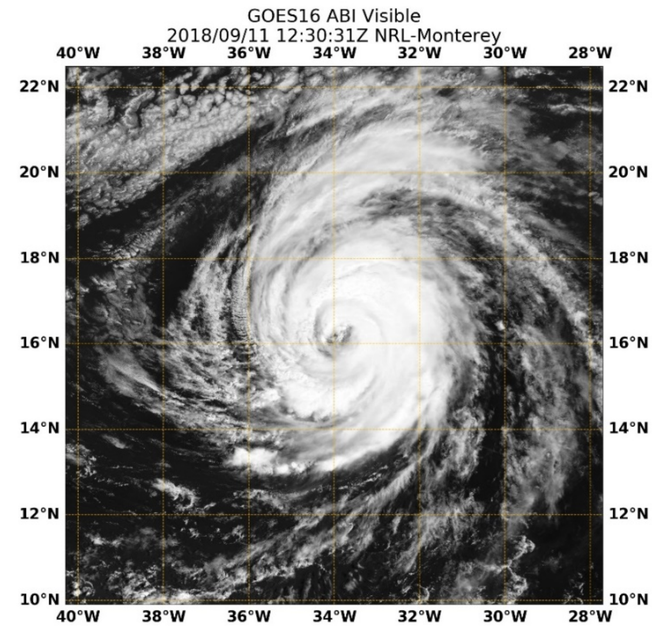


TEMPEST-D 164 GHz Brightness Temperature (K)

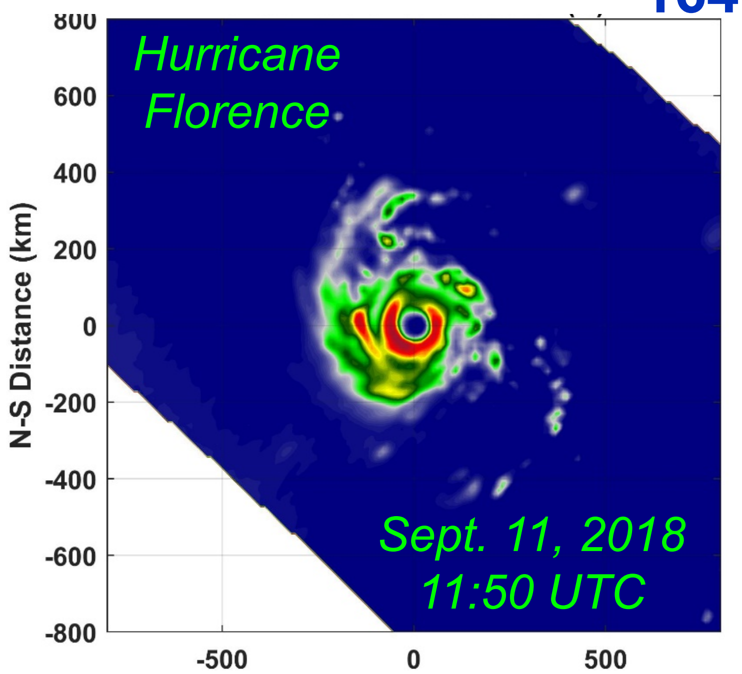


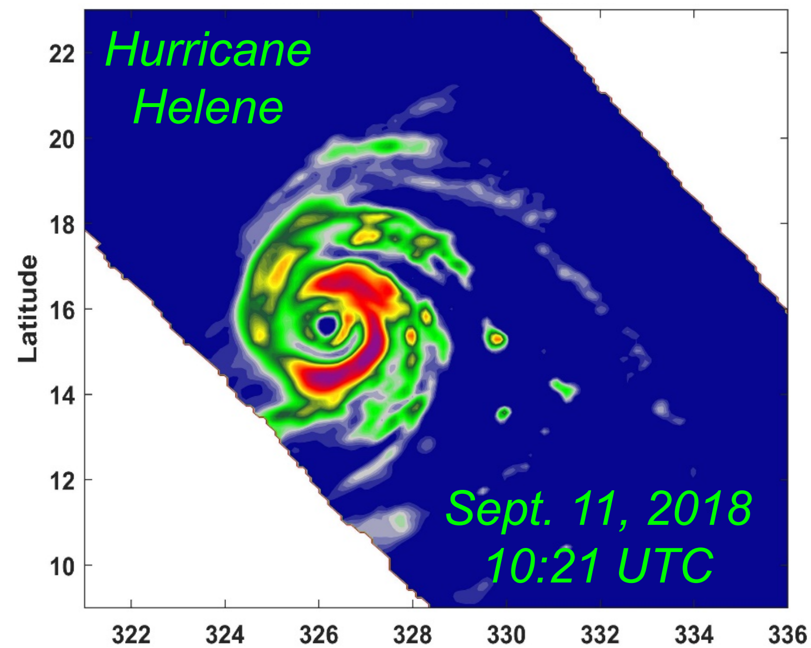


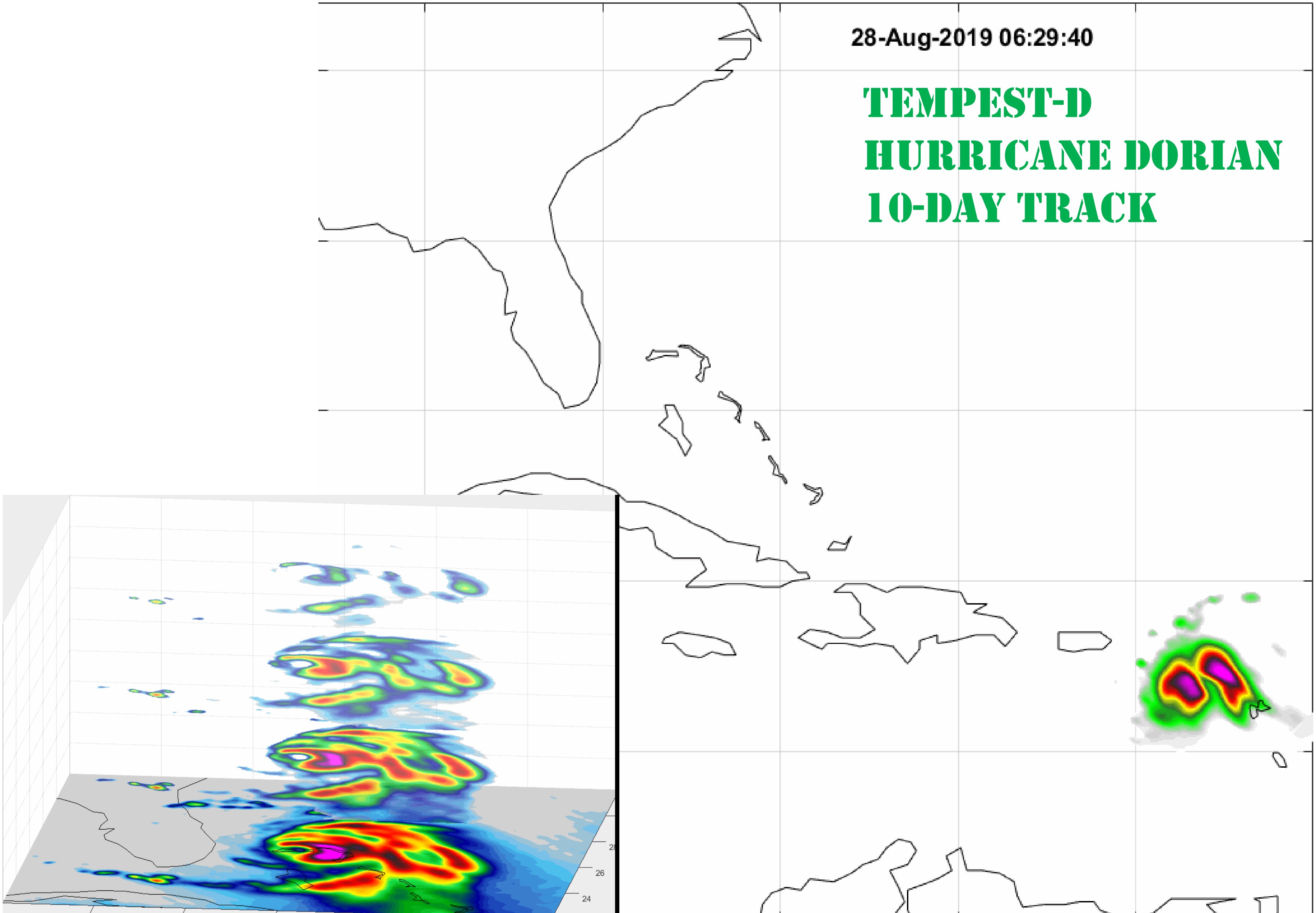

GOES16 ABI Visible
2018/09/11 12:30:31Z NRL-Monterey
70°W 68°W 66°W 64°W 62°W 60°W
32°N 30°N 28°N 26°N 24°N 22°N


GOES16 ABI Visible
2018/09/11 12:30:31Z NRL-Monterey
40°W 38°W 36°W 34°W 32°W 30°W 28°W
22°N 20°N 18°N 16°N 14°N 12°N 10°N

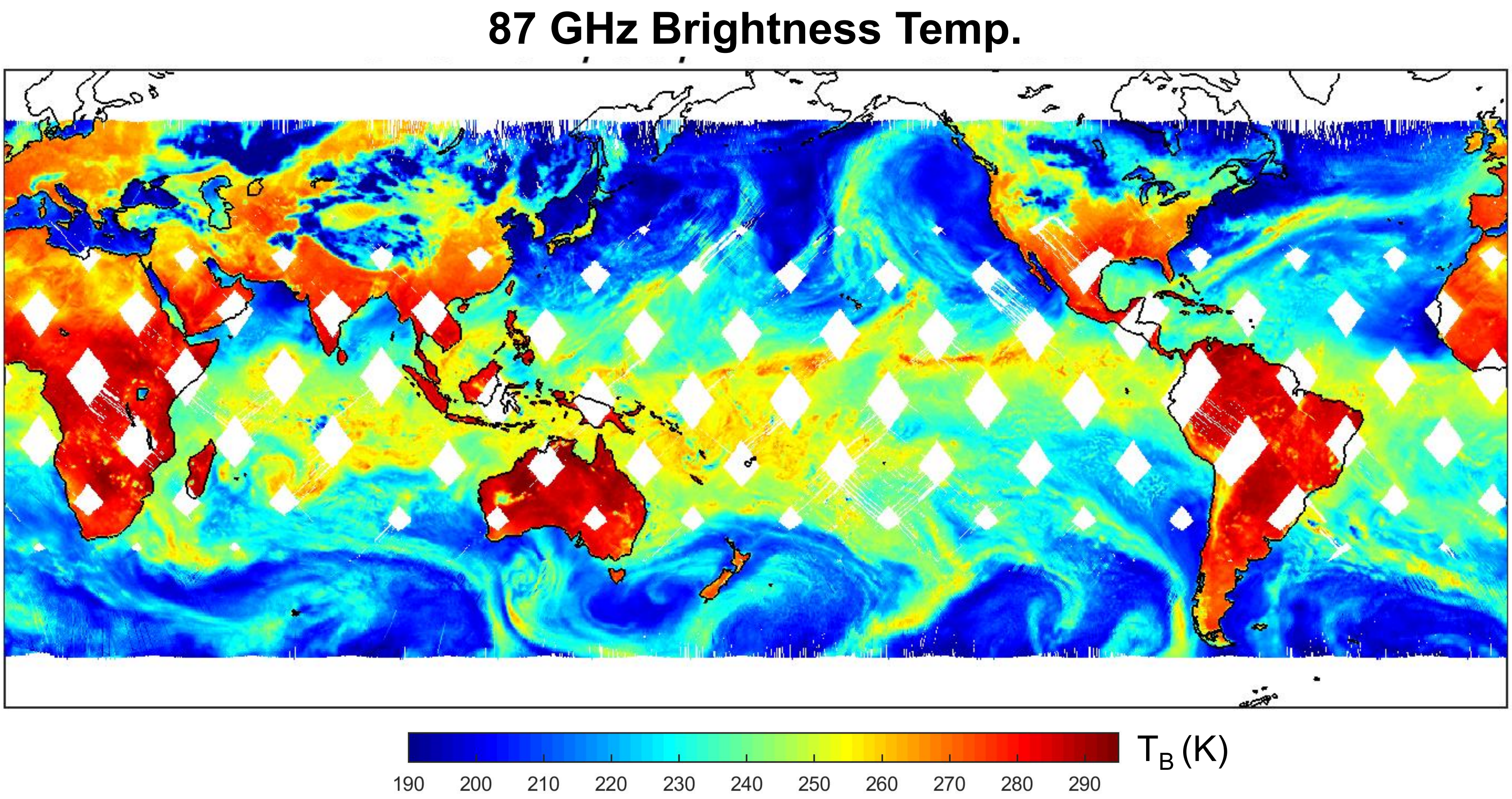
164 GHz TB (K)


Hurricane
Florence
Sept. 11, 2018
11:50 UTC
N-S Distance (km)
800 600 400 200 0 -200 -400 -600 -800
-500 0 500

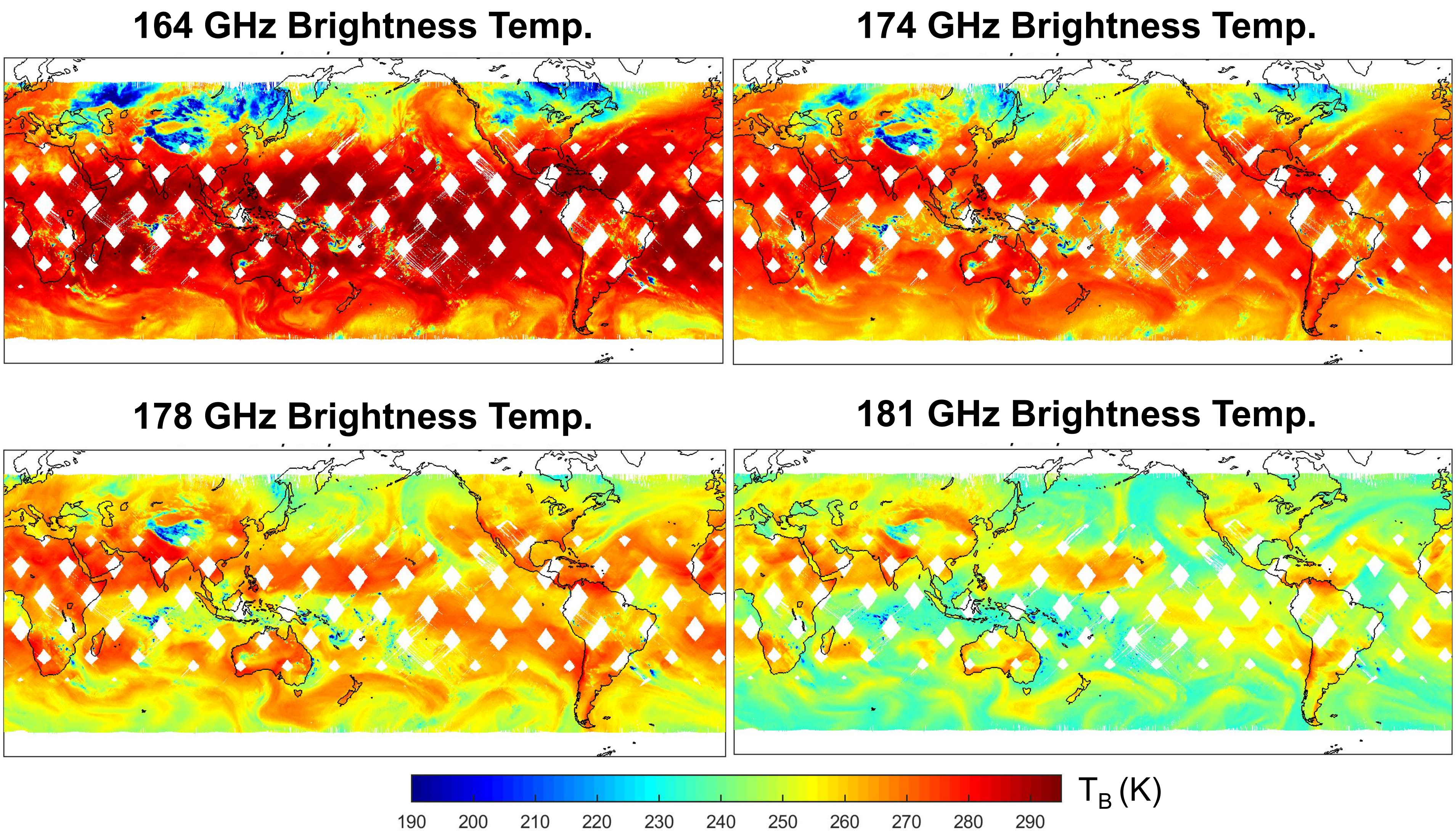

Hurricane
Helene
Sept. 11, 2018
10:21 UTC
Latitude
22 20 18 16 14 12 10
322 324 326 328 330 332 334 336

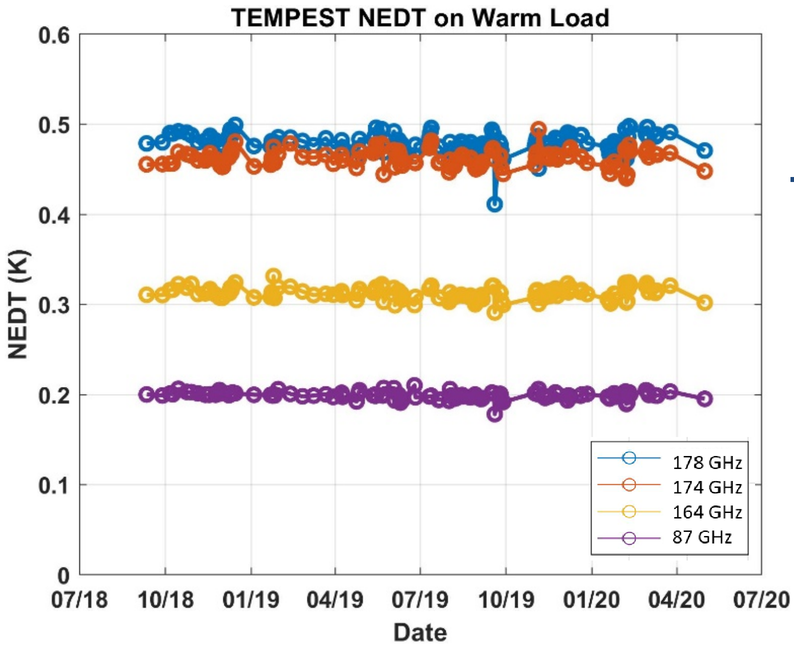

28-Aug-2019 06:29:40
TEMPEST-D
HURRICANE DORIAN
10-DAY TRACK

TEMPEST-D Brightness Temperatures at 87 GHz on February 9, 2020



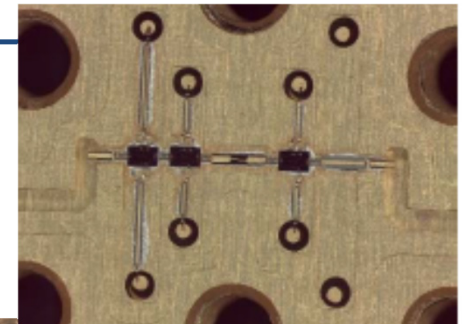
TEMPEST-D Brightness Temperatures at 164-181 GHz on February 9, 2020

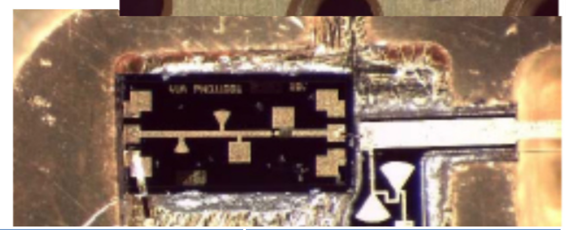




Radiometer Noise

- Extremely low-noise due to new InP HEMT amplifier technology
- Stable over mission to date



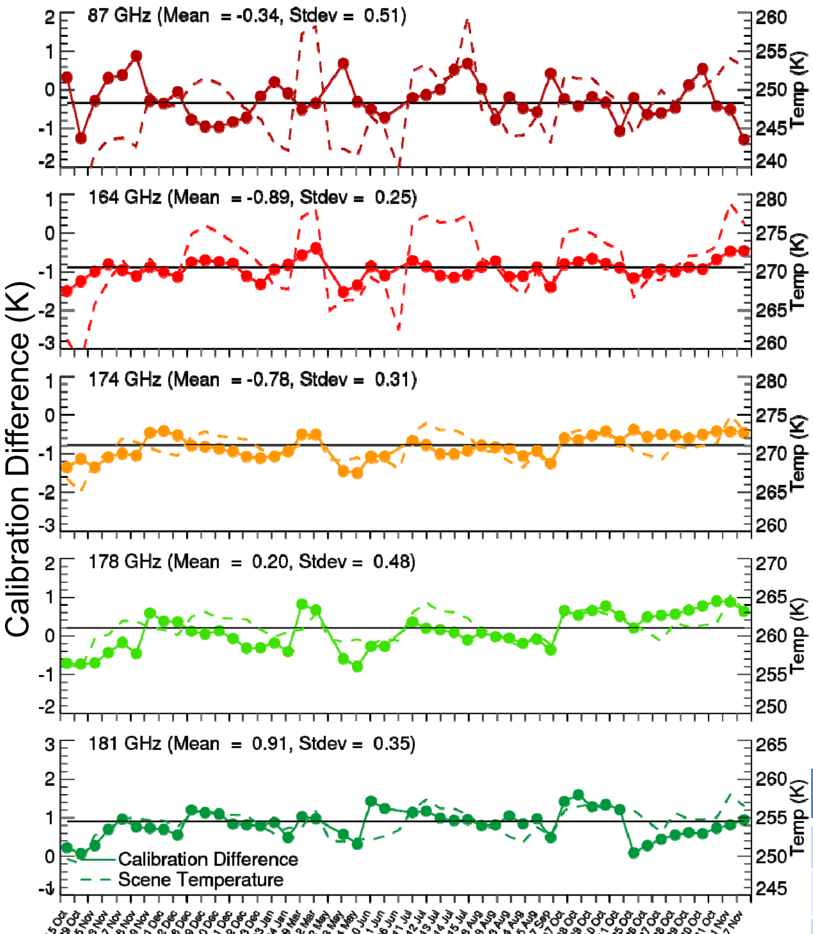


TEMPEST-D demonstrates improved receiver performance over the current generation of NOAA operational sensors

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., 2014

TEMPEST-D Sensor Cross-Calibration Results after 1.5 Years of Operations



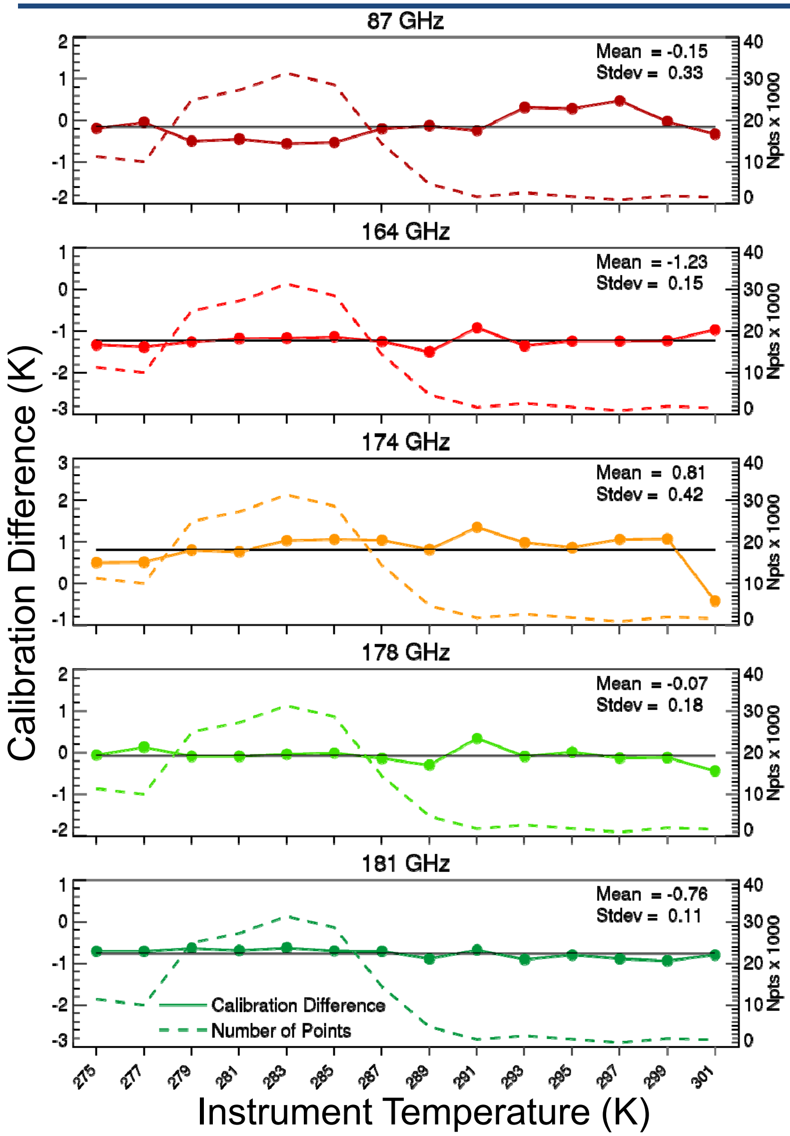
Mean calibration differences between TEMPEST-D and four reference sensors based on 50 days of data over a 13-month period. Dashed lines indicate corresponding mean scene brightness temperatures. From Berg et al., *IEEE TGRS*, accepted, May 2020.

- Double difference technique developed for GPM used to validate TEMPEST-D data compared to GMI and 3 MHS sensors on NOAA and EUMETSAT sensors
- TEMPEST absolute calibration accuracy within 1 K of reference sensors, well within 4 K accuracy requirement.
- TEMPEST calibration precision (std. dev.) within 0.7 K of reference sensors, well within 2 K precision requirement.
- Due to differences from MHS frequency and polarization (157 GHz, QV) and radiative transfer model errors, actual cal diff. for 164 GHz channel is closer to GMI, i.e., 0.33 K.
- **Results indicate TEMPEST-D is 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 (1DVar)	-0.28	-0.33	-0.88	0.62	0.95
MetOp-A MHS	-0.38	-0.94	-0.36	0.12	1.41
MetOp-B MHS	-0.37	-1.26	-0.82	-0.29	1.21
NOAA-19 MHS	-0.45	-1.88	-0.77	-0.33	0.35
Mean (MHS + GMI)	**-0.34**	**-0.89**	**-0.78**	**0.20**	**0.91**
Standard Deviation	**0.07**	**0.65**	**0.23**	**0.44**	**0.46**

TEMPEST-D Instrument Temperature Stability after One Year of Operations

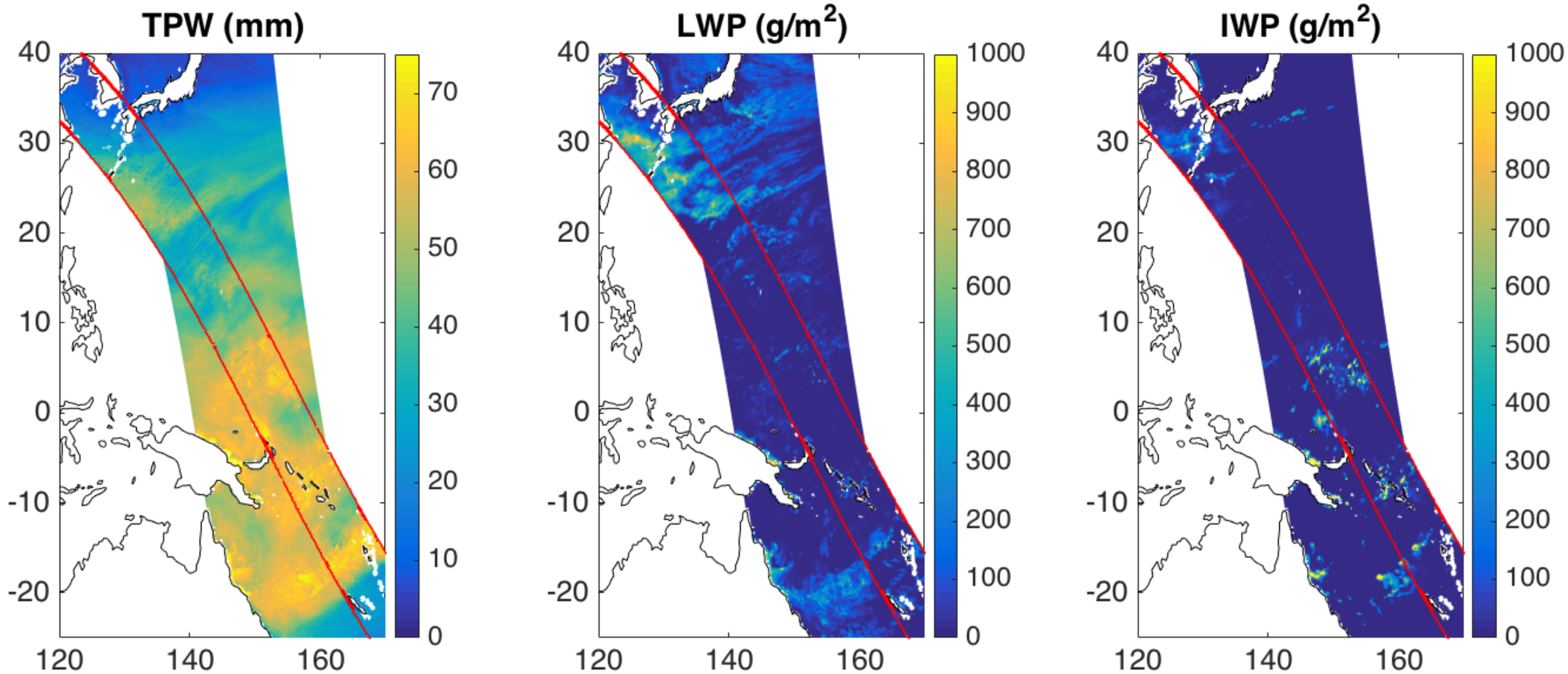


- Mean calibration differences between TEMPEST-D and four reference sensors as a function of instrument temperature based on 50 days of data over 13-month period of on-orbit operations.
- Solid lines show calibration difference (K, left axis). Dashed lines show the number of observations in the 2-degree interval (right axis).
- All five channels exhibit consistent calibration differences across the full range of observed instrument temperatures, **showing no evidence of calibration errors associated with changes in instrument temperature**.

Figure adapted from Berg et al., 2020, “Calibration and Validation of the TEMPEST-D CubeSat Radiometer,” *IEEE TGRS*, accepted with minor revisions, May 2020.

TEMPEST-D Water Vapor and Cloud Retrievals

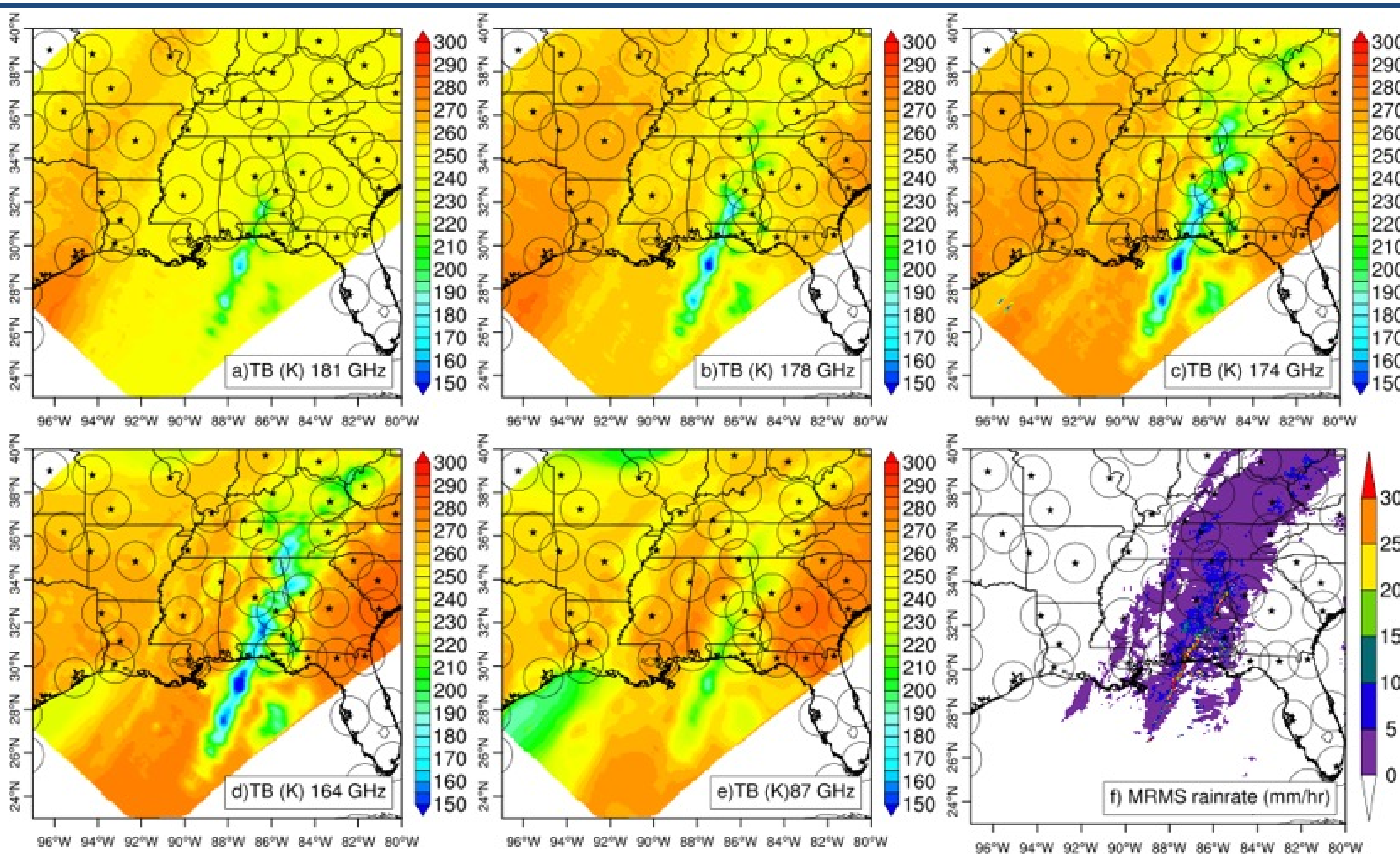
Plotted over NOAA/NESDIS STAR MiRS Retrieval from MHS



Water Vapor Cloud Liquid Cloud Ice

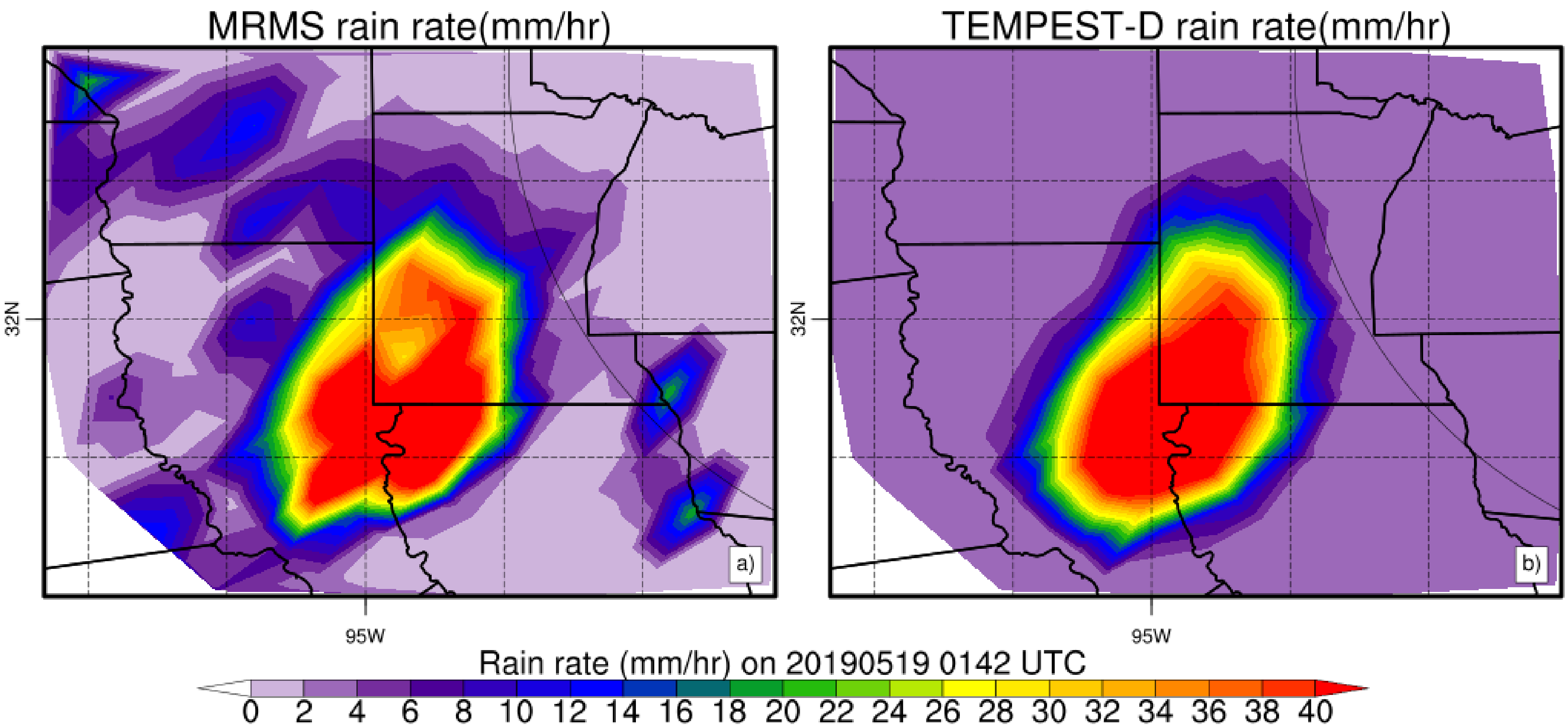
- Near-coincident observations with MHS on MetOp-B on Dec. 9, 2018 at 11:24 UTC
- The two instruments and retrieval algorithms agree on the main features of the water vapor field, with no sharp gradients between the two swaths.
- They also agree well on the location of liquid phase clouds to the south of Japan, as well as the existence of ice particles to the north of Papua New Guinea.
- Figure adapted from Schulte, R., et al., *JTECH*, Feb. 2020, doi:10.1175/JTECH-D-19-0163.1

Southeastern U.S. Precipitation: Comparison to Ground Radar Rainfall



TEMPEST-D observations from Jan. 29, 2019 over a southeastern U.S. winter storm, with ground-based weather radar rainfall estimates shown in the lower-right panel. Circles show the area covered by each ground-based radar.

Precipitation Retrievals over Land and Comparison to Ground Radar

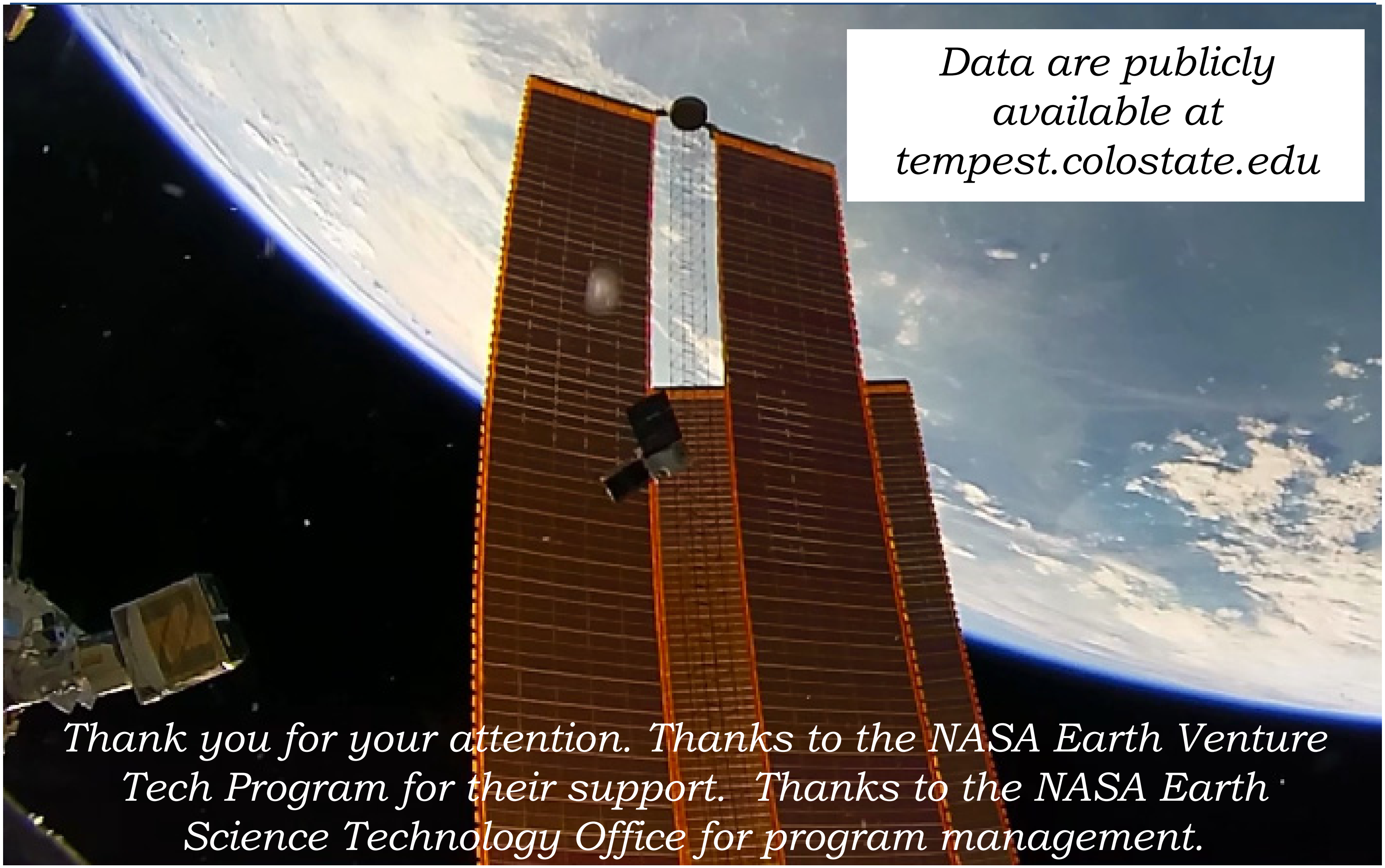


Retrieval of rainfall from storm at ground level over Texas on May 19, 2019, at 01:42 UTC comparing ground-based radar MRMS rain rate (left) with TEMPEST-D rain rate (right). The two rain rate retrievals have a correlation coefficient of 0.93.

Public Distribution of TEMPEST-D Data

TEMPEST-D calibrated Level 1b data are publicly available (after user registration) at https://tempest.colostate.edu/data. 23 users from 8 countries on 4 continents have downloaded TEMPEST-D calibrated data, as shown in the table below.

Institution	Location	Country
Aerospace Corporation	El Segundo, CA and Merritt Island, FL	USA
Andrew Seidl	San Mateo, CA	USA
CGM	Asheboro, NC	USA
CNES	Toulouse, Occitanie	France
CNR Institute of Atmospheric Sciences & Climate	Bologna	Italy
Colorado State University	Fort Collins, CO	USA
Dominion Energy	Richmond, VA	USA
Georgetown University	Washington, DC	USA
Hancock Whitney Bank	New Orleans, LA	USA
Harp Technologies Ltd.	Espoo	Finland
Japan Meteorological Agency	Tokyo	Japan
Karlsruhe Institute of Technology	Karlsruhe	Germany
NASA/Caltech Jet Propulsion Laboratory	Pasadena, CA	USA
NASA/Goddard Space Flight Center	Greenbelt, MD	USA
Météo-France	Toulouse, Haute Garonne	France
Mississippi State University	Starkville, MS	USA
National Meteorological Service	Buenos Aires	Argentina
Naval Research Laboratory	Monterey, CA	USA
NOAA Headquarters	Silver Spring, MD	USA
NOAA/NESDIS/STAR	College Park, MD	USA
Orbital Micro Systems	Boulder, CO	USA
University of Leicester	Leicester, Leicestershire	United Kingdom
University of Maryland	College Park, MD	USA



Data are publicly available at tempest.colostate.edu

Thank you for your attention. Thanks to the NASA Earth Venture Tech Program for their support. Thanks to the NASA Earth Science Technology Office for program management.