ESTF2020

TEMPEST-D: Temporal Experiment for Storms and Tropical Systems Demonstration

Presenter & PI: Steven C. Reising, *Colorado State University*

Team Members:

W. Berg, C. D. Kummerow, V. Chandrasekar, R. Schulte,
Y. Goncharenko and C. Radhakrishnan; *Colorado State University*

S. T. Brown, T. C. Gaier, S. Padmanabhan, B. H. Lim & C. Heneghan;
NASA Caltech/Jet Propulsion Laboratory

M. Pallas, D. Laczkowski, N. Gaytan & A. Bullard; *Blue Canyon Tech.*

Program: EVI-2

Thanks to NASA Wallops for ground comms.

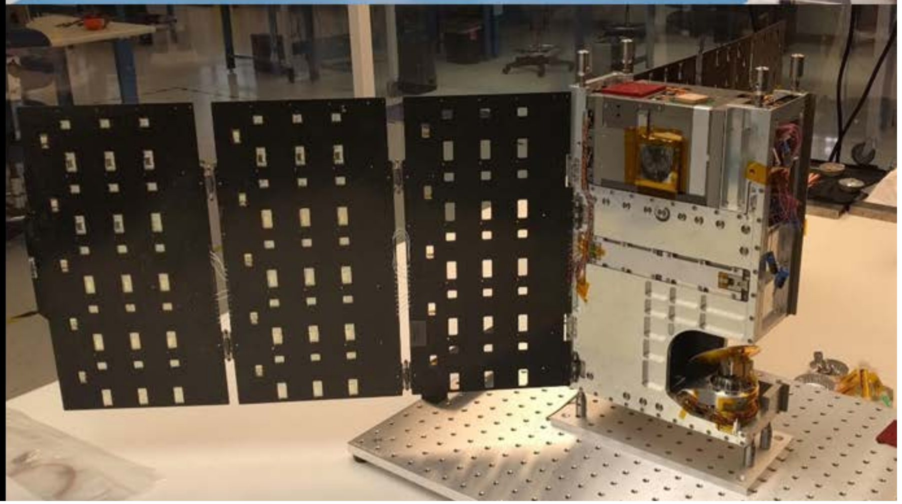
Temporal Sampling of Passive Microwave

- 2017 Earth Science Decadal Survey:
  - Most Important Science Question W-4: *"Why do convective storms, heavy precipitation, and clouds occur exactly when and where they do?"*
- Geostationary satellites with frequent temporal sampling provide only visible & IR, measuring cloud-top location and temperature, lacking the capability to provide all-weather sounding.
  - Microwave atmospheric humidity and temperature sounding has the greatest quantitative impact on weather forecasting (AMSU/MHS/ATMS)
- Satellite microwave sounders profiling all-weather atmospheric temperature & humidity, as well as microwave imagers measuring storms & precipitation, have *limited temporal sampling*.
  - Microwave sensors in LEO have long revisit times (constellations have refresh times of hours).
  - A variety of technological limitations and cost have prevented deployment of microwave sounders in GEO, or greater numbers of microwave sounders & imagers in LEO, to date.

TEMPEST-D CubeSat Sounding Radiometer

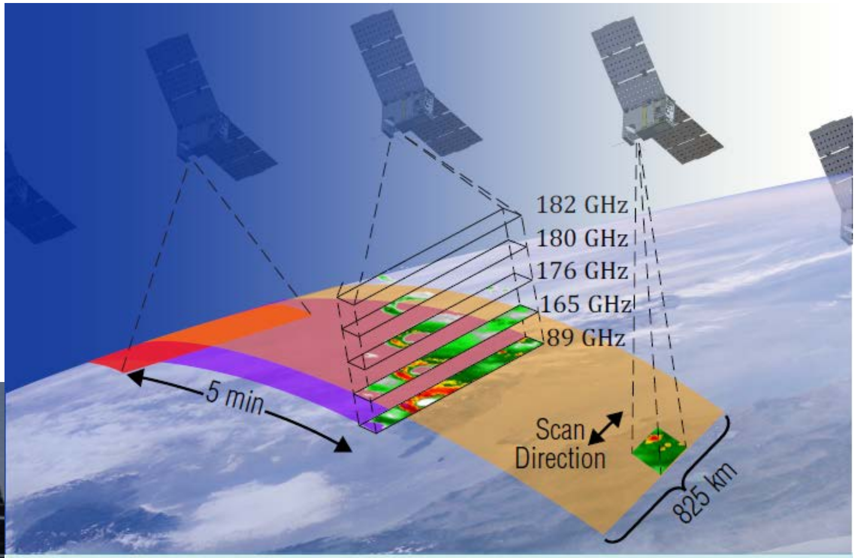
NOAA Advanced Technology Microwave Sounder (ATMS)
75 kg, 100 W, $$$$

TEMPEST-D
3.8 kg, 6.5 W, $



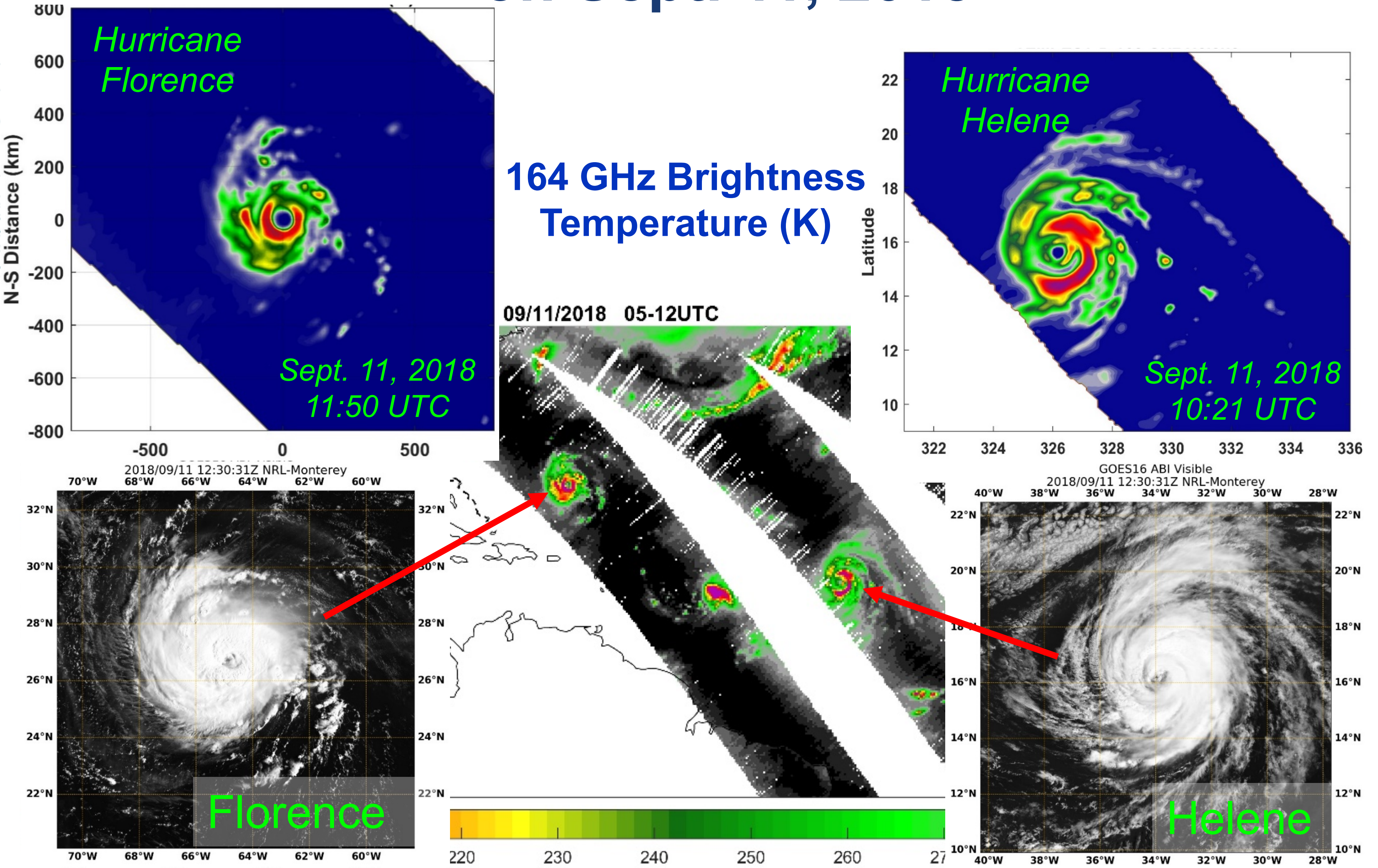
Temporal Experiment for Storms and Tropical Systems Tech Demo (TEMPEST-D) Mission

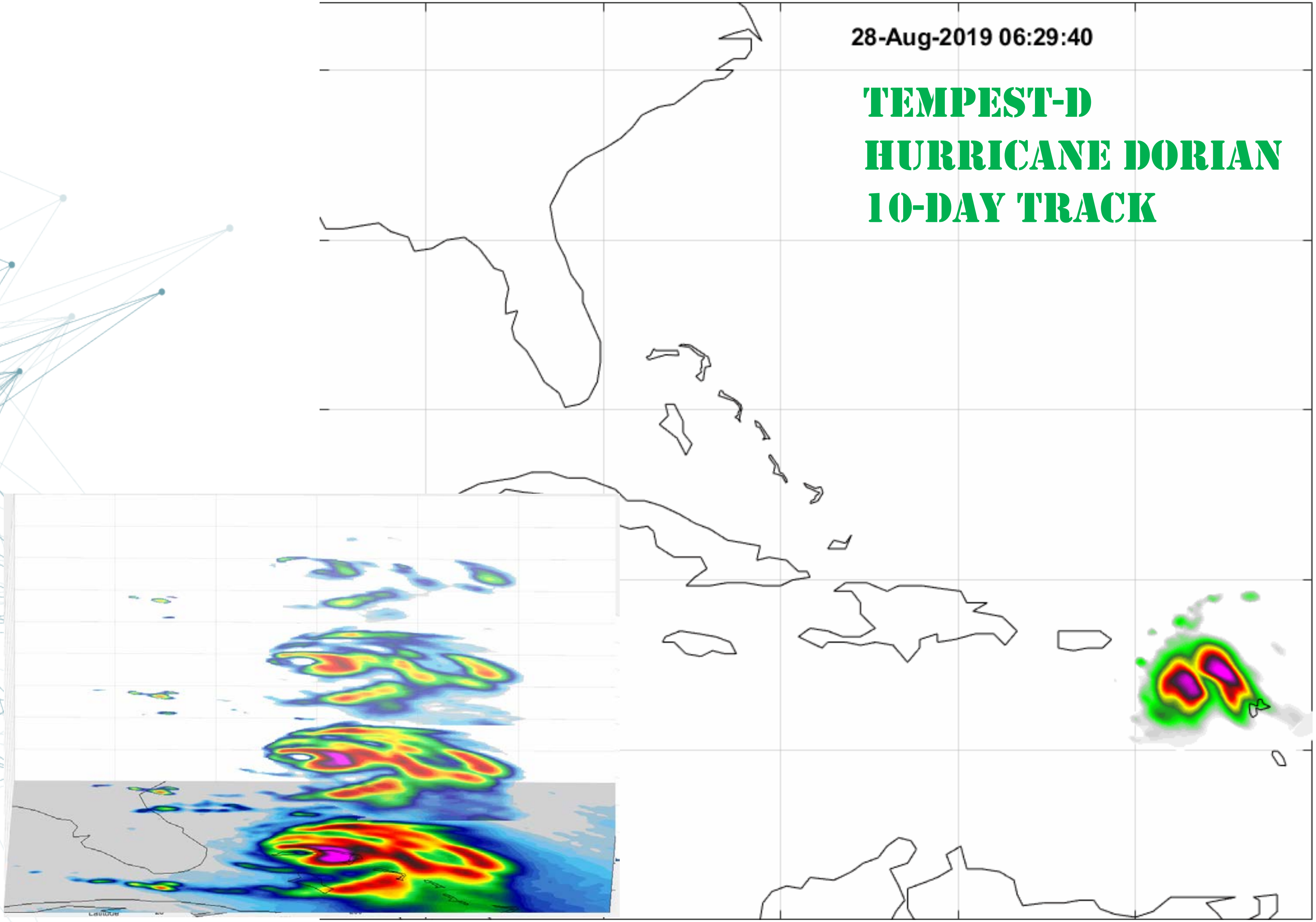
- Proposed to EVI-2 as a constellation of 5 identical 6U CubeSats to sample clouds & water vapor every 3-5 minutes for up to 30 minutes.
- Chosen as Earth Venture Tech Demo 90-day mission and delivered a 6U CubeSat with multi-channel millimeter-wave radiometer for launch less than 2 years after PDR.
- Launched by Orbital ATK (now Northrop Grumman) from NASA Wallops to ISS on May 21, 2018. Deployed into orbit by Nanoracks on July 13, 2018.



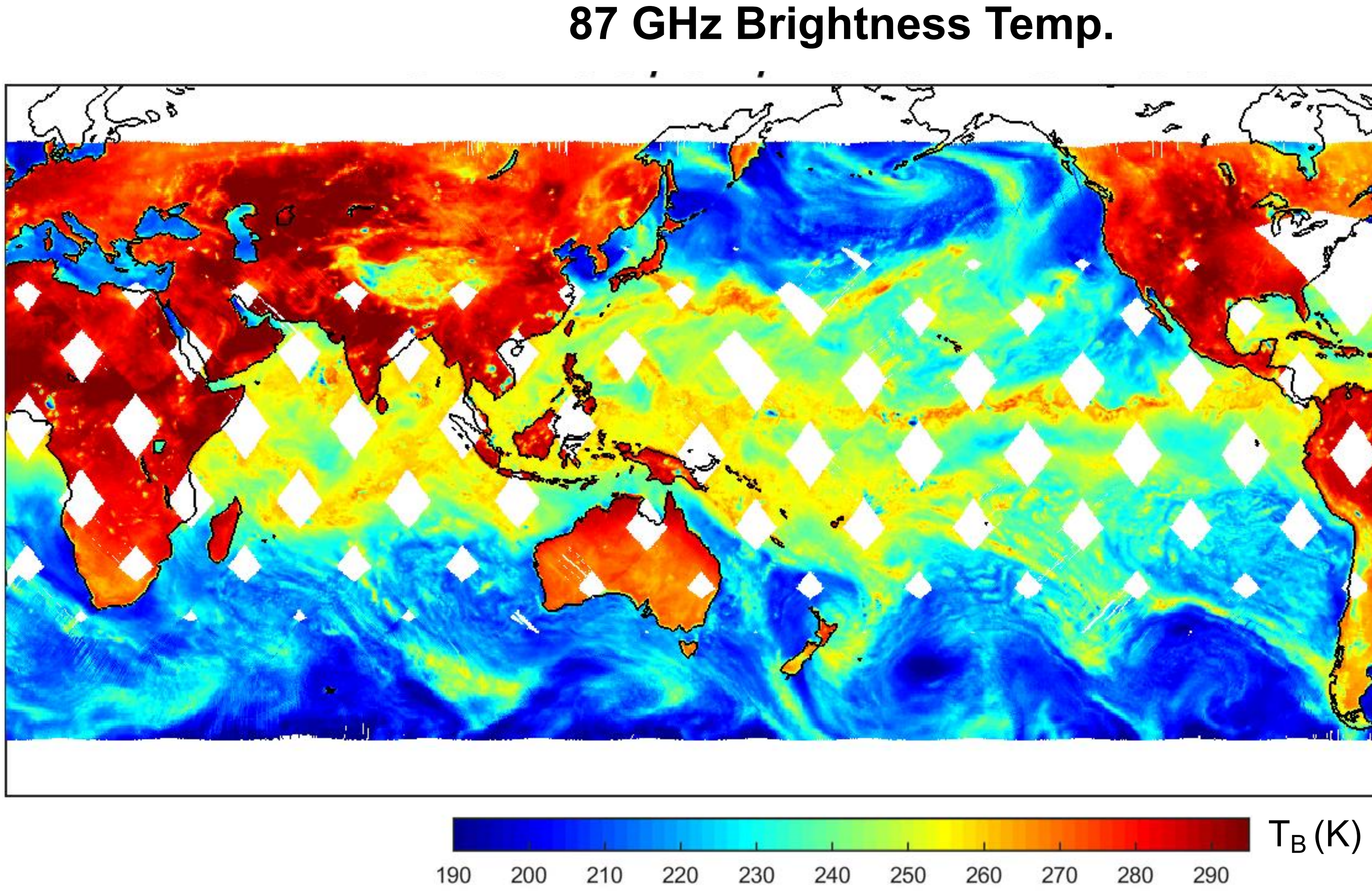
5 identical 6U small sats, each with an identical 5-channel radiometer, flying 5 minutes apart

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

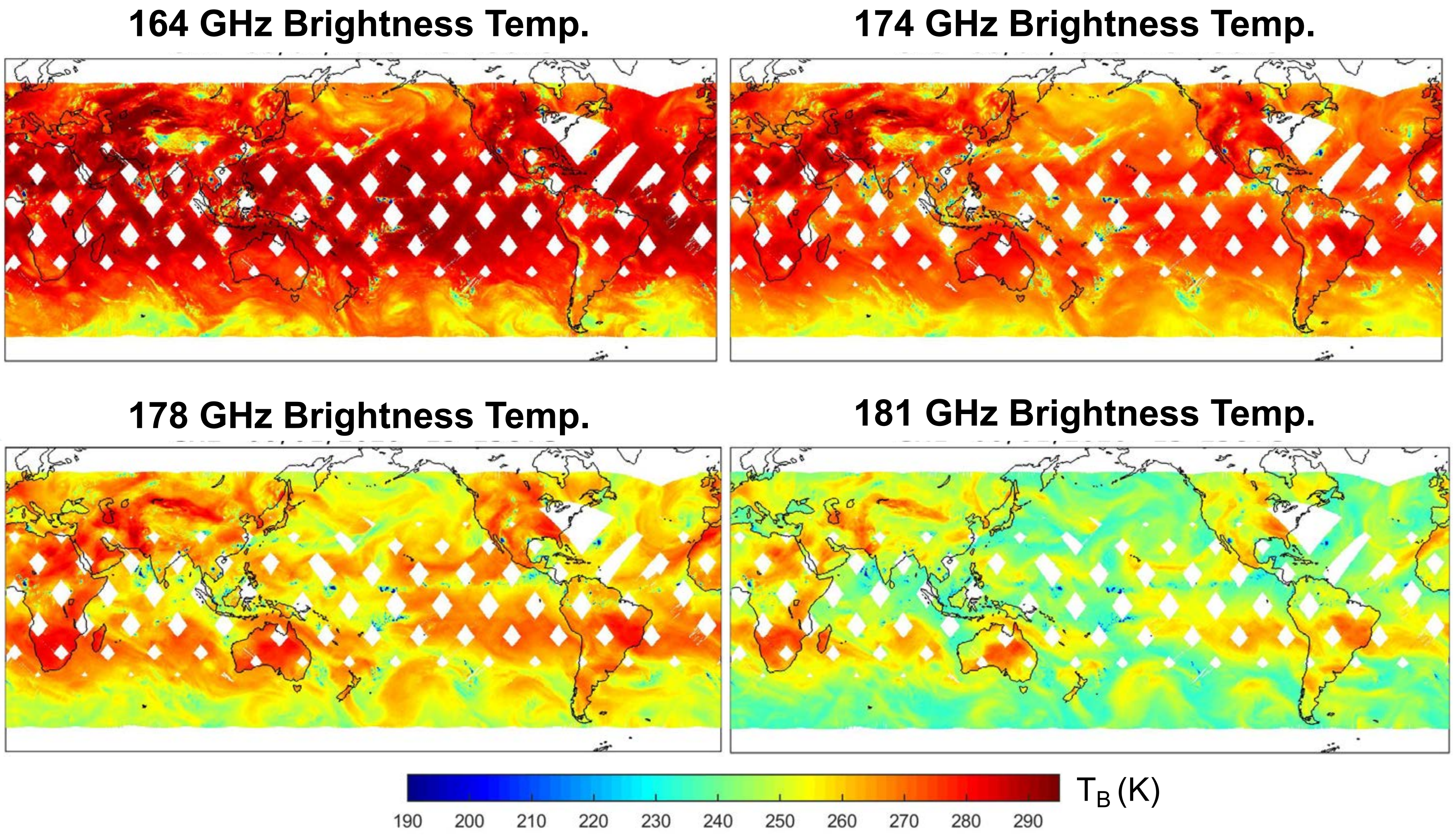



28-Aug-2019 06:29:40
TEMPEST-D
HURRICANE DORIAN
10-DAY TRACK

TEMPEST-D Brightness Temperatures at 87 GHz on June 1, 2020

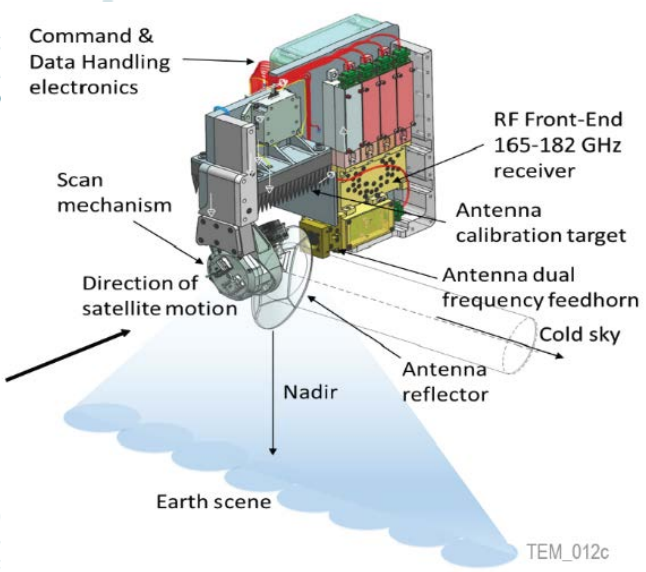


TEMPEST-D Brightness Temperatures at 164-181 GHz on June 1, 2020

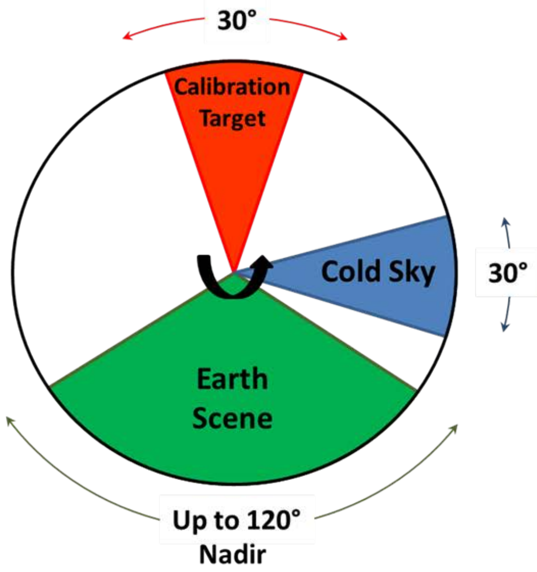


TEMPEST-D Instrument Performs End-to-End Radiometric Calibration

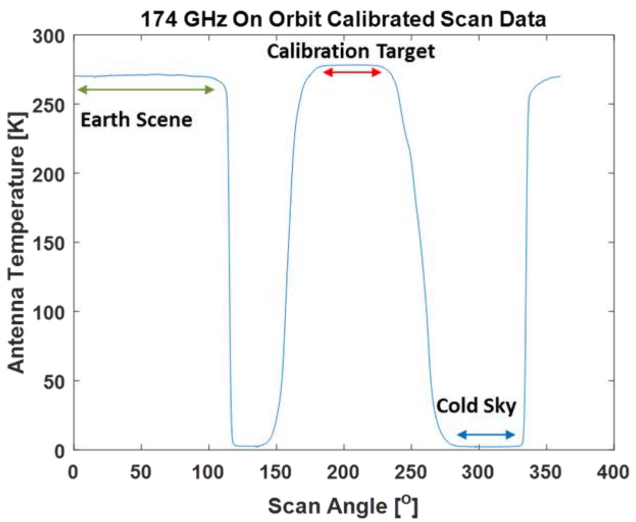
TEMPEST-D Instrument



Observing Profile

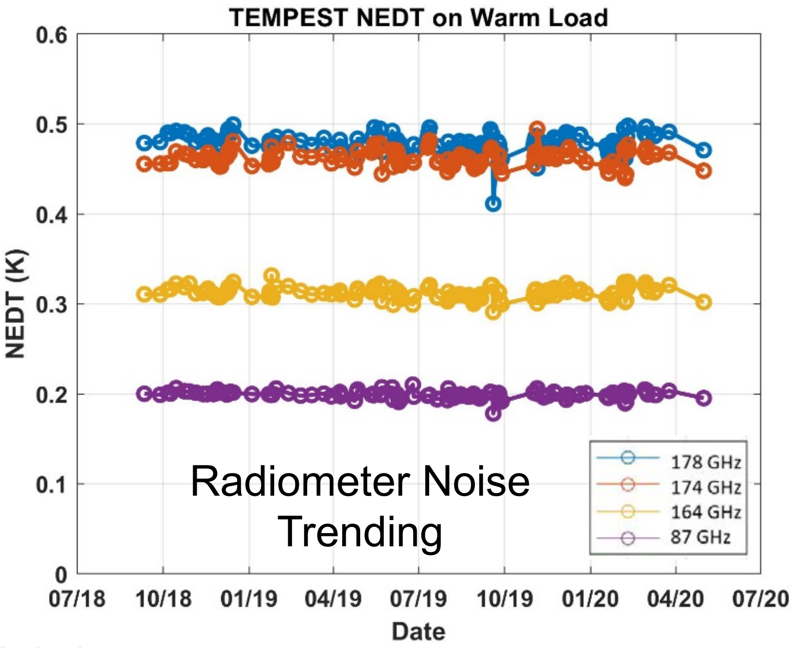


Brightness Temp. Time Series

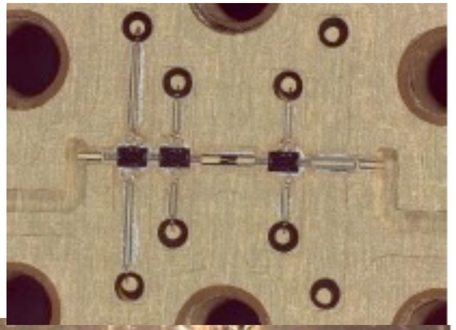


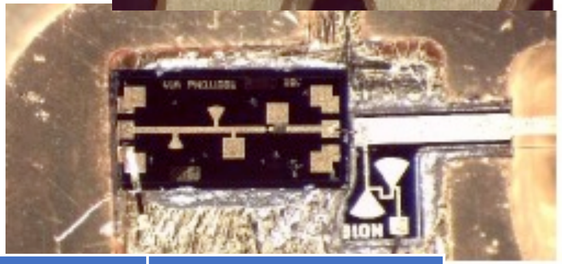
- Five-frequency millimeter-wave radiometer measures Earth scene up to ±60° nadir angles, for an 1550-km swath width from a initial orbit altitude of 400 km. Spatial resolution ranges from 13 km at 181 GHz to 25 km at 87 GHz.
- TEMPEST-D performs two-point end-to-end calibration every 2 sec. by measuring cosmic microwave background at 2.73 K (“cold sky”) and ambient blackbody calibration target each revolution (scanning at 30 RPM).

Radiometer Noise



- Extremely low-noise due to NGC/JPL InP HEMT amplifier technology
- On-orbit trending reduces risk for future operational sensors
- Noise and gain **stable** over mission to date



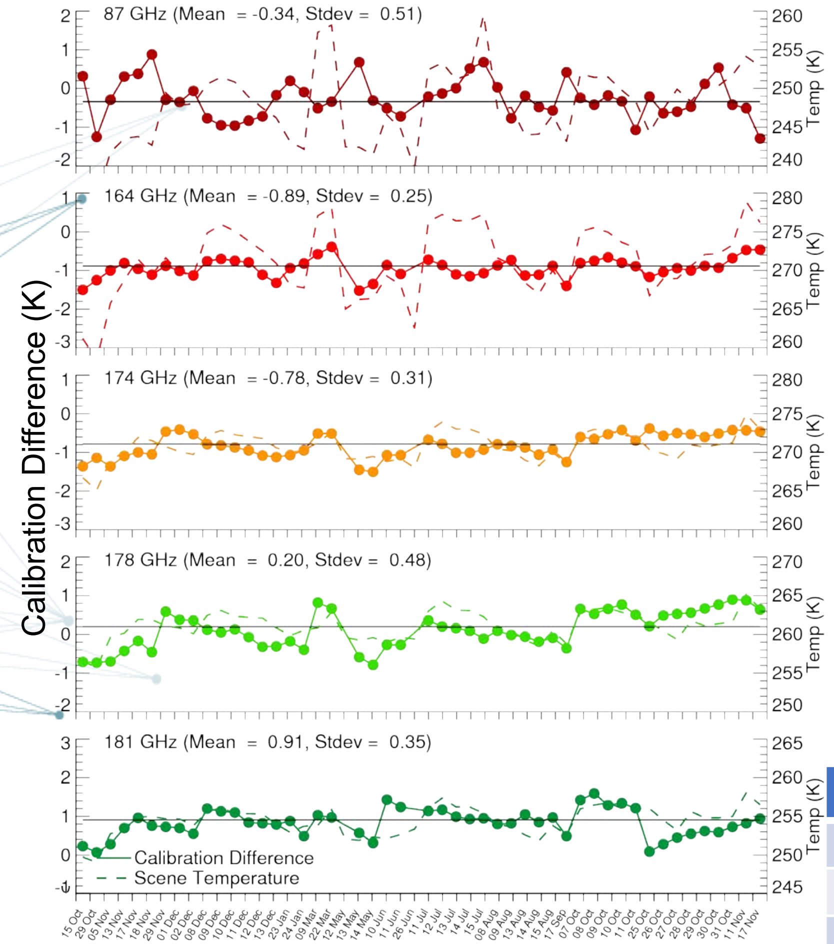


TEMPEST-D demonstrates improved receiver performance over current generation of NOAA operational sensors

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 Results after 21 Months of Operations



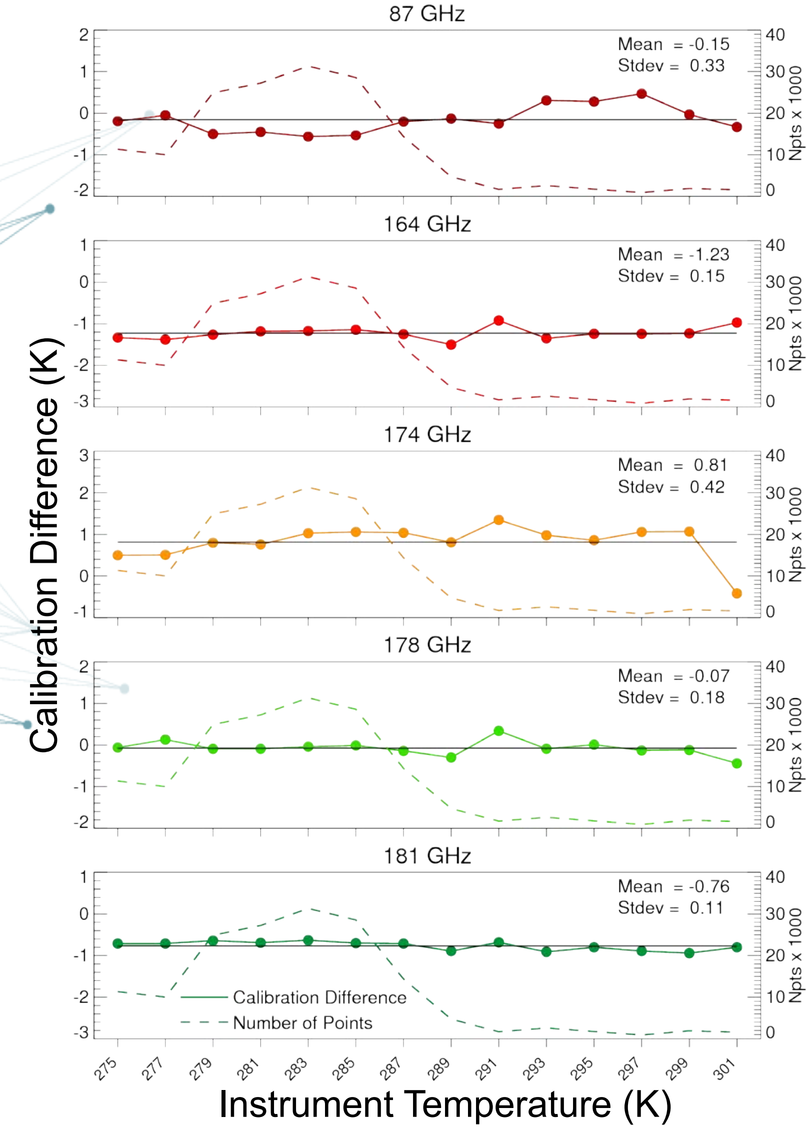
Mean calibration differences between TEMPEST-D and four reference sensors based on 50 days of data over a 13-month period. Dashed lines indicate corresponding mean scene brightness temperatures. From Berg et al., *IEEE TGRS*, accepted, May 2020.

- 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 21 Months of Operations

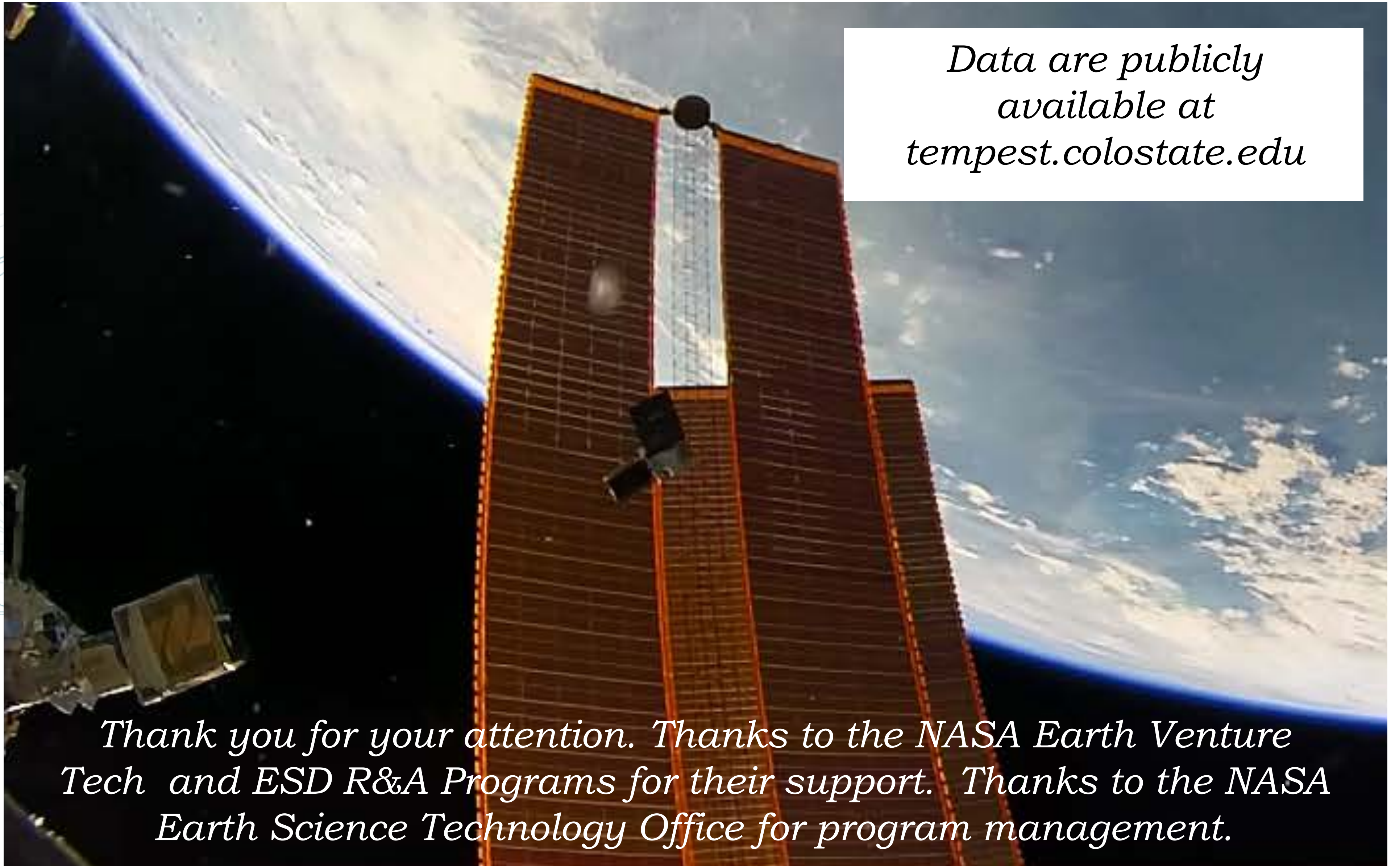


- Mean calibration differences between TEMPEST-D and four reference sensors as a function of instrument temperature based on 50 days of data over 13-month period of on-orbit operations.
- Solid lines show calibration difference (K, left axis). Dashed lines show the number of observations in the 2-degree 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 Mission Contributions

- TEMPEST-D, a NASA Earth Venture Tech Demo mission, met all of its Level 1 requirements within the first 90 days of operations.
- Demonstrated rapid development cycle with delivery of CubeSat with multi-frequency millimeter-wave radiometer within 2 years after PDR.
- TEMPEST-D is a very well calibrated and stable radiometer with very low noise, rivaling that of much larger operational satellite sensors.
- Shows no evidence of calibration errors associated with instrument temperature changes on orbit.
- Demonstrated infusion of ESTO-funded technology development from TRL 2 (ACT-08) to TEMPEST-D tech demo/science mission at TRL 9.
- Advancing atmospheric science, e.g. studying microphysics of tropical cyclones and squall lines through comparison with polarimetric radar.
- Continuing to produce atmospheric science data after 21 months of operations to date.



Data are publicly available at tempest.colostate.edu

Thank you for your attention. Thanks to the NASA Earth Venture Tech and ESD R&A Programs for their support. Thanks to the NASA Earth Science Technology Office for program management.