TEMPEST-based CubeSat Microwave Sounder Constellation to Improve Revisit Times of LEO Satellites for Weather Forecasting

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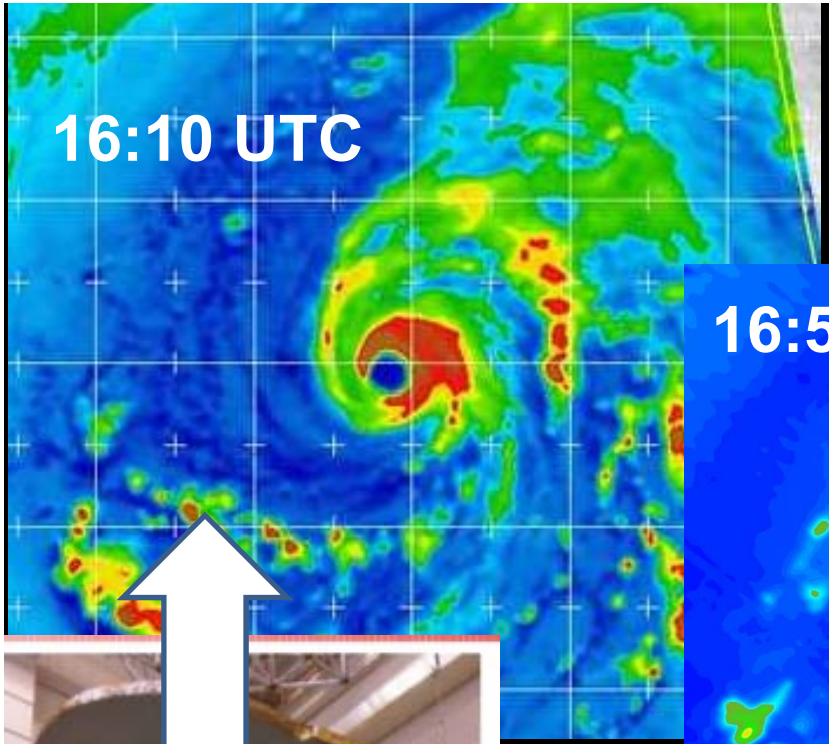
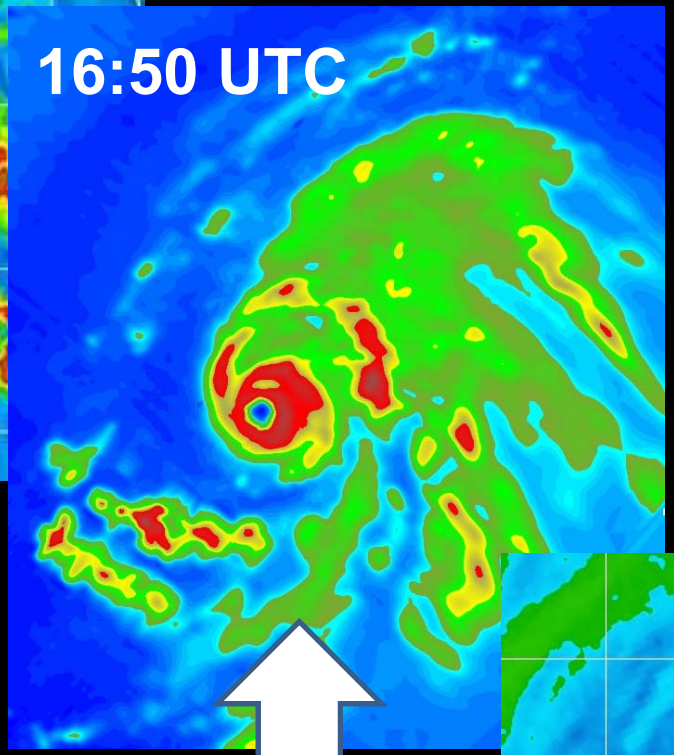
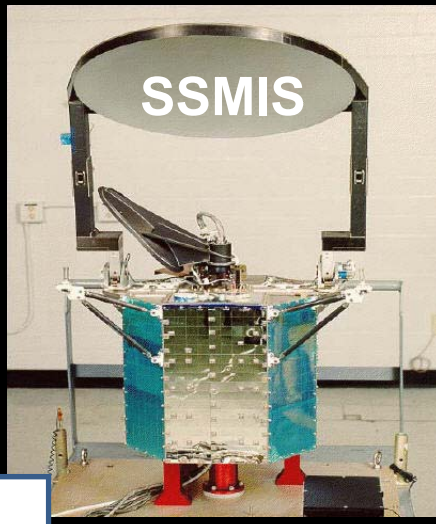
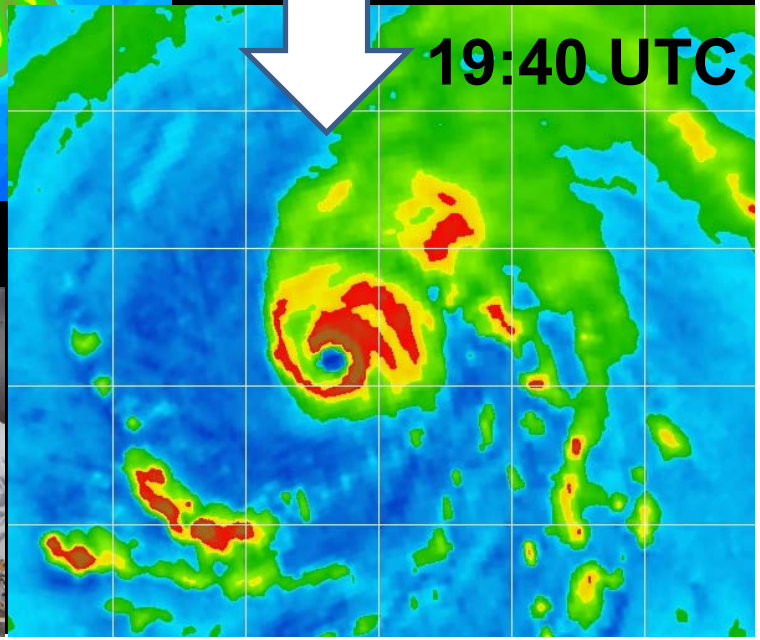
All thoughts and opinions expressed herein represent those of the authors alone and do not in any way represent those of any U.S. Government agency, including NOAA.

Hurricane Lorenzo, Sept. 26, 2019





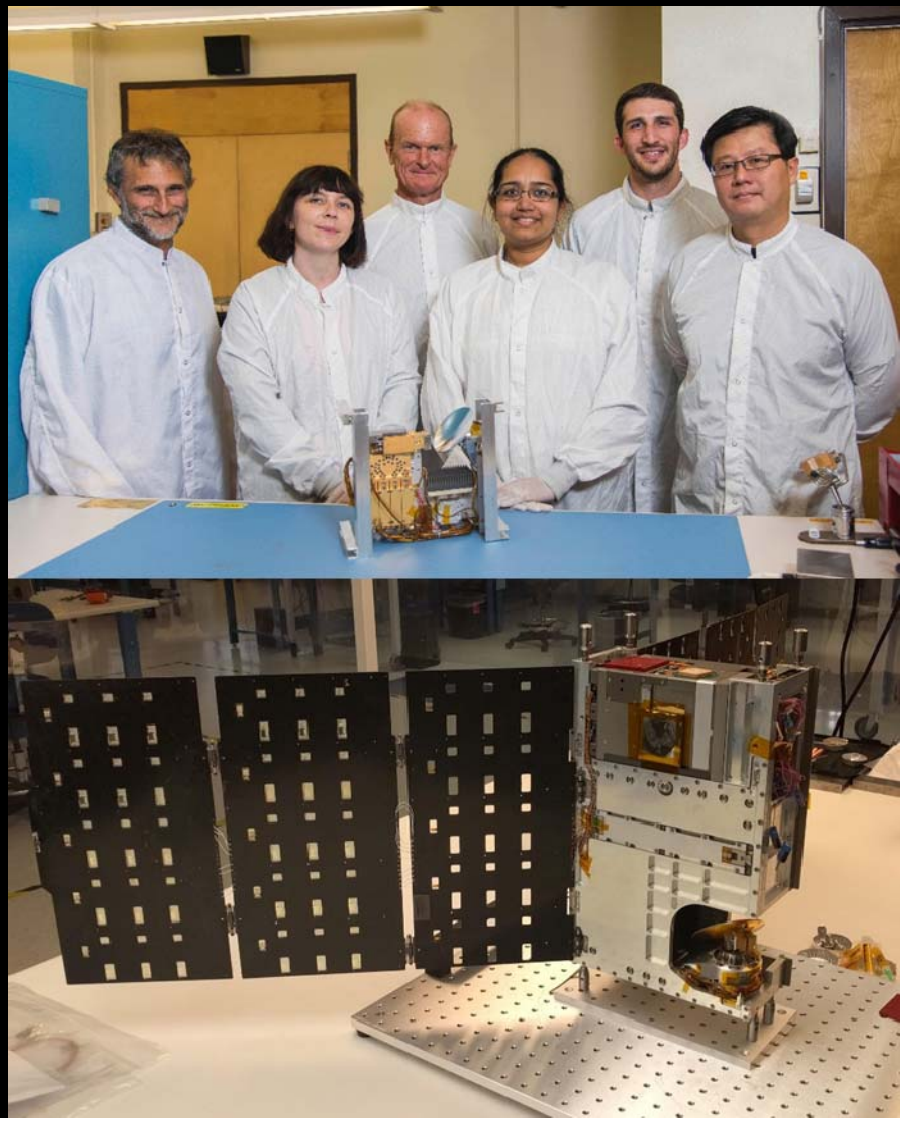




TEMPEST-D

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

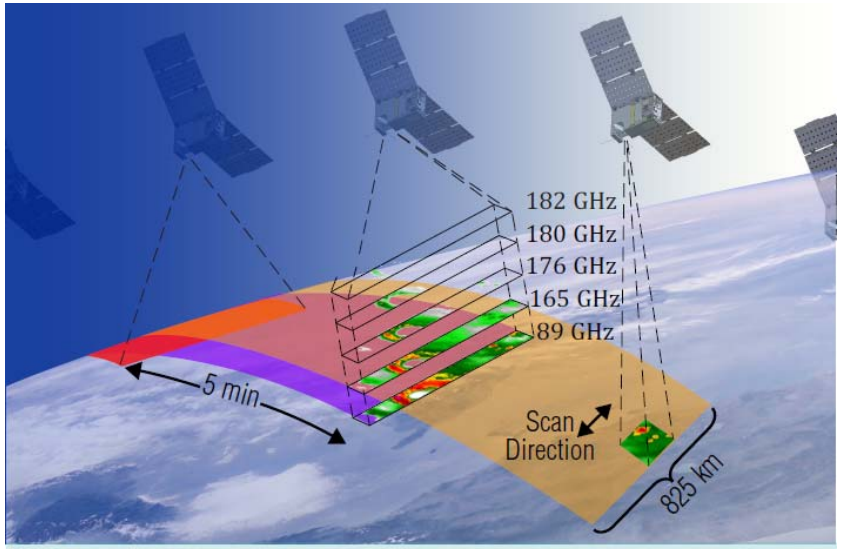
TEMPEST-D
3.8 kg, 6.5 W, $



Temporal Experiment for Storms and Tropical Systems (TEMPEST)

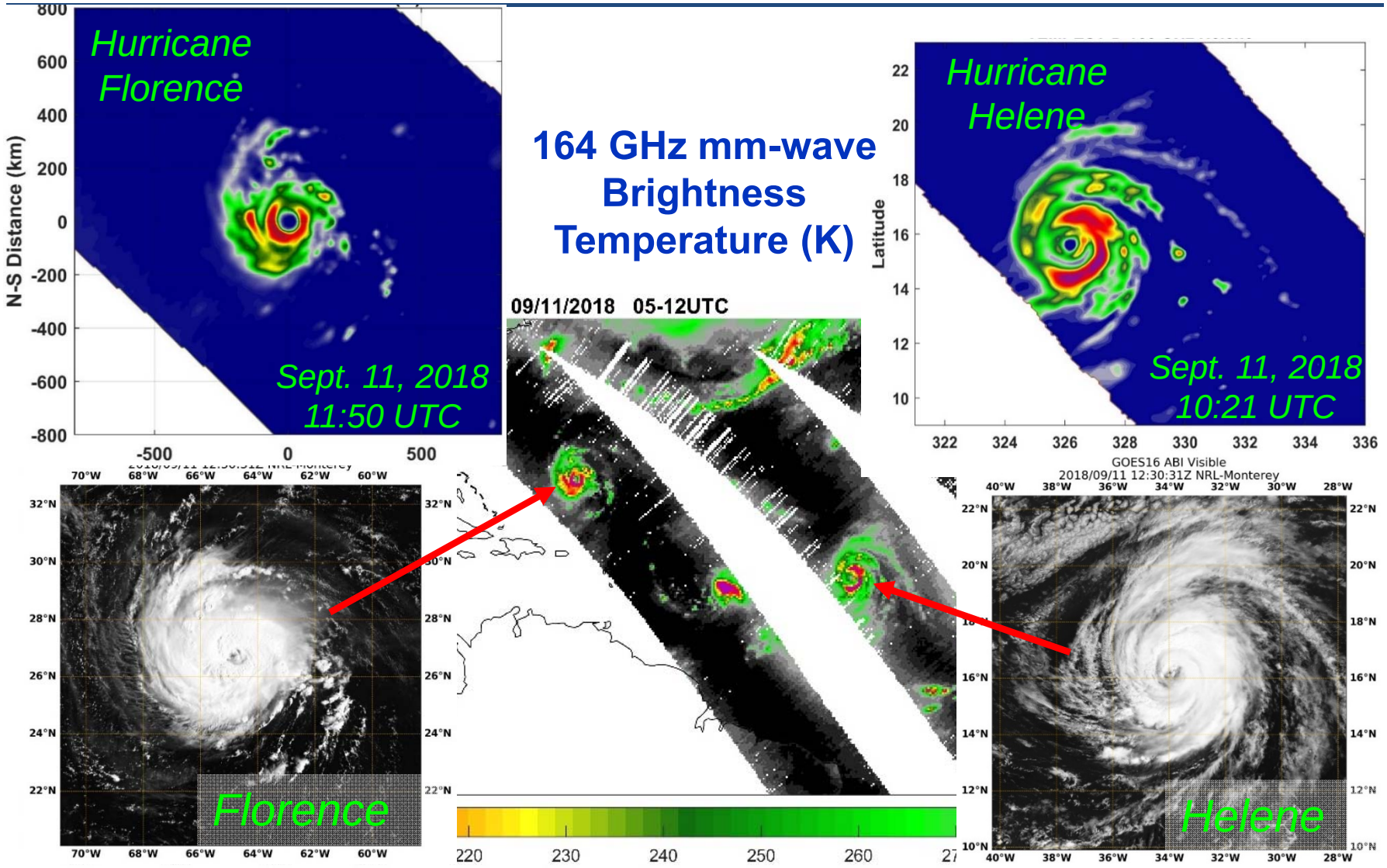
TEMPEST addresses 2017 National Academies Earth Science Decadal Survey:

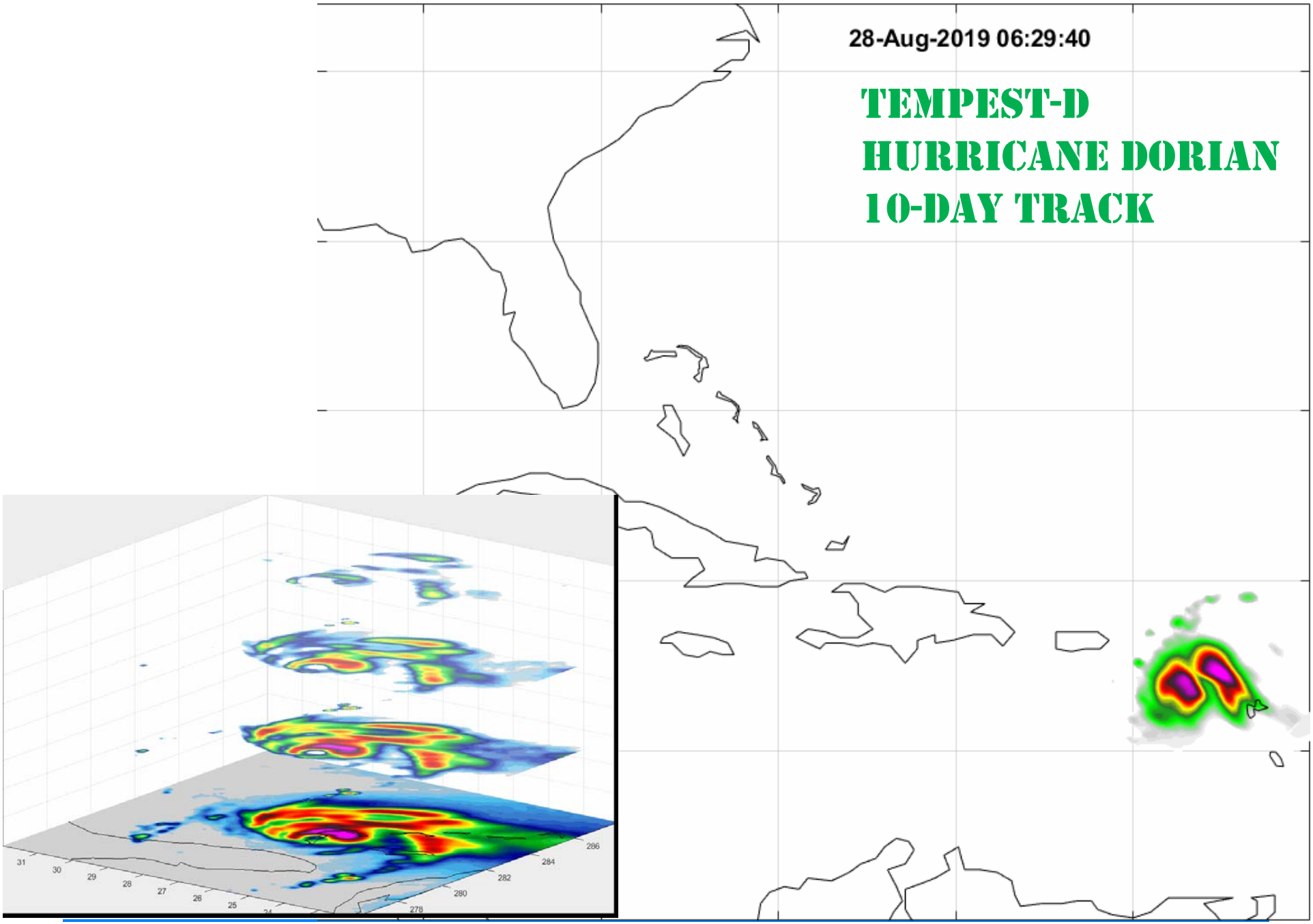
- *Why do convective storms, heavy precipitation, and clouds occur exactly when and where they do?* (Most Important Science Question W-4)
- Proposed in 2013 as a constellation of 5 identical 6U CubeSats to provide *temporally-resolved observations of clouds and humidity* every 5 minutes for up to 30 minutes.
- Chosen as NASA Earth Venture Tech Demo mission for 90 days 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.
- Additional TEMPEST flight instrument to be deployed on-board ISS in December 2021 for 3 years, yielding global, near-real time brightness temperature data.



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 CubeSat Microwave Sounder: 2 Years, 9 Months on Orbit

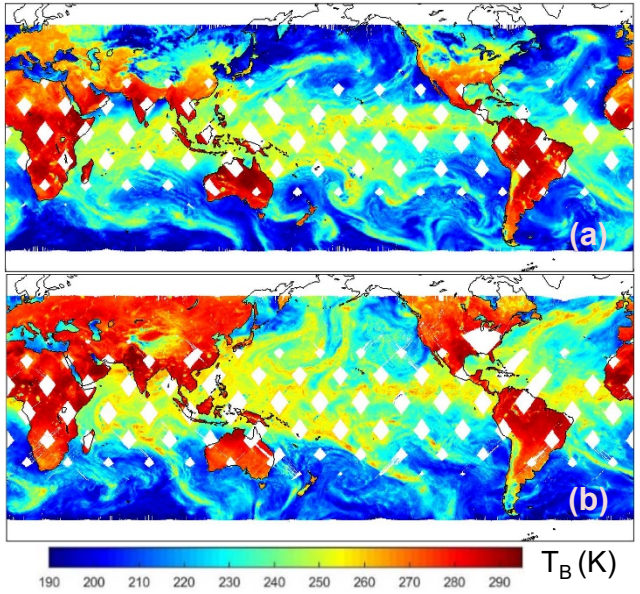
Accomplishments:

- Performing global, science-quality observations after 2 years and 9 months
- Met all Level-1 requirements within first 90 days of operations; demonstrated TRL-9
- Sensor is well-calibrated and highly stable, with performance rivaling that of operational satellite sensors

Continuing Operations:

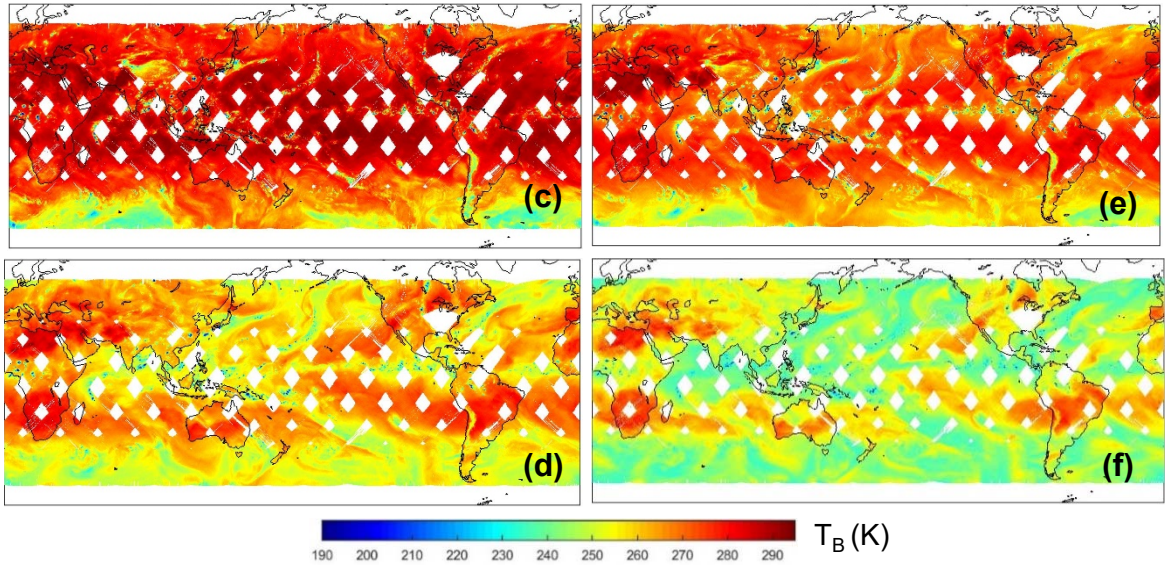
- Monitoring hurricanes, typhoons and TCs for 3 hurricane seasons to date, 2018-20
- Providing new atmospheric science data, in correlation with other satellite sensors, such as GPM/GMI, ATMS and MHS, as well as ground-based polarimetric radar networks.

TEMPEST-D 87 GHz Brightness Temperatures



(a) Dec. 9, 2018; (b) July 3, 2020

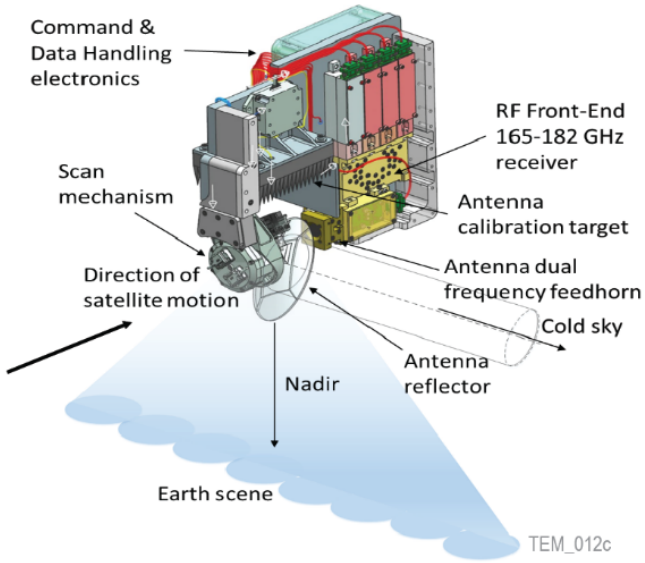
TEMPEST-D Brightness Temperatures Observed on July 3, 2020



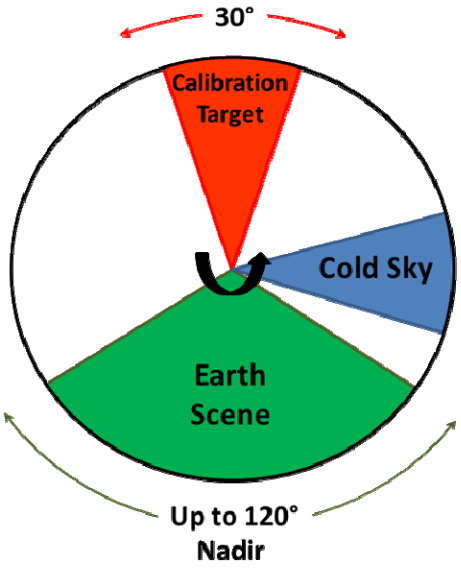
(c) 164 GHz; (d) 174 GHz; (e) 178 GHz; (f) 181 GHz

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

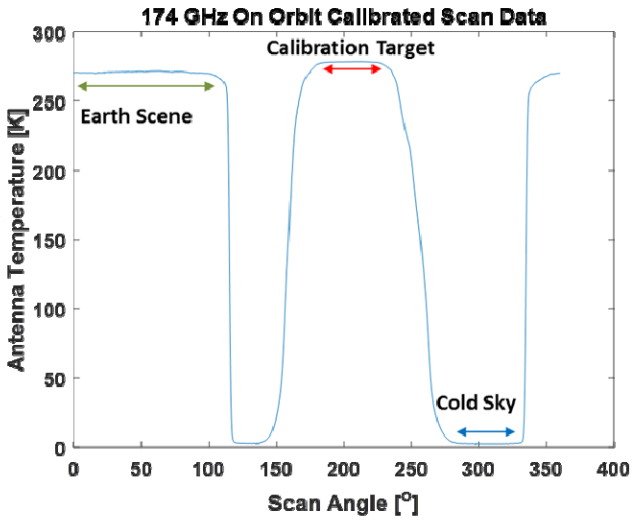
TEMPEST-D Instrument



Observing Profile

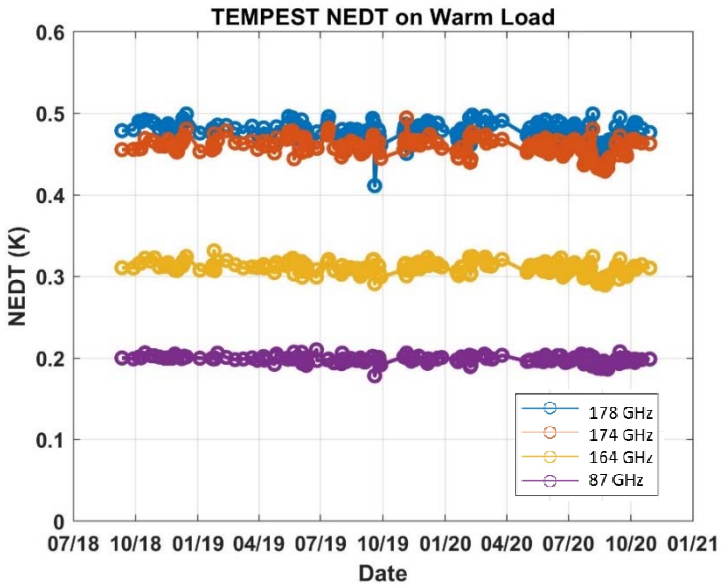


Brightness Temp. Time Series

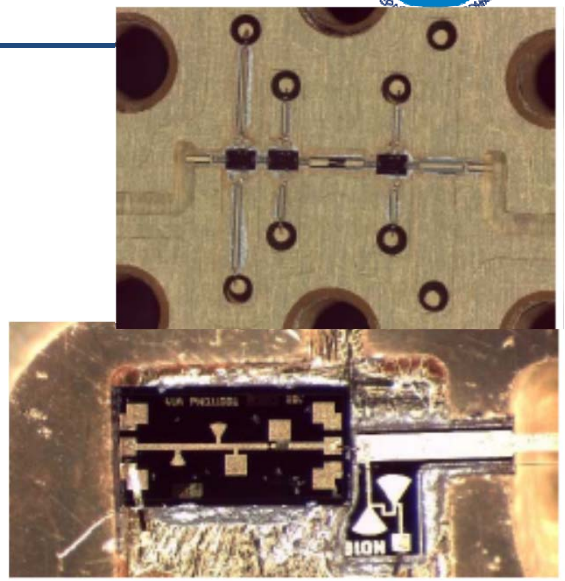


- Five-frequency millimeter-wave radiometer measures Earth scene up to ±60° nadir angles, for an 1550-km swath width from a initial orbit altitude of 410 km. Spatial resolution ranges from 12.5 km at 181 GHz to 25 km at 87 GHz.
- TEMPEST-D performs two-point end-to-end calibration every 2 sec. by measuring cosmic microwave background at 2.73 K (“cold sky”) and ambient blackbody calibration target each revolution (scanning at 30 RPM).

TEMPEST-D Radiometer Noise Trending



- Very 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



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

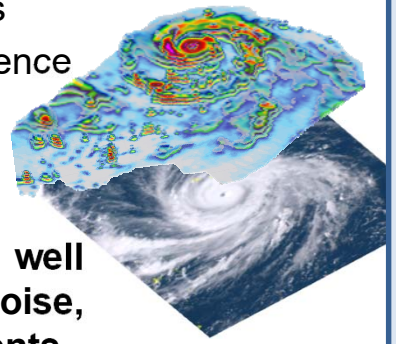
[1] Equivalent NEDT for ATMS bandwidth/integration time
[2] Kim, E., et al., *JGR*, 2014.

- TEMPEST-D demonstrates improved receiver performance over the current generation of NOAA operational sensors
- S. Padmanabhan et al., "TEMPEST-D Radiometer: Instrument Description and Pre-Launch Calibration," *IEEE Trans. Geoscience and Remote Sensing (TGRS)*, published Dec. 2020.

TEMPEST-D CubeSat Microwave Sounder: Calibration and Validation

Calibration and Validation of TEMPEST-D Radiometer:

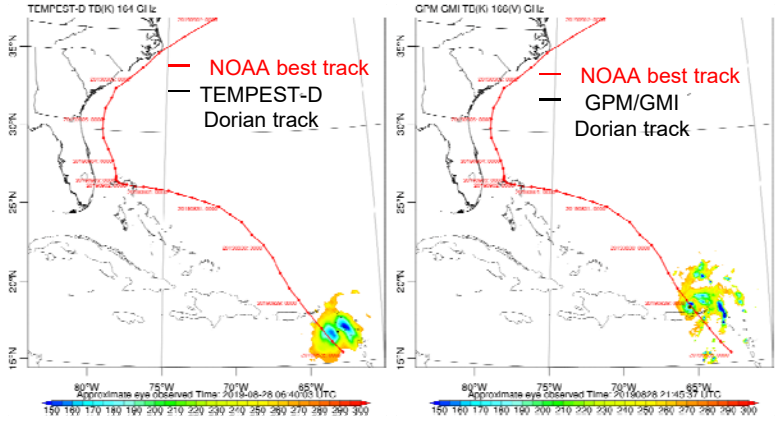
- Double difference technique used to validate TEMPEST-D data through comparison with GPM/GMI and 4 MHS sensors on NOAA-19 & MetOp-A, B and C satellites
- **Absolute calibration accuracy within 1 K** of reference sensors.
- **Calibration precision within 0.6 K** of reference sensors.
- **Results conclude that TEMPEST-D is a very well calibrated and stable radiometer with very low noise, rivaling that of much larger operational instruments.**



Project Website:
https://tempest.colostate.edu

Data are publicly available at:
https://tempest.colostate.edu/data

TEMPEST-D data has been downloaded by users at 32 institutions in 9 countries on 4 continents.



TEMPEST-D CubeSat has average altitude decay rate of 12.5 km/year for mission to date.

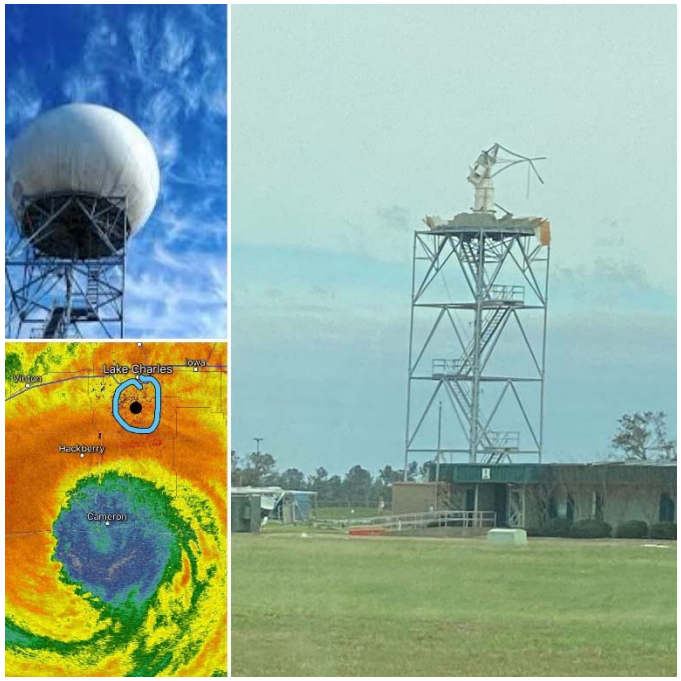
Thermal Stability of TEMPEST-D Radiometer:

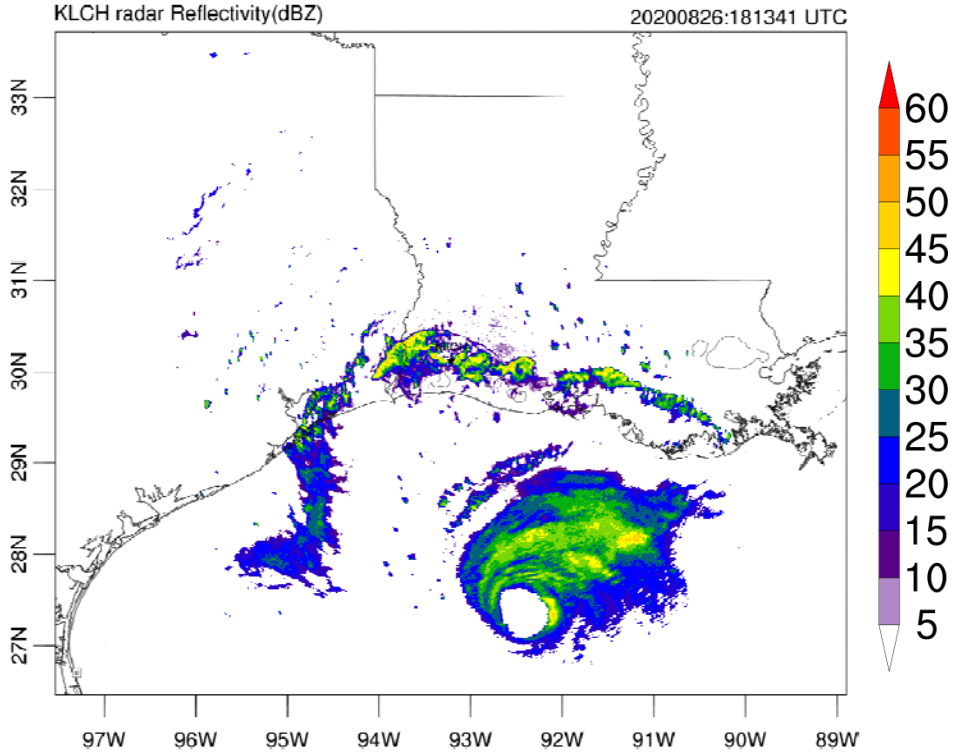
- Mean calibration differences between TEMPEST-D and five reference sensors as a function of instrument temperature over a 13-month period.
- All five channels exhibit consistent calibration differences across the full range of observed instrument temperatures, **showing no evidence of calibration errors associated with changes in instrument temperature.**
- See W. Berg et al., "Calibration and Validation of the TEMPEST-D CubeSat Radiometer" *IEEE TGRS*, early release, Sept. 2020, doi:10.1109/TGRS.2020.3018999.

Hurricane Laura Observations from NEXRAD KLCH Radar on Aug. 26, 2020

Last 6 hours of observations from NEXRAD radar in Lake Charles, LA

- **Hurricane Laura** was a deadly and damaging Category 4 hurricane that tied the historical record set in 1856 for the highest sustained wind speeds of 150 mph during landfall in Louisiana.

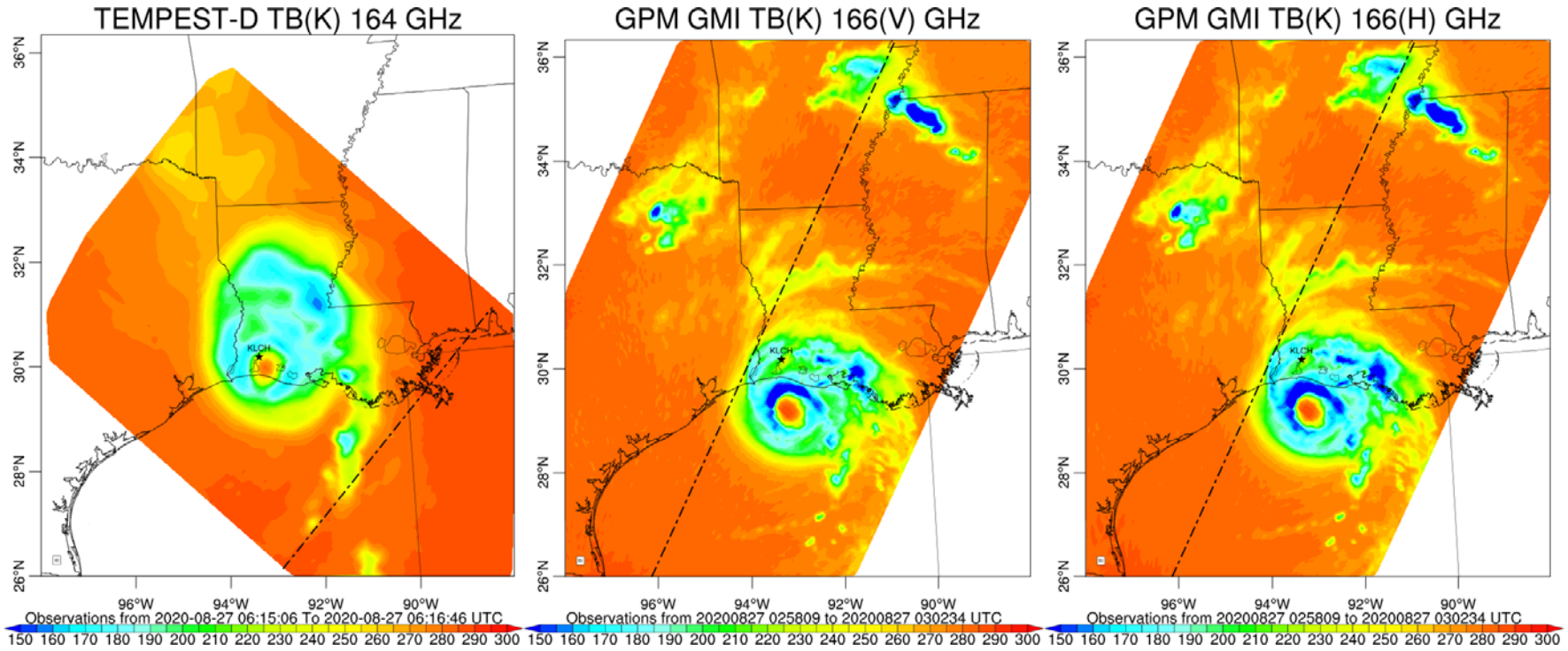




- **Hurricane Laura** destroyed the KLCH NEXRAD radar as it made landfall early on Aug. 27, 2020.

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

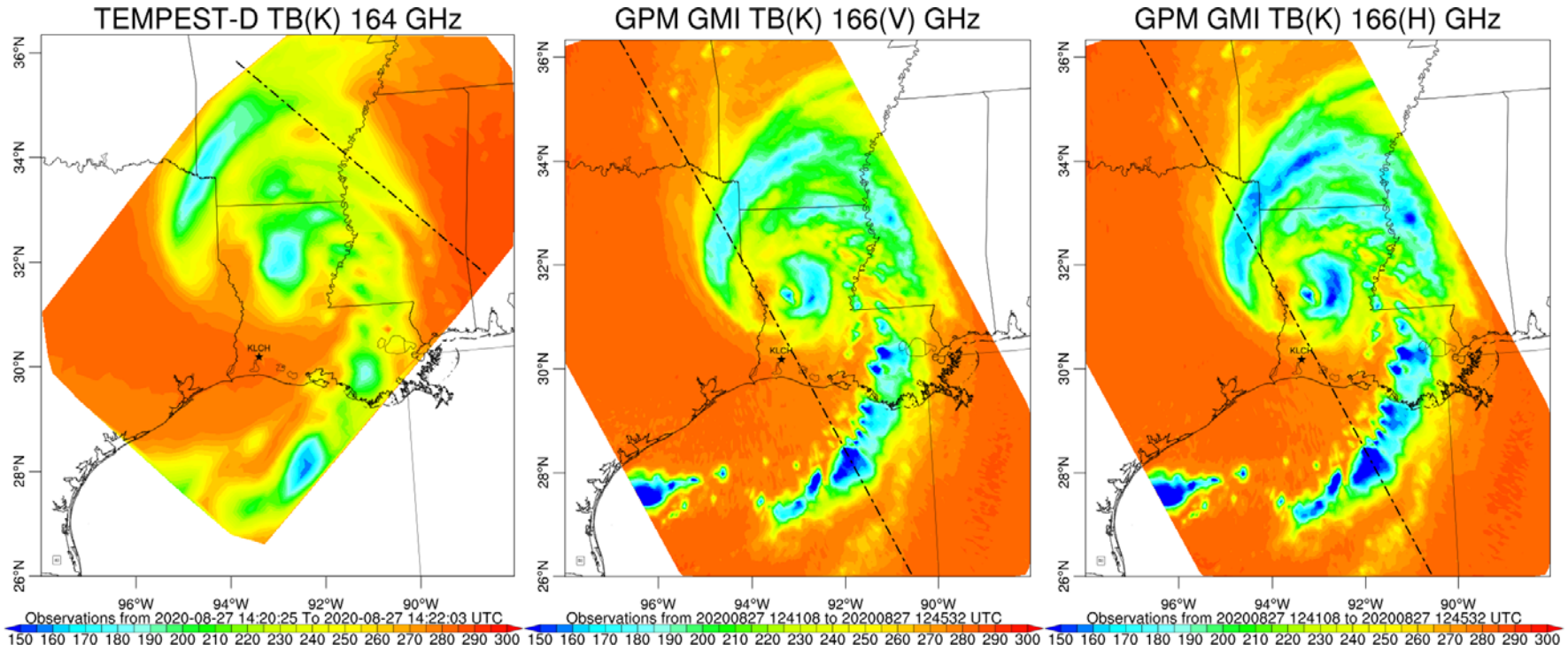
August 27, 2020 at 06:15 UTC (TEMPEST-D)



- TEMPEST-D observed Hurricane Laura **3.3 hours after** GPM.

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

August 27, 2020 at 14:20 UTC (TEMPEST-D)



- TEMPEST-D observed Hurricane Laura **1.6 hours after** GPM.

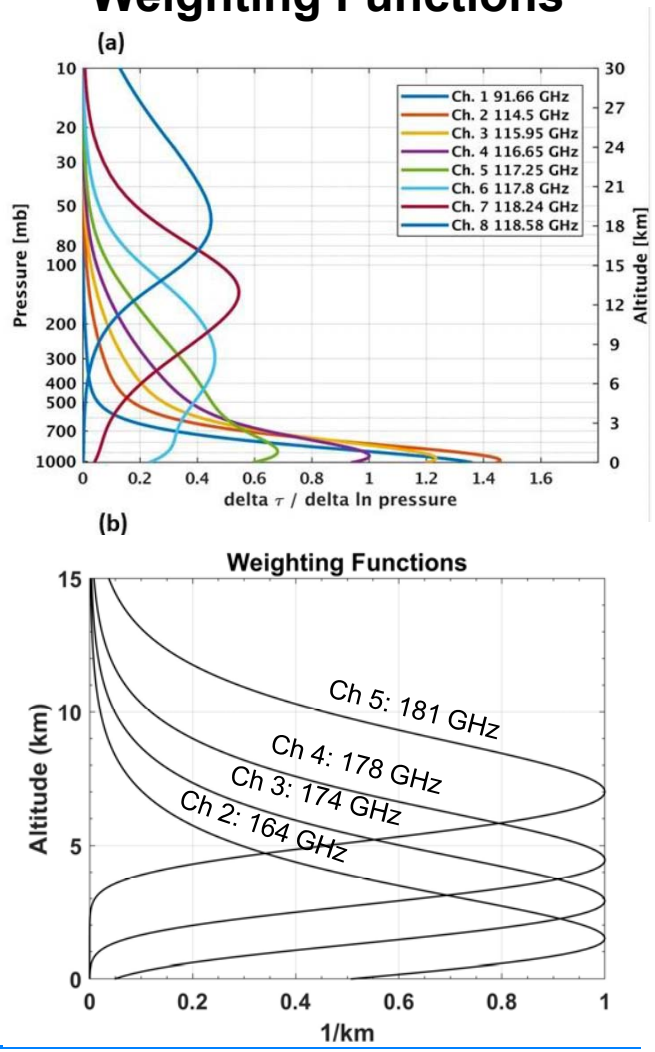
TEMPEST-based Microwave Sounder: Channel Frequencies and Bandwidths

TEMPEST Channel Specifications

Channel No.	Center Freq. (GHz)	Bandwidth (MHz)	NEDT (K)	Integration Time (ms)
1	87.1	3200	0.20	5
2	164.1	3900	0.35	5
3	173.8	2232	0.55	5
4	178.4	1848	0.55	5
5	180.8	1989	0.75	5
6	114.5	1000	0.55	8.3
7	116.0	800	0.60	8.3
8	116.7	600	0.70	8.3
9	117.3	600	0.70	8.3
10	117.8	500	0.75	8.3
11	118.2	380	0.85	8.3
12	118.6	300	1.00	8.3

Channels 1-5 are the channel specs of the TEMPEST-D on-orbit radiometer. Channels 6-12 are temperature sounding channels of the TROPICS radiometer channels 2-8 for 114-118 GHz.

Weighting Functions



TEMPEST-based Microwave Sounder Constellations at 830 km Altitude

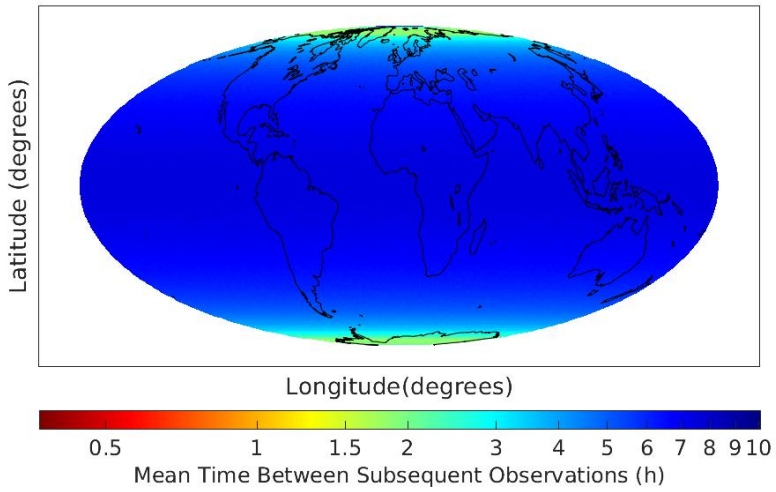
1. **CP: Current Polar Orbiters,** i.e. NOAA-20 and MetOp-C.

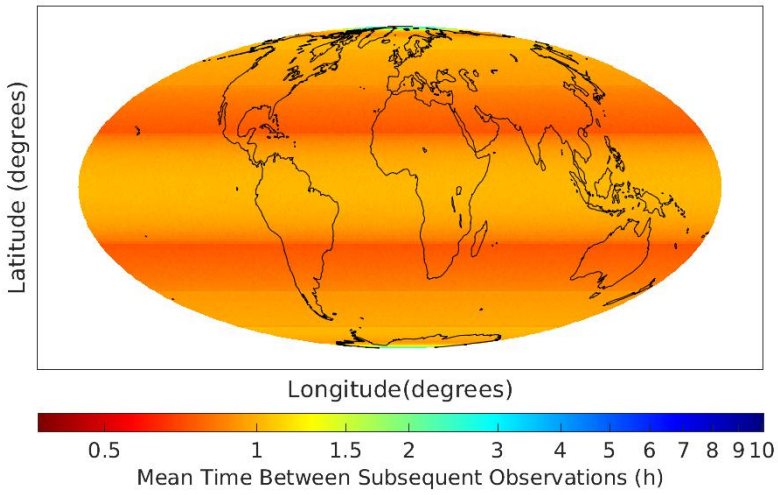
2. **TEMPEST-9 + CP:** 9 TEMPEST-based CubeSats, 3 in each of 3 orbital planes at inclinations of 30º, 50º and 70º, plus CP.

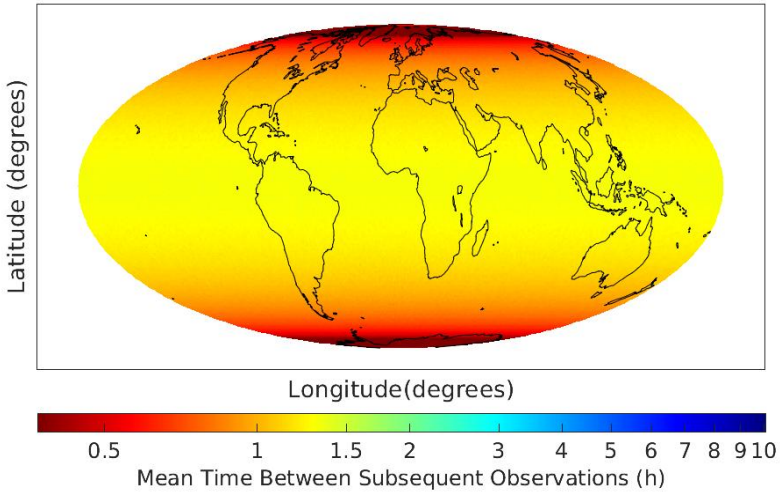
3. **Polar TEMPEST-9 + CP:** 9 TEMPEST-based CubeSats in polar orbit, i.e. 98.7º inclination (similar to CP), in 3 different orbital planes, plus CP.

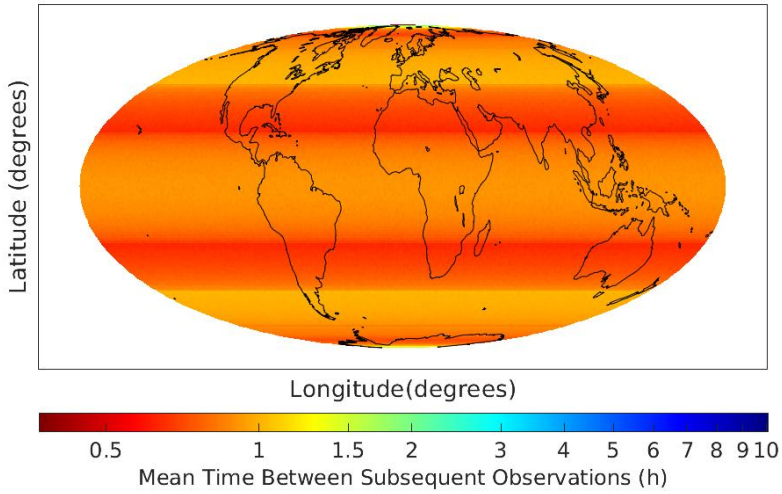
4. **TEMPEST-12:** TEMPEST-9 constellation plus 3 TEMPEST-based CubeSats in polar orbit.

Mean Revisit Time of TEMPEST CubeSat Constellations

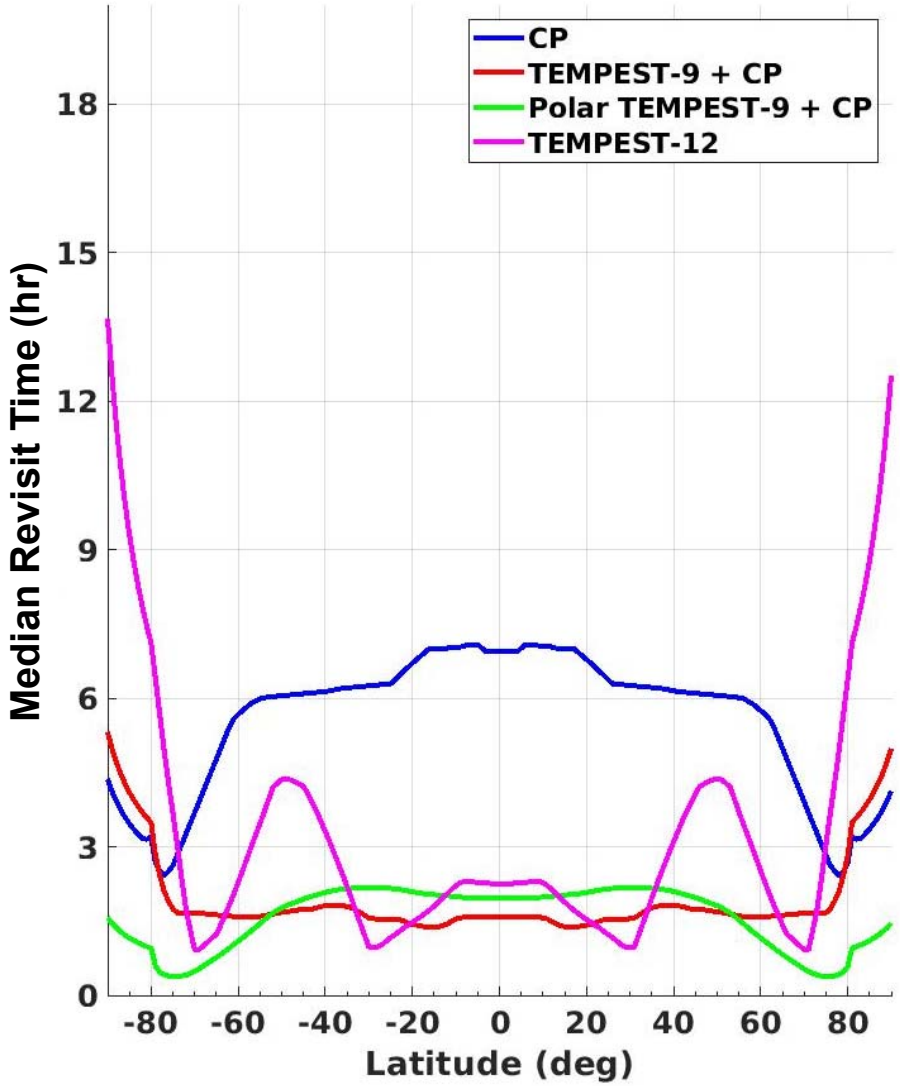








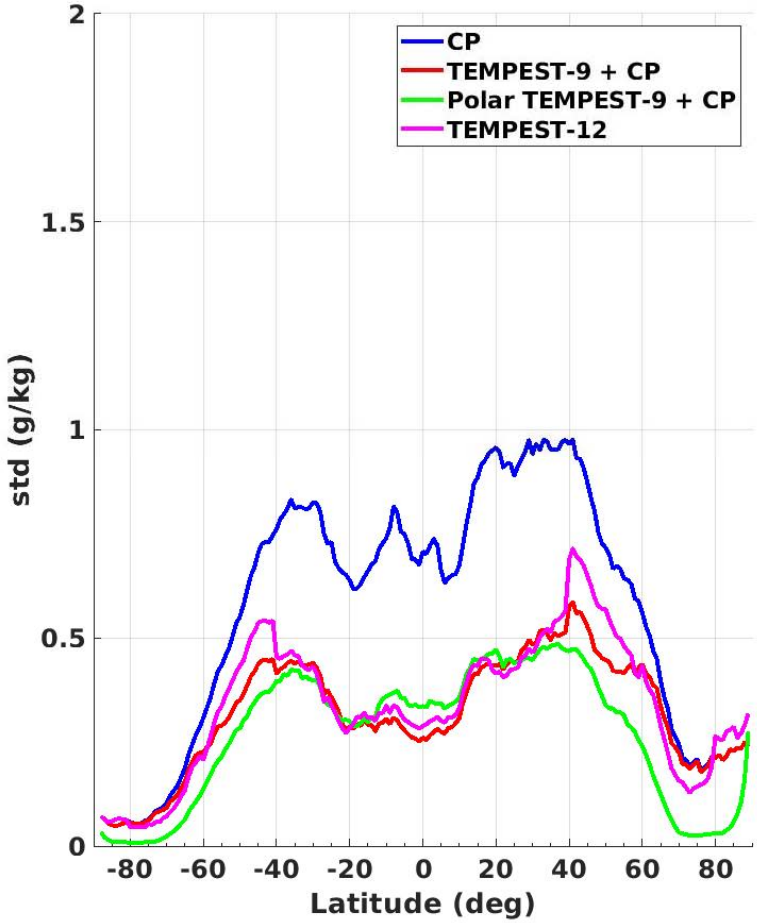
Median Revisit Time of TEMPEST CubeSat Constellations



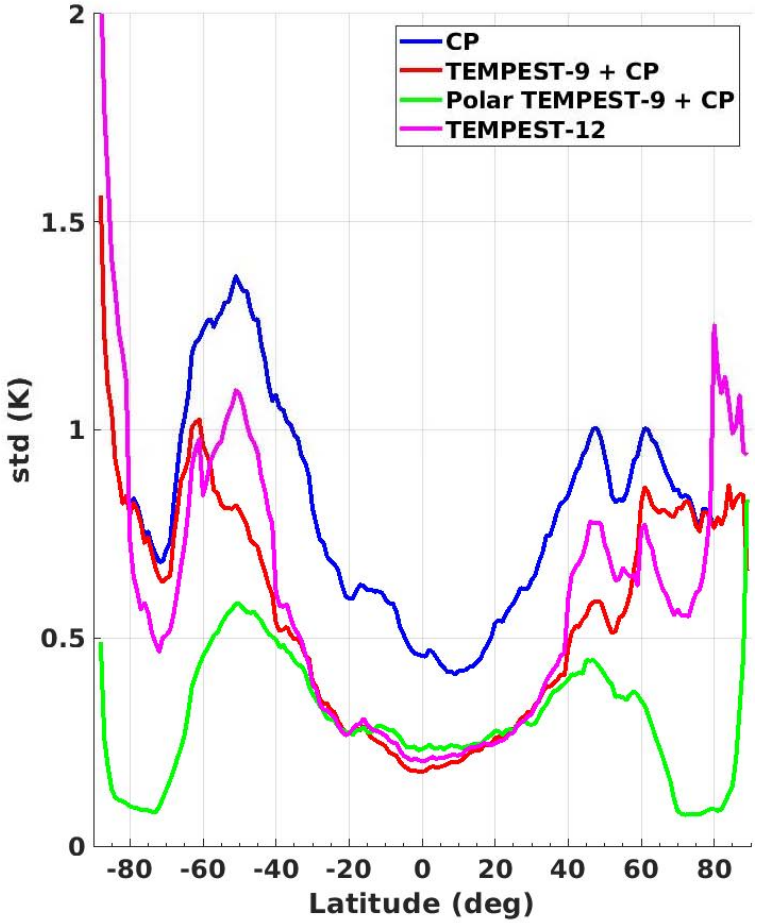
- Zonally-averaged median revisit time for TEMPEST-based CubeSat constellations is shown for all latitudes.
- The current polar orbiting satellite configuration (CP, blue) has median sampling time of 6-7 hours or better globally.
- The TEMPEST-9 CubeSat constellation plus CP (red) improves the median sampling time to 1.5 hours or better nearly globally.

Sampling of Moisture and Temperature by TEMPEST CubeSat Constellations

Sampling Error of ECMWF Nature Run
Specific Humidity at 700 mb



Sampling Error of ECMWF Nature Run
Temperature at 700mb



Conclusions

- TEMPEST-D CubeSat Microwave Sounder has successfully demonstrated global measurements of moisture profiles, cloud liquid water and ice water path over more than 2 years and 9 months on orbit to date.
- Through quantitative comparisons with GPM/GMI and MHS sensors on NOAA and MetOp satellites, we have demonstrated that **TEMPEST-D accuracy and precision are comparable to those of much larger operational satellites**.
- TEMPEST-D radiometers are highly stable over the mission to-date, with no evidence of calibration errors with on-orbit instrument temperature.
- Validation and trending results show that TEMPEST-D is a **very well calibrated and highly stable radiometer with very low noise, rivaling that of much larger operational instruments.**
- Experienced industry vendors of CubeSat buses and radiometer instruments, as well as ground communication networks, launch providers and constellation mission operations, are ready to enable **low-cost, rapid schedule for production, deployment and operation** of a TEMPEST-based constellation.
- Deployment of a TEMPEST-based 9-satellite constellation to add to polar-orbiting satellites could **improve revisit time of moisture and temperature sounding of NOAA and MetOp satellites from 6-7 hours to 1-1.5 hours** nearly globally.