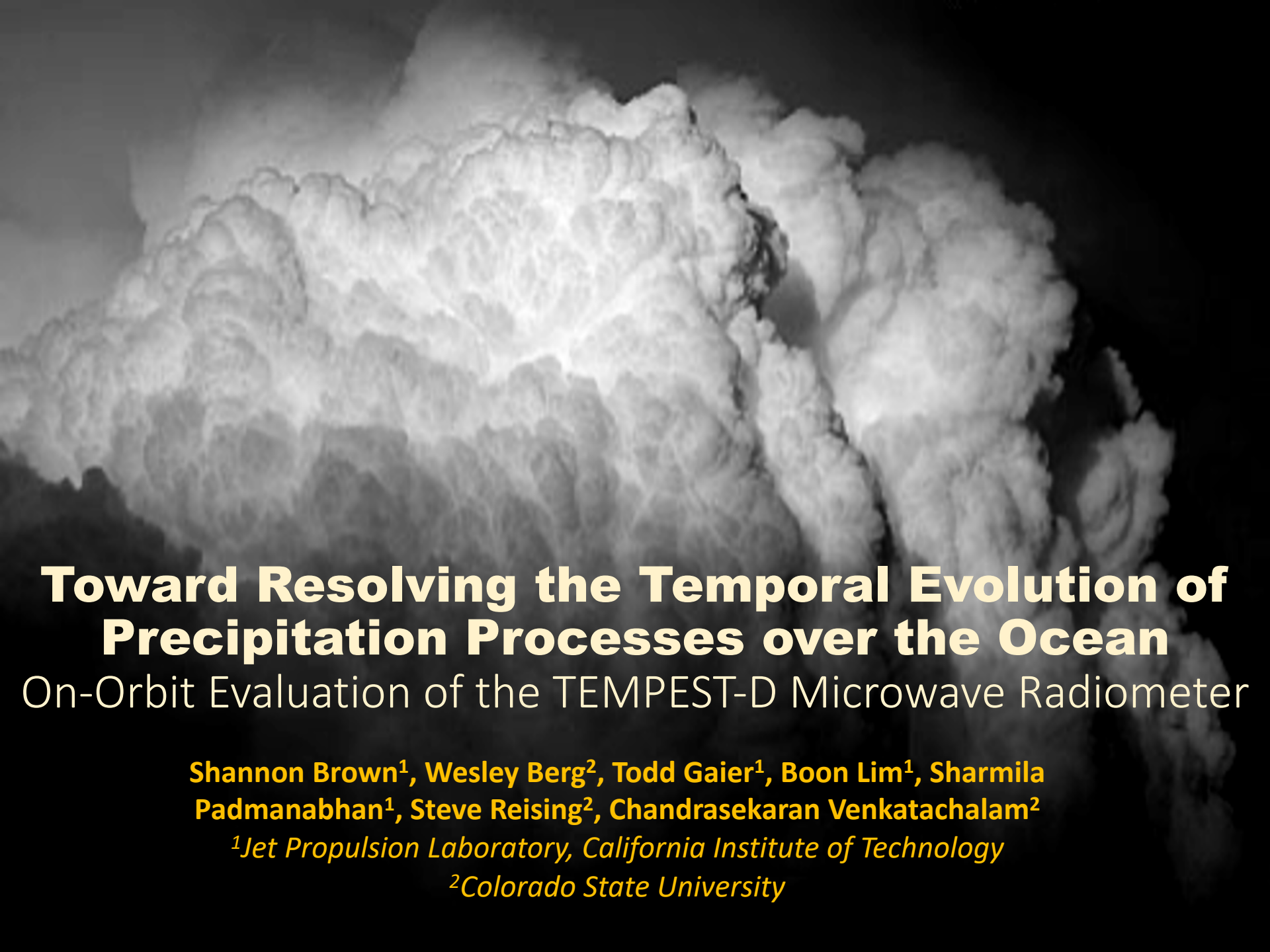


Toward Resolving the Temporal Evolution of Precipitation Processes over the Ocean

On-Orbit Evaluation of the TEMPEST-D Microwave Radiometer

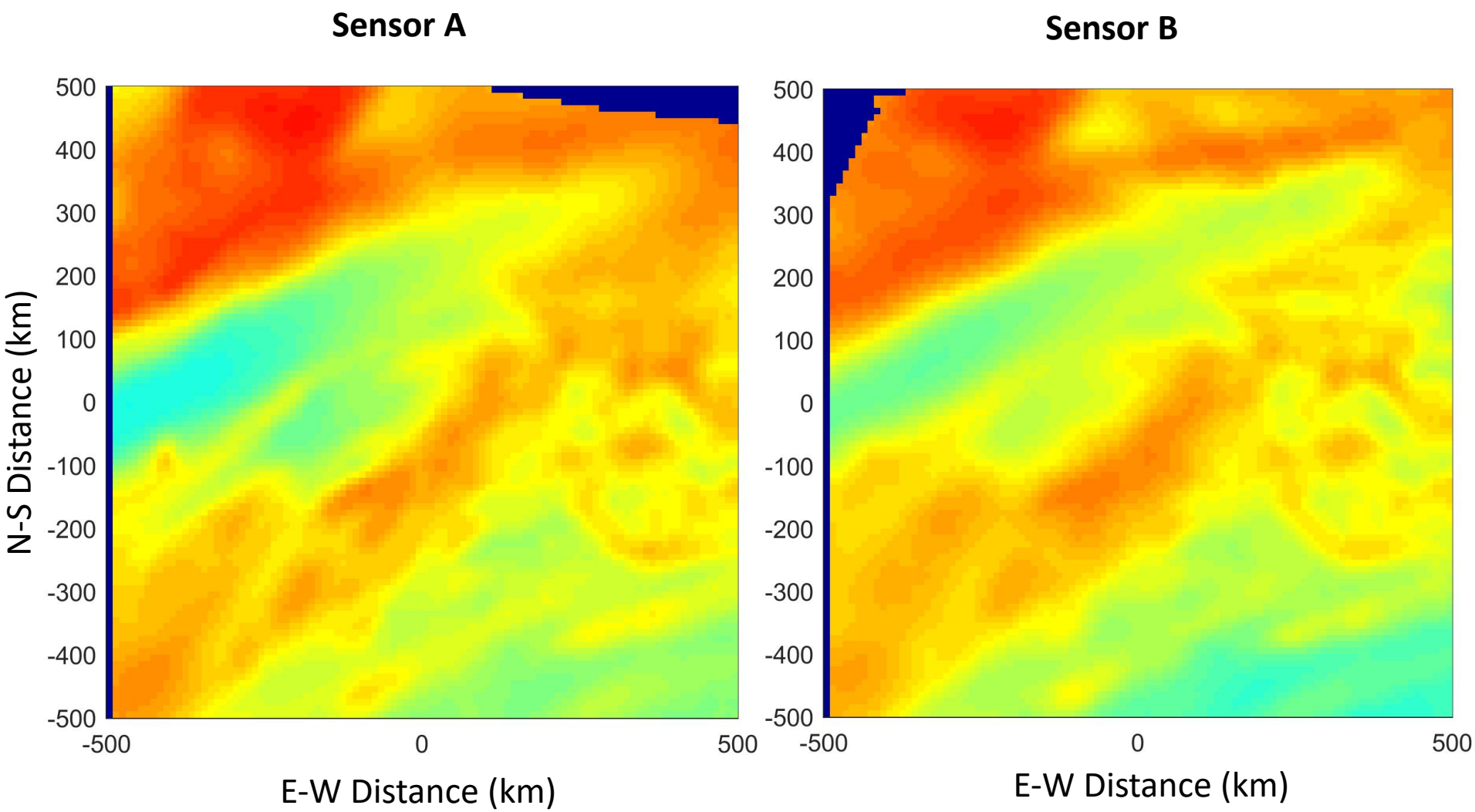
Shannon Brown[1], Wesley Berg[2], Todd Gaier[1], Boon Lim[1], Sharmila Padmanabhan[1], Steve Reising[2], Chandrasekaran Venkatachalam[2]

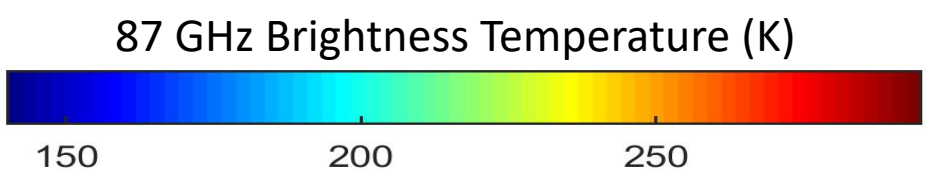
[1]Jet Propulsion Laboratory, California Institute of Technology

[2]Colorado State University

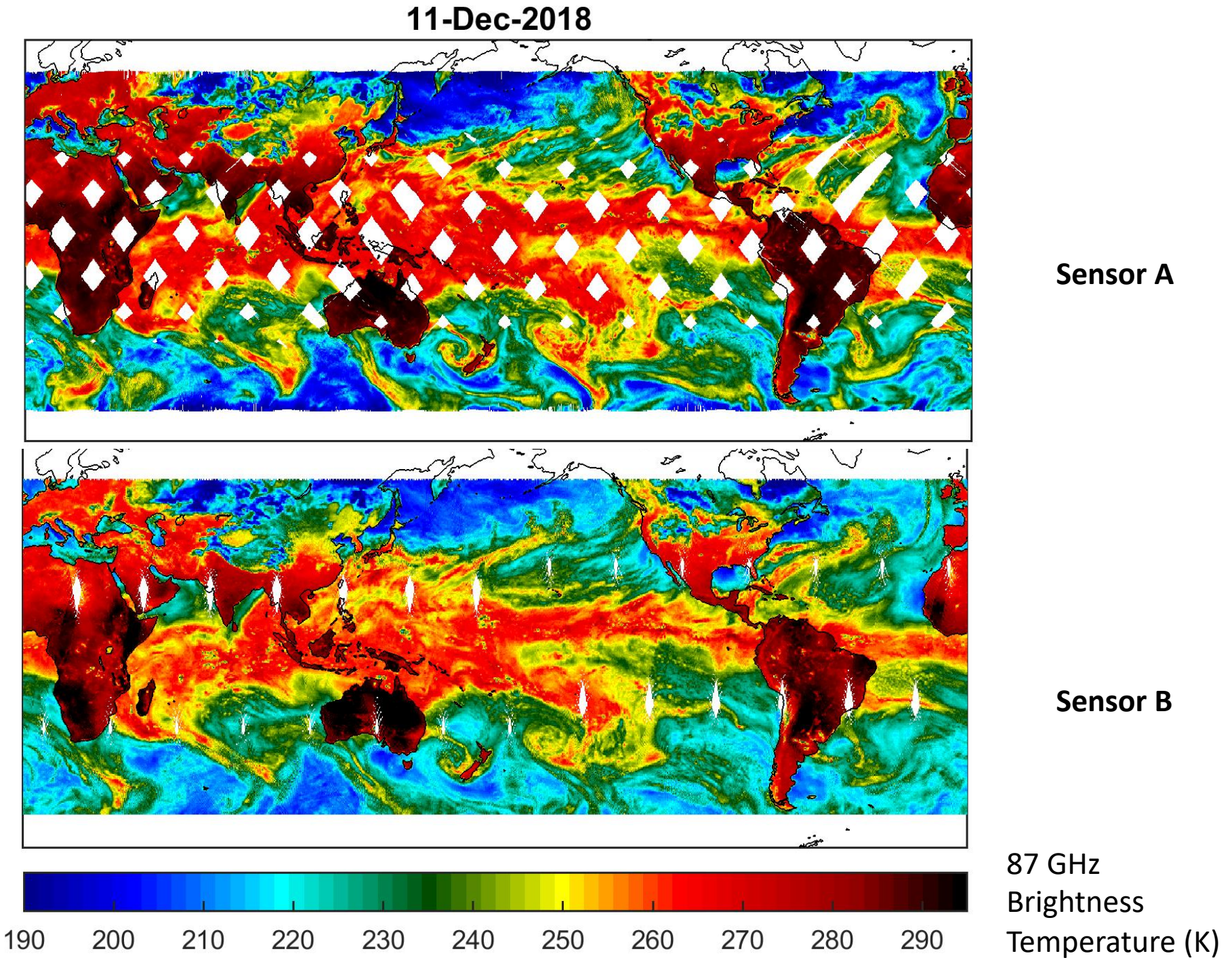
CubeSats for Science?

- Calibration ?
- Sensor noise quality ?
- Capability ?
- Pointing accuracy ?
- Data rate ?
- Reliability ?





Oct 16, 2018
12 UTC
Southern Ocean


11-Dec-2018
Sensor A
Sensor B
190
200
210
220
230
240
250
260
270
280
290
87 GHz
Brightness
Temperature (K)

Sensor B

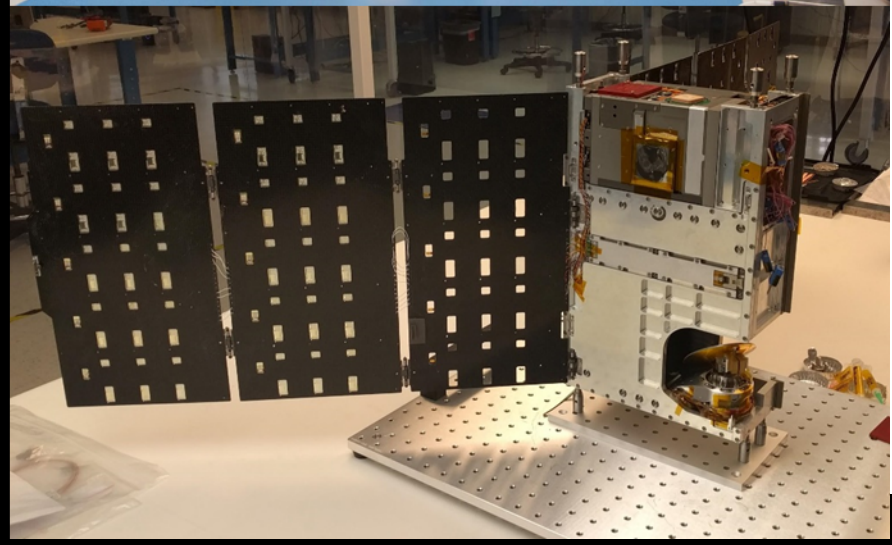
NOAA Advanced Technology Microwave Sounder (ATMS)

75kg, 100W, $$$$

Sensor A

TEMPEST-D

2.8 kg, 6.5W, $

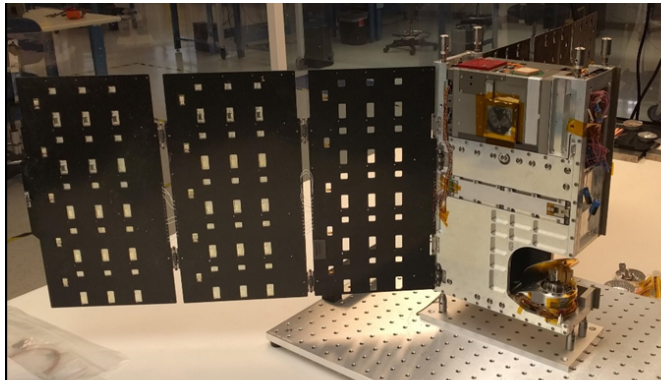


TEMPEST-D

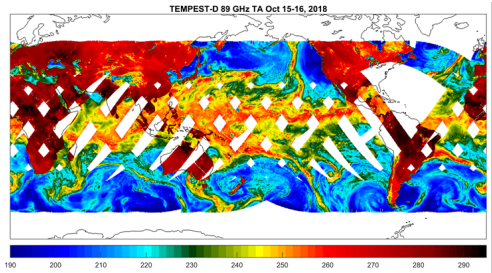
- Well calibrated mm-wave imager on a 6U CubeSat
- Designed for observing precipitation processes through time resolved observations (3-4 min revisit)
- Ultra-low noise InP MMIC receivers, direct detect, low power
- Selected as Earth Ventures technology demonstrator (EVI-2) for risk reduction

- **13km resolution at 180 GHz**
- **25km resolution at 87 GHz**
- **1400km swath (+/- 60°)**
- **Blackbody calibration**

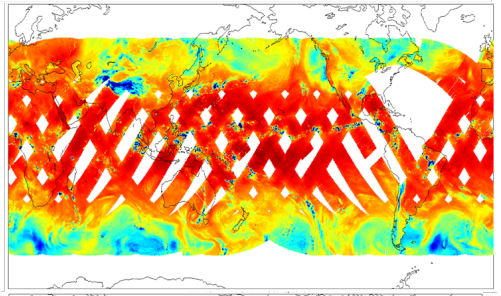
Mass	3.8 kg
Power	6.5 W
Volume	3U
Precision	0.5 K (CBE)
Accuracy	1.0 K (CBE)



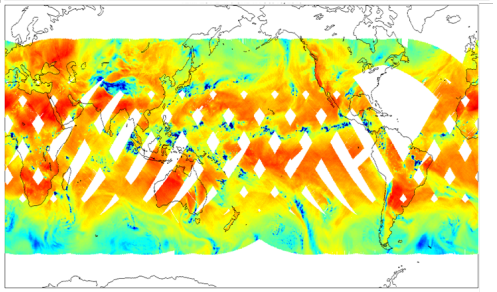
87 GHz



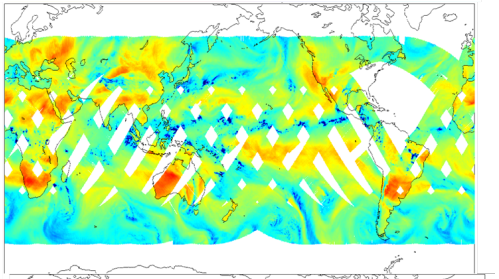
164 GHz



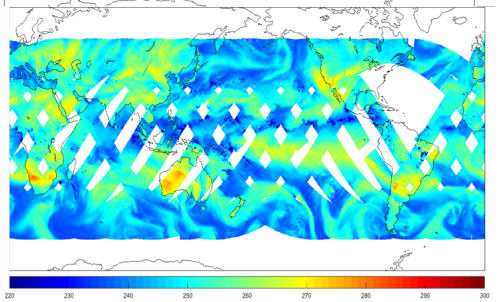
174 GHz



178 GHz

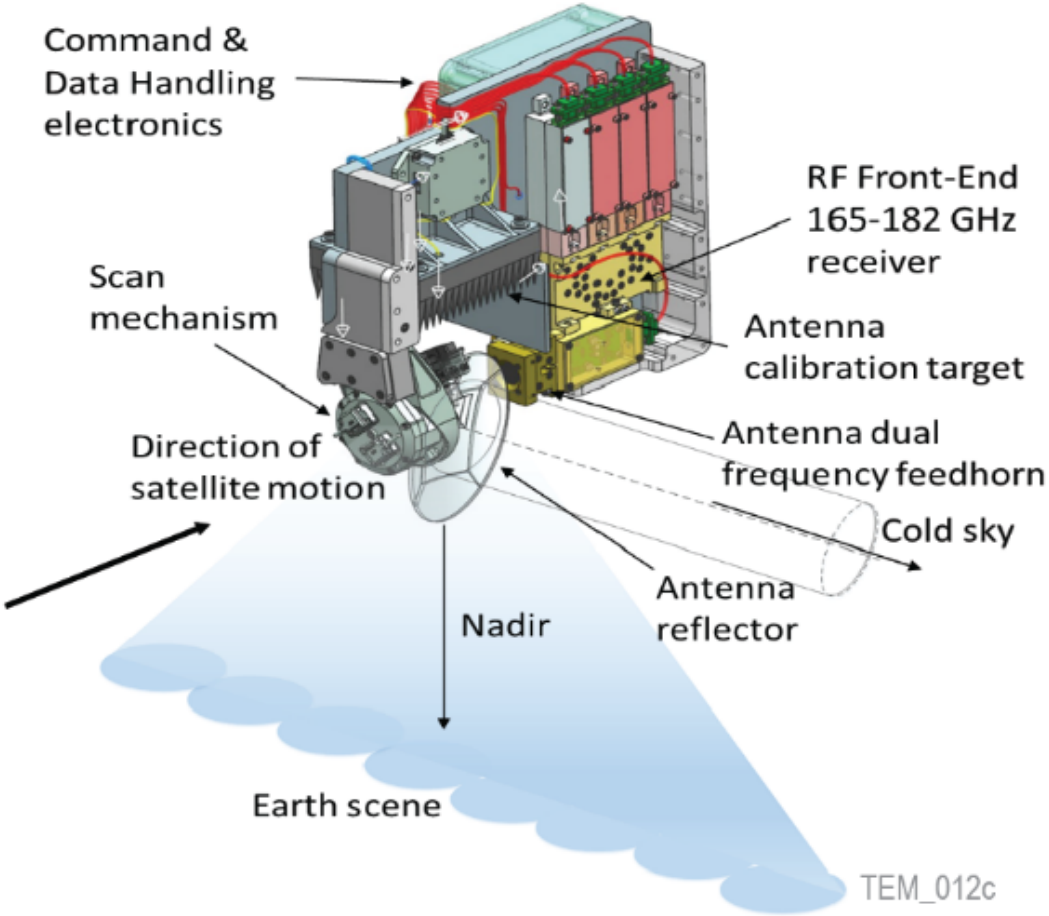


181 GHz

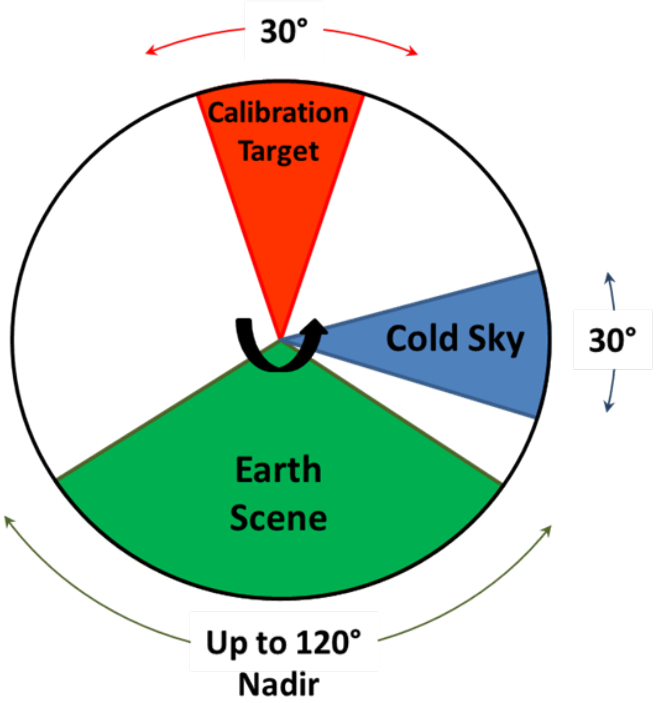


TEMPEST-D Instrument Performs End-to-End Radiometric Calibration

TEMPEST-D Instrument



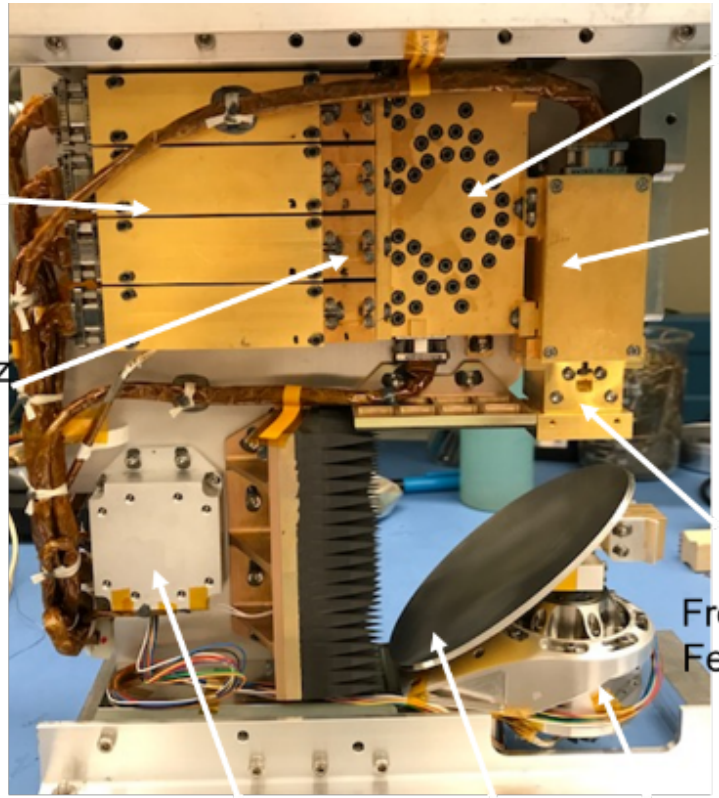
Observing Profile

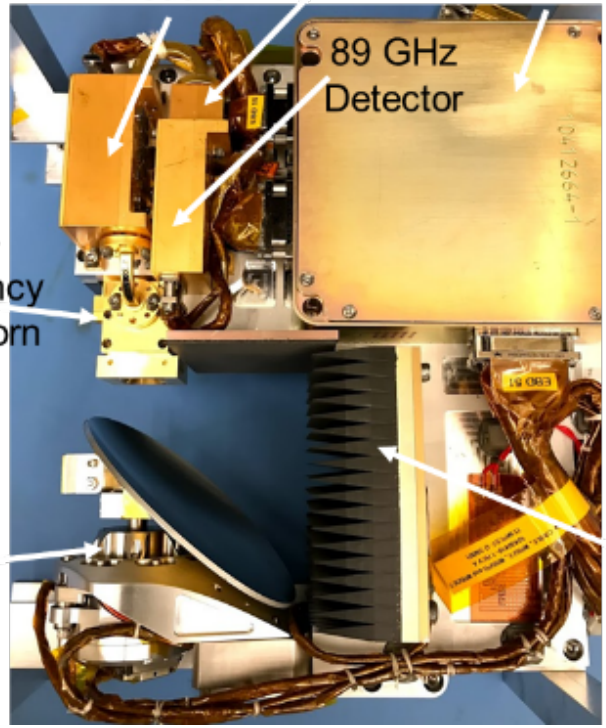


+/- 65° cross-track scan

End-to-end blackbody calibration every scan – equivalent to operational sensors (AMSU, ATMS)

Flight Model Radiometer Instrument Built and Integrated at JPL



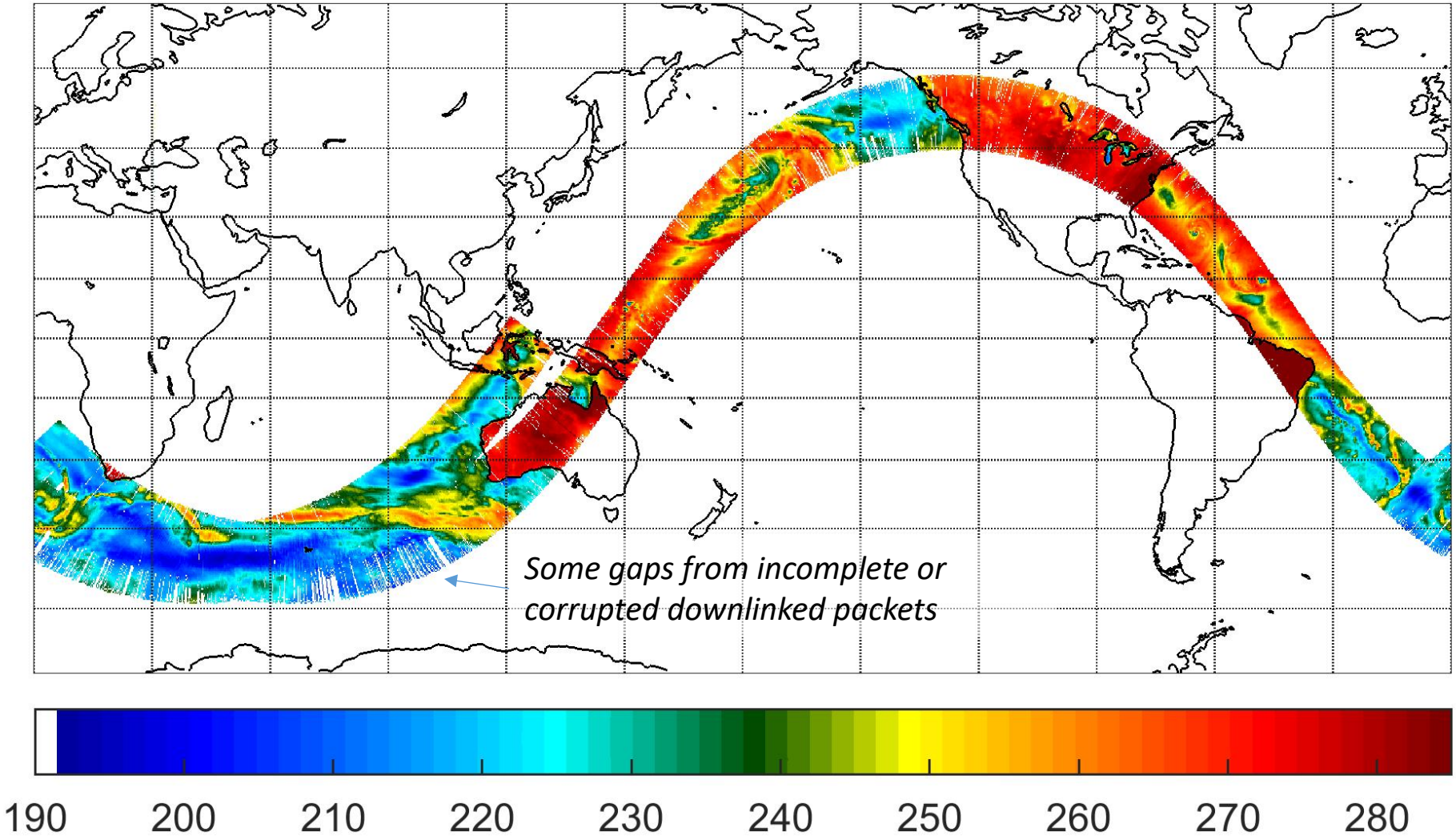


Tempest-D Status

- Successfully deployed from ISS July 13
- Payload first turned on Sept 5, 2018
- Currently in routine operations

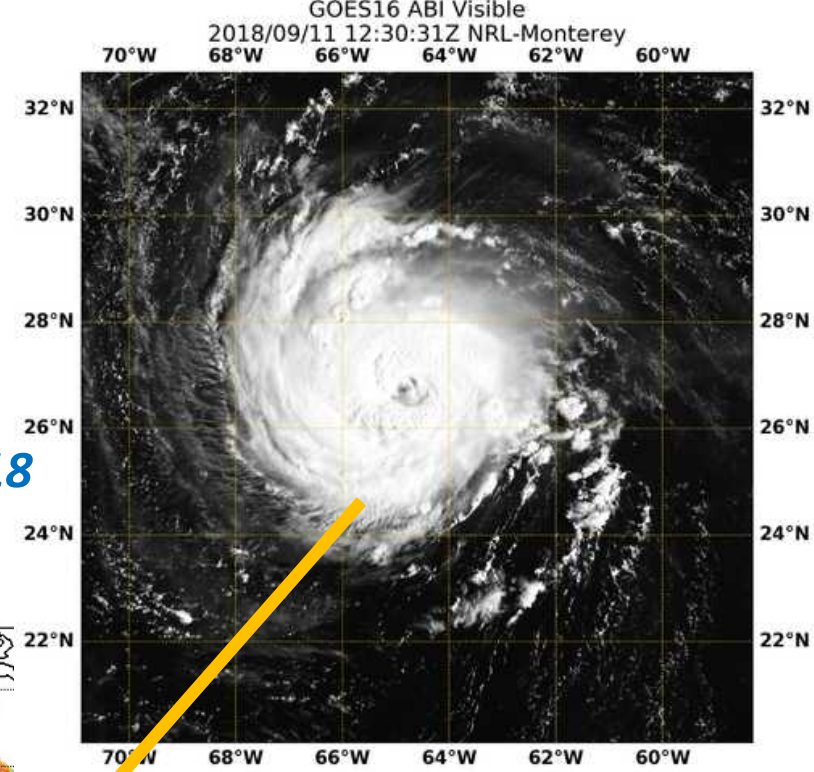
87 GHz Window Channel – first full orbit

TEMPEST-D 87 GHz Brightness Temperature (K)

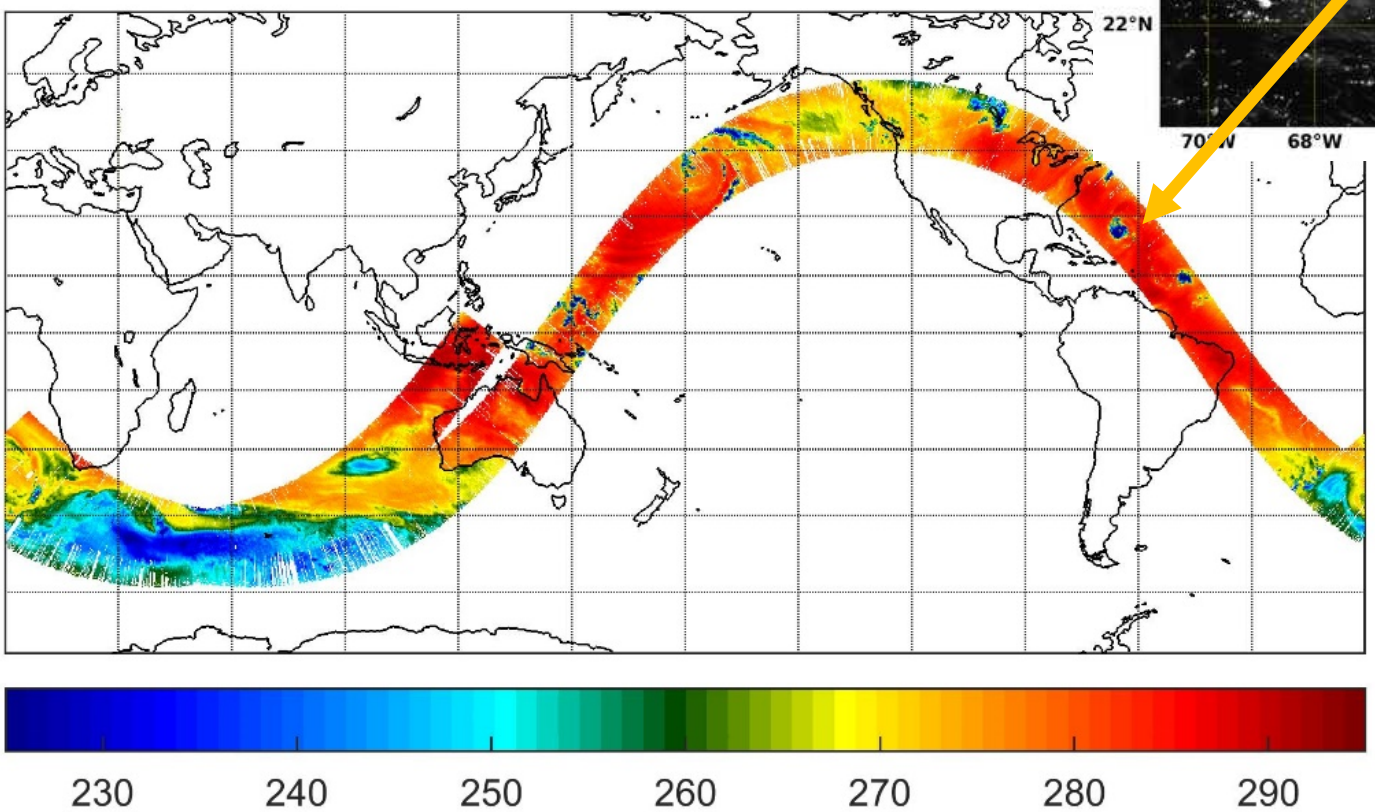


87 GHz window channel sensitive to water vapor, clouds and precipitation.

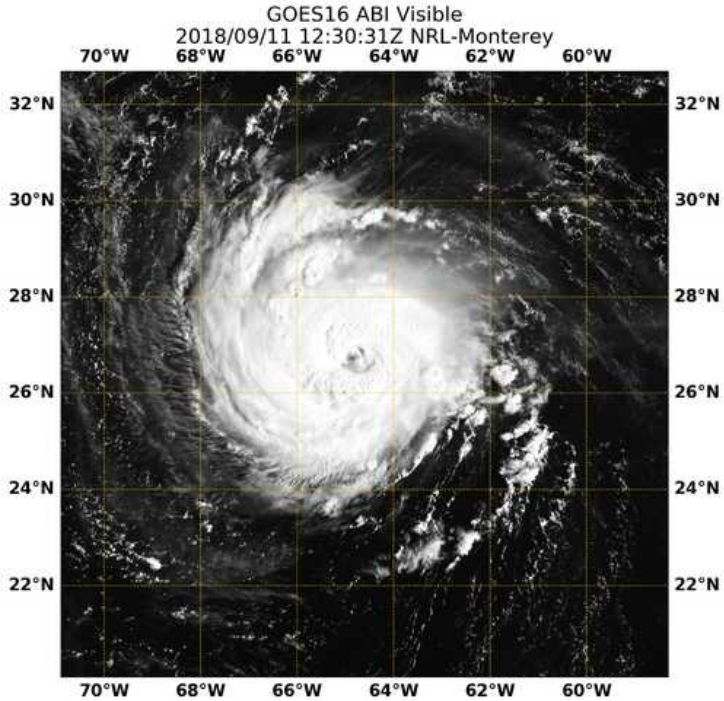
TEMPEST-D caught Hurricane Florence in its first fully operational full-swath orbit on Sept 11, 2018

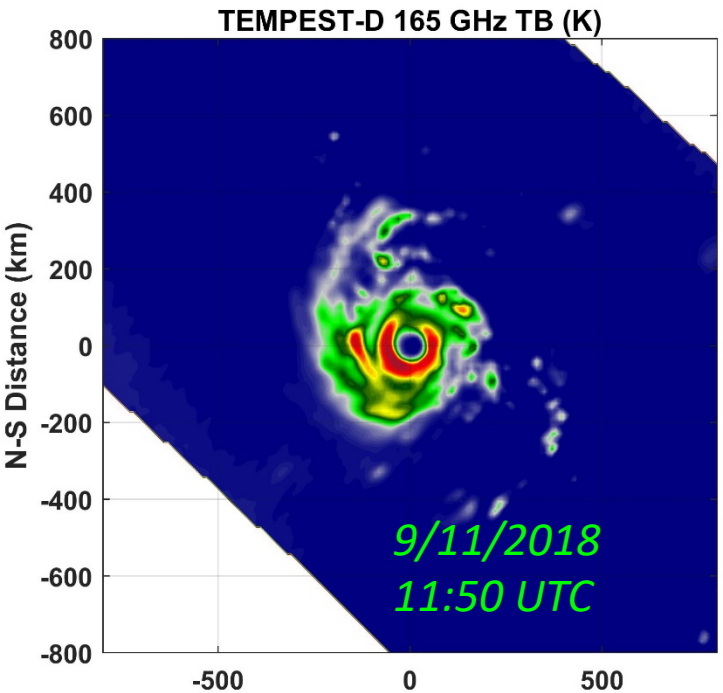


TEMPEST-D 164 GHz



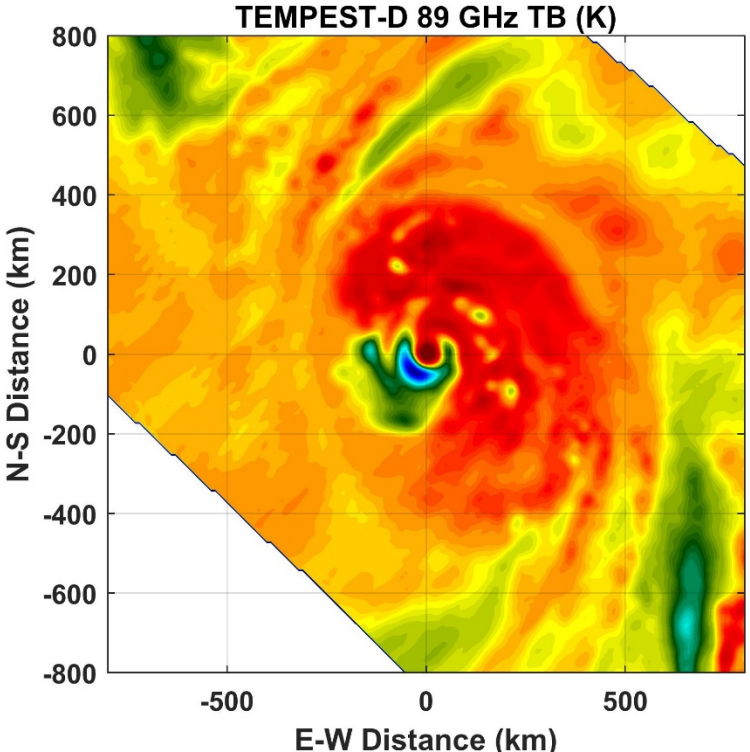
Hurricane Florence



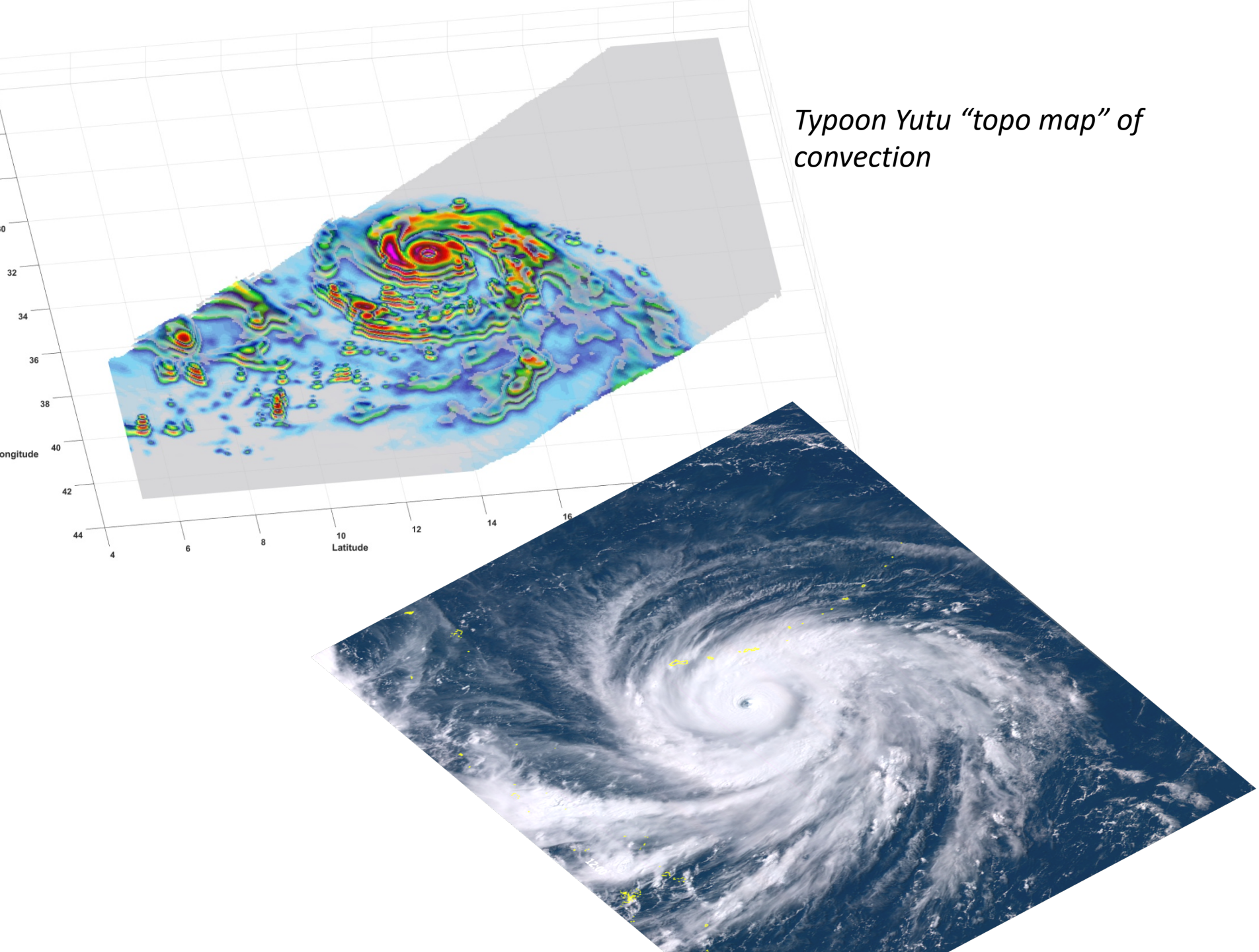


164 GHz images convection around inner core through ice scattering signature

87 GHz sensitive to clouds, precipitation, water vapor and strong convection

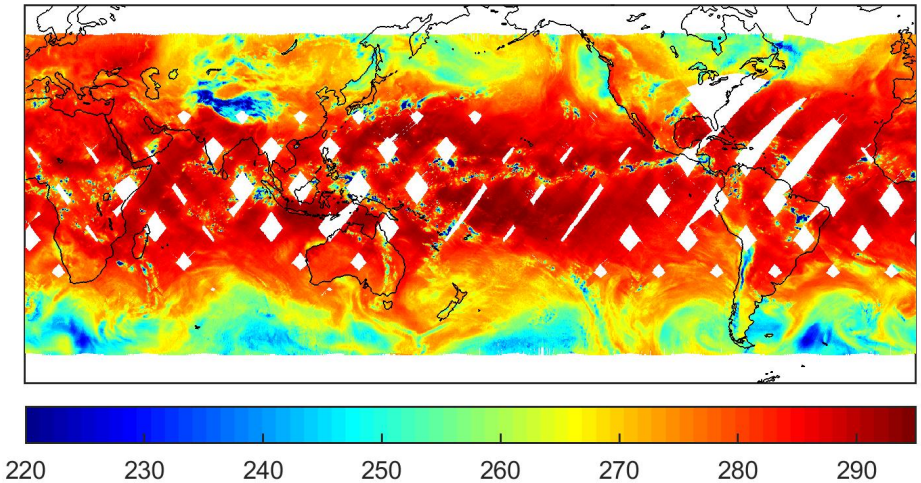


Typoon Yutu "topo map" of convection

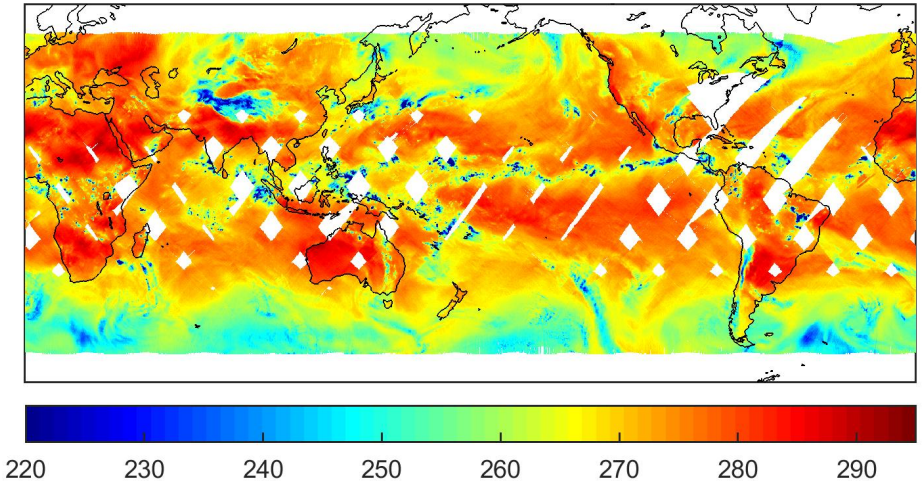


183 GHz Sounding Channels T_B (K) 10/15 – 10/16, 2018

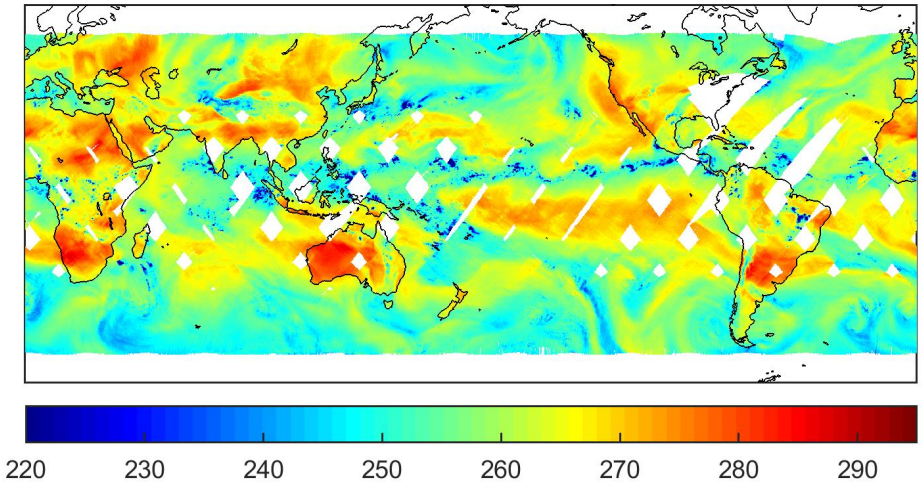
TEMPEST-D 164 GHz



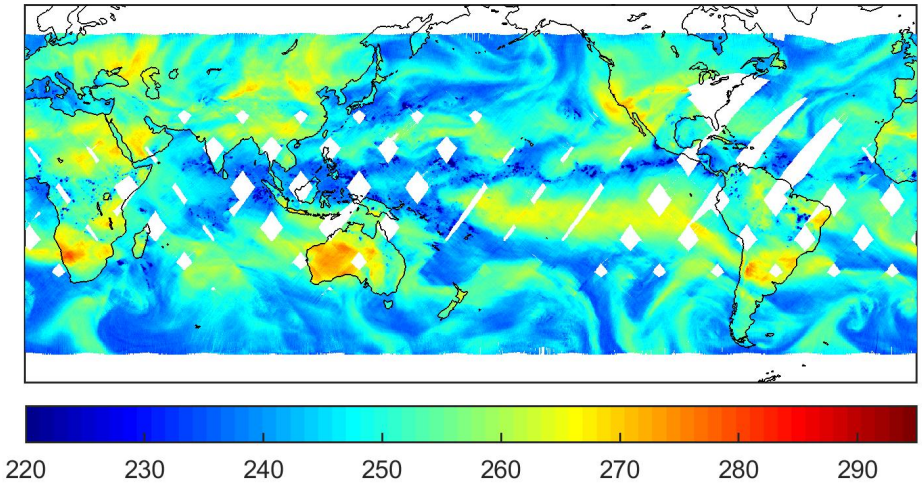
TEMPEST-D 174 GHz



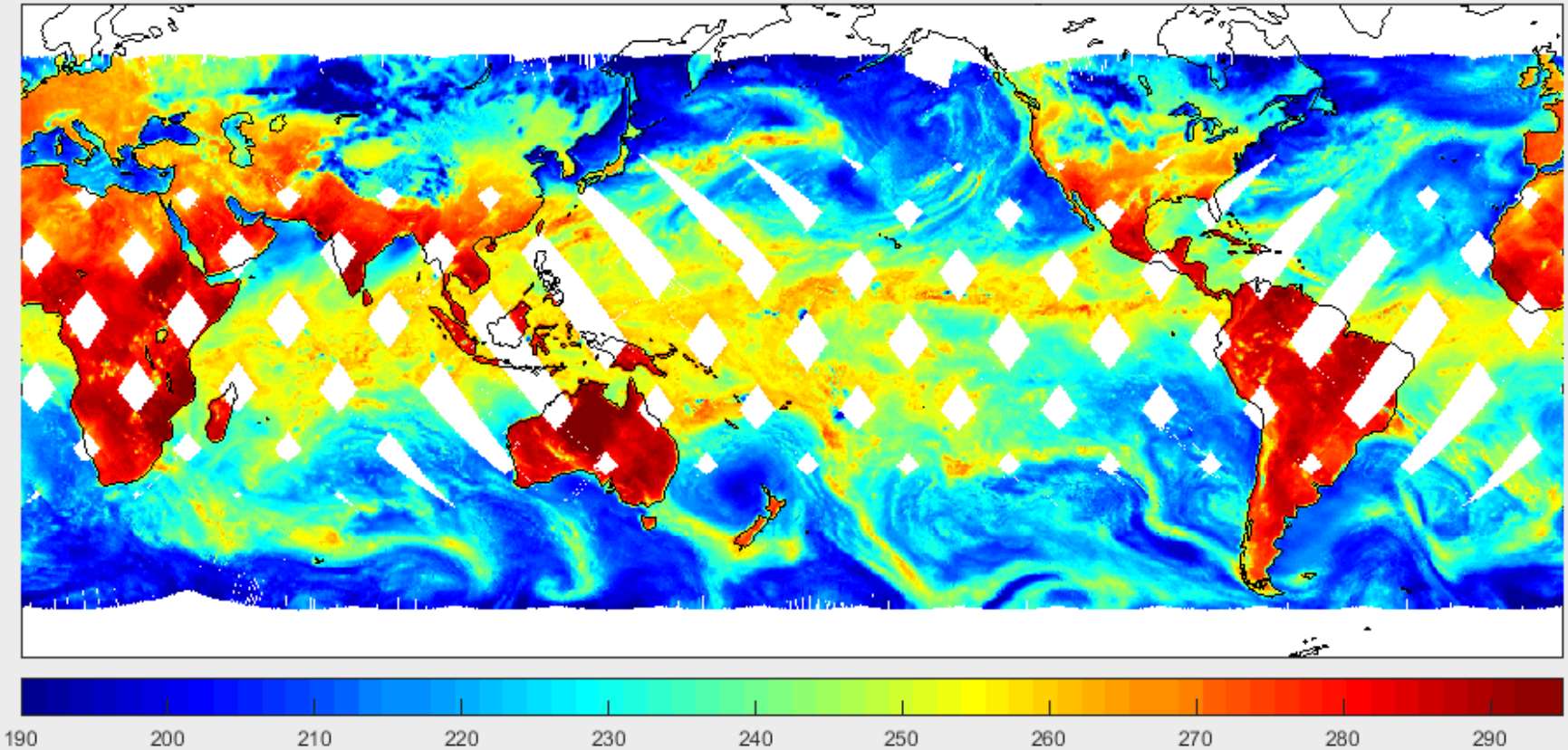
TEMPEST-D 178 GHz



TEMPEST-D 181 GHz



Sounding channels sensitive to water vapor at increasing altitudes in the atmosphere up to 10km
Band of convection in inter-tropical convergence zone (ITCZ) clearly evident near equator

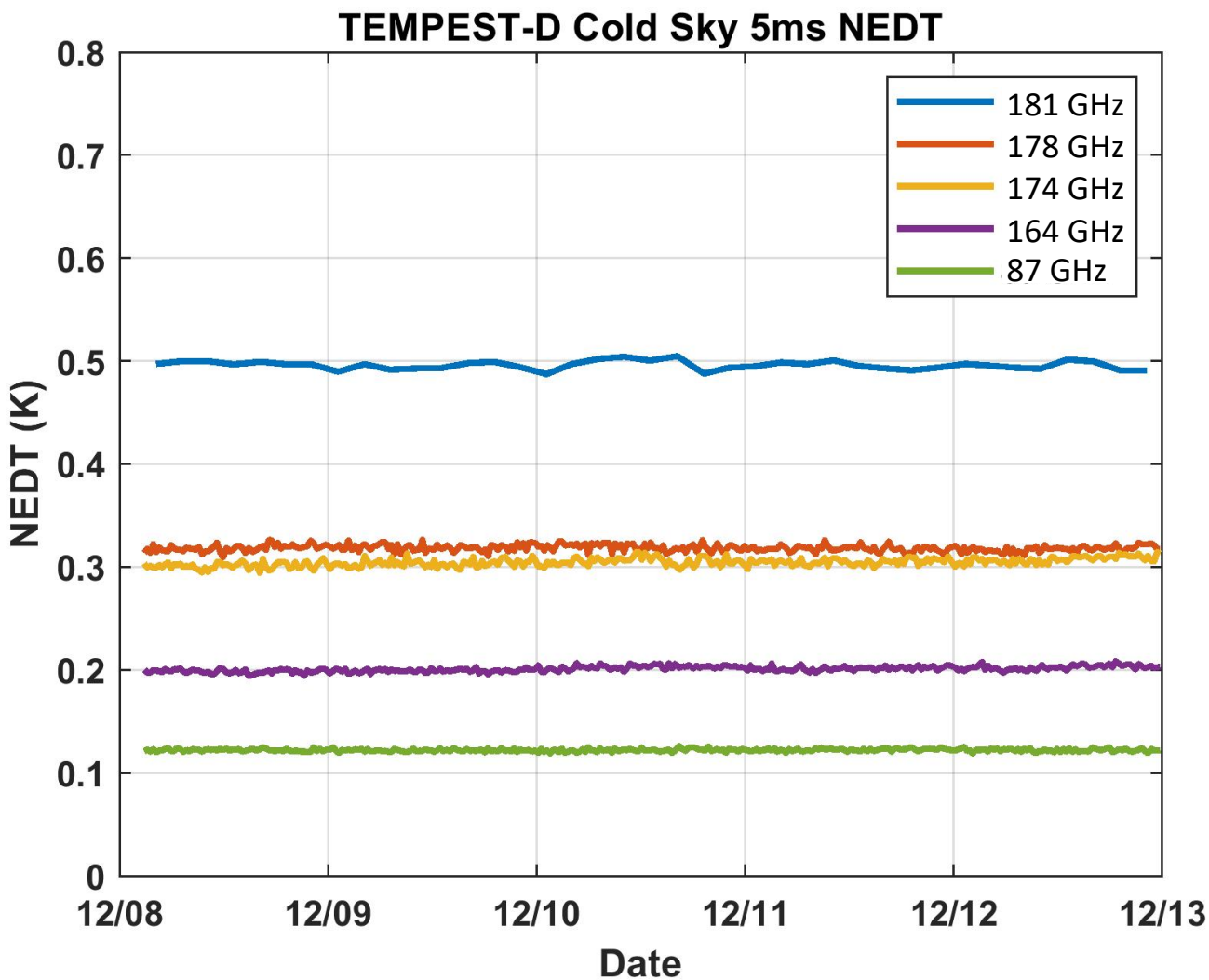


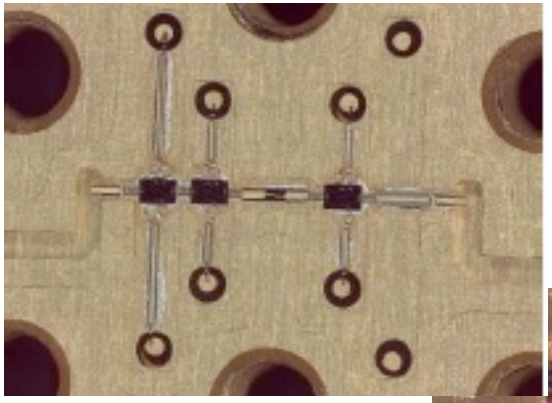
87 GHz Brightness Temperature
December 8-12, 2018

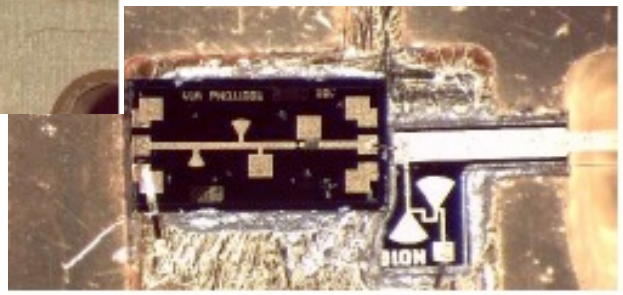
Performance

Radiometer Noise

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





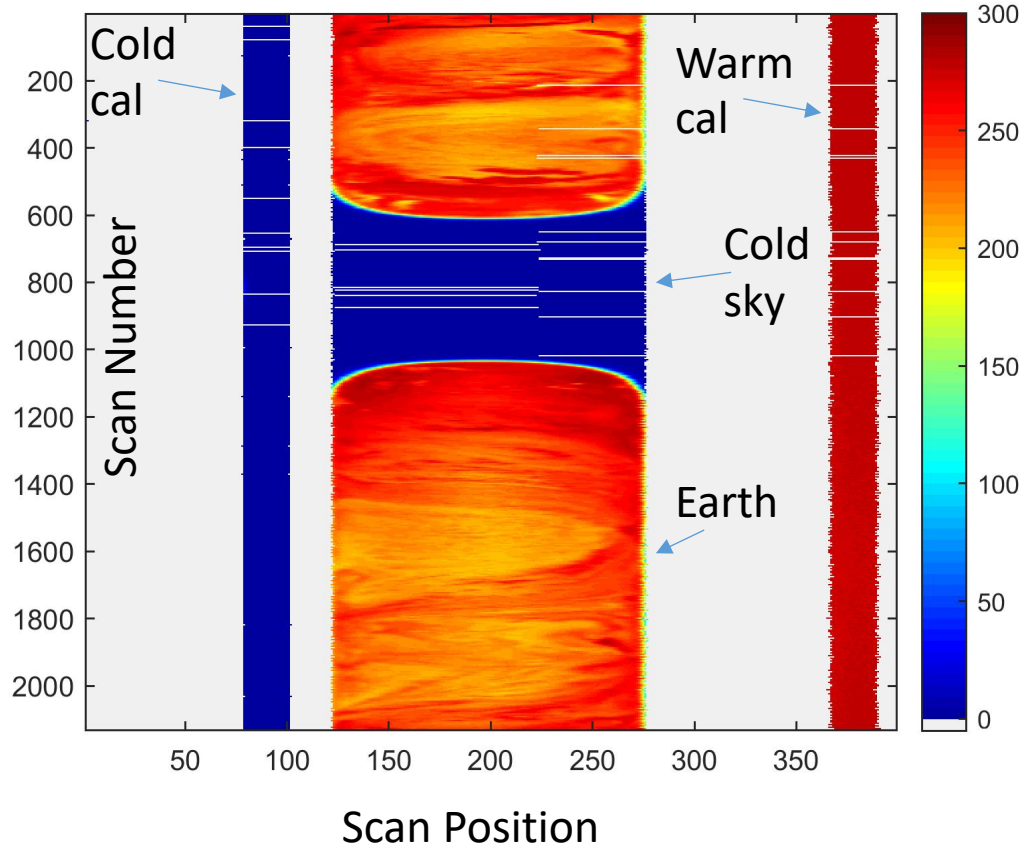


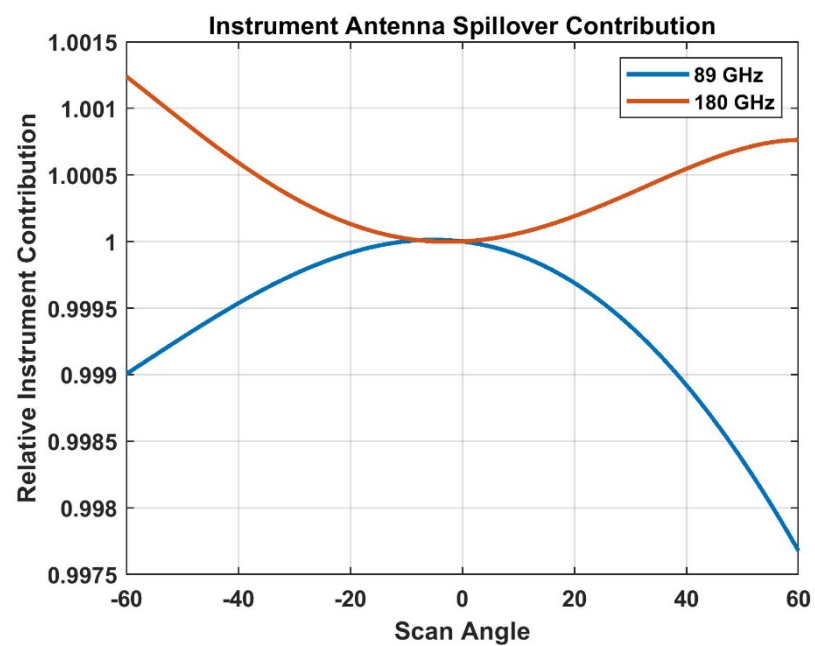
TEMPEST-D demonstrates improved receiver performance over current generation NOAA operational sensors

@ TA=300K 18ms integration time ATMS BWs	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 et al., 2014

Antenna Pattern Correction



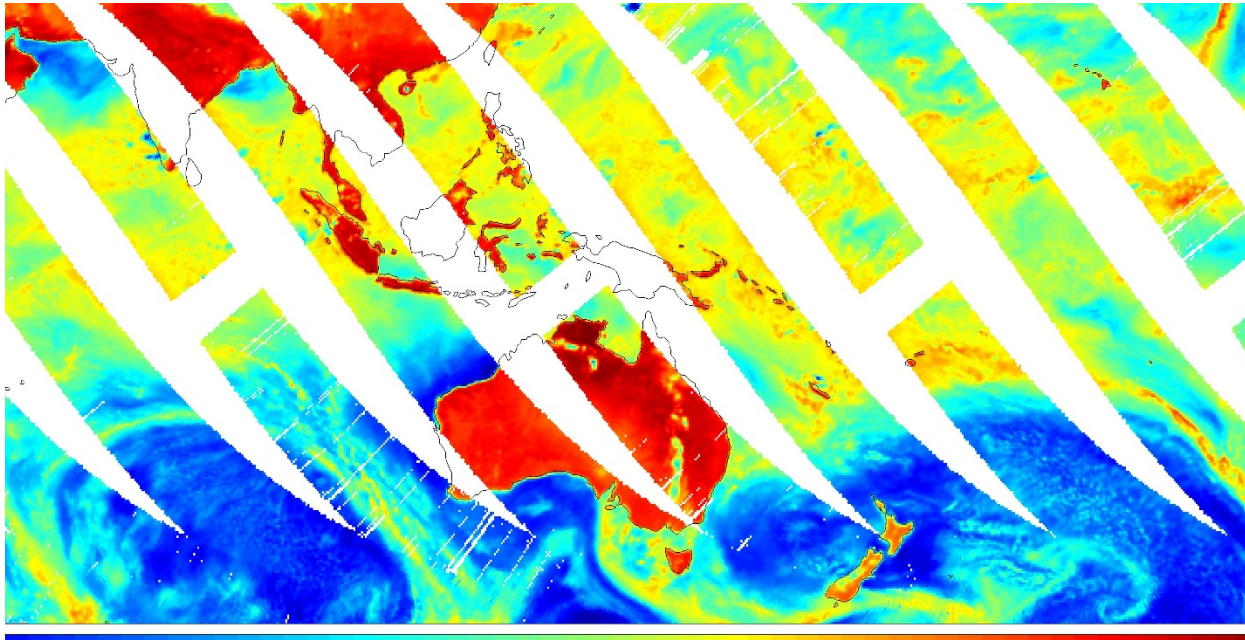


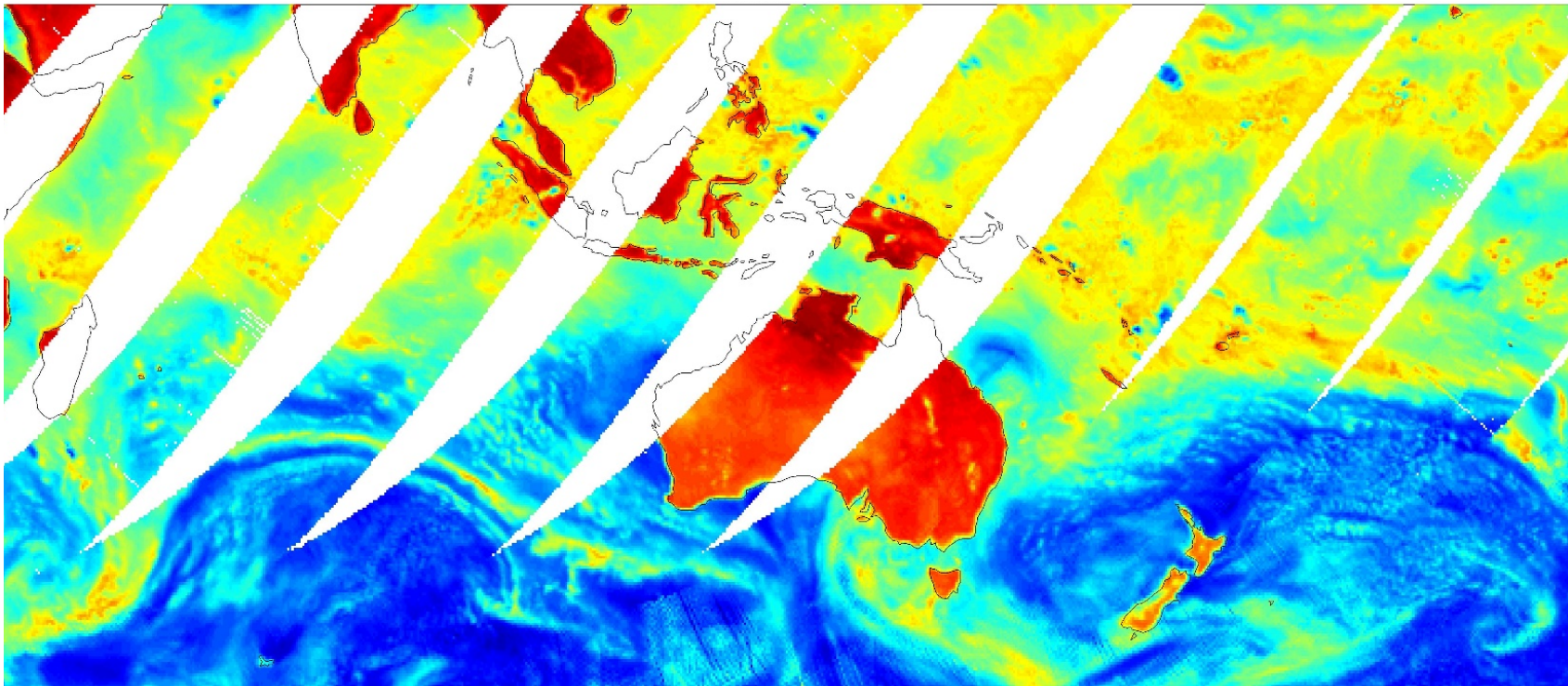
- 360° pitch maneuver performed to characterized antenna pattern correction over scan

- **Scan dependent biases < 0.5 K for all channels prior to antenna pattern correction**

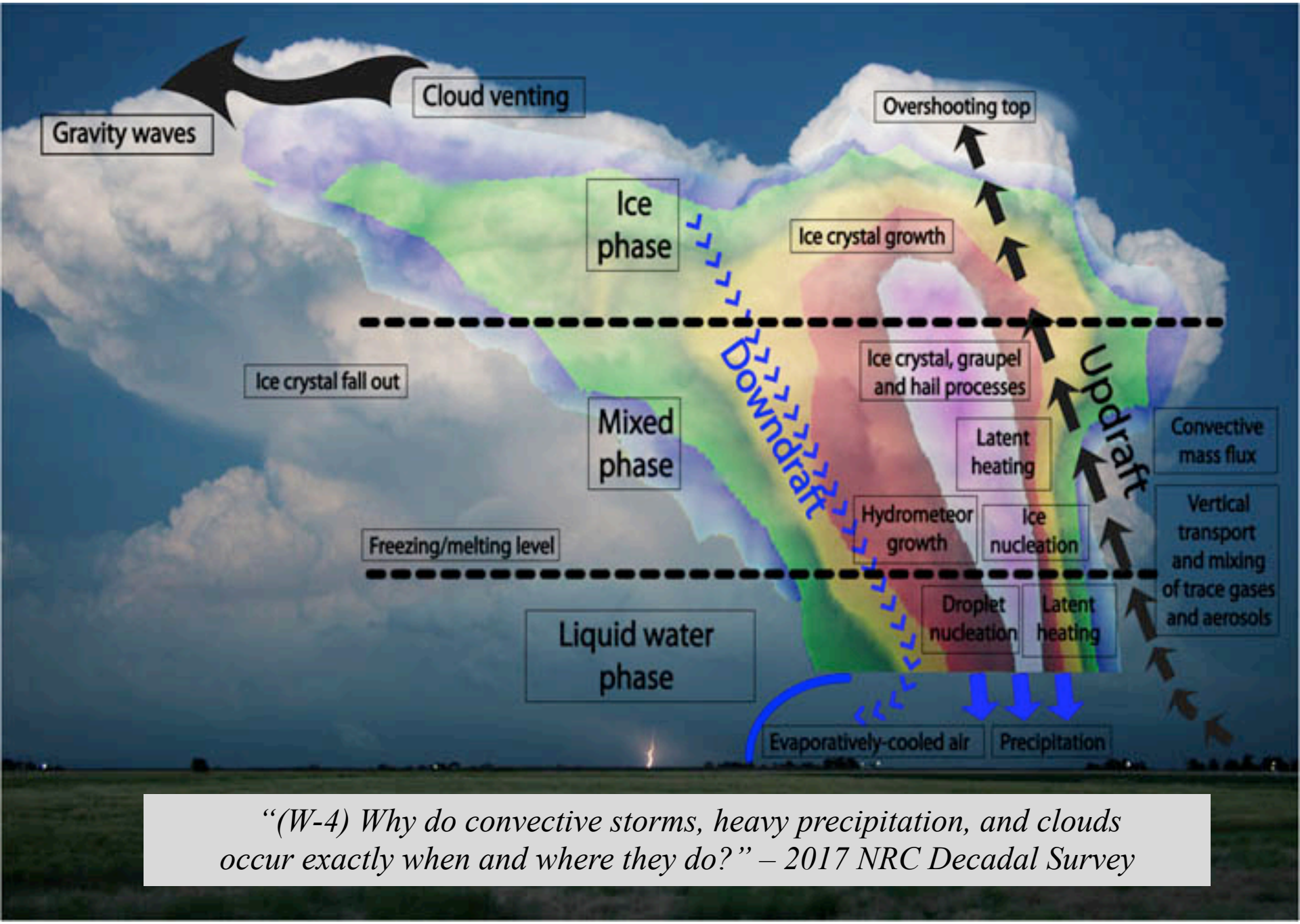
Geolocation (pointing) accurate to pixel resolution

detailed analysis on-going as dataset grows





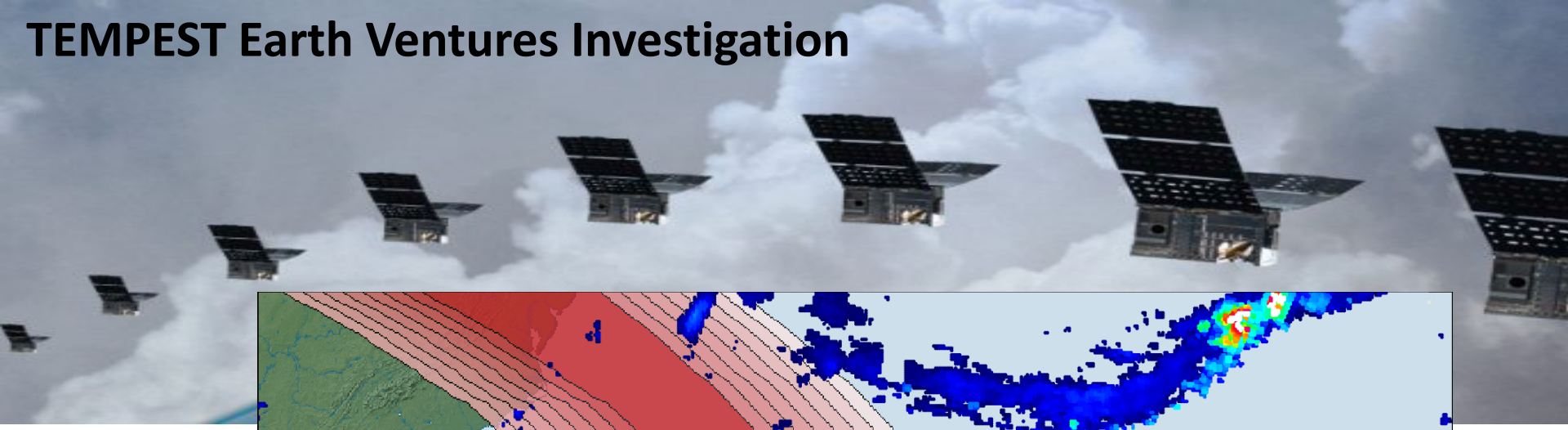
TEMPEST Mission

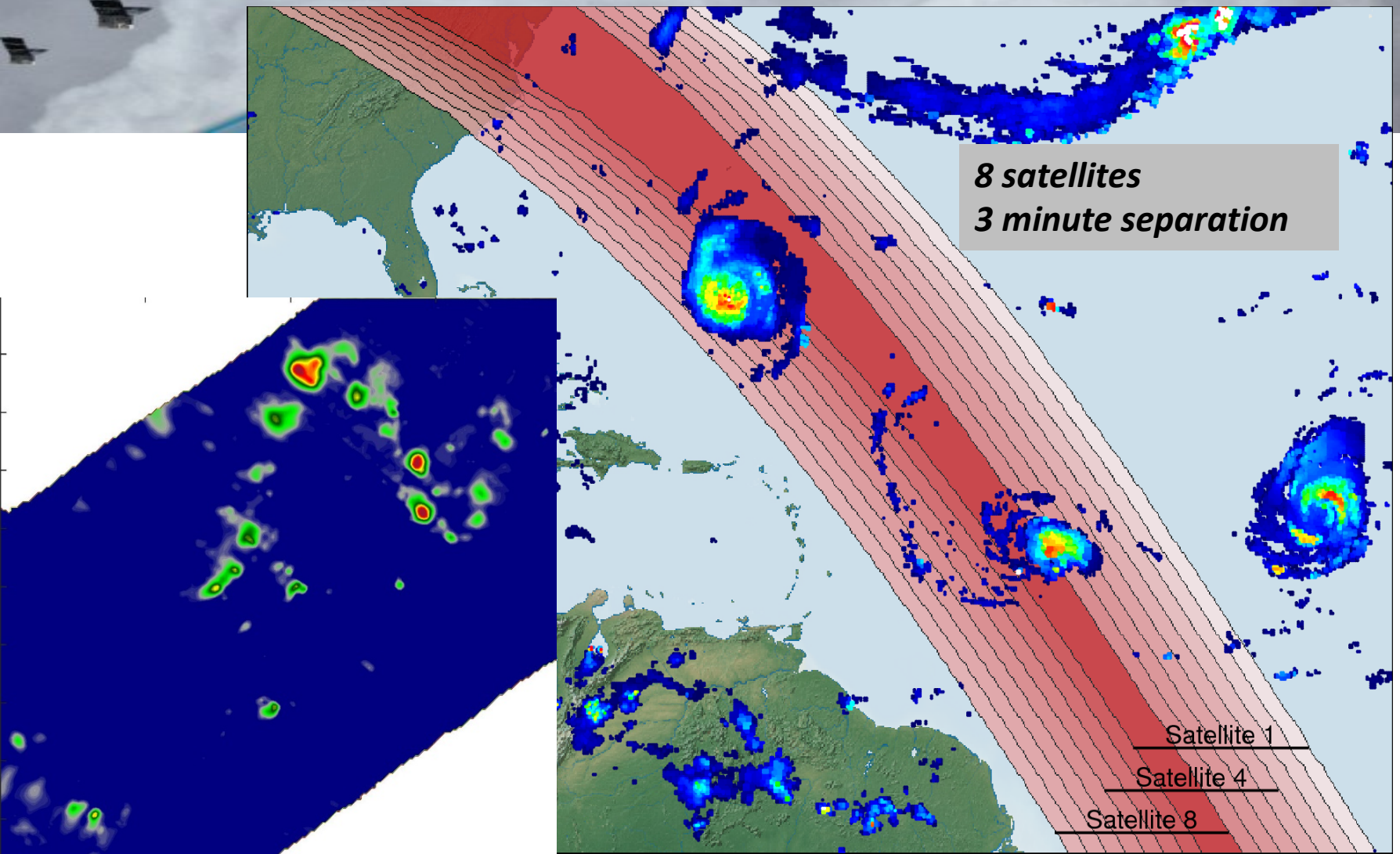


"(W-4) Why do convective storms, heavy precipitation, and clouds occur exactly when and where they do?" – 2017 NRC Decadal Survey

Courtesty CaPPM White Paper, 2016

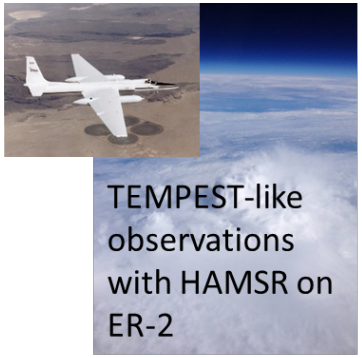
TEMPEST Earth Ventures Investigation

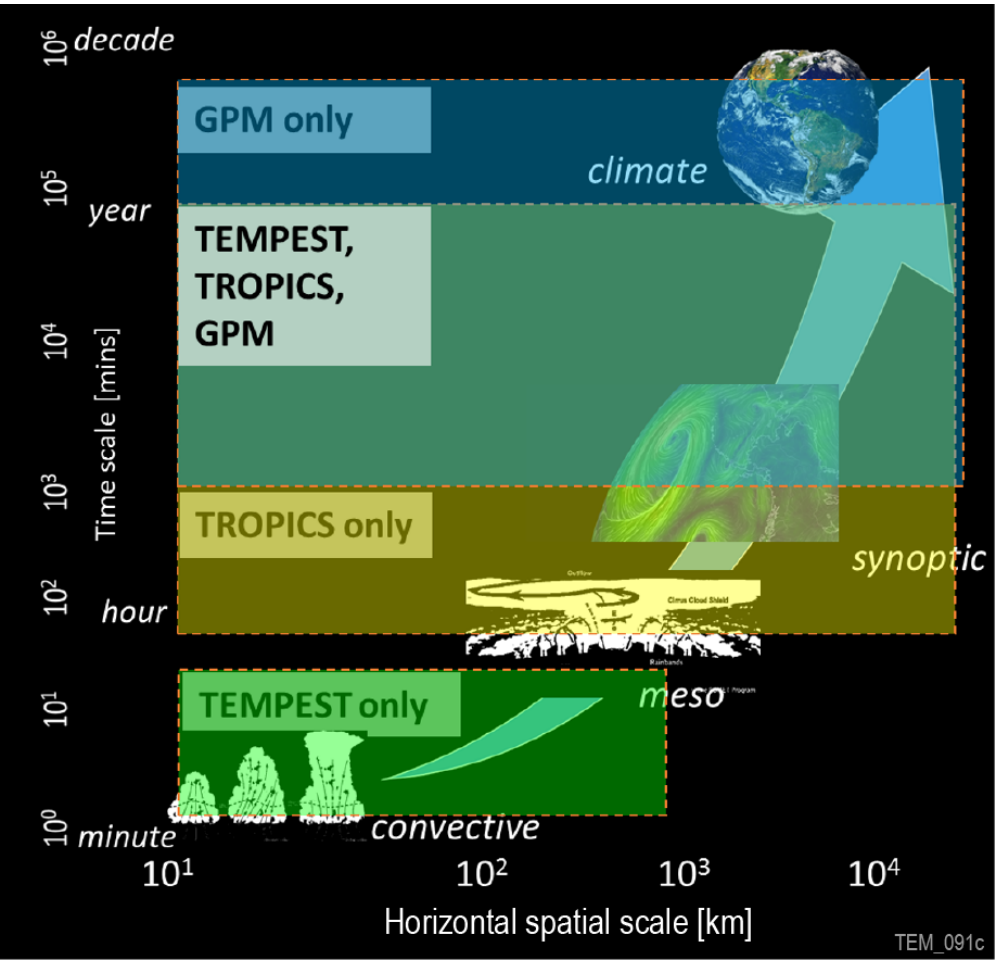


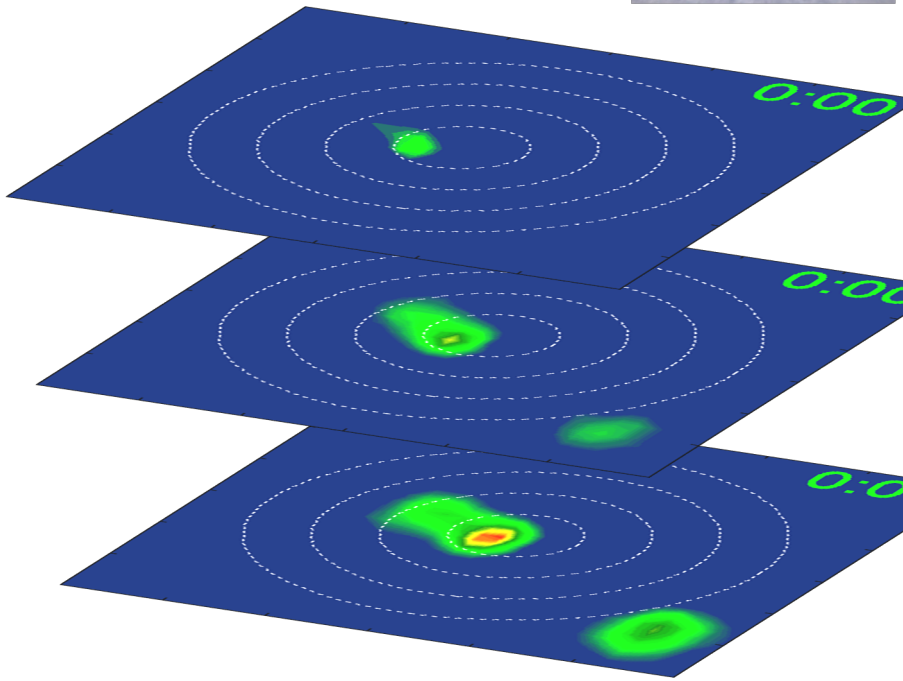


Occupying a Unique Observational Space

Investigating convective processes and the linkage to mid-tropospheric water vapor



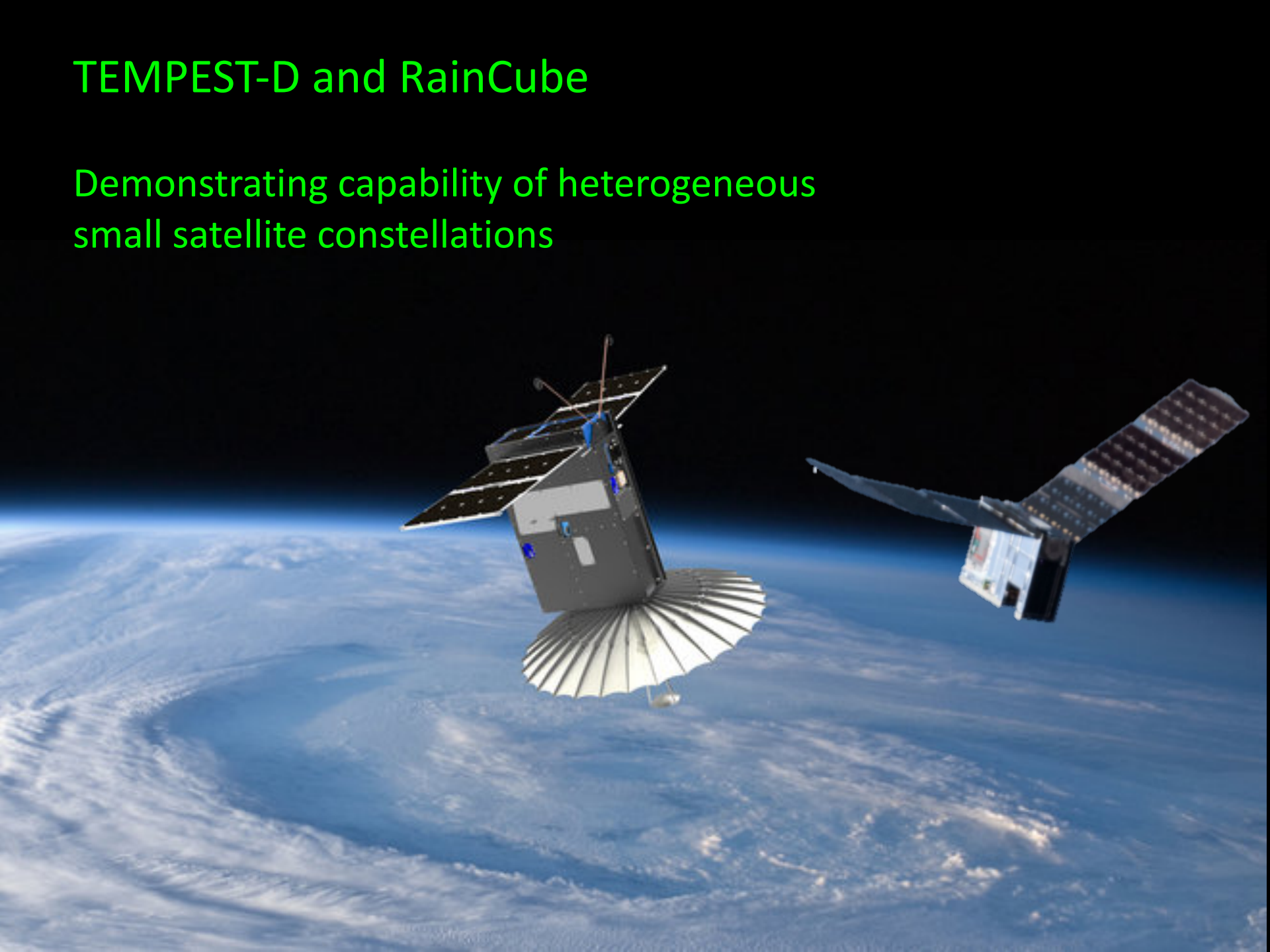


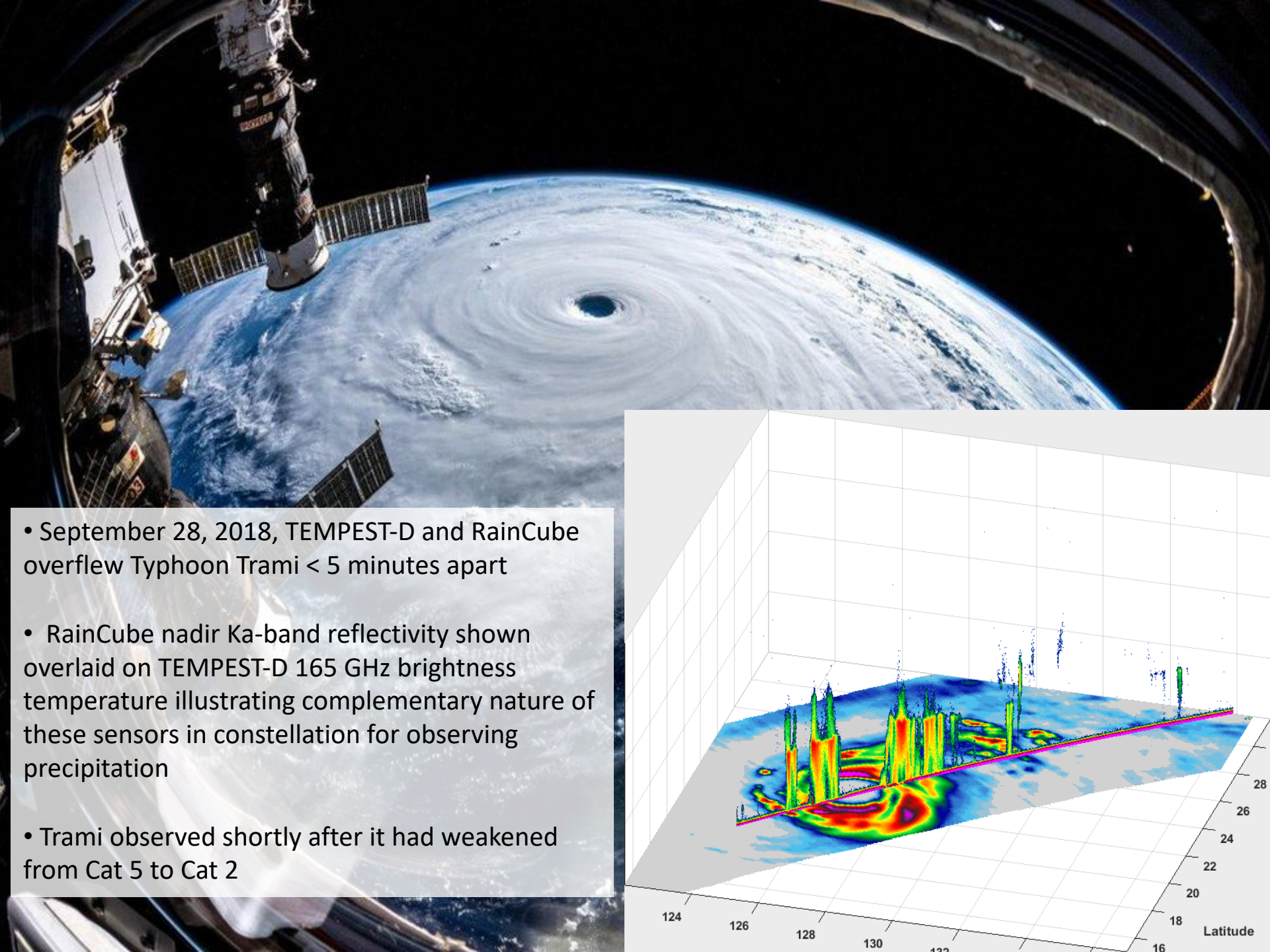


Uniquely samples developing convection over 3-30 minute time scales

TEMPEST-D and RainCube

Demonstrating capability of heterogeneous small satellite constellations



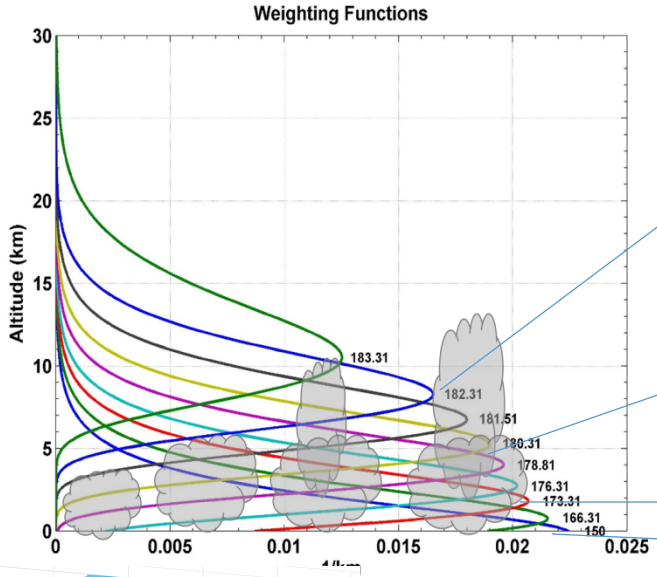


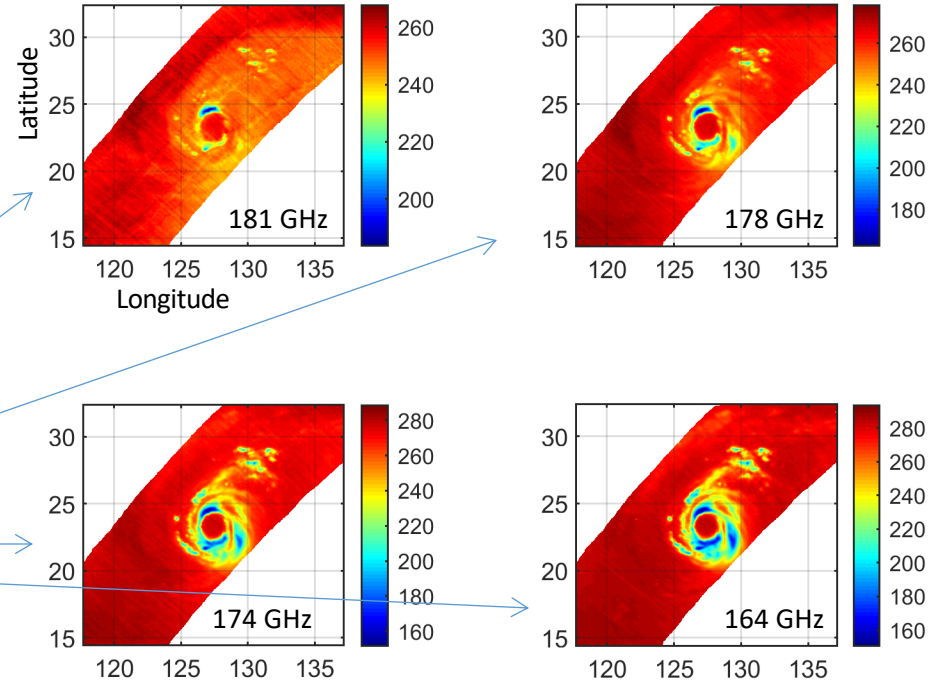
- September 28, 2018, TEMPEST-D and RainCube overflew Typhoon Trami < 5 minutes apart

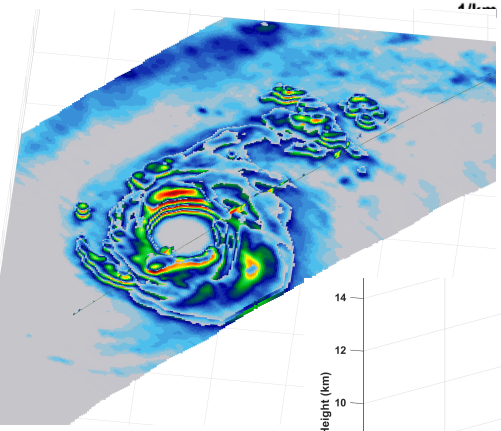
- RainCube nadir Ka-band reflectivity shown overlaid on TEMPEST-D 165 GHz brightness temperature illustrating complementary nature of these sensors in constellation for observing precipitation

- Trami observed shortly after it had weakened from Cat 5 to Cat 2

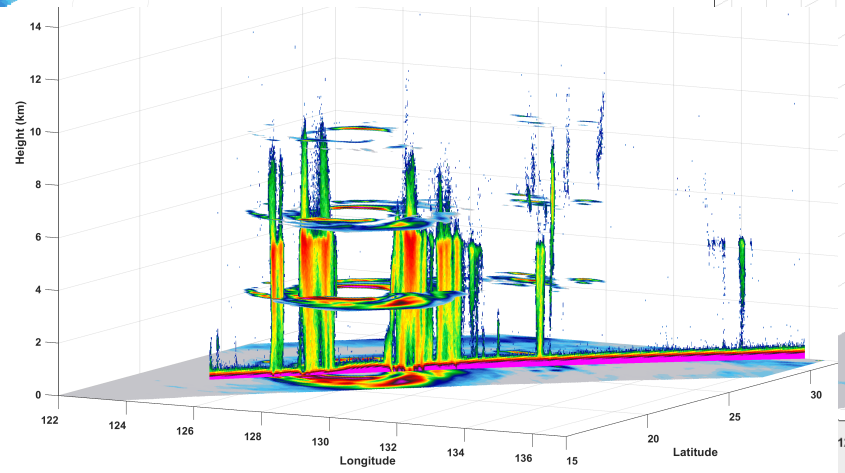
TEMPEST-D Sounding Channels provide 4 levels of vertical resolution to "slice" precipitation and compare with RainCube profile

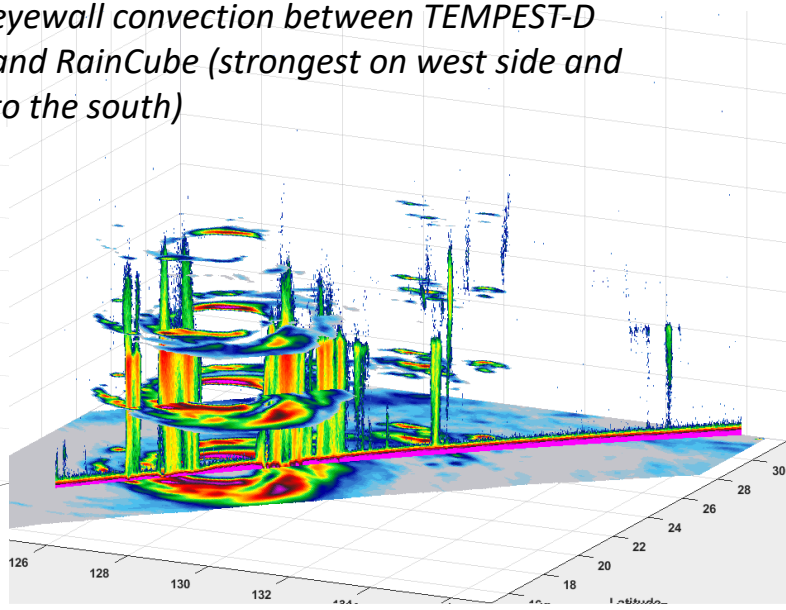




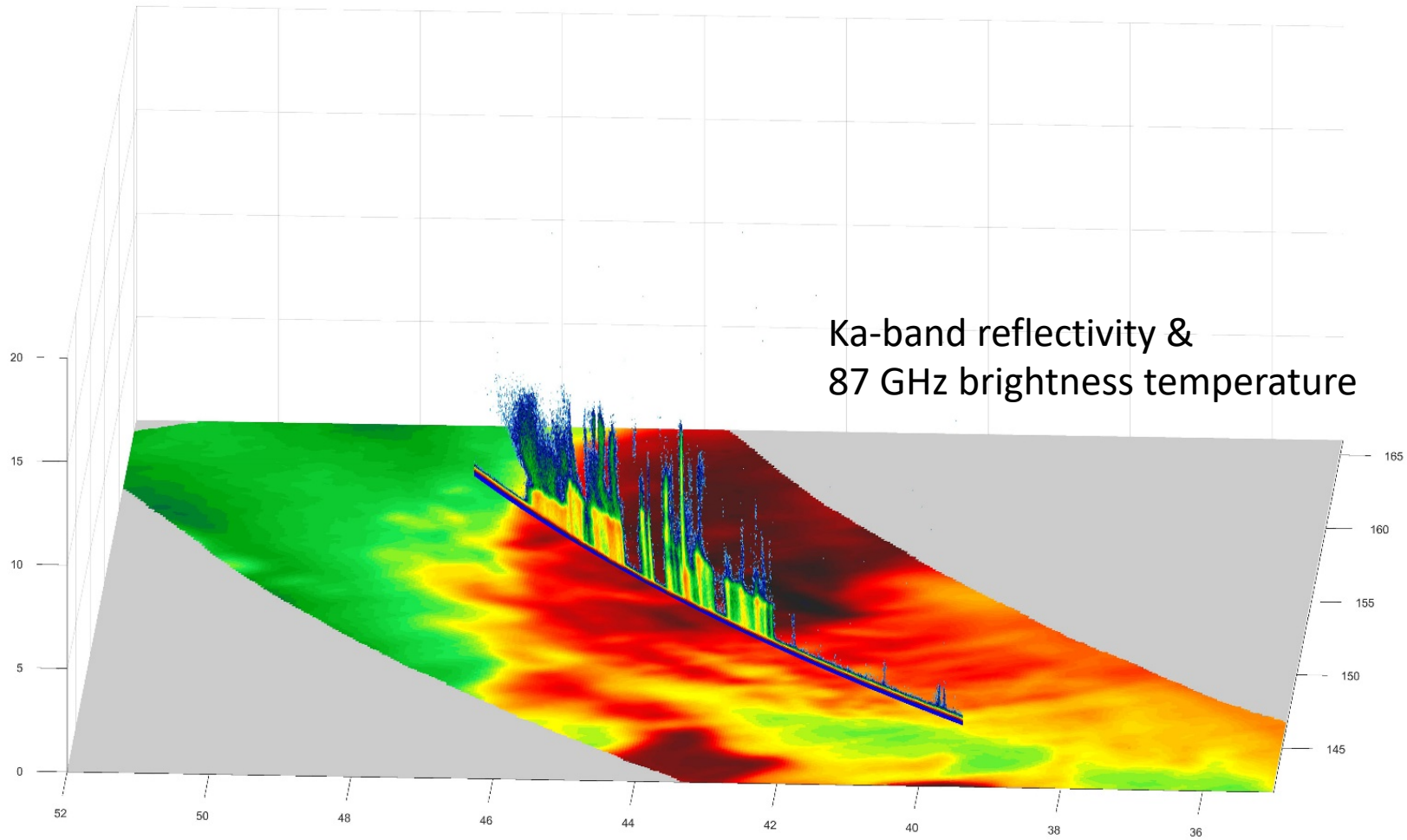


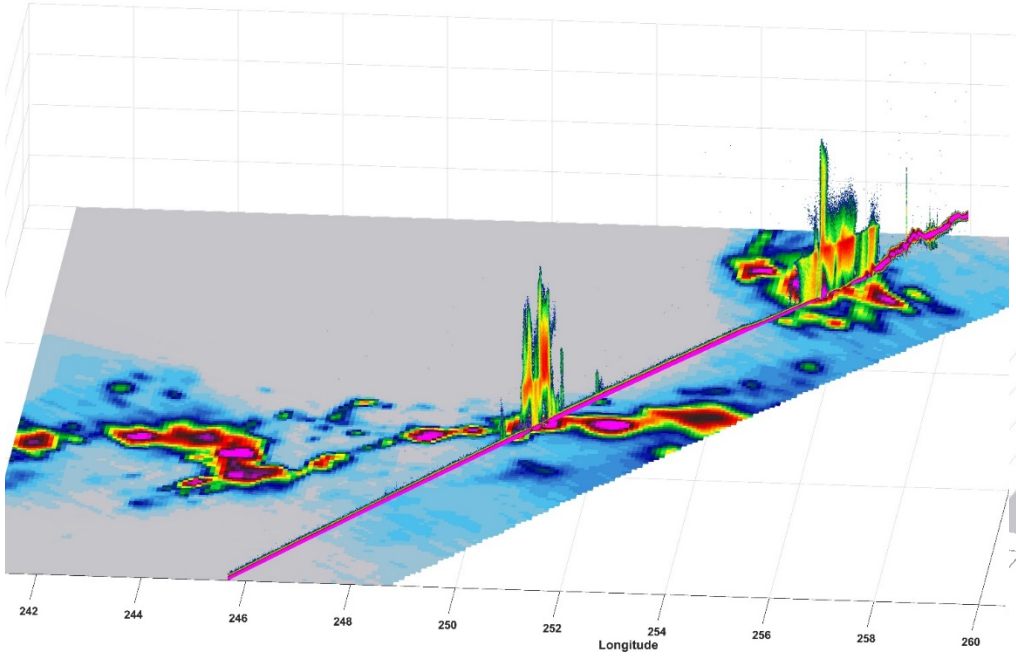
Similar asymmetry observed in depth of eyewall convection between TEMPEST-D and RainCube (strongest on west side and to the south)

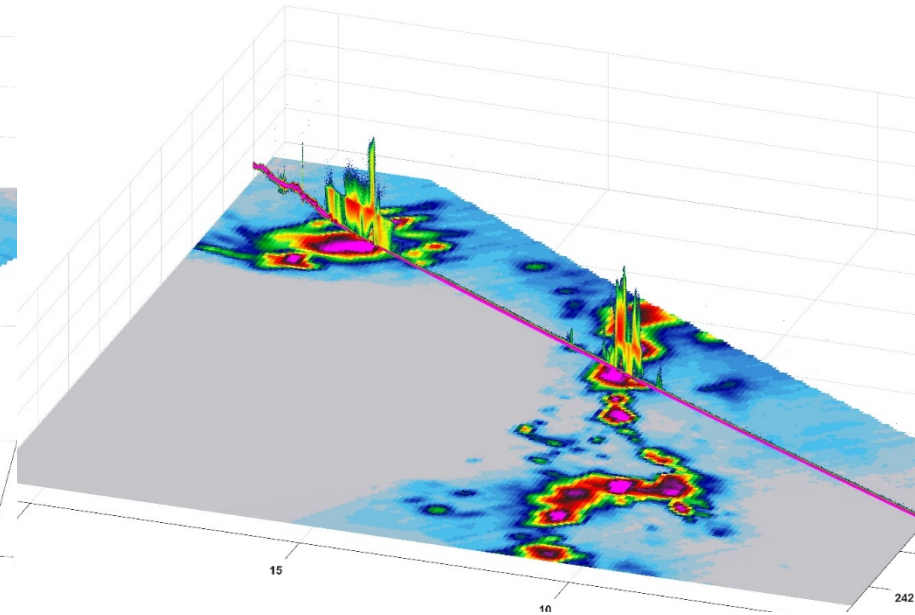


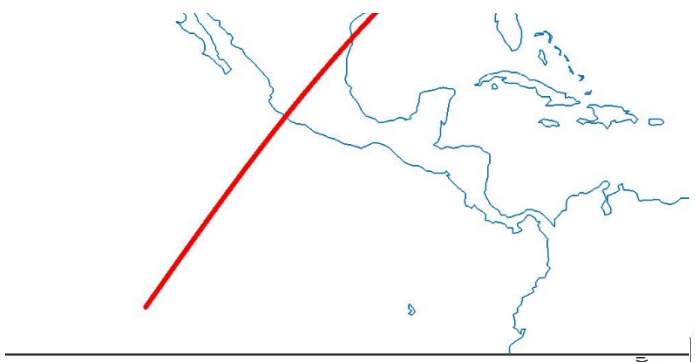


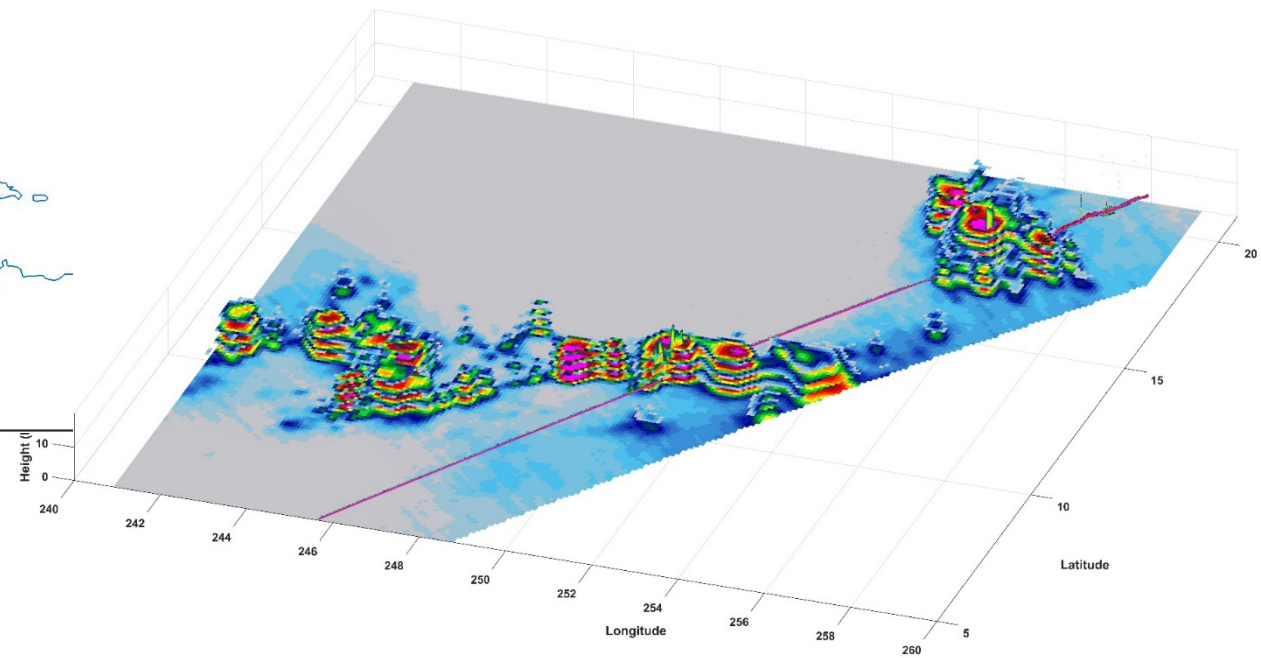
Sept 28 – Mid-latitude front











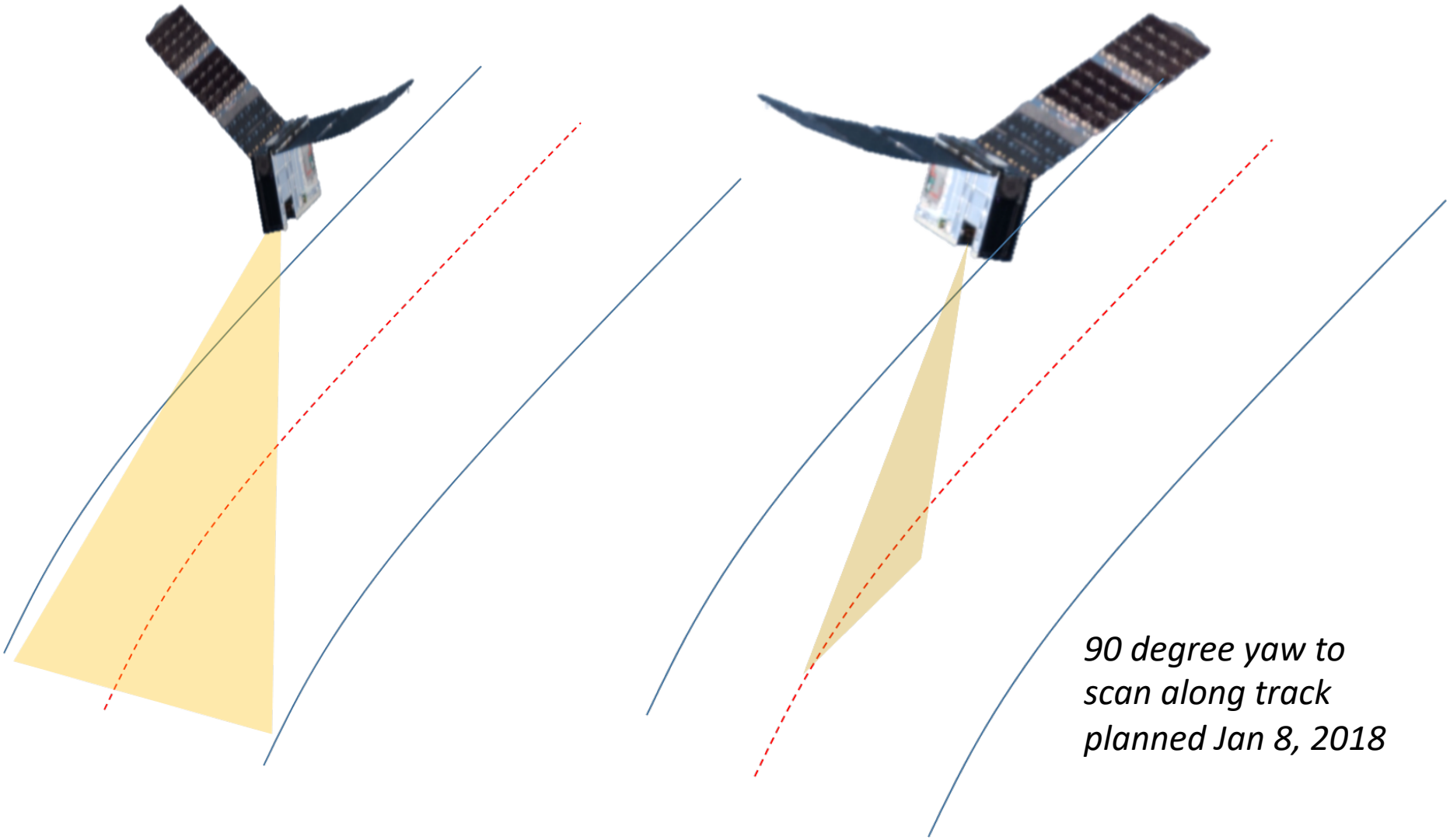
Oct 15 15:25 UTC
Orographic precipitation off
Mexican coast

TEMPEST-D

- Calibration ✓
- Sensor noise quality ✓
- Capability ✓
- Pointing accuracy ✓
- Reliability …
- Data rate …

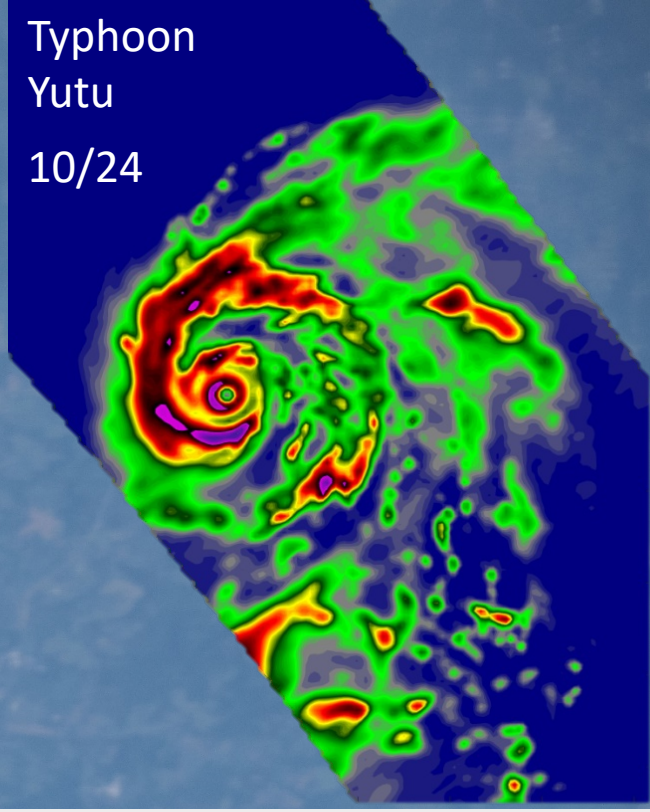
Upcoming

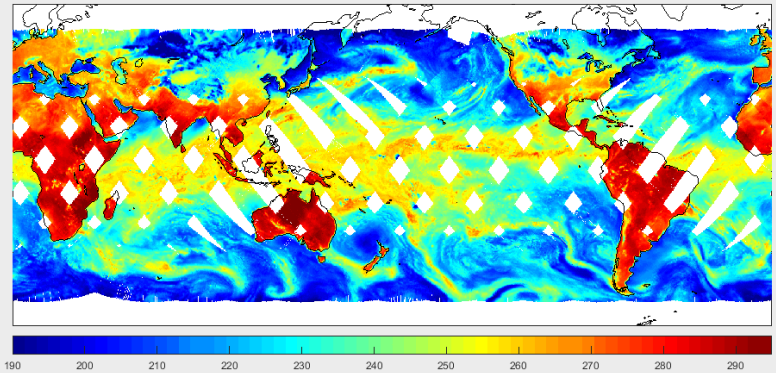
Multi-angle observations (along-track scanning)



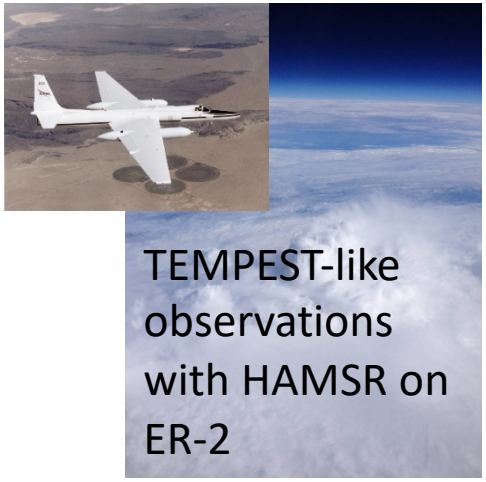
Summary

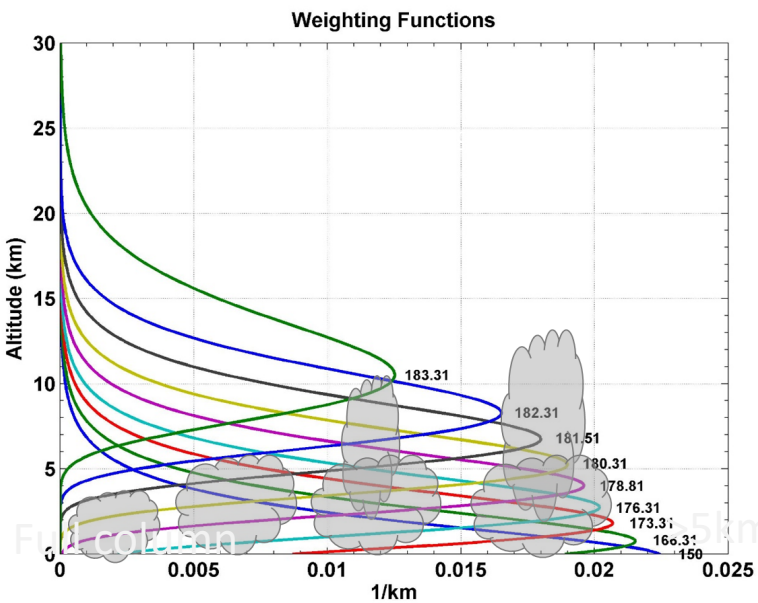
- TEMPEST-D demonstrating enormous potential for small sat payloads
- Operational class data at high temporal resolution will enable investigation of precipitation processes

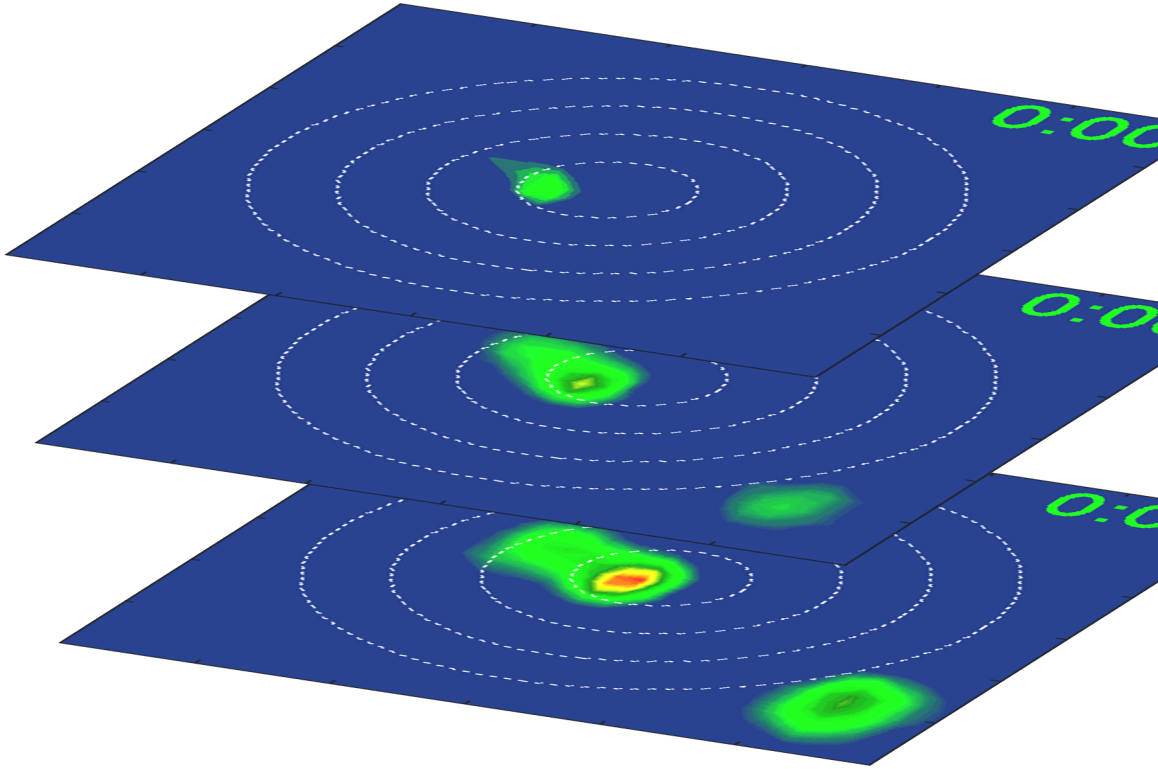




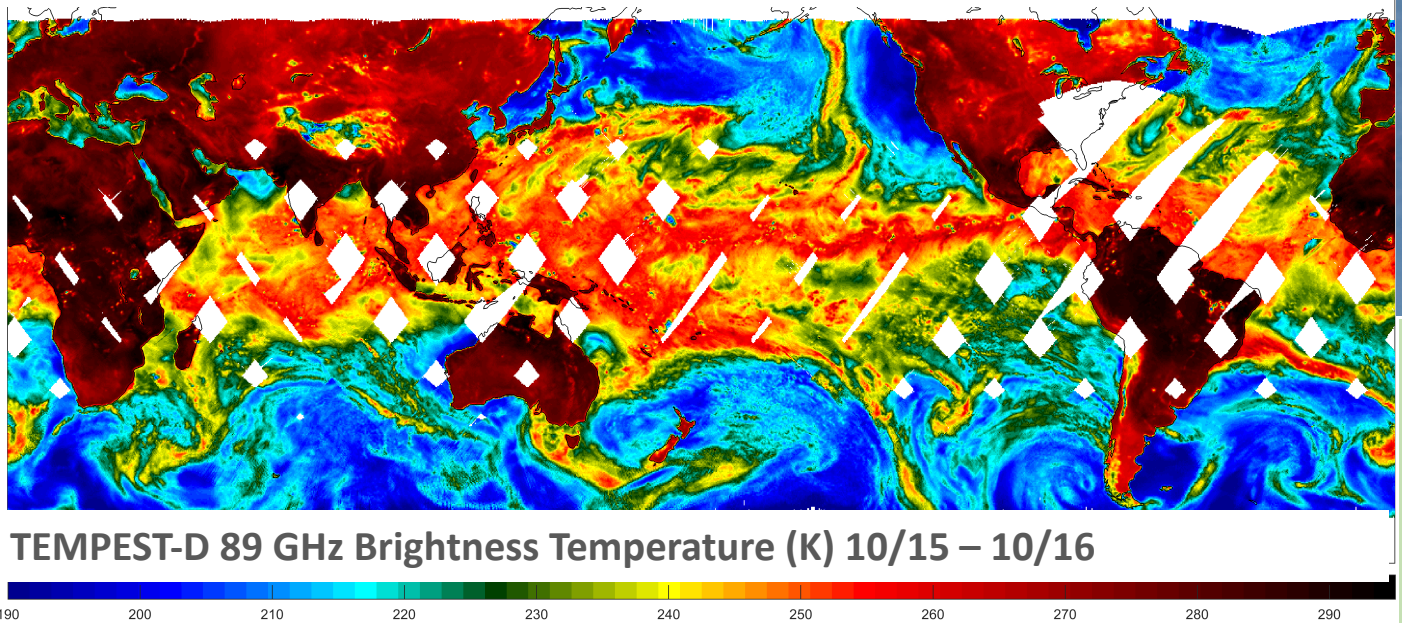
TEMPEST-Like Measurements from JPL/HAMSR on ER-2 Aircraft







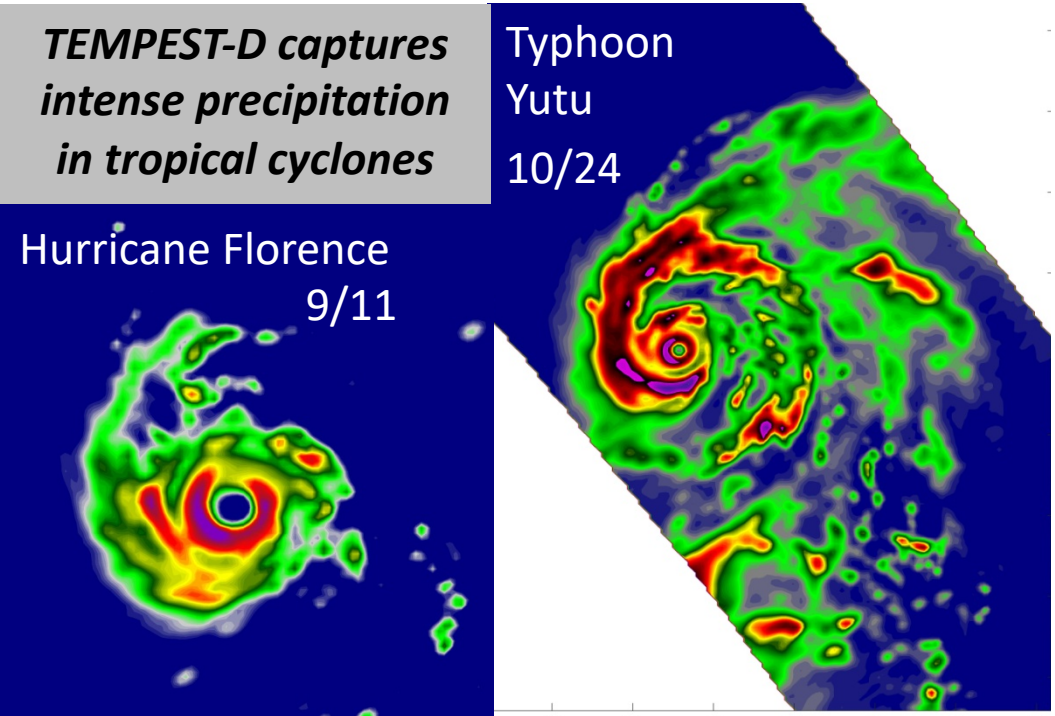
TEMPEST-D: Proving good observations can come in small packages

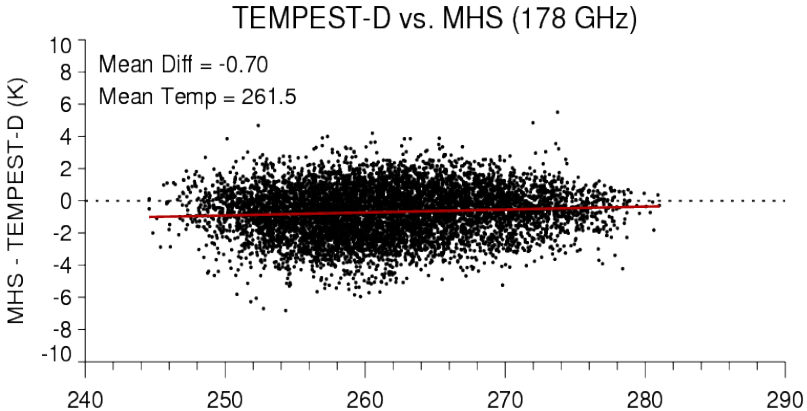


TEMPEST-D 89 GHz Brightness Temperature (K) 10/15 – 10/16

TEMPEST-D data show excellent calibration and pointing stability over multiple orbits from a CubeSat platform right out of the box

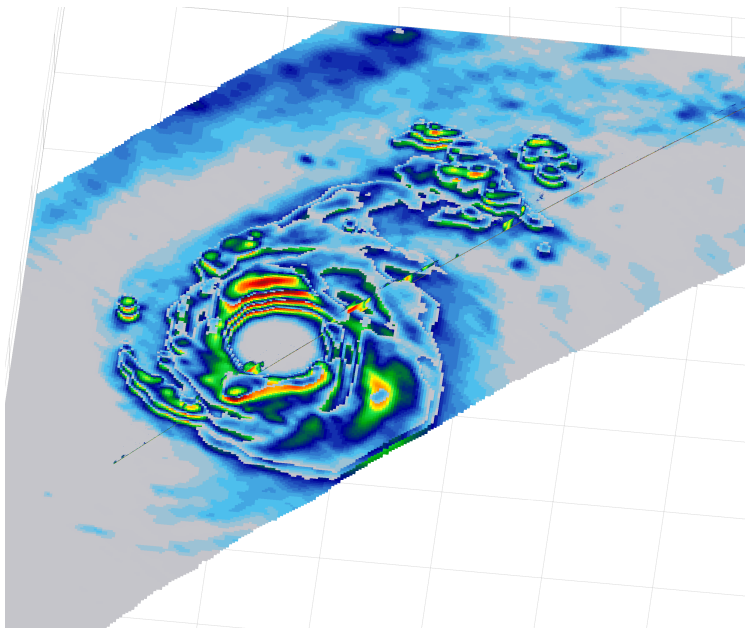
TEMPEST-D captures intense precipitation in tropical cyclones

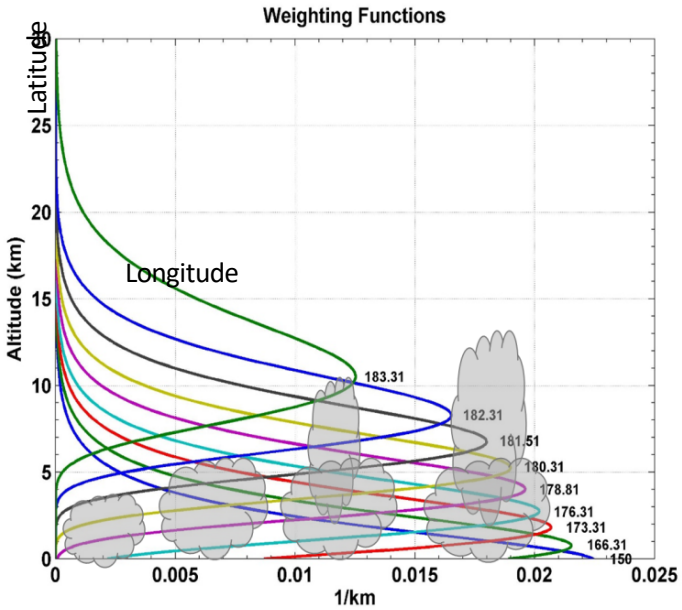
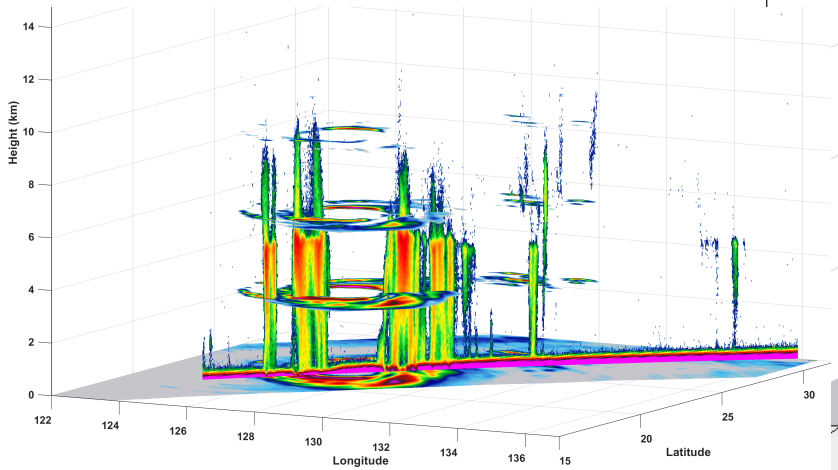
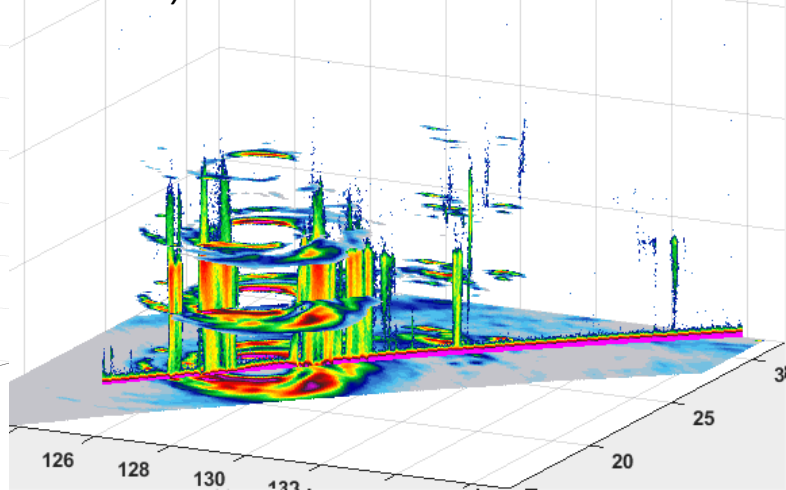




Remarkable agreement between TEMPEST-D and NOAA operational MHS sensor from day 1

TEMPEST-D Sounding Channels provide 4 levels of vertical resolution to "slice" precipitation and compare with RainCube profile





Similar asymmetry observed in depth of eyewall convection between TEMPEST-D and RainCube (strongest on west side and to the south)