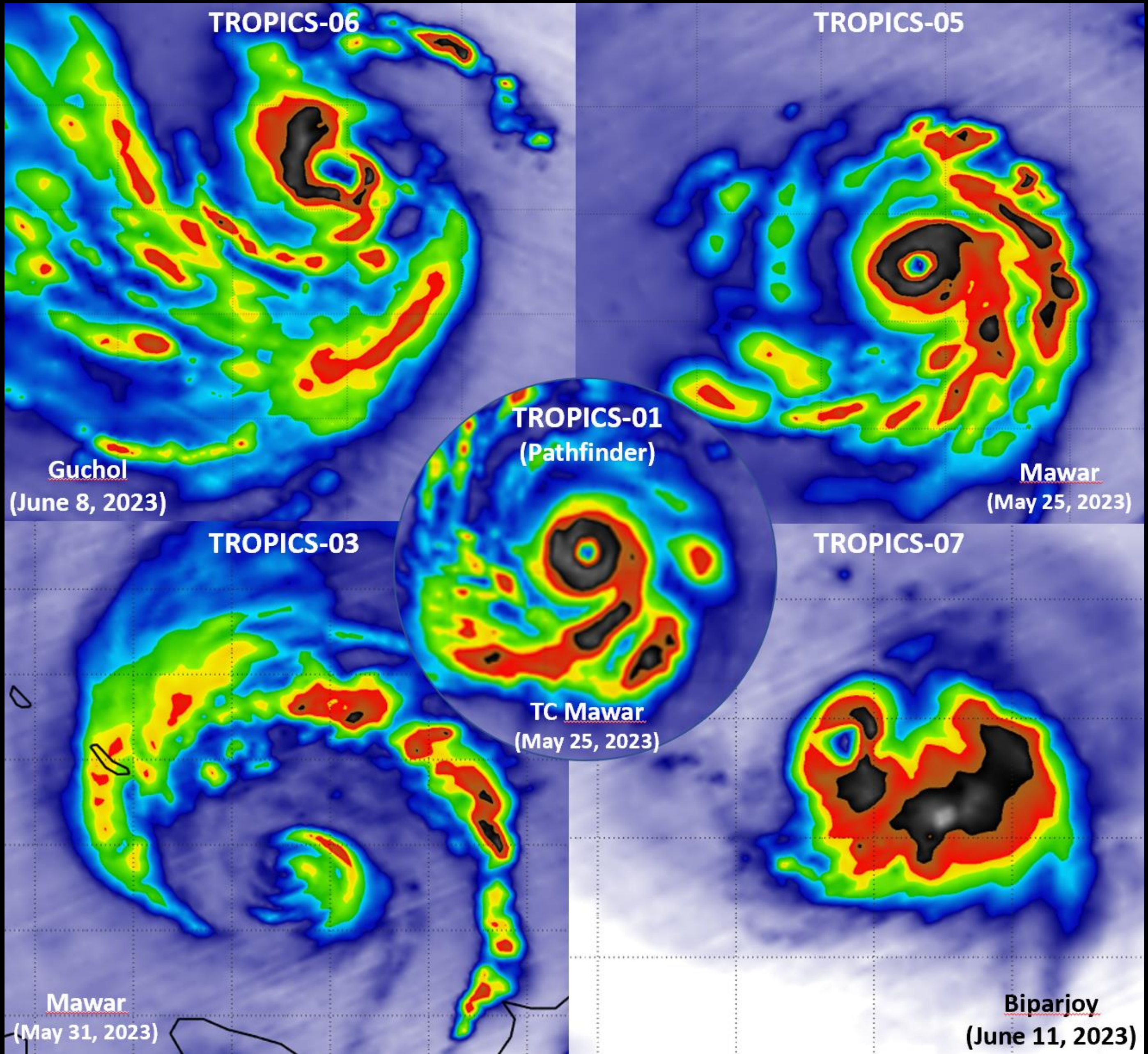
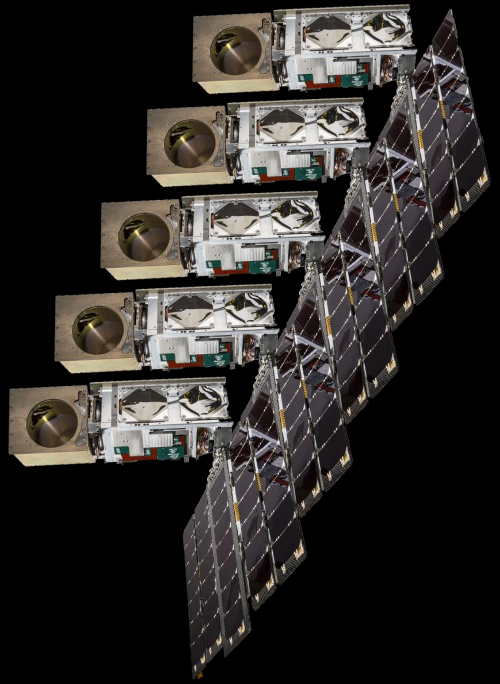
New Frontiers in Atmospheric Sensing from Small Satellites: TROPICS and CREWSR

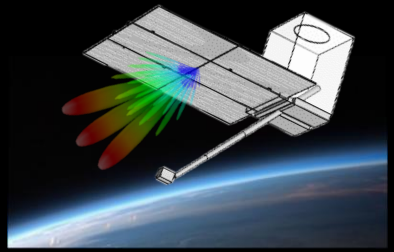
William J. Blackwell
MIT Lincoln Laboratory

September 26, 2023
NASA GESTAR Seminar





~5×10^{-5} m^2 aperture



~4 m^2 aperture

New Frontier #1 in Earth Observing: Better Persistence Through Constellations

Traditional Approach: Small Number of Big, Multifunction Satellites

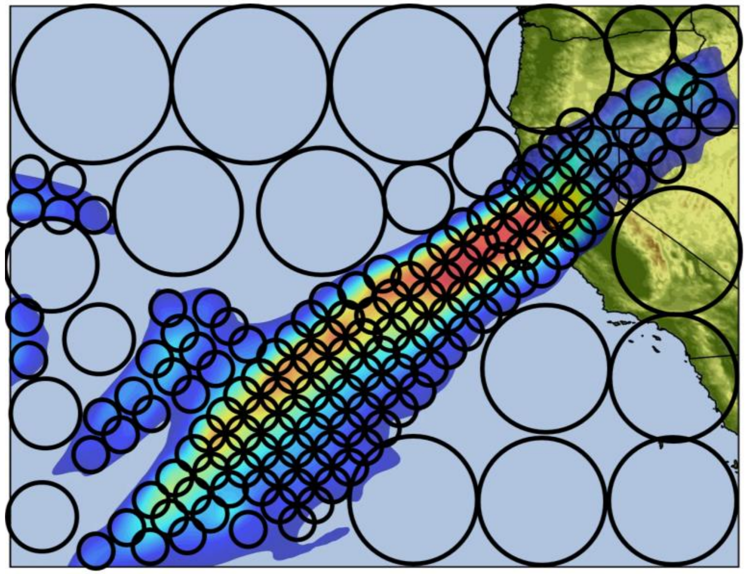
- Large: 2100 kg
- Expensive: ~$2B/Satellite
- Three polar orbits with ~4 hr revisit rate
- Need international partners and multiple US departments

Improved Approach: Large Number of Small, Specialized Satellites

- Small: <10 kg
- Affordable: ~$1M/Satellite
- Constellation yields ~30 min revisit rate
- Permits rapid infusion of new technologies

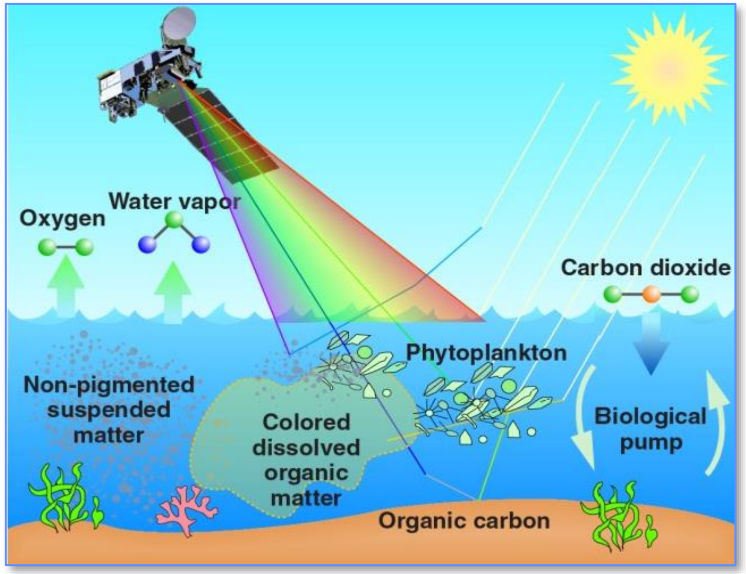
New Frontier #2 in Earth Observing: Configurable Sensors that are Collaborative & Intelligent

Spatial Configurability



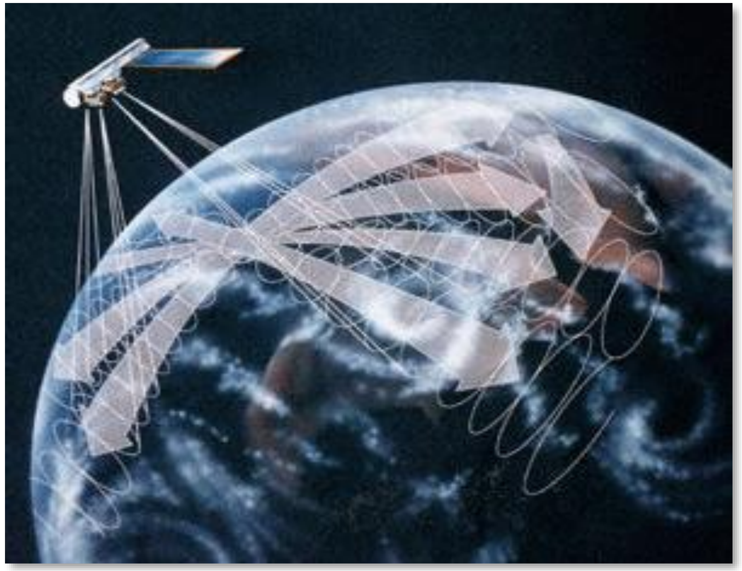
Highest resolution reserved for spatially dynamic areas of the scene

Spectral Configurability



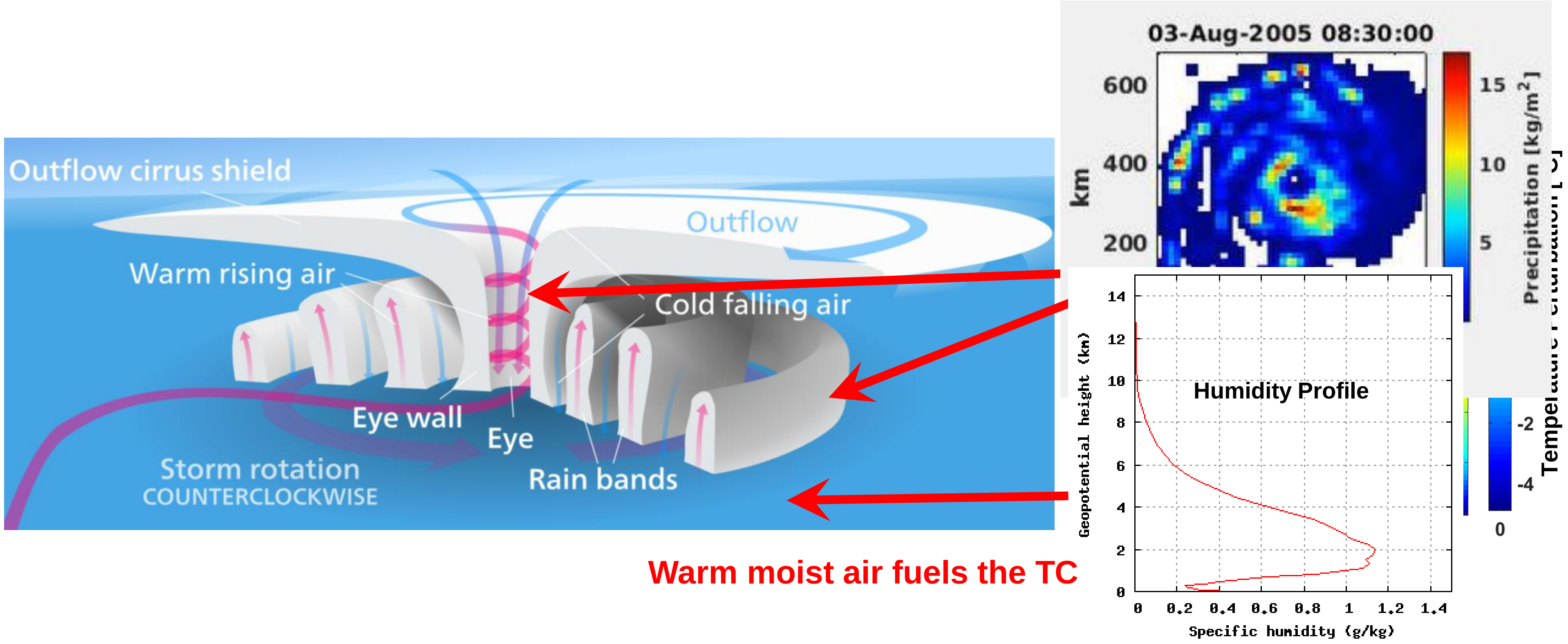
Molecular spectroscopy versus coarse-band imaging

Look-Angle Configurability



Multiple observations from different vantage points permits tomography

Case Study #1:
TROPICS Earth Venture Mission to study Tropical Cyclones



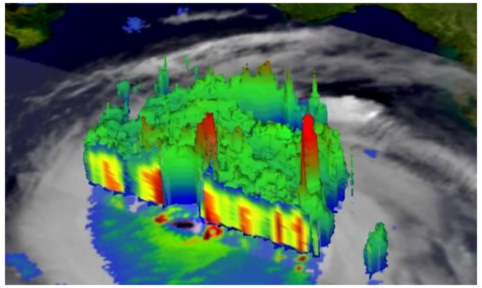
Need to measure 4-D temperature, humidity and precipitation to better understand hurricane science and therefore improve the forecast models

Methods for Sensing Tropical Cyclones

Radar

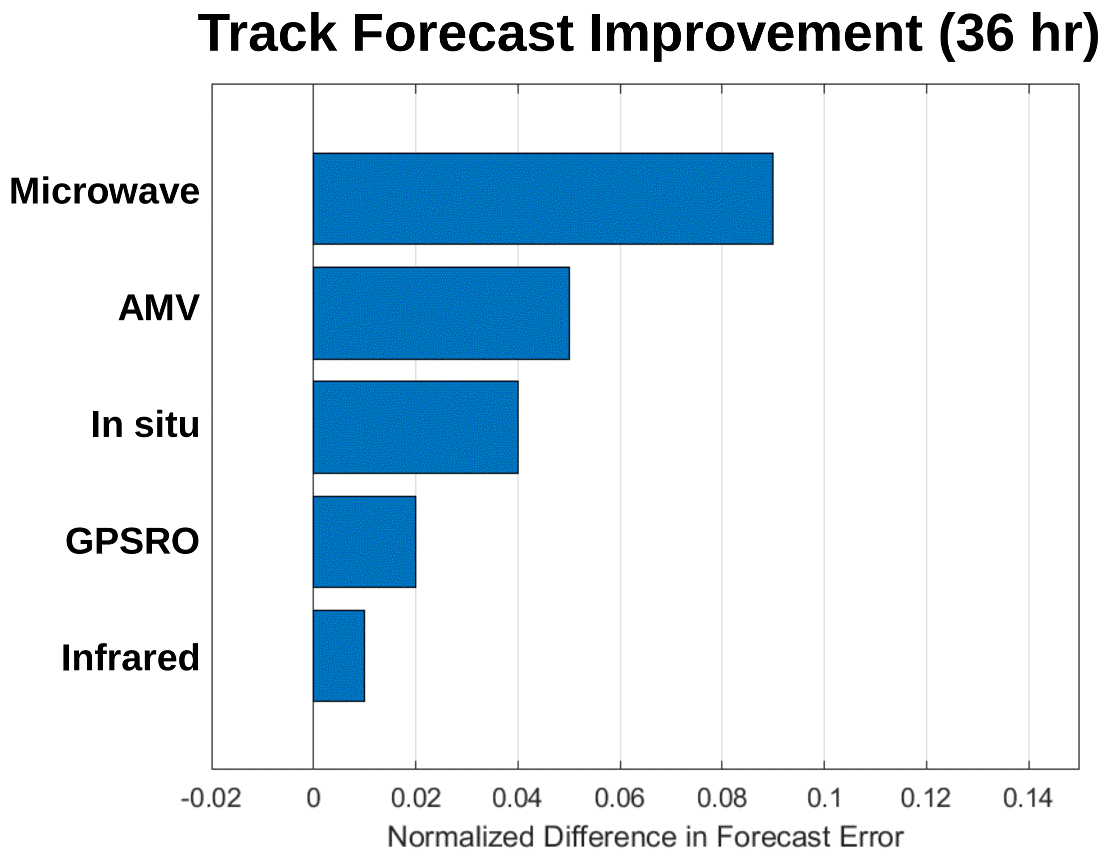
Dropsonde from Aircraft

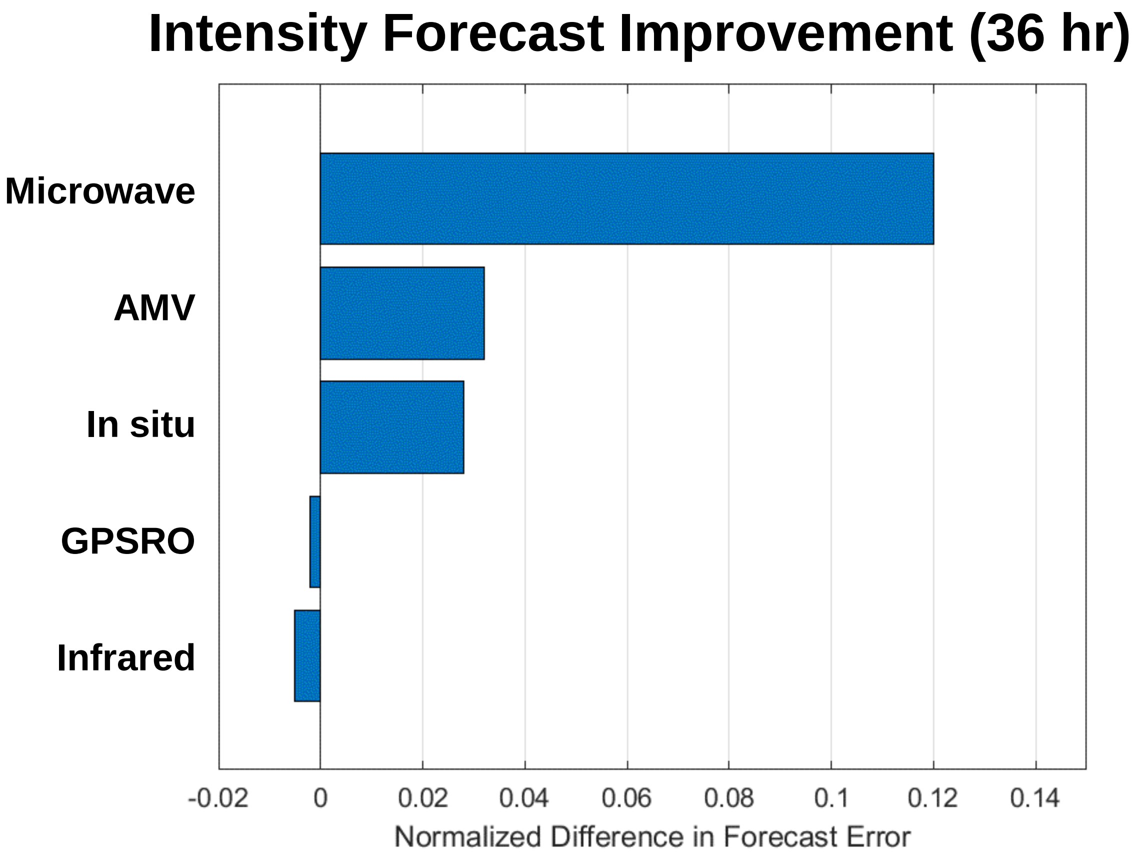

Vis/IR Imaging & Sounding


Passive Microwave Sounding

- **Passive microwave sounding can provide measurements of 3-D storm structure that is essential to accurately predict future path**
- **Key Measurements:**
  - **3-D Temperature**
  - **3-D Humidity**
  - **3-D Precipitation**

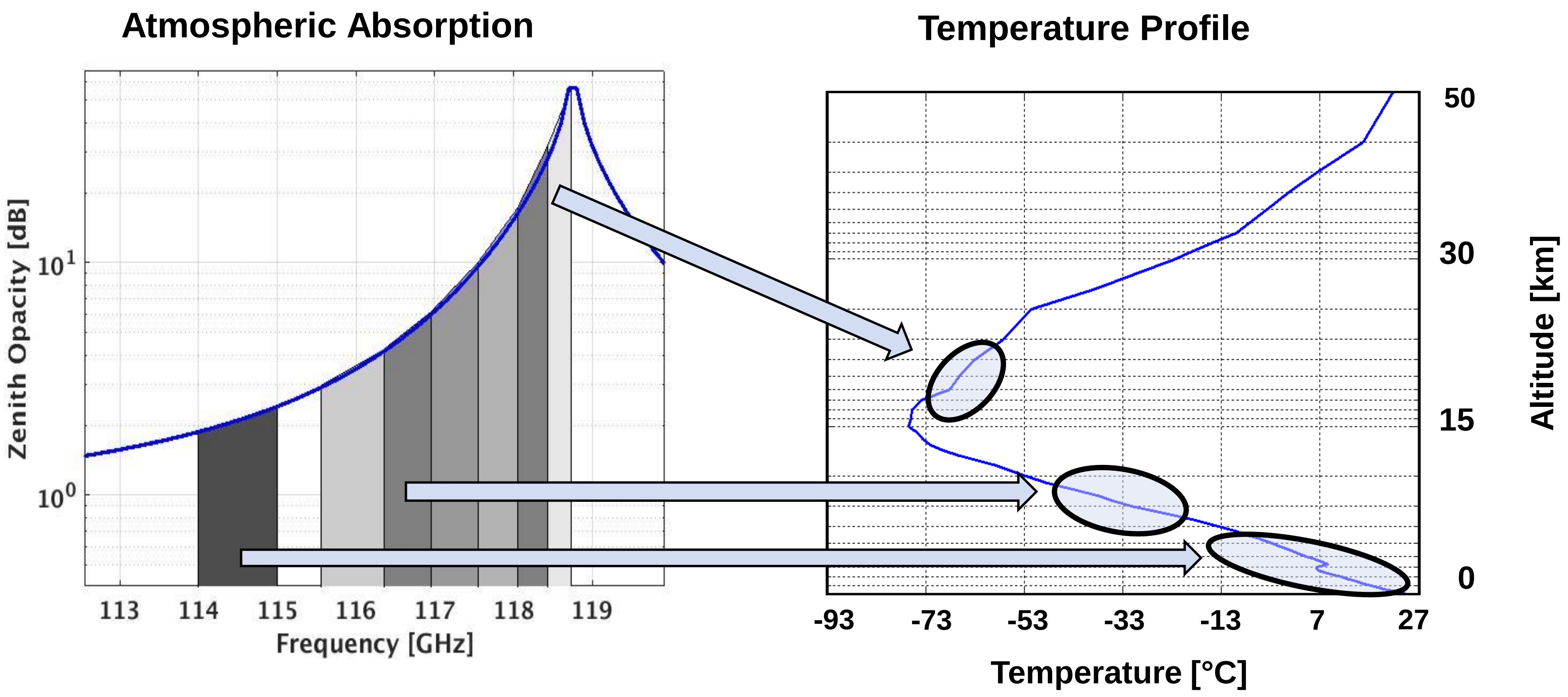
Microwave Observations have a Large Impact on Tropical Cyclone Track and Intensity Forecasts





Plots derived from data in Magnusson, L. et al. (Oct 2021). Tropical cyclone activities at ECMWF. ECMWF Tech Memo 888

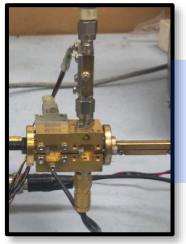
Microwave Sounding or Profiling



Progression of MIT LL Microwave Atmospheric Sounding CubeSats

Low noise and low-power receiver

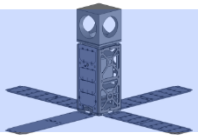
UMass-Amherst
2010/2011
Receiver Development



2U Bus development

Lincoln Tech Office

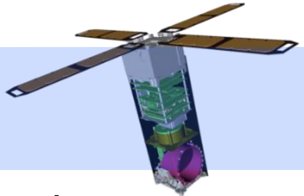
Beaverworks III
2010/2011
MIT Aero/Astro

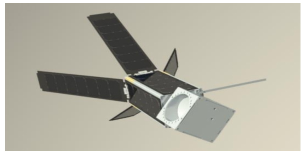


Not to scale

Spinning 3U CubeSat only measured temp.

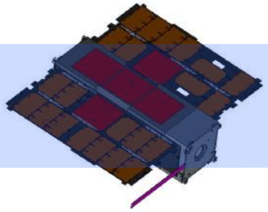
MicroMAS-1
Deployed
Mar ‘15





NASA ESTO

MiRaTA
Launch Nov ’17
MIT Aero/Astro

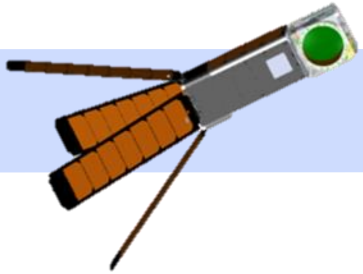


3U CubeSat with temp., humidity, and precip.

Spinning 3U CubeSat humidity, precip., & temp.

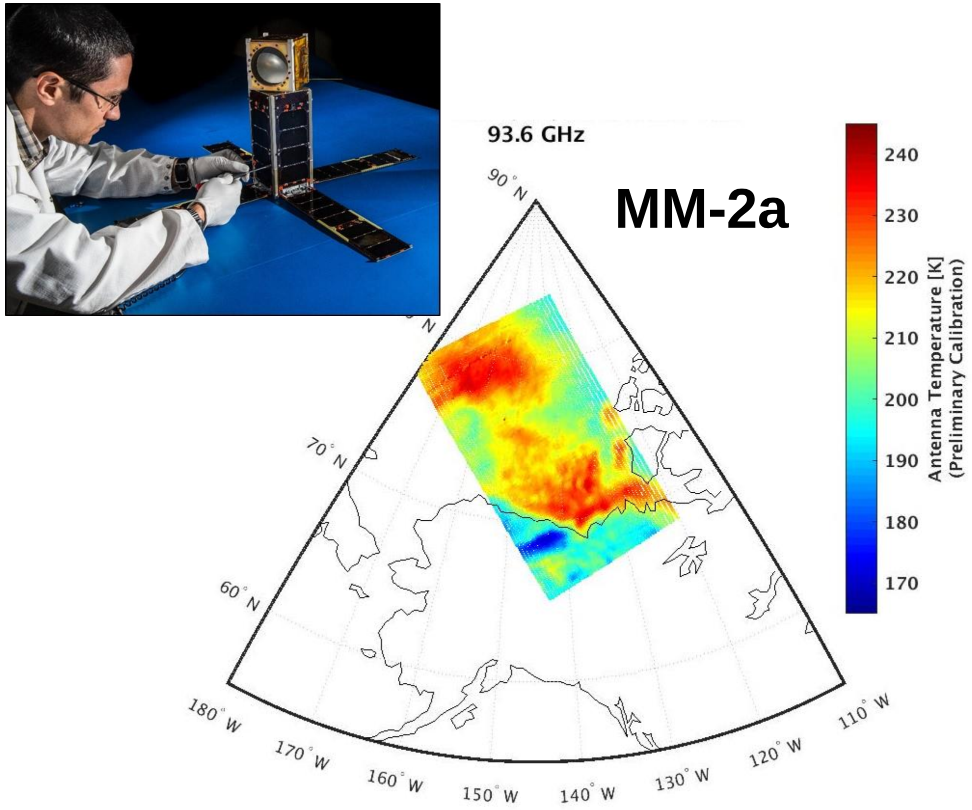
Lincoln Tech Office

MicroMAS-2a
Launch Jan 2018

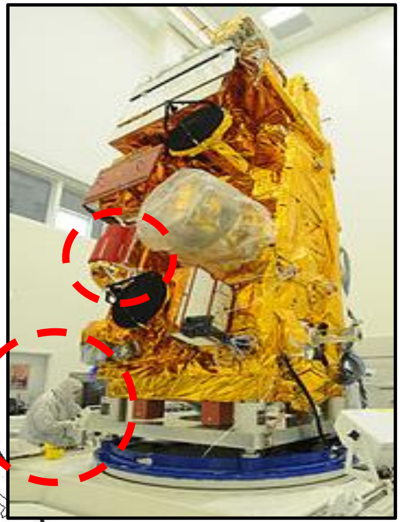


Key Enabling Technology: CubeSat Sounders

MIT LL demonstrates the first CubeSat Sounder: MicroMAS-2a



Suomi-NPP



A. Crews, W. Blackwell, et al., "Initial Radiance Validation of the Microsized Microwave Atmospheric Satellite-2A," in *IEEE Transactions on Geoscience and Remote Sensing*, doi: 10.1109/TGRS.2020.3011200.

Recent and Near Future in CubeSat Microwave Sounding

First CubeSat sounder demonstration

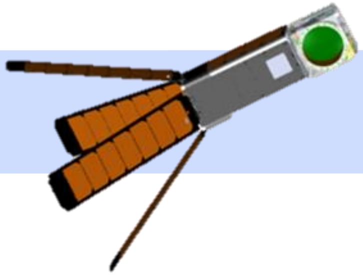
First “long-life” (3 years) CubeSat sounder

First commercial CubeSat sounder demonstration

First CubeSat sounder to provide a global image

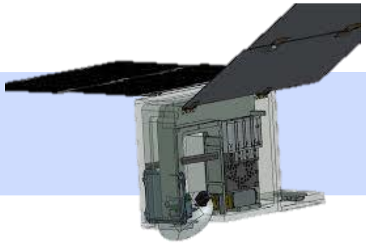
First CubeSat sounder constellation demonstration

MicroMAS-2a
Deployed Jan 2018



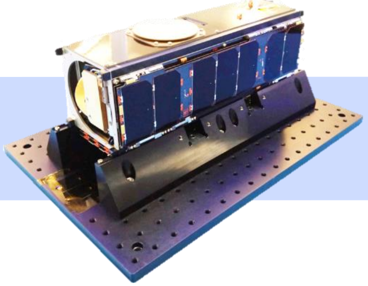
$T + H_{2}0$

TEMPEST-D
Deployed May 2018



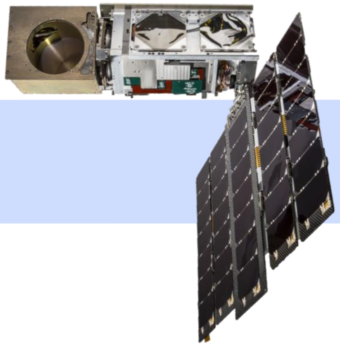
H_2O only

OMS GEMS-1
Deployed July 2019



T only

TROPICS Pathfinder
Deployed June 2021



$T + H_{2}0$ + 205 GHz

TROPICS Constellation
Launches June/July 2023

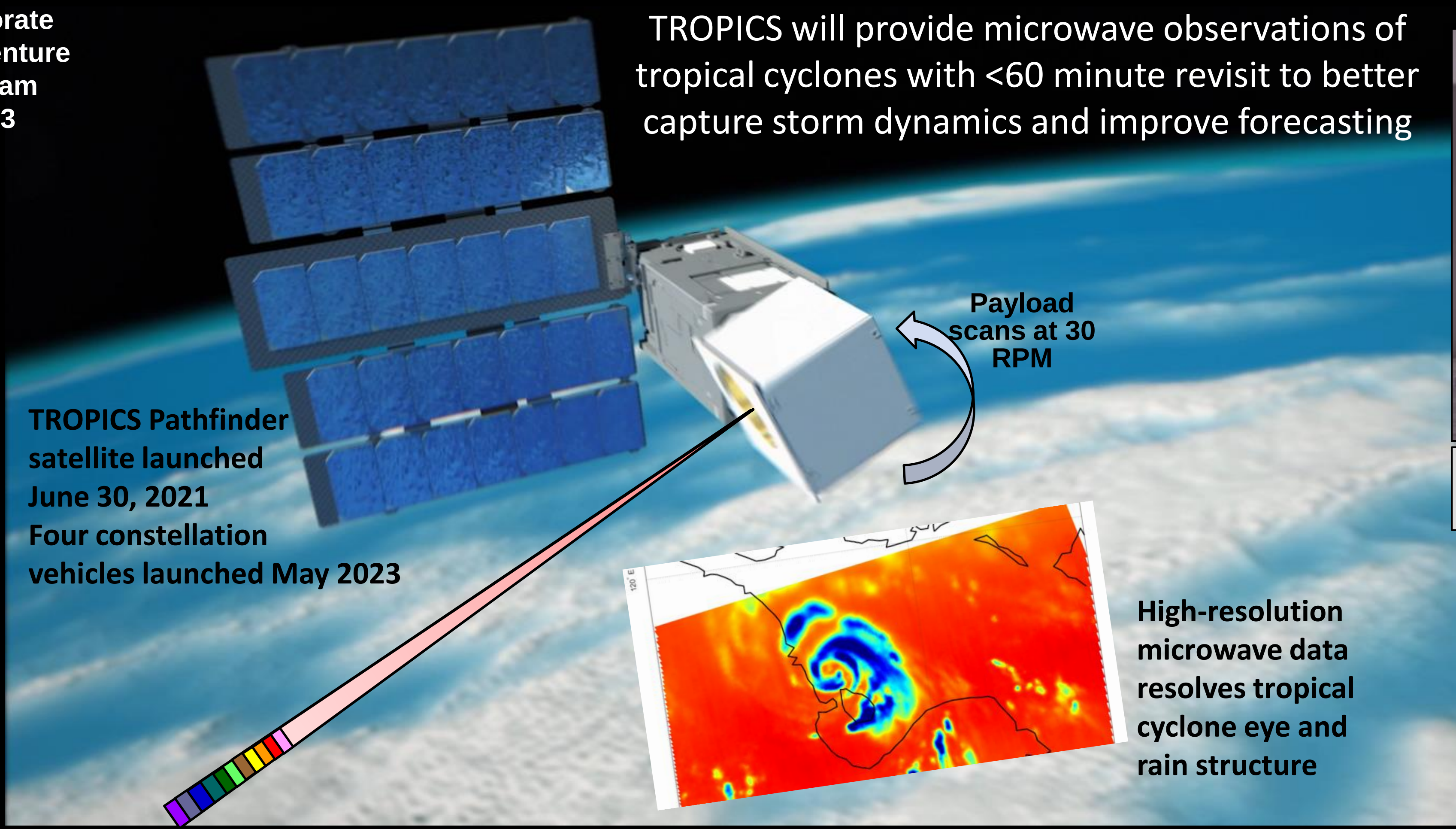
$T + H_{2}0$ + 205 GHz
High Revisit

TROPICS: Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats

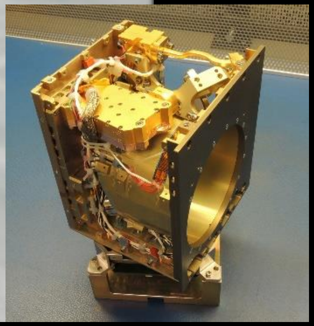
William J. Blackwell (MIT LL), Principal Investigator Scott A. Braun (NASA GSFC), Project Scientist

**Science Mission Directorate
Earth Venture Program
EVI-3**

TROPICS will provide microwave observations of tropical cyclones with <60 minute revisit to better capture storm dynamics and improve forecasting



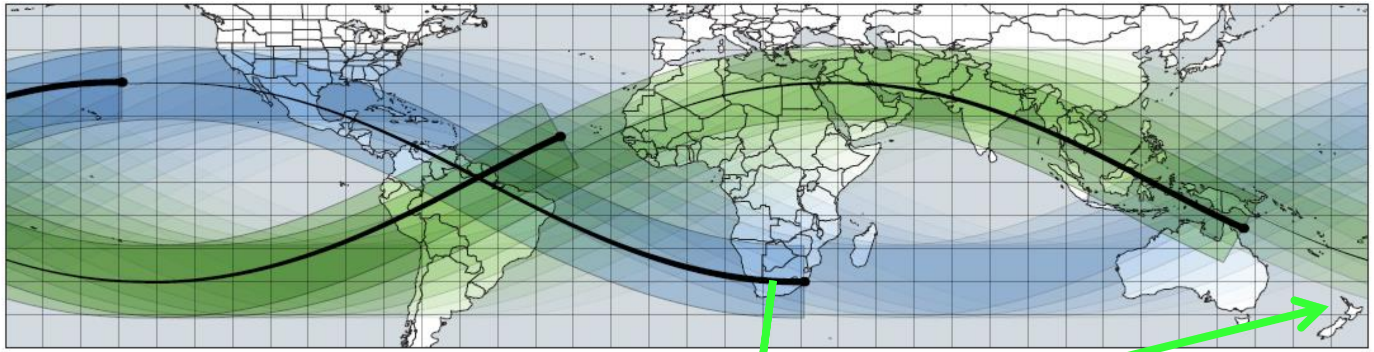
Constellation of Four 3U CubeSats
MIT LL payload; BCT bus; KSAT downlink



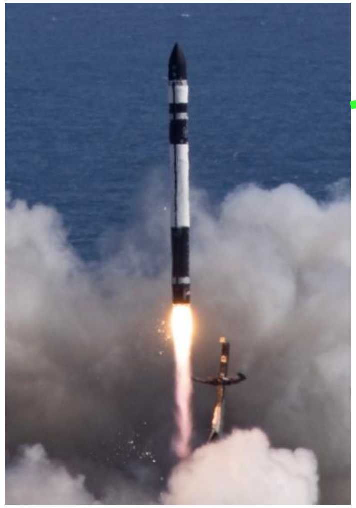
TROPICS Microwave Sounder
12 channels (90-205 GHz)
Temperature, Moisture, Rain Rate

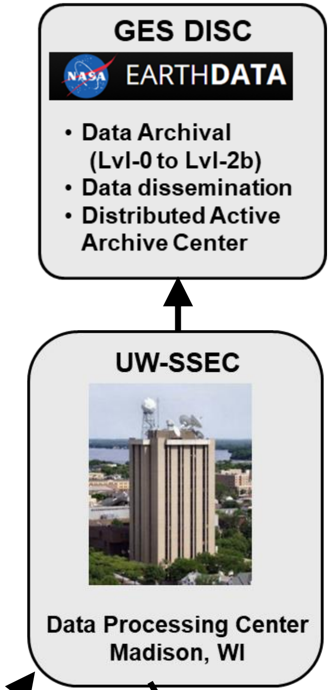
TROPICS Mission Overview

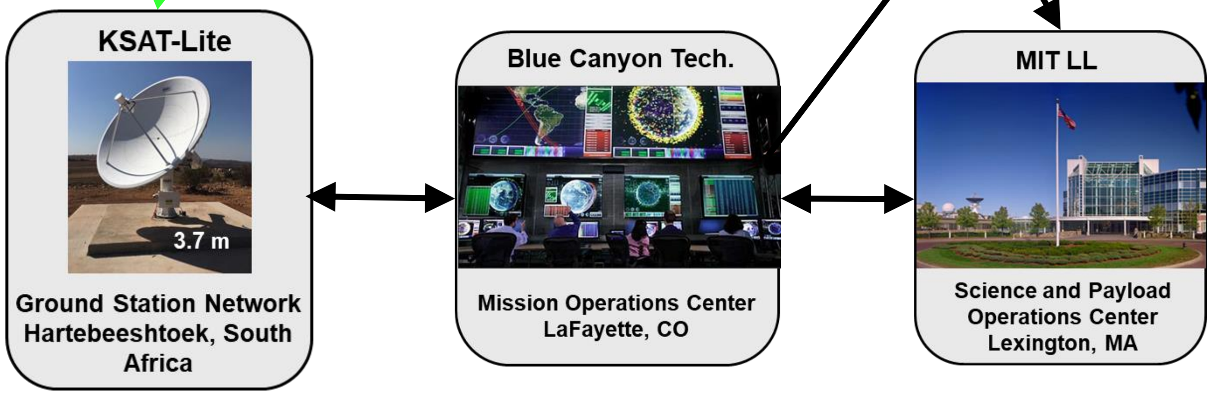
Two orbital planes (33° inclination at 550 km altitude) with two Cubesats in each will provide < 60 minute median revisit rate



- Rocket Lab was awarded two launches from Mahia, NZ into two orbital planes
- Launched on May 8th & 26th, 2023
- Mission has four CubeSats with a year-long science operations
- **Data latency 45 minutes**



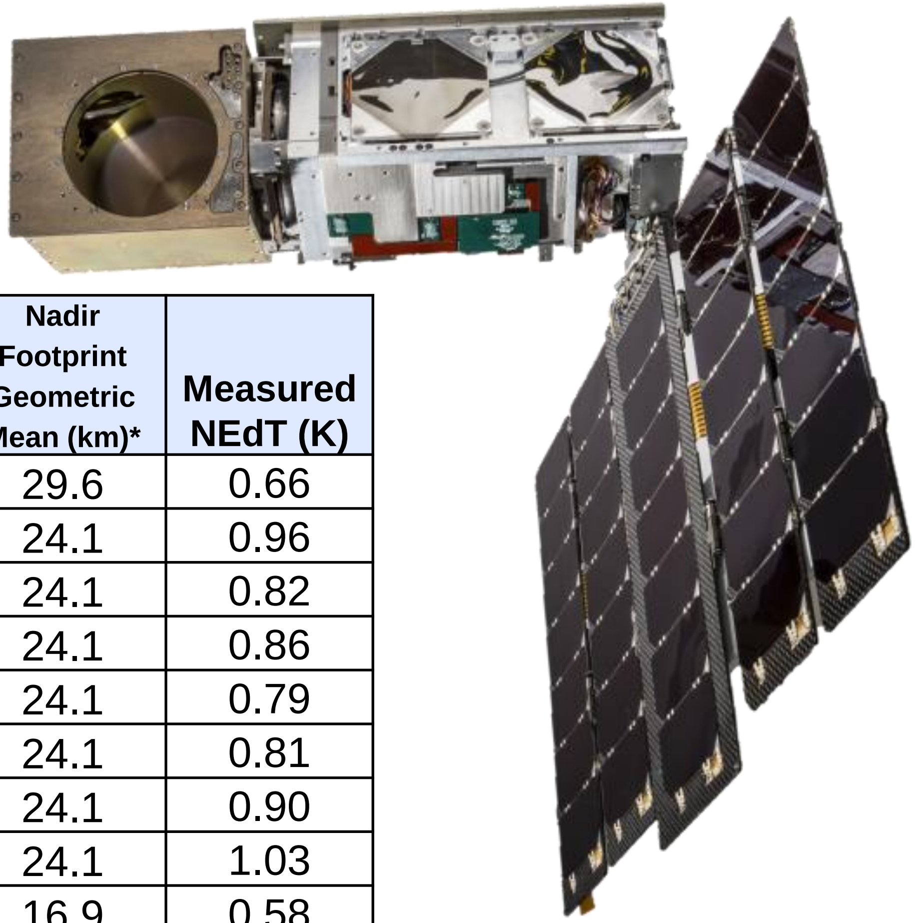




Backup Ground Stations: Mauritius, West Australia, & Puertollano

TROPICS Satellite ("CubeSat") (TROPICS Millimeter-wave Sounder = TMS)

- **3U CubeSat: 10 cm x 10 cm x 36 cm**
- **Mass: 5.4 kg; Power: 15 W (payload is 3W)**
- **Blue Canyon Technologies bus**
- **LL passive millimeter-wave payload**
- **Innoflight SCR-100 S-band radio**



TMS Channel	Central frequency	ATMS Channel	MHS Channel	*MWHS-2 Channel*
1	91.655±1.4 GHz	88.2 GHz	89.0 GHz	*89.0 GHz*
2	114.50 GHz	-	-	*118.75±5.0*
3	115.95 GHz	-	-	*118.75±3.0*
4	116.65 GHz	-	-	*118.75±2.5*
5	117.25 GHz	-	-	*118.75±1.1*
6	117.80 GHz	-	-	*118.75±0.8*
7	118.24 GHz	-	-	*118.75±0.3*
8	118.58 GHz	-	-	*118.75±0.2*
9	184.41 GHz	183.31±1.0	183.31±1.0	*183±1.0*
10	186.51 GHz	183.31±3.0	183.31±3.0	*183±3.0*
11	190.31 GHz	183.31±7.0	190.31	*183±7.0*
12	204.8 GHz	-	-	-

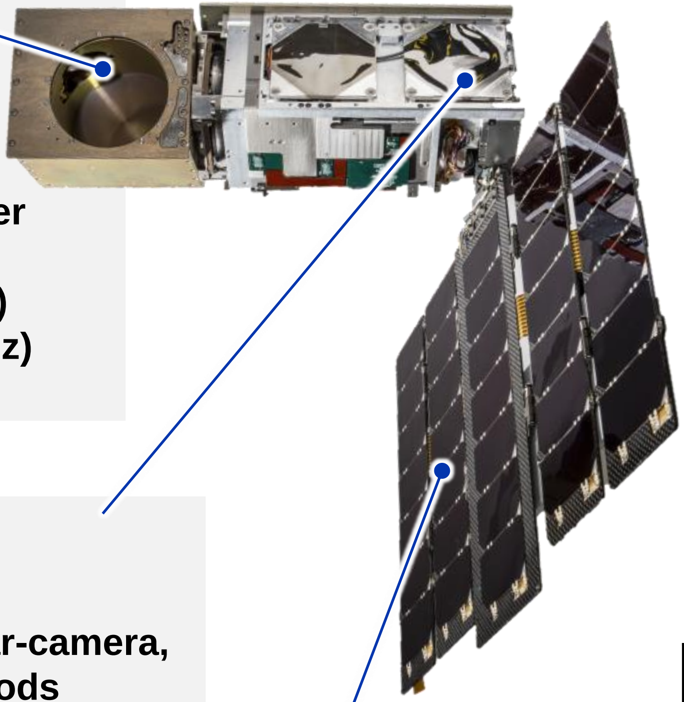
Beamwidth (degrees) Down/Cross	Nadir Footprint Geometric Mean (km)*	Measured NEdT (K)
3.0/3.17	29.6	0.66
2.4/2.62	24.1	0.96
2.4/2.62	24.1	0.82
2.4/2.62	24.1	0.86
2.4/2.62	24.1	0.79
2.4/2.62	24.1	0.81
2.4/2.62	24.1	0.90
2.4/2.62	24.1	1.03
1.5/1.87	16.9	0.58
1.5/1.87	16.9	0.55
1.5/1.87	16.9	0.53
1.35/1.76	15.2	0.52

Satellite Overview

1U Payload
- Rotating microwave radiometer
- Scanner assembly
- 83 mm aperture
- Noise-diode / deep space calibration

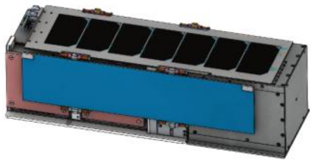
Ultra-compact W / F / G radiometer
- W-band 92 GHz
- F-band 7 chan. (114-119 GHz)
- G-band 4 chan. (183 & 204 GHz)

3U CubeSat
10 cm x 10 cm x 36 cm
5.4 kg

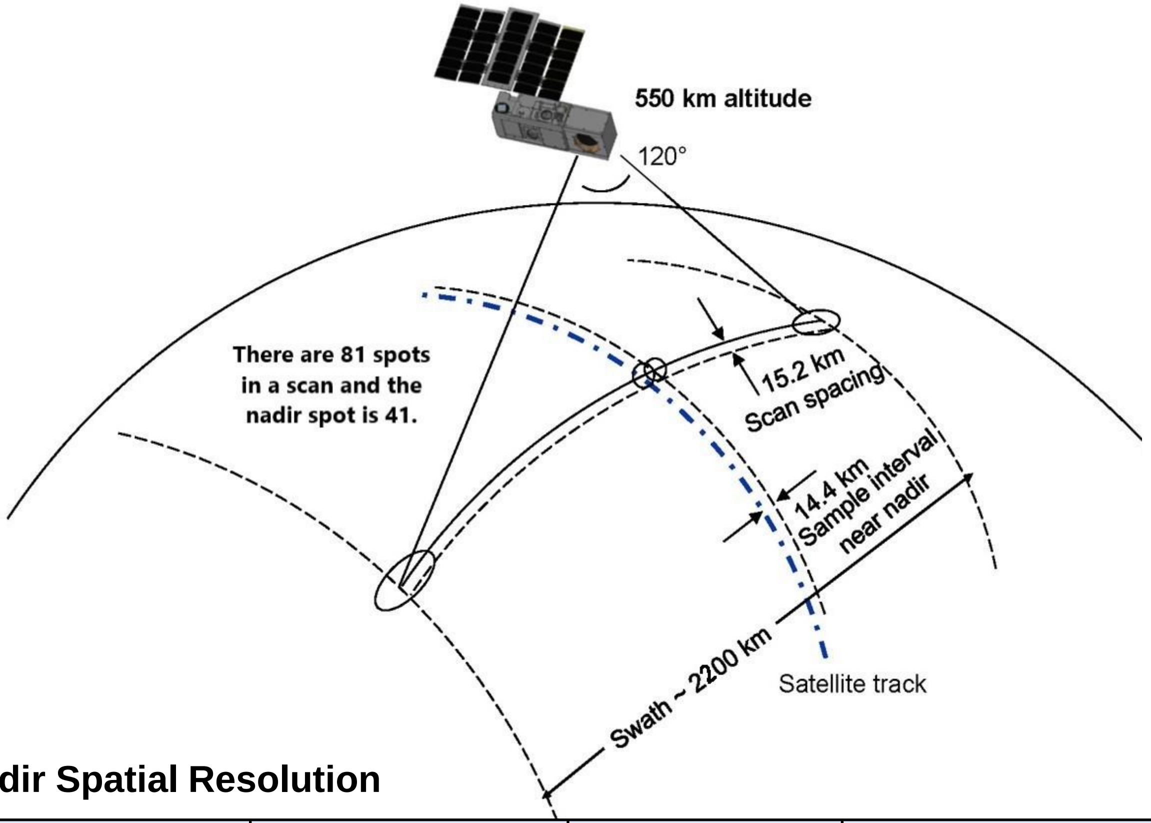


2U Bus: BCT XB-1
- S-band radio
- ADCS: sun sensor(s), star-camera, reaction wheels, torque rods

Deployed Articulating 5-panel solar array



Stowed

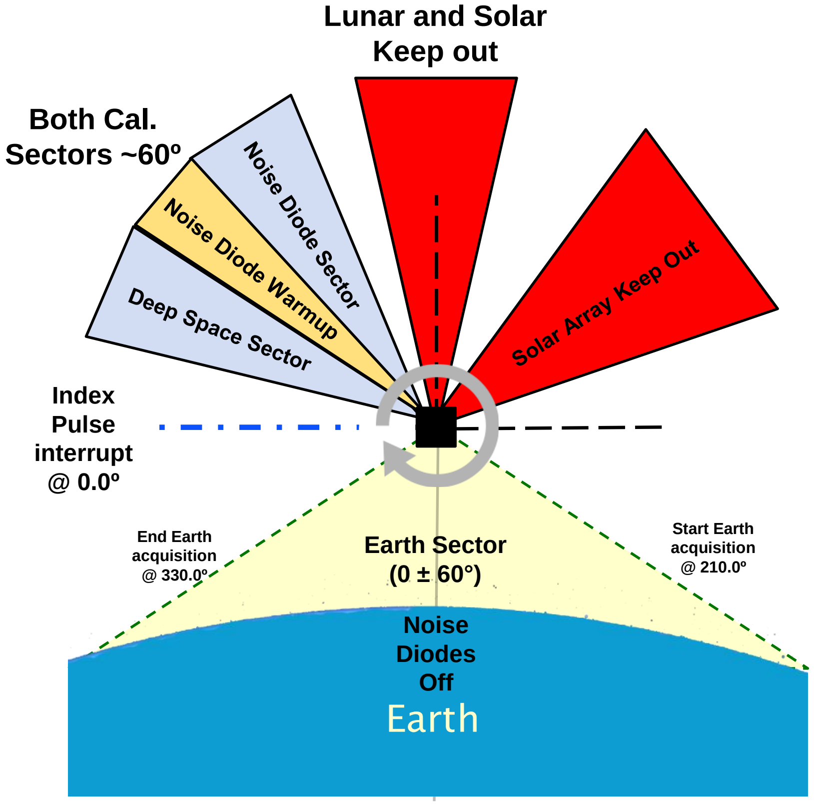


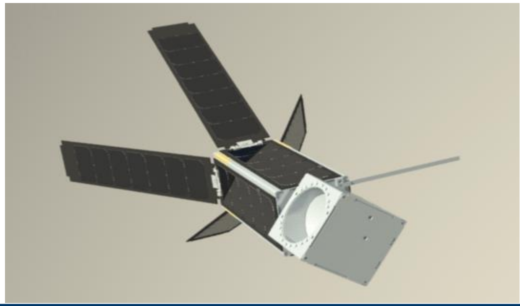
Nadir Spatial Resolution

Direction	W-band (Ch. 1)	F-band (Ch. 2-8)	G-band (Ch. 9-12)
Down-track	27.2 km	23.0 km	14.4 km
Cross-track	28.9 km	25.2 km	17.9 km

Scan Profile for TROPICS

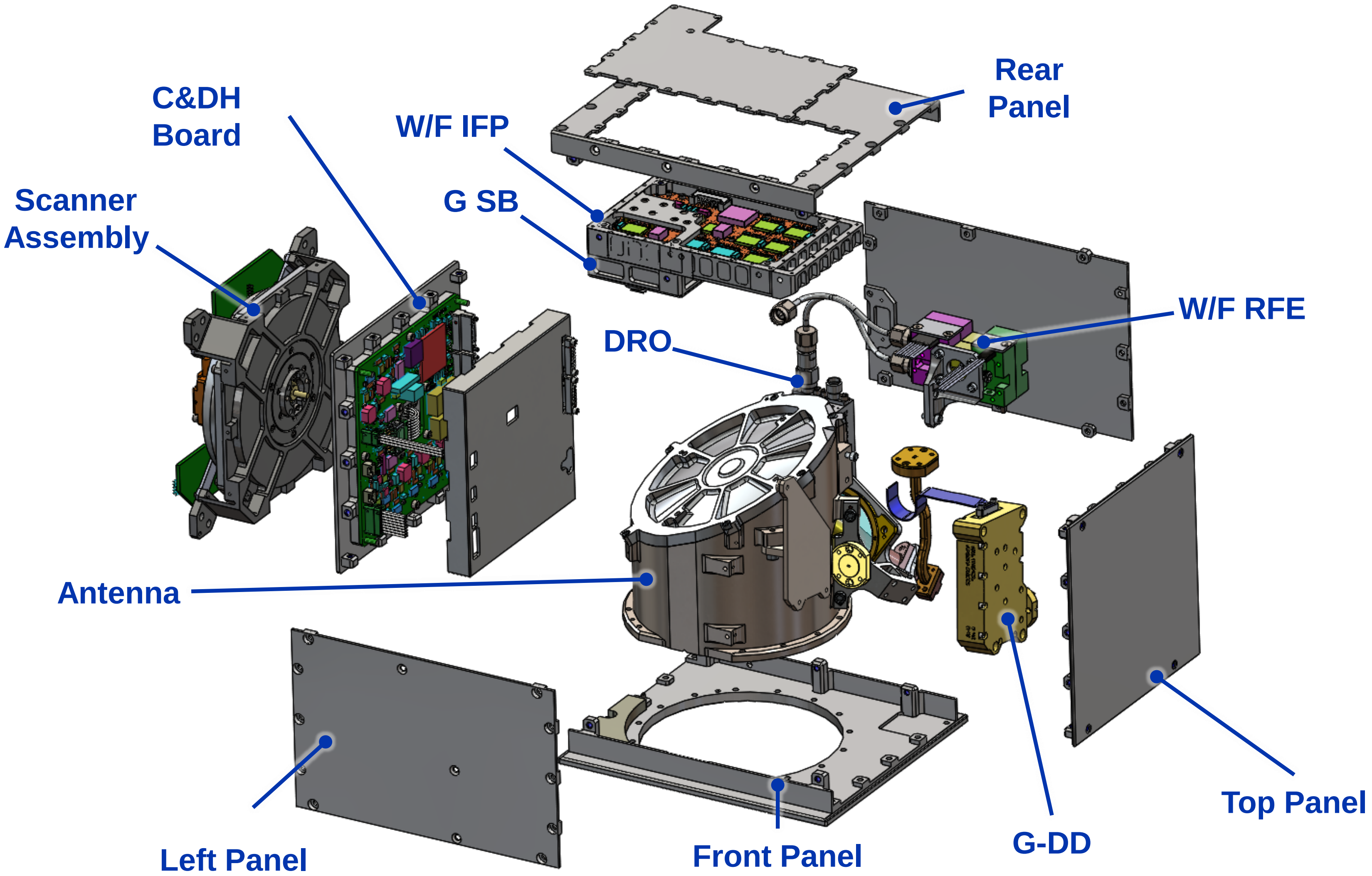
- Rotation rate is 30 RPM (2 sec. period)
- 81 Earth Sector samples per scan
- 10 samples each in Space & ND Sectors
- Integration time: 8.333 msec (1/120 second)
- Spatial Information (at 550 km):
  - Beamwidth (FWHM):
    - W-band 3.0° DT (3.2° CT)
    - F-band 2.4° DT (2.62° CT)
    - G-band 1.5° DT (1.87° CT)
    - Sample spacing: 1.5°
  - Swath: ~2000 km
  - Nadir footprint diameter
    - W-band: 26-km DT, ~28-km CT
    - F-band : 22-km DT, ~24-km CT
    - G-band : 13.1-km DT, ~17.1-km CT



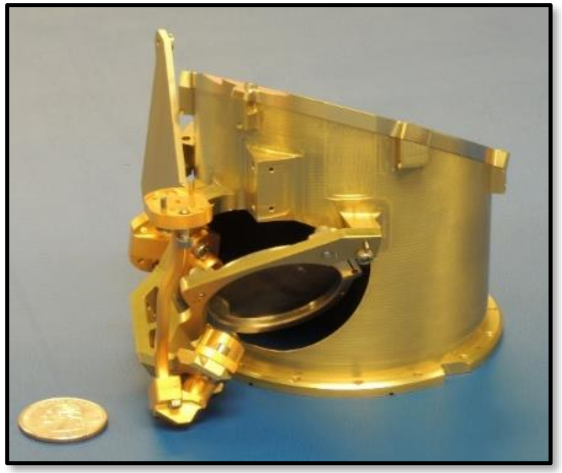


DT = down track CT = cross track

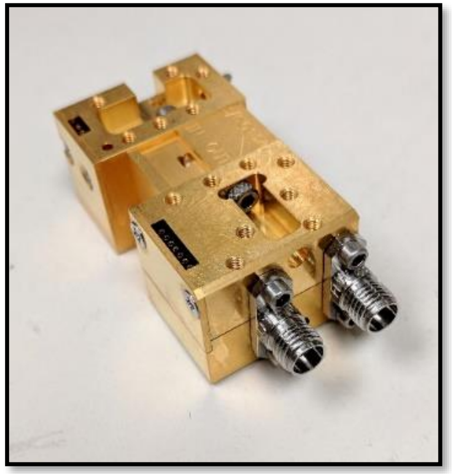
TROPICS Payload Details



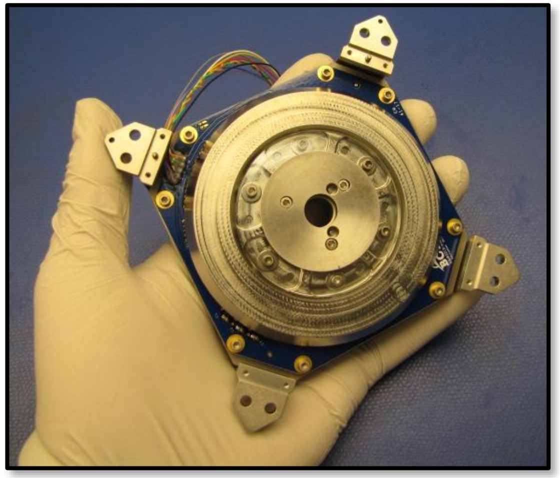
TROPICS Radiometer Flight Hardware



Dual-band antenna and
wire grid diplexer



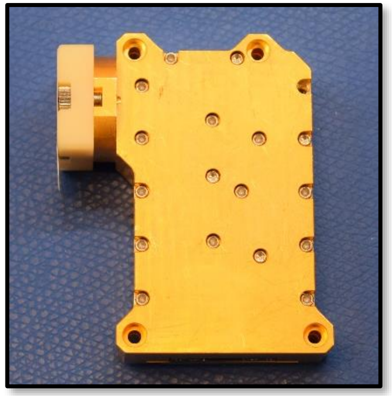
90/120-GHz receiver
front end (“WF-RFE”)



Precision Scanning Assembly

Radiometer back-end
processor (“WF-IFP”)

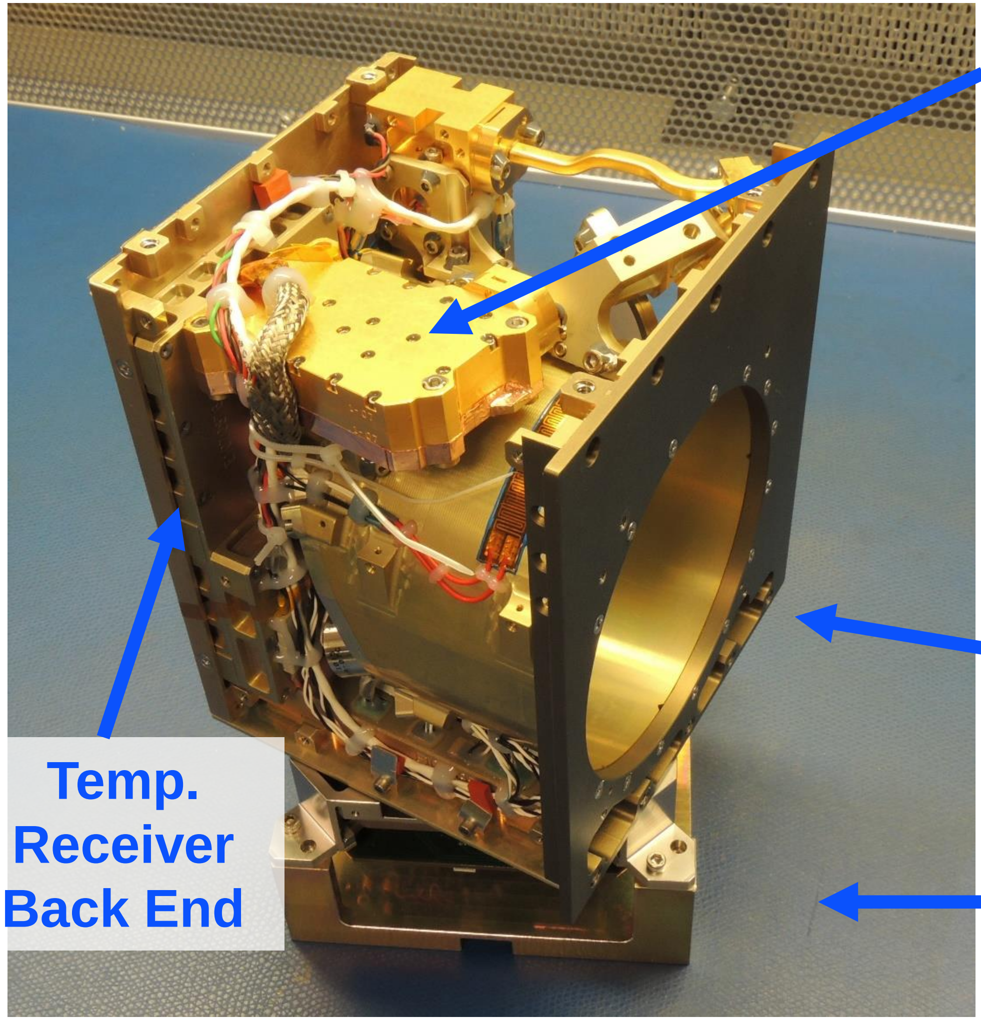
Payload control and
data handling board



180-205-GHz direct
detection receiver

Leverages significant advancements funded by NASA ESTO

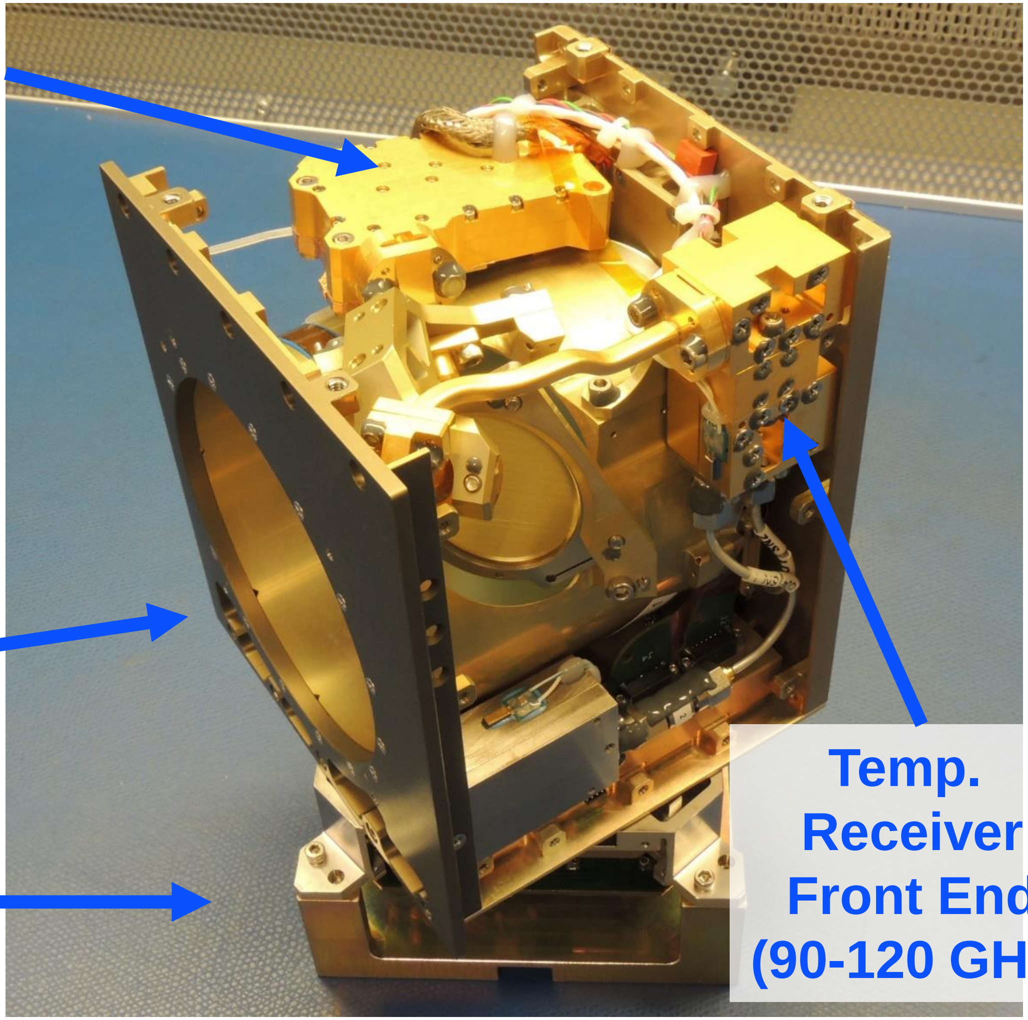
TROPICS Radiometer Payloads Yield Excellent Performance



Humidity &
Precipitation
Receiver
(180-205 GHz)

Aperture
83 mm

Scanner &
slipring



Seven Flight Units Ready for Launch

TROPICS Pathfinder (Qualification Unit)
Launched June 30, 2021

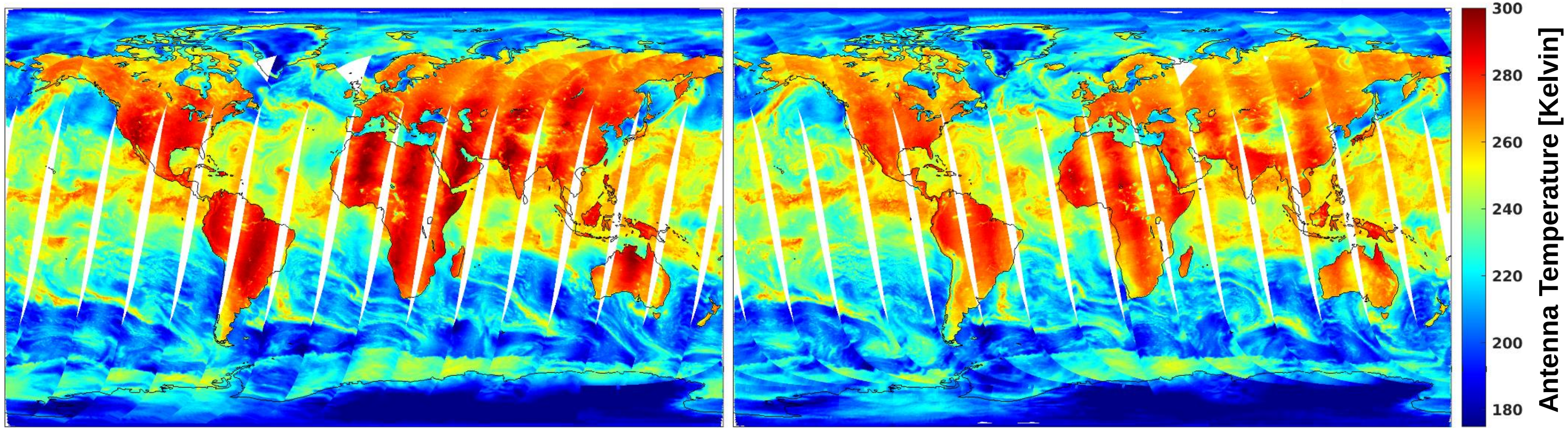
Pathfinder "precursor" mission provided checkout of operations, ground links, data processing & science

Preliminary cal/val indicates that radiometric calibration performance is better than 1 K in all channels

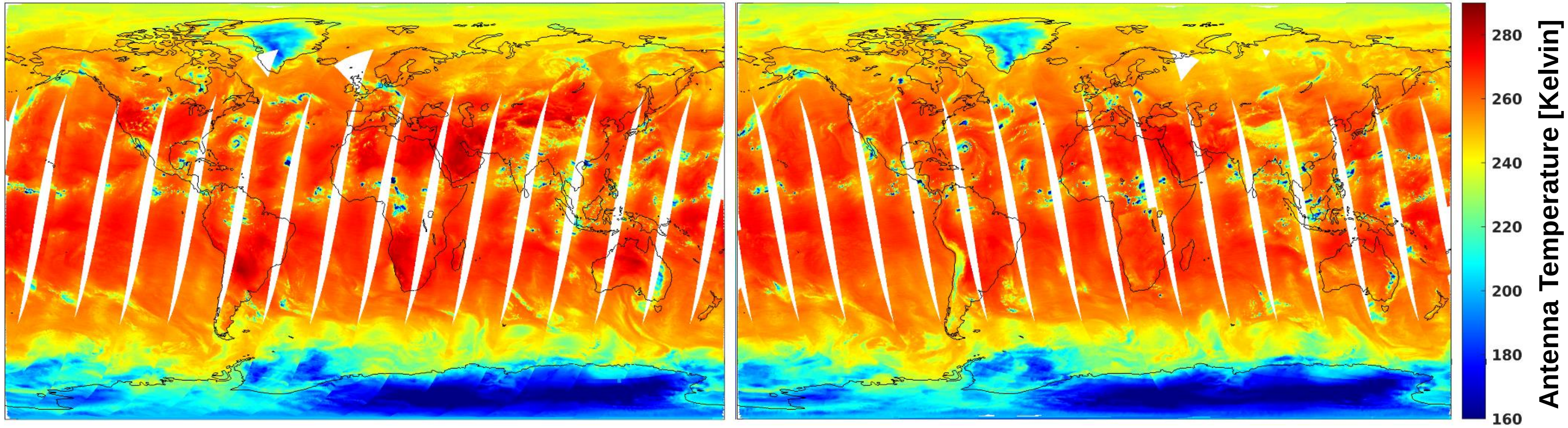
NOAA-funded low-latency experiment conducted in April 2022

Data will be available to general public via GES-DISC

Pathfinder’s Twice-Daily Global Collections



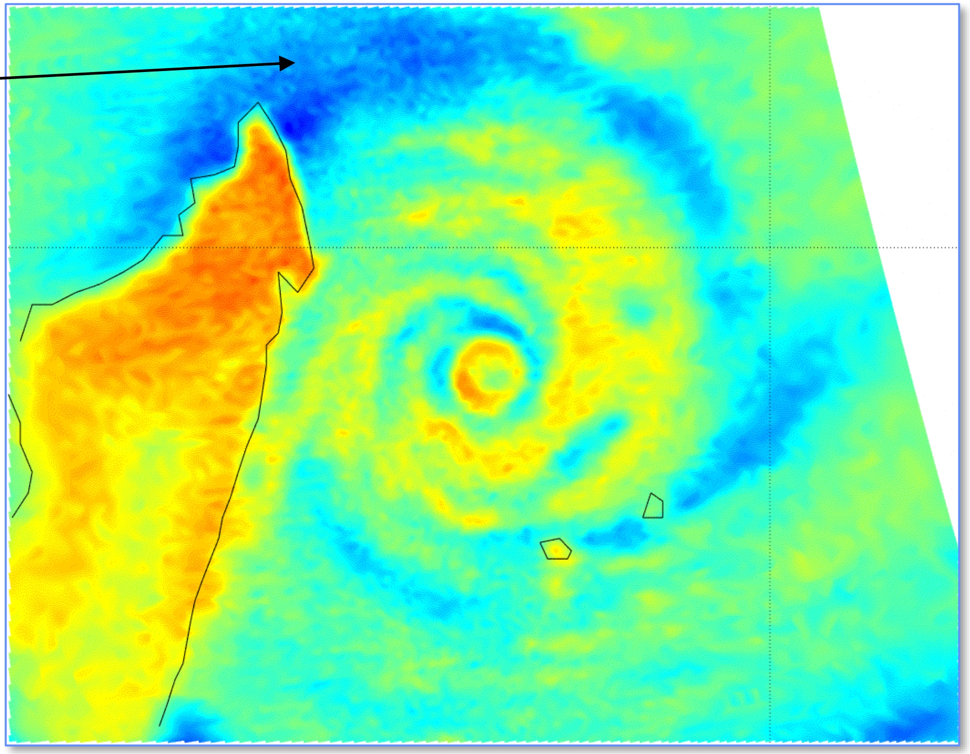
91.656 GHz – Channel 1 (W) – Daytime and Nighttime Mosaics



204.8 GHz – Channel 12 (G4) – Daytime and Nighttime Mosaics

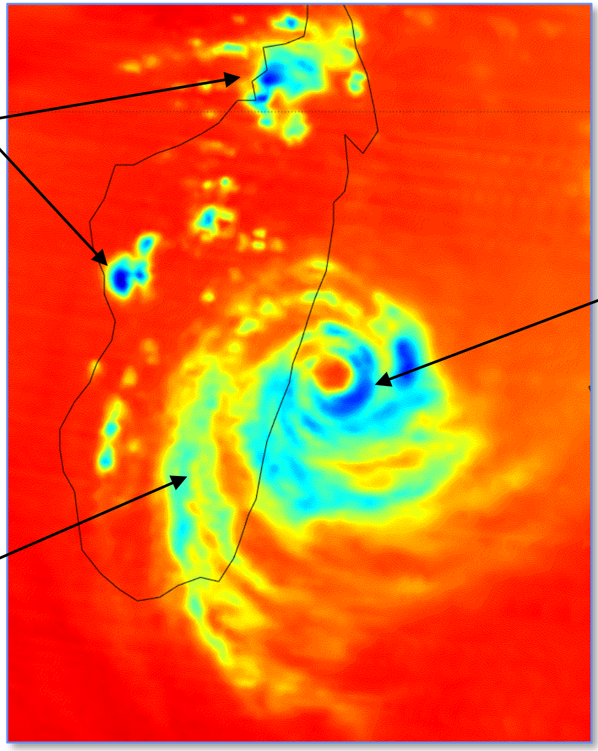
TROPICS Data Addresses Critical Science Questions

What is the relationship between environmental conditions and storm intensification?



TC Emnati, Feb 10, 2022, 92 GHz

What is the relationship between structural features of the storm and intensification?

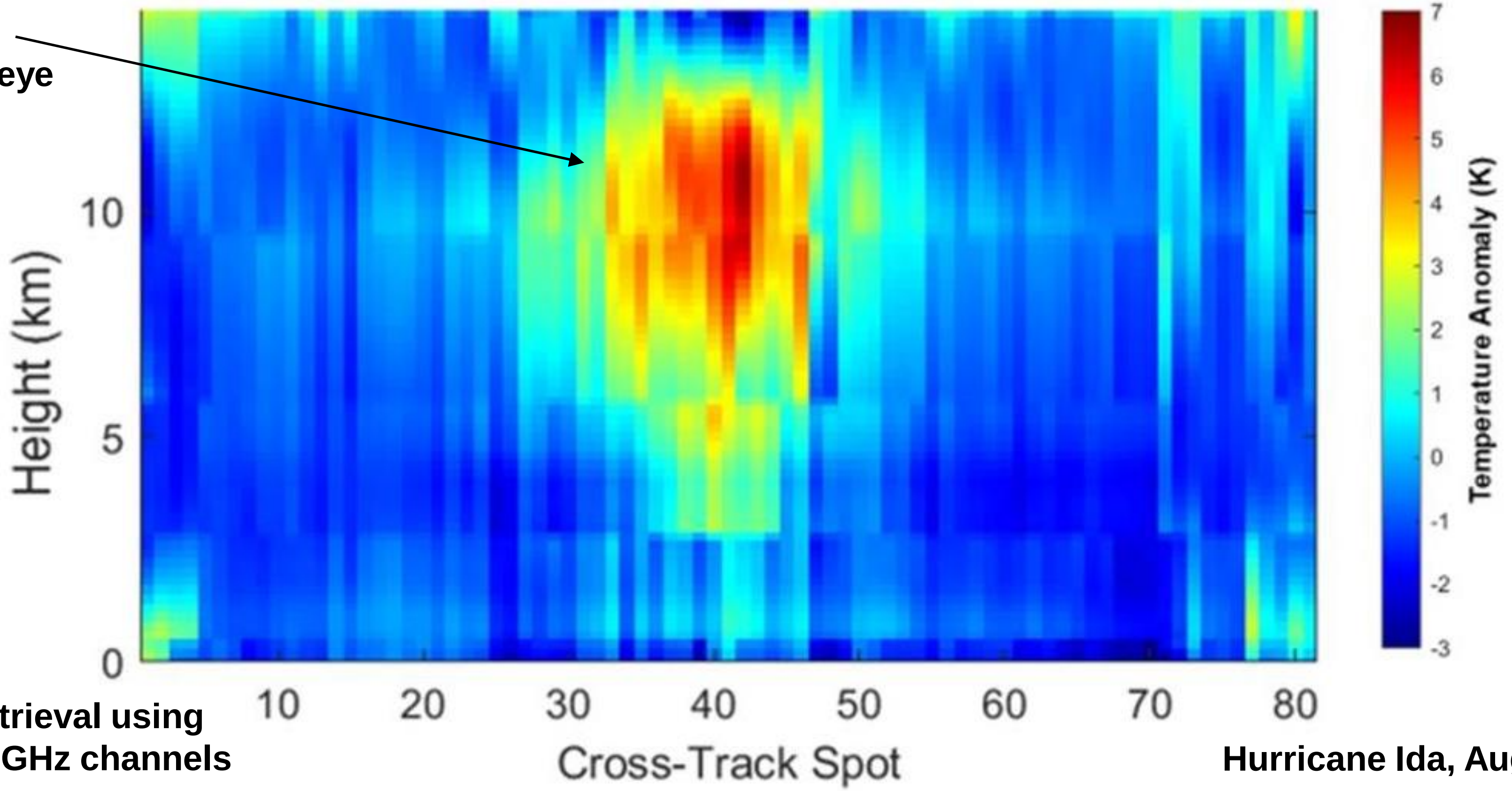


TC Batsirai, Feb 5, 2022, 205 GHz

TROPICS Data Addresses Critical Science Questions

What is the relationship between structural evolution and warm core evolution and what role does the diurnal cycle play?

Warming aloft in the inside of the hurricane eye



Temperature retrieval using TROPICS 118.75-GHz channels

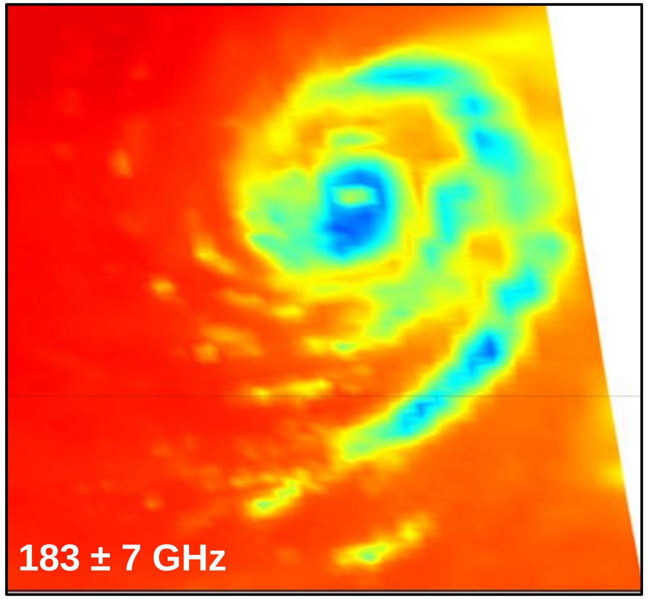
Hurricane Ida, Aug 28, 2021

Ultimately, we want to show that TROPICS data will improve forecasting of tropical cyclone track and intensity

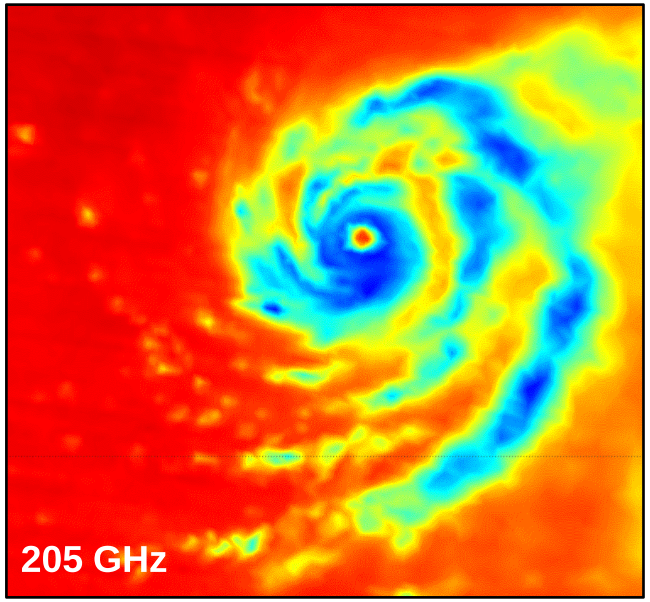
TROPICS Pathfinder Data Compares Favorably to State-of-the-Art Sensors

Super Typhoon Mindulle (Sep 26, 2021)

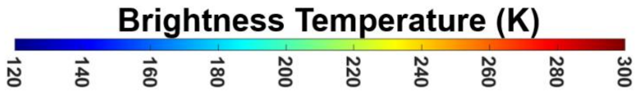
NOAA-20 Satellite (ATMS)
>2000 kg



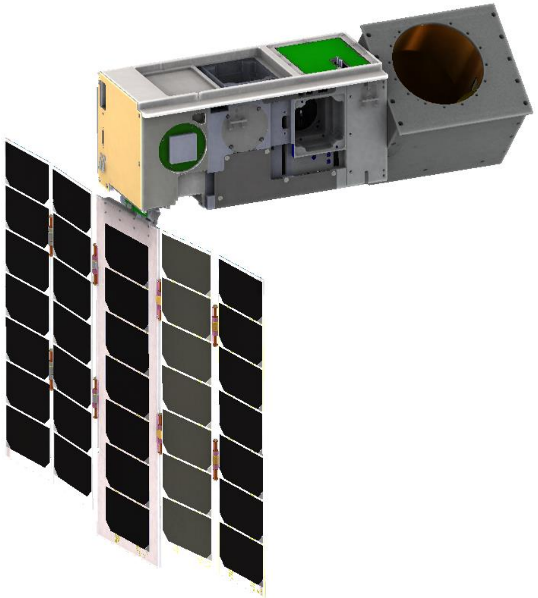
9/26/2021 04:48 UTC



9/26/2021 05:21 UTC

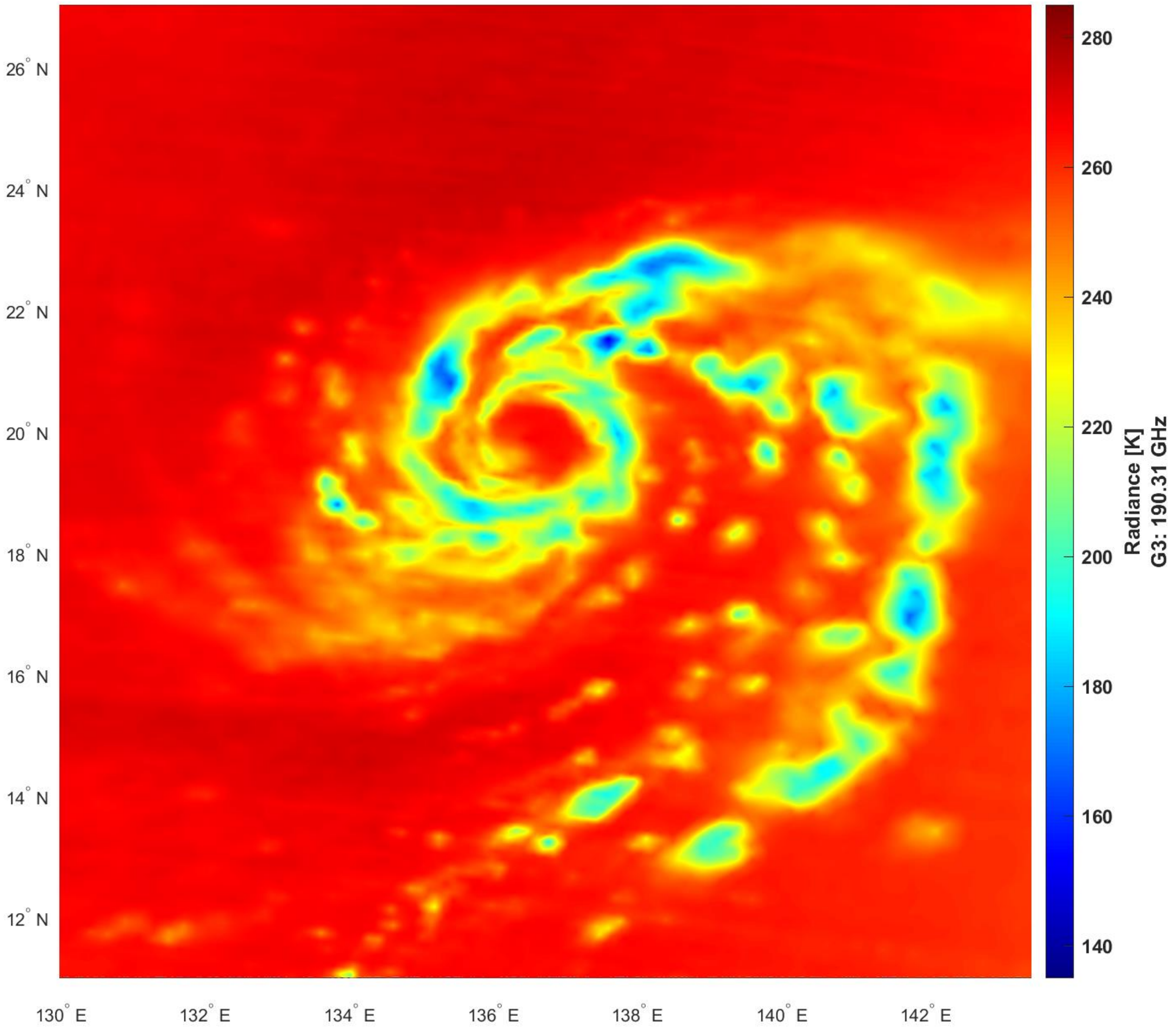


TROPICS Pathfinder Satellite
5.4 kg

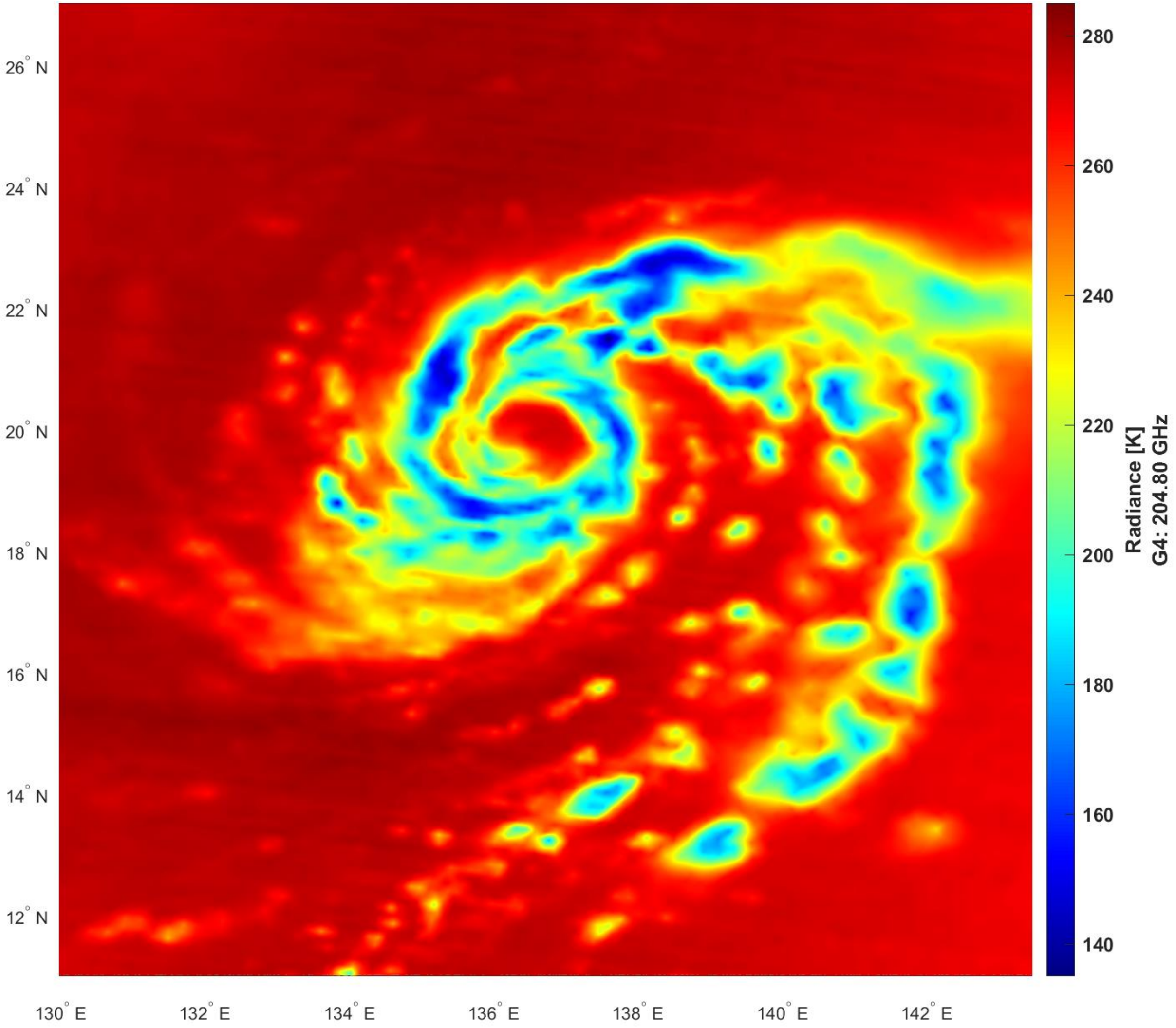


A More Detailed Look at 190 GHz vs 205 GHz (Super Typhoon Mindulle, Sep 27, 2021 05:10 UTC)

190 GHz

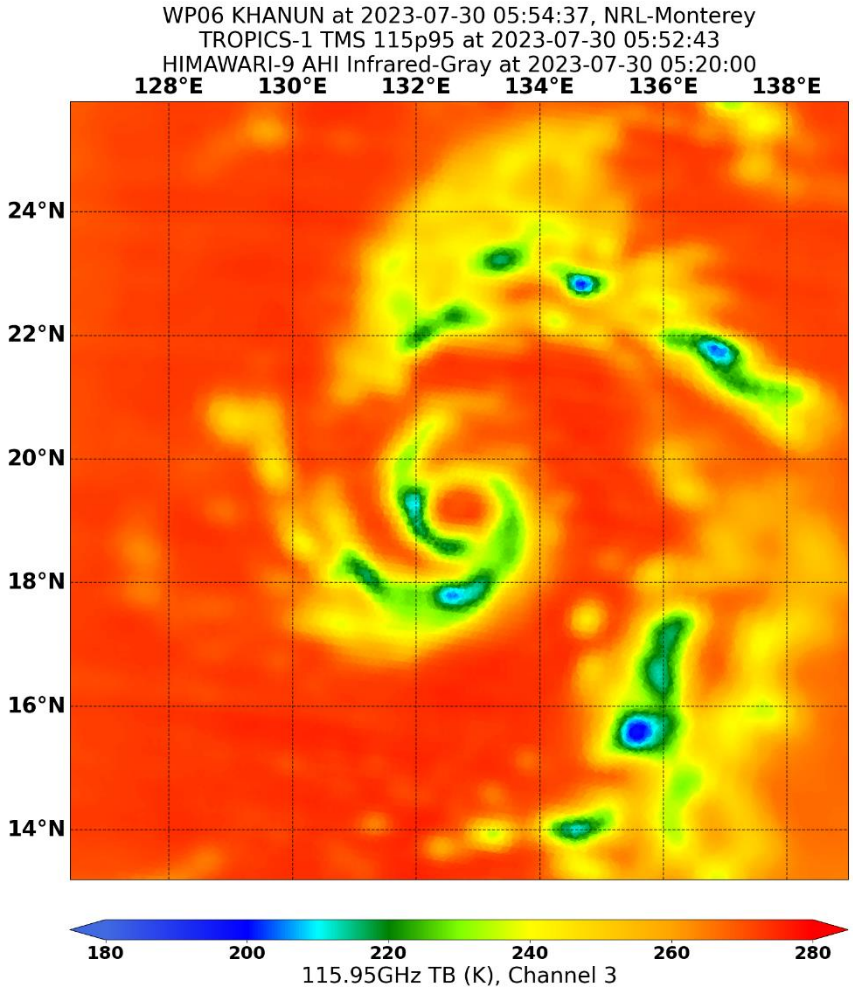


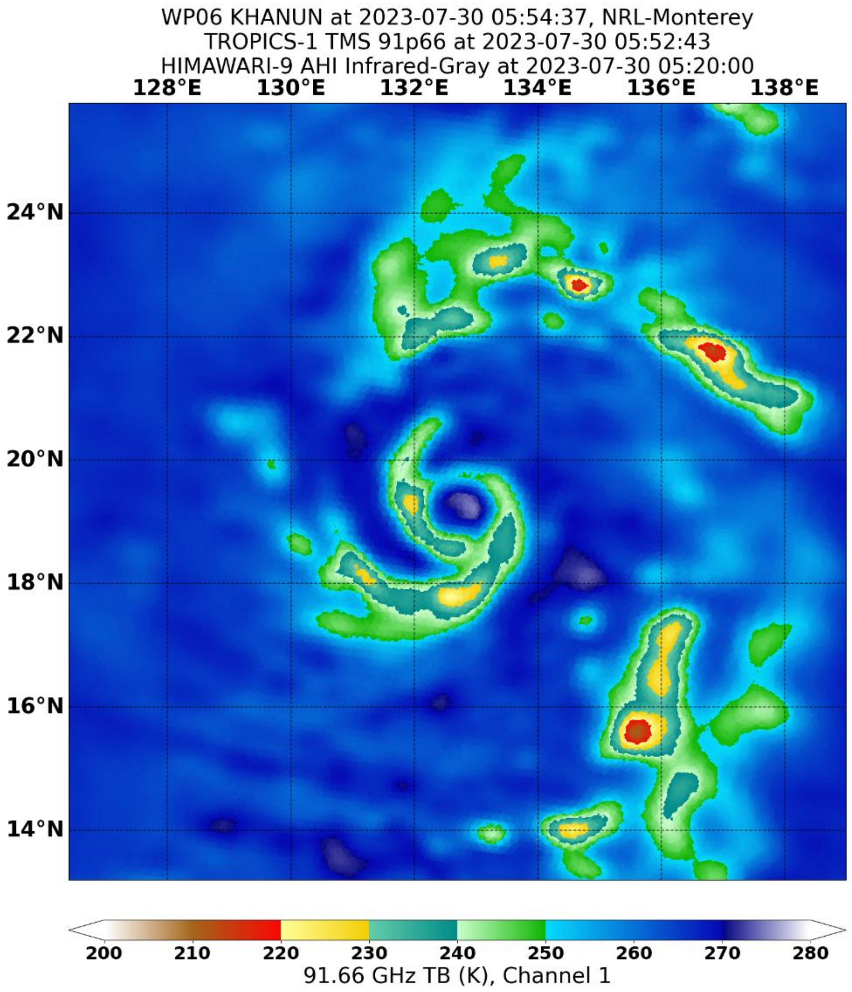
205 GHz



Near-Realtime TC Imagery and Data Assimilation

- US Naval Research Laboratory has incorporated TROPICS into operational tropical cyclone (TC) imagery https://www.nrlmry.navy.mil/tcweb/
- NRL is hosting imagery for TROPICS-03, TROPICS-05, & TROPICS-06, but on hold for TROPICS-01 (Pathfinder)
- Team is working toward providing imagery & data assimilation at
  - NOAA National Hurricane Center
  - Joint Typhoon Warning Center
  - NESDIS Common Cloud Framework
  - WMO WIS 2.0
  - LANCE





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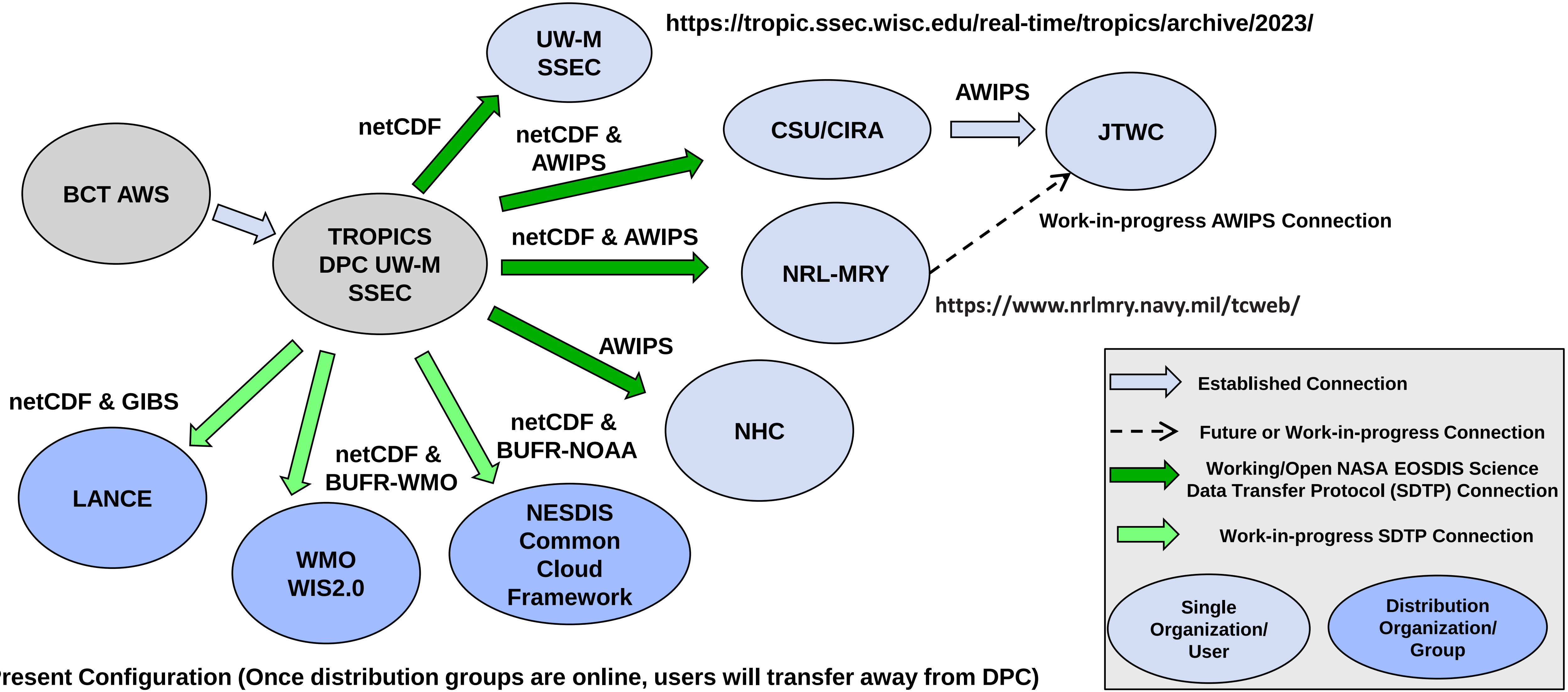
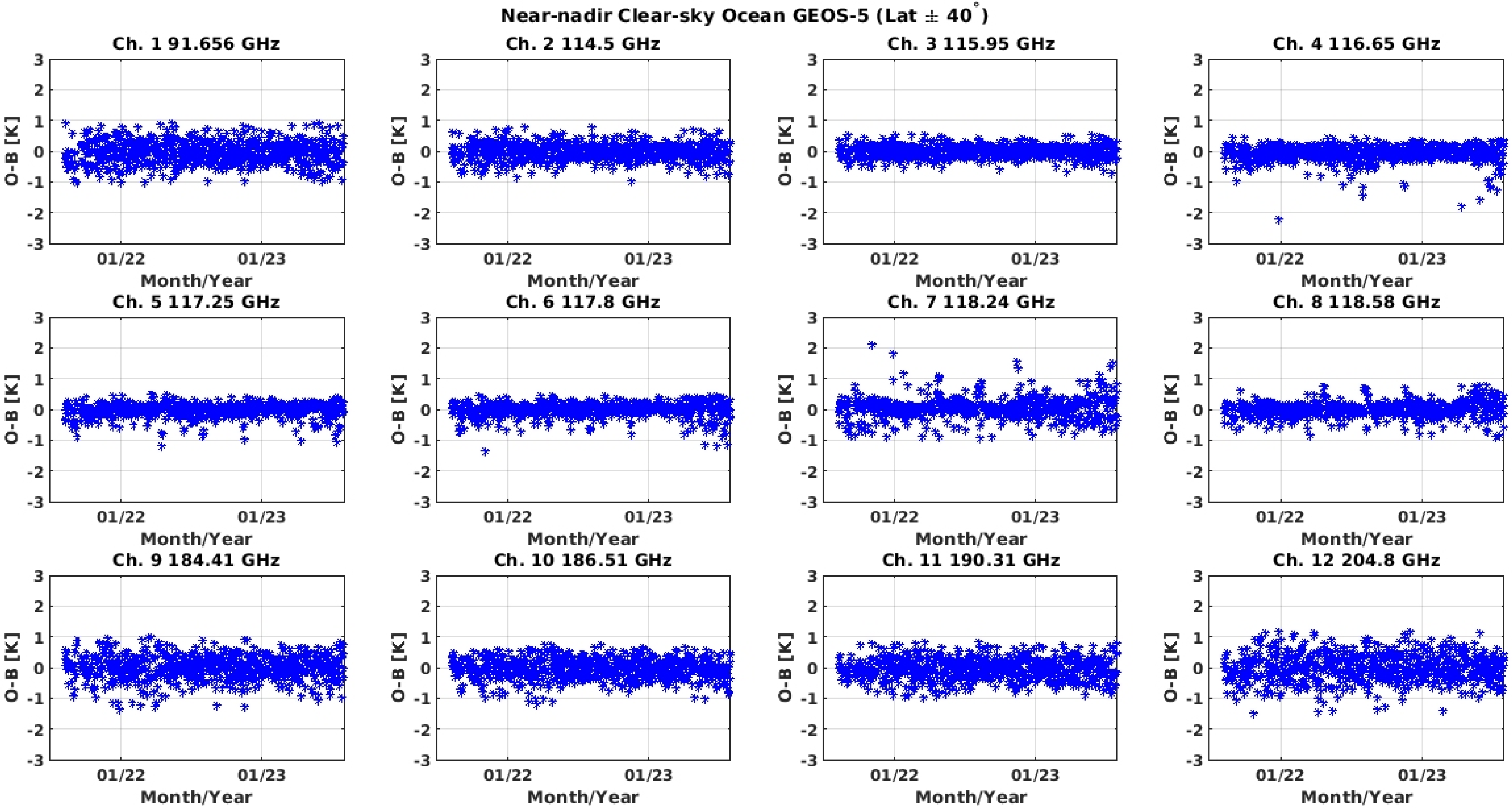
TROPICS Near-Real-Time Data Flowchart

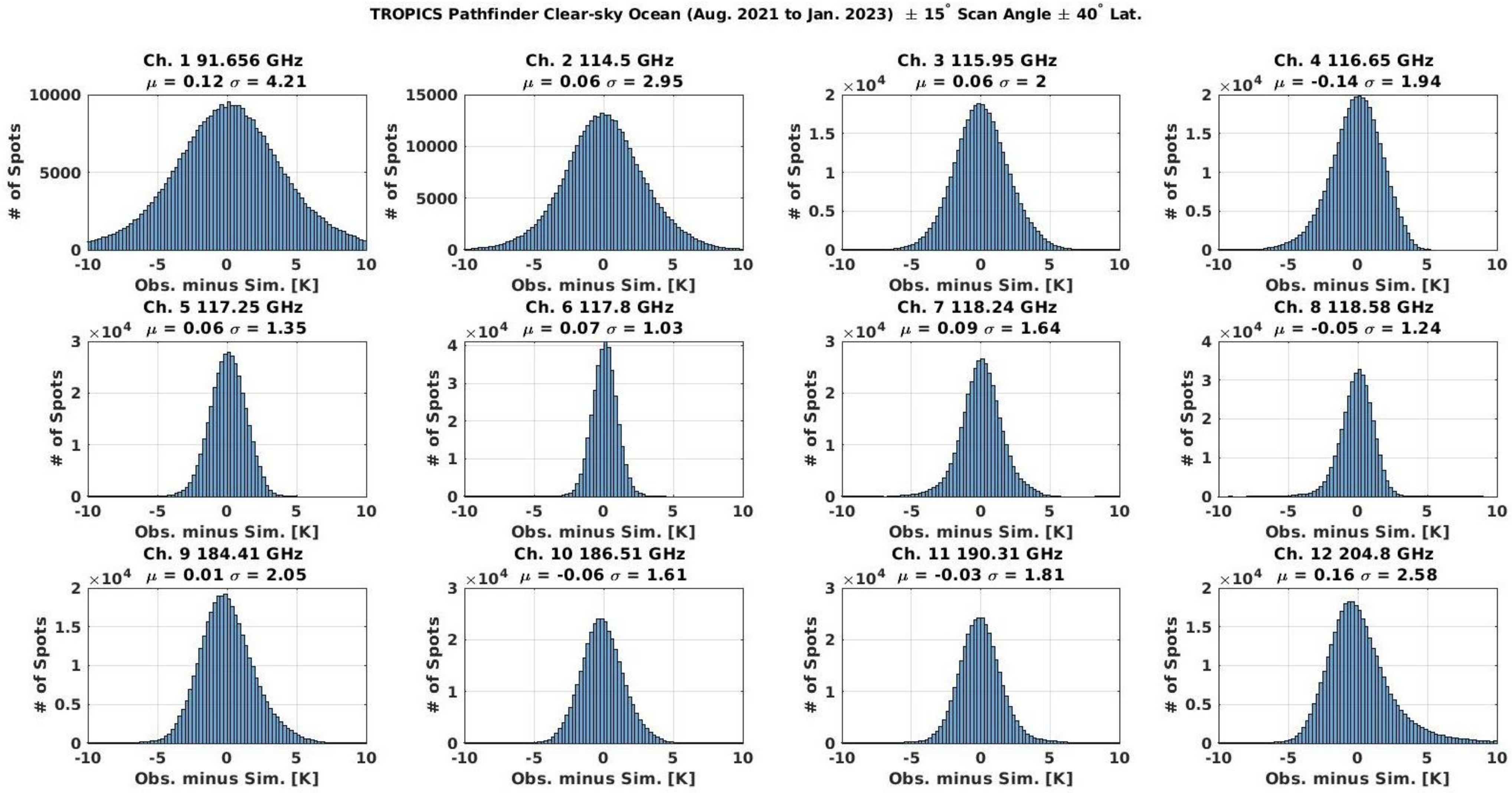


Present Configuration (Once distribution groups are online, users will transfer away from DPC)

Level 1B Product Shows Negligible Drift over 2 Years



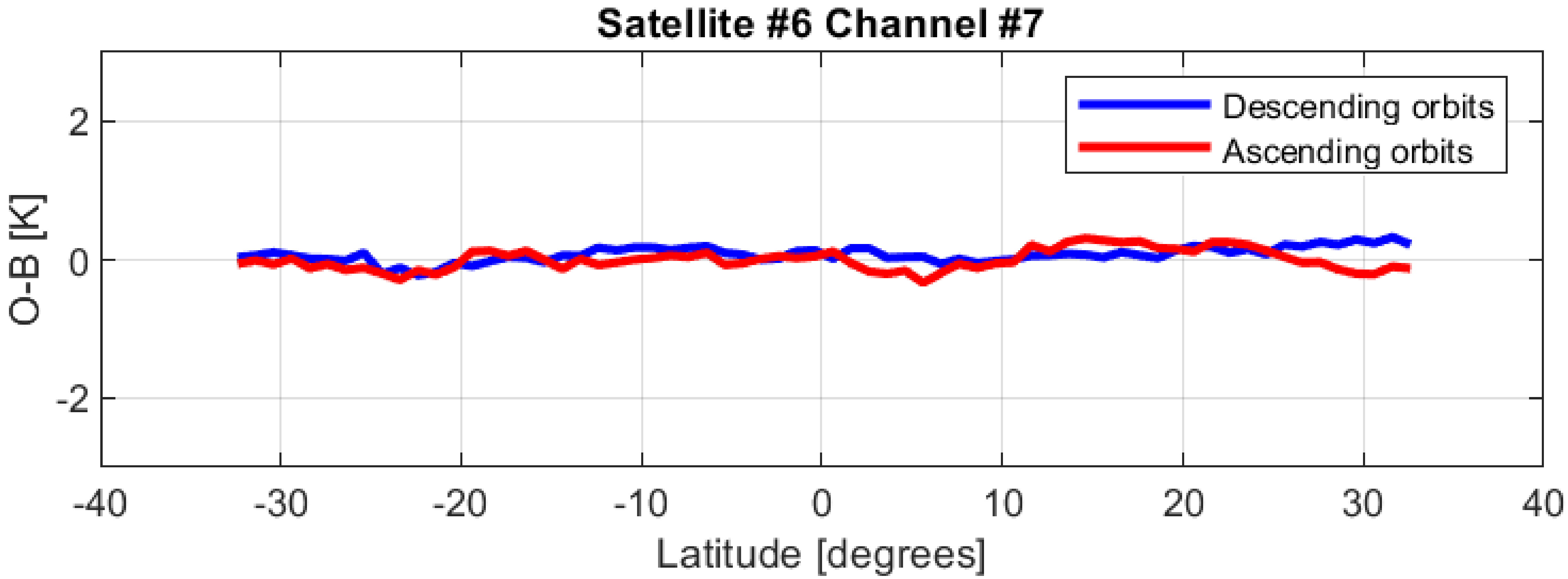
Level 1B Departures from GEOS-5 are Relatively Small and Gaussian



Chan.	Post-launch Global bias
1	0.73
2	0.57
3	0.56
4	0.66
5	0.60
6	0.64
7	0.71
8	0.83
9	0.43
10	0.42
11	0.41
12	0.36

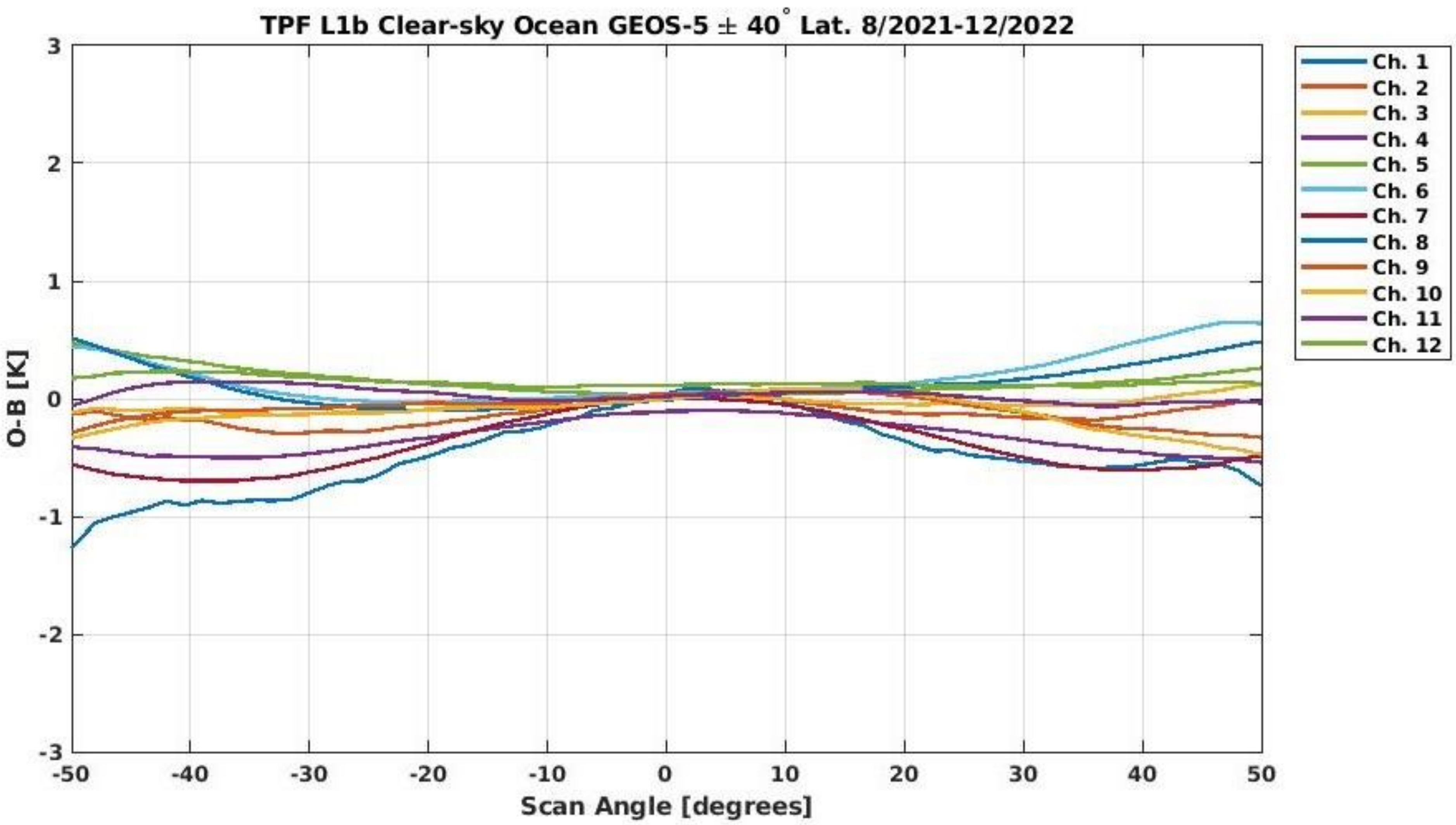
* Converted from ND NEDT calibration sector (Gain x count std. dev) to 300K scene

Orbital Biases are Relatively Small



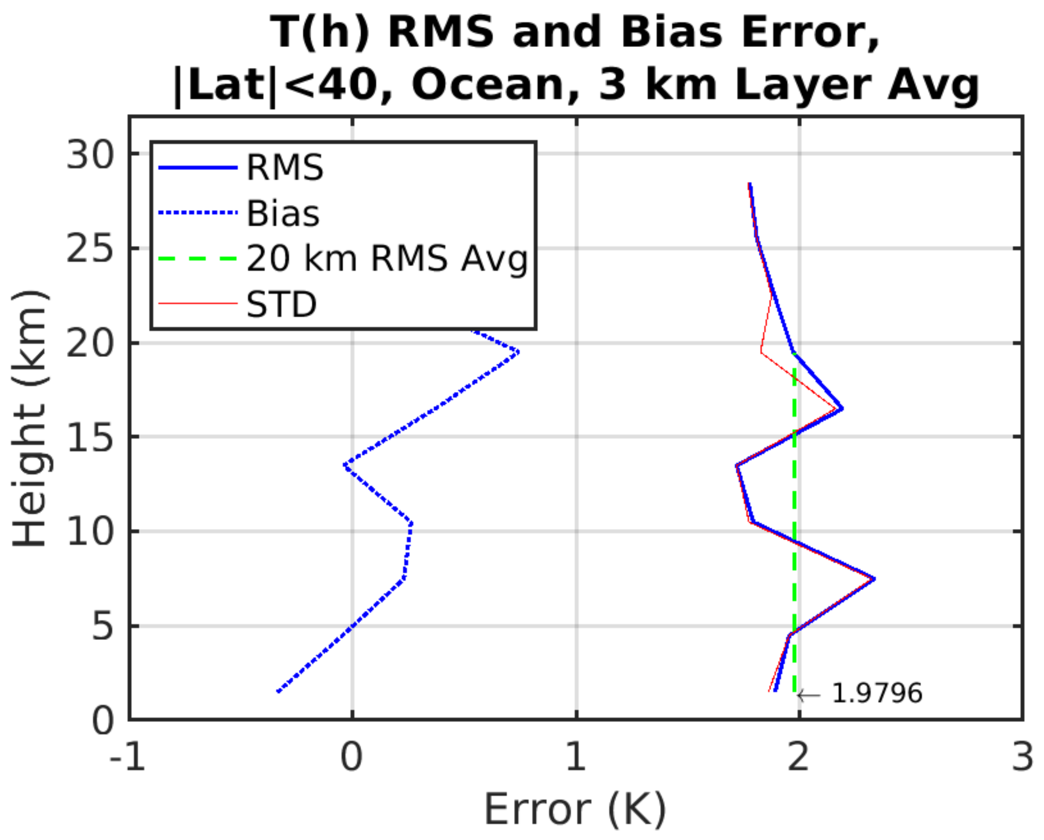
Wide variety of cases included here: clear, cloudy, land, and ocean

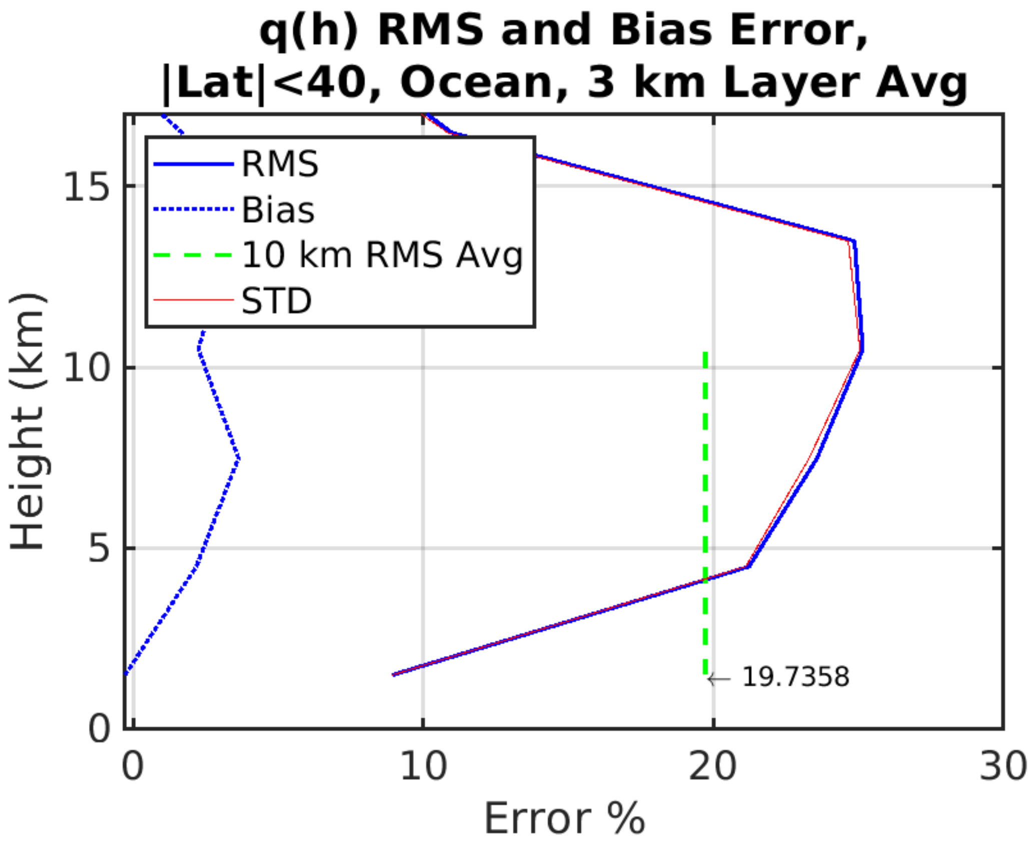
Scan Biases are Relatively Small



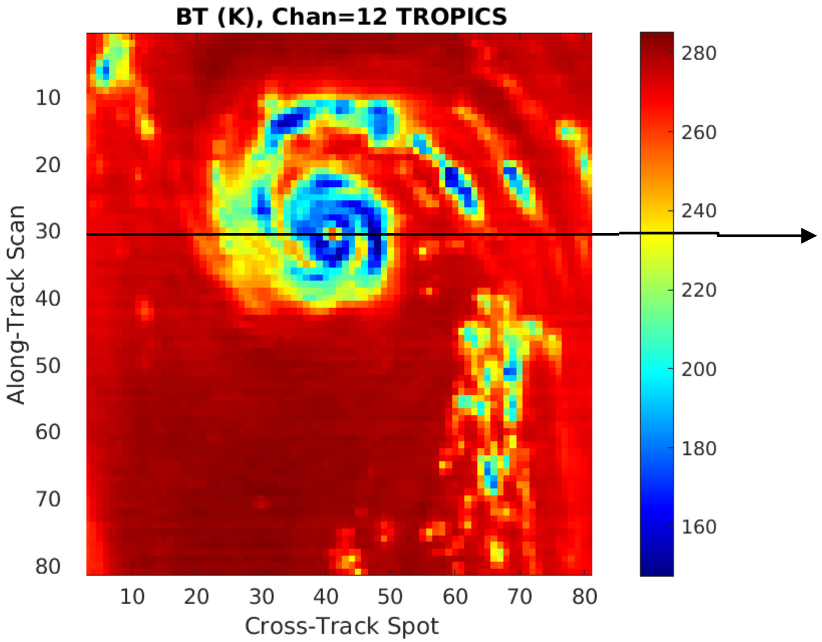
Pathfinder Temp/Moisture Retrievals Meet Requirements (Cloudy, mostly non-precipitating atmospheres)

TROPICS Pathfinder

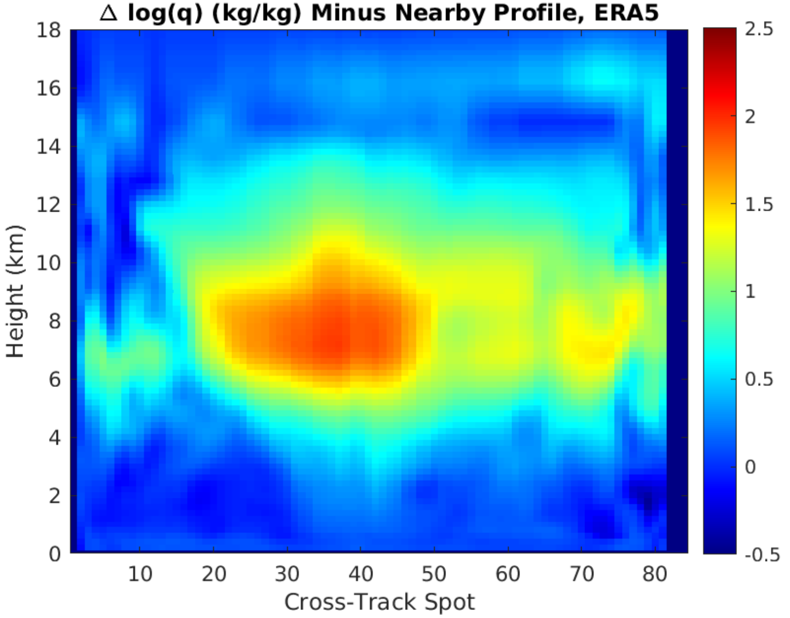




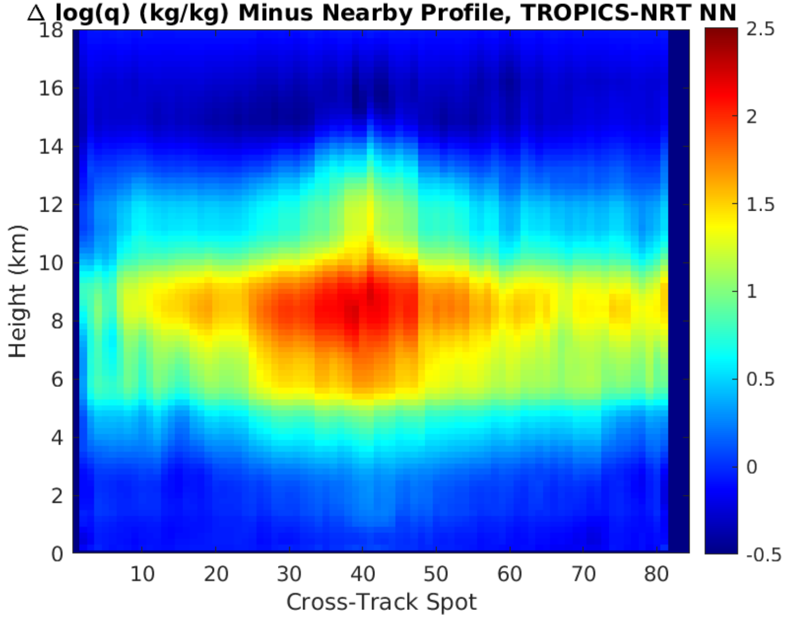
Moisture Anomaly: Hurricane Ida, 8/28/2021



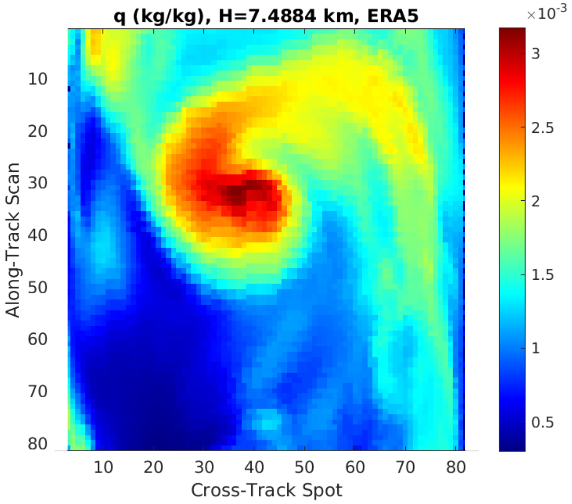
ERA5

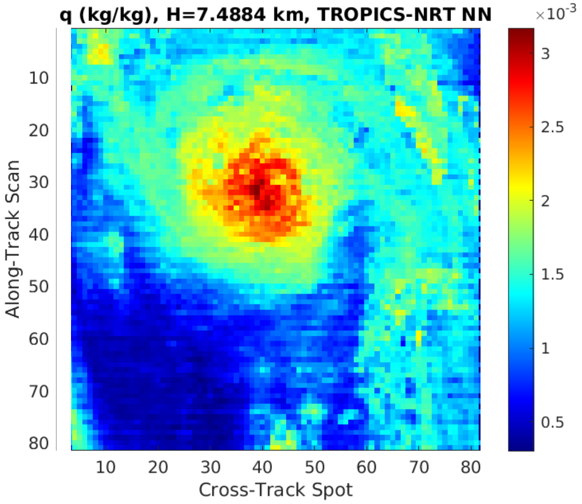


TROPICS Retrievals

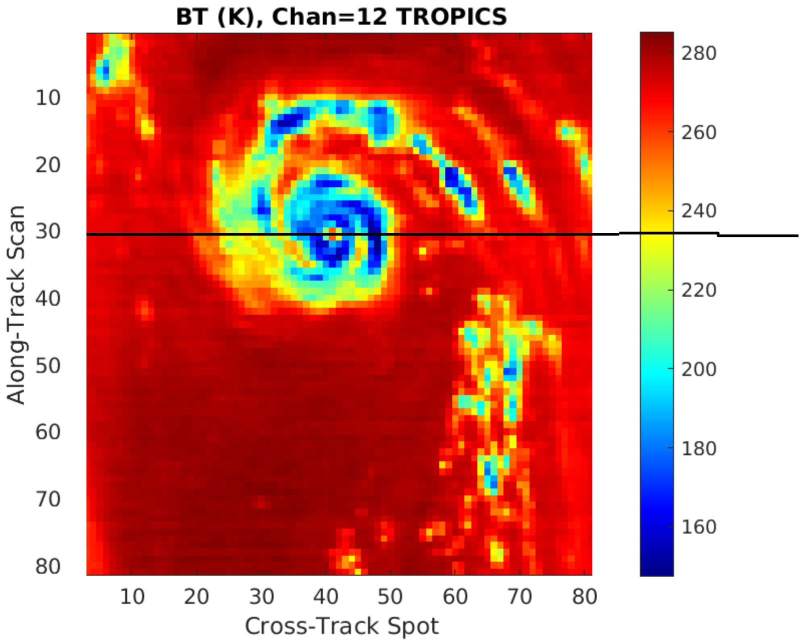


- **Despite multiple scattering, NRT retrievals of show expected features near storm center**

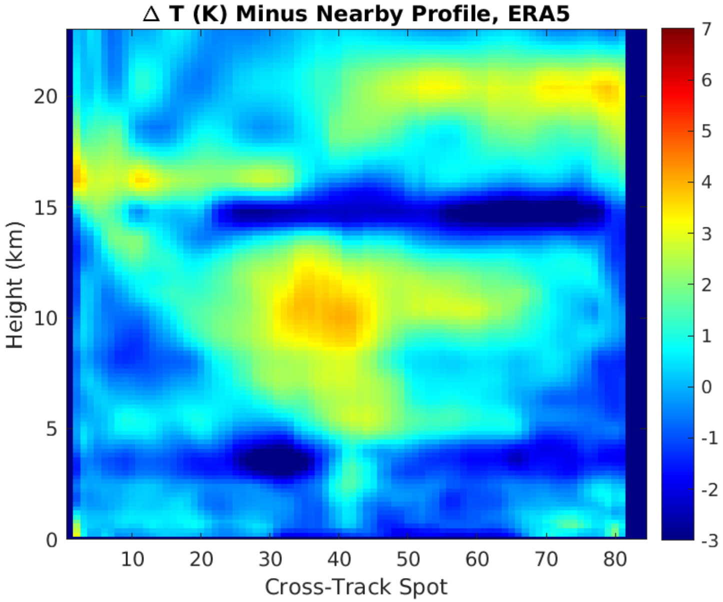




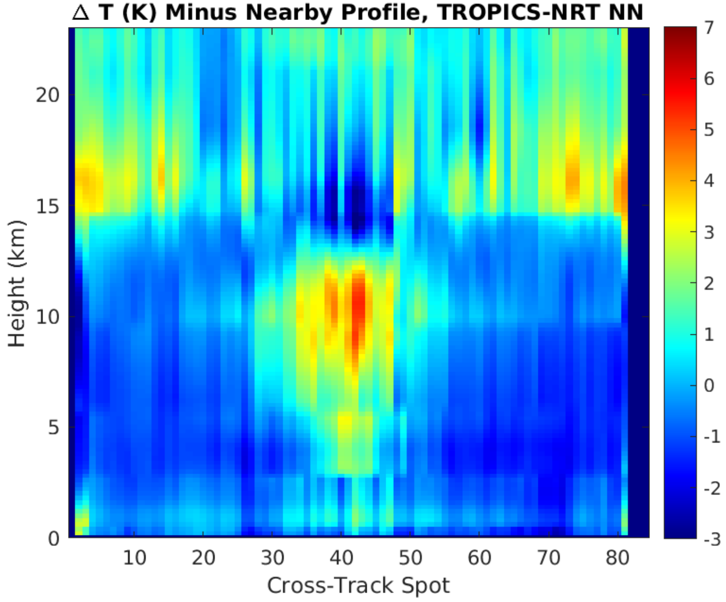
Temperature Anomaly: Hurricane Ida, 8/28/2021



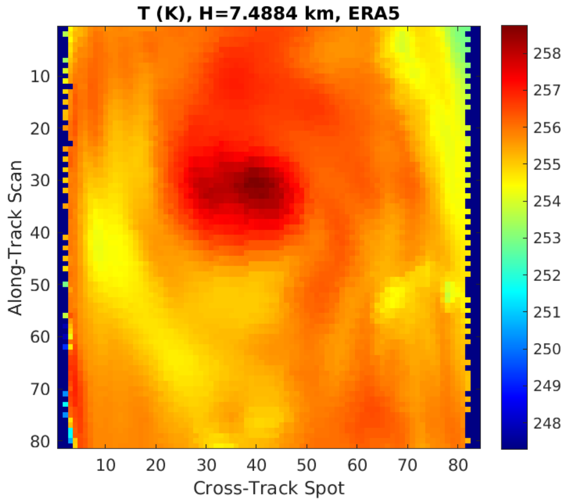
ERA5

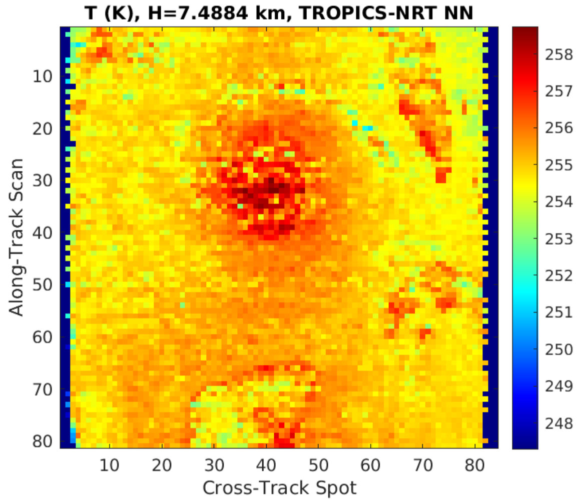


TROPICS Retrievals

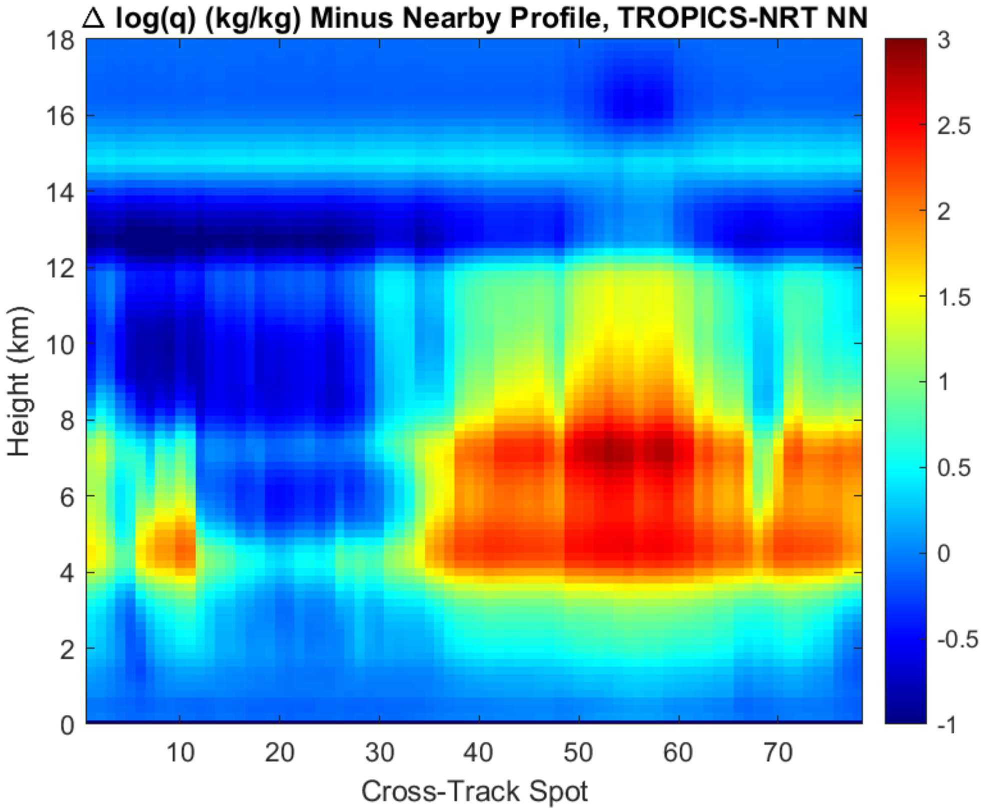


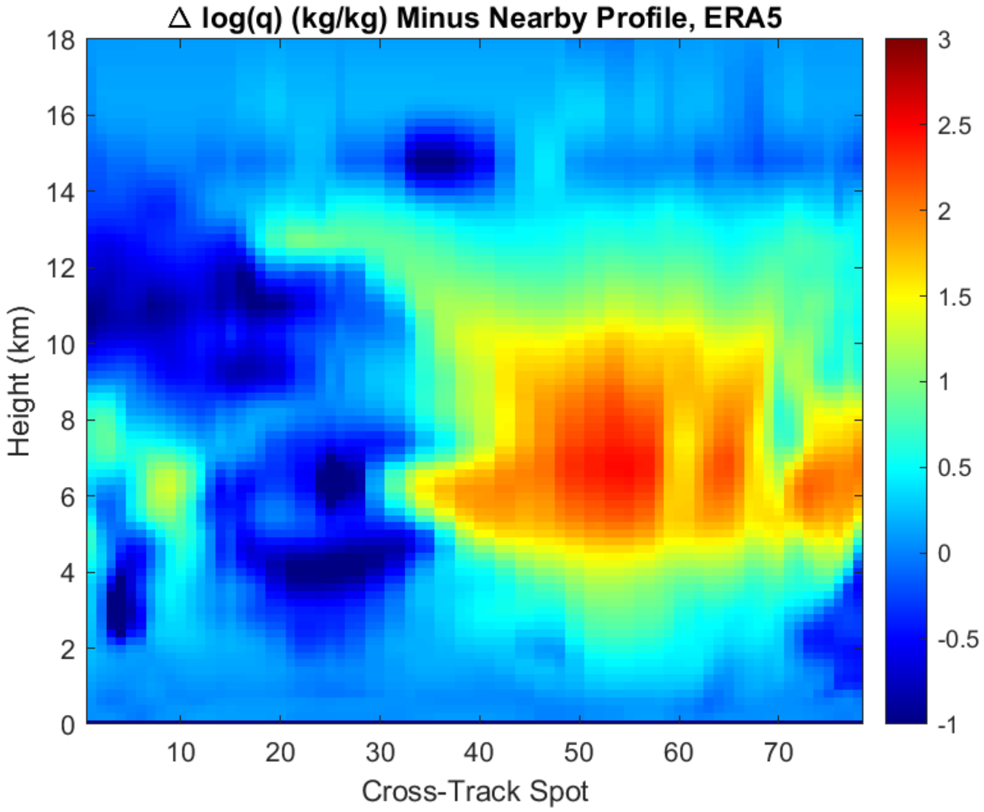
- **Despite multiple scattering, NRT retrievals of show expected features near storm center**





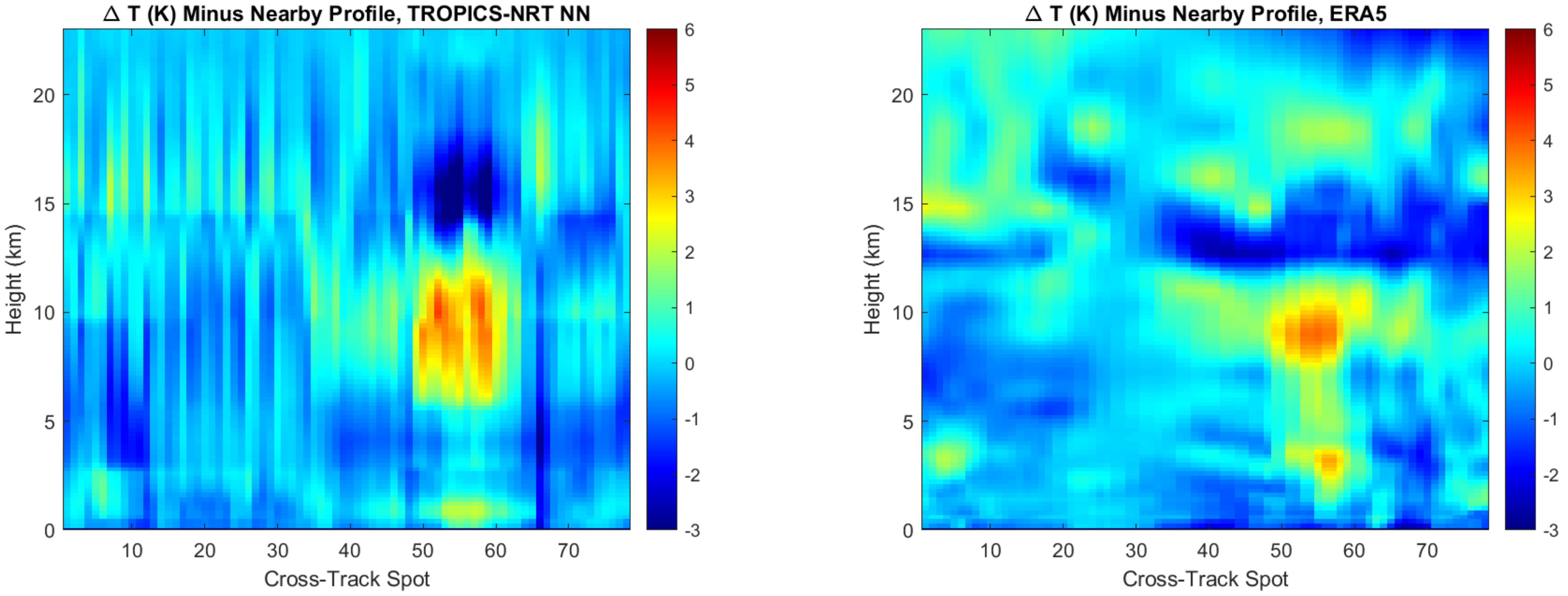
Moisture Anomaly: Hurricane Sam, 9/27/2021





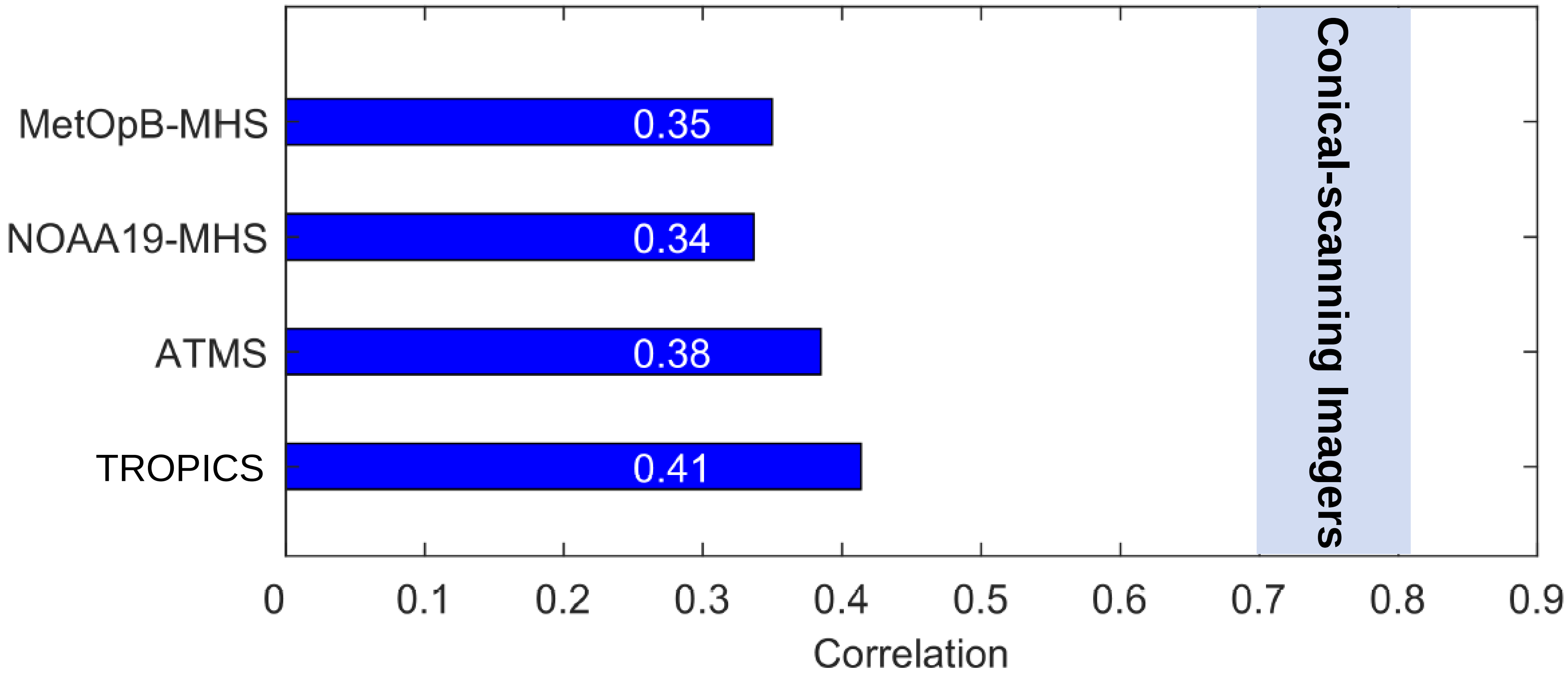
105 knots

Temperature Anomaly: Hurricane Sam, 9/27/2021



105 knots

TROPICS Rain Rate Estimation On-par with State-of-the-Art Sounders



Reference: Y. You, et al., "Evaluating and Improving TROPICS Millimeter-Wave Sounder's Precipitation Estimates over Ocean," JGR: Atmospheres, 128 (16), e2023JD038697

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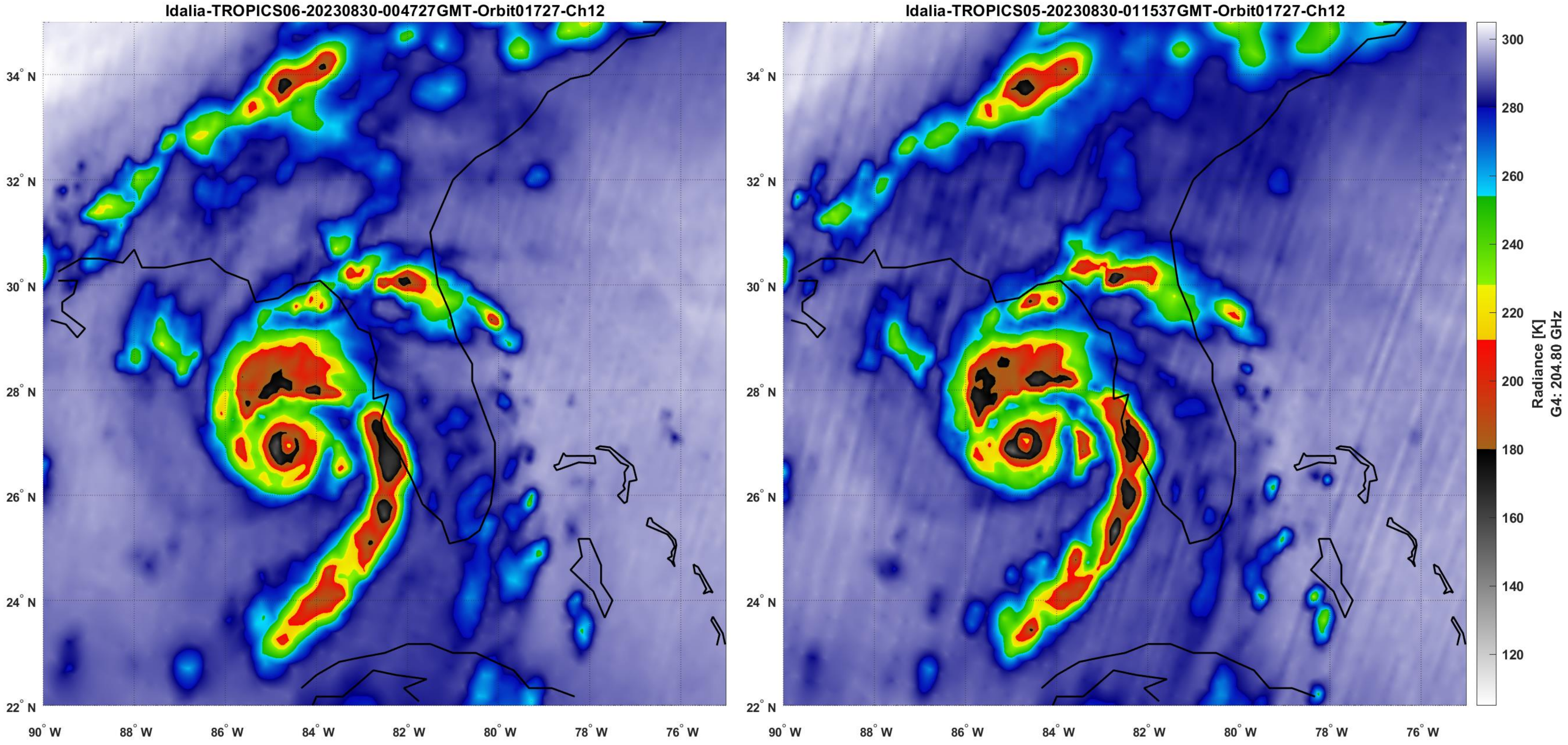
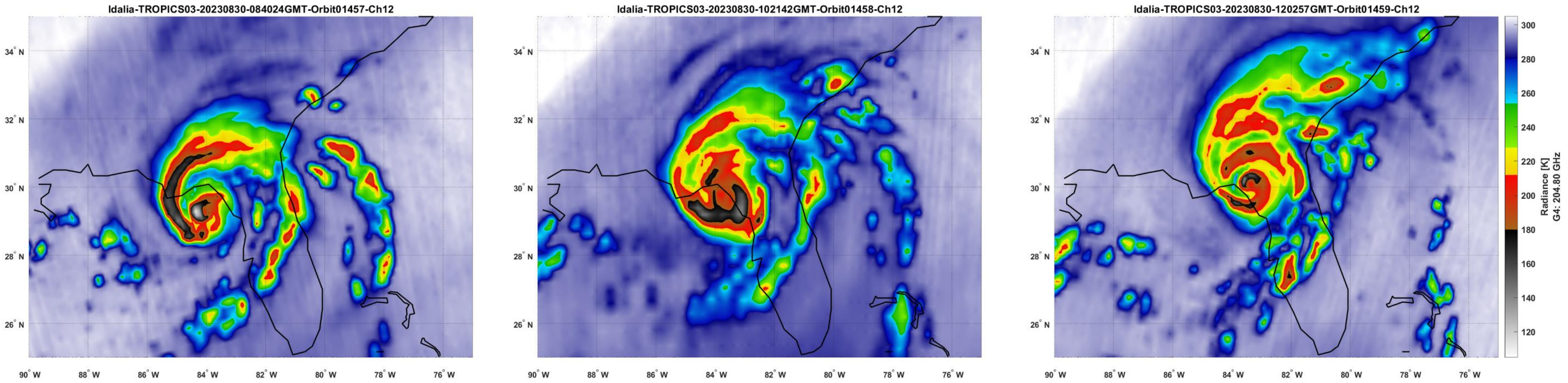
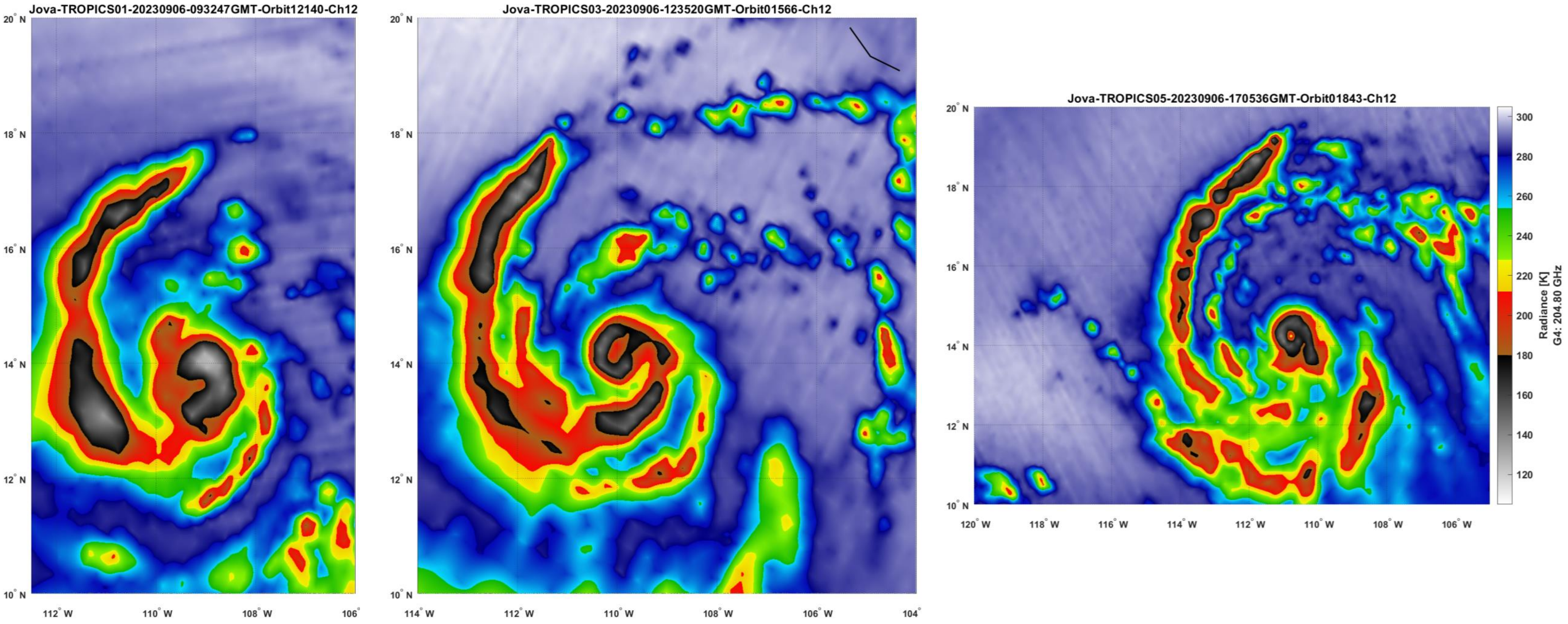
Hurricane Idalia in US Gulf Coast (Aug 30, 2023)



Hurricane Idalia Landfall in Florida (Aug 30, 2023)



TC Jova (September 6, 2023)



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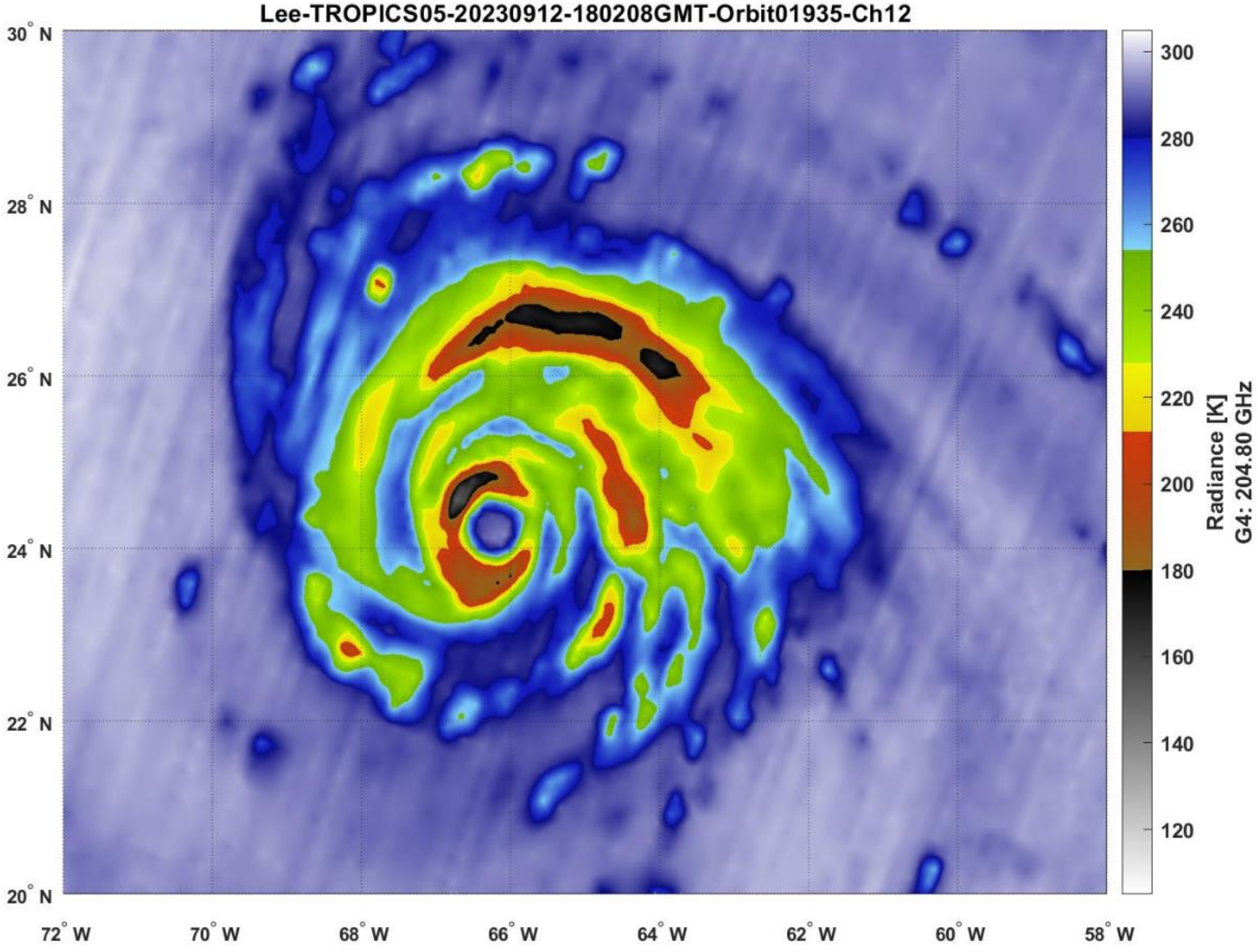
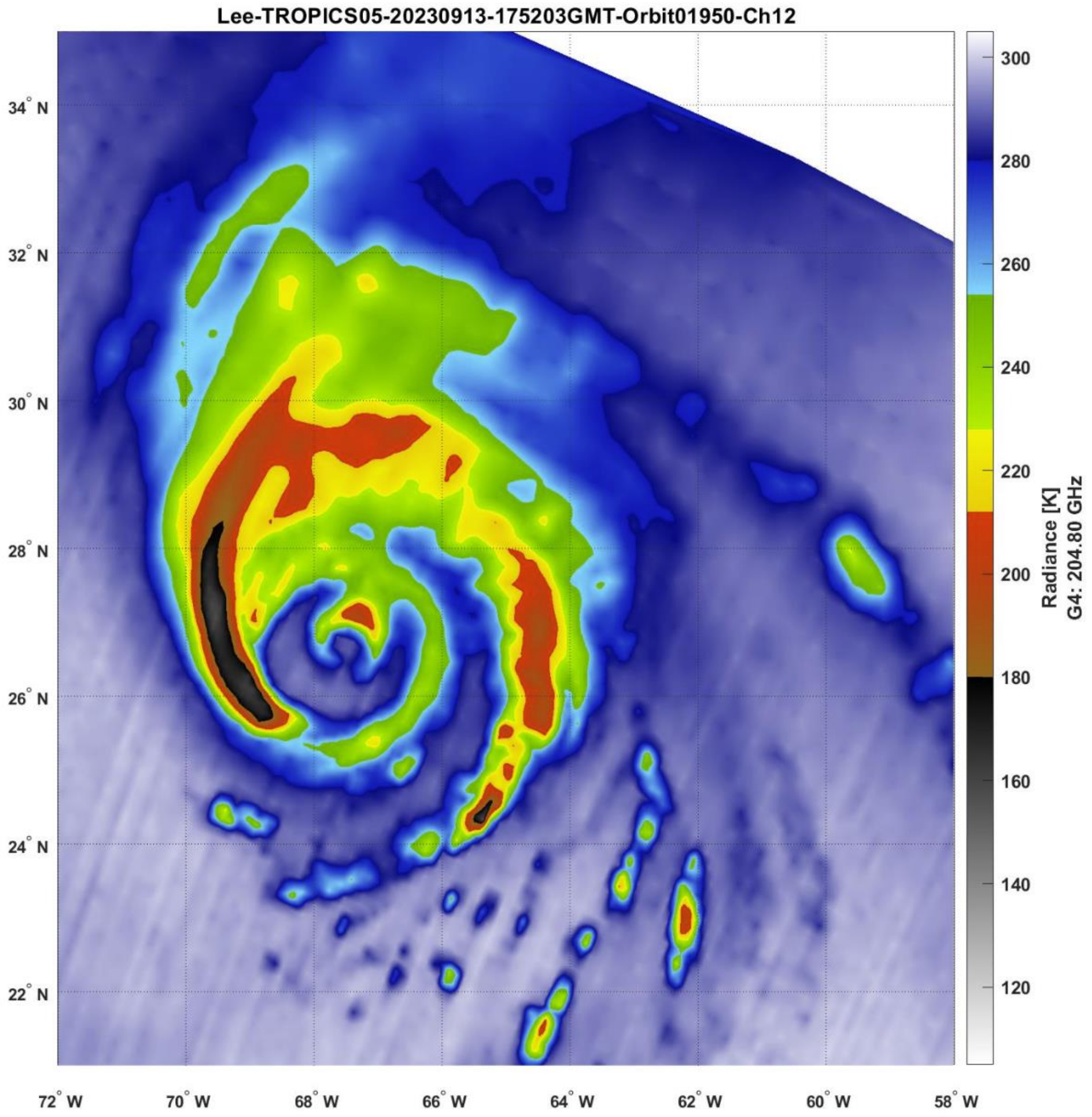
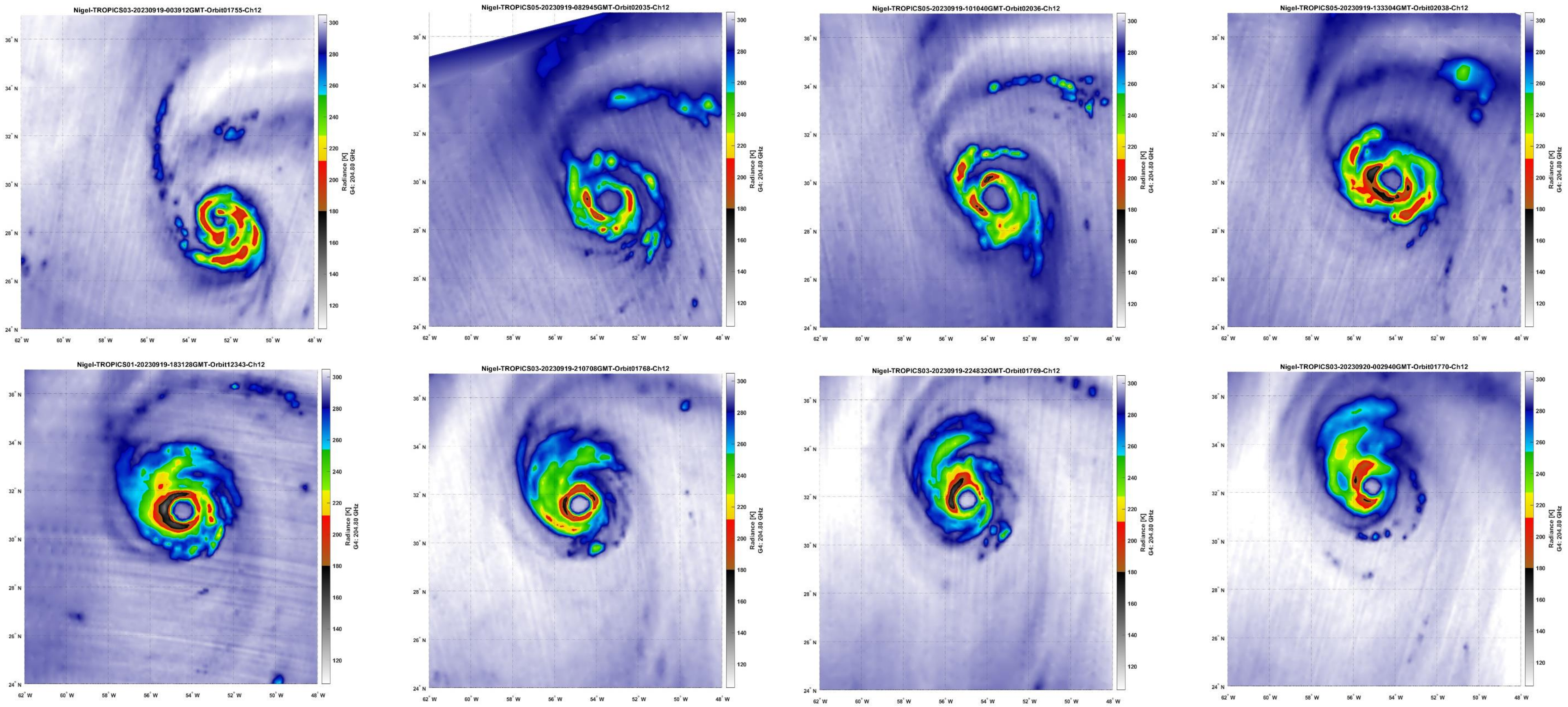
Hurricane Lee (Sep 12-13, 2023)





Hurricane Nigel (Overnight Sep 19-20, 2023) Cat2



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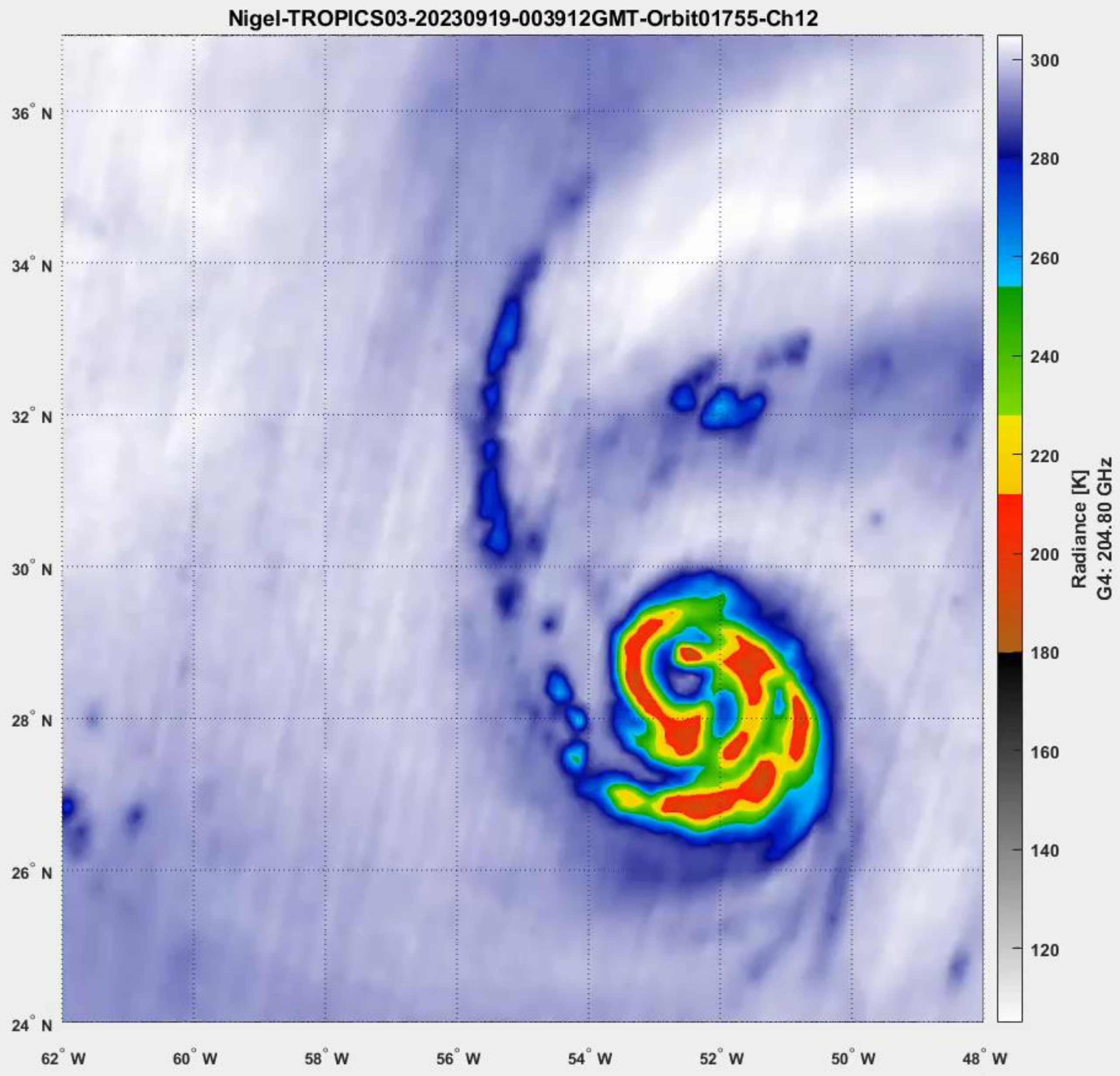
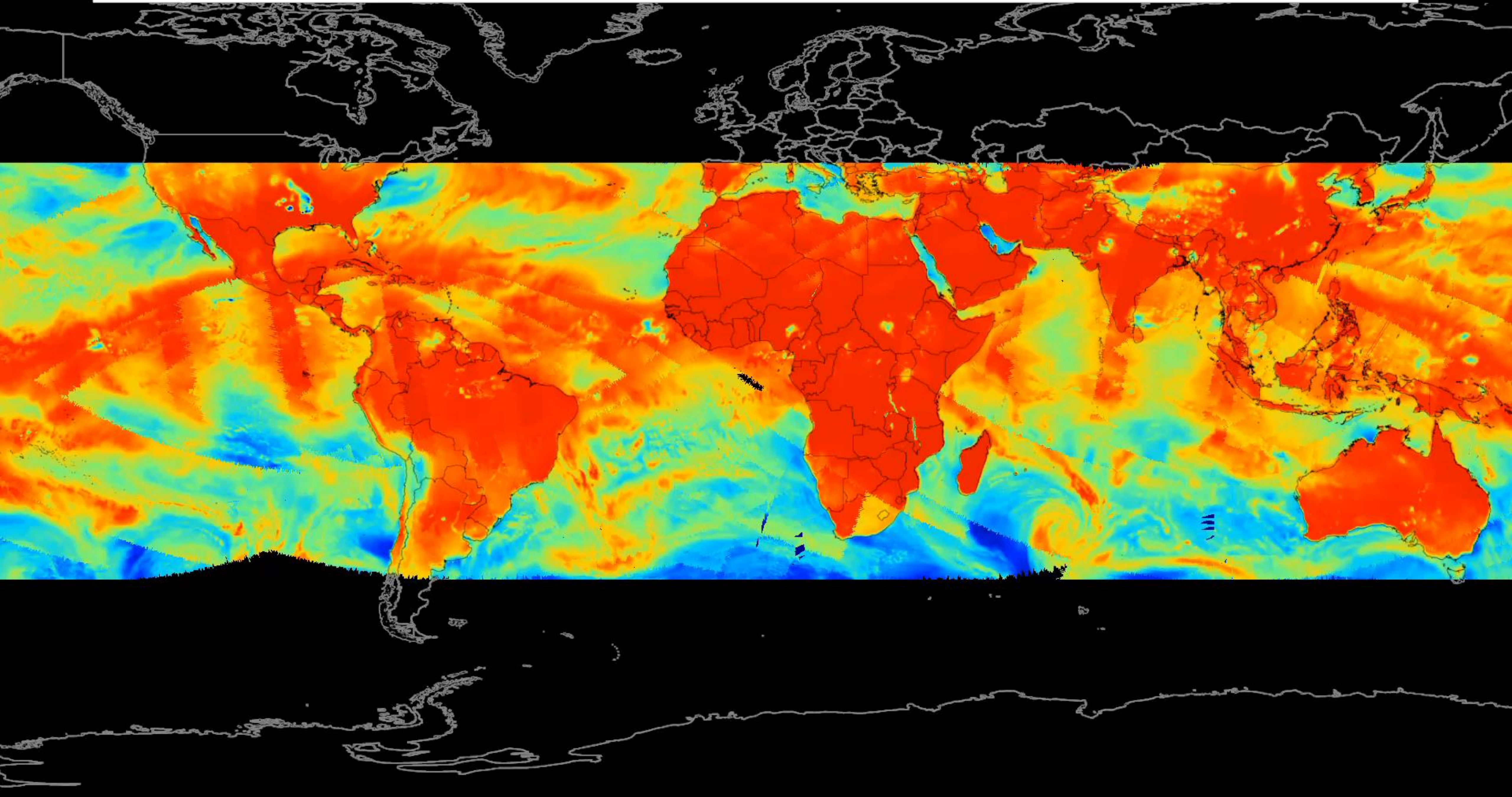

Nigel-TROPICS03-20230919-003912GMT-Orbit01755-Ch12
36° N
34° N
32° N
30° N
28° N
26° N
24° N
62° W
60° W
58° W
56° W
54° W
52° W
50° W
48° W
300
280
260
240
220
200
180
160
140
120
Radiance [K]
G4: 204.80 GHz

Tropics Constellation Channel 01 2023-06-18 09:55



TROPICS Technology Transfer

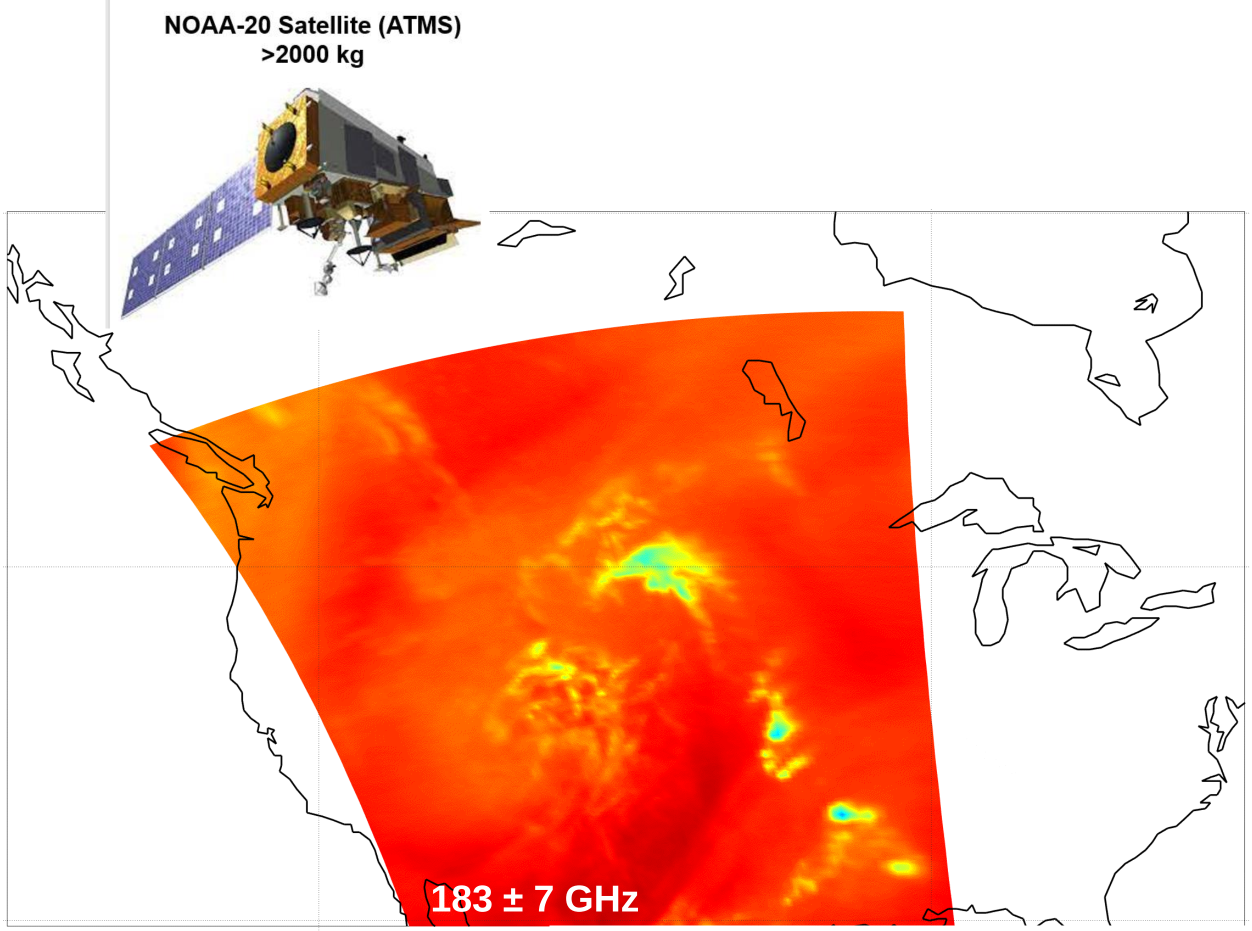
- The TROPICS Pathfinder satellite showed the compact TROPICS design performs comparably to state-of-the-art sounders
  - Lessons learned will help commission and operate constellation

- Boston-based Tomorrow.io has funded a Cooperative Research and Development Agreement with MIT LL to improve the payload, host on 6U bus, and deploy an initial constellation of 18 satellites

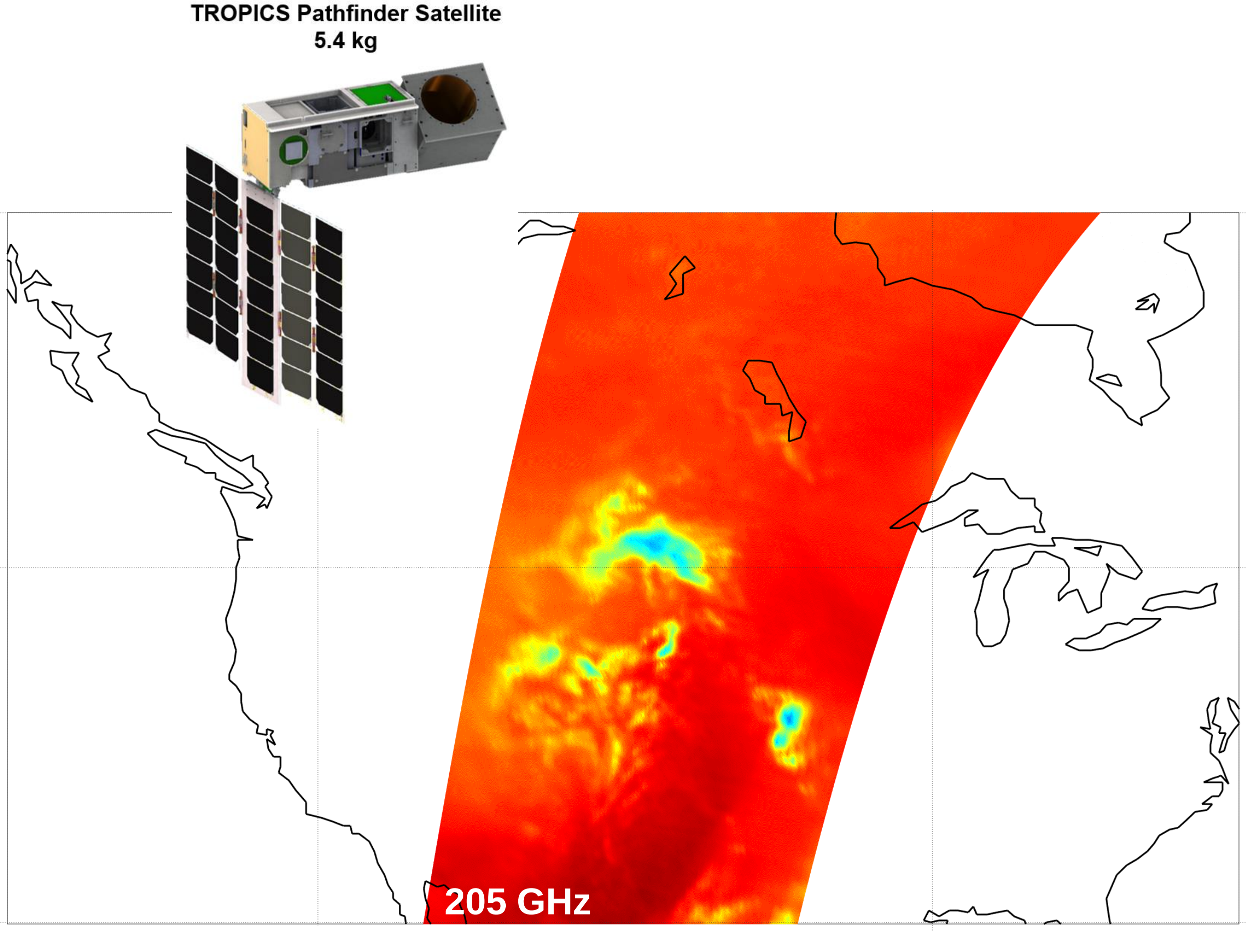
Rendering of Tomorrow.io's microwave sounder. Credit: Tomorrow.io

https://www.tomorrow.io/space/
https://spacenews.com/diu-selects-startups-for-u-s-military-weather-modeling-project/

Heavy Snowfall Over Central US on Oct 12, 2021

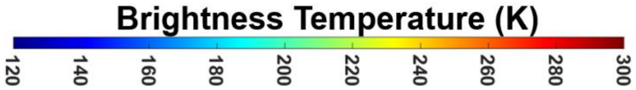


Oct 12, 2021 20:00:21 UTC



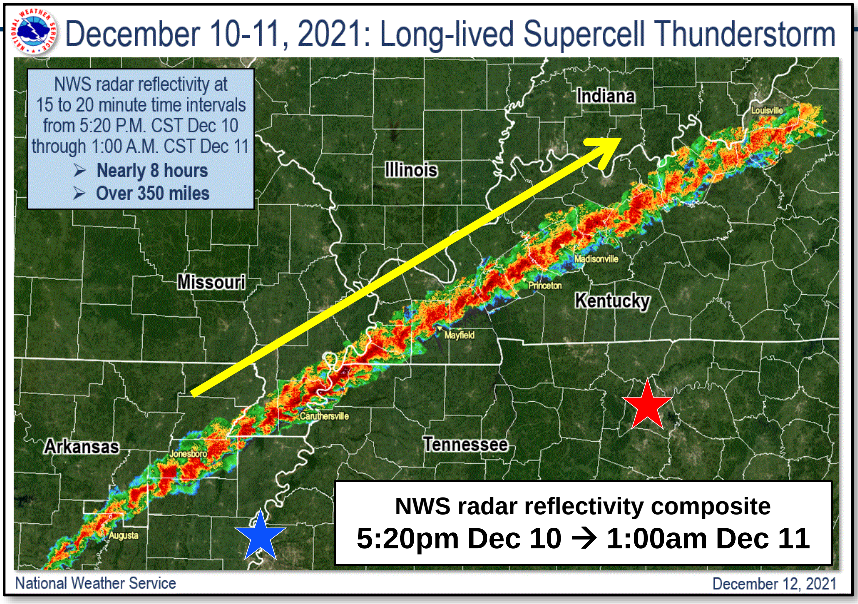
Oct 12, 2021 20:45:51 UTC

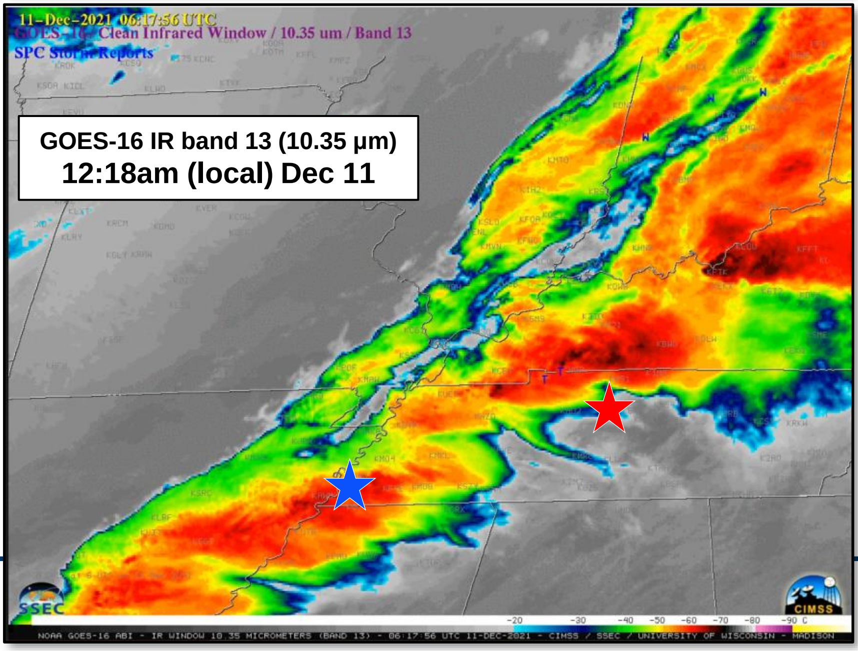
Lowest-level 183-GHz water vapor channel shown

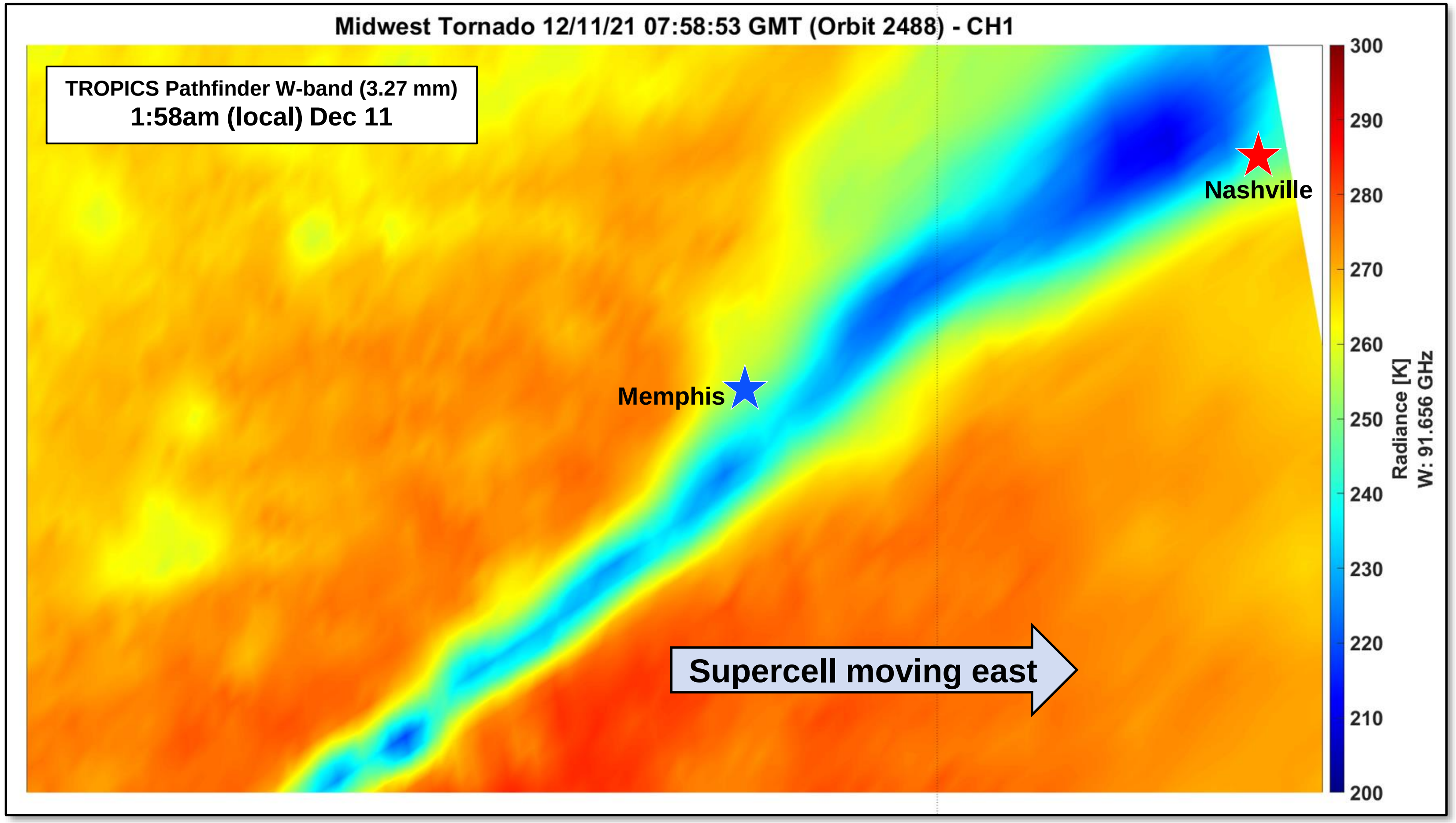


Note: Snowfall is not a TROPICS PLRA data product

Tornadoes in Midwest USA, 10-11 Dec 2021





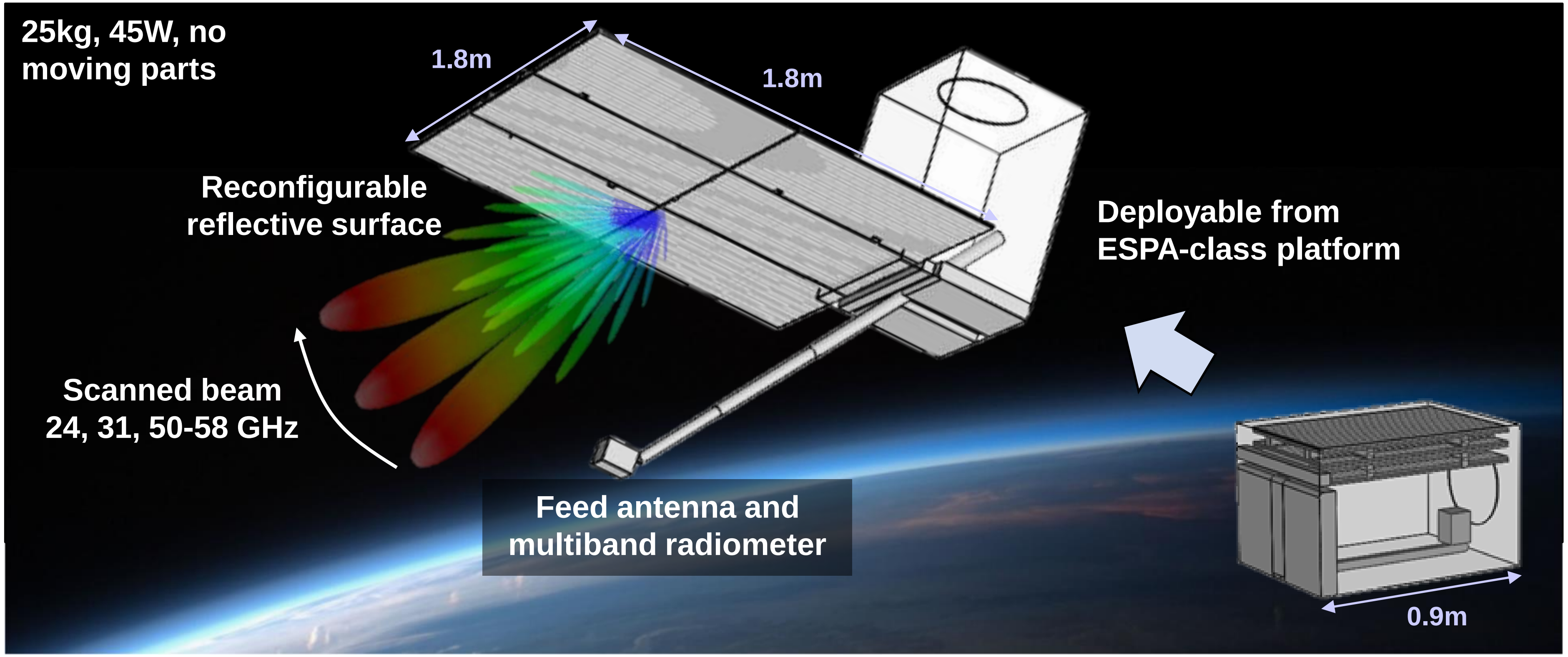


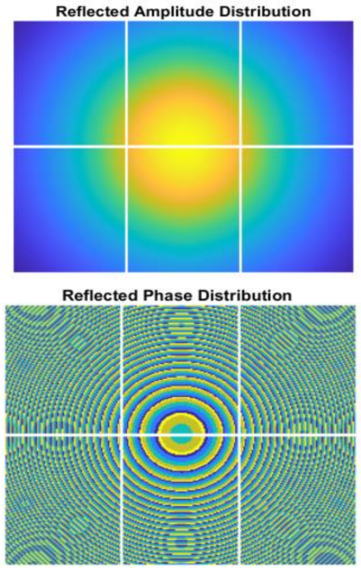
TROPICS Pathfinder overflew the aftermath of the deadly tornadoes and captured temperature anomalies associated with the eastwardly-moving supercell thunderstorm

Source: https://cimss.ssec.wisc.edu/satellite-blog/archives/43754

CREWSR

Configurable Reflectarray for Electronic Wideband Scanning Radiometry

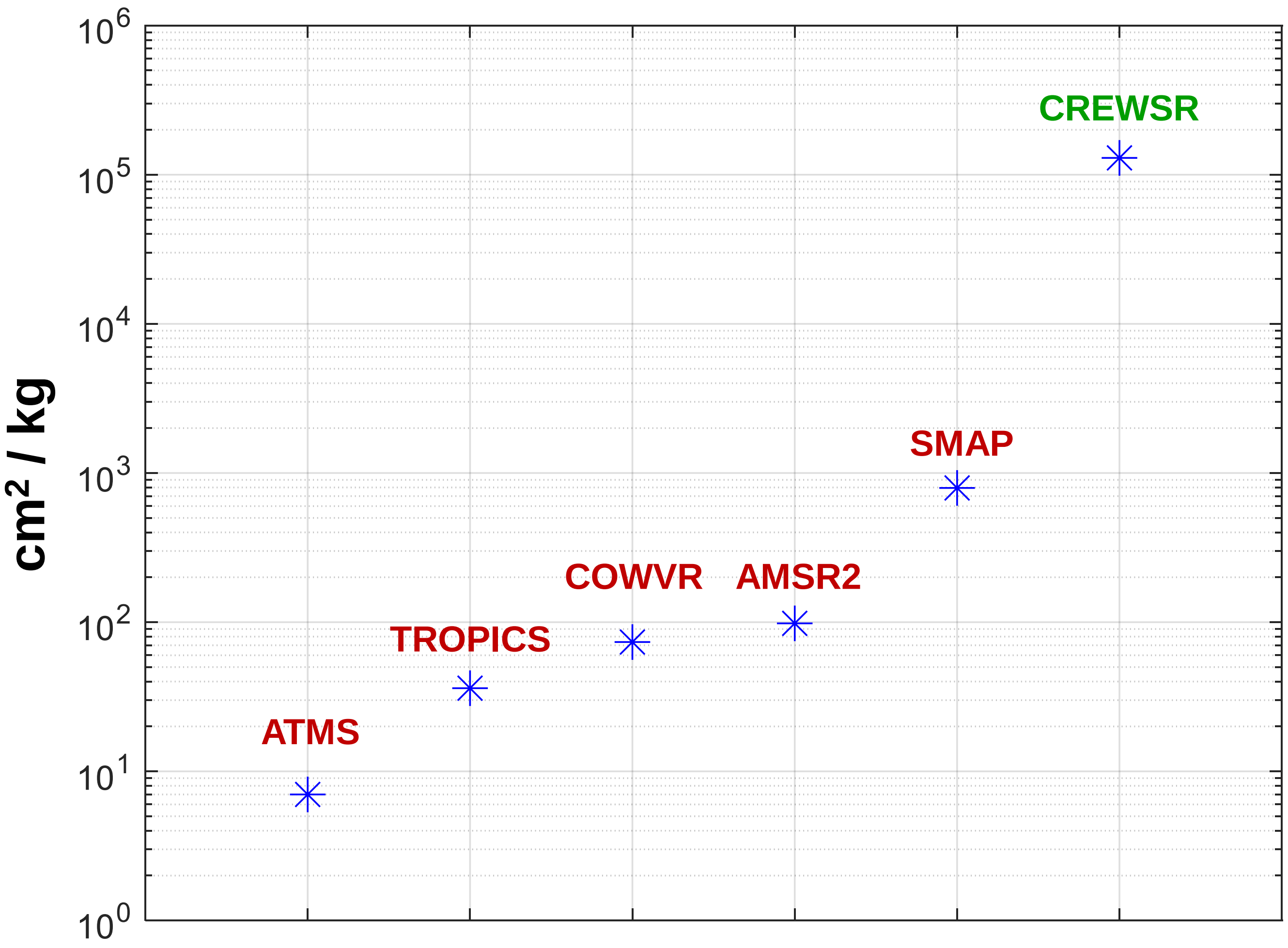




- **Enables large apertures from SmallSats**
- **Agile pointing and resolution**
- **Software-defined spectral resolution/coverage**
- **Multiple spatial beams and spectral bands**

ESTO IIP has funded a prototype of ONE sub-panel

Ratio of Aperture Area to Payload Mass



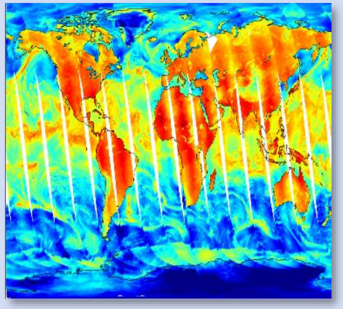
Mechanical Scanning

Electronic Scanning

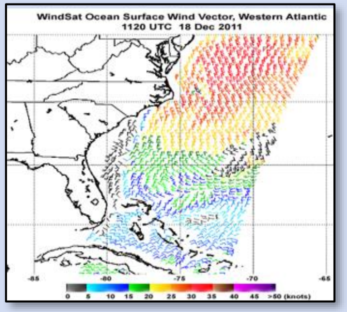
CREWSR Provides Improved Observing Capabilities Relevant to Many NASA Science Mission Areas

Earth Science

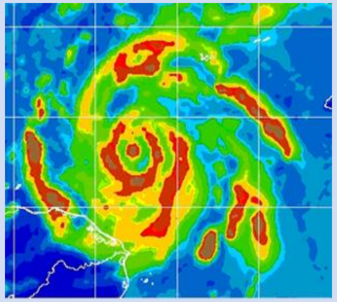
High-Resolution Atmospheric Sounding (23/31/50-58 GHz)



Wind Speed/Direction (10/18/36 GHz)

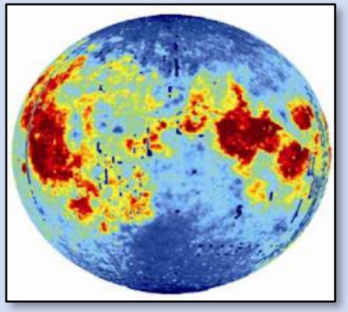


Polarimetric Imaging (37 GHz)



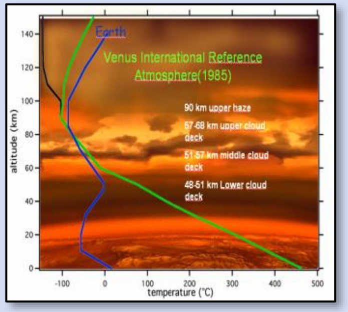
Planetary Science

Lunar surface mapping (1-5 GHz, polarimetry)



Mars wind sensing (100 GHz)

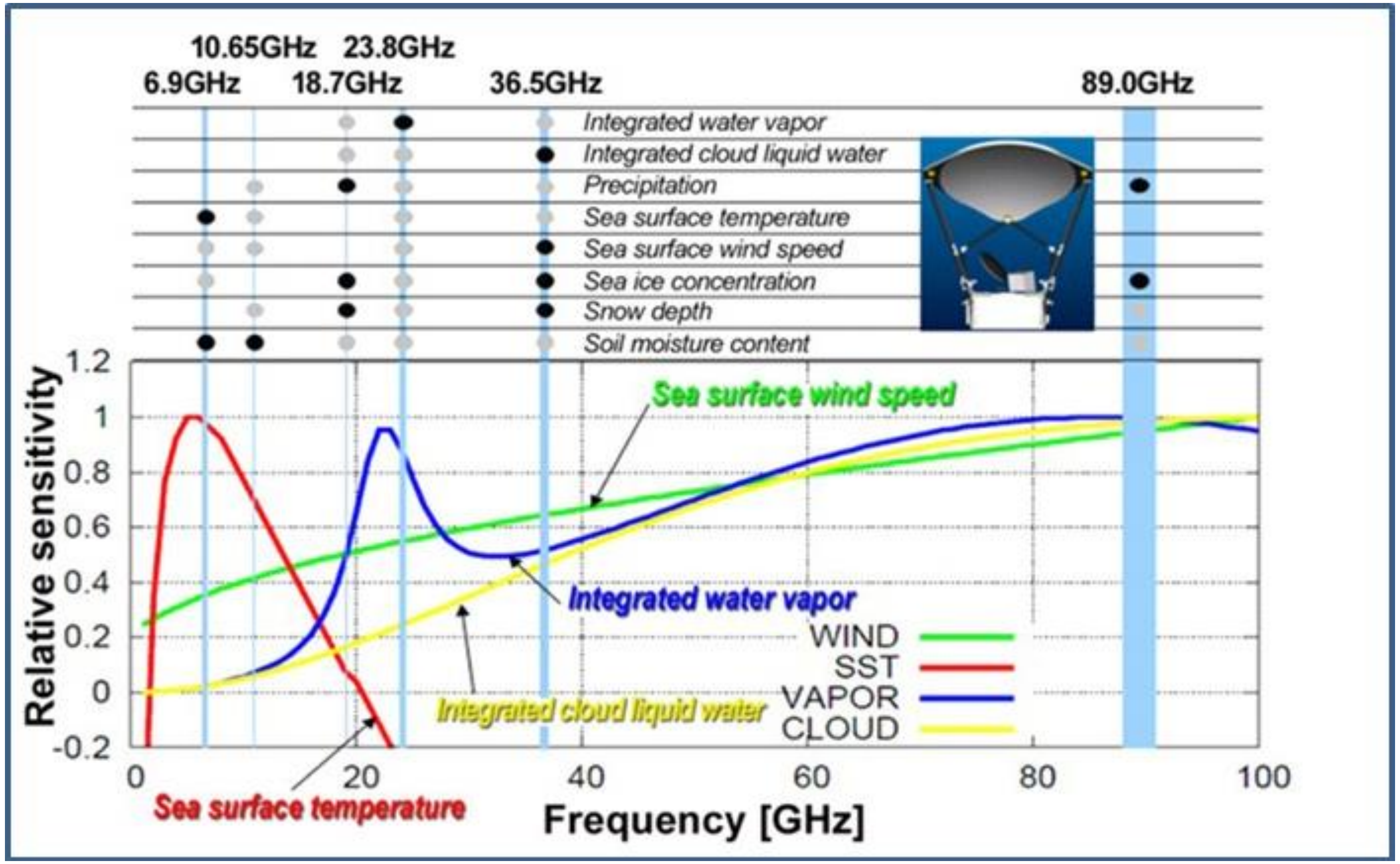
Thermal profiling Venus: 20-60 GHz Titan: 115 GHz



Heliophysics

Lower thermospheric winds (118 GHz)

CREWSR Band Selection: 23.8 and 31.4 GHz (water vapor) & 50-58 GHz (temperature)



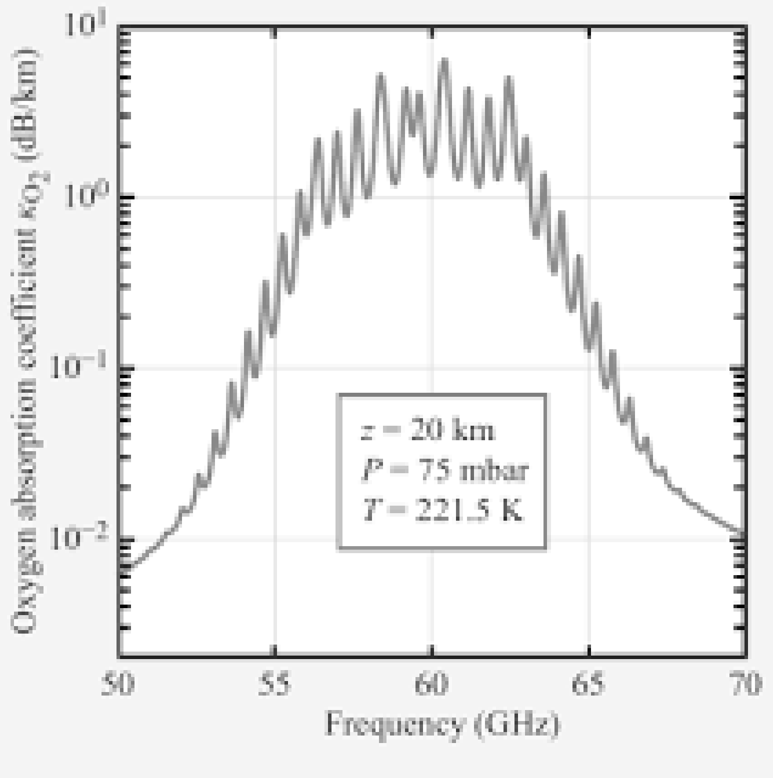
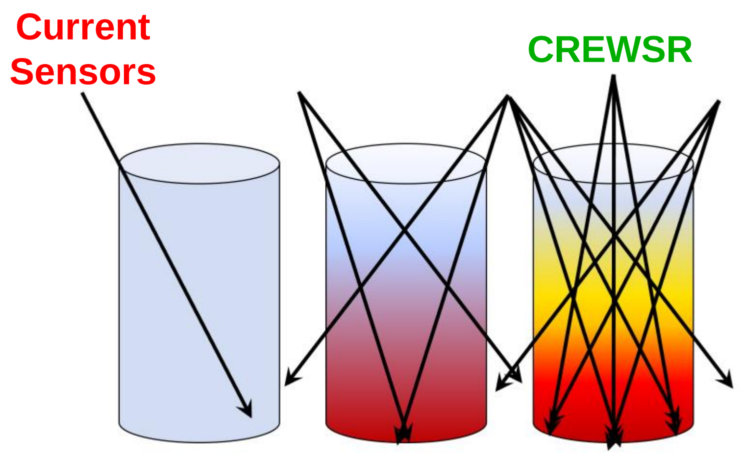
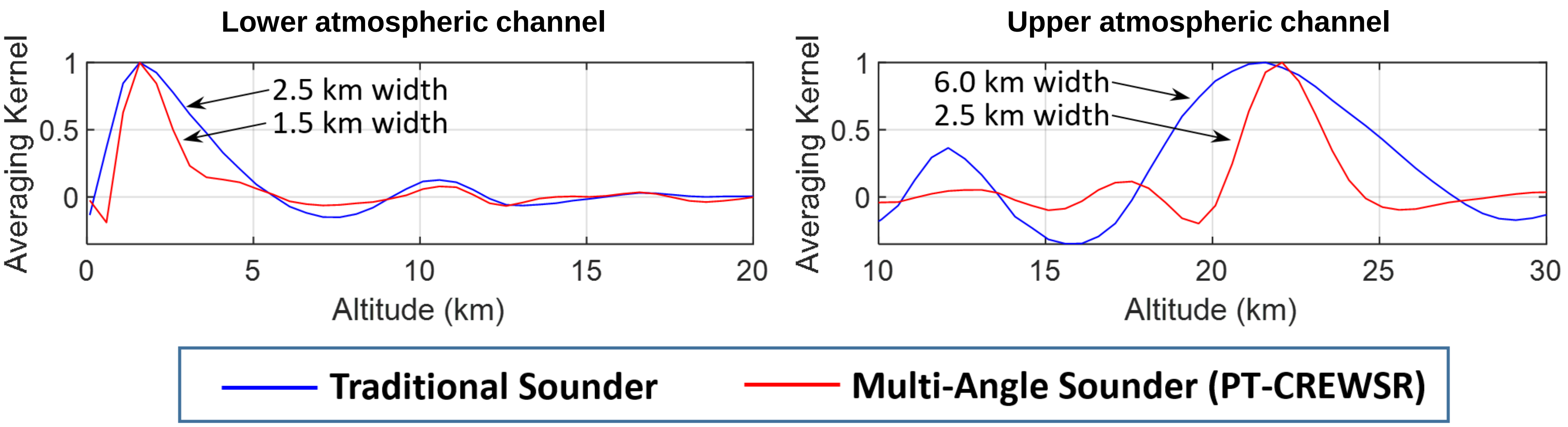


Figure 8-6: Absorption spectrum of the 60 GHz oxygen complex at an altitude of 20 km.

CREWSR supports (in principle) polarimetric sensing and RADAR

Agile Beam Pointing Enables Improved Vertical Sampling (Tomography) of the Atmosphere

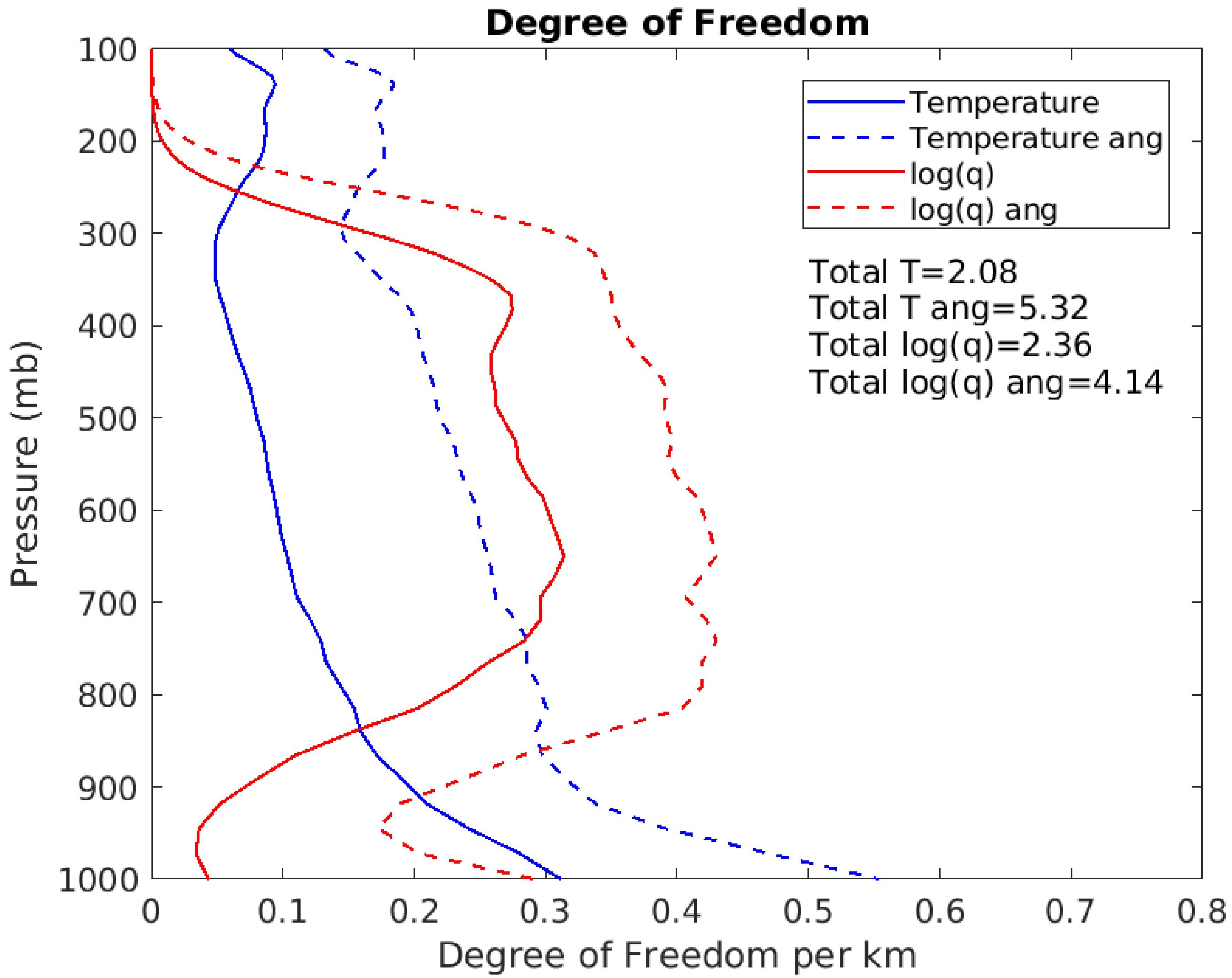




2017 Decadal Survey calls out 1-km vertical resolution in PBL as a threshold requirement

ATMS: Slide provided by Zhenglong Li (UW)

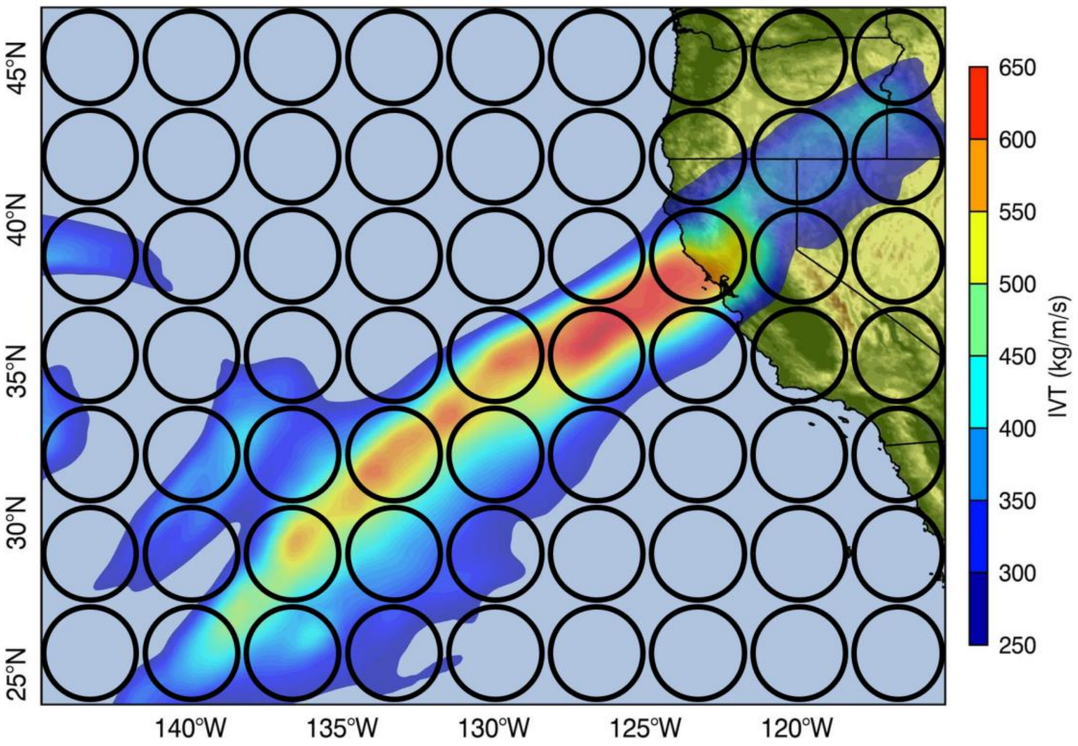
1976 US Standard Atmosphere



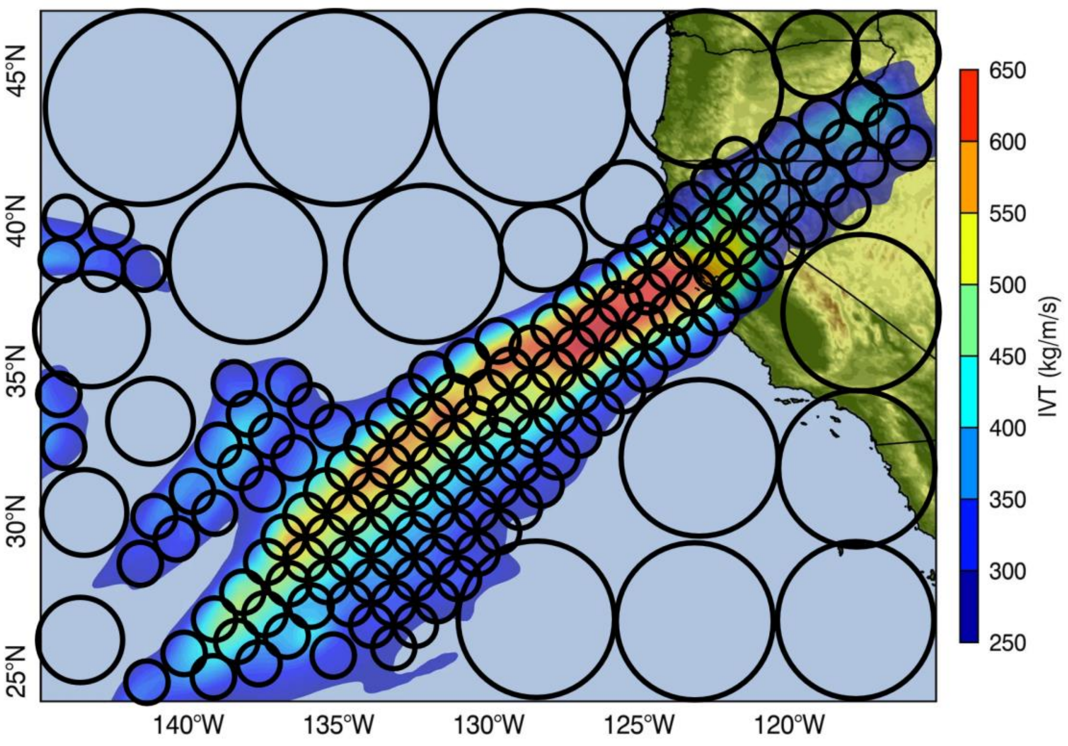
Solid lines: single angle (nadir);
Dash lines: multiple angles (11);

Agile Beam Resolution Enables Improved Horizontal Sampling of the Atmosphere

Current Sensors



CREWSR

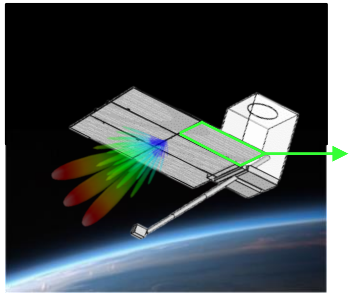


Observing System Simulation Experiment now in progress to assess and optimize CREWSR configurability benefits

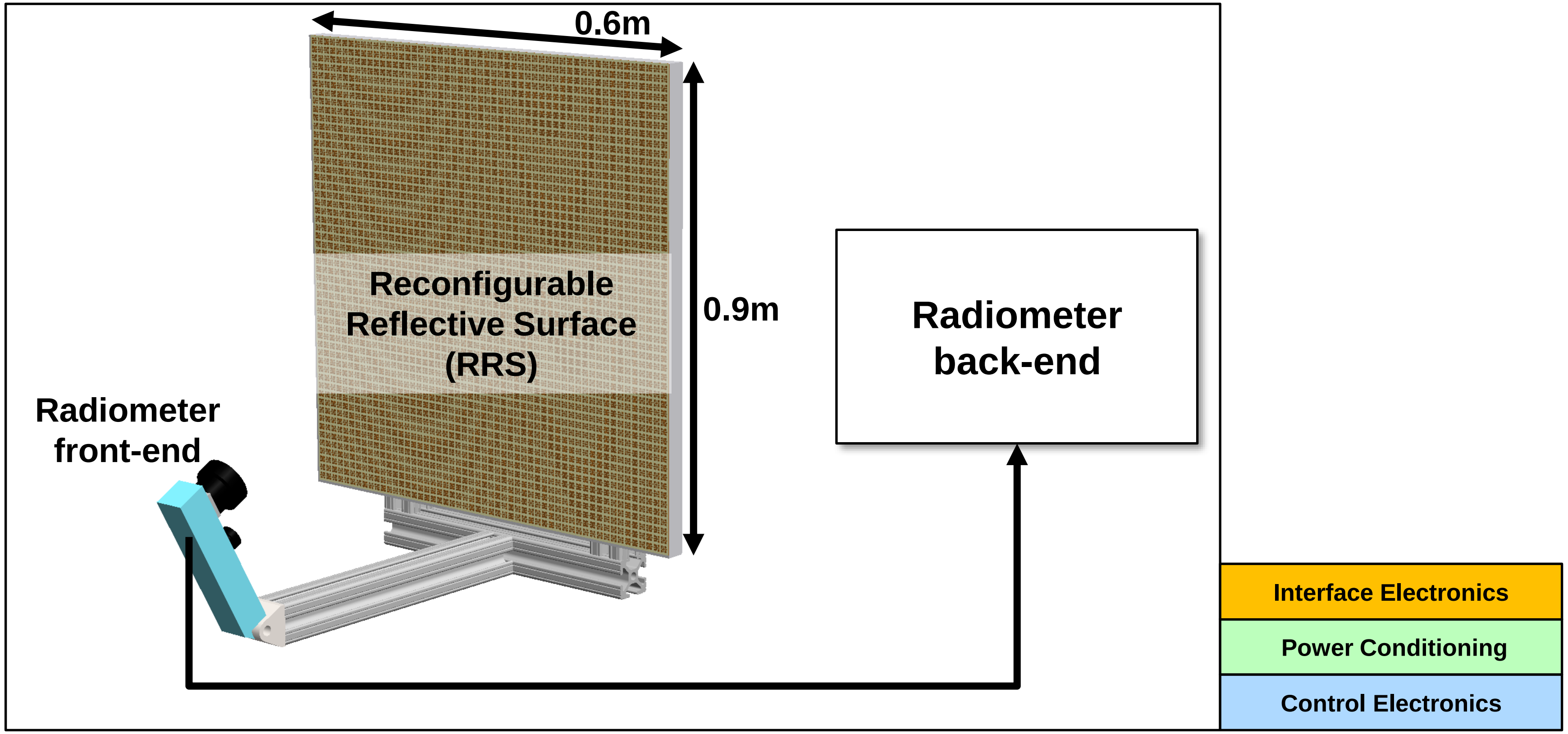
Prototype Instrument: PT-CREWSR

<u>Program Objective:</u> Realization and assessment of PT-CREWSR instrument

CREWSR

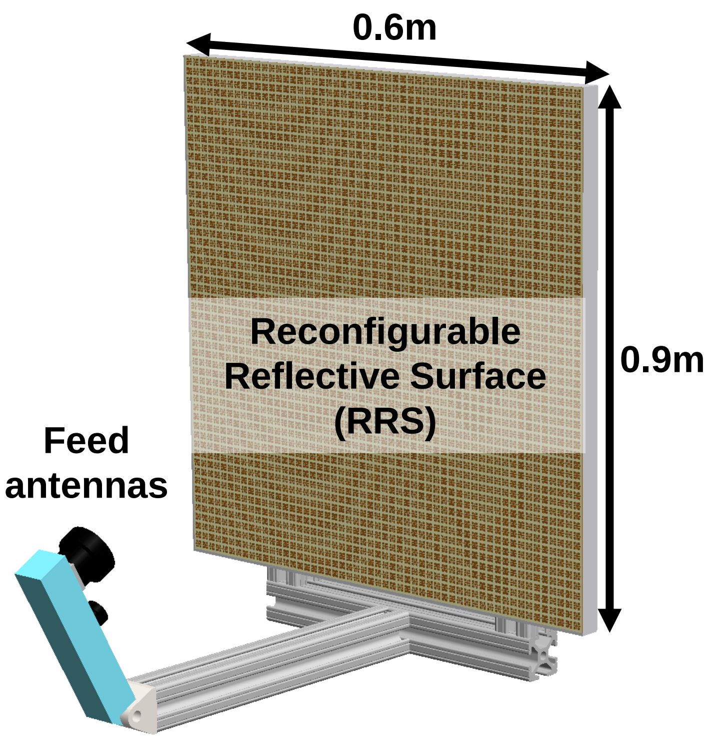


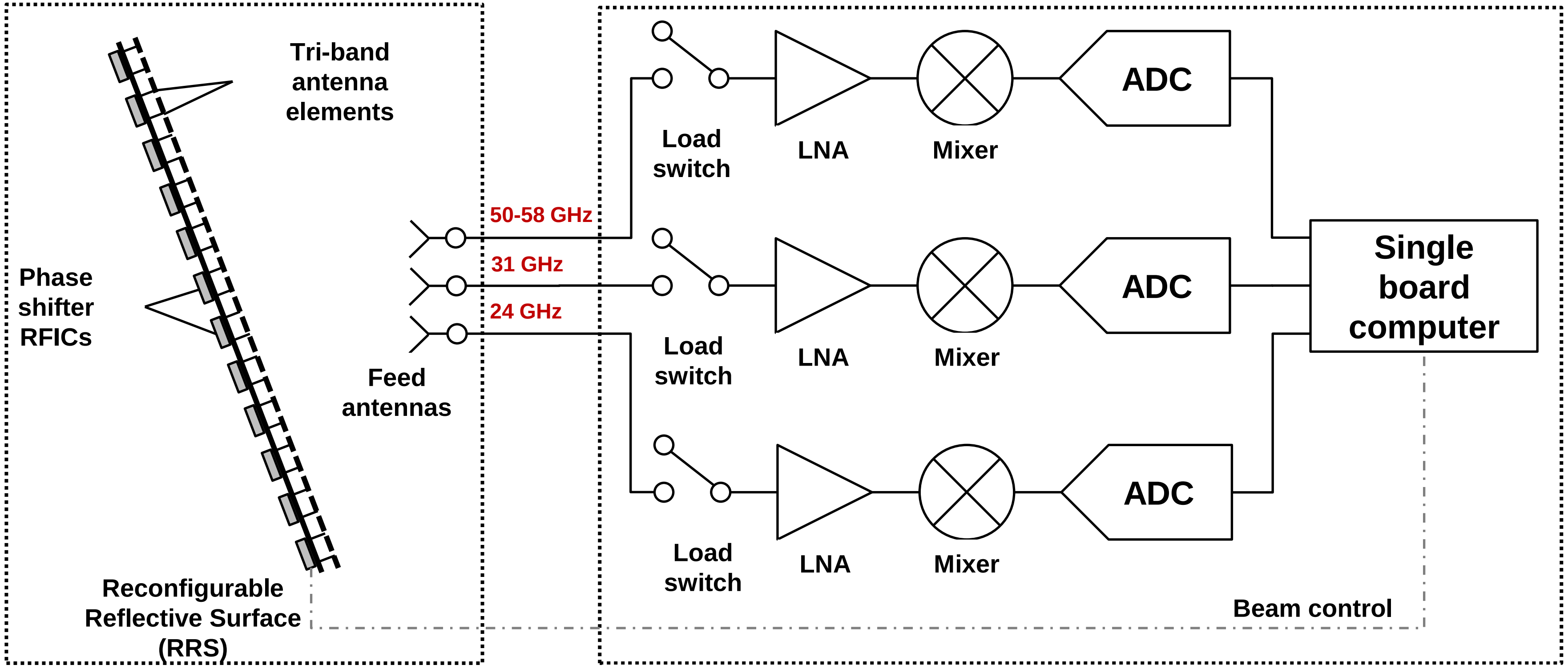
PT-CREWSR



Prototype Unit: PT-CREWSR Instrument

PT-CREWSR: 0.6m x 0.9m scanning reflectarray, brassboard radiometer, control, power supply, and interface electronics



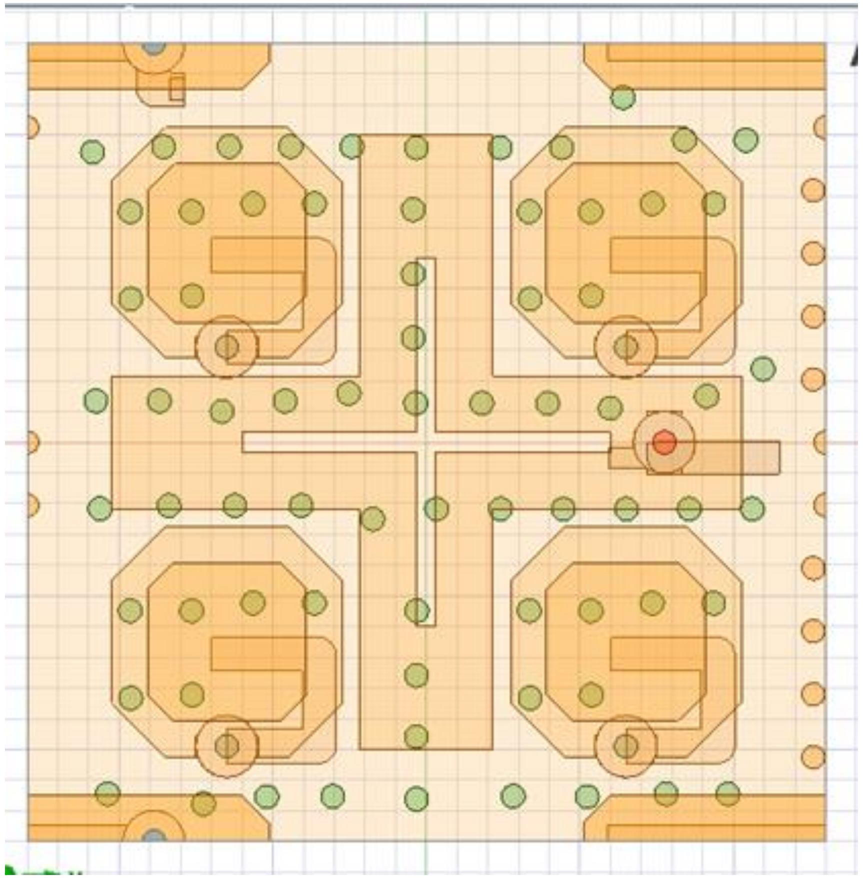


Scanning Reflectarray

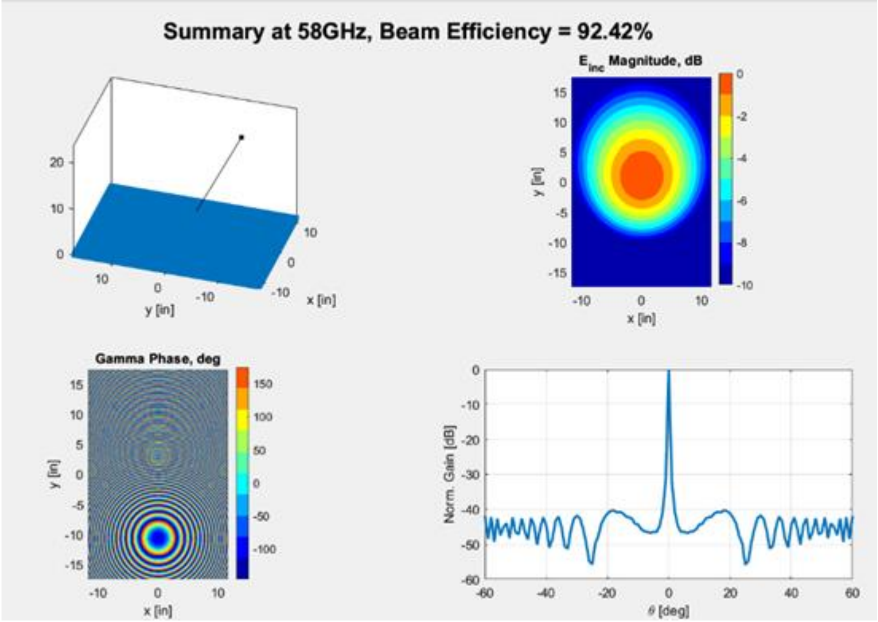
Electronically-calibrated radiometer

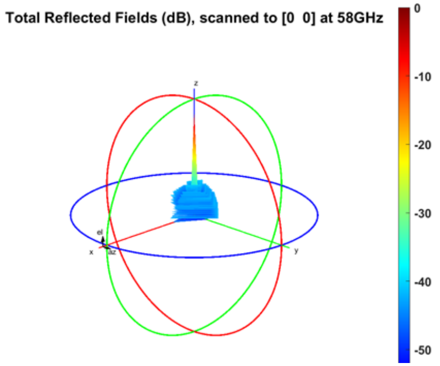
Antenna “Unit Cell”

Unit Cell Design



Unit Cell Reflection Performance



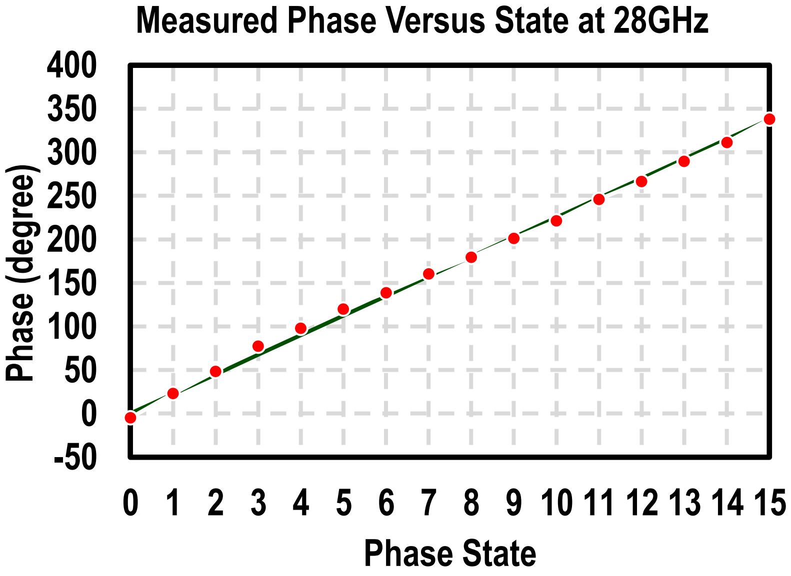


RFIC Measurements

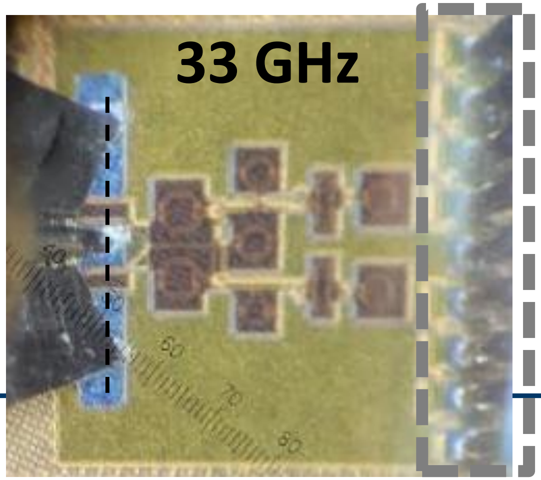
Developed by Univ. California, San Diego

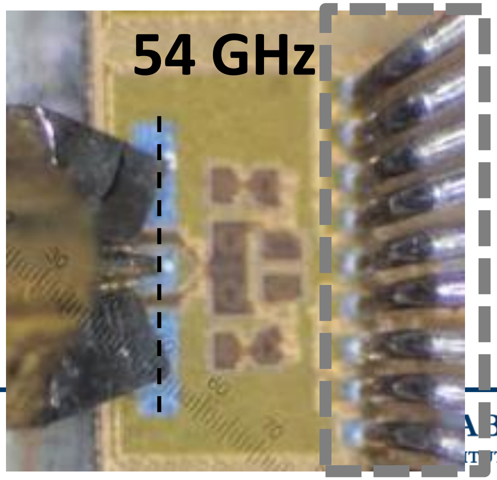
PNA-X (N5247A): 100MHz-67 GHz

Pout=-10 dBm



DC probing





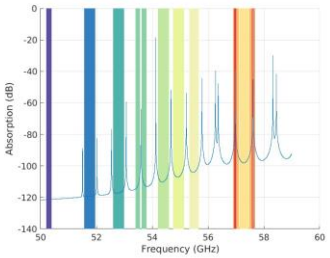
Summary of Progress (After Year 1 of 3): Key Performance Parameters

	Threshold	Objective	Current Status
Frequency bands	50-58 GHz	Low: 22-26GHz Mid: 31-35GHz High: 50-58GHz	23.6-24GHz 31.3-31.6GHz 50-58GHz
Beam Efficiency (co-polarized power within 2.5*HPBW)	90%	95%	Low: 83% Mid: 92% High: 90% (mean)
Aperture Size	0.3m x 0.3m	0.6m x 0.9m	Planned fabrication: 0.6m x 0.9m
DC power consumption per 6-channel RFIC	1.2mW	0.2mW	Mean: 1.2mW *
Phase shifter losses	4dB	3dB	RMS: 4-5dB *
Beam update rate	1 kHz	55 Hz	5 Hz (for system power estimates)

* Measured on first MPW (RF only)

CREWSR vs. State-of-the-Art (SOA)

- **CREWSR Advantages:**
  - Temporal efficiency (τ)
    - 25% "time on earth" = 6 dB / 2 = 3 dB
  - Spectral efficiency (B)
    - 3.188 / 8 = 4 dB / 2 = 2 dB



- **CREWSR Disadvantages:**
  - RFIC loss (T_{RCVR})
    - 4.0 dB
  - Antenna element loss (T_{RCVR})
    - 0.7 dB
  - Radiometer RF switch loss (T_{RCVR})
    - 0.7 dB

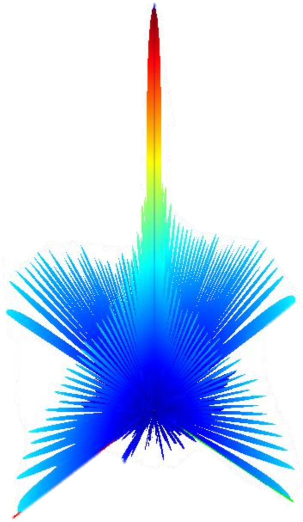
These "efficiency" and "loss" terms effectively cancel:
CREWSR will offer noise performance at least as good as SOA, but with much LARGER APERTURE and ELECTRICALLY STEERED BEAM

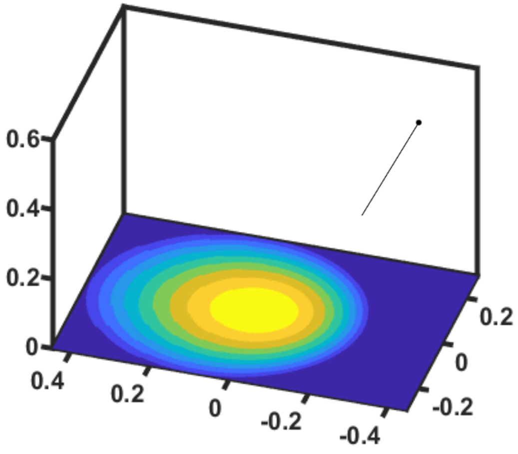
NEDT = $\frac{T_A + T_{RCVR}}{\sqrt{B\tau}}$

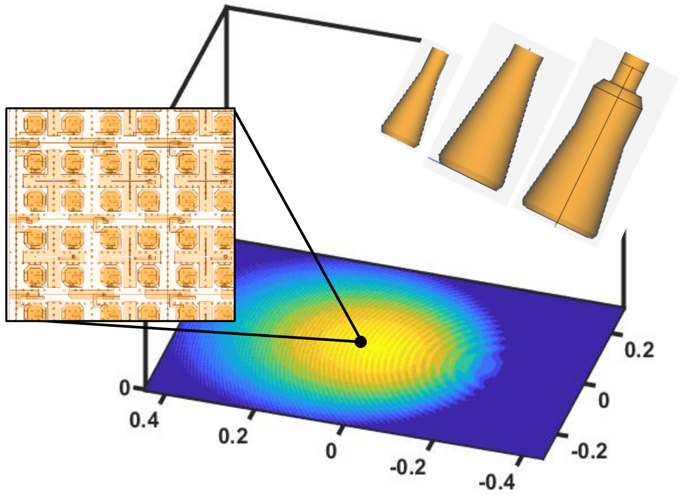
Summary of Array Simulation Results

Frequency Band	Directivity	HPBW	Beam Efficiency, Idealized	Beam Efficiency, Antenna Fields Modeled
Low (24GHz)	44 dBi	1.1˚	95%	83%
Mid (31GHz)	47 dBi	0.8˚	94%	92%
High (mean over 50-58GHz)	51 dBi	0.5˚	95%	90%

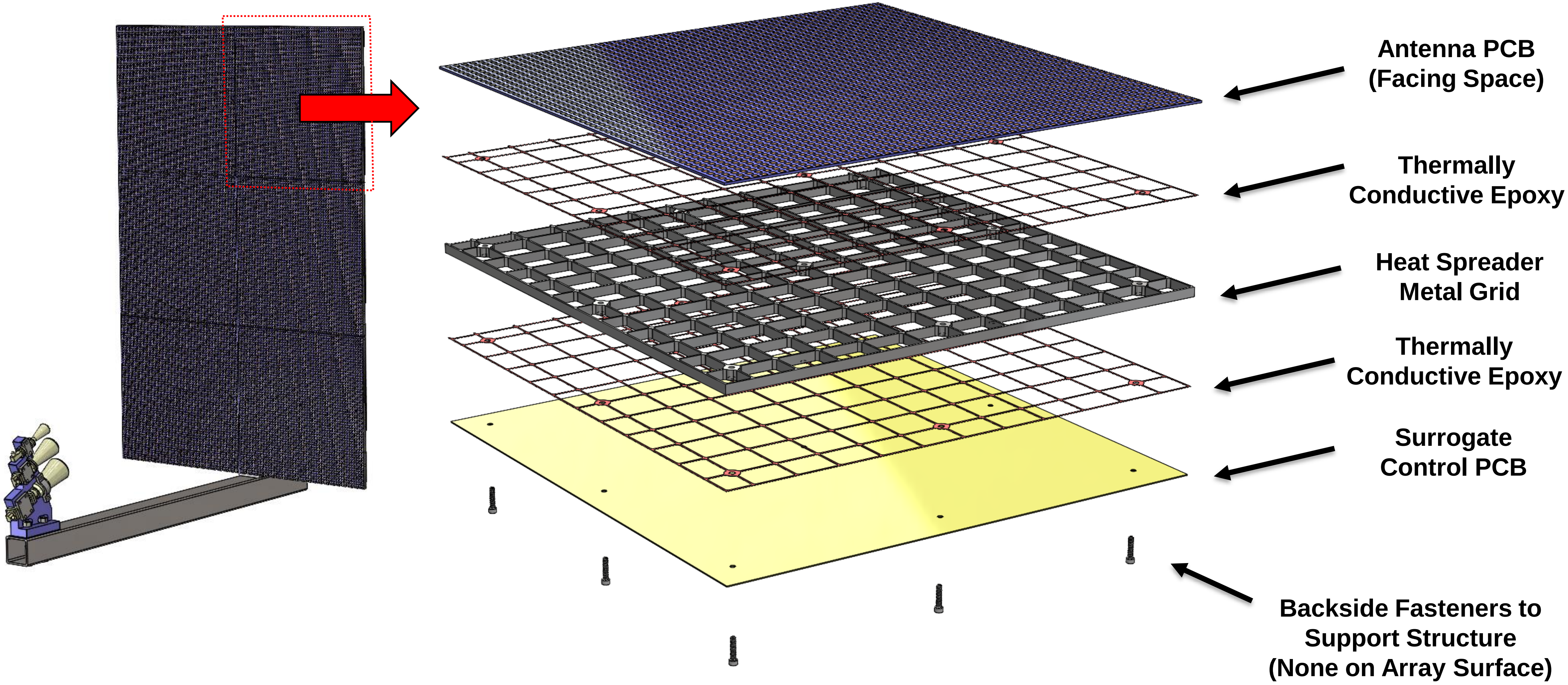
- **Idealized model: point sources for array, cos^{15} taper for feed horns**
- **Model with antenna fields: includes simulated fields for feed horns, phase and amplitude response for "infinite" array**





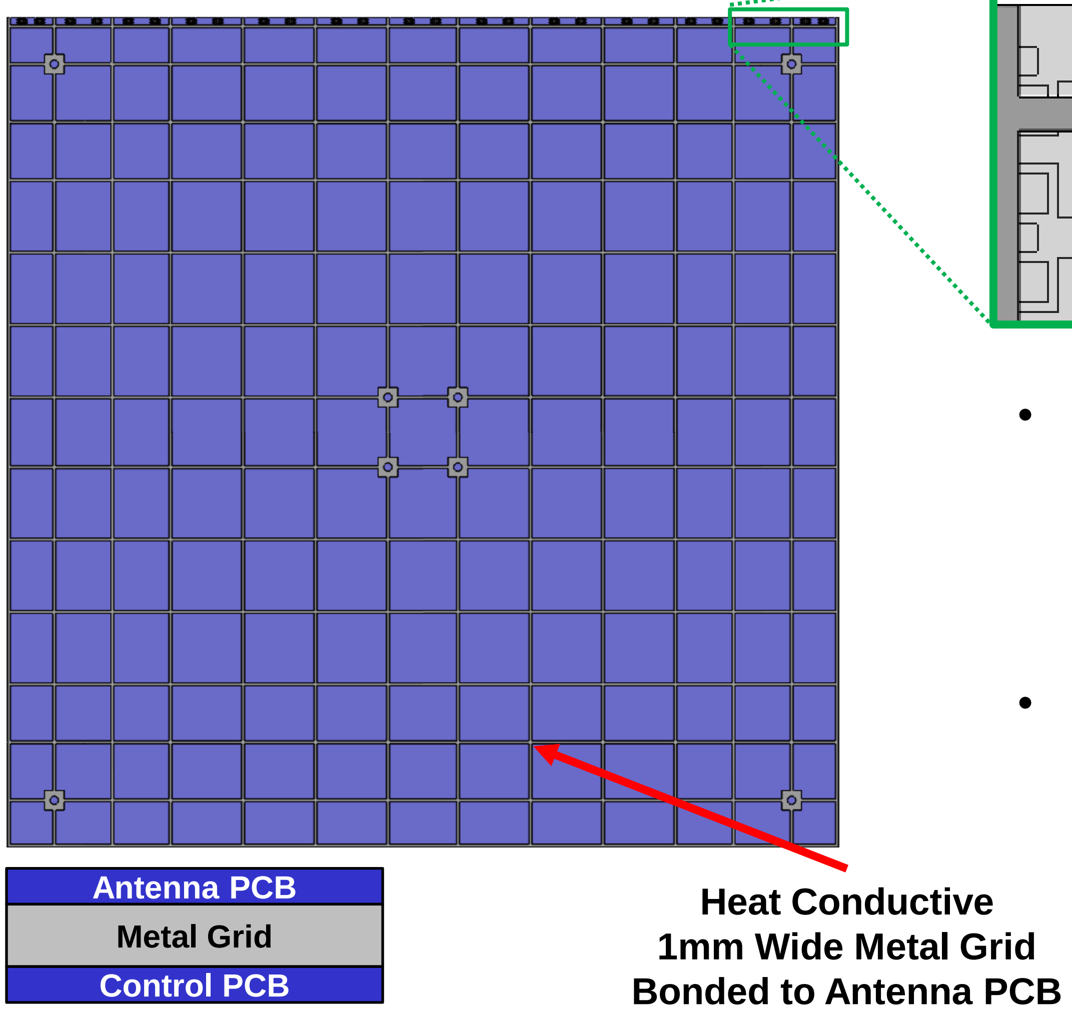


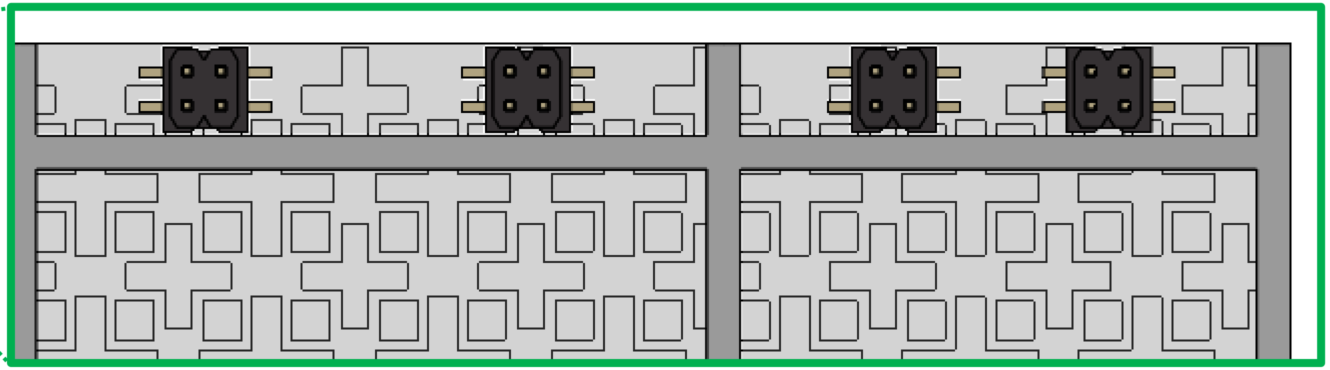
Exploded View of Fixed Beam CREWSR Subpanel



Structural-Thermal Grid Design

Antenna PCB Non-Radiating Side

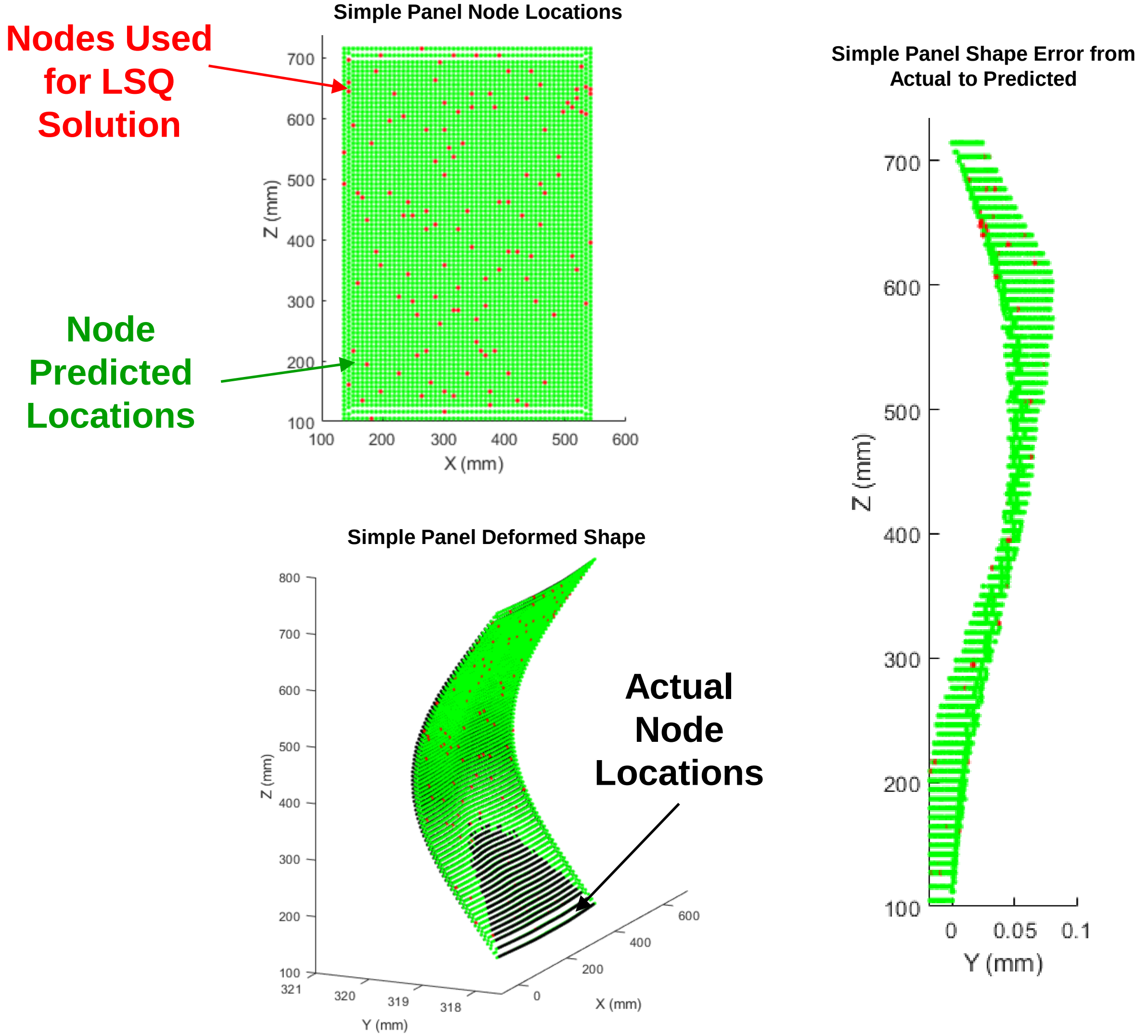




- **Antenna PCB and Control PCB connected across grid via pin headers**
  - **Using 2x2 SMT headers with 1mm spacing**
- **Headers located on one tile edge**
  - **Accessible after assembly for rework**
  - **Minimal impact on structural symmetry**
  - **Located to minimize line length impacts from antenna control electronics**

Deformation Monitoring for Calibration

- **Fiber Bragg Grating (FBG) strain sensors:**
  - **Past work shows promising results**
  - **Limited by 1 micro-strain minimum resolution**
    - **Borderline to detect 0.25mm RMS deformations**
    - **Shape prediction accuracy degradation**
  - **Temperature dependence**
    - **Investigating athermal mounting fixture**
  - **May require dozens to hundreds of sensors to achieve desired accuracy**
- **Can we use temperature instead?**
  - **Shape deformations on orbit are thermally driven.**
  - **Full field measurements possible with cameras**
  - **CTE deformation is linear**
    - **Superposition applies -> Valid for LSQ approach**
- **Other approaches to investigate**
  - **Combination of first two bullets**
  - **Regression techniques**



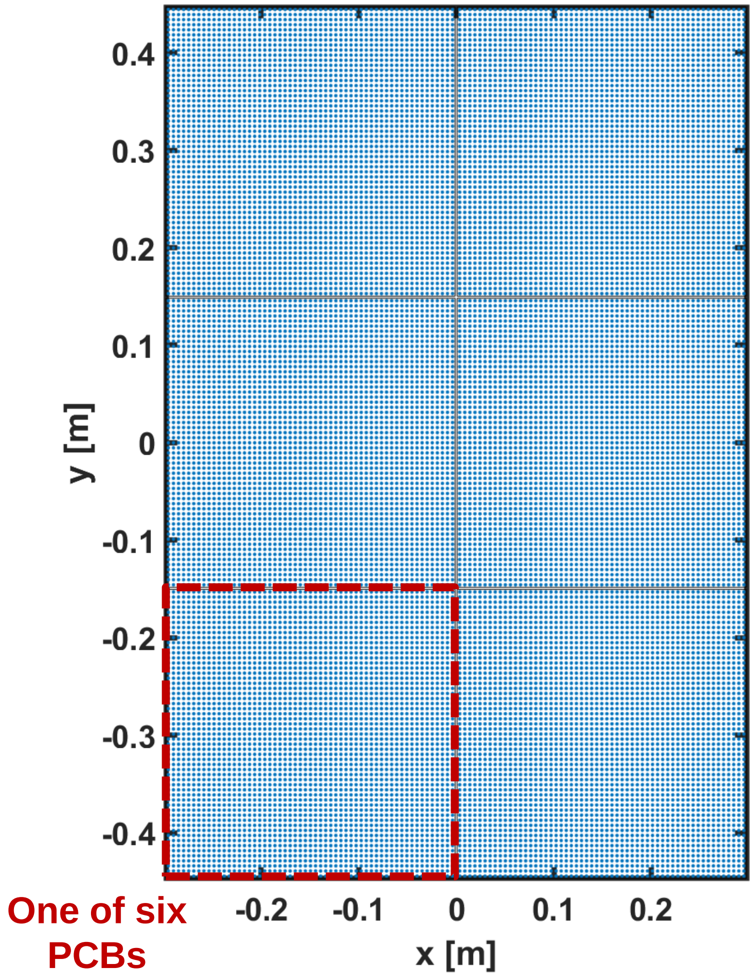
Fixed Beam Array Antenna Development

Current Status

- Updated stackup to reduce complexity and cost
- Preliminary PCB layout complete
  - 6 boards + backups
  - Risk reduction: fabricate a single board and test on frame to verify expected pattern
- Simulated performance using Ansys HFSS + Circuit
- Evaluation of expected levels of beam efficiency using antenna model

Next Steps

- Design review of antenna to move forward with fabrication
- Finalize layout/oversee fabrication
- Update test plan



Summary

- **TROPICS will provide the first high-revisit microwave observations of precipitation, temperature, and humidity**
  – **Pathfinder Mission (one CubeSat) launched in June 2021 EXCELLENT DATA!!**
  – **Constellation Mission (four Cubesats) launched in 2023   EXCELLENT DATA!!**
  – **Tomorrow.io will launch a TROPICS follow-on constellation**
- **CREWSR will provide fully configurable microwave sensing with large aperture from a small satellite platform**

Backup Material