The Tomorrow.io Weather Constellation: Status and Early On-Orbit Results

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International Precipitation Working Group

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Overview

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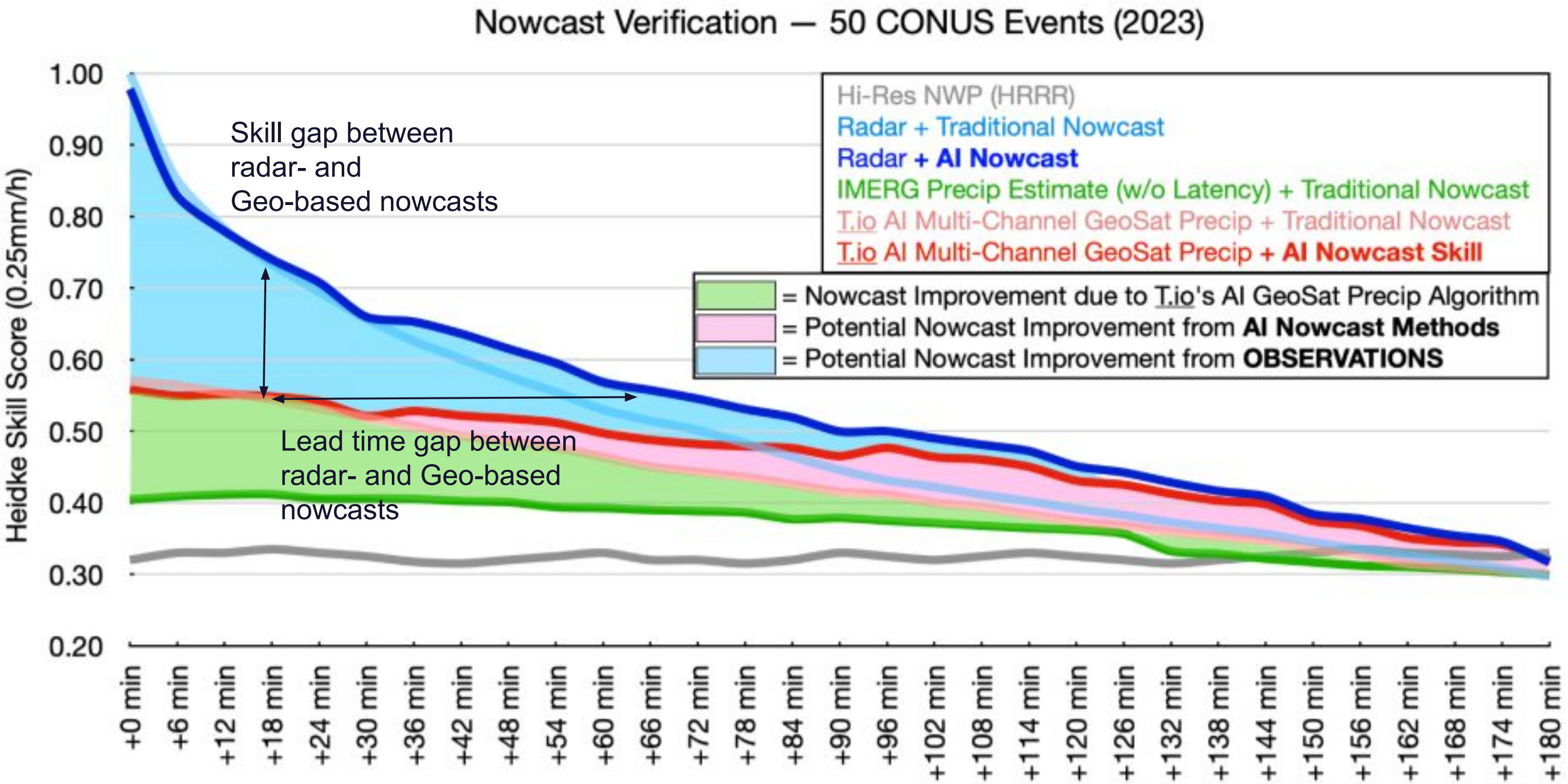
Enabling Accurate Global Precipitation Nowcasts and Improved Medium-Range Weather Forecasts

The global radar gap

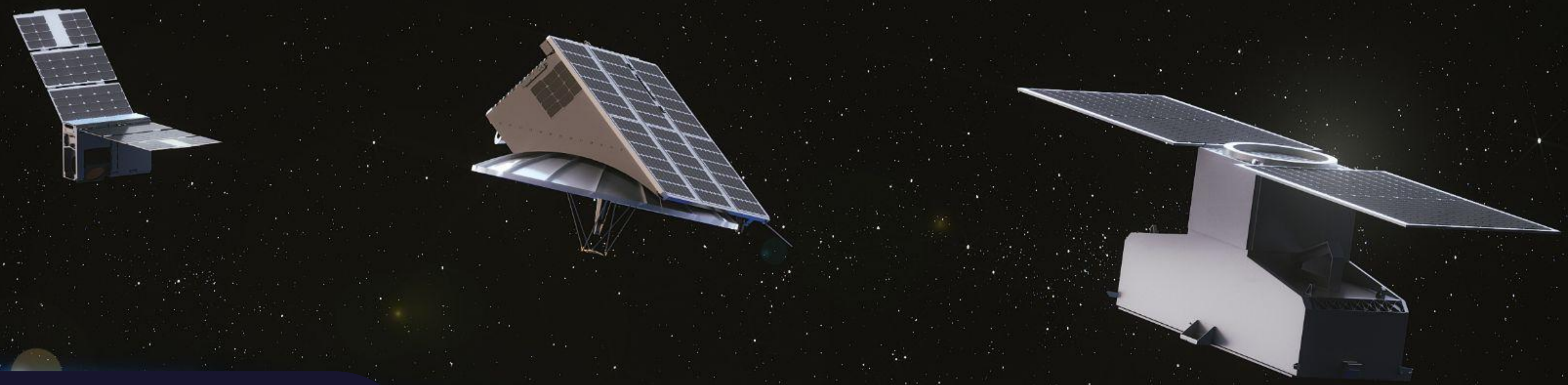
- IMERG (IR + PMW – PDIR algorithm) has been the standard for Satellite Precip Estimation, but has substantially lower skill than radar (and w/ >3h latency).



Most of the globe does not have radar, and precipitation nowcasting is fundamentally different/less skillful in these regions.

- New satellite observations are essential to improve traditional and ML precipitation nowcasting at global scales.
- Tomorrow.io sounder/radar constellation is expected to fill much of the skill/lead time gap between ground radar- and Geo satellite-based precipitation nowcasts worldwide.
- Global, rapid-revisit microwave sounder and scanning radar observations will have a positive impact on medium-range NWP (Ryan Honeyager’s talk)

Meet the Tomorrow.io Satellite Constellation



Tomorrow.io's constellation of 30 small satellites will provide:

- Full Global Coverage
- <1 hour average revisit rate
- World's first near real-time precipitation measurements and 3D atmospheric profiles
- Dramatic improvement in real-time weather forecasts, tropical cyclone warnings and flood alerts

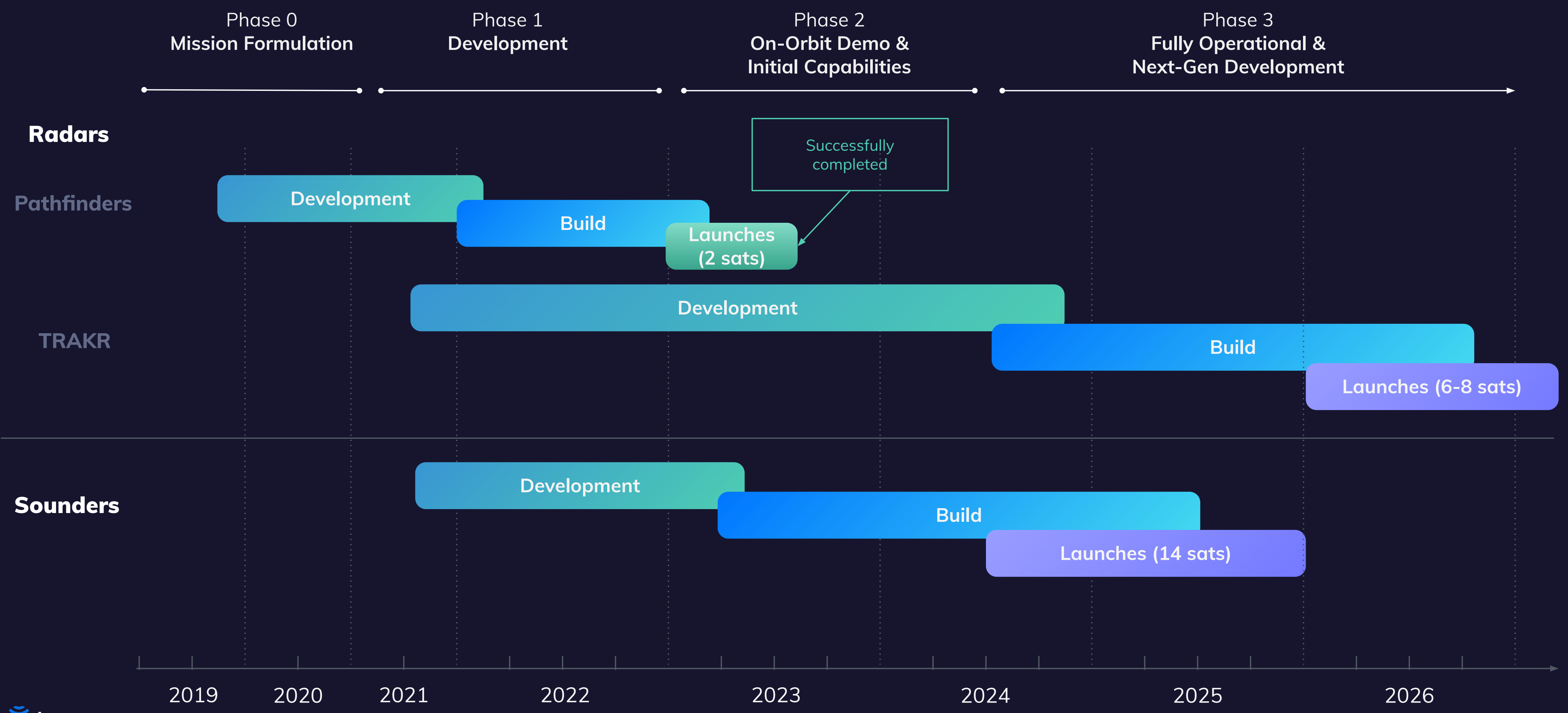
Hybrid constellation of 26 small satellites in Low Earth Orbit

- 8 Ka-band radars
- 18 MW radiometers

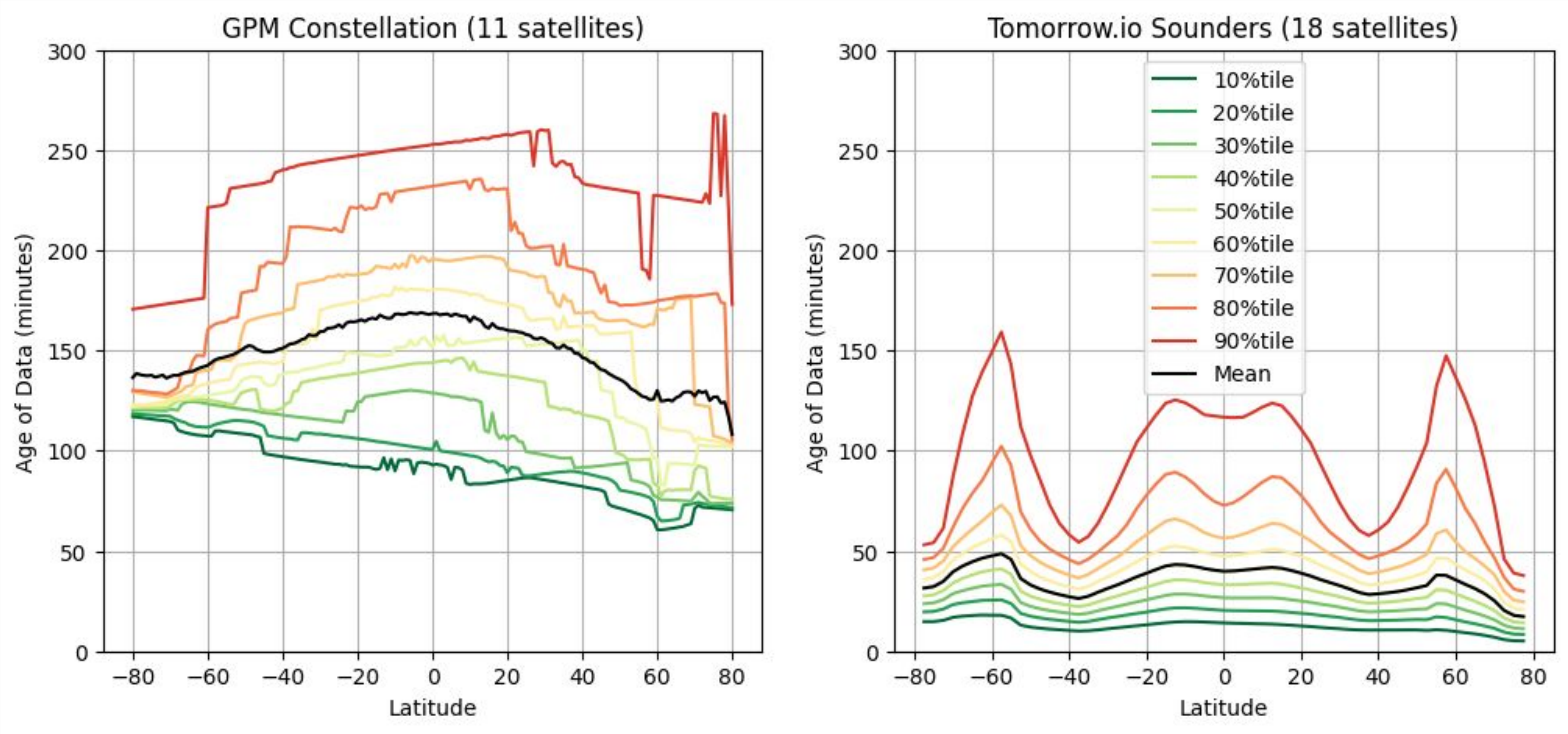
Timeline:

- Launches began in Q2/23
- Constellation fully operational by EOY 2026

Development & Launch Timeline



The TMS constellation will vastly improve upon the program of record's revisit, latency, and age-of-data:



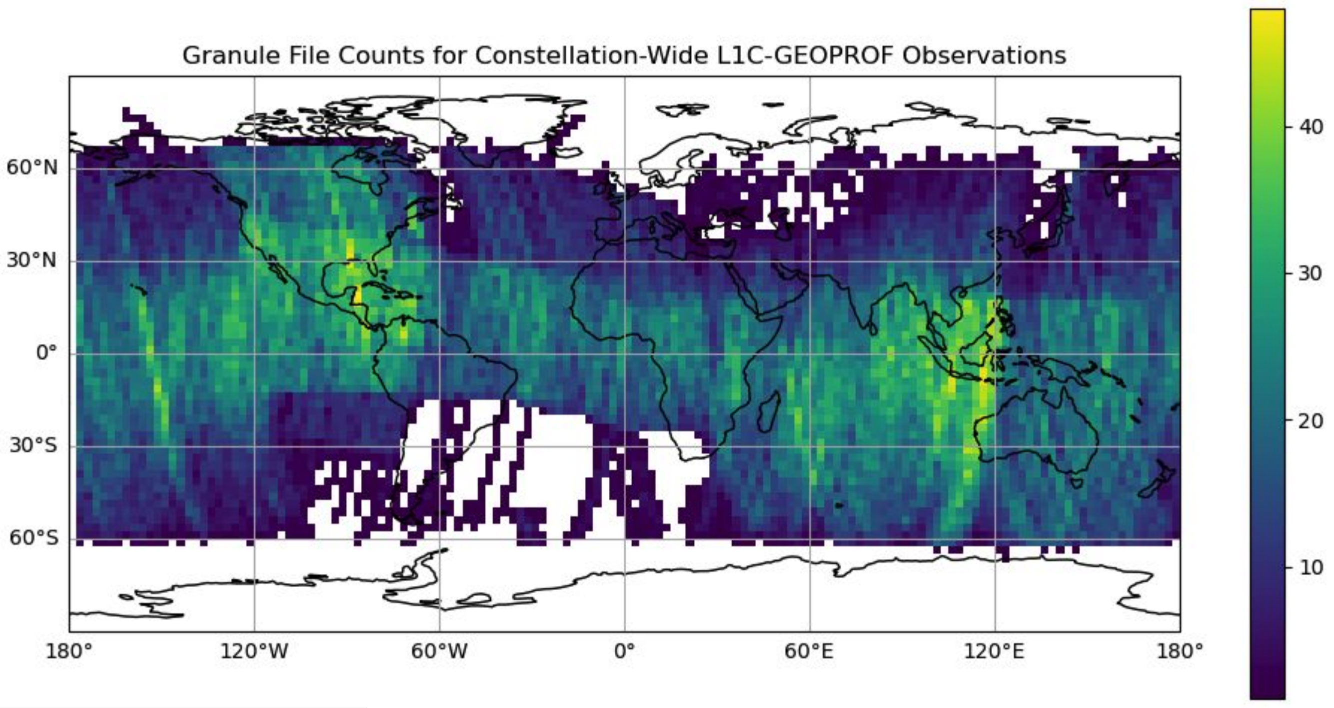
Age of data (age of most recent observation available in real-time) by latitude for 11 PMW sensors in current GPM constellation (3xATMS, 3xMHS, 3xSSMIS, GMI, AMSR2). Age of data depends on revisit rate and latency. 10th-90th percentiles and mean are shown.

Age of data for the full Tomorrow.io sounder constellation (18 satellites). Mix of SSO and 45-degree inclined orbits. 10th-90th percentiles and mean are shown.

Pathfinder Radar Program Update

Tomorrow.io Radar Pathfinder Program Status

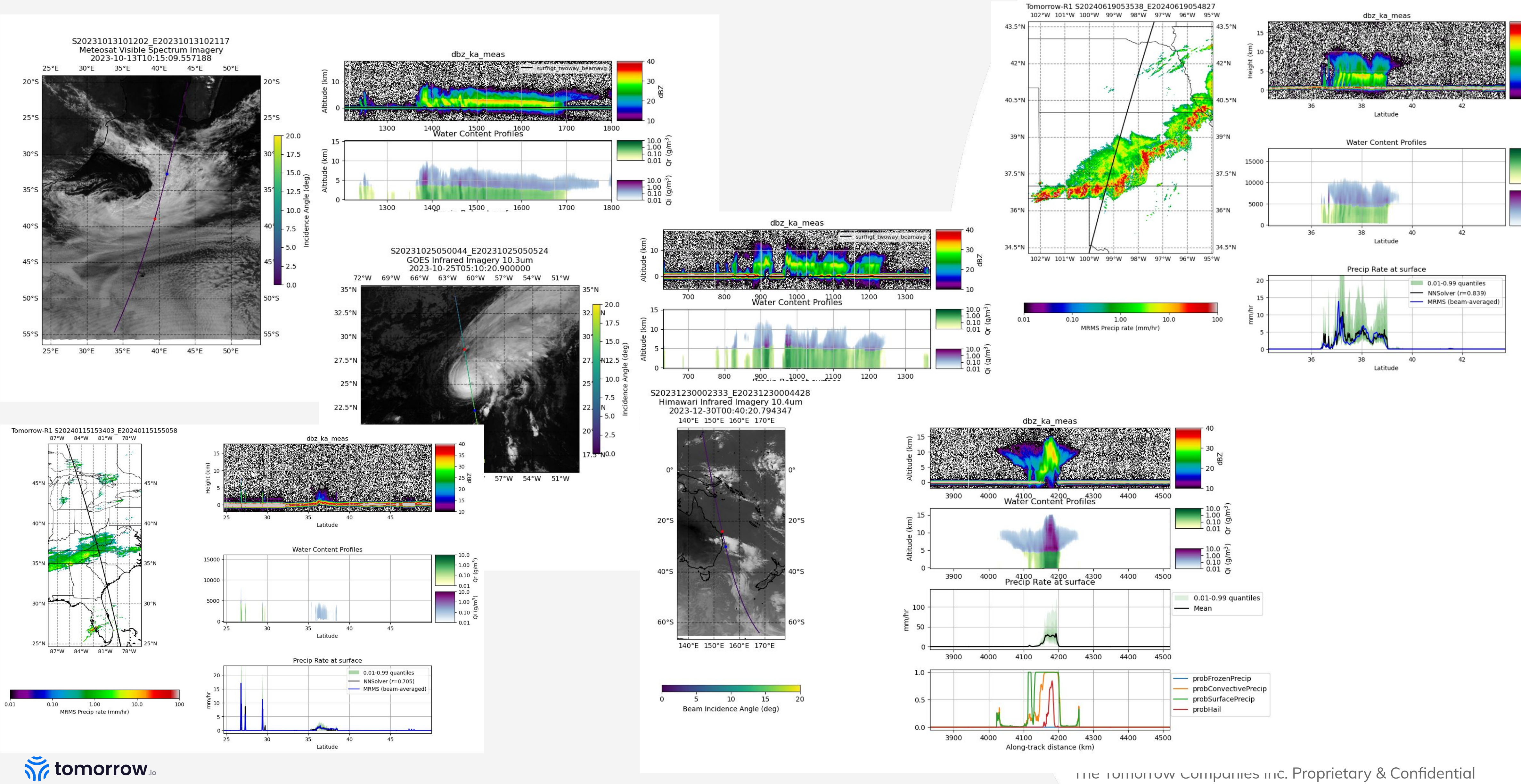
Pathfinder (Tomorrow-R1/R2):
Reflector-based Ka-band PR
TR1 Launch: SpaceX Transporter-7, April 14, 2023
TR2 Launch: SpaceX Transporter-8, June 12, 2023



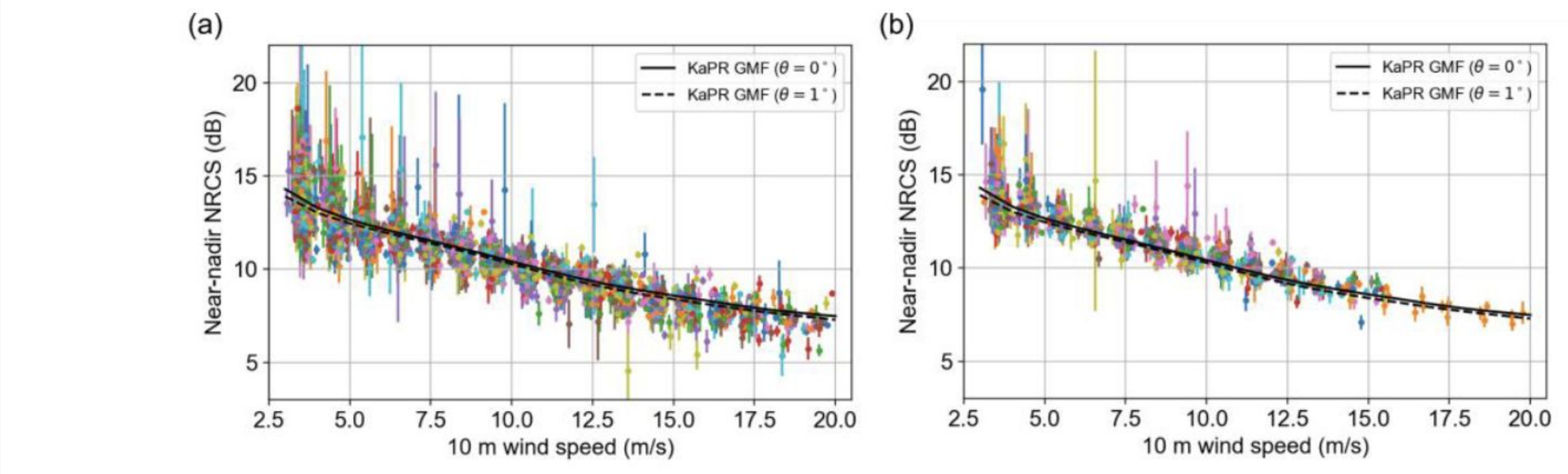
Key Parameters/Objectives:

- Deploy ARENA® SDR in space for the first time
- Acquire precipitation and ocean scattering measurements across 40° swath for operational algorithm development
- Validate radar calibration methods and precipitation retrieval accuracy

Tomorrow.io Radar Pathfinder Highlights



Tomorrow.io Radar Pathfinder Validation

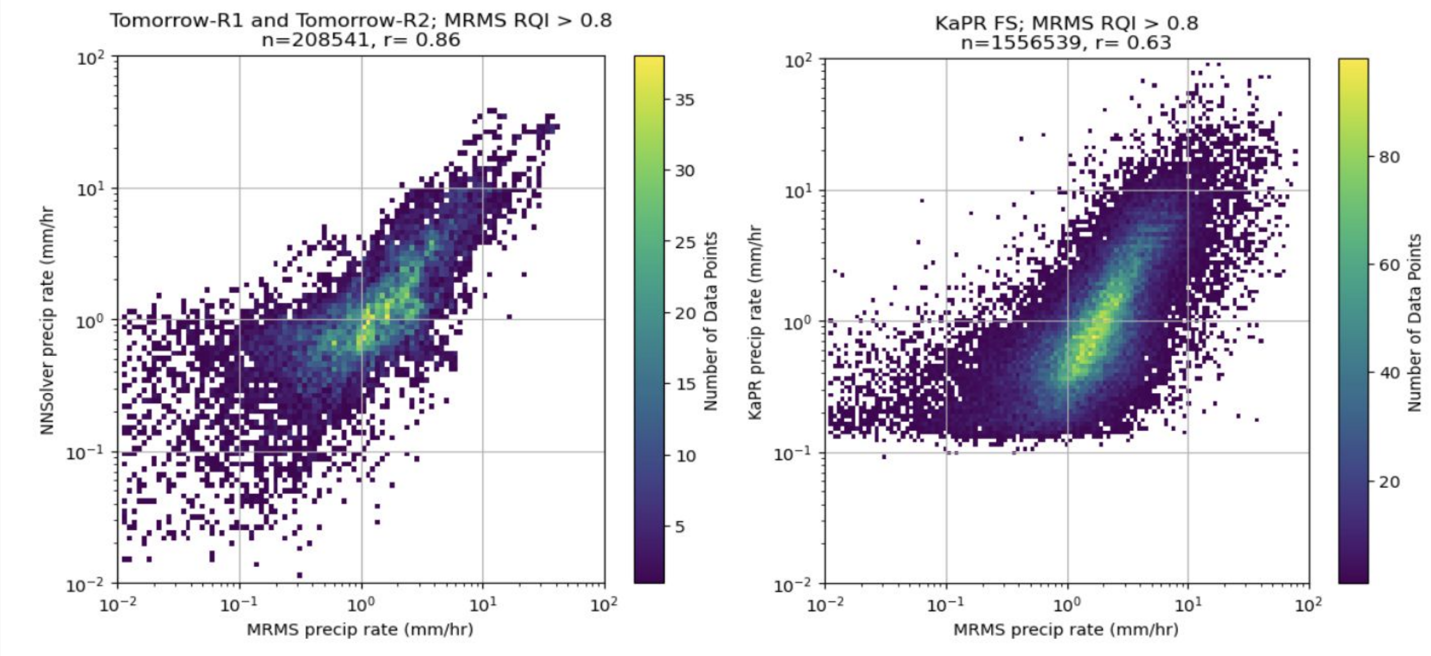


L1C-GEOPROF

Comparison of Tomorrow-R1 ocean NRCS versus wind speed with KaPR GMF prediction using NWP model winds and accounting for attenuation. Observations are restricted to clear sky and near-nadir incidence. ***Overall bias versus KaPR is -0.4 dB.*** *(b)* ***Same for Tomorrow-R2, with overall bias of <0.1 dB.***

L2A-PRECIP

(Left) Scatter density diagram of Tomorrow-R1 and -R2 surface precipitation rate against NOAA MRMS matched to the R1 and R2 beam patterns. Data are from August 2023-March 2024. (Right) Same analysis for the GPM KaPR product during October 2023.



Microwave Sounder Program Update

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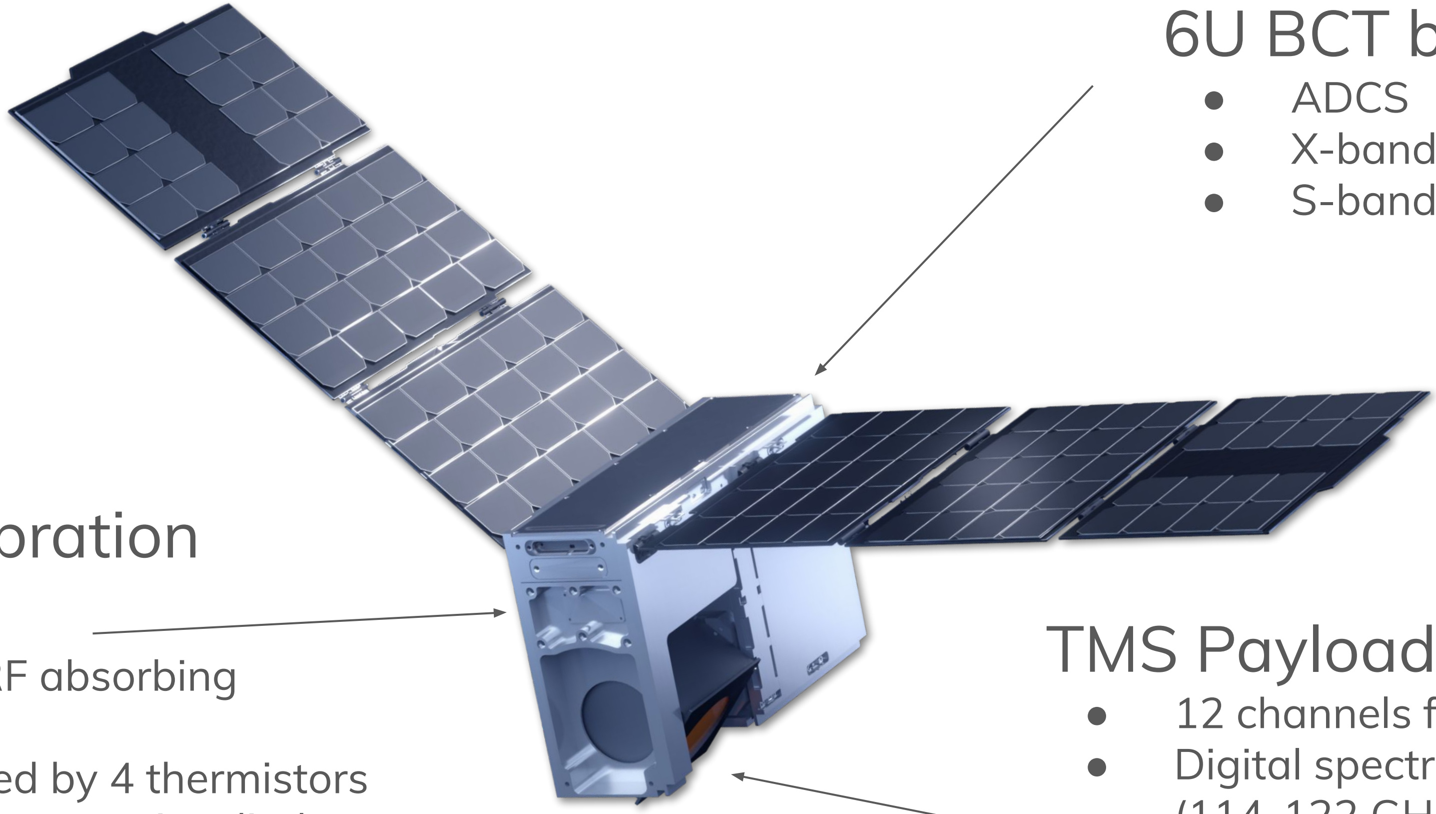
Tomorrow.io Microwave Sounder: Bus and Payload



6U BCT bus

- ADCS
- X-band downlink
- S-band uplink

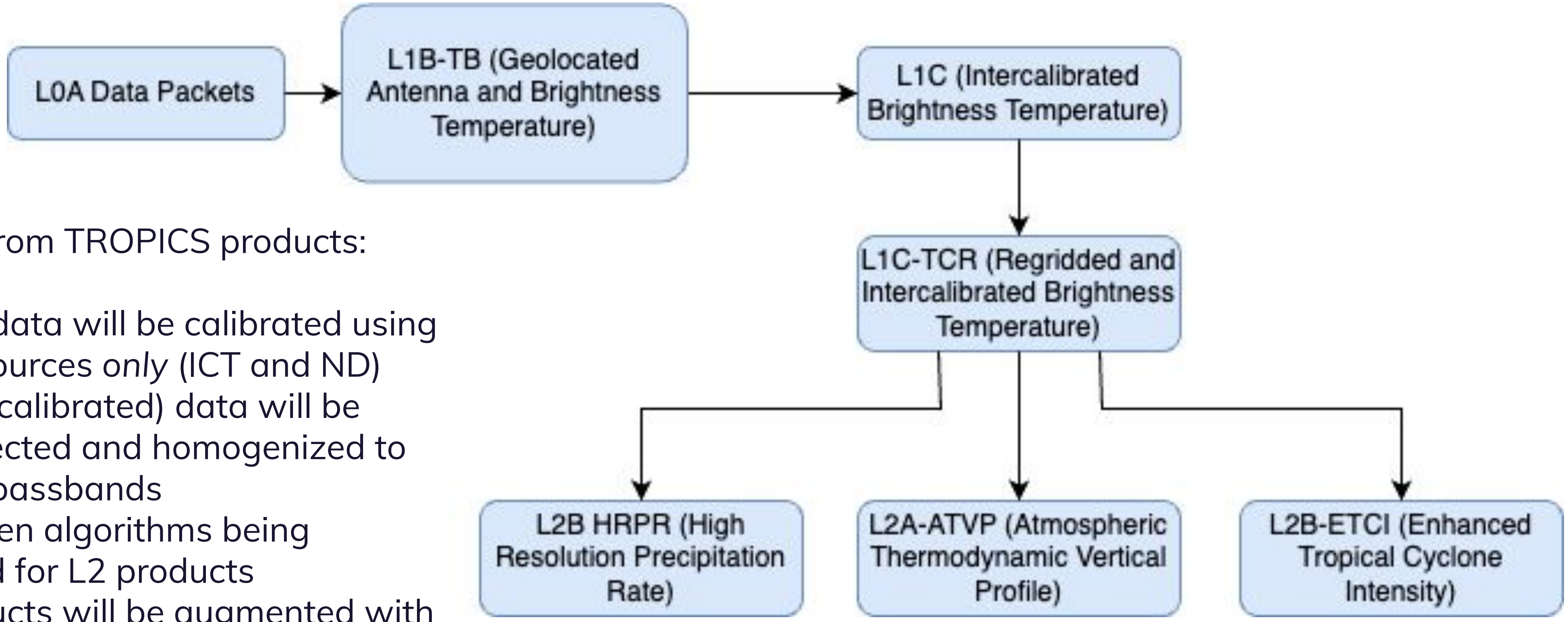
Internal Calibration Target (ICT)

- Pyramidal RF absorbing material
- Characterized by 4 thermistors
- Will complement noise diodes and characterize noise diode drift

TMS Payload

- 12 channels from 91-204 GHz
- Digital spectrometer for 7 F-band channels (114-122 GHz)
- Direct detect W-band and G-band channels
- Detectors rotate with antenna, giving constant polarization angle

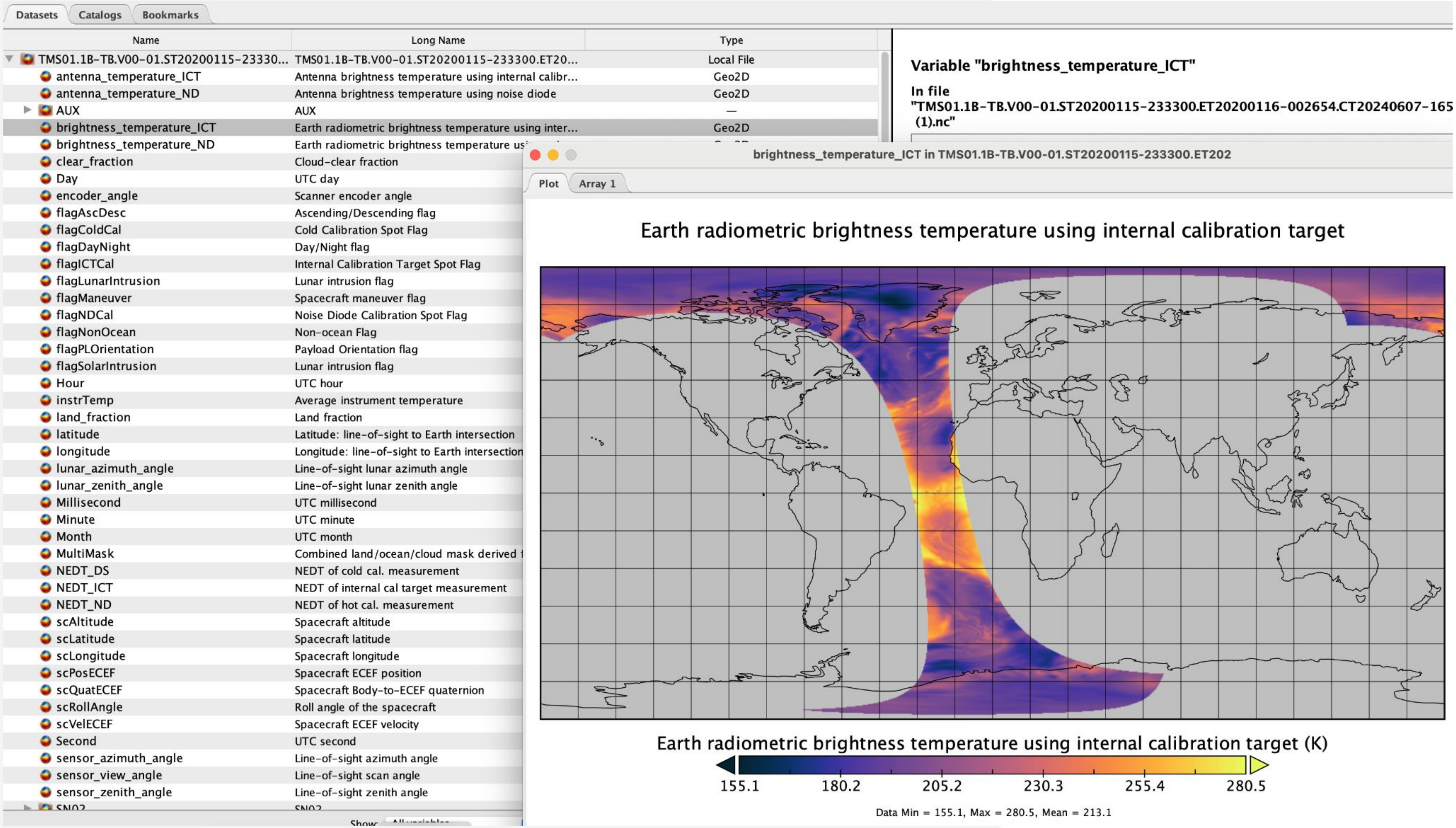
TMS Products



Some changes from TROPICS products:

- L1A/L1B data will be calibrated using internal sources *only* (ICT and ND)
- L1C (intercalibrated) data will be bias-corrected and homogenized to common passbands
- Data-driven algorithms being developed for L2 products
- L2B products will be augmented with geostationary Vis/IR data

Sample L1B product (simulation from DYAMONDv2 nature run)



Unified Precipitation Developments

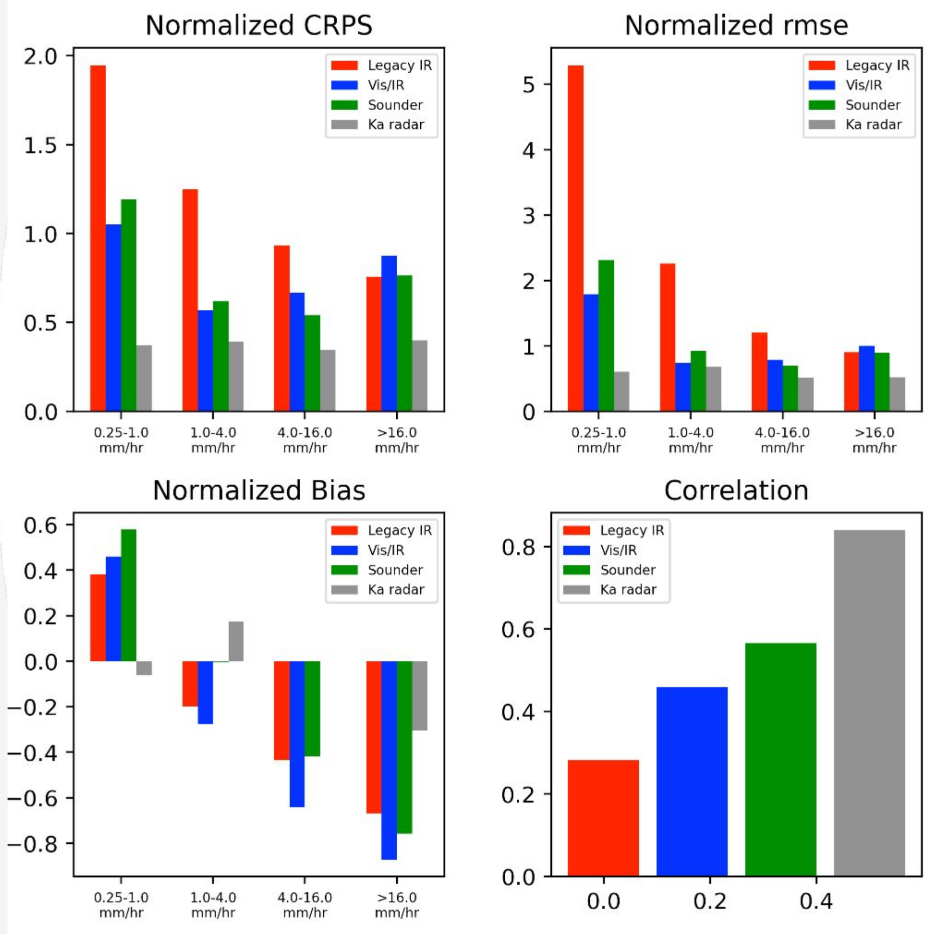
Tomorrow.io Approach to multi-sensor synthesis: Unified Precipitation

Tomorrow.io aims to deliver a seamless global real-time precipitation analysis and Nowcast (rapid-refresh 0-3 hr forecast driven by initial conditions) by blending all available sources (ground radar, spaceborne radar, geostationary imagers, and passive microwave sensors).

This poses many of the same challenges faced by developers of IMERG and other multi-satellite precipitation products:

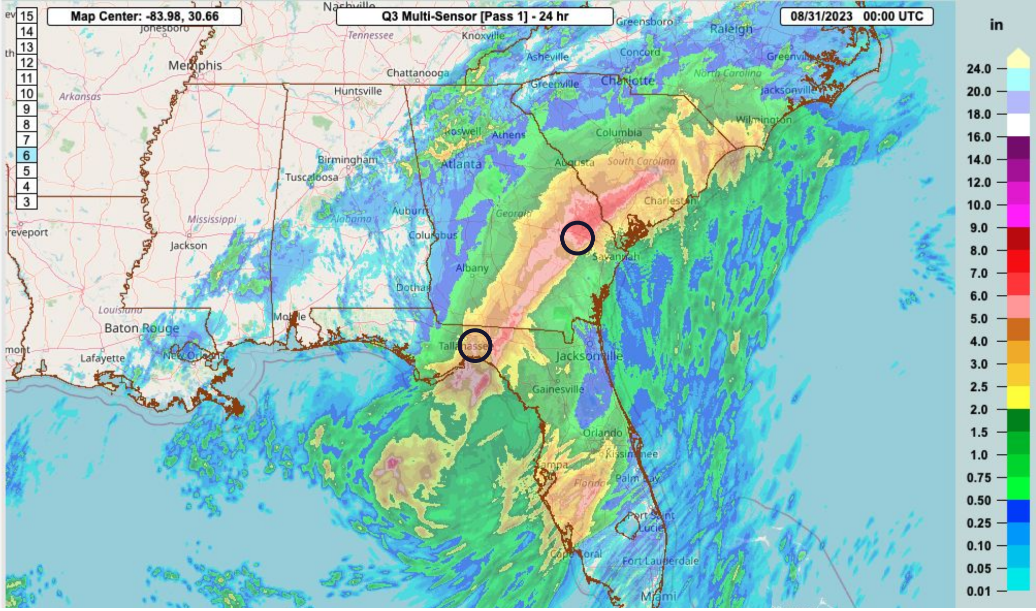
- Observations with low information content (IR) are spatiotemporally dense
- Observations with high information content (PMW and radar) are spatiotemporally sparse

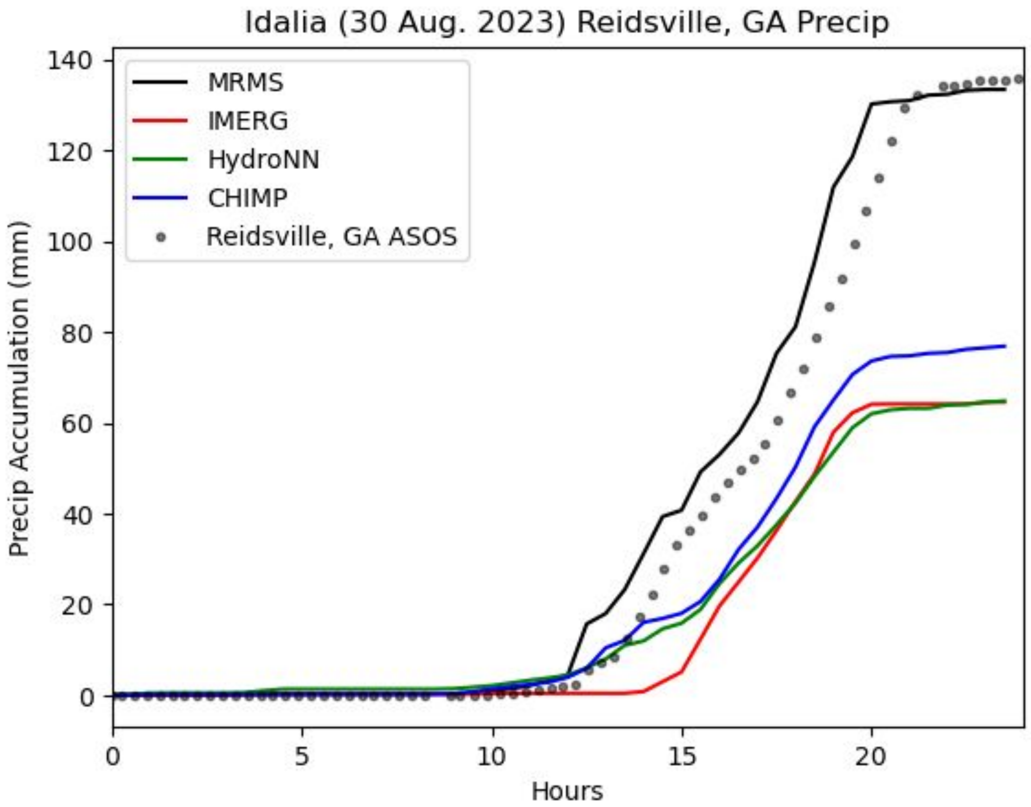
A machine learning framework, CHIMP (the Chalmers/CSU Integrated Multi-Satellite Retrieval Platform), can accommodate input with these characteristics.

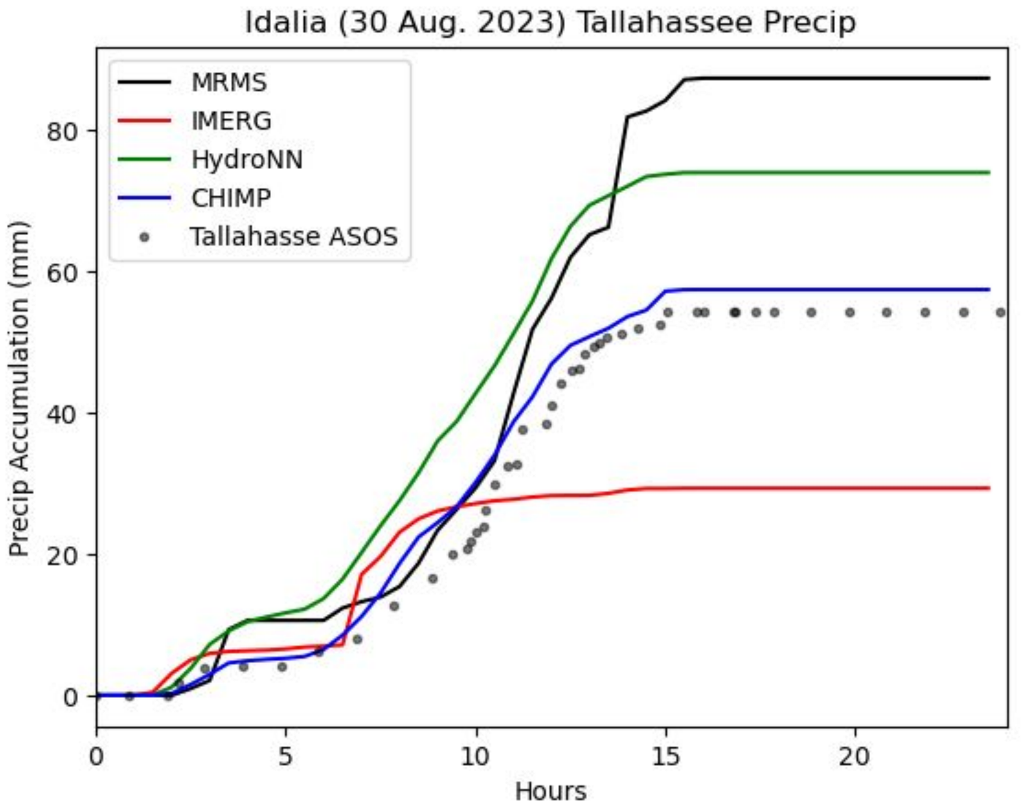


Hurricane Idalia - Gauge Verification

- CHIMP estimates Timing/Magnitude better than other satellite products
- NASA IMERG-Early Calibrated Precip is a poor estimate
- CHIMP is a significant advancement over the HydroNN system that Tomorrow.io currently runs

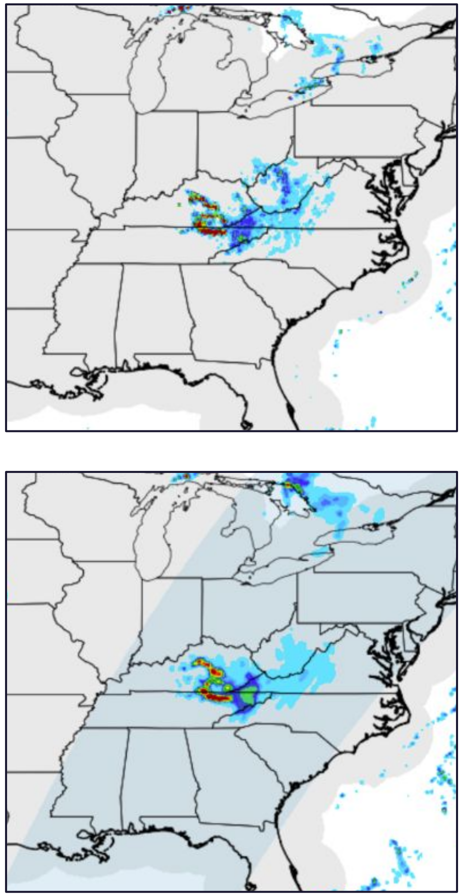






Impact of Incorporating Passive Microwave Sensors

GMI

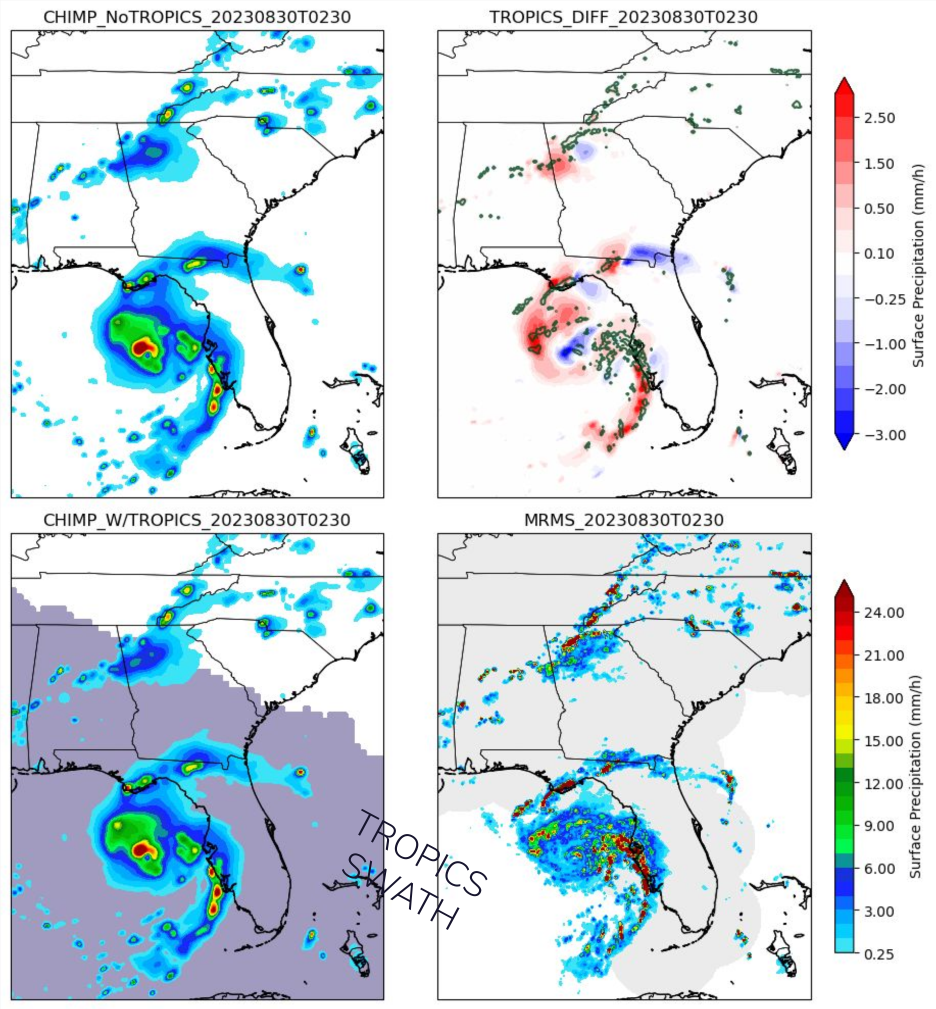


UP: Satellite Precip w/ Sounders

30 June 2023 Validation w/ GPM CMB	Heidke Skill Score 0.25 mm/h	Heidke Skill Score 12 mm/h
Current	0.56	0.16
Next-Gen Geo-Only	0.67	0.36
Next-Gen + Sounders	0.72	0.65

An example case demonstrates the potential improvement of the next-generation UP satellite precipitation retrieval model from incorporating orbiting microwave sounders (e.g., GMI, TROPICS). ***Nowcast impact will only be positive if the data can be obtained with latency < 1 hr.***

TROPICS



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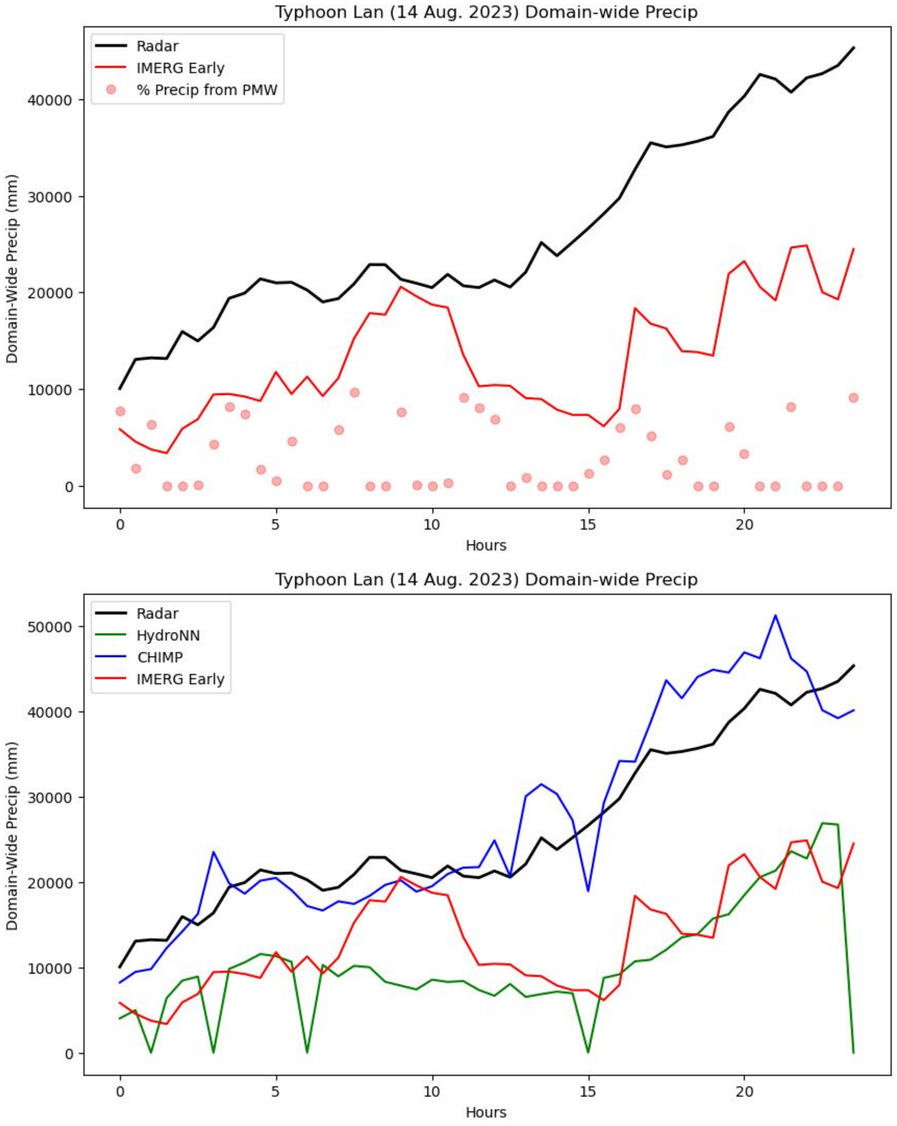
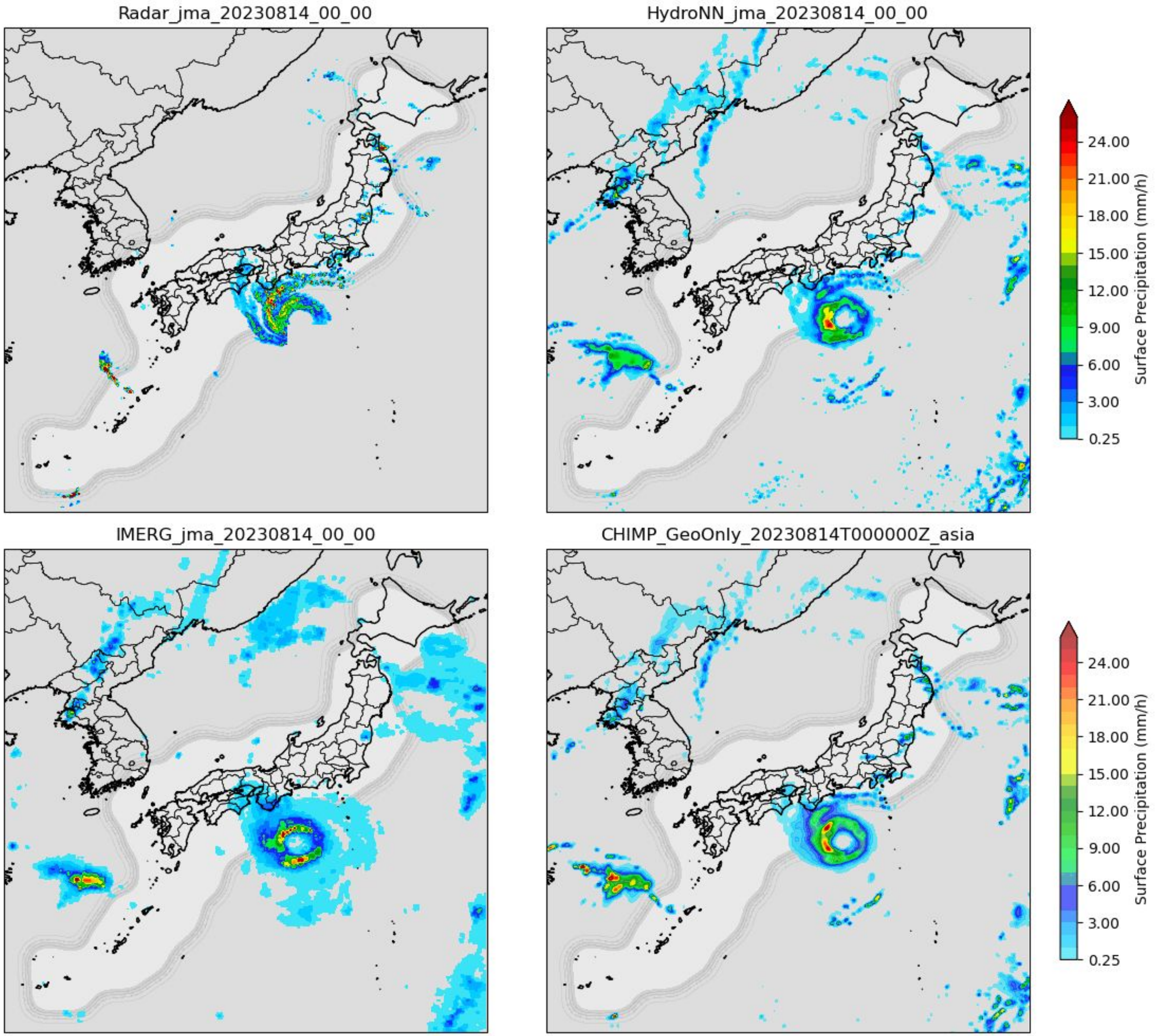
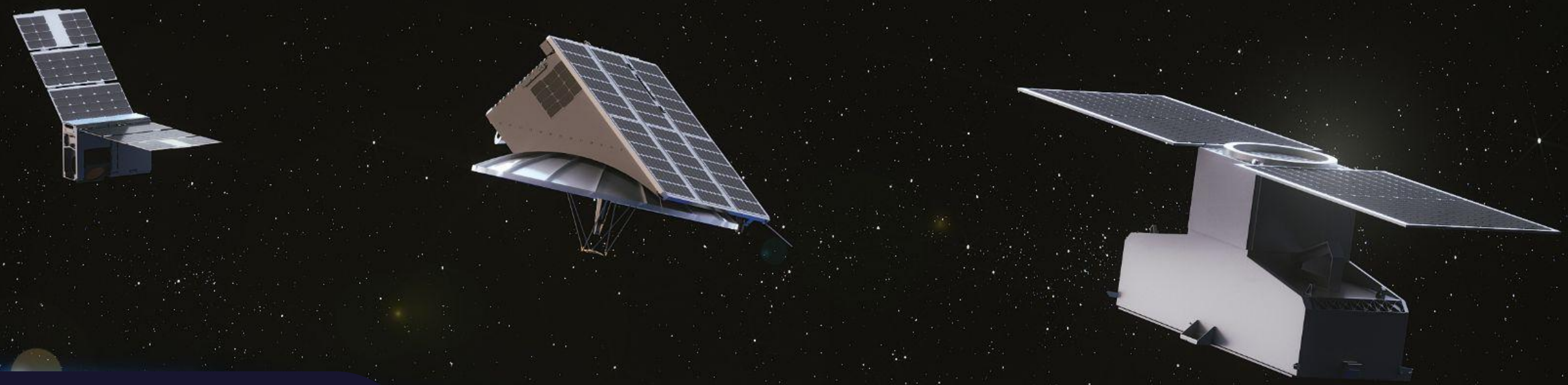
14 Aug. 2023 - Typhoon Lan (Japan)

- Global Satellite Product Verification
- TROPICS Impact





Summary



Tomorrow.io Radar Pathfinder program continues to collect data after more than one year on orbit

- Passive configuration recently implemented
- Just-in-time tasking targets tropical cyclones, buoys (for surface characteritzation), and other precipitation targets of interest
- L2 validation showcases capability of Ka-only radar for precipitation monitoring

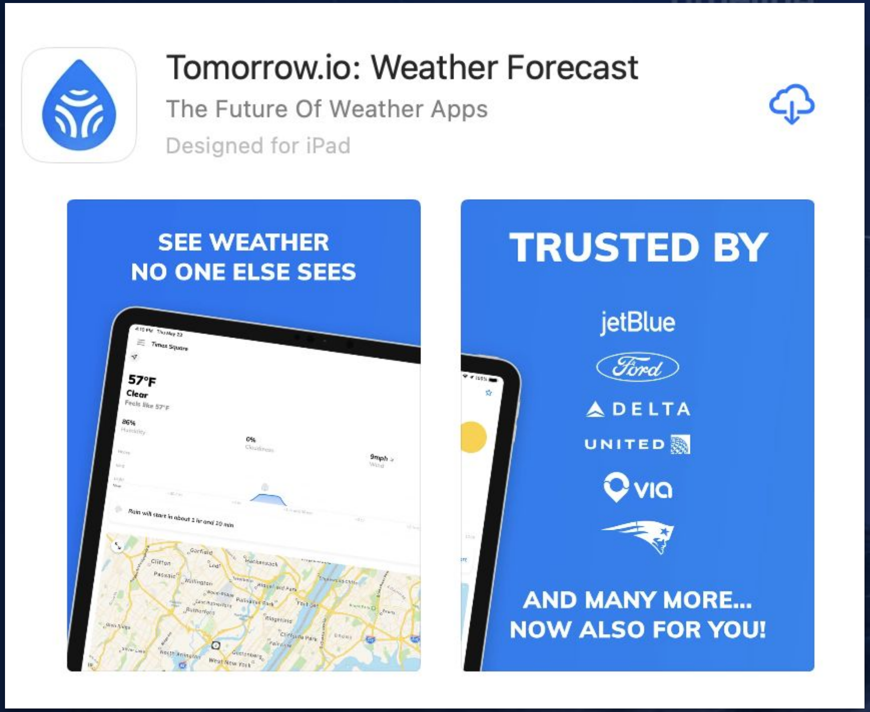
Microwave sounder constellation will be coming online over the next year

- 18 payloads being built, launches scheduled through 2025
- Improvements and lessons learned from TROPICS incorporated into design

Improvements coming to real-time and nowcast precipitation

- Testing ML analysis/nowcast shows improvements over IMERG
- WIll begin incorporating near-real-time inputs by EOY 2024

Thank you!



Questions?

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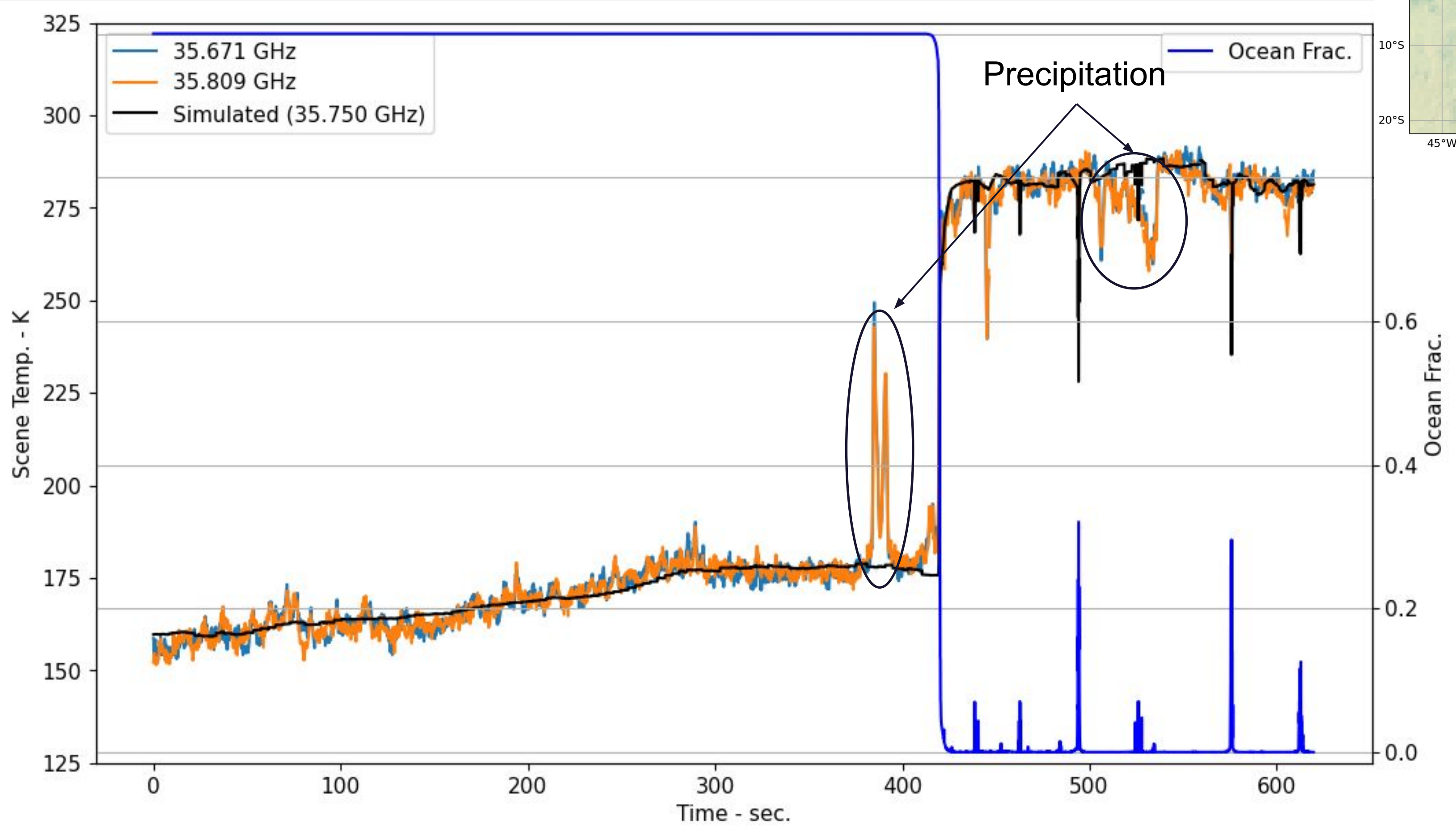
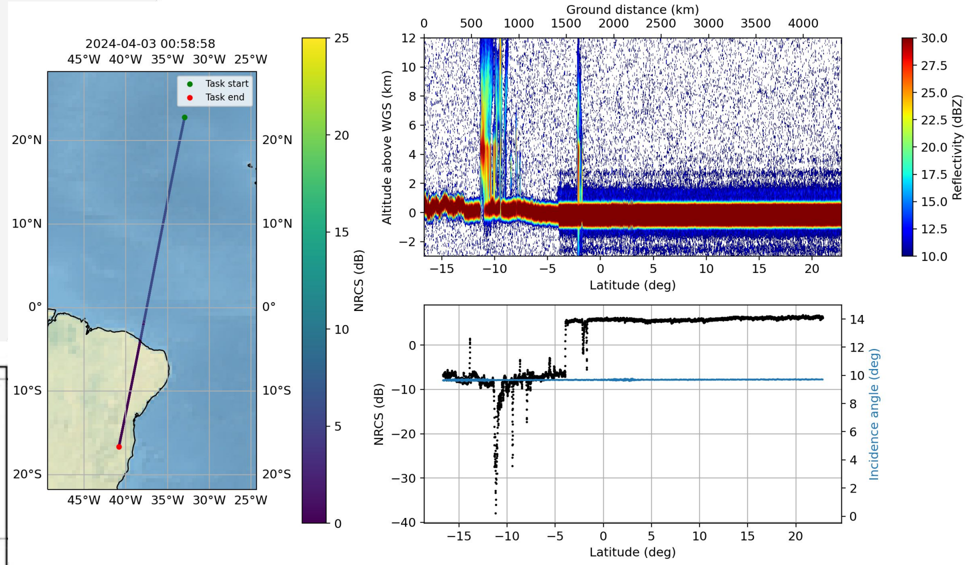
Supplemental Slides

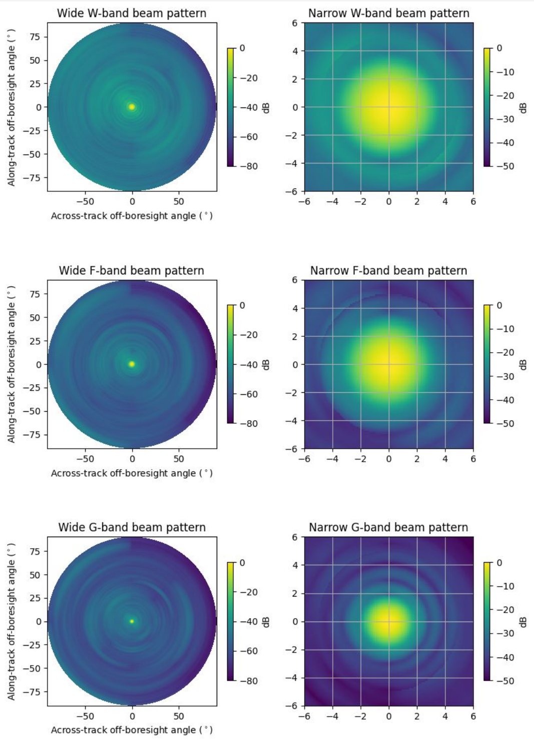
Tomorrow.io Radar Pathfinder Passive Mode



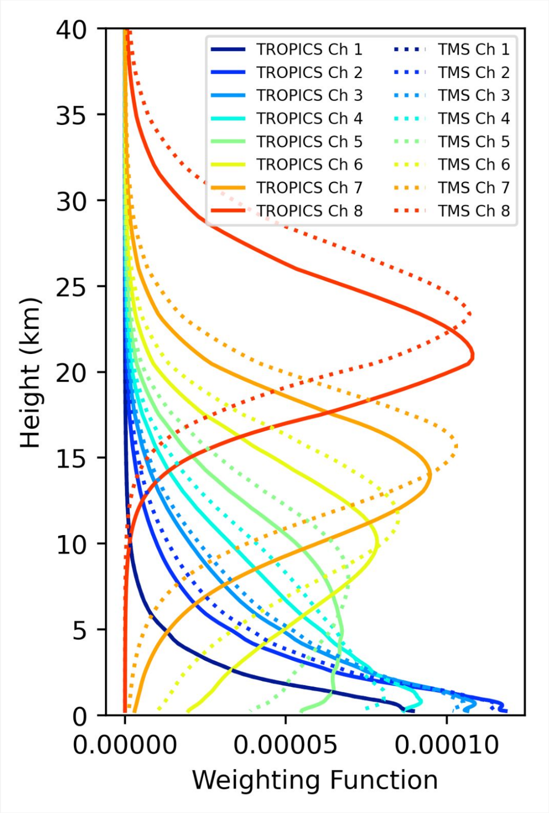


- Pathfinder is configured to collect two wideband (65 MHz) noise channels outside of the transmit band
- So called “Single-Point” radiometer calibration approaches match our configuration
  - Requires characterization of receiver noise temperature as a function of physical temperature
- Pathfinder receiver was characterized by fitting measurements to simulated brightness temperatures

TMS Instrument Specifications



Channel	TROPICS Center Freq. (GHz)	TROPICS Bandwidth (GHz)	TROPICS NEDT (K)	TMS Center Freq. (GHz)	TMS Bandwidth (GHz)	TMS NEDT Pre-launch Estimate (K)
1	91.65 +/- 1.4	1	0.66	91.65	2	0.38
2	114.5	1	0.96	118.75±3.5	1	0.75
3	115.95	0.8	0.82	118.75±2.625	0.75	0.87
4	116.65	0.6	0.86	118.75±1.875	0.75	0.73
5	117.25	0.6	0.79	118.75±1.25	0.5	0.78
6	117.8	0.5	0.81	118.75±0.75	0.5	0.77
7	118.24	0.38	0.9	118.75±0.375	0.25	1.00
8	118.58	0.3	1.03	118.75±0.125	0.25	0.96
9	184.41	2	0.58	184.41	2	0.54
10	186.51	2	0.55	186.51	2	0.57
11	190.31	2	0.53	190.31	2	0.65
12	204.8	2	0.52	204.8	2	0.63



Orbit Altitude	Swath Width
450 km	1780 km
500 km	2016 km
550 km	2265 km
600 km	2528 km

Band	Beamwidth	Beam Efficiency	FOV* @ nadir	FOV* (scan mean)
W (91 GHz)	2.94°	91.1%	27.7 km	44.3 km
F (114-122 GHz)	2.47°	97.6%	23.5 km	37.6 km
G (184-190 GHz)	1.47°	96.6%	15.1 km	24.2 km
G (204 GHz)	1.44°	97.7%	14.9 km	23.8 km

*geometric mean from 525 km altitude