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The Tomorrow Microwave Sounder program: an assessment of the observations and observing system impacts

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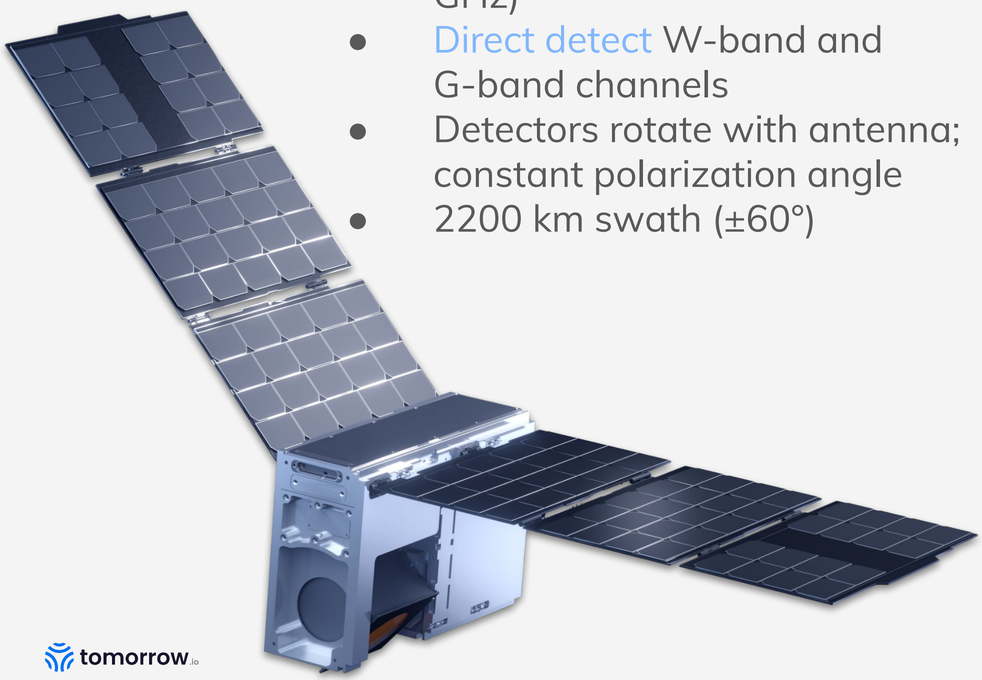
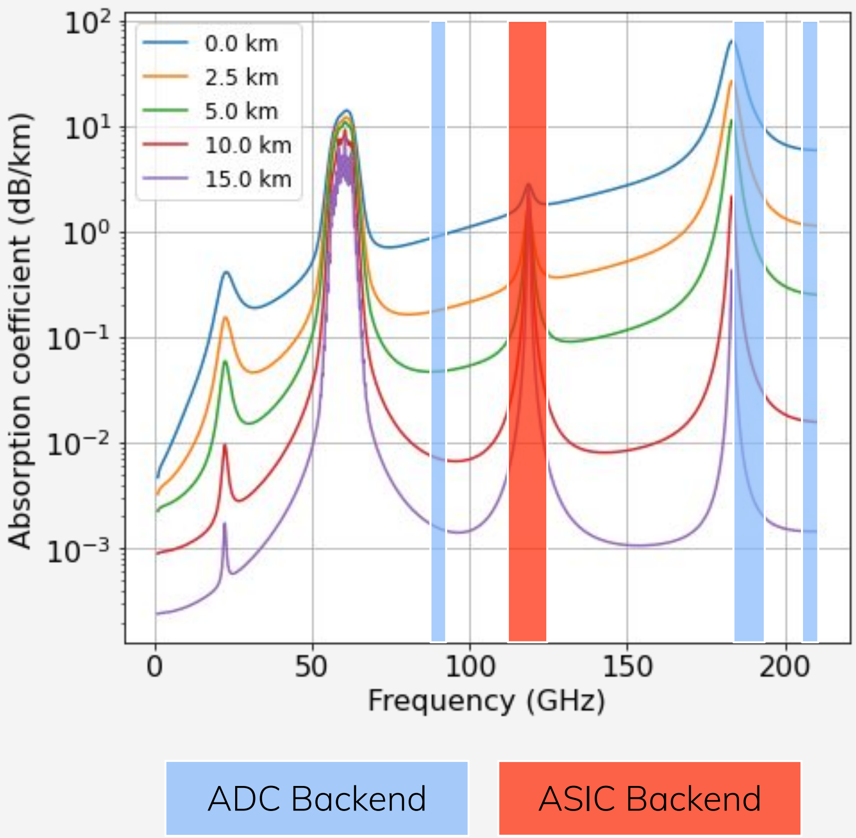
Tomorrow.io Microwave Sounders (TMS 1.1)

Heritage: NASA/MIT-LL TROPICS Microwave Sounder (v1.0)

- 12 channels from 91-204 GHz (2 window, 7 O_2, 3 H_2O)
- Calibration: deep space, noise diodes, and an internal calibration target
- **Digital spectrometer (ASIC)** for 7 F-band channels (114-122 GHz)
- Direct detect W-band and G-band channels
- Detectors rotate with antenna; constant polarization angle
- 2200 km swath (±60°)





Tomorrow.io Sounders Constellation 2025

Successful Launch
Ready for Launch
Building for Launch
Operational
Commissioning (Cal/Val)
Recovery Not Expected

S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12+

Transporter-11 LTAN 22:38 Aug 16, 2024	Bandwagon-2 45° Dec 21, 2024	Transporter-13 LTAN 10:26 Mar 14, 2025	BW-3 45° Apr 20, 2025	Q3/Q4 2025	Q3/Q4 2025	2026+

IOC - Initial Operational Capability

EOC - Early Operational Capability

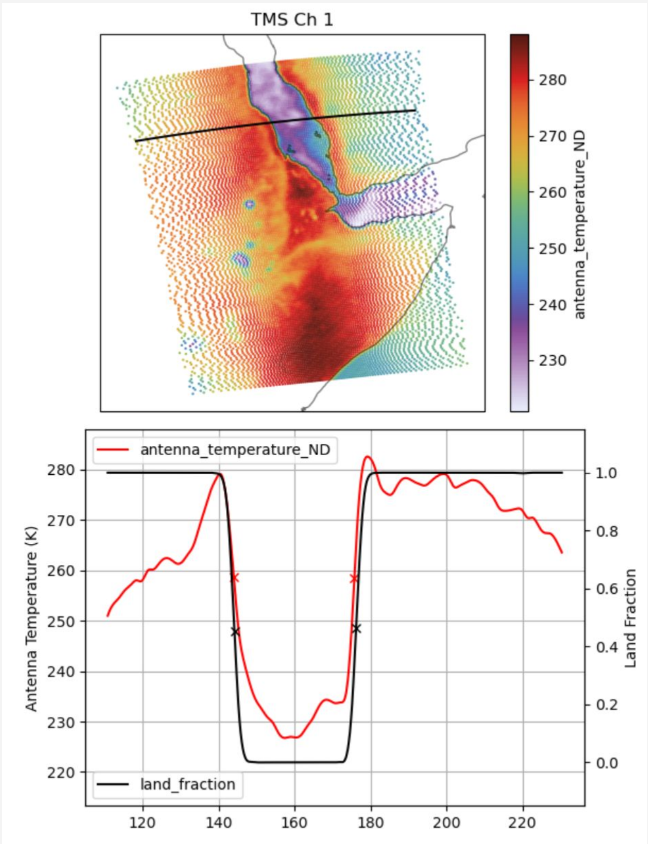
FOC - Full Operational Capability

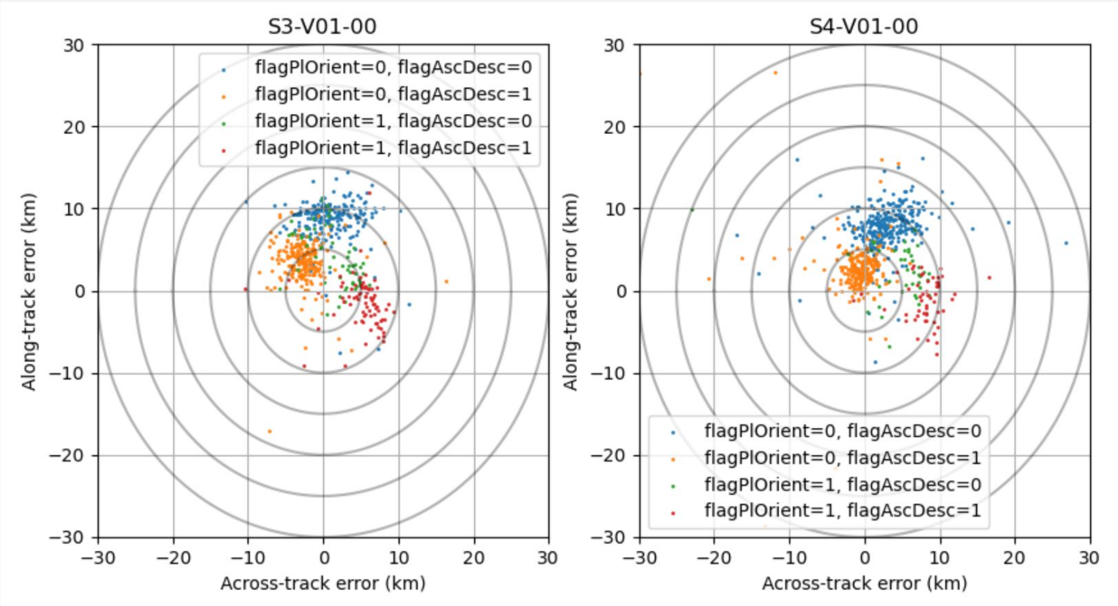
Planned Revisit	683	219	125	105	79	63

TMS revisit rate in minutes — Goal is sub-hourly (<60min)
Comparing to NOAA / NASA programs of record

Modest Improvement	Notable Improvement	Significant Improvement

Geolocation Calibration Accuracy





Geolocation accuracy is assessed using a coastline crossing method similar to Han et al. (2016). Above figure shows an example of Tomorrow-S1 for a granule covering the Red Sea and Gulf of Aden on 14 October 2024.

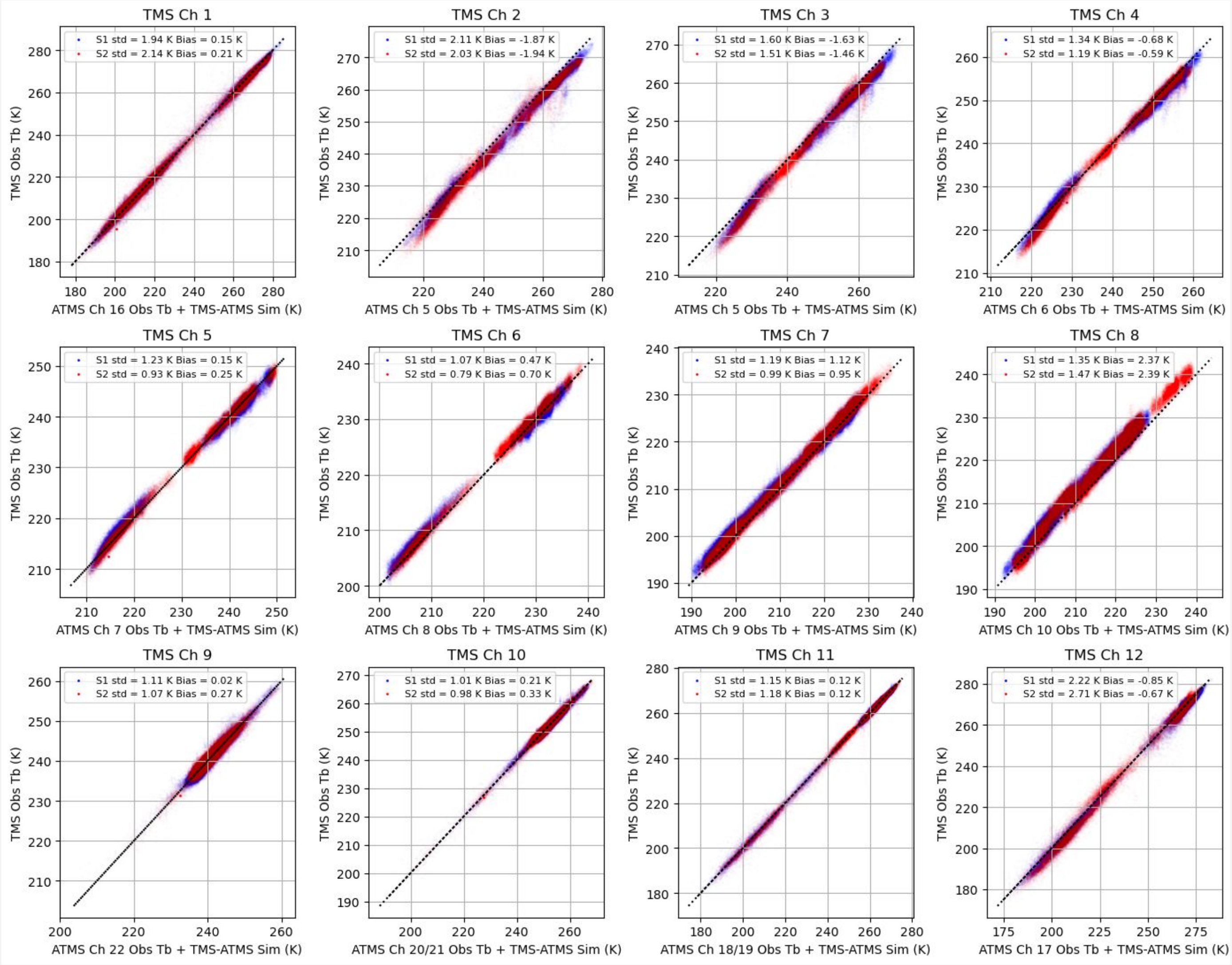
For Tomorrow-S1 through S4, the mean geolocation bias is approximately 7 km, and standard deviation is approximately 4 km. Additional corrections are anticipated in future product versions.

Radiance Calibration

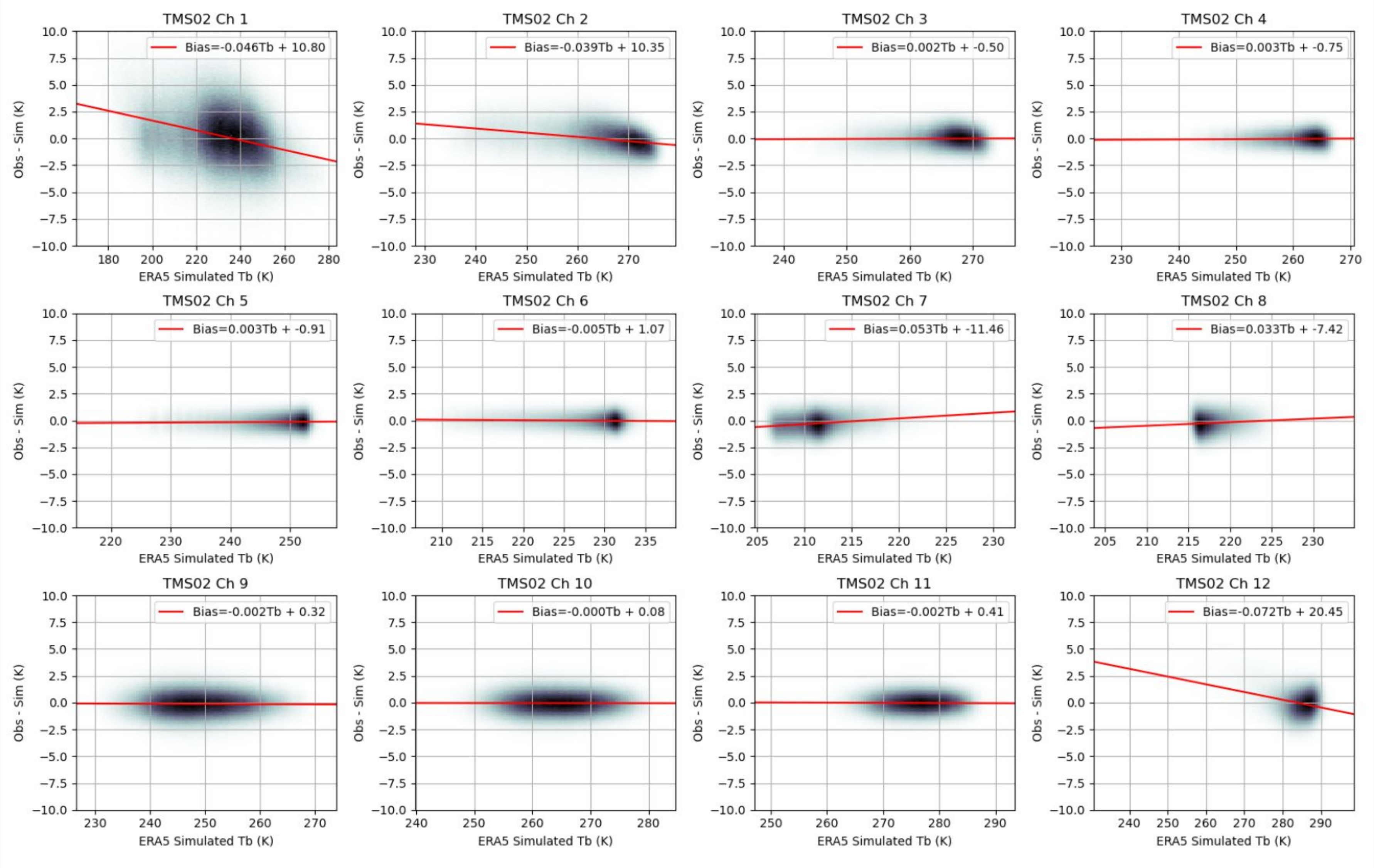
Channel	Primary vicarious calibrator	Secondary (independent) cal/val sources	TMS NEDT On-orbit average (K)	TMS NEDT Pre-launch target (K)	TMS beamwidth (degrees)
1 (91.65 GHz)	ATMS	ERA5, GMI	0.502*	0.38	2.8
2 (118.75±3.5 GHz)	ERA5	ATMS, sonde	0.499	0.75	2.4
3 (118.75±2.625 GHz)	ERA5	ATMS, sonde	0.553	0.87	2.4
4 (118.75±1.875 GHz)	ERA5	ATMS, sonde	0.521	0.73	2.4
5 (118.75±1.25 GHz)	ERA5	ATMS, sonde	0.581	0.78	2.4
6 (118.75±0.75 GHz)	ERA5	ATMS, sonde	0.586	0.77	2.4
7 (118.75±0.375 GHz)	ERA5	ATMS, sonde	0.786	1.00	2.4
8 (118.75±0.125 GHz)	ERA5	ATMS, sonde	0.780	0.96	2.4
9 (184.41 GHz)	ATMS	ERA5, sonde	0.401	0.54	1.5
10 (186.51 GHz)	ATMS	ERA5, GMI, sonde	0.389	0.57	1.5
11 (190.31 GHz)	ATMS	ERA5, GMI, sonde	0.343	0.65	1.5
12 (204.8 GHz)	ERA5	ATMS, GMI	0.410	0.63	1.4

* Calibration sectors are not uniform at 91 GHz, so the true NEDT is likely lower than what we report here.

Calibration Assessment: ATMS Double Differences



Calibration Assessment: TMS02 Residual Bias vs ERA5



Observing System Experiments (OSEs): Observations and DA Configuration

PMW Sounders
- AMSR2 (1)
- ATMS (2)
- AMSUA (5)
- COWVR (1)
- GMI (1)
- MHS (3)
- SSMIS (3)
- TMS (3)
- TROPICS (3)

In-situ
- Radio-sondes
- Station
- Ship /Buoy
- Aircraft

IR Sounders
- CrIS (2)
- IASI (2)

UV
- GOME (2)
- OMI (1)
- OMPS (3)

Sat. derived
- GNSS
- Satellite AMVs

GEO-IR Imagers
- SEVIRI (2)
- AHI (1)
- ABI (2)

Active MW
- DPR, EarthCARE, TRAKR

Data Assimilation

- FV3-JEDI (SkyLab 8); work in progress at NOAA-EMC and JCSDA. System configuration is a snapshot of EMC's GDASApp repository circa Jan 2025.
- 3DEnVar; B-matrix uses 30-member C192 forecasts initialized from GEFS
- Obs availability and QC modeling reflect upstream efforts.

↑ ↓

Current experiment period: January 1-31, 2025

Next experiment period

Future consideration

Forecast

- UFS-ATM
- Global C768 (13-km) mesh
- 127 vertical levels

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Observation Error Model

We exclude areas of known surface and cloud contamination and define an observation error model using a per-channel symmetric cloud impact (SCI) predictor (Okamoto et al. 2013, 2023).

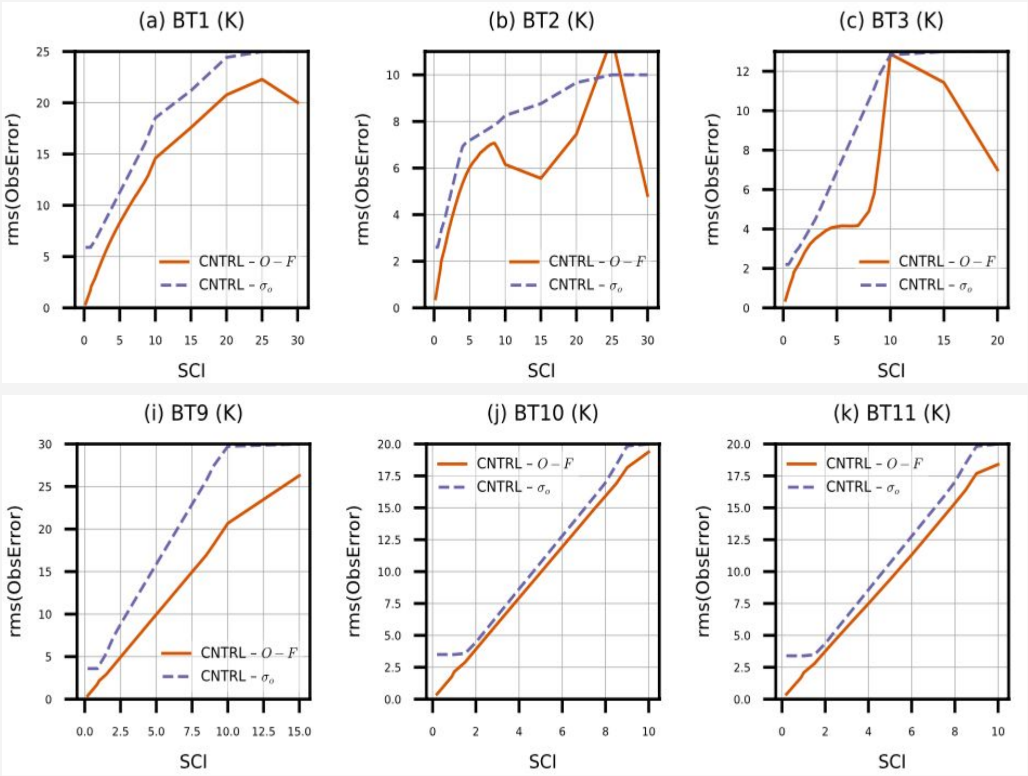
$$SCI = (|TB_{clear} - TB_{obs}| + |TB_{clear} - TB_{modeled}|) / 2$$

Error is assigned proportional to the SCI.

Thinning is used to suppress inter-observation correlations (JEDI introduced super-obbing support quite recently).

Inter-channel error correlations are diagonal, but in general error assignments are close to diagnosed values.

Obs error (σ_0) and RMS of 6 hr O-F at select channels



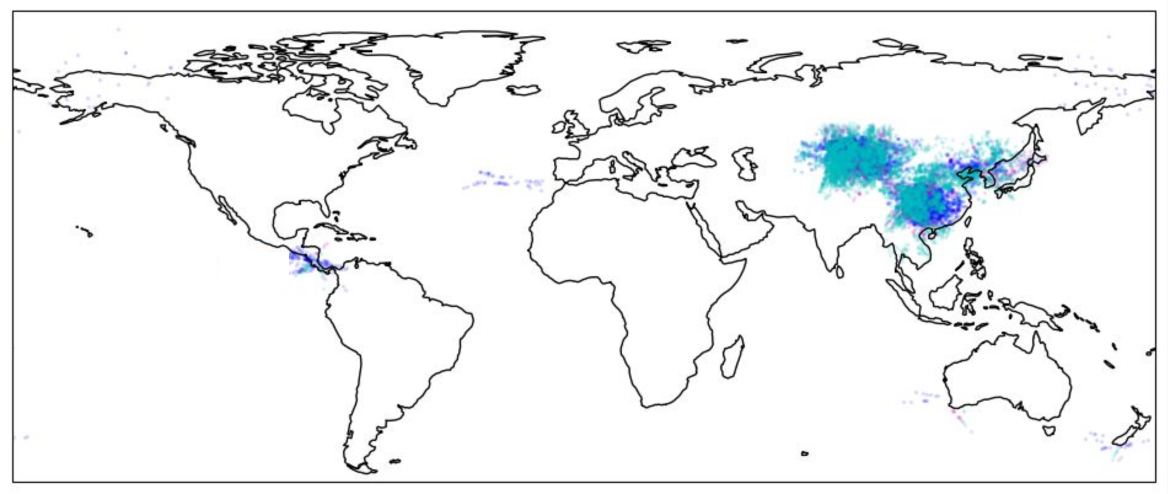
Observation QC and Bias Predictors

L1 QC flags:

- Spacecraft maneuvers
- Indeterminate geolocation quality
- Transmissions from spacecraft to ground
- ICT, ND, cold calibration inconsistencies
- Solar and lunar intrusions
- Payload / bus timing inconsistencies
- Potential RFI

Predictors vary by experiment:

- Global constant
- Lapse rate
- Emissivity
- Scan angle
- Position in orbit (e.g. EMC and ECMWF treatments for SSMIS)



We note candidate ground-source RFI in channel 3 (lower sideband; 115.75 – 116.5 GHz; equiv to ch. 7 on MWHS-2). RFI is flagged by both crude checks and interchannel discrepancies. Colors denote satellite (S2 = blue, S4 = cyan). Sep 2024 - Jan 2025.

6-h Forecast Verification versus GDAS Analyses

Verification metric on right, delta RMSE (%):

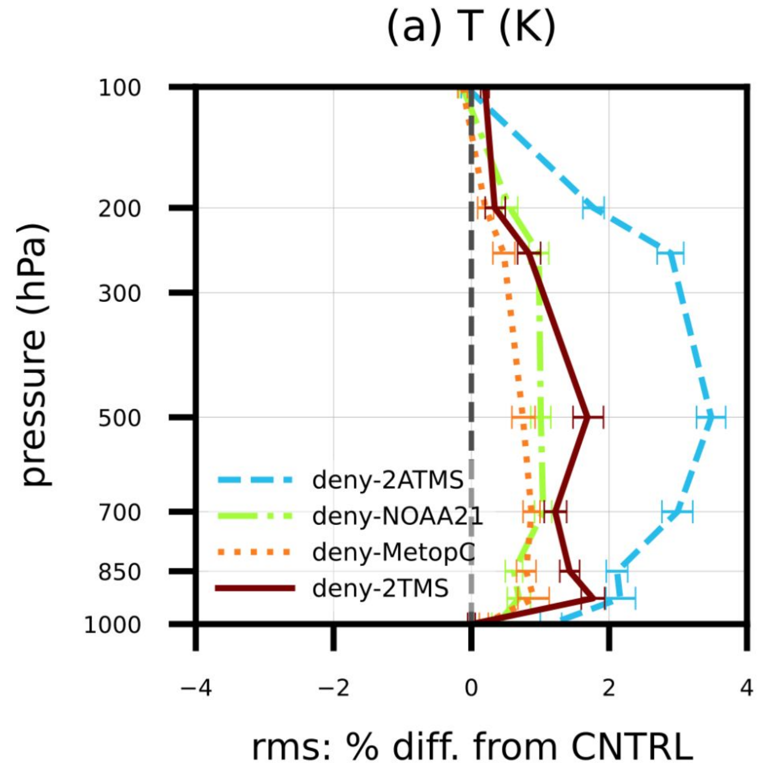
1. Evaluate RMSE of C768 (13km) UFS forecasts w.r.t. GFS analyses
2. Calculate relative change in RMSE compared to a control experiment (**CNTRL; x-axis**), which uses T.io observations plus many used in GDAS
3. Experiments here focus on data denial of microwave observations to examine questions about orbital overlap and availability of comparable observations
4. A larger <u>positive delta RMSE</u> in a data-denial experiment indicates larger <u>positive observation impacts</u> in **CNTRL**

Takeaways:

- Demonstrated TMS performance exceeds pre-launch expectations.
- TMS imparts comparable impact aloft (925 hPa to 200 hPa) as ATMS onboard NOAA-20 and NOAA-21.
  - First launch in SSO provided overlap with existing sensor swaths (AMSU-A, MHS), is great for cross-calibration, but masks impact somewhat. 45° inclination fills in gaps.
- Refinement of bias correction and QC models is ongoing.

Data denial cases:

ATMS (N20/21)
ATMS (N21)
AMSU-A + MHS (MetopC)
TMS (S02, S04)



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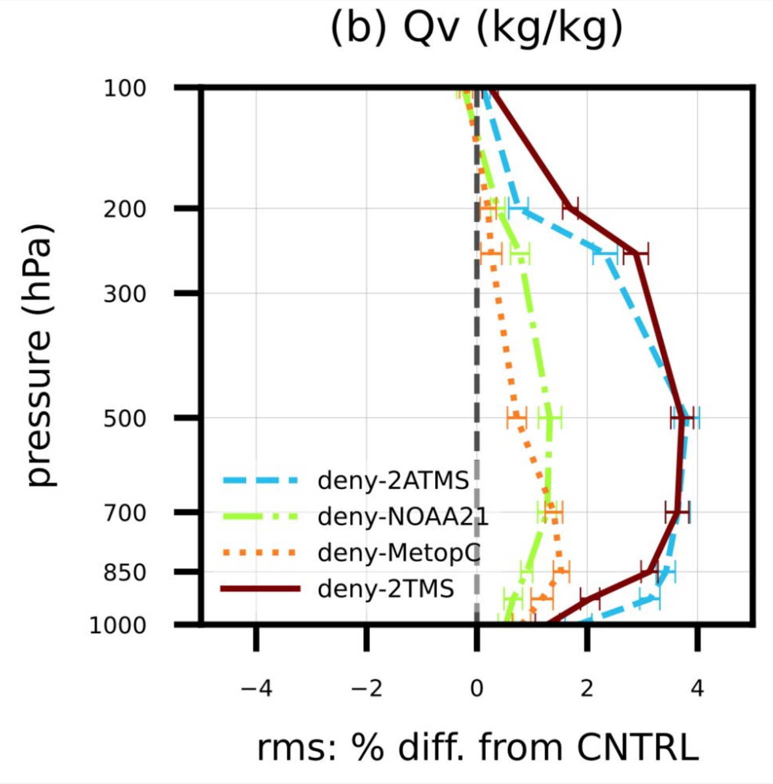
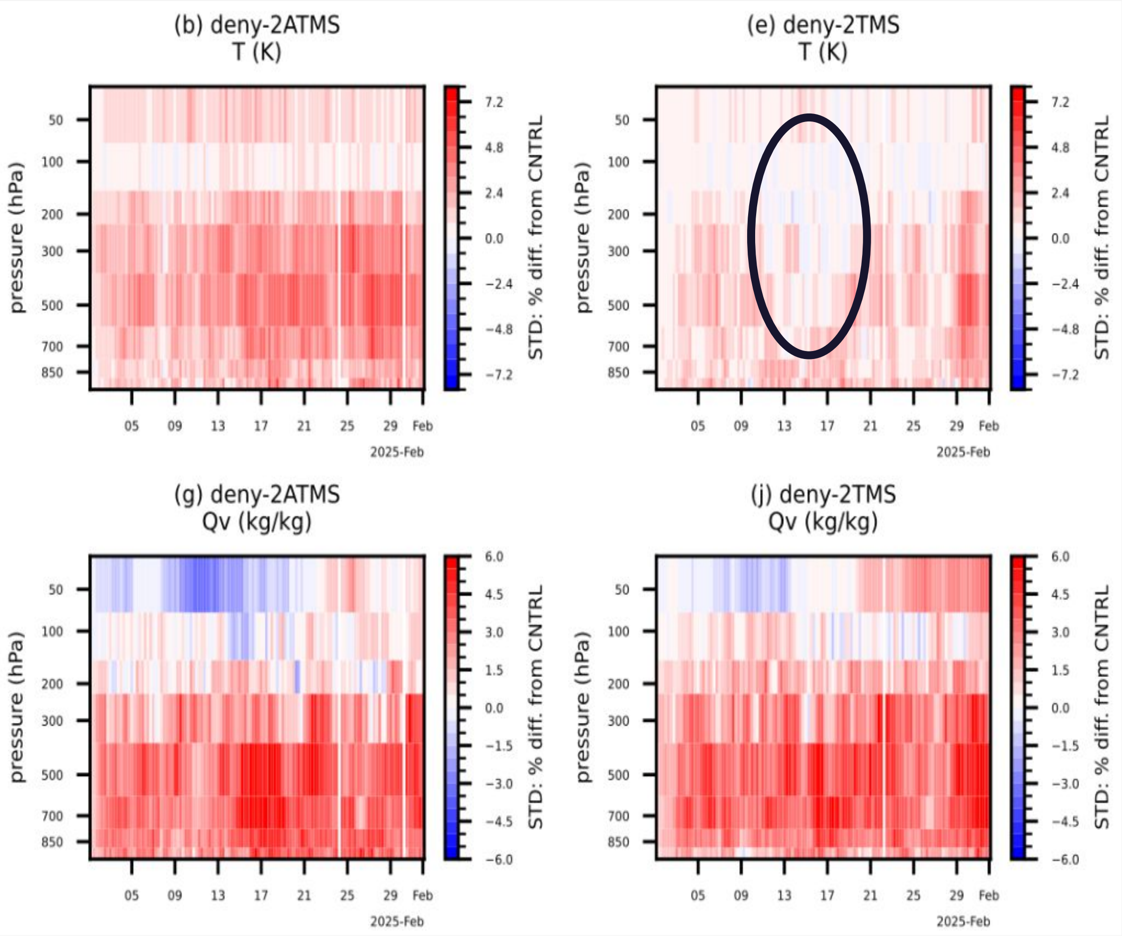
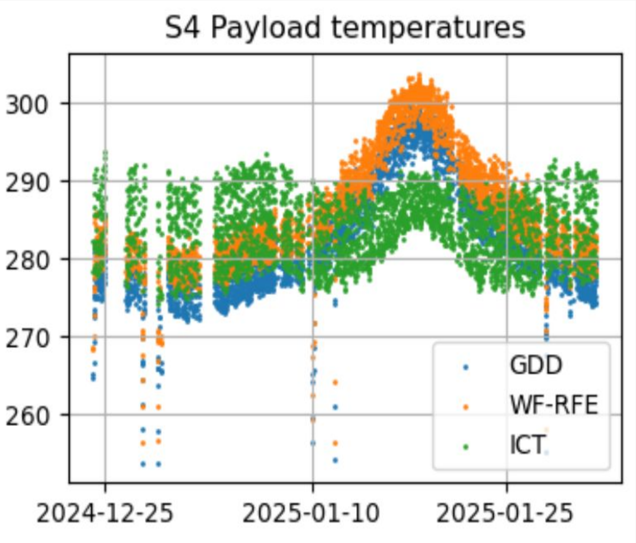
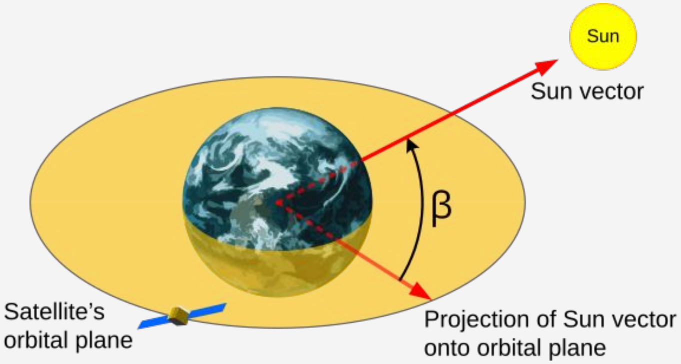


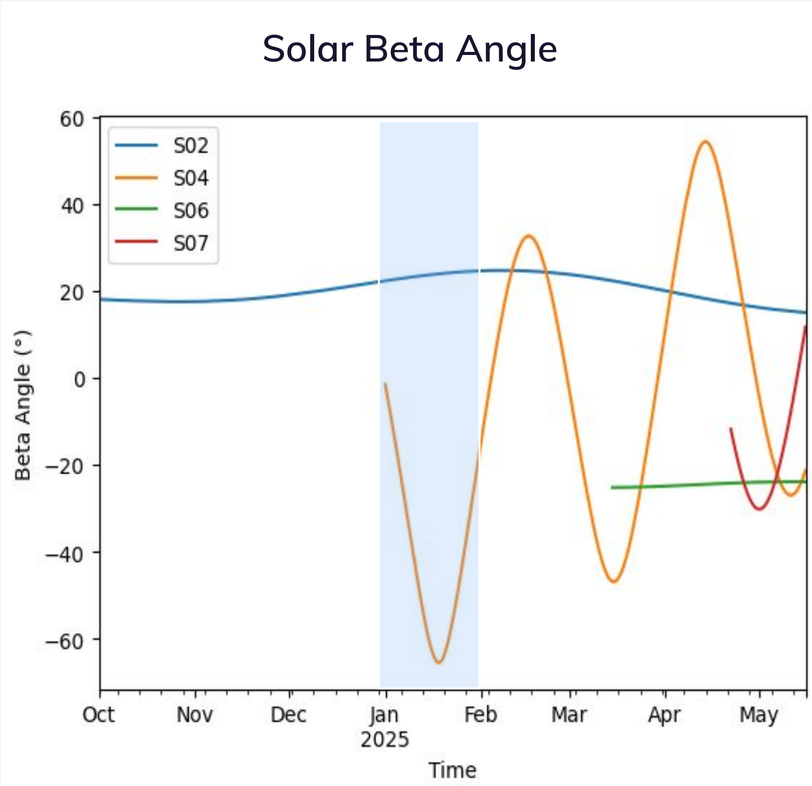
Performance over Time

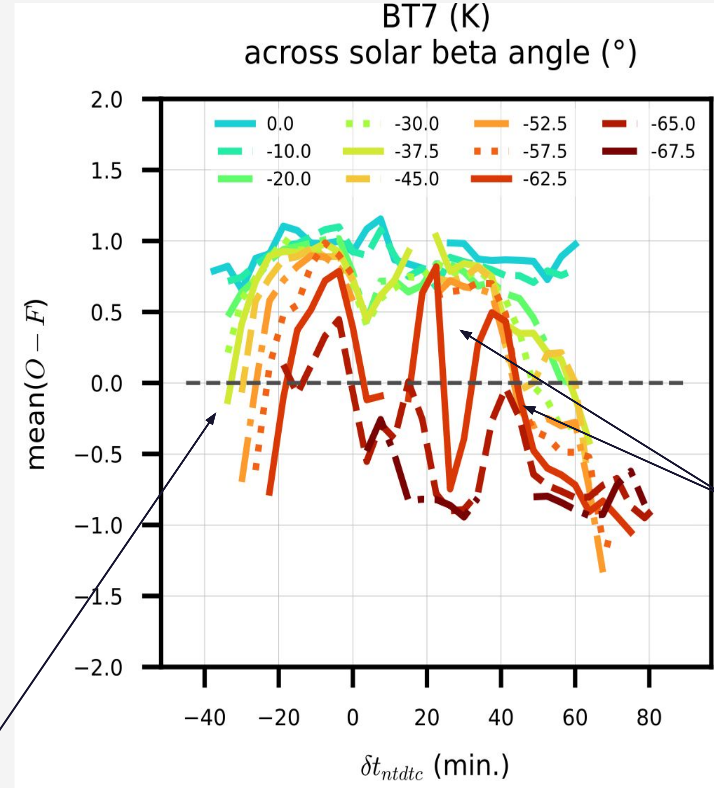






Spacecraft Thermal Cycle





Spacecraft geometry effects

Last day-to-night crossing

Time since nearest night-to-day terminator crossing

- Beta angle cycles are sinusoidal with overlapping multi-month periods.
- Different launches to same inclination have cycles that are out of phase.
- Thermal biases are partly addressed using predictors derived for SSMIS; further L1 development suggested, particularly for inclined orbits.

Thank You

Instrument characteristics: [WMO OSCAR]

How to get the L1/L2 data:
- NOAA / NASA / EUMETSAT are evaluating (looking for independent yet collaborative evaluators)
- Ask us

Besides instrument data, we can provide:
- L1 / L2 ATBDs
- On-orbit cal/val assessment reports
- Documentation of data products and formats
- CRTM and RTTOV coefficients; spectral response functions