



Inter-calibration of Tomorrow.io Microwave Sounder constellation

GSICS Microwave Sub-Group
SNO / Vicarious Calibration focus group

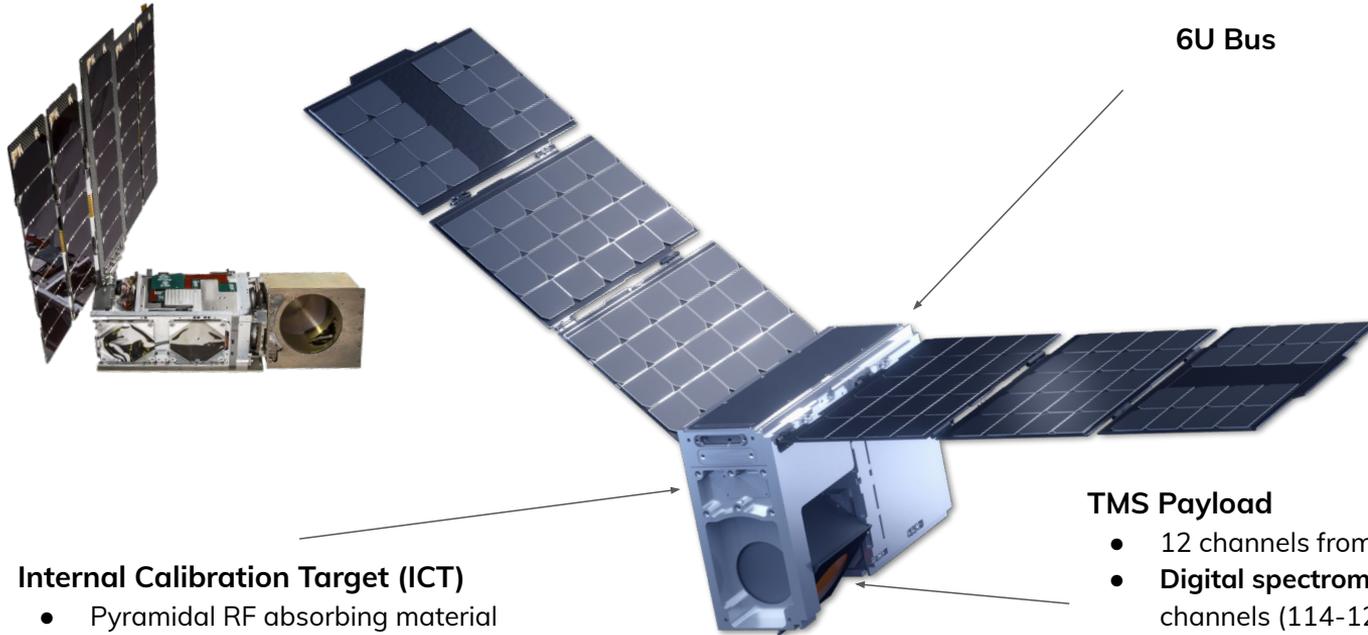
13 Nov 2025

Agenda

1. TMS Overview
2. TMS Intercalibration

Tomorrow.io Microwave Sounder: Bus and Payload

Heritage: NASA/MIT-LL TROPICS Microwave Sounder



Internal Calibration Target (ICT)

- Pyramidal RF absorbing material
- Characterized by 4 thermistors
- Complements noise diodes (improves calibration stability and striping)

6U Bus

TMS Payload

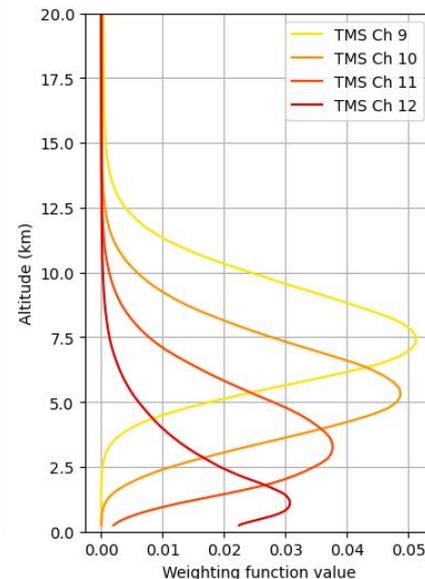
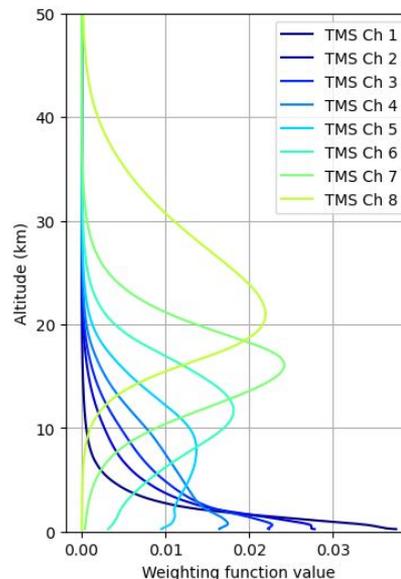
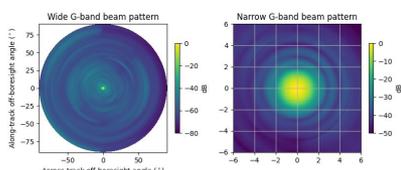
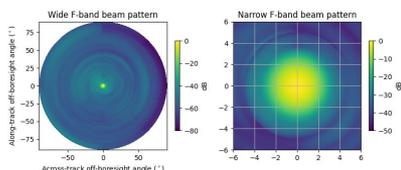
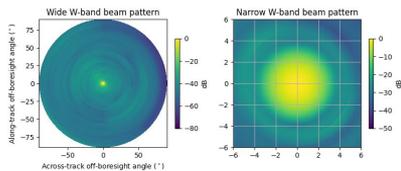
- 12 channels from 91-204 GHz
- **Digital spectrometer (ASIC)** for 7 F-band channels (114-122 GHz)
- Direct detect W-band and G-band channels
- Detectors rotate with antenna, giving constant polarization angle



Photo credit: SpaceX

TMS Instrument Specifications

Channel	TMS Center Freq. (GHz)	TMS Bandwidth per sideband (GHz)	TMS NEDT Pre-launch Estimate (K)
1 (W)	91.65	2	0.38
2 (F1)	118.75±3.5	1	0.75
3 (F2)	118.75±2.625	0.75	0.87
4 (F3)	118.75±1.875	0.75	0.73
5 (F4)	118.75±1.25	0.5	0.78
6 (F5)	118.75±0.75	0.5	0.77
7 (F6)	118.75±0.375	0.25	1.00
8 (F7)	118.75±0.125	0.25	0.96
9 (G1)	184.41	2	0.54
10 (G2)	186.51	2	0.57
11 (G3)	190.31	2	0.65
12 (G4)	204.8	2	0.63

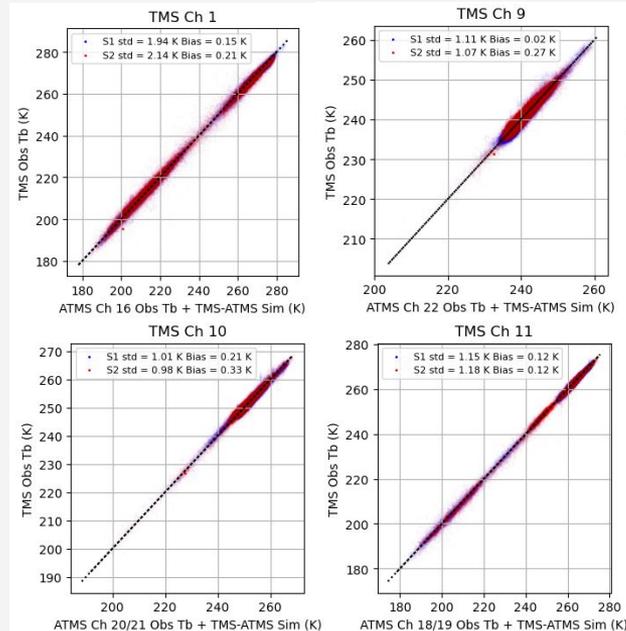
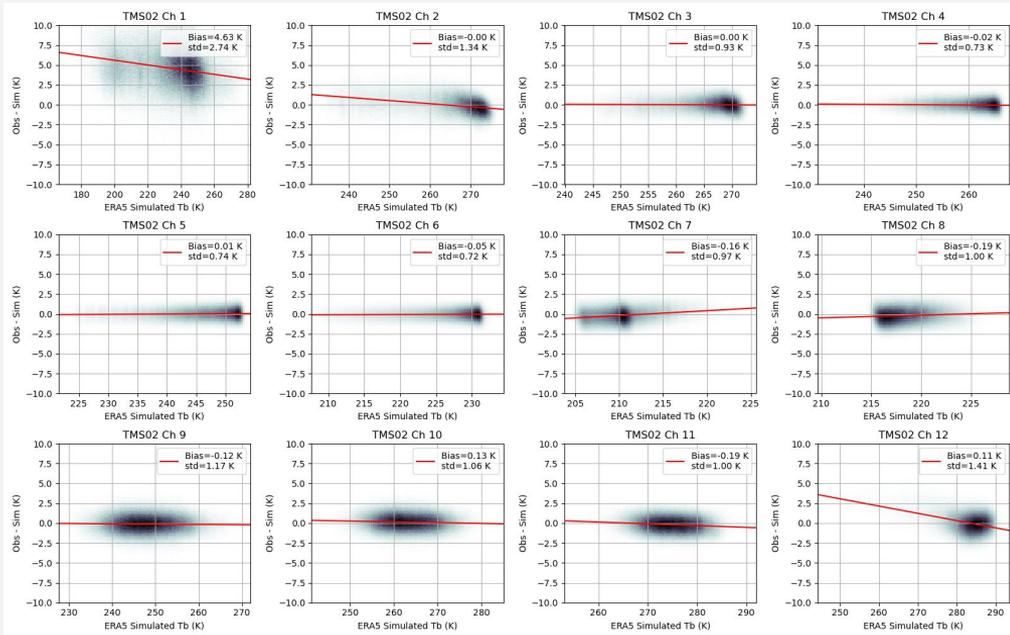


Orbit Altitude	Swath Width
450 km	1780 km
500 km	2016 km
550 km	2265 km
600 km	2528 km

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

TMS On-orbit Calibration Assessment vs. ERA5 and ATMS



TMS calibration accuracy was assessed against clear-sky ERA5 simulations, ATMS/GMI double differences, and radiosonde simulations. More details in the manuscript submitted to JTECH and available in the following preprint:

Munchak et al., 2025: On-orbit Calibration of the Tomorrow.io Microwave Sounders. *ESS Open Archive*. July 14, 2025.

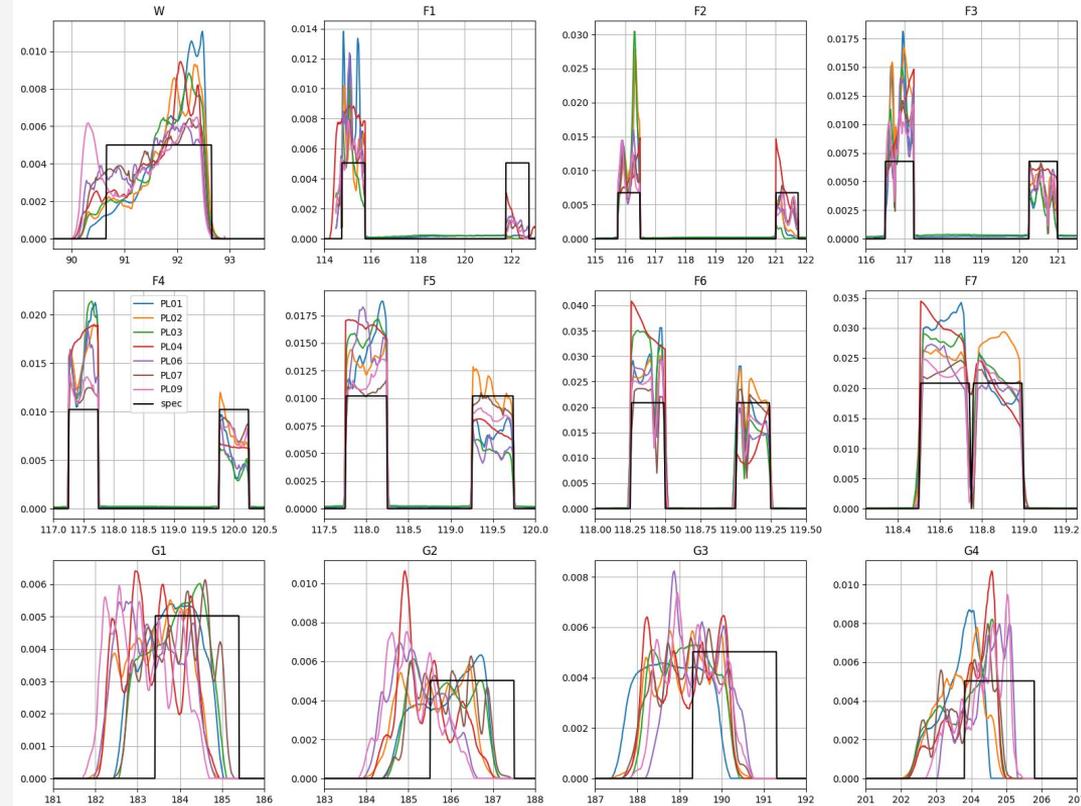
[DOI: 10.22541/essoar.175250254.43121152/v1](https://doi.org/10.22541/essoar.175250254.43121152/v1)



Intercalibration Technique and Results

What is meant by intercalibration, and why is it needed?

TMS Spectral Response Functions



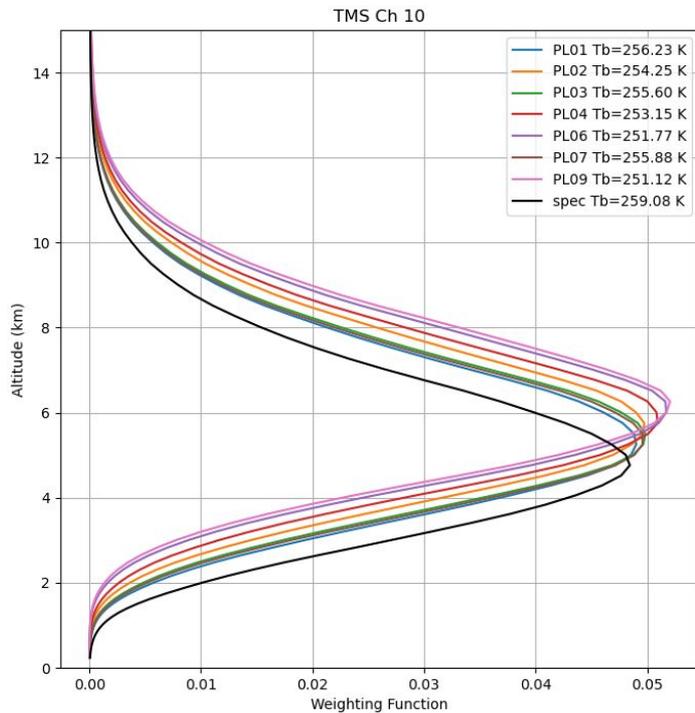
TMS radiometers are manufactured with an emphasis on passband *knowledge* instead of precise control. This is most evident in the G-band channels, since the DIFP very repeatably transforms the F-band spectrum to 7 channels.

The TMS Level 1C (1C-TC and 1C-TCR) products aim to provide brightness temperatures that are valid at the *specified* (boxcar) spectral response functions.

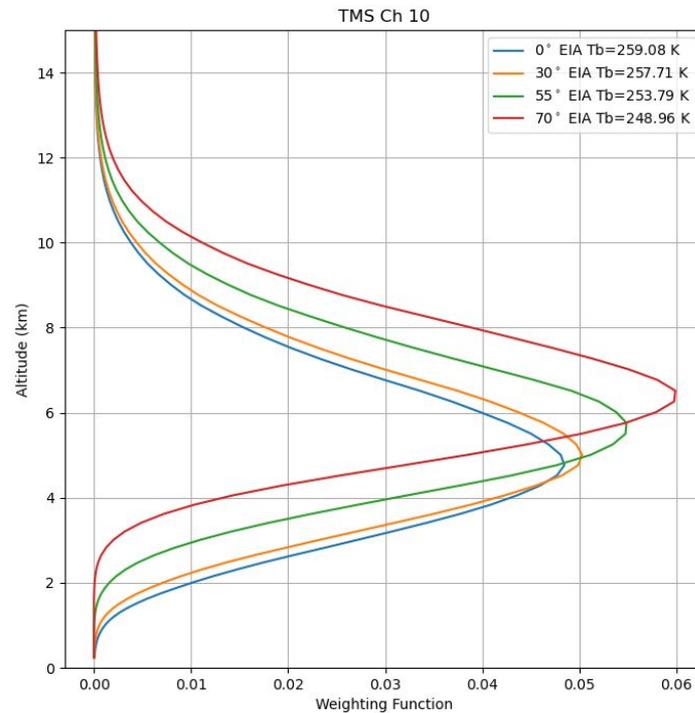
Envisioned use case is Level 2 products and AI data assimilation methods that benefit from large record of *homogeneous* training data.

Analogy to Limb Adjustment

Weighting Functions for Different Payloads



Weighting Functions for Different Scan Angles

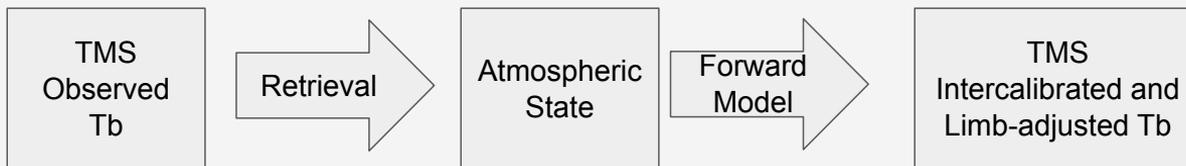


Techniques for Limb Adjustment/Intercalibration

Statistical approach (Goldberg et al., 2001):

$$F(\mathbf{b}) = (\mathbf{X}^T \mathbf{b} - \mathbf{T}_1)^T (\mathbf{X}^T \mathbf{b} - \mathbf{T}_1) + \gamma (\mathbf{b} - \mathbf{b}_p)^T (\mathbf{b} - \mathbf{b}_p) + 2\lambda (1 - \mathbf{u}^T \mathbf{b}),$$

Physical approach:



Neural Network approach (QRNN*):



*Quantile Regression Neural Network (Pfreundschuh et al., 2018 *AMT*)

Also used for intercalibration of VIIRS/AVHRR (S. Eliasson presentation at EUMETSAT)

QRNN Training Data

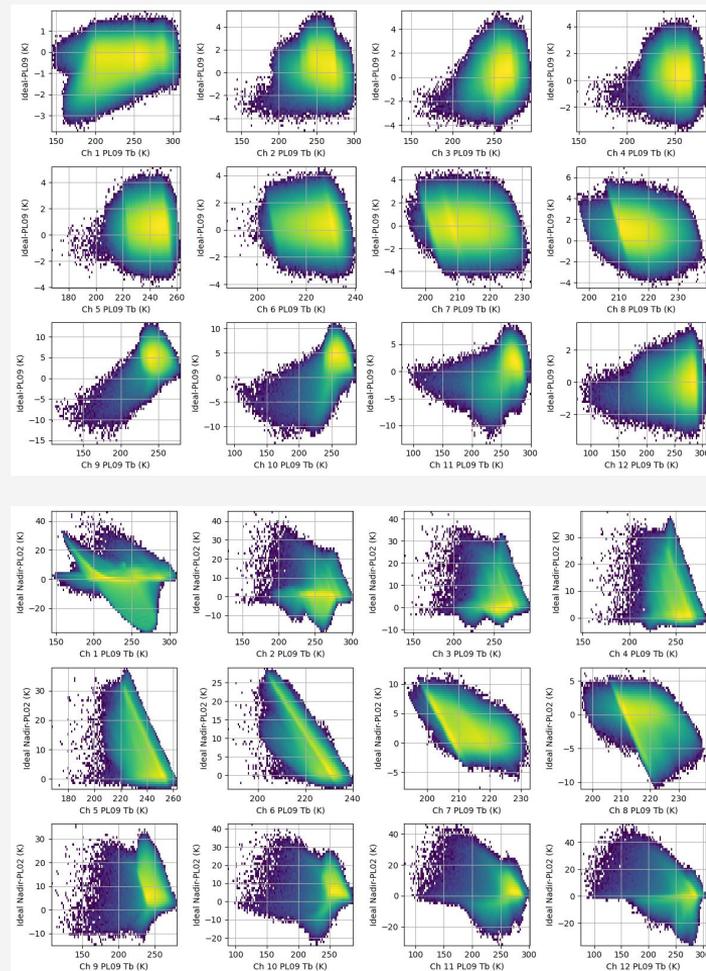
Problem: We don't have real measurements with the desired SRF that are perfectly co-located with actual TMS measurements...so how do we train a neural network?

Solution: Use simulated data! We have 40 days of simulated TMS measurements for every payload from pre-launch OSSEs based on the GMAO DYAMOND 3km convection-allowing nature run - over 100M profiles.

Input is simulated, payload-specific 12-channel TMS Tb (**with simulated, properly correlated noise**), plus incidence angle, land fraction, and surface elevation

Top: Target is 12-channel adjustments (delta-Tb) to correct for SRF difference from ideal (**without noise**).

Bottom: Similar approach used for limb adjustment (target is ideal TB at nadir incidence angle).



QRNN Internal Validation

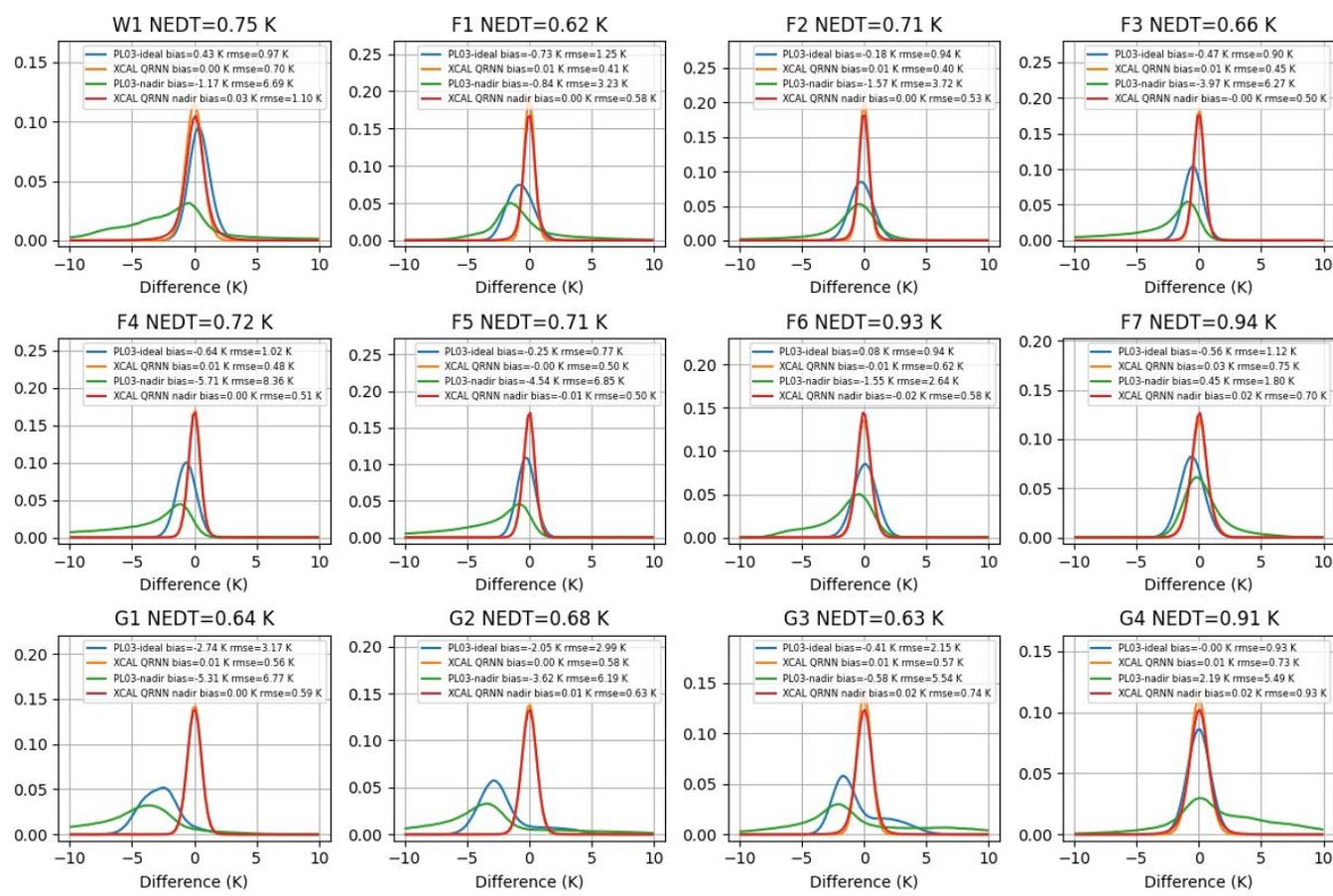
Blue: payload-specific Tb minus ideal Tb

Green: payload-specific Tb minus ideal nadir Tb

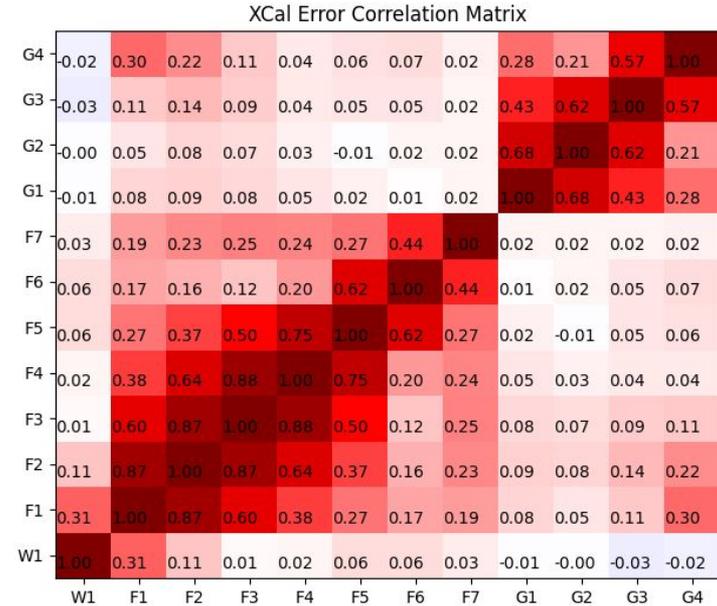
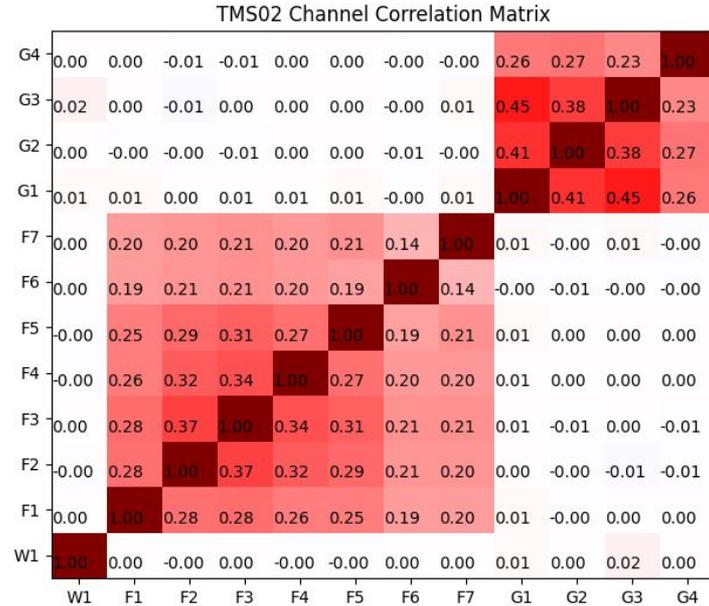
Orange: intercalibrated Tb minus ideal Tb

Red: intercalibrated, limb-adjusted Tb minus ideal nadir Tb

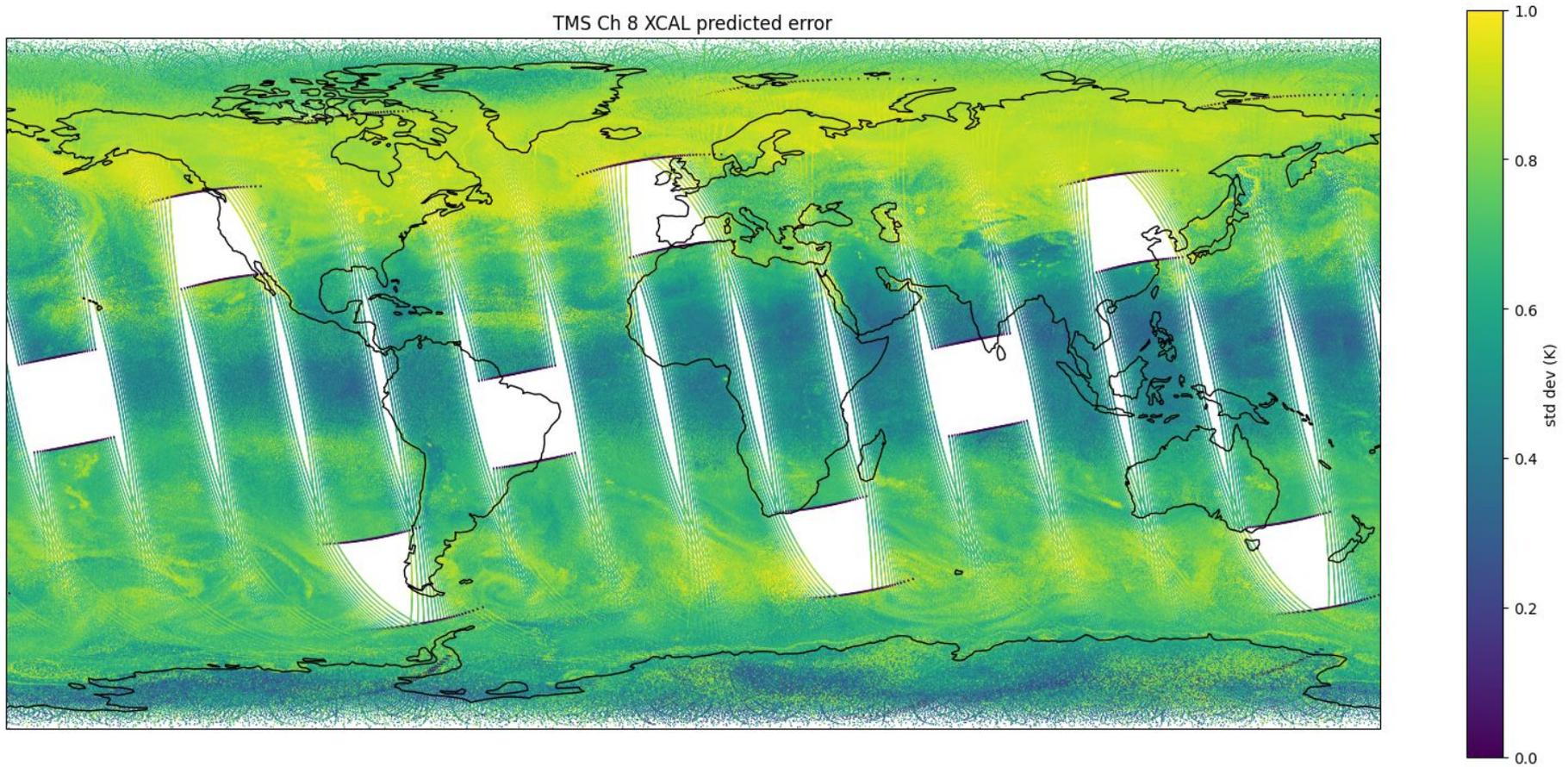
Both intercalibration and intercalibration with limb adjustment produce unbiased estimates of the targets *with reduced noise relative to the input data!* How?



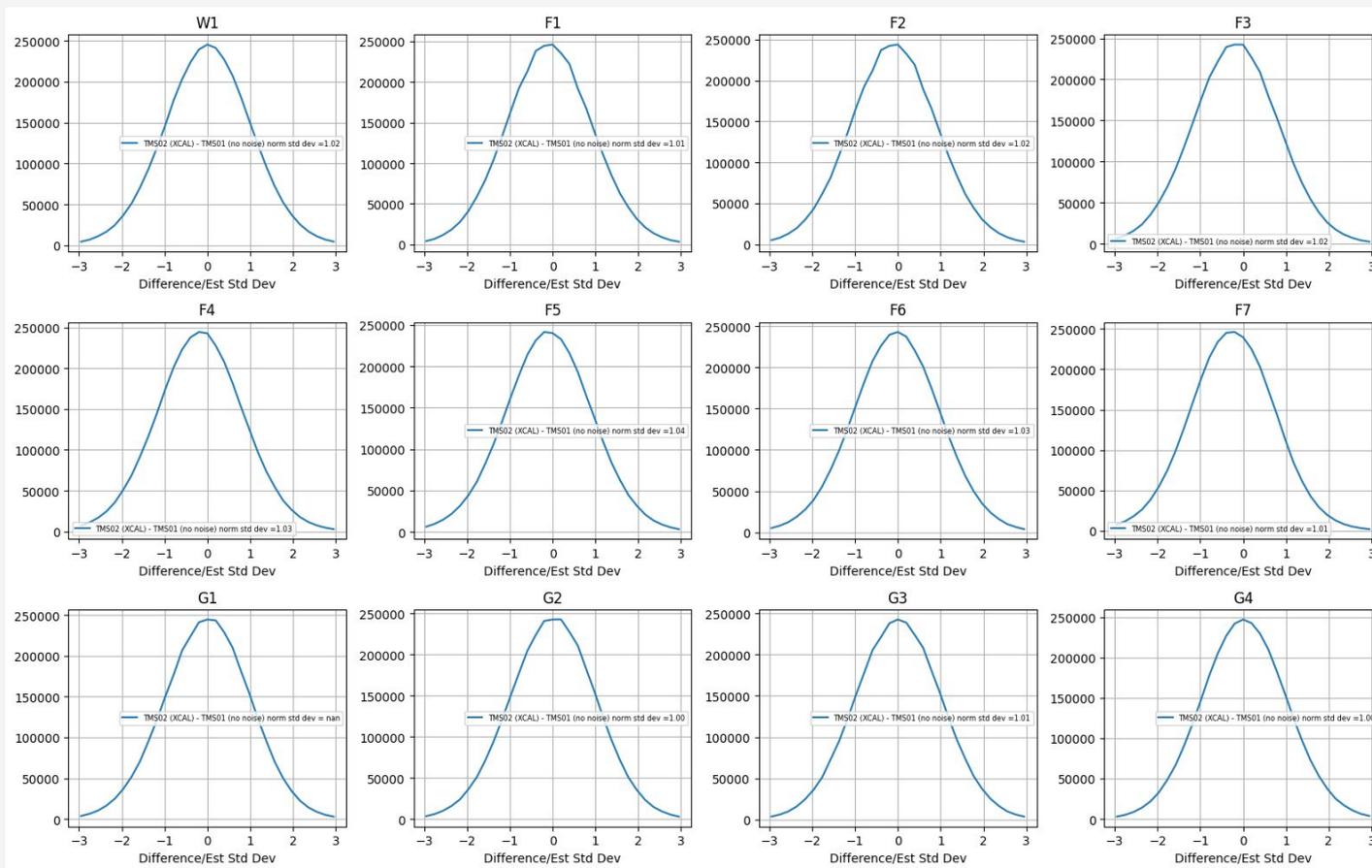
Change in Error Correlation (1B vs 1C) from internal validation data



Quantile regression neural network (QRNN) also produces error estimates:

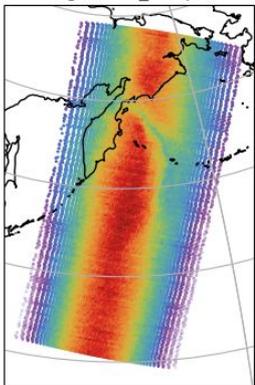


These error estimates are well-calibrated:

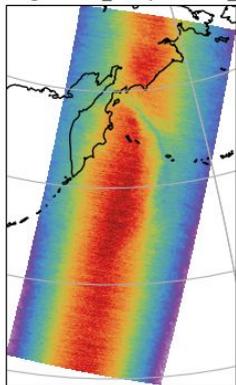


Intercalibration and Limb Adjustment Results from S2

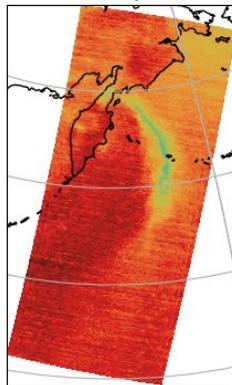
Ch 5 brightness_temperature



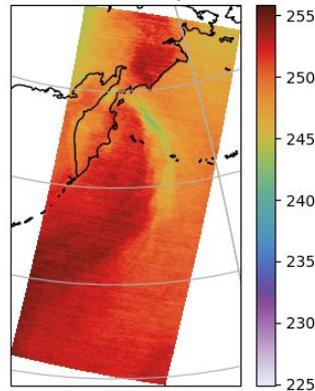
1C-TCR brightness_temperature_gridded



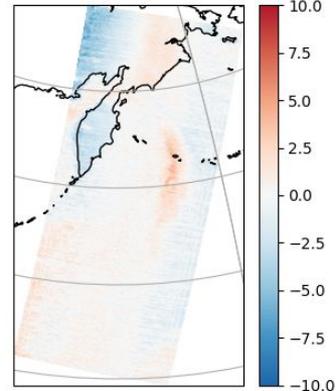
MG Limb Adjustment



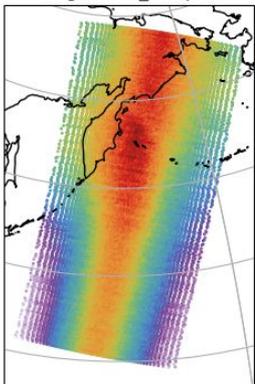
T.io XCAL + Limb Adjustment



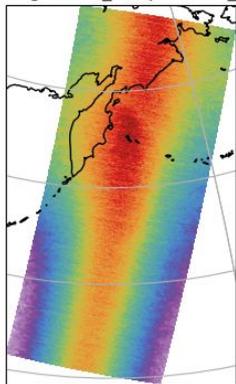
T.io - MG



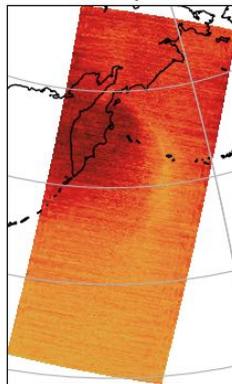
Ch 6 brightness_temperature



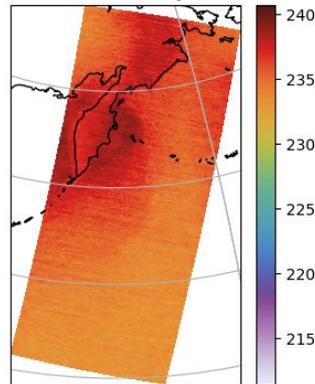
1C-TCR brightness_temperature_gridded



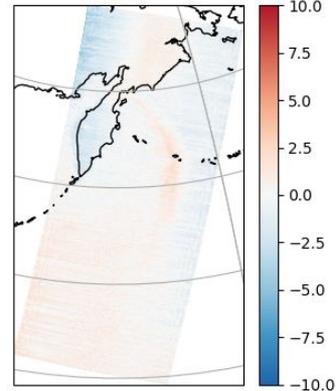
MG Limb Adjustment



T.io XCAL + Limb Adjustment



T.io - MG

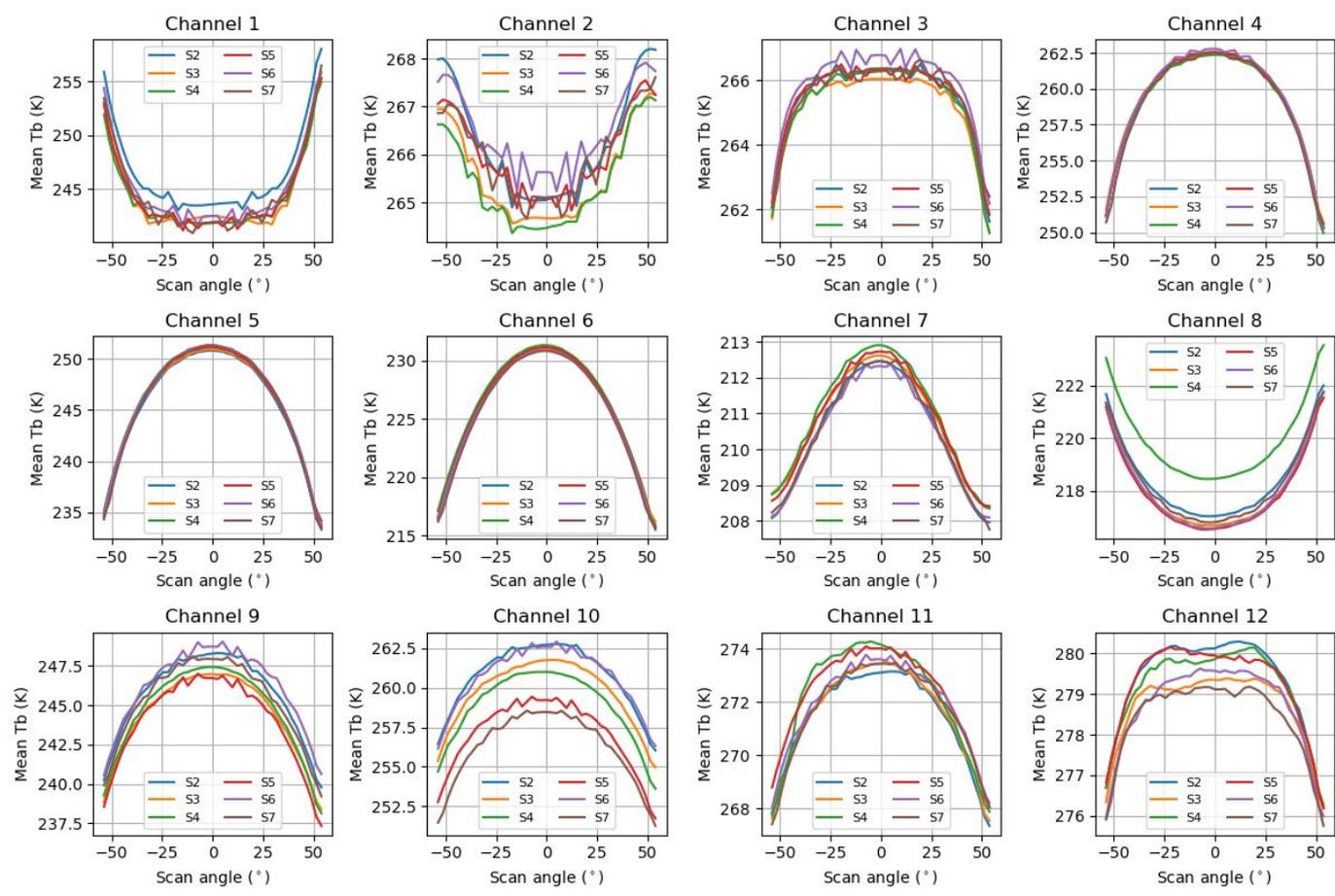


Level 1B Brightness Temperature vs. scan angle

35S to 35N
 Ocean only
 May 1 - June 15 2025

Note that S2, S5, and S6 have similar equator crossing times (10:20/10:45)

S3, S4, and S7 precess on ~60 day cycle

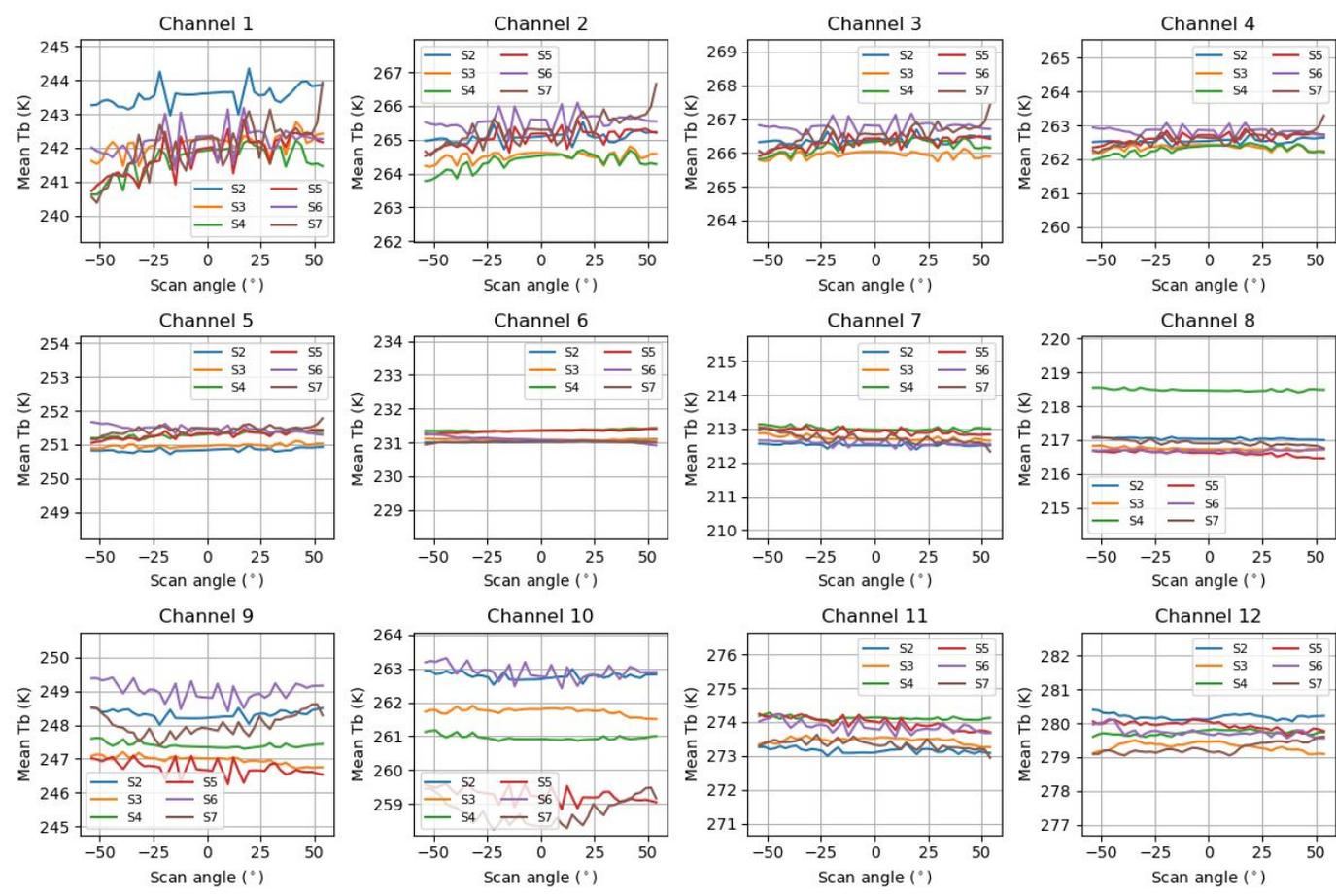


Level 1C Statistical Limb Adjustment vs. scan angle

35S to 35N
 Ocean only
 May 1 - June 15 2025

Note that S2, S5, and S6 have similar equator crossing times (10:20/10:45)

S3, S4, and S7 precess on ~60 day cycle

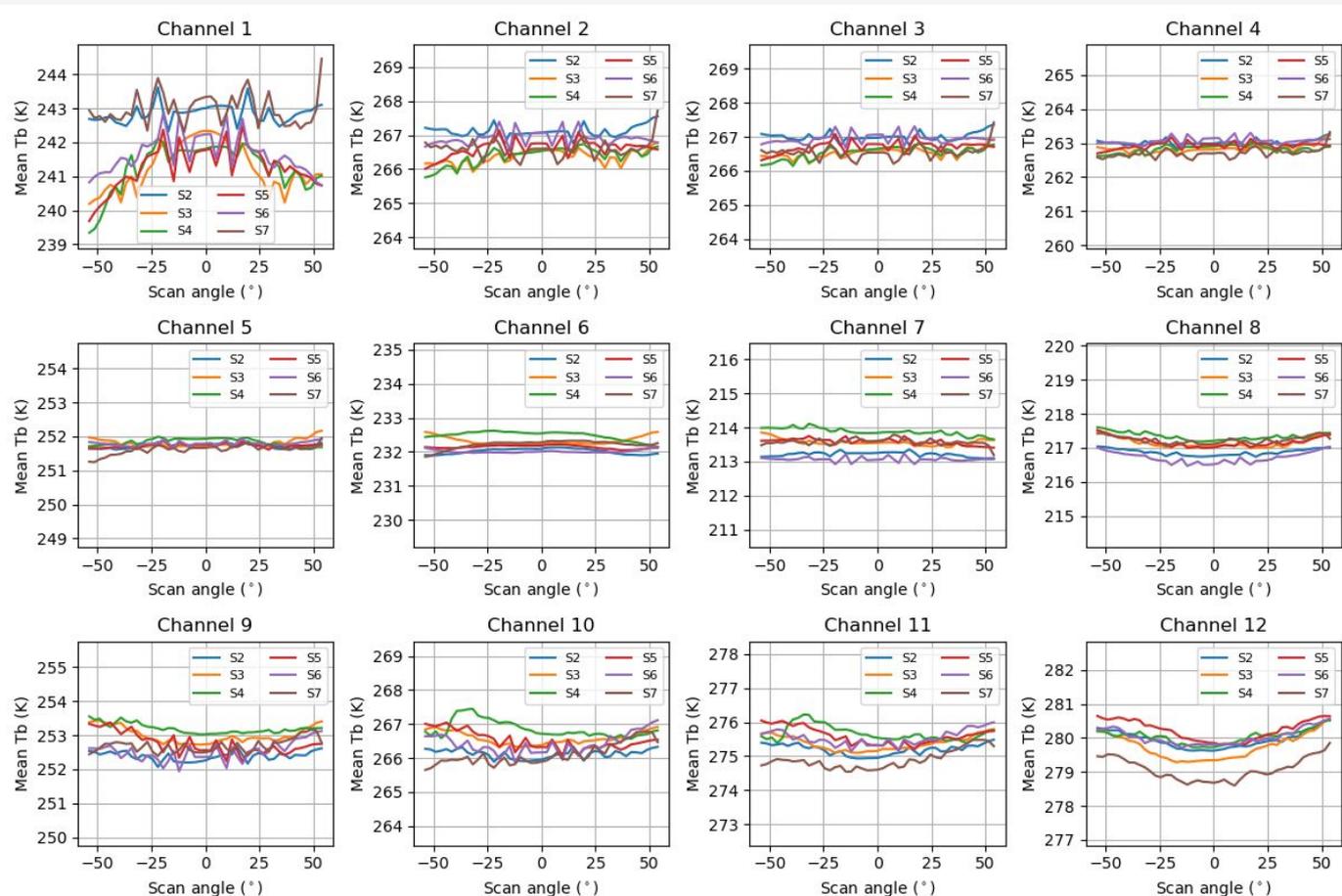


Level 1C Intercalibration + Limb adjustment vs. scan angle

35S to 35N
Ocean only
May 1 - June 15 2025

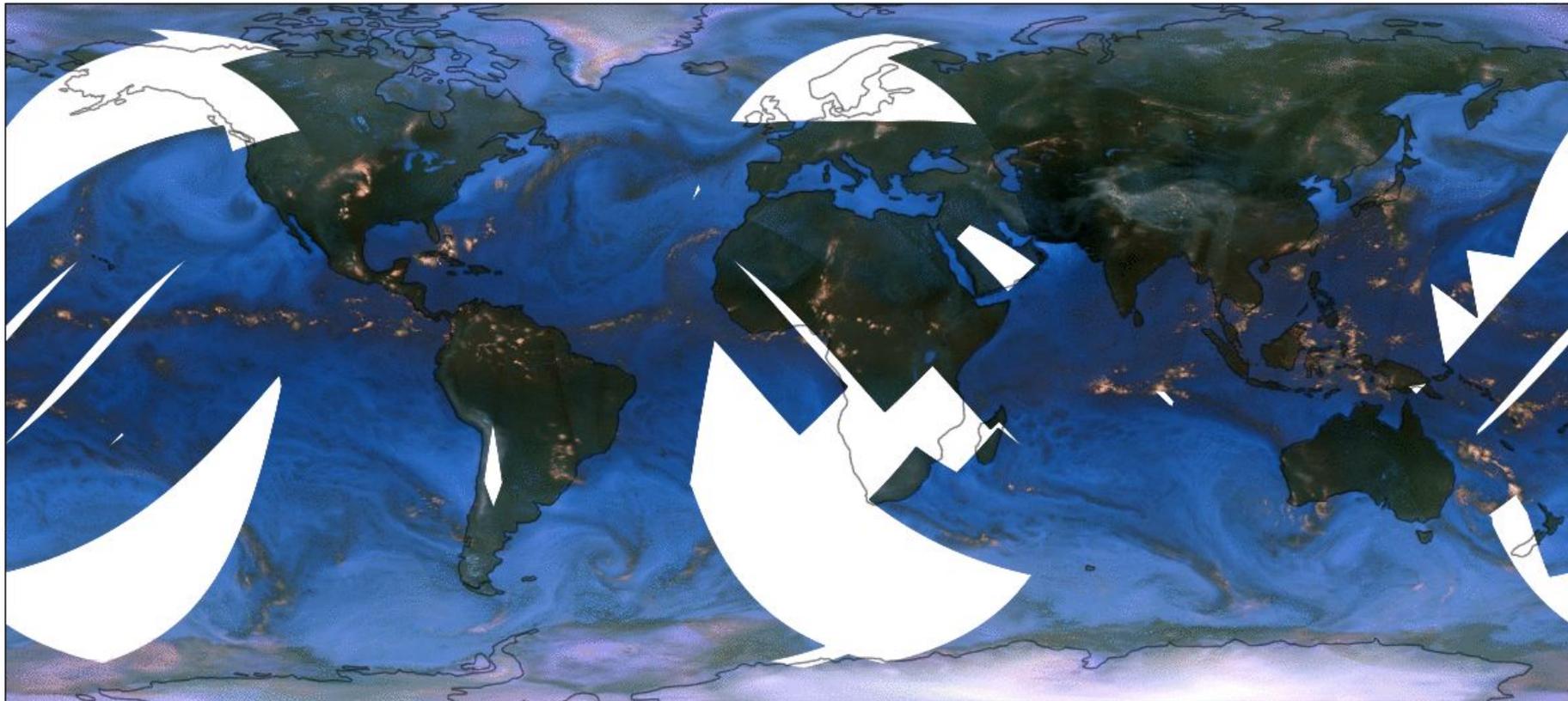
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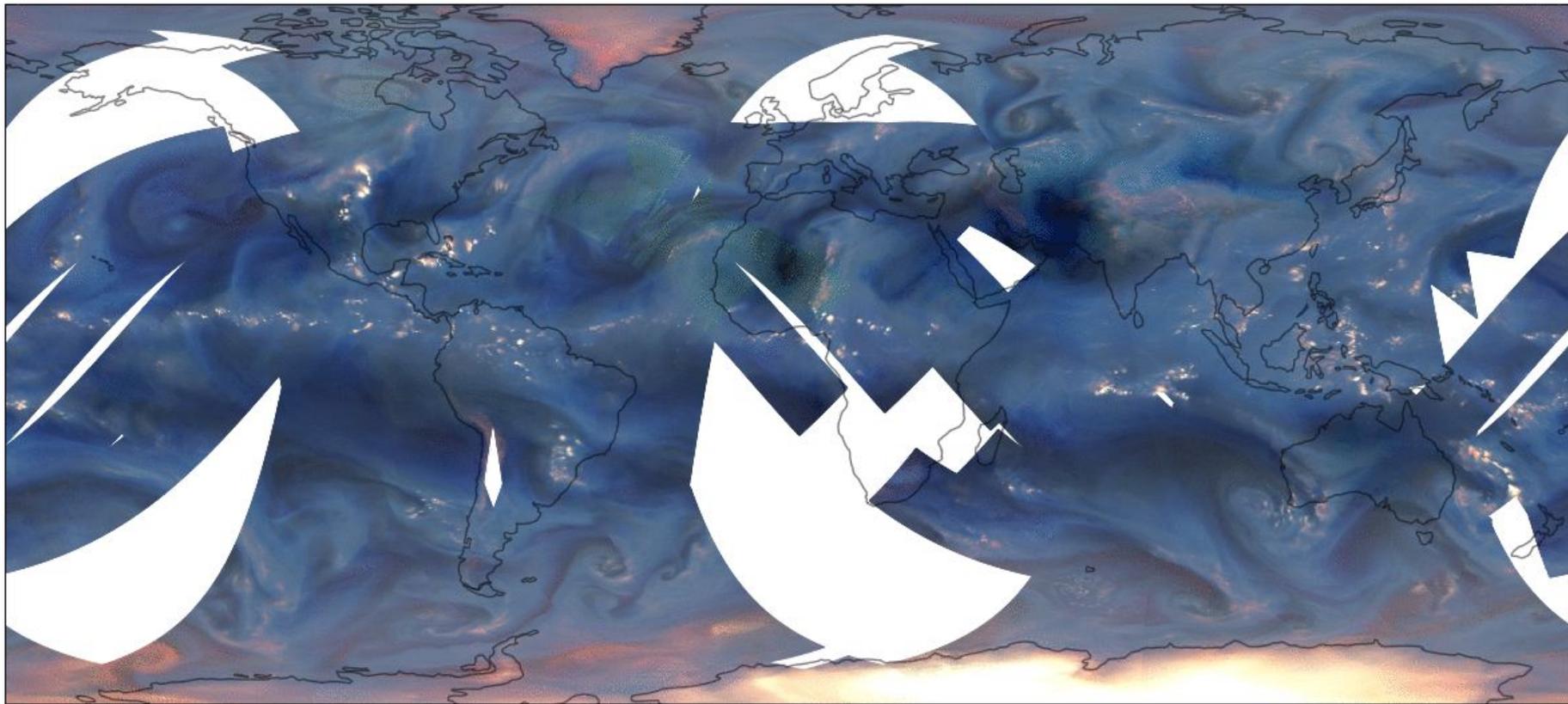
TMS 6-hourly coverage - Window Channel (ch 1,2,12) RGB composite from 1C-TCR with limb adjustment and intercalibration

All TMS Observations 2025-06-03 0000Z-0600Z



TMS 6-hourly coverage - Water Vapor (ch 9,10,11) RGB composite from 1C-TCR with limb adjustment and intercalibration

All TMS Observations 2025-06-03 0000Z-0600Z



Example Application of 1C-TCR product: CIMSS DMINT183 tropical cyclone intensity estimates (CNN trained on ATMS and SSMIS)

tropic.ssec.wisc.edu/Tomorrow/DMINT/2025/2025_32W_history_MWIR_TOMORROW.html



20251108	0649 UTC	SSMISF18	963 hPa	87 kts	80 kts	93 kts	<p>Estimated Max Wind Speed for 32W based on SSMISF18 at 20251108 0649UTC and IR from 12 previous hours IR from 20251108 at 0600UTC</p>
20251108	0308 UTC	TMS03	972 hPa	71 kts	66 kts	77 kts	<p>Estimated Max Wind Speed for 32W based on TMS-03 at 20251108 0308UTC and IR from 15 previous hours IR from 20251108 at 0300UTC</p>
20251108	0157 UTC	TMS02	966 hPa	79 kts	74 kts	85 kts	<p>Estimated Max Wind Speed for 32W based on TMS-02 at 20251108 0157UTC and IR from 15 previous hours IR from 20251108 at 0100UTC</p>
20251108	0123 UTC	TMS05	965 hPa	82 kts	77 kts	88 kts	<p>Estimated Max Wind Speed for 32W based on TMS-05 at 20251108 0123UTC and IR from 15 previous hours IR from 20251108 at 0100UTC</p>
20251107	2157 UTC	SSMISF16	973 hPa	80 kts	73 kts	87 kts	<p>Estimated Max Wind Speed for 32W based on SSMISF16 at 20251107 2157UTC and IR from 12 previous hours IR from 20251107 at 2100UTC</p>



Summary and Data Availability

- TMS initial operating capacity reached and deployments continuing, with recent launch of S8 and S9 into 45-degree inclination orbit
- Intercalibration and limb adjustment technique using QRNN demonstrates consistency of calibration among payloads with different spectral responses
- Level 1C intercalibrated (1C-TC and 1C-TCR) products are produced in real time and already used by CIMSS for tropical cyclone intensity estimates
- Questions? Reach out to me at joe.munchak@tomorrow.io

Thank You 