NASA TROPICS Earth Venture Mission: Update on Pathfinder's 18+ Months of Calibration and Validation

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

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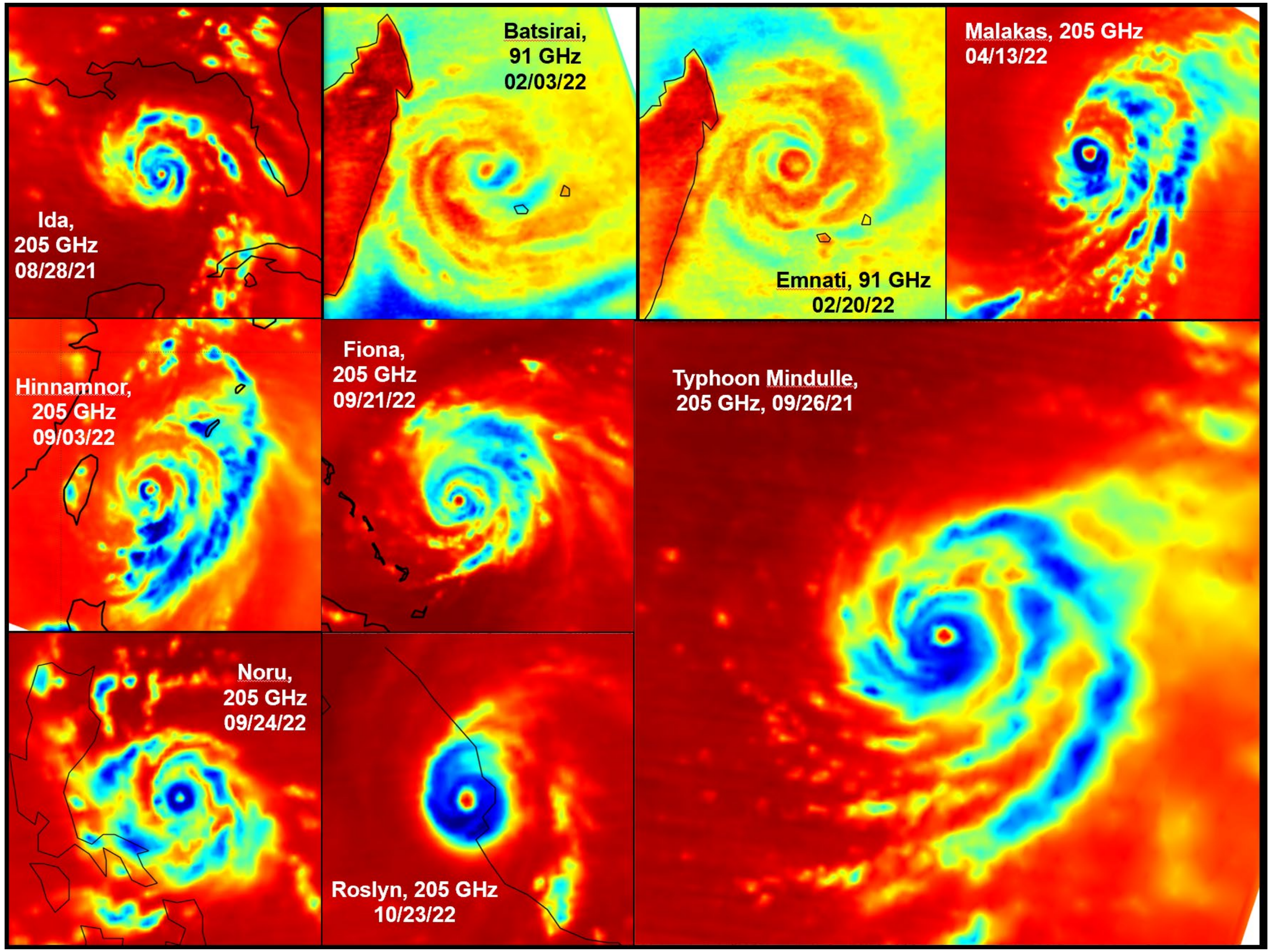
Outline

- Mission & Space Vehicle Overview
- Pathfinder Calibration Overview
- New Post-launch Calibration Optimization
- Validation Results

https://tropics.ll.mit.edu

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

- **NASA Earth Venture Program led by MIT LL**
  - Principal Investigator: Dr. William J. Blackwell
  - Project Scientist: Dr. Scott A. Braun (NASA GSFC)
- **Innovative solution to provide high-revisit temperature, moisture, and precip. data for tropical cyclone studies**
  - Observations in 12 channels spanning 90/118/183/205 GHz
- **Constellation of four 3U cubesats (2 lost in LV failure)**
  - 2U spacecraft bus from Blue Canyon Technologies
  - 1U microwave radiometer payload from MIT LL
- **An identical Pathfinder cubesat (QUAL) launched on 30-June-2021 & is still operating**
- **Rocket Labs was chosen as the new launch provider with launches NET May 2023 (VA, USA or Mahia, NZ launch sites)**



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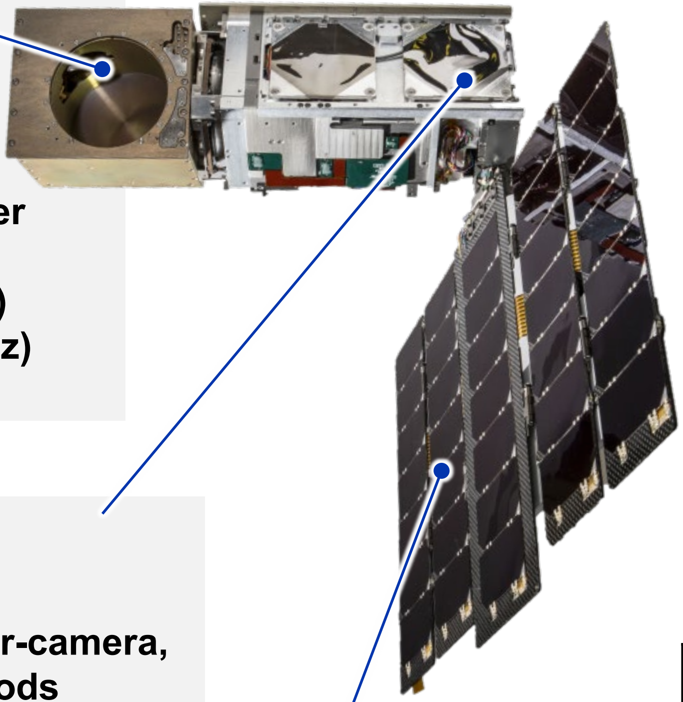
Space Vehicle Highlights

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

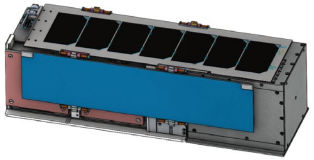
1U Payload
- Rotating microwave radiometer
- Scanner assembly
- 83 mm aperture
- Noise-diode / deep space calibration

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

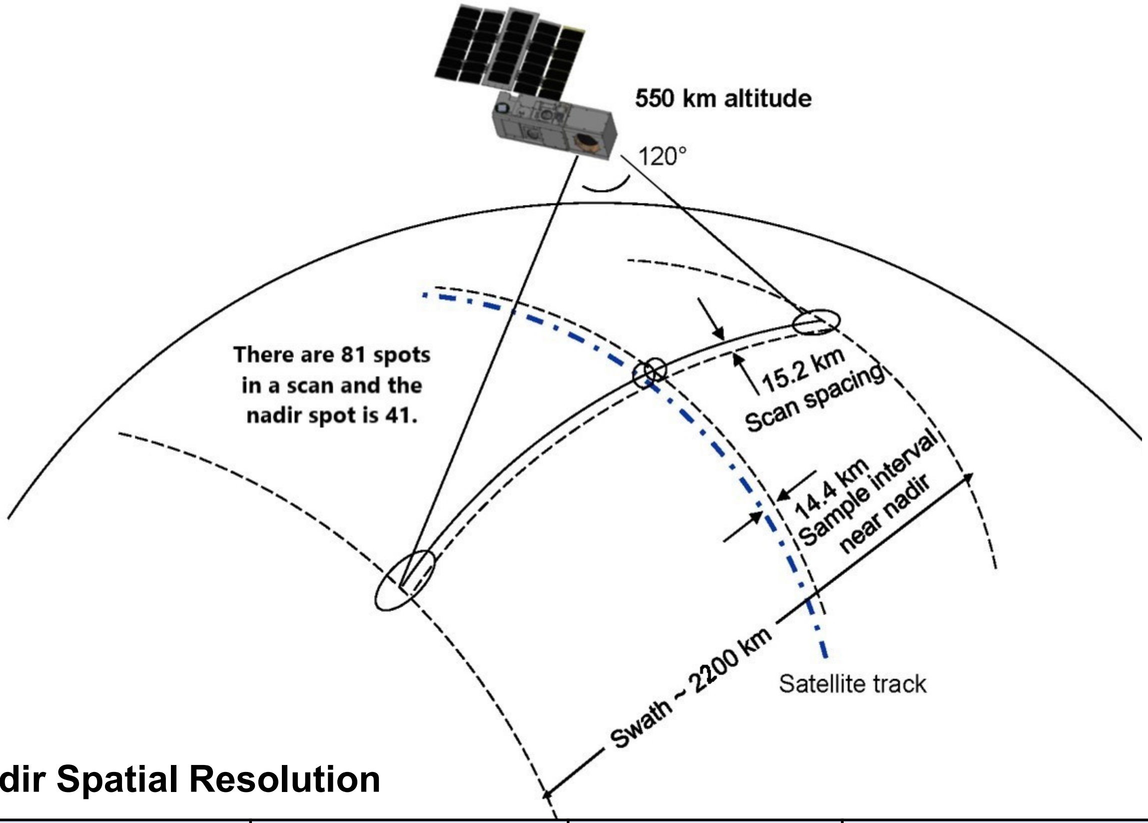


2U Bus: BCT XB-1
- S-band radio
- ADCS: sun sensor(s), star-camera, reaction wheels, torque rods

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

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Radiometric Counts (L0)

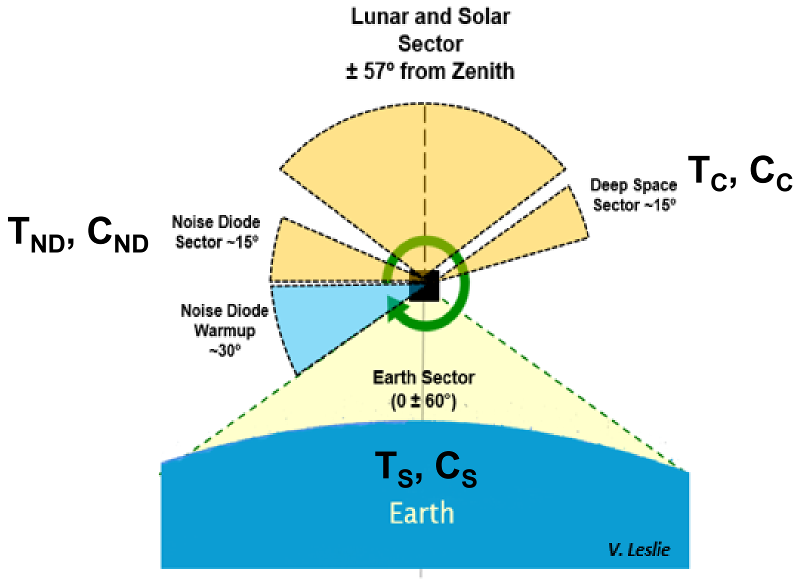
↓

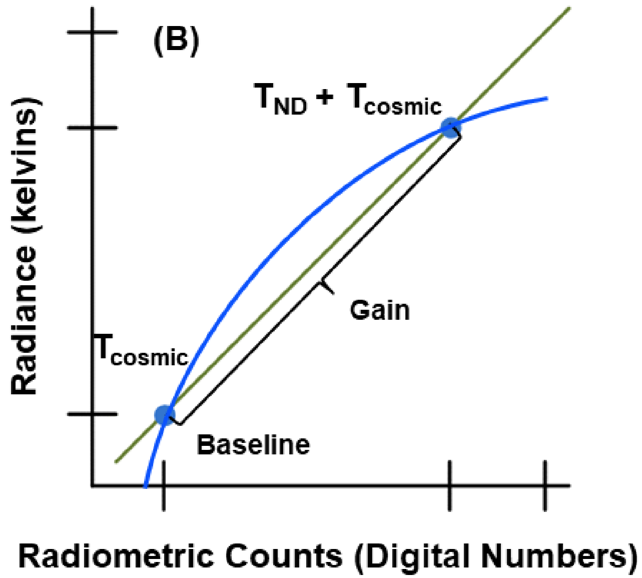
Calibration Algorithm

← **Non-linearity (T_{NL}) & ND Temp. (T_{ND})**

↓

Estimated Scene Radiance (L1)





L1a Cal. Eq.

$$T_S = T_C + g * (C_S - C_C) + 4 * (x - x^2) * T_{NL}$$

$$g = \frac{T_{ND} - T_C}{C_{ND} - C_C} \qquad x = \frac{T_S - T_C}{T_{ND} - T_C}$$

L1b Cal. Eq.

$$T_B = \frac{T_A - \eta_{DS} \cdot T_C}{\eta_E}$$

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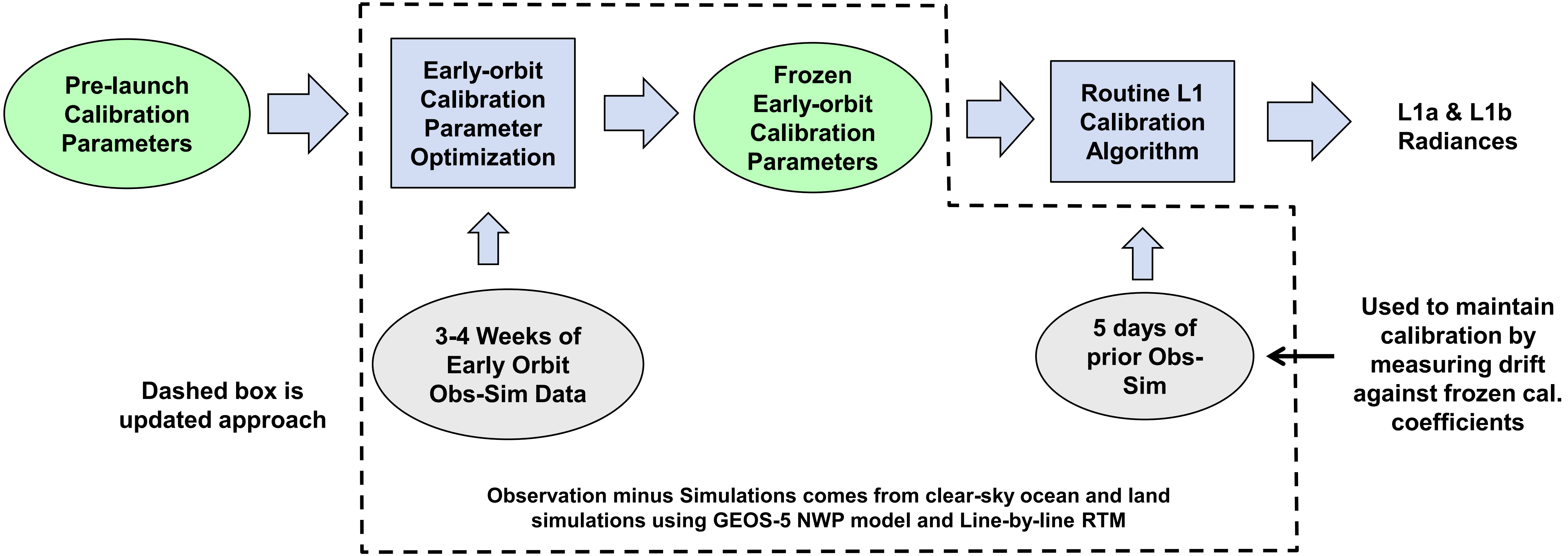
Updated On-orbit Calibration Approach



This on-orbit calibration system anchors and stabilizes the L1 calibration against a particular NWP and RTM combo (GEOS-5 & Rosenkranz line-by-line) and allows upstream data products to maintain their own static bias corrections

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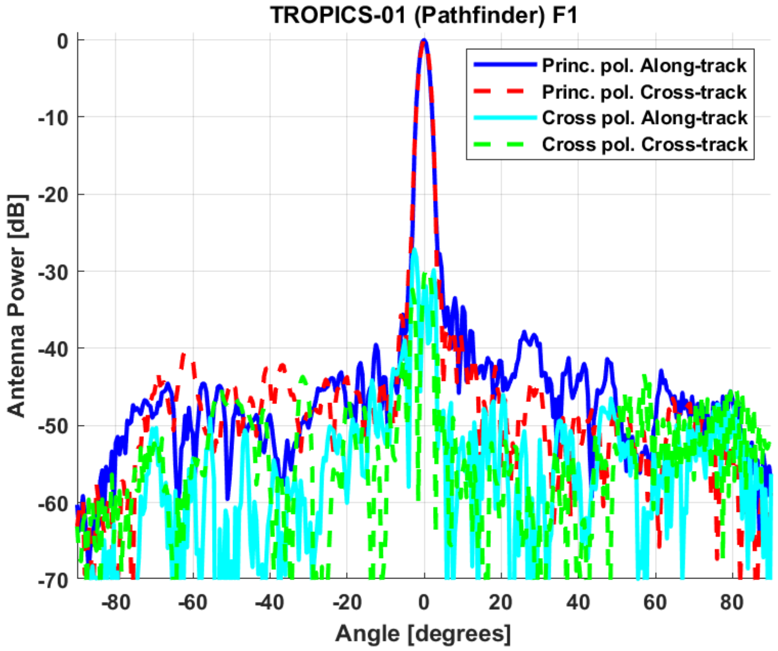
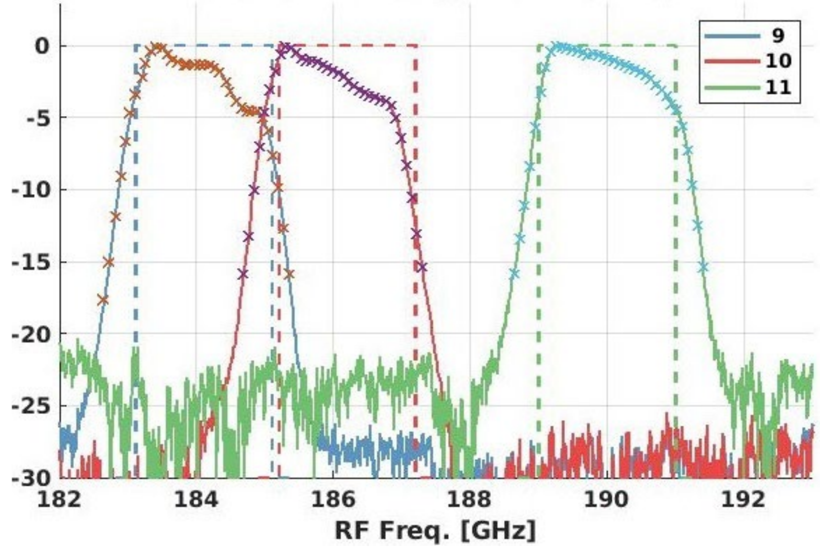
Pre-Launch Characterization

Antenna Range



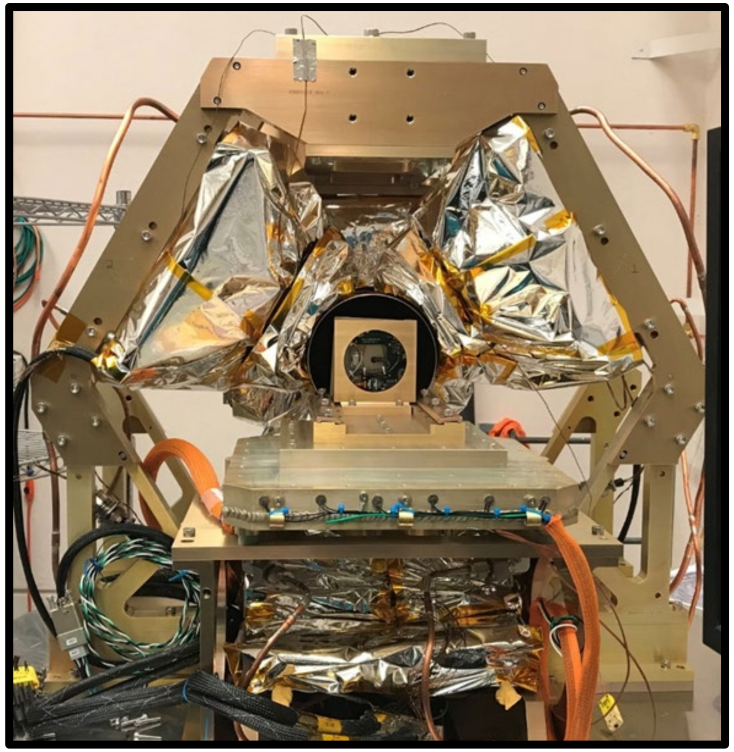
Antenna requirement verification
Scan Bias Correction

Oven with RF Freq. Synthesizer



Passband requirement verification
Spectral Response Function for radiative transfer

Thermal Vacuum Chamber



Performance requirement verification
Noise Diode and non-linearity characterization

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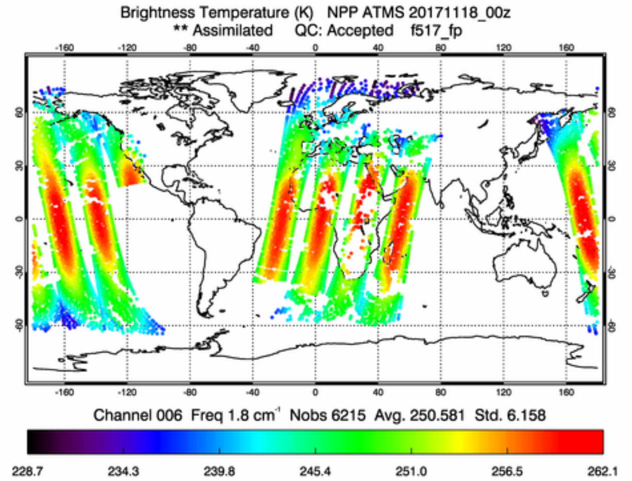
Simulation System for Observation Minus Backgrounds

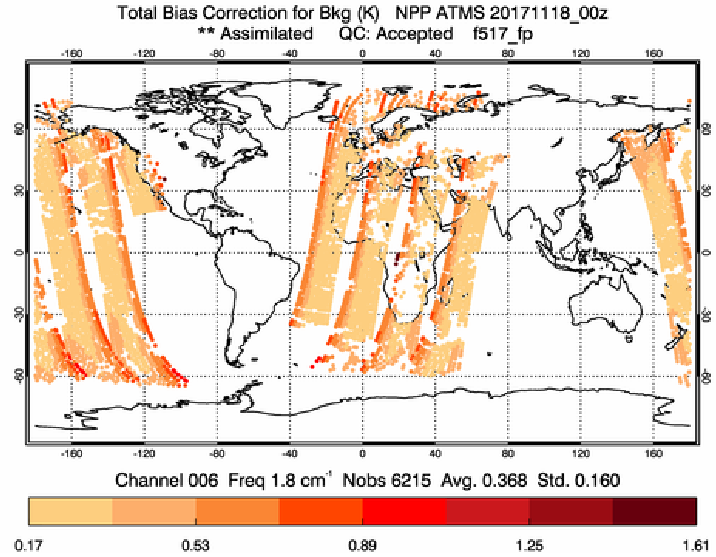
- TROPICS Radiances
- Land mask
- Binary Cloud Mask (GOES)



TROPICS Clear-sky Ocean Radiances

GEOS-5 Radiances from LBL RTM using SRF

Difference the Measured and Simulated Radiances



Radiometric Bias

Scan bias correction for each space vehicle, channel, and Earth measurement.

Calibration Equation Parameterization

L1a Cal. Eq.

$$T_A = T_C + \frac{T_{ND} - T_C}{C_{ND} - C_C} \cdot (C_S - C_C) + T_{NL}(T_{instr}) \cdot 4 \cdot (s - s^2) \qquad s = \frac{C_S - C_C}{C_{ND} - C_C}$$

L1b Cal. Eq.

$$T_B = \frac{T_A - \eta_{DS} \cdot T_C}{\eta_E}$$

$$T_A = a_0 + a_1 \cdot s + a_2 \cdot 4 \cdot (s - s^2)$$

$$T_B = d_1 \cdot T_A + d_0$$

1st Step: Early Orbit Optimization of T_A using near-nadir clear-sky ocean measurements

$$\min_{a_i} \sum_{n=1}^{N} (T_B^n(a_i) - T_{sim}^n)^2$$

with a_0 constraints and placeholder d_i

2nd Step: Early Orbit Optimization of T_B using all-spots clear-sky ocean measurements

$$\min_{d_i} \sum_{n=1}^{N} (T_B^n(d_i) - T_{sim}^n)^2$$

with constraints to match sidelobe corruption model

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L1a Equation Parameterization

Non-linearity parameterization

$$a_2 = c_0 + c_1 \cdot T_{instr} + c_2 \cdot {T_{instr}}^2$$

$$T_A = a_0 + a_1 \cdot s + a_2 \cdot 4 \cdot (s - s^2)$$

$$s = \frac{C_S - C_C}{C_{ND} - C_C}$$

Noise Diode Temp. parameterization

$$a_1 = b_0 + b_1 \cdot T_{instr} + b_2 \cdot {T_{instr}}^2 + \ b_3 \cdot NDcnts + \ b_4 \cdot \ NDcnts^2$$

NDcnts are the radiometric difference between the noise diode powered on and powered off

A de-mixing correction is required for Ch. 4-8 using Ch. 2

$$\widehat{C_S} = e_1 \cdot C_s + e_2 \cdot C_s^{Ch.2}$$

e_i parameters are derived separately in a minimization using clear-sky land & ocean simulations

The calibration sustainment that anchors to GEOS-5 FP NWP

$$a_1 = \ f_0 + \left(b_0 + b_1 \cdot T_{instr} + b_2 \cdot {T_{instr}}^2 + \ b_3 \cdot NDcnts + \ b_4 \cdot \ NDcnts^2\right)$$

f_0 is derived every orbit using a minimization between T_B and T_{sim} from the prior five days

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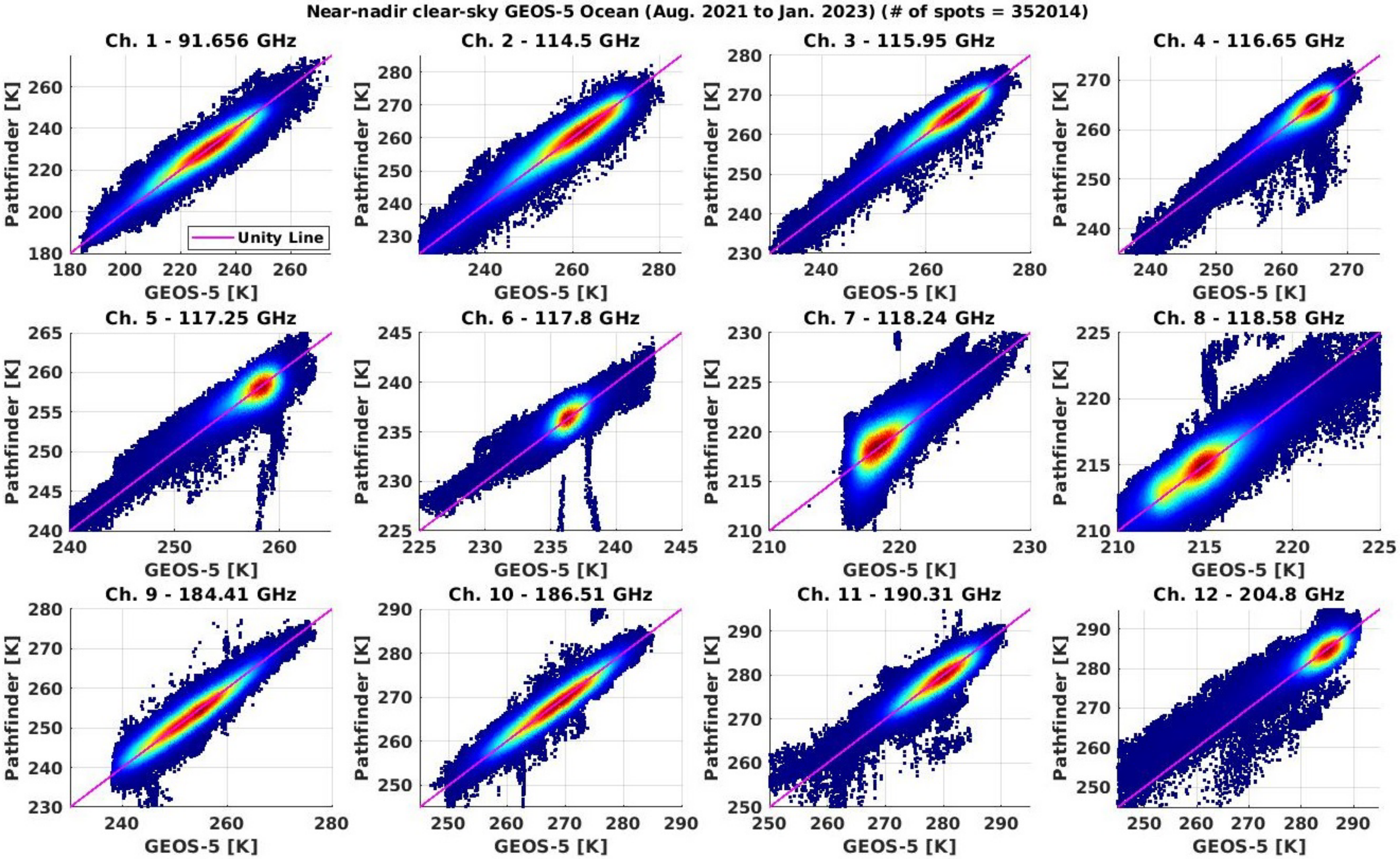
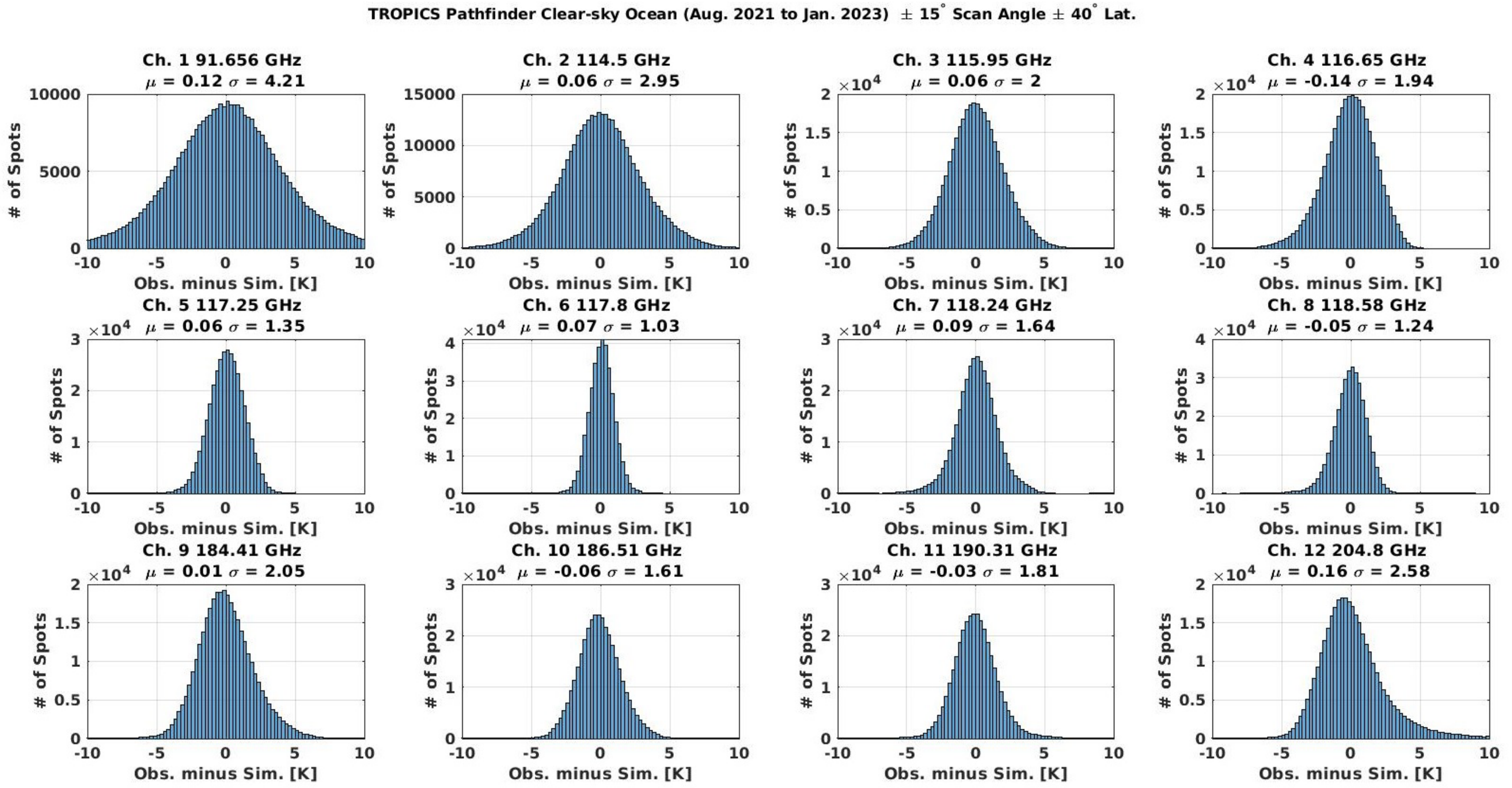
Pathfinder Scatterplots vs GEOS-5 FP NWP



Near-nadir clear-sky ocean ±40˚ lat. (Five random days from each month)

GEOS-5 FP O-B Histograms (Aug. 2021 to Jan. 2023)



Chan.	Post-launch NEDT (K)*
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**

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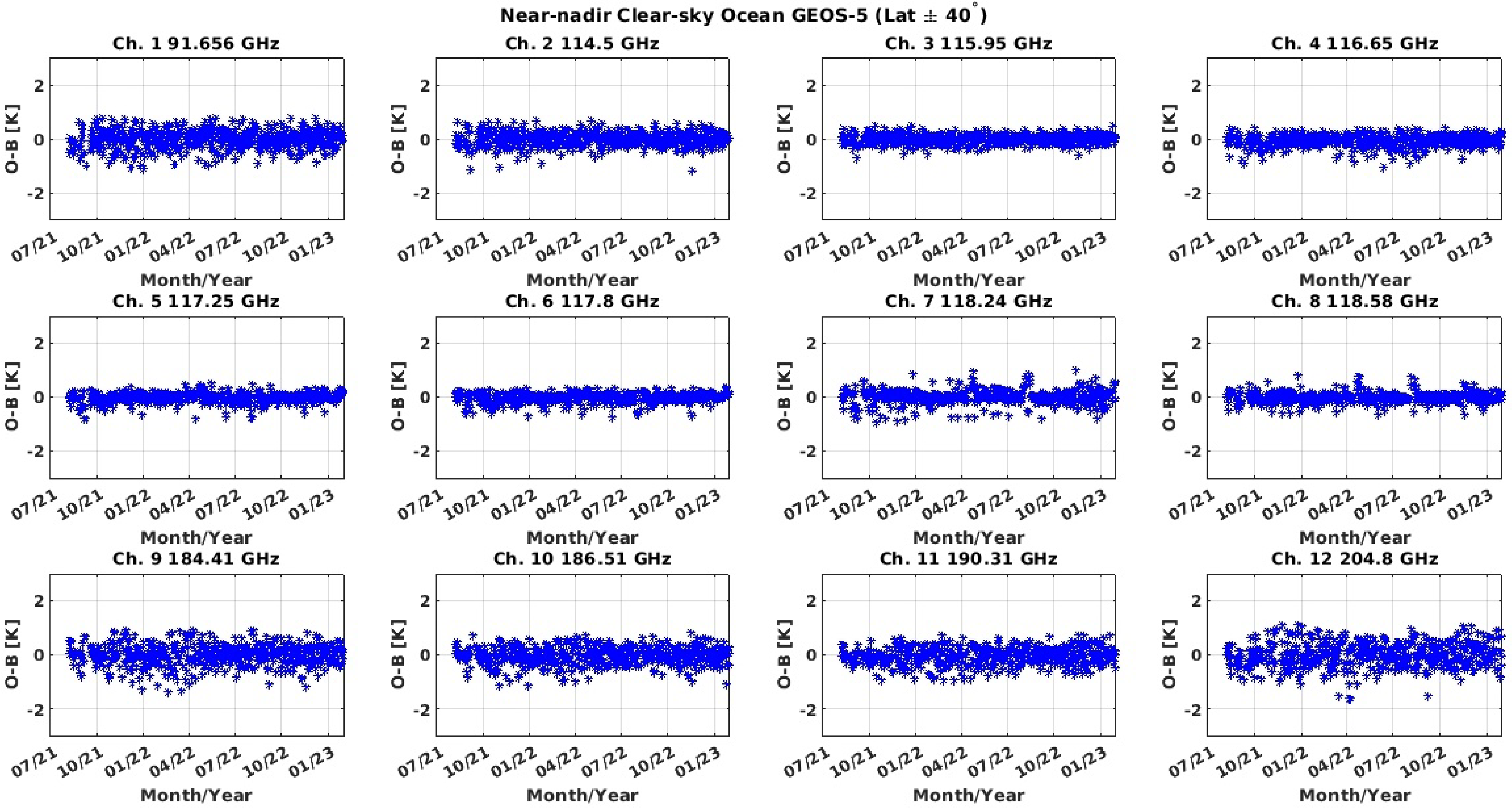
Calibration Sustainment Verification Using Average Daily Obs-Sim



Daily Mean

L1b Scan Bias Correction Optimization

Non-scene sources of radiance
(e.g., spacecraft or deep space)

$$T_A = \eta_{SC} \cdot T_{SC} + \eta_{DS} \cdot T_{DS} + \eta_E \cdot T_B$$

η is the integrated antenna pattern within the angular extent of the spacecraft, deep space, or Earth that sum to one.

Combine into non-scene contributions
(SL is antenna pattern side lobes)

$$T_B = \frac{1}{\eta_E} \cdot T_A - \frac{\eta_{SL} \cdot T_{non-scene}}{\eta_E}$$

Gain ranges from 1 to 1.2

This contribution needs to be less than zero

$$T_B = d_1 \cdot T_A + d_0$$

$$d_0 = x_0 + \sum_{k=1}^{N} x_k BP^k$$

d_0 is constrained to be less than zero (because of plus sign) to follow model above

$$d_1 = y_0 + \sum_{k=1}^{M} y_k BP^k$$

d_1 is constrained to range between 1.0 to 1.2 to follow model above

BP is beam position and ranges from -40 to 40 (passing through zero) to match the 81 Earth Sector spots

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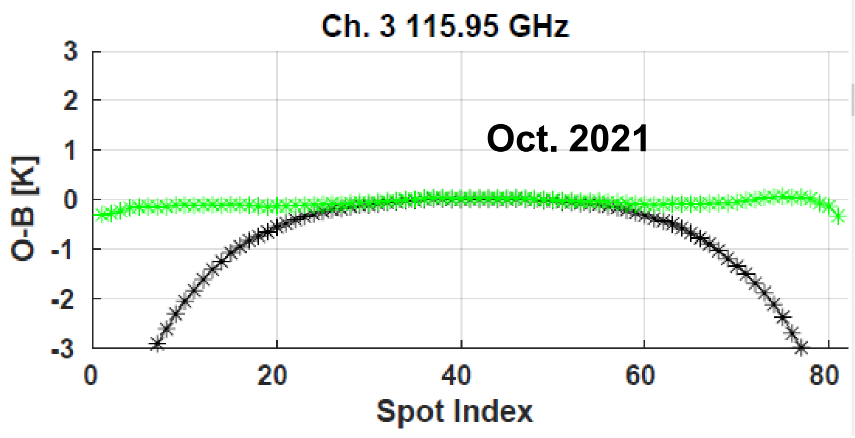
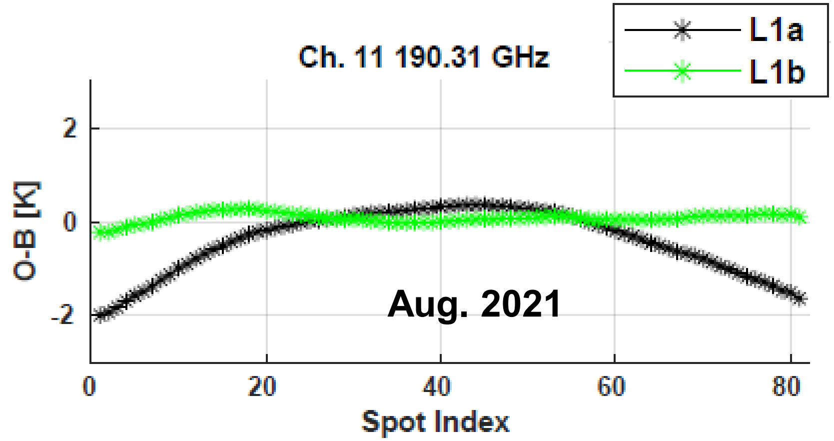
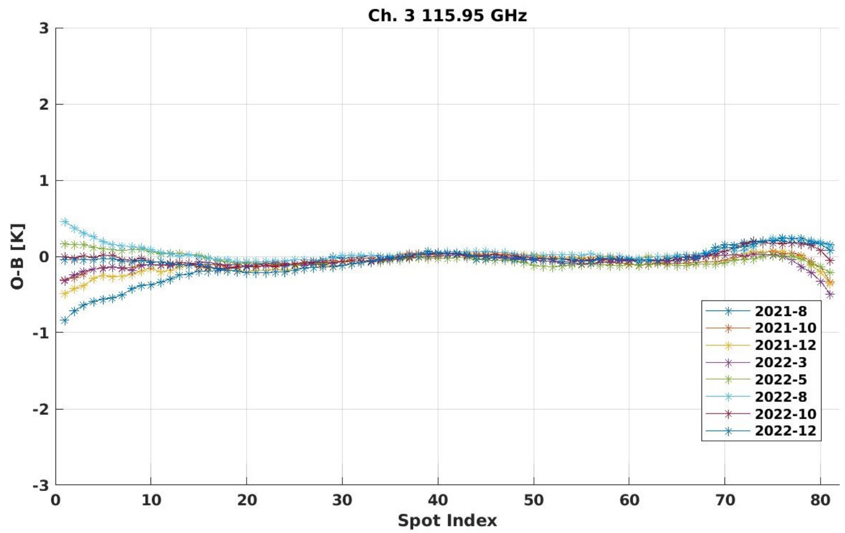
L1b Scan Bias Correction

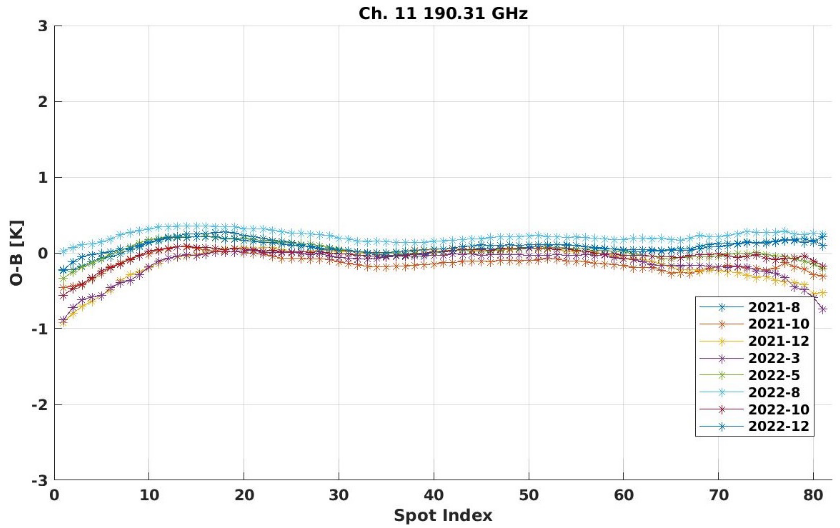


Empirically derived corrections



Clear-sky
Ocean
± 40˚ Lat.
GEOS-5
L-by-L RTM
fastem v2

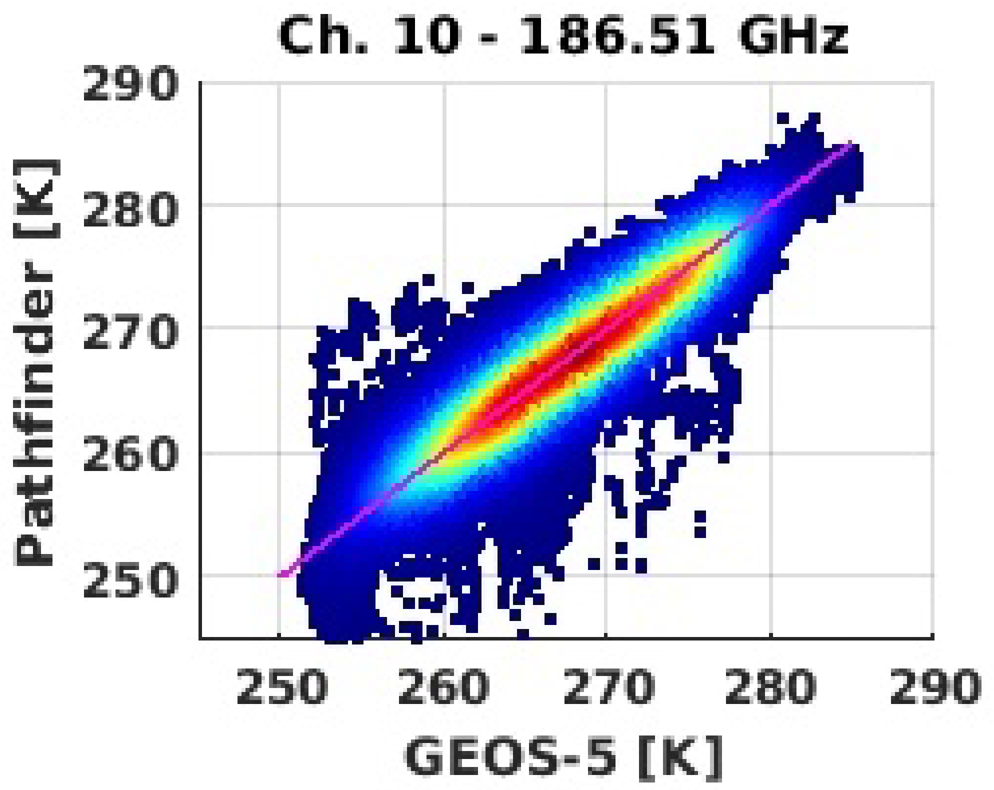




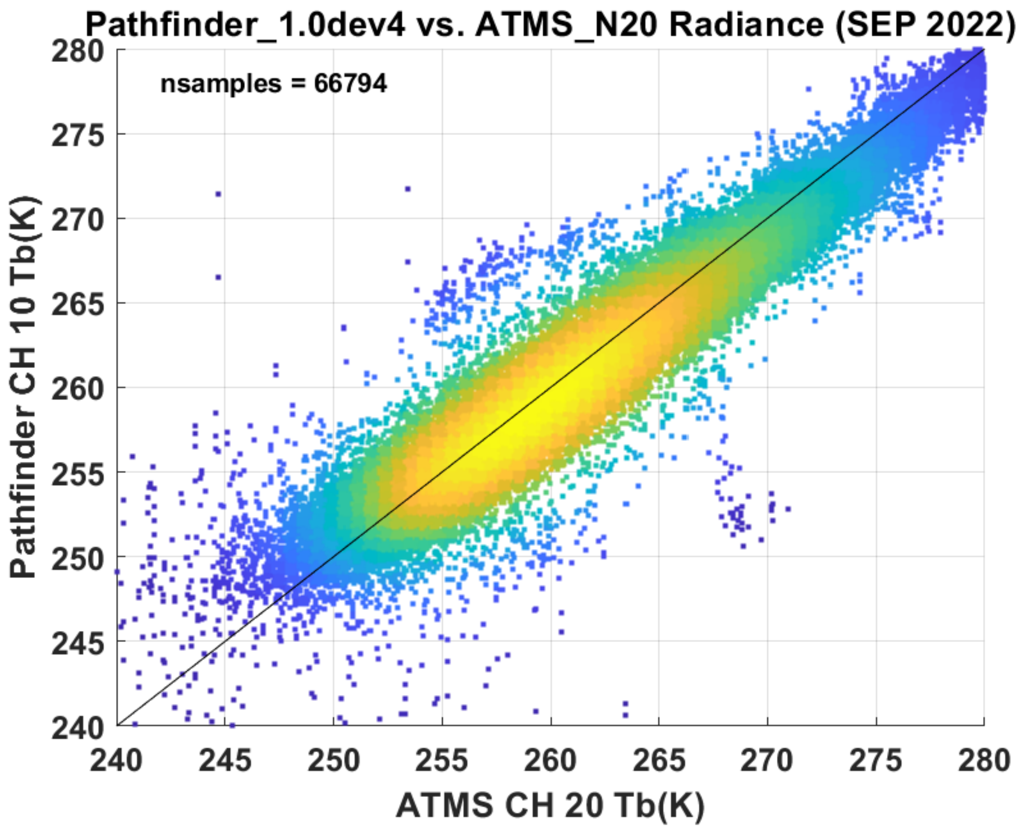
Showing errorbars with mean and ± 1 sigma

Comparisons with ATMS Overpasses

Comparisons against ATMS Simultaneous Overpasses was used to validate simulation system



Clear-sky near-nadir



Global matching of all spots and all weather conditions (< 1 hr, < 50 km, & <1˚ scan angle)

Sept 2022 GEOS-5/LbL & N-20 ATMS

Summary & Path Forward

- Pathfinder (TROPICS-01) L1a & L1b has reached Validated 1 data product maturity
  - Validated against clear-sky ocean GEOS-5 & Line-by-line model to <0.2 K over mission lifetime (± 40° Lat.)
  - All channels NEDTs are meeting or exceeding expectations
  - Released to TROPICS Early Adopters and available soon to the public at GES DISC
  - W- and G-band validated against global all-sky ATMS collocated and co-incidental measurements
- Constellation calibration approach will be similar to Pathfinder
- Updated CRTM/RTTOV coefficients required due to updated polarization angles
- A pair of constellation launches are scheduled no-earlier-than May 2023 (Rocket Lab) with two CubeSats per launch/plane
- Upcoming validation activities:
  - Verifying simulation system with ATMS as input
  - TROPICS Obs-Sim using ERA-5 reanalysis and CRTM (MIT LL Prof. Cahoy)
  - Adding FY-3 MWHS-2 single differences comparisons for TROPICS F-band channels validation
  - Implement double-difference validation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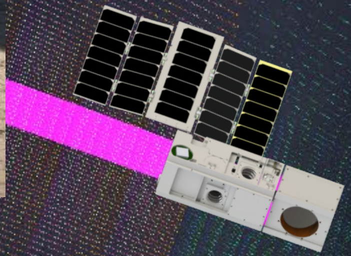


Questions?

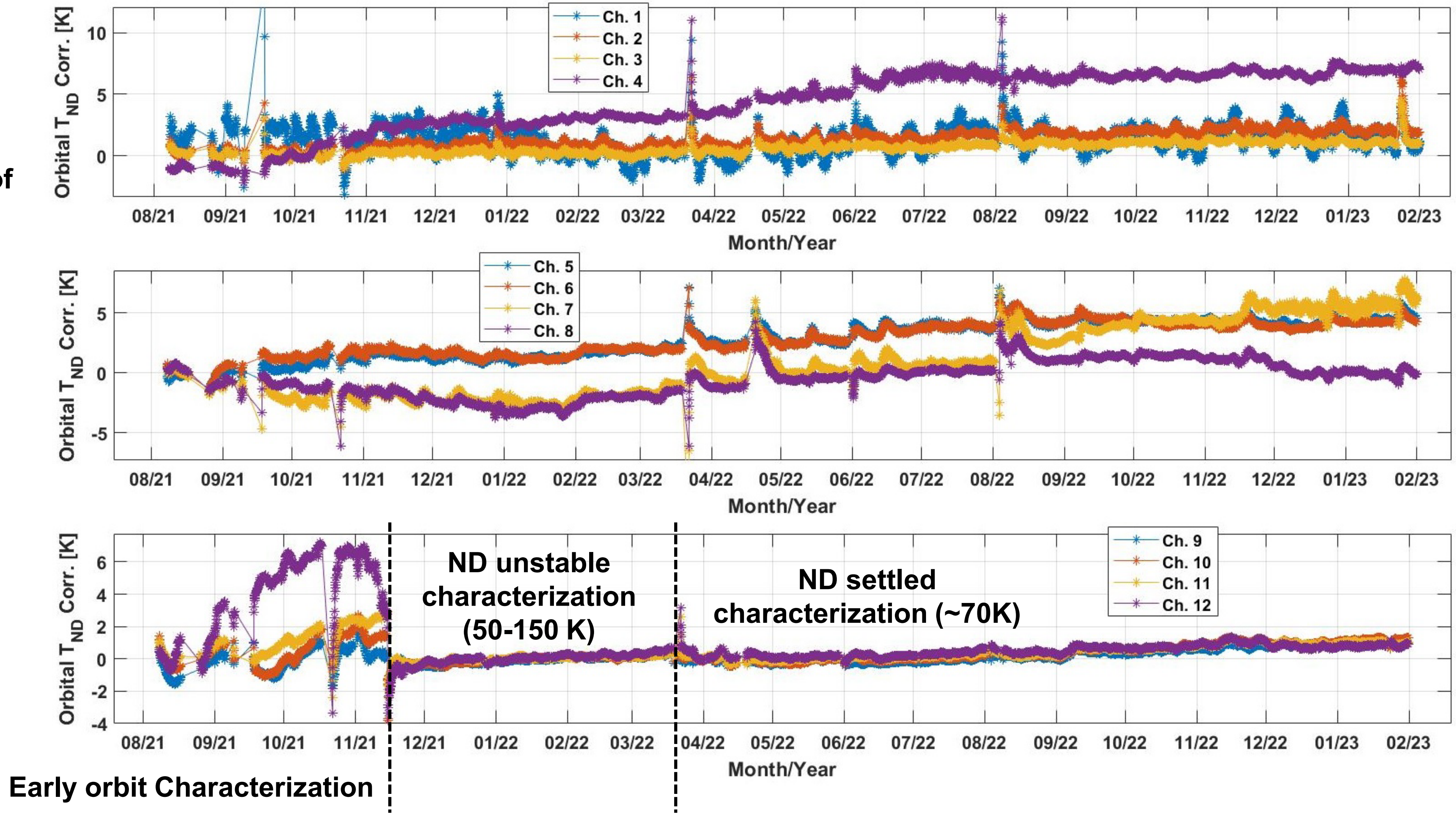
Parameter Overview

Cal. Parameter	Description	Notes
a0	Deep space offset	Initialized using modified Rayleigh-Jeans equation
a1	Warm calibration point	Initialized with TND estimator derived from TVac cal.
a2	Peak non-linearity for parabolic correction	Initialized using pre-launch TVac coefficients converted to roughly on-orbit calibration points
b	Coefficients used to estimate a1 above	Predictors: 2nd order instr. temp. for Ch. 1-3 and F1/F2 ND differences for Ch. 4-8 (pre-launch Tvac cal.); Ch9-12 use instr. temp., G1-G4 ND diff., and F1 & F2 ND diff.
c	Coefficients used to estimate a2 above	Predictors: 2nd order instr. temp.
d	Scan bias corrections	Linear and initialized using parameters informed from antenna patterns
e	De-mixing coefficients of W/F band channels with crosstalk (W/F band only)	Used Ch.2 as interferer and initialized using coefficients derived from clear-sky ocean O-B statistics and qualitative land/sea boundaries of highest peaking weighting functions
f	Causal time-dependent Tnd correction	Uses past N-days of GEOS-5 O-B observations using the Tnd derived from using b coefficients to generate Obs

Calibration Sustainment (f_0)

f_0 calculated every orbit using the prior five days of clear-sky ocean Obs-Sim

The Pathfinder G-band ND anomaly on 14Nov2021 required re-characterizing the ND based on ND behavior



TROPICS Calibration Equation

$$T_B^{MRJ} = \frac{hf}{k} \cdot \left[\left(e^{hf/kT} - 1 \right)^{-1} + 0.5 \right]$$ **Modified Rayleigh-Jeans**

$$T_H = T_C + T_{ND}(X) + T_{sidelobe}^{Ch}$$

$$\acute{T}_C = RJM_{Corr}^{Ch}\left(T_C + T_{sidelobe}^{Ch}\right)$$

$$T_A = \acute{T}_C + \frac{T_H - \acute{T}_C}{C_{ND} - C_C} \cdot (C_A - C_C) + T_{NL}(T_{instr}) \cdot 4 \cdot (s - s^2)$$

$$s = \frac{C_S - C_C}{C_{ND} - C_C}$$

$$T_{NL}(T_{instr}) = a_0 + a_1 \cdot T_{instr} + a_2 \cdot T_{instr}^2$$

Planck-equivalent Antenna Temperature

Radiometric counts from cold or deep space sector

C_A = radiometric counts from Earth measurement
C_{ND} = radiometric counts from hot or Noise Diode sector