Low Uncertainty in a Small Package:

Results from the first year of on-orbit operations of the CTIM CubeSat instrument and implications for future solar observations from SmallSats

Dave Harber, Brian Boyle, Karen Bryant, Zach Castleman, Beth Cervelli, Graham Dean, Sierra Flynn, Adalyn Fyhrie, Timothy Hellickson, Karl Heuerman, Joel Rutkowski, Alan Sims, Jacob Sprunck, Cameron Straatsma, Brandon Stone, McKenzie Hawkins, Mathew Can Den Heeever, Matt Watwood, Odele Coddington, Greg Kopp, Erik Richard, Peter Pilewskie

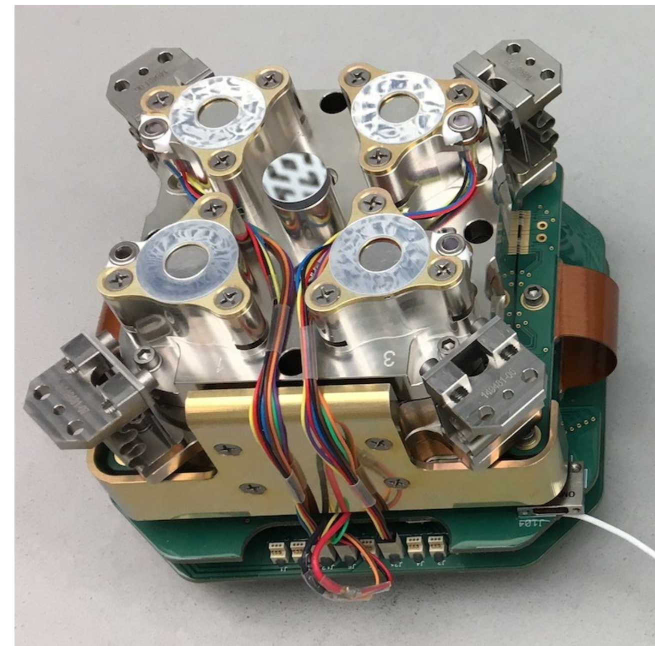
Nathan Tomlin, Michelle Stephens, Chris Yung, Malcolm White, and John Lehman

Quantum Electronics and Photonics Division, Sources and Detectors Group

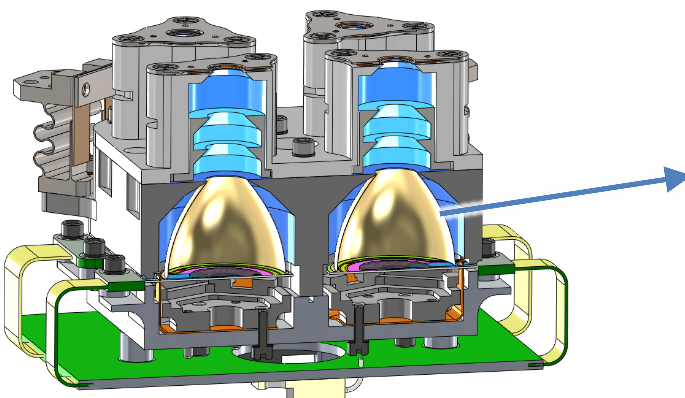
CTIM Instrument

- Detectors
  - Vertically aligned carbon nanotubes on silicon
  - Designed and fabricated by NIST Sources and Detectors group
  - Thermally integrated reflector
- Detector Head
  - Four channels per detector head
  - Silicon precision aperture and shutter for each channel

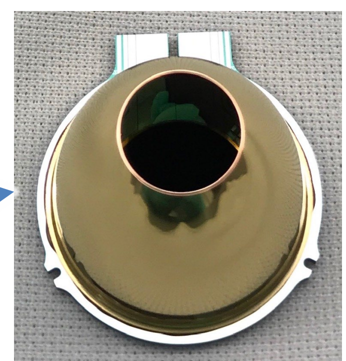
Integrated Detector Head



Cut-Away Model of Detector Head



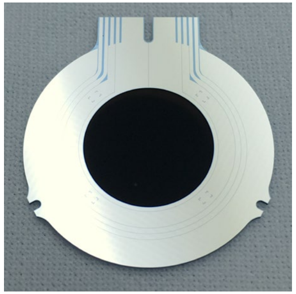
CTIM Detector



CTIM Detectors

Create a cavity from a flat detector

Silicon Detector



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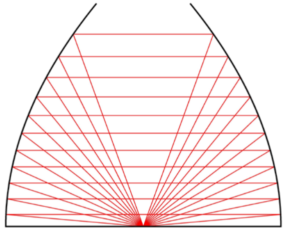
Reflector

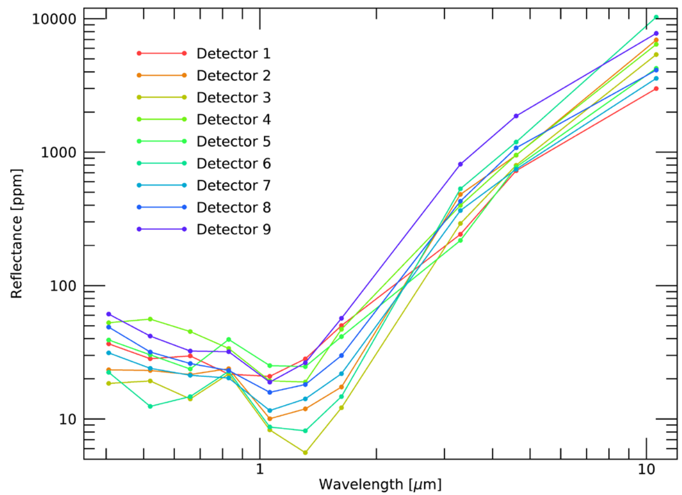


=

CTIM Detector

- Thermally integrated reflector
  - Light absorbed by the dome is also measured as heating
  - Only 51 μm thick, gold plated
- ~10x better optical absorption with reflector
  - Absorbance >99.99%
- Reflector also improves non-equivalence

Detector Reflectance



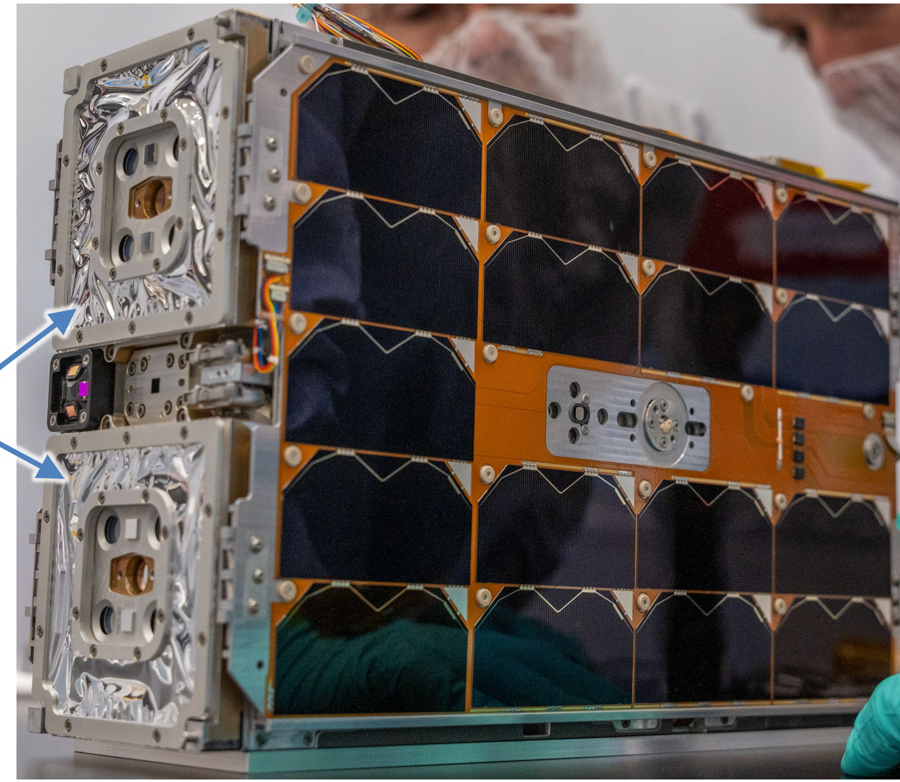
Compact Total Irradiance Monitor CubeSat

- 6U CubeSat
- Dual 4-Channel Heads
  - *Operated as two separate TSI instruments*
  - This allows us to check short and long-term stability between heads
- Launch:
  - Virgin Orbit launch on July 1st, 2022
  - Operations started August 2022

LauncherOne on Cosmic Girl

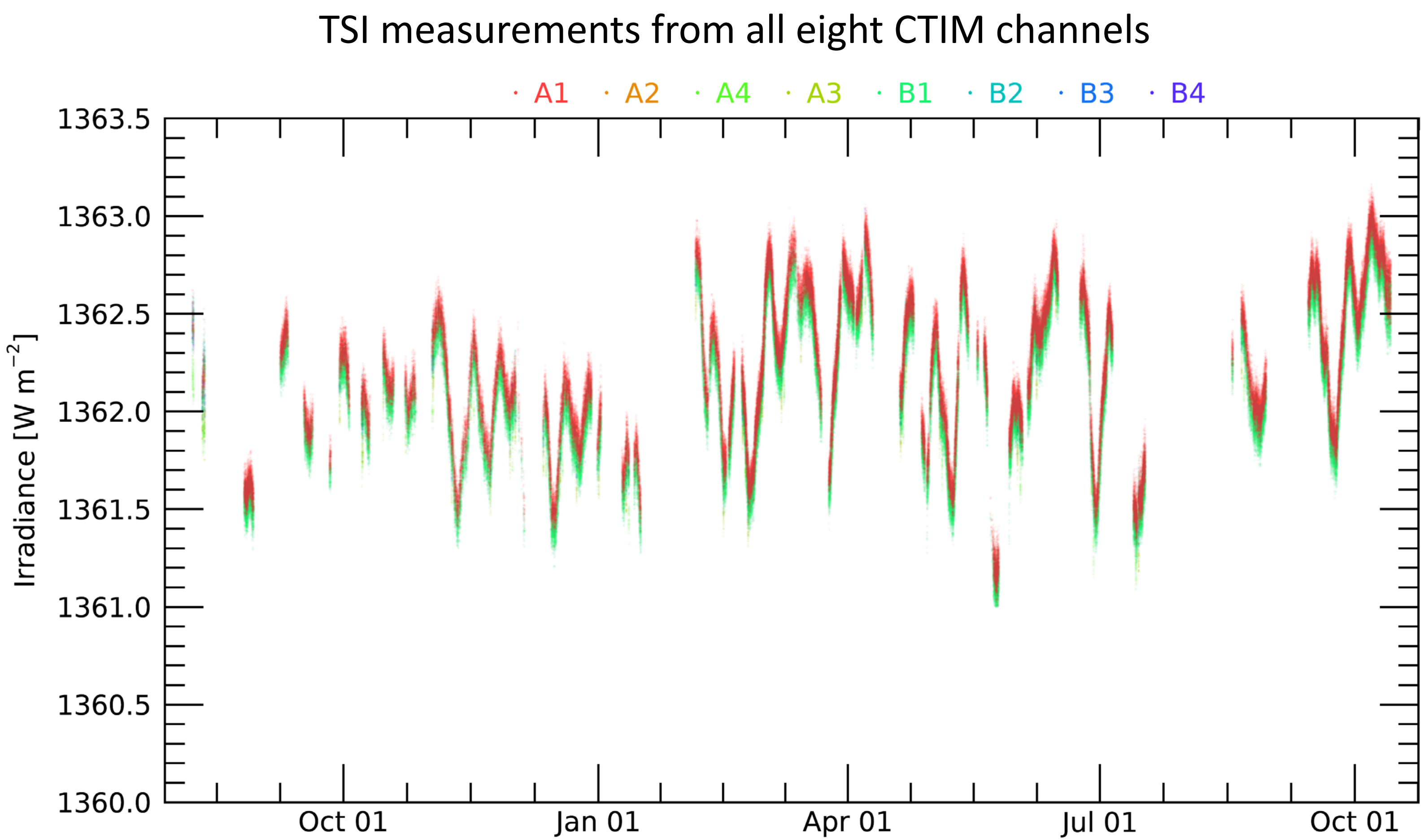
CTIM Prior to Launch Vehicle Integration

Dual Detector Heads



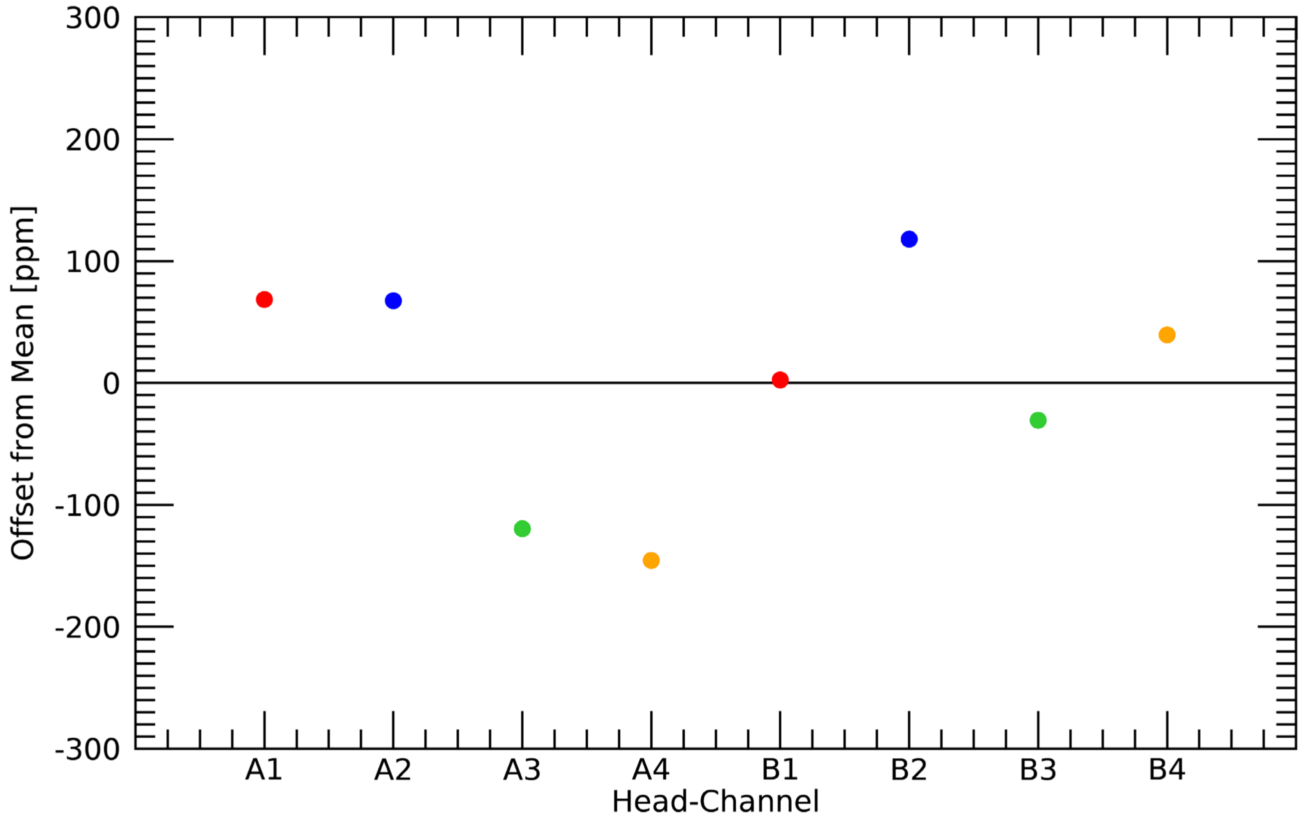
3D model of CTSIS is here, can see size of single CTIM detector head

CTIM TSI Measurements

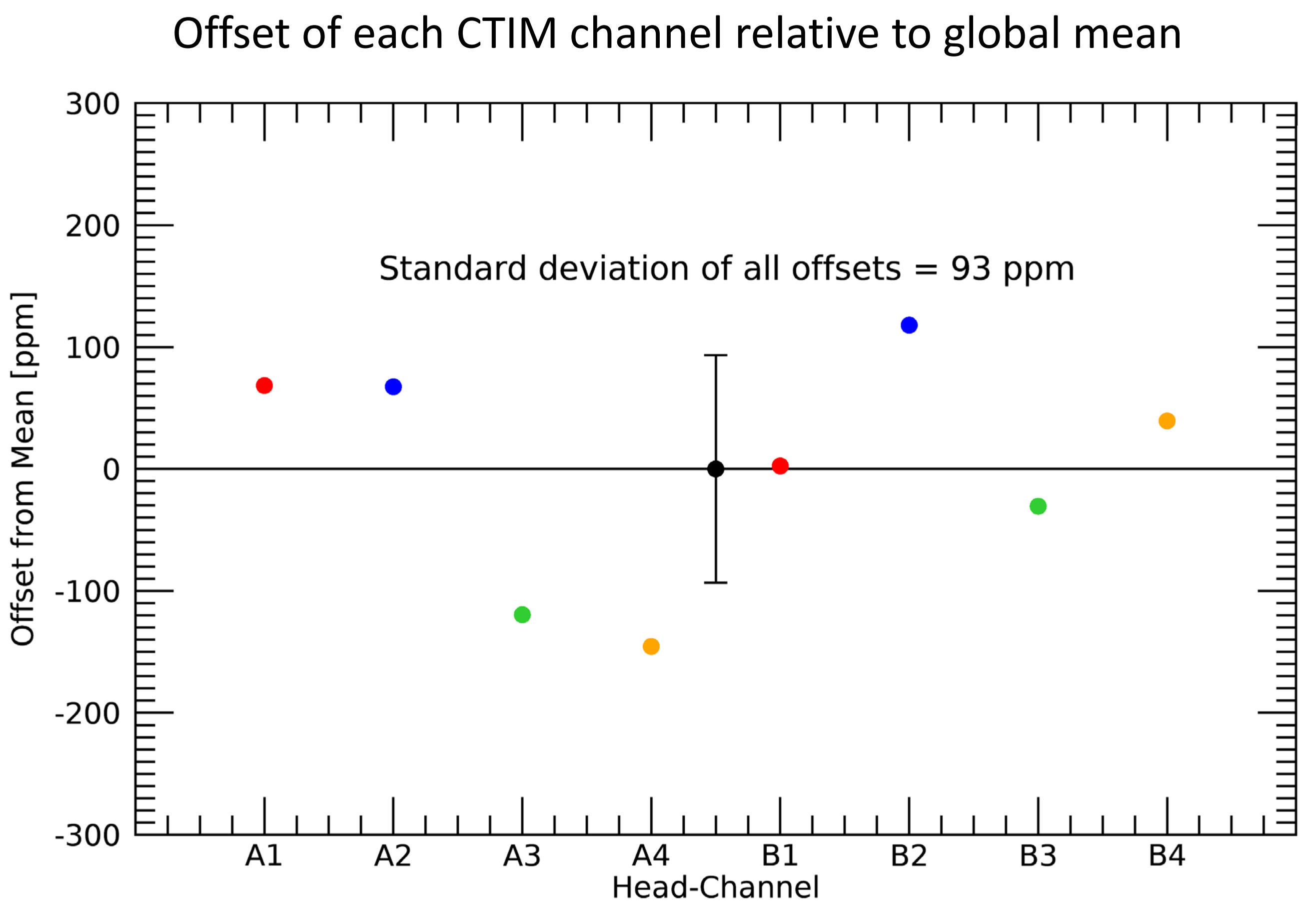


CTIM Channel-Channel Offsets

Offset of each CTIM channel relative to global mean

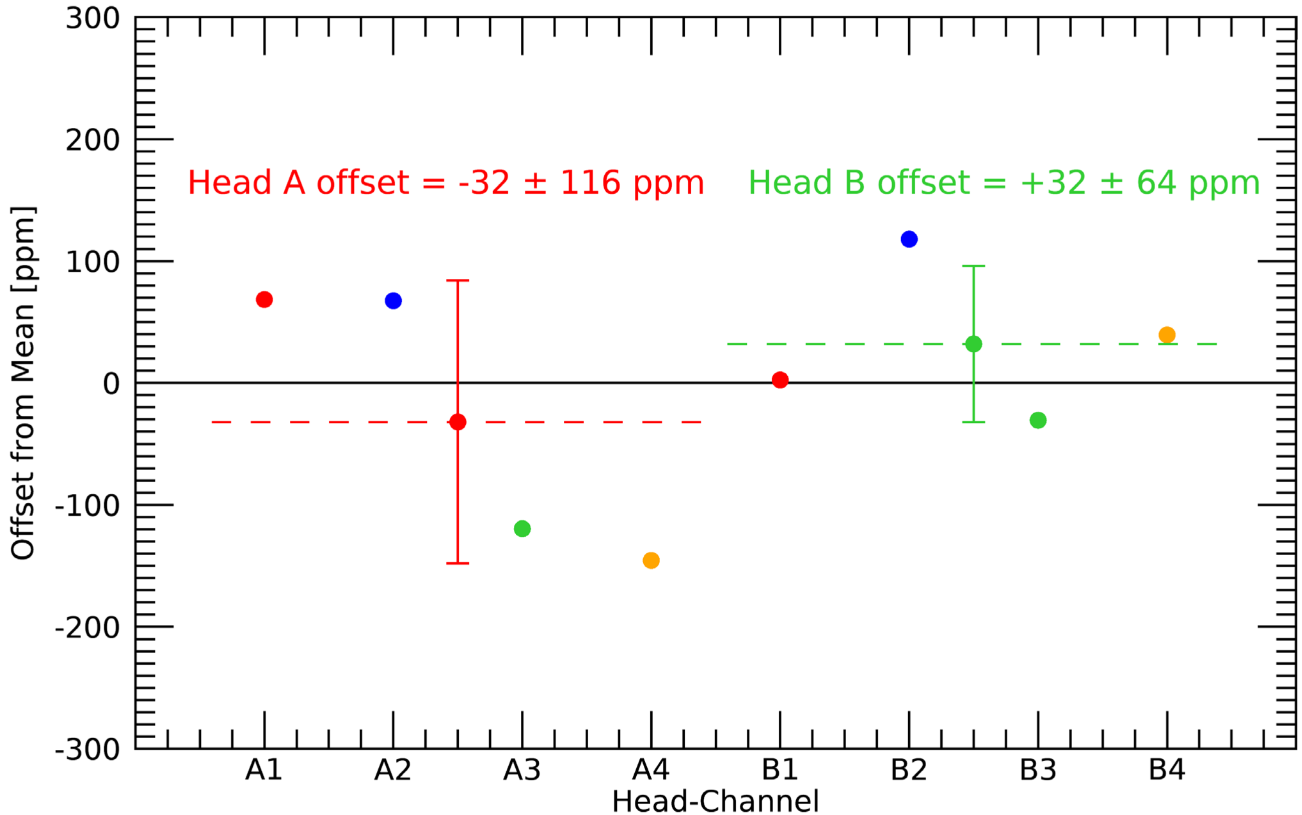


CTIM Channel-Channel Offsets



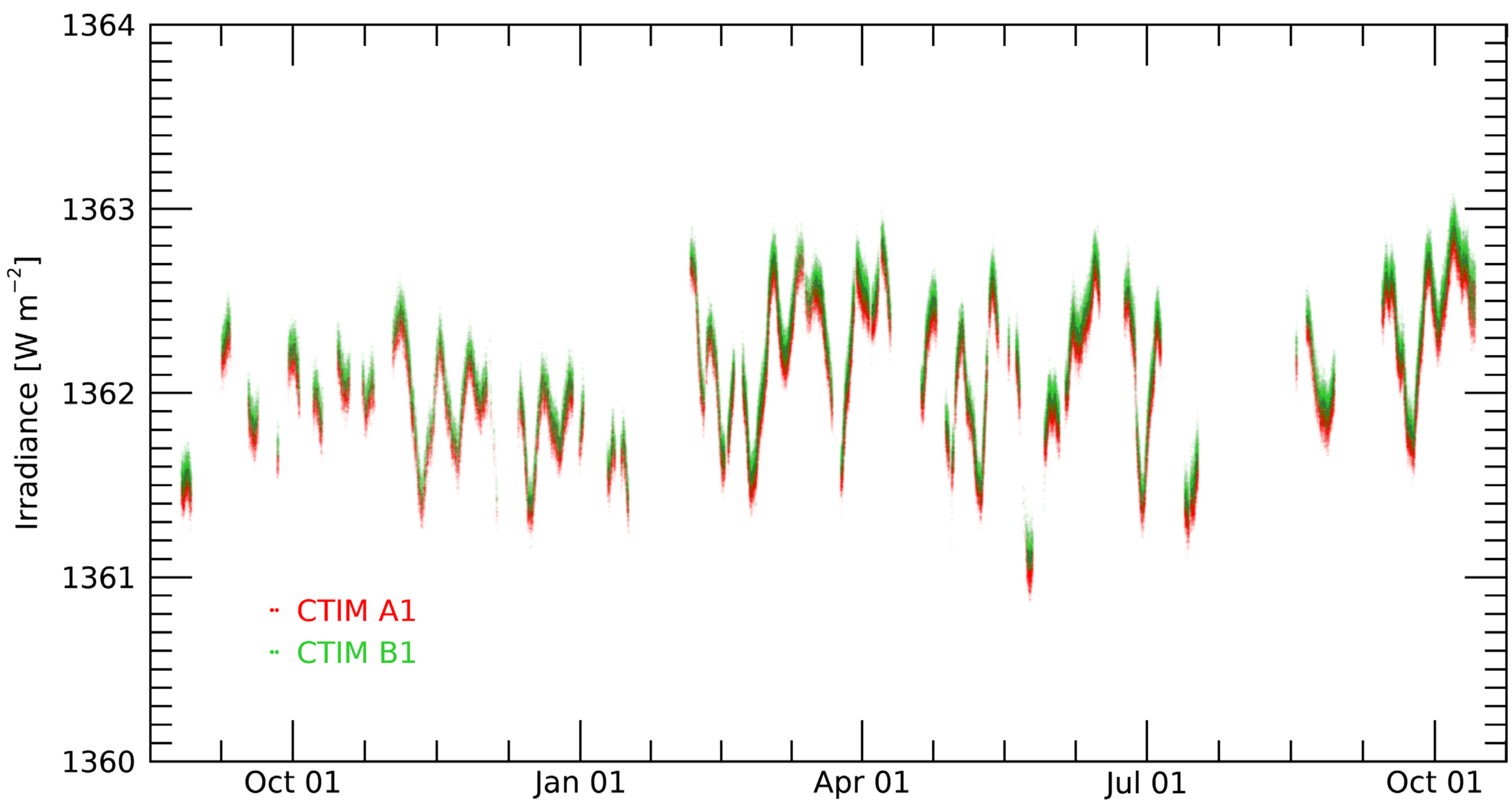
CTIM Channel-Channel Offsets

Head mean A is 64 ppm lower than head B



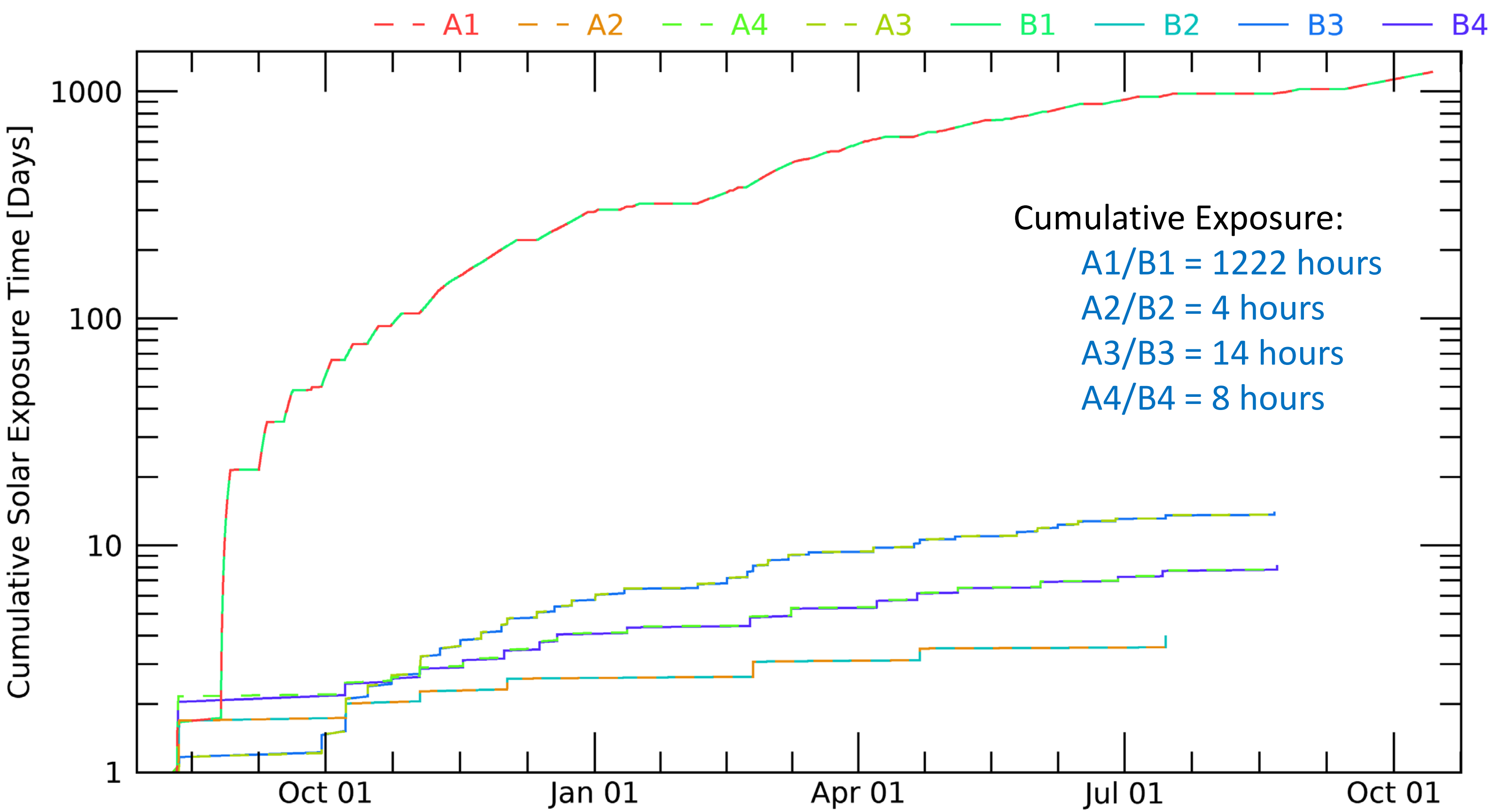
CTIM Head A/B TSI Measurements

Correct all A and B channels to first-light mean for each head



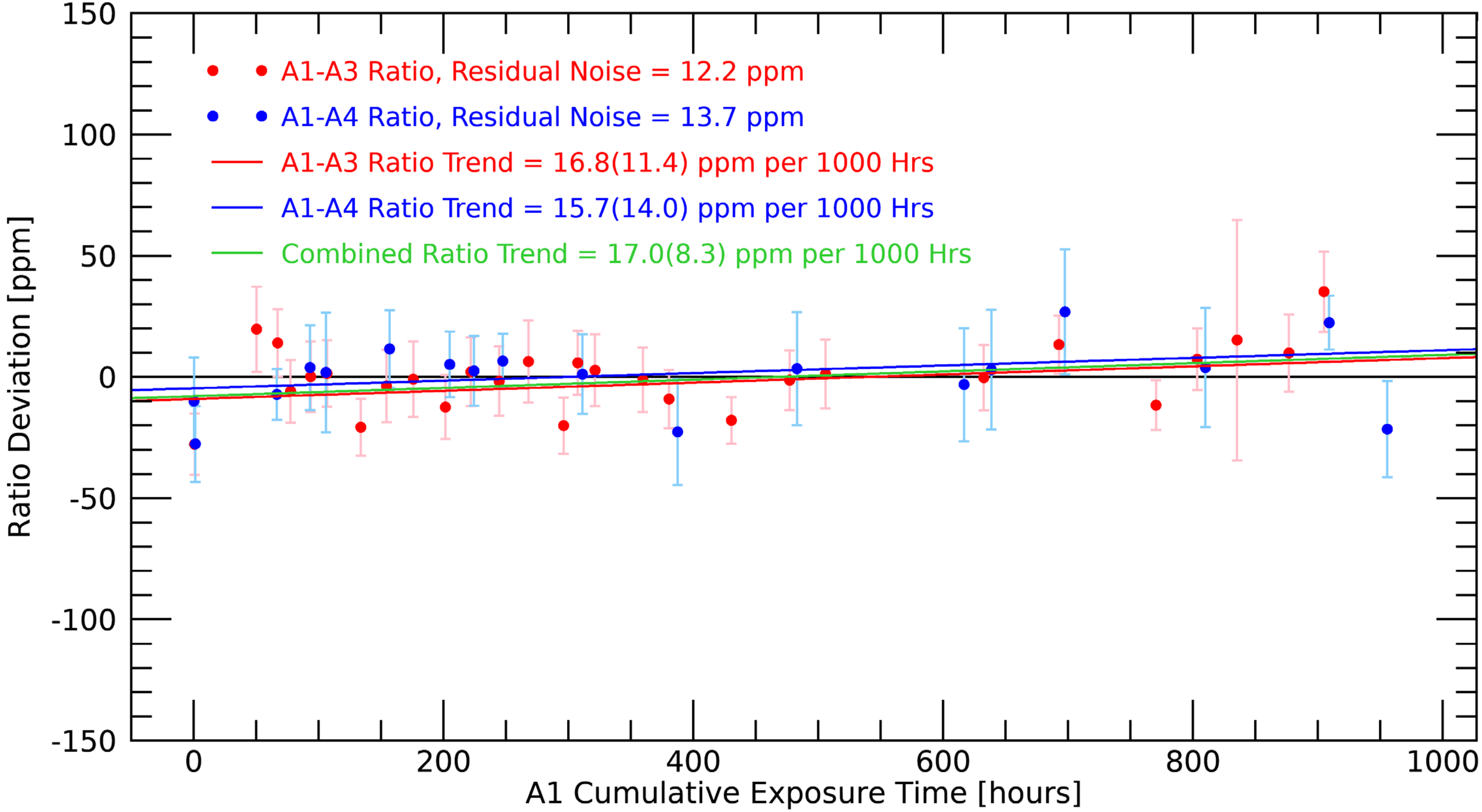
Cumulative Solar Exposure

Primary CTIM channels have accumulated ~1200 hours of exposure



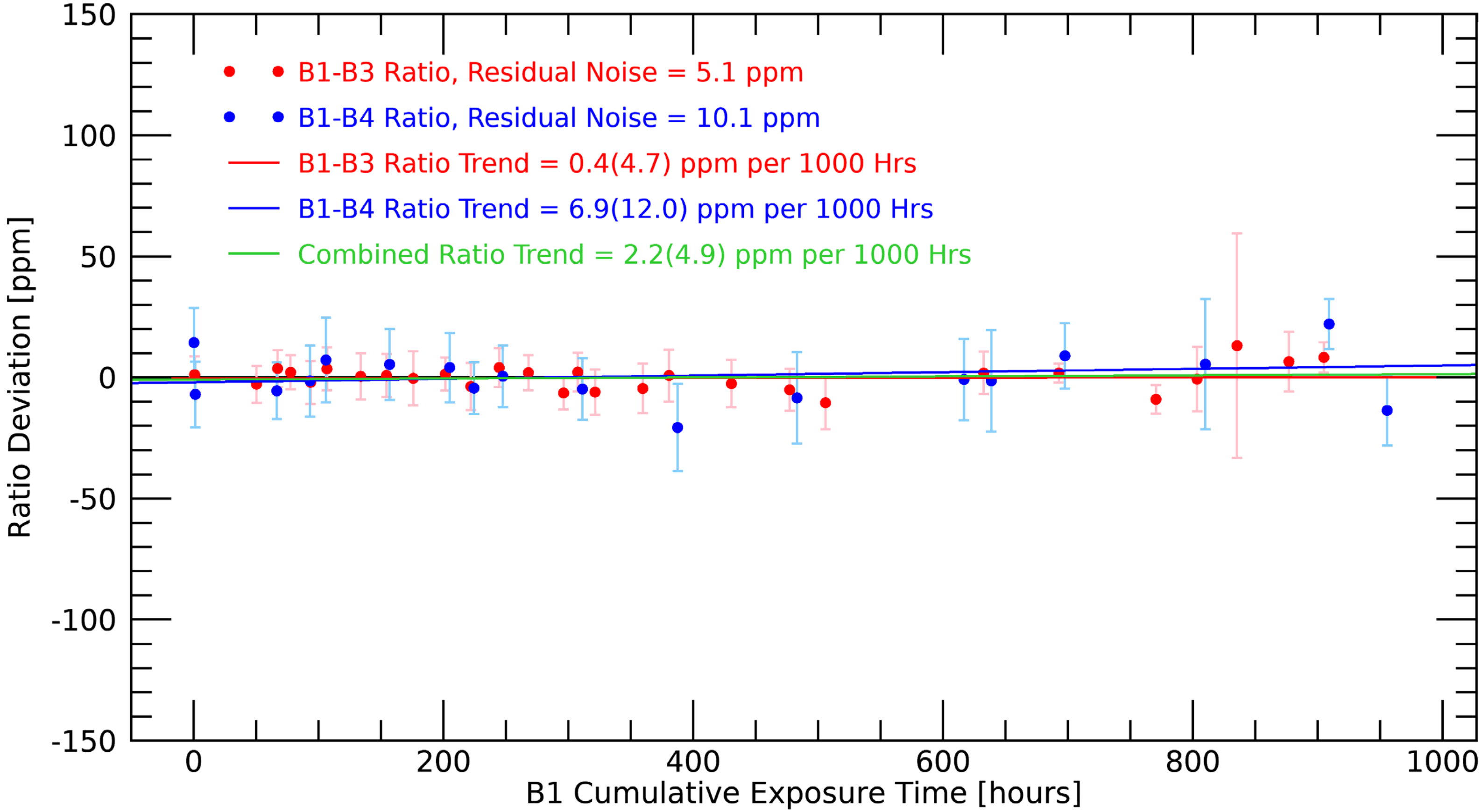
Head A Channel-Channel Ratios

A1-A3 and A1-A4 ratios indicate 17 +/- 8 ppm of degradation per 1000 hours of exposure



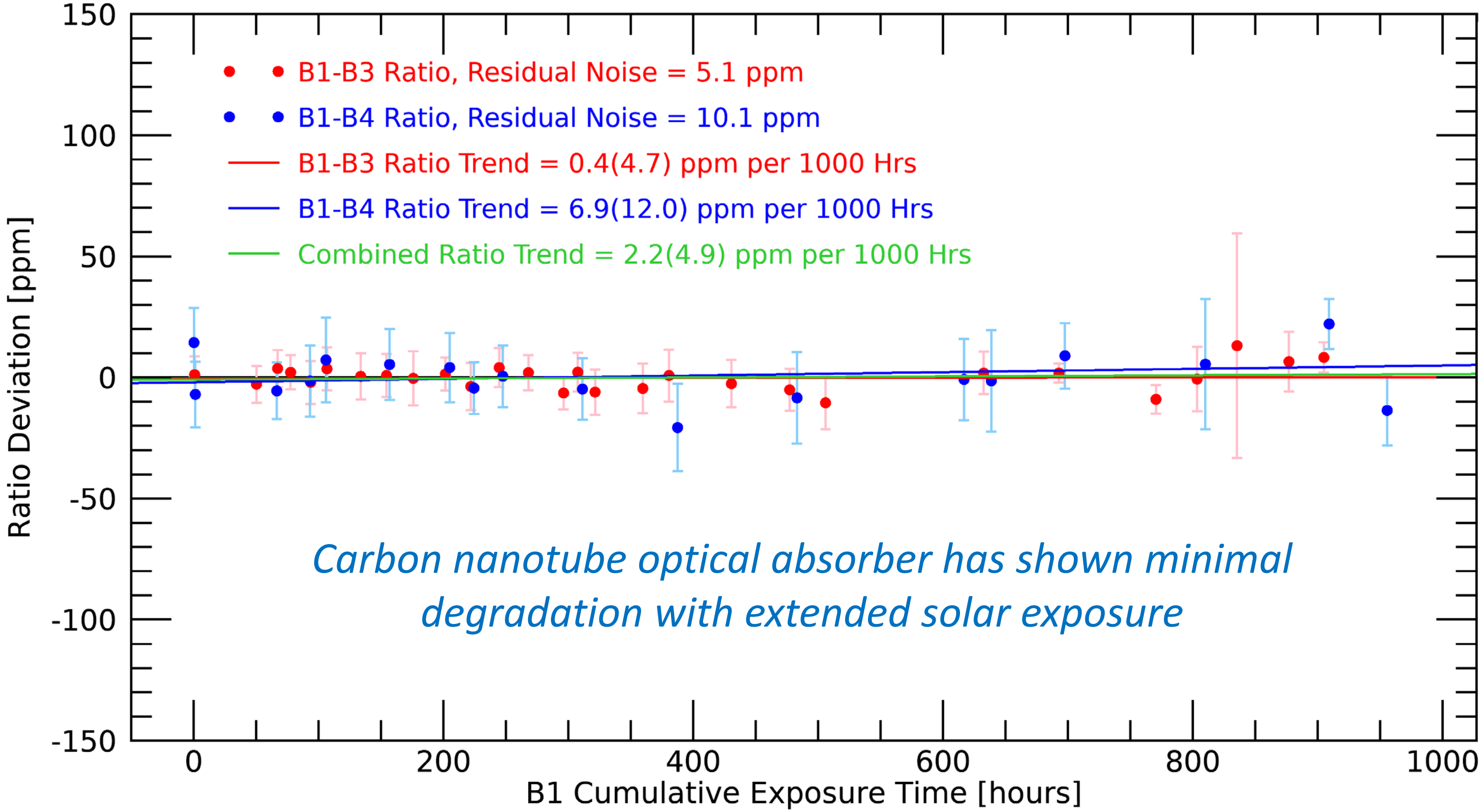
Head B Channel-Channel Ratios

B1-B3 and B1-B4 ratios indicate 2 +/- 5 ppm of degradation per 1000 hours of exposure



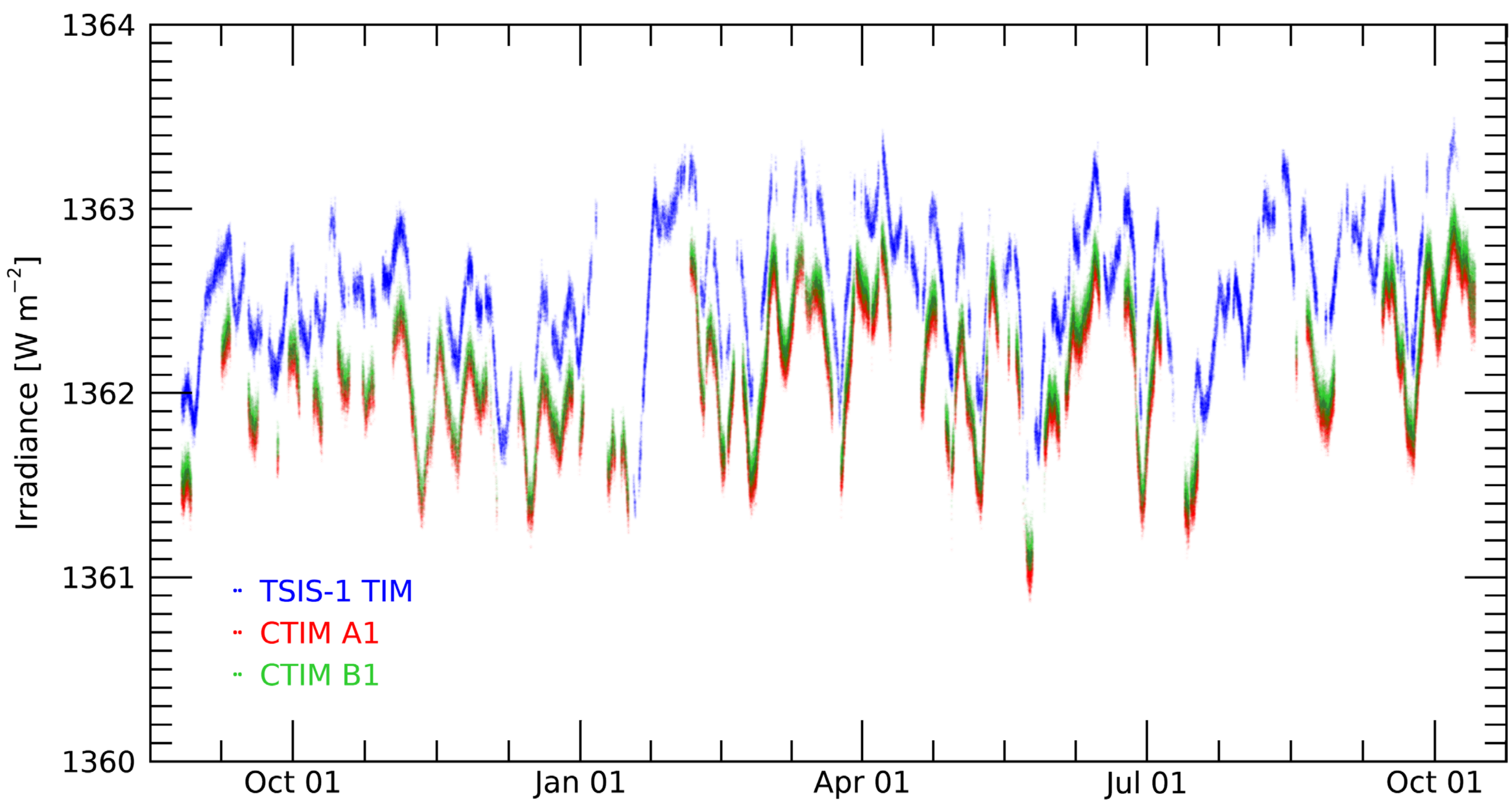
Head B Channel-Channel Ratios

B1-B3 and B1-B4 ratios indicate 2 +/- 5 ppm of degradation per 1000 hours of exposure



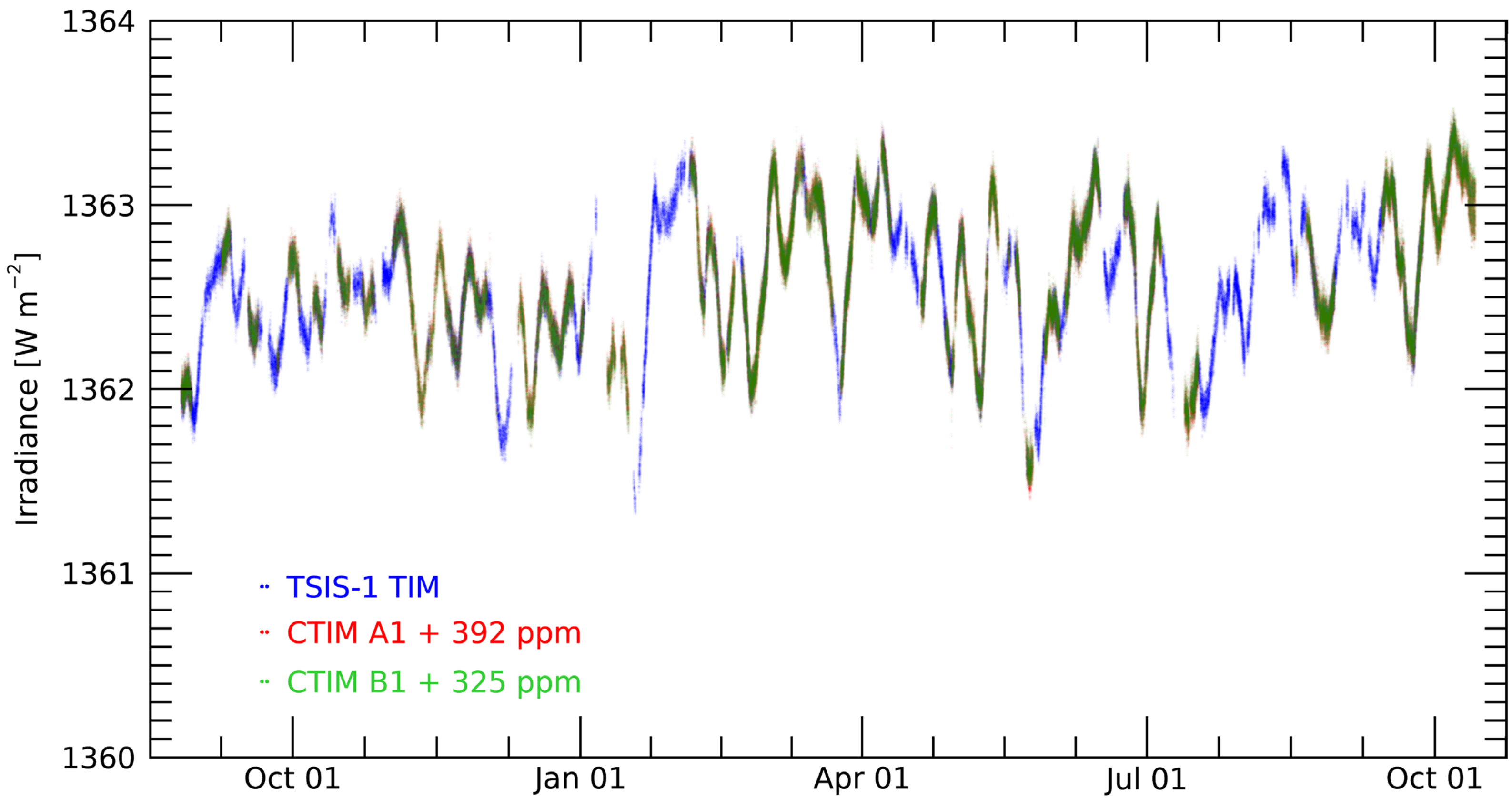
Corrected TSI Measurements

Correct for A1 and B1 degradation, compare against TSIS-1 TIM



Corrected TSI Measurements

A1 is 392 ppm lower than TSIS-1 TIM, B1 is 325 ppm lower than TSIS-1 TIM



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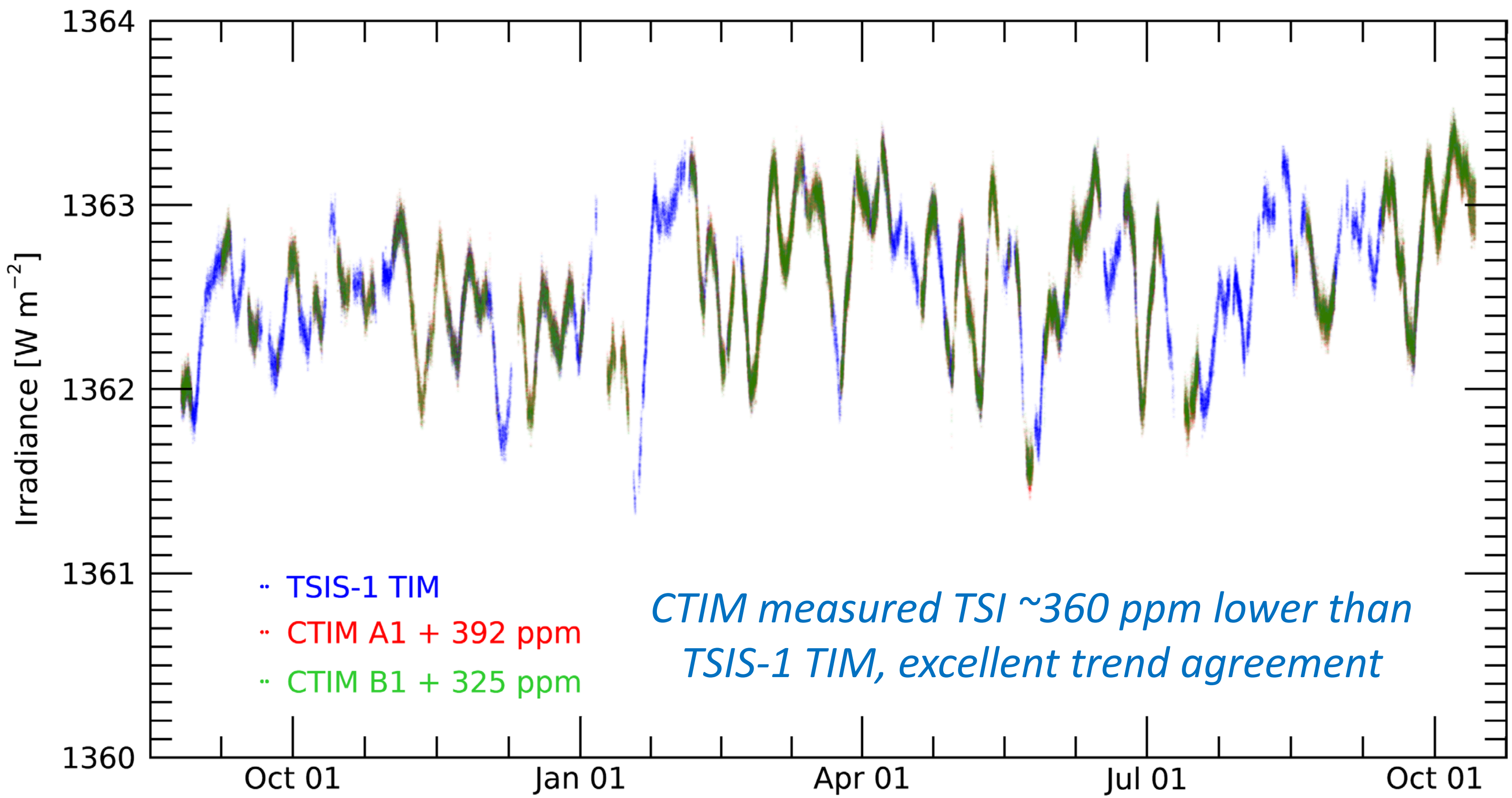
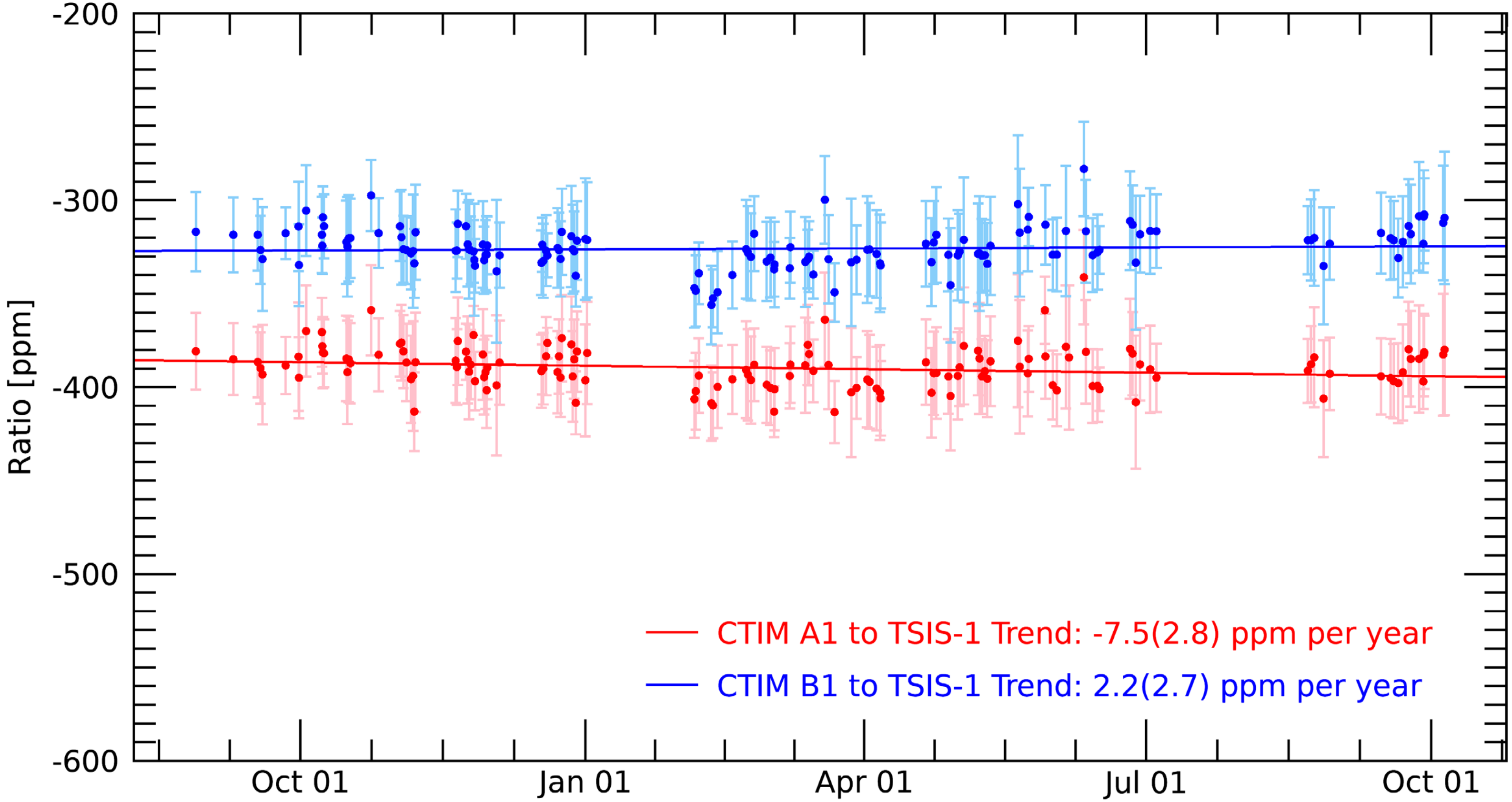


Long-Term CTIM vs TSIS-1 TIM Trends

CTIM A and B and TSIS-1 trends agree to <10 ppm per year



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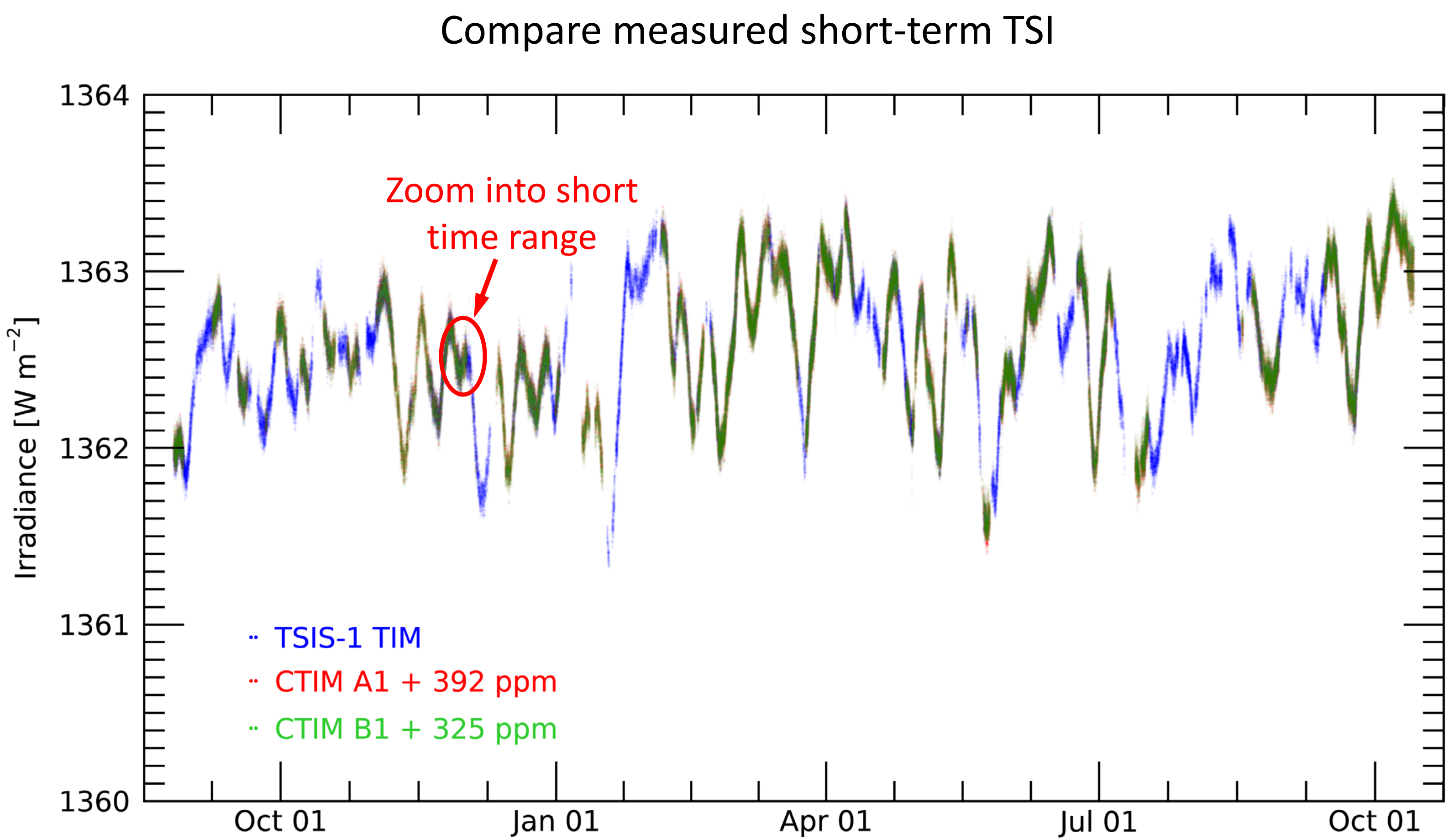
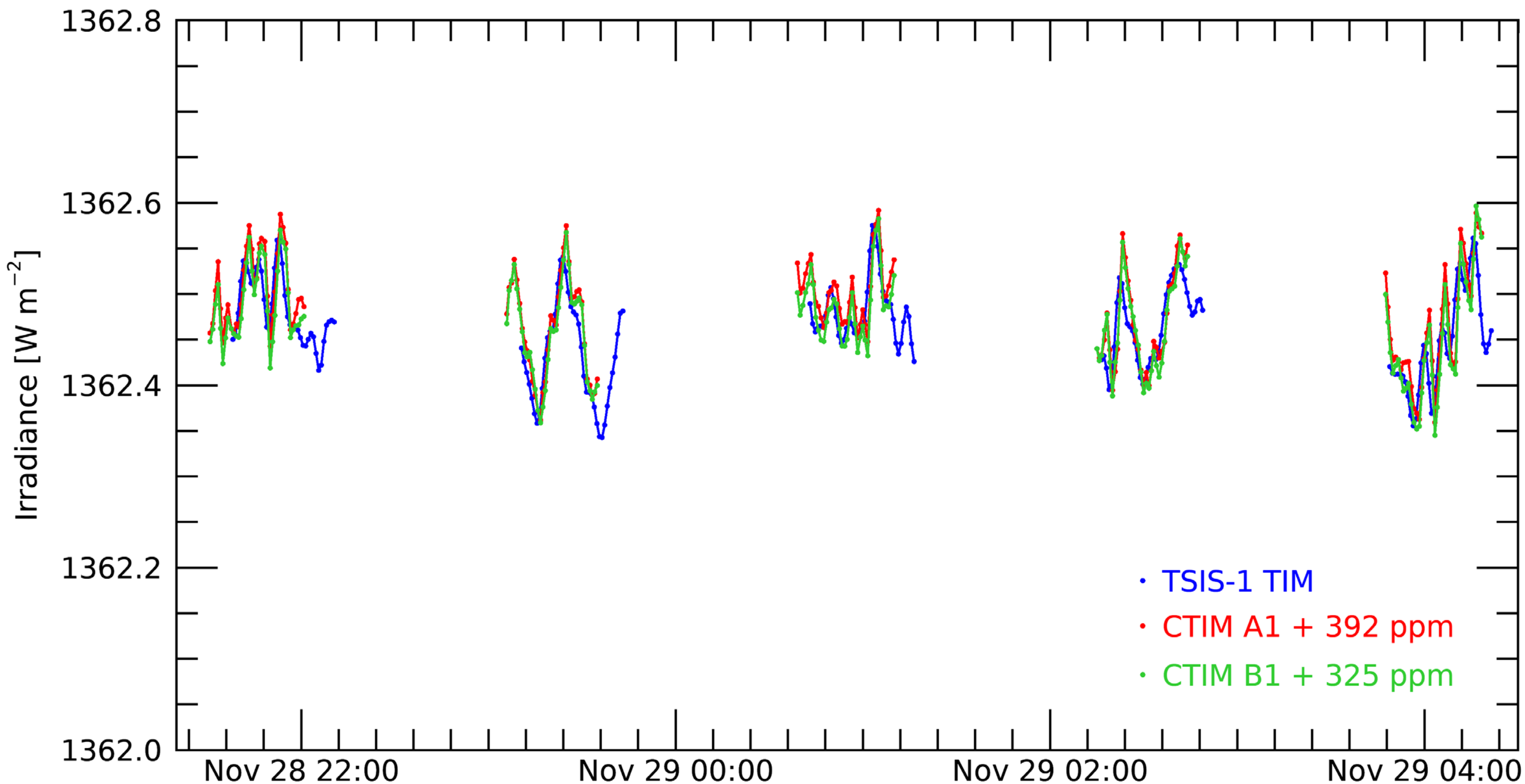


Short-Term TSI Comparison

Five orbits around November 29th, 2022



CTIM TSI Uncertainty

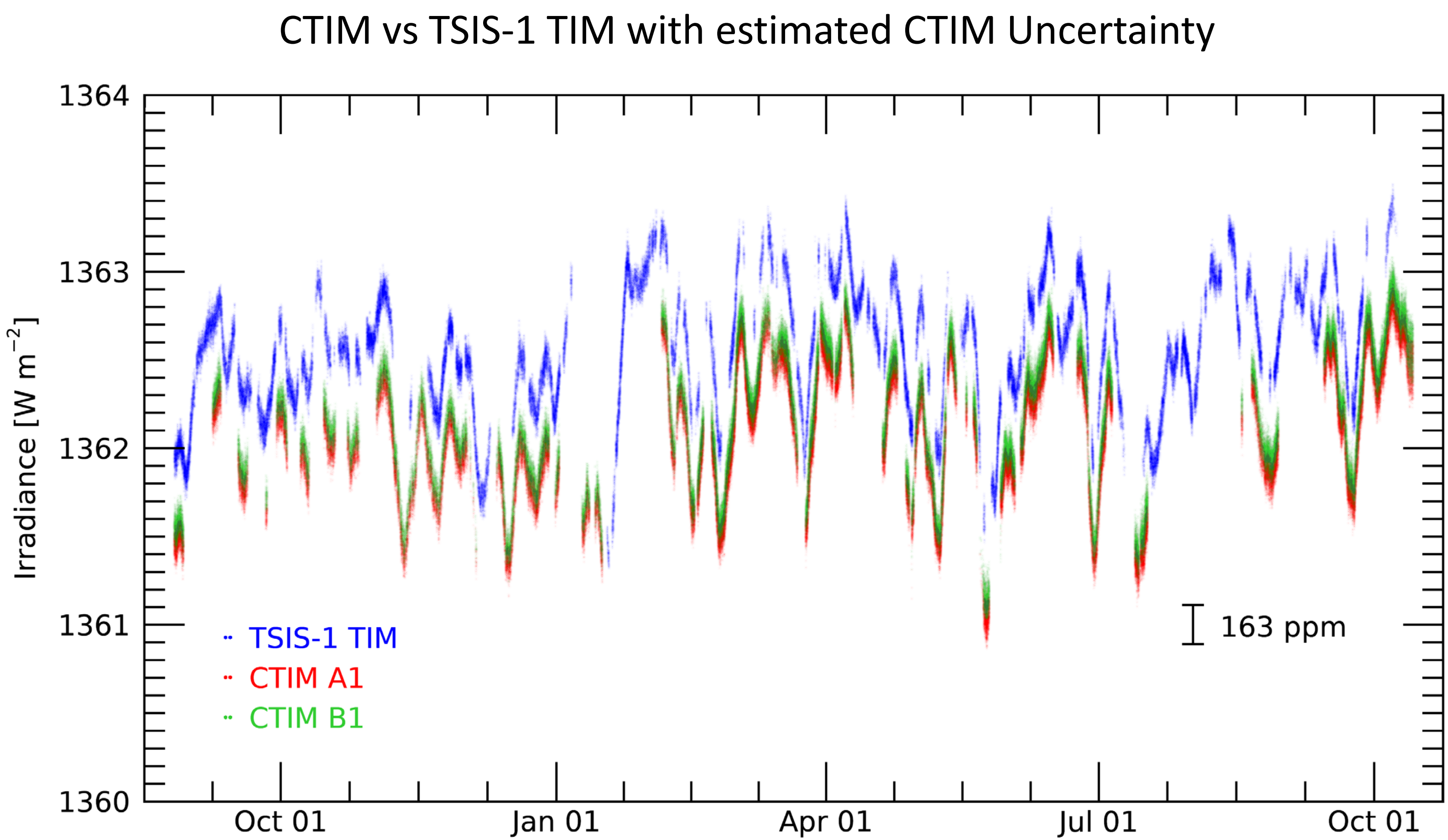
The current estimated CTIM standard uncertainty is 143-173 ppm:

CTIM Standard Uncertainties in ppm (k=1)

Source	A1	A2	A3	A4	B1	B2	B3	B4
Aperture area at T0	14	14	27	12	13	13	14	14
Aperture area expansion	10	10	10	10	10	10	10	10
Diffraction loss	42	42	42	42	42	42	42	42
Detector reflectance	4	6	4	7	5	7	5	7
Reference voltage	52	52	49	49	50	50	66	66
Top resistor	41	41	41	41	40	40	41	41
Wire bond resistance	23	23	19	24	23	22	23	23
Lead resistance	40	10	12	17	18	15	13	10
Heater resistance	9	6	9	8	10	9	4	10
Linearity	20	20	20	20	20	20	20	20
Non-equivalence	131	149	118	126	119	131	113	105
Noise	9	9	9	9	9	9	9	9
Dark signal	11	11	11	11	11	11	11	11
Total	*163*	*173*	*148*	*153*	*148*	*157*	*149*	*143*

Measured against a ground reference detector → Non-equivalence

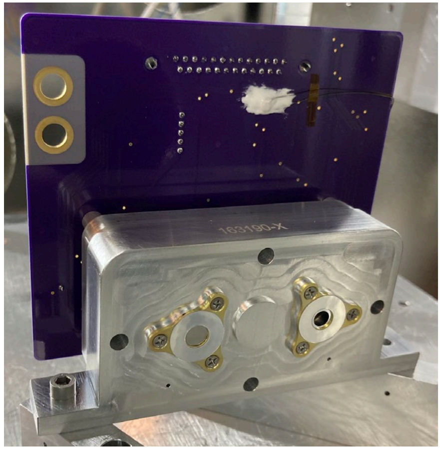
Corrected TSI Measurements



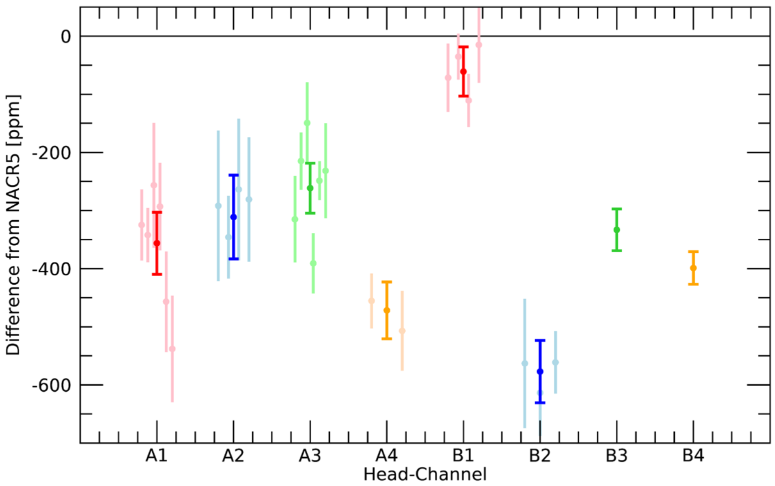
CTIM Traceability

- Calibrated directly against a ground reference detector (NACR5) in the LASP TSI radiometer facility (TRF)
- The CTIM non-equivalence values are derived from the offset measured against NACR5
  - CTIM measured lower than NACR5 without a non-equivalence correction applied
  - Mean Offset = -346 ppm, Standard Deviation of Offset = -152 ppm
- NACR5 is available for future irradiance intercomparisons

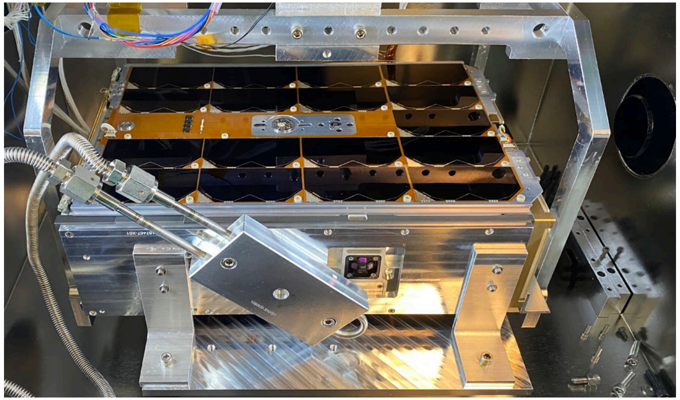
NACR5



CTIM Relative to NACR5 Prior to Correction



CTIM in TRF

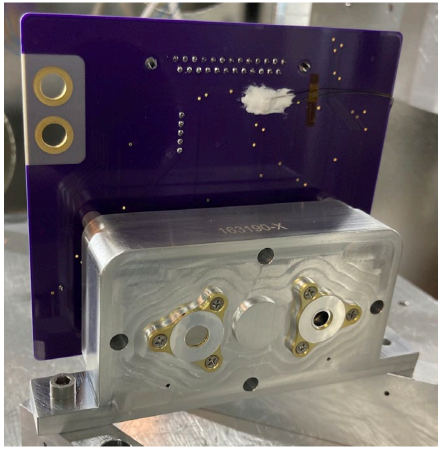


NACR5 Uncertainty

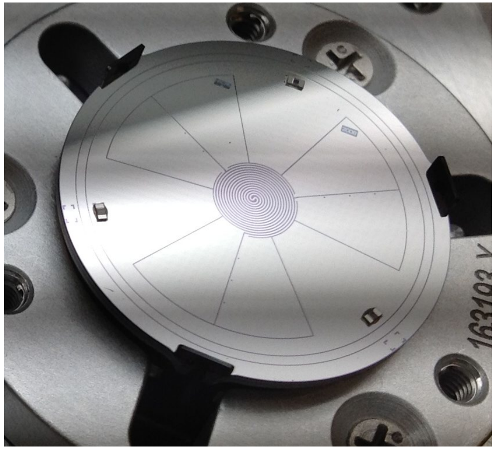
- NACR5 was developed after CTIM, includes lesson learned from CTIM
- NACR5 treated as a primary standard based on component-level calibrations
- The intercomparison with the NIST trapped diode is an independent check of the NACR5 measurement scale
- NACR5 was compared in against a NIST calibrated trapped diode
  – NACR5 measured 215 +/- 257 ppm higher than NIST POWR

    White, et al, Metrologia, 59 065006, 2022.

NACR5



NACR5 Detector



NACR5 Standard Uncertainties

Source	ppm (k=1)
Aperture Area at T0	17
Aperture Area Expansion	20
Diffraction Loss	25
Detector Reflectance	20
Non-equivalence	21
Heater voltage	7
Sense resistor voltage	7
Frequency response	10
Wire bond resistance	60
Total	*77*

CTIM vs NACR5 Uncertainty

CTIM Standard Uncertainties in ppm (k=1)

Source	A1	B1
Aperture area at T0	14	13
Aperture area expansion	10	10
Diffraction loss	42	42
Detector reflectance	4	5
Reference voltage	52	50
Top resistor	41	40
Wire bond resistance	23	23
Lead resistance	40	18
Heater resistance	9	10
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Wire bond resistance	60
Total	*77*

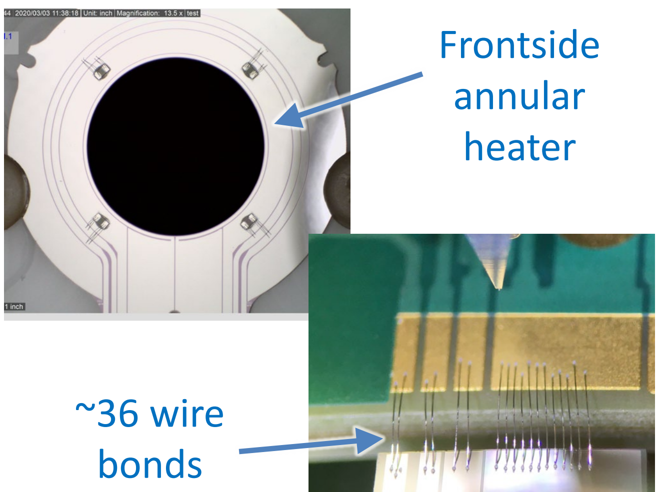
CTIM vs NACR5 Non-Equivalence

CTIM

- Replacement heater an annular heater around the perimeter of the VACNT optical absorber
- Large number of wire bonds to minimize lead resistance
- Future iterations of CTIM would use a NACR5 style detector

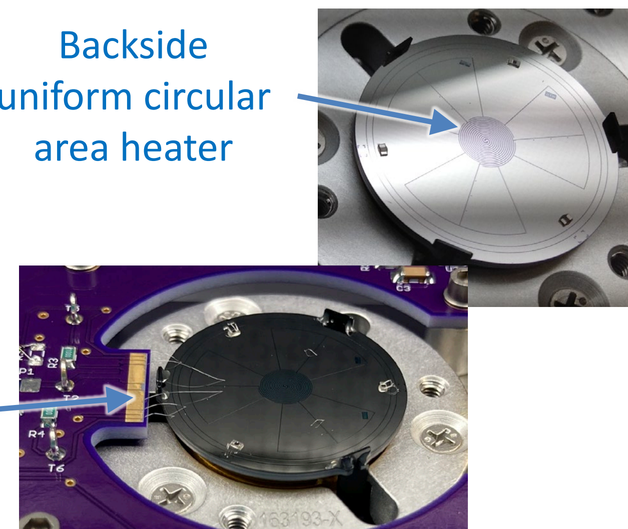
NACR5

- Replacement heater on the backside of the silicon substrate and matched the illumination region
- Minimal wire bonds to optimize non-equivalence



Frontside annular heater

~36 wire bonds



Backside uniform circular area heater

5 wire bonds

CTIM TSI Summary

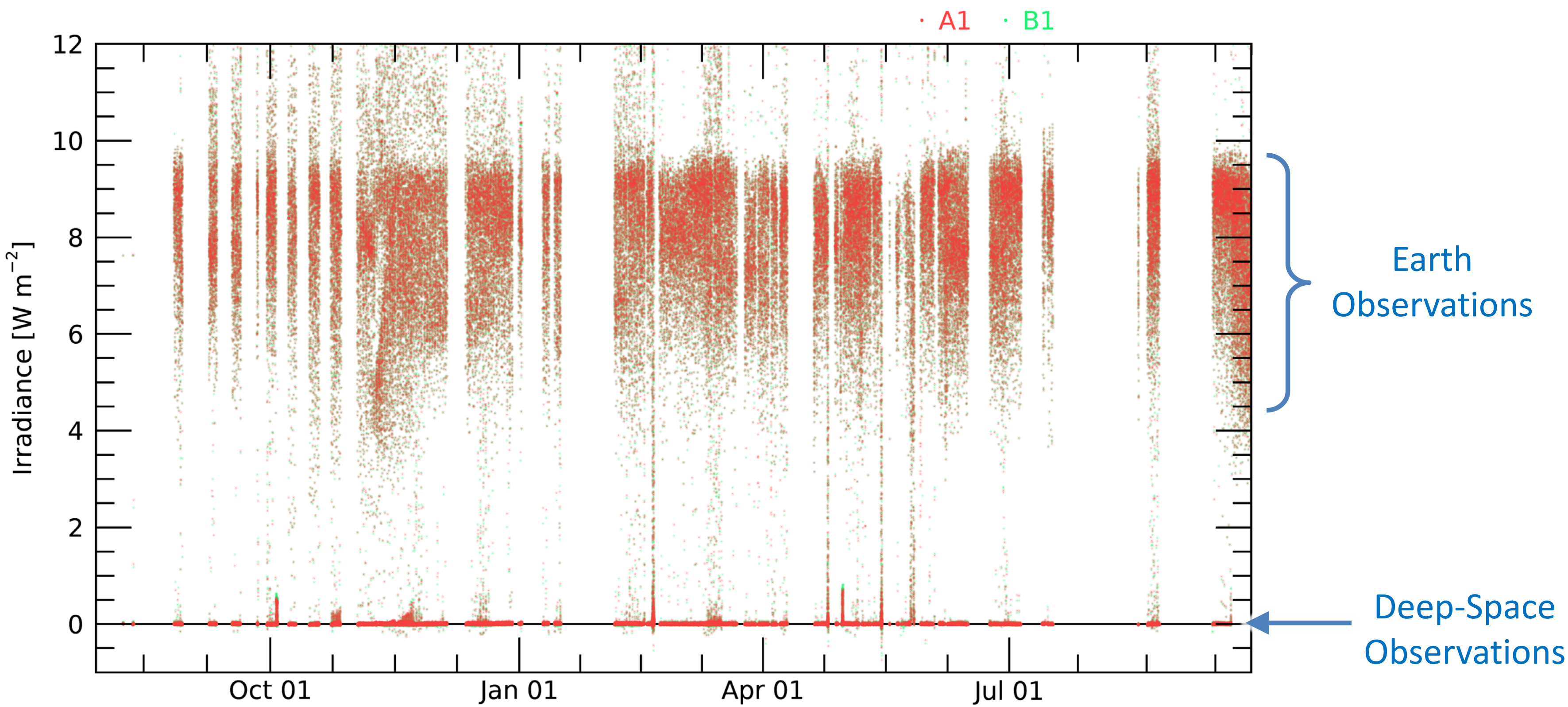
- CTIM has been making TSI observations since August 2022
  - Expected to continue until April 2024
- CTIM measured TSI ~360 ppm lower than TSIS-1 TIM
  - Excellent agreement in short and long-term trends
  - Long-term trend agreement <10 ppm/year
- CTIM, a CubeSat sized TSI instrument, has demonstrated on-orbit performance on par with TSIS-1 TIM
- CTIM Data is available:
  - https://lasp.colorado.edu/ctim/data/
- **CTIM is a key part of Compact TSIS, see Tom Patton's talk on Thursday:**

  Compact TSIS: Future Program Implementation for Solar Irradiance Data Continuity

CTIM Earth Radiance Observations

New Experimental Measurement:

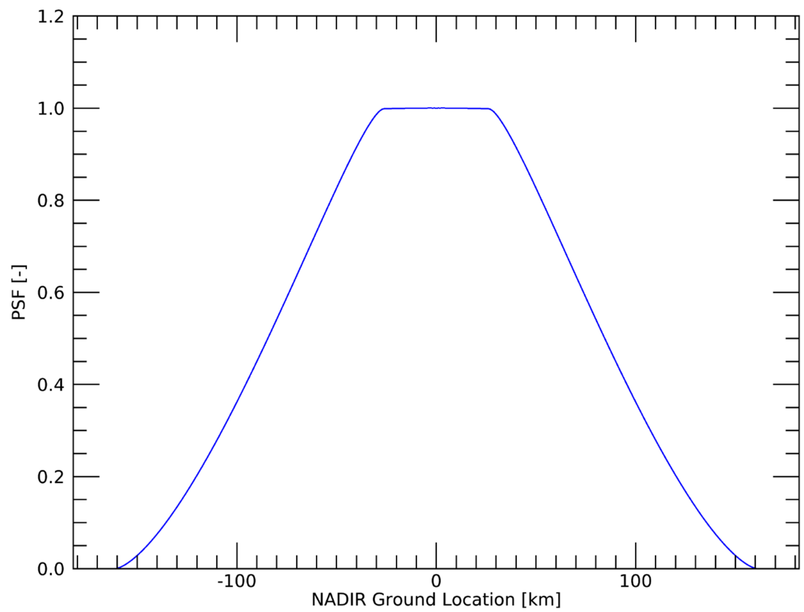
CTIM alternates between deep-space and NADIR Earth observations during eclipse

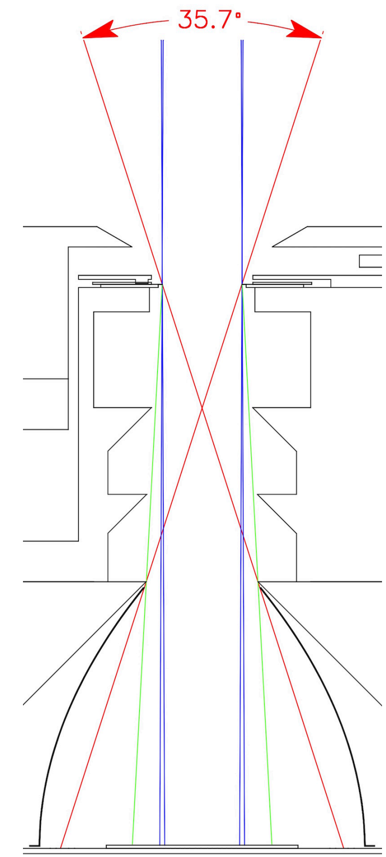


CTIM Earth Observations

- *CTIM is not performing a wide-angle irradiance measurement*
- Radiance measurement over a ~170 km region
- Estimated Solid Angle: 0.0939 +/- 0.0019 steradians
  - ~2% Uncertainty

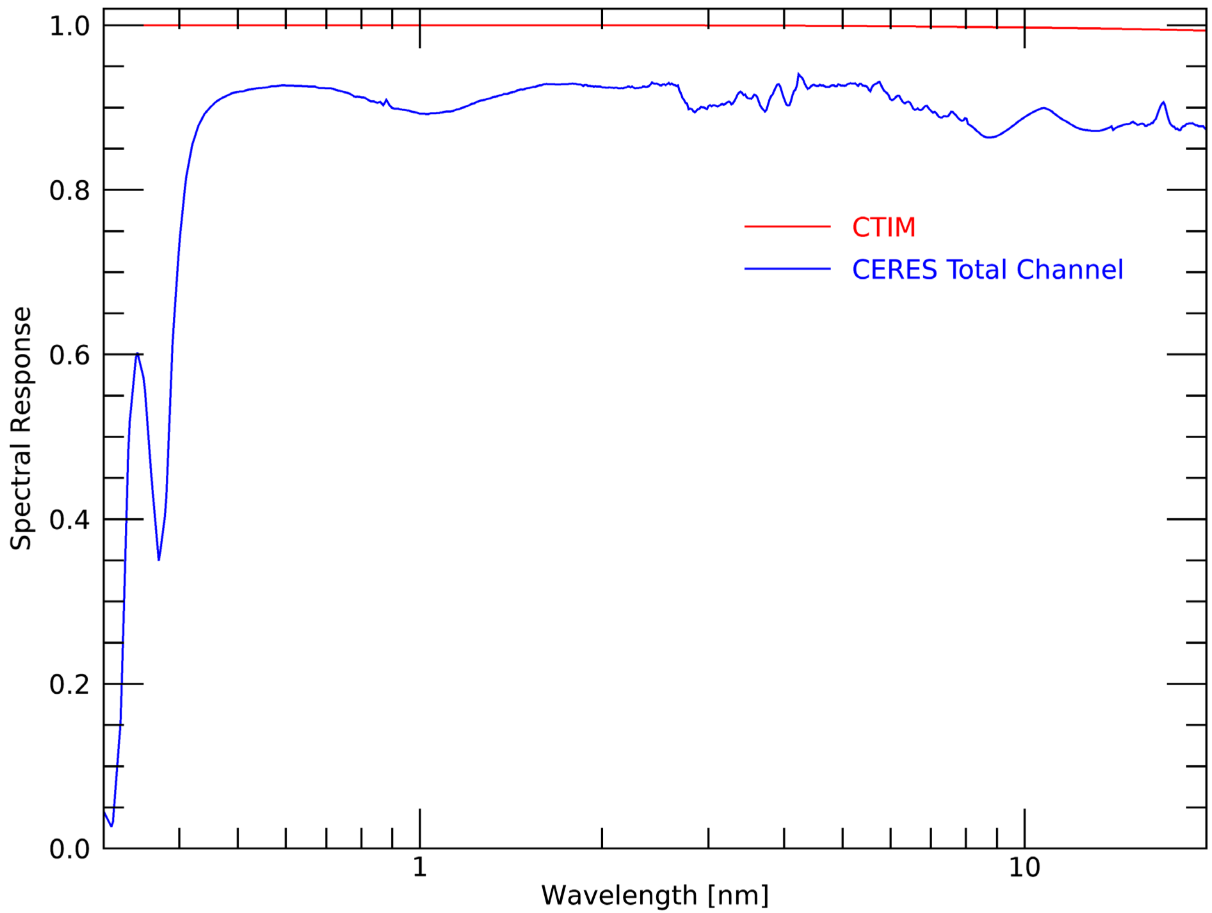
Modeled FOV a 500 km Orbit





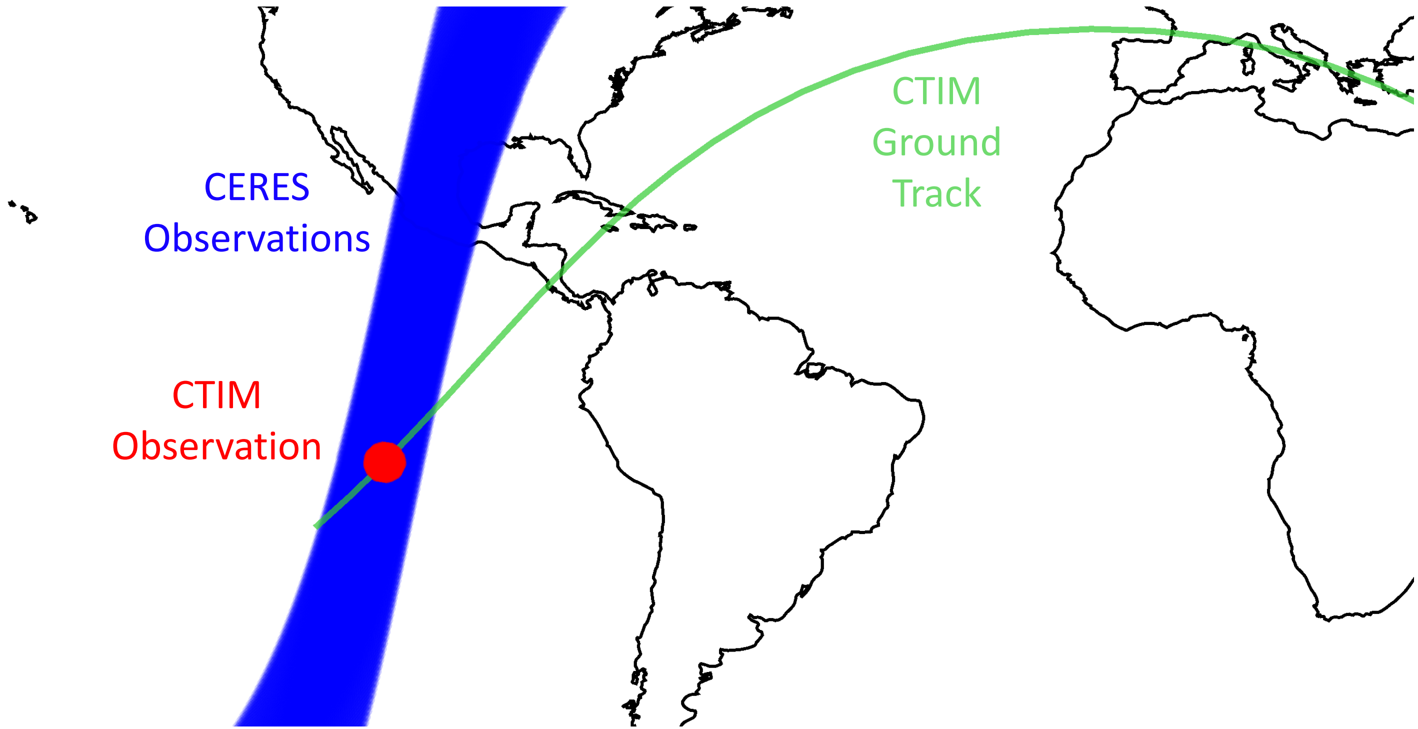
CTIM Estimated Spectral Response

CTIM spectral response is extremely flat



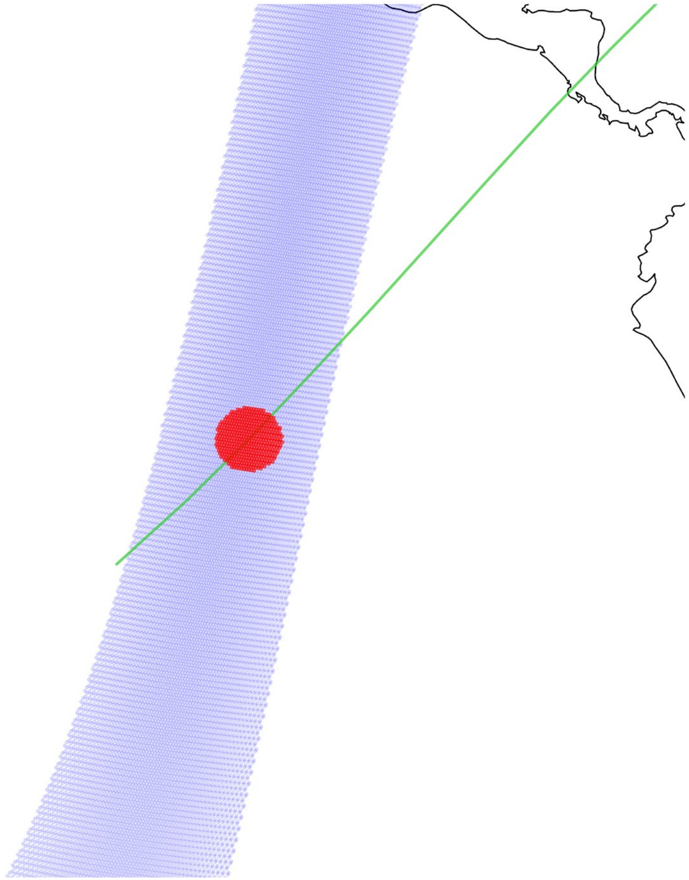
CTIM vs CERES Analysis

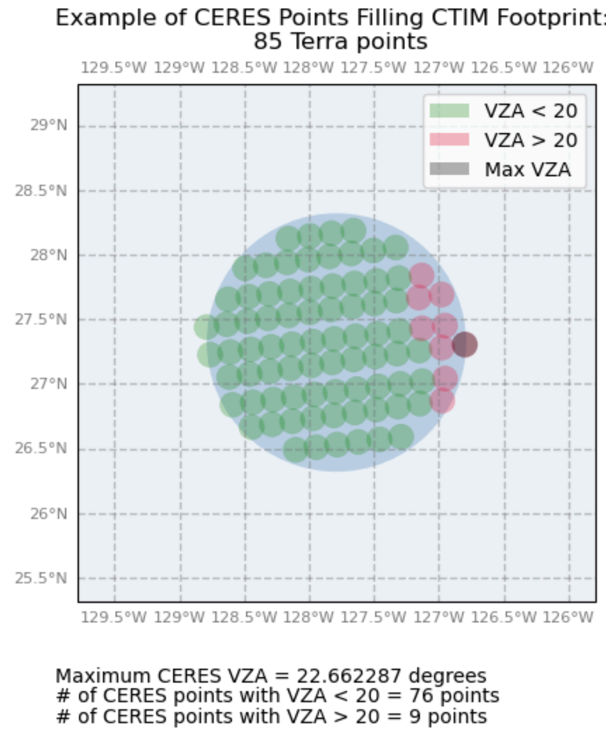
Find night-side coincident observations with CERES



CTIM Footprint Filling

Filling CTIM footprint with multiple CERES observations, perform weighted average

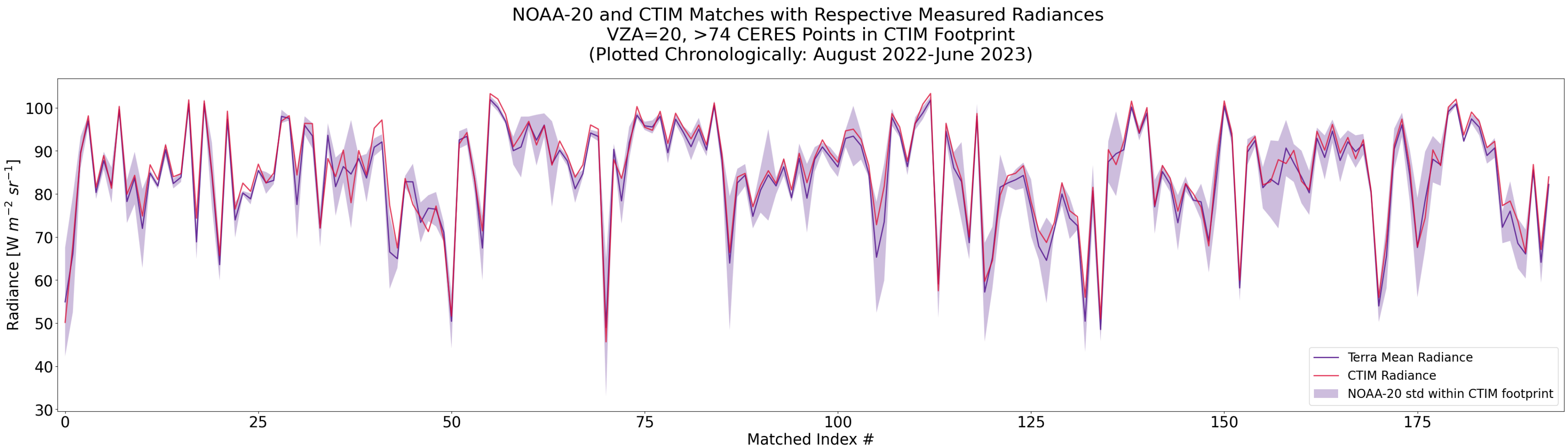




Analysis from McKenzie Hawkins

CTIM vs CERES NOAA-20 Radiance

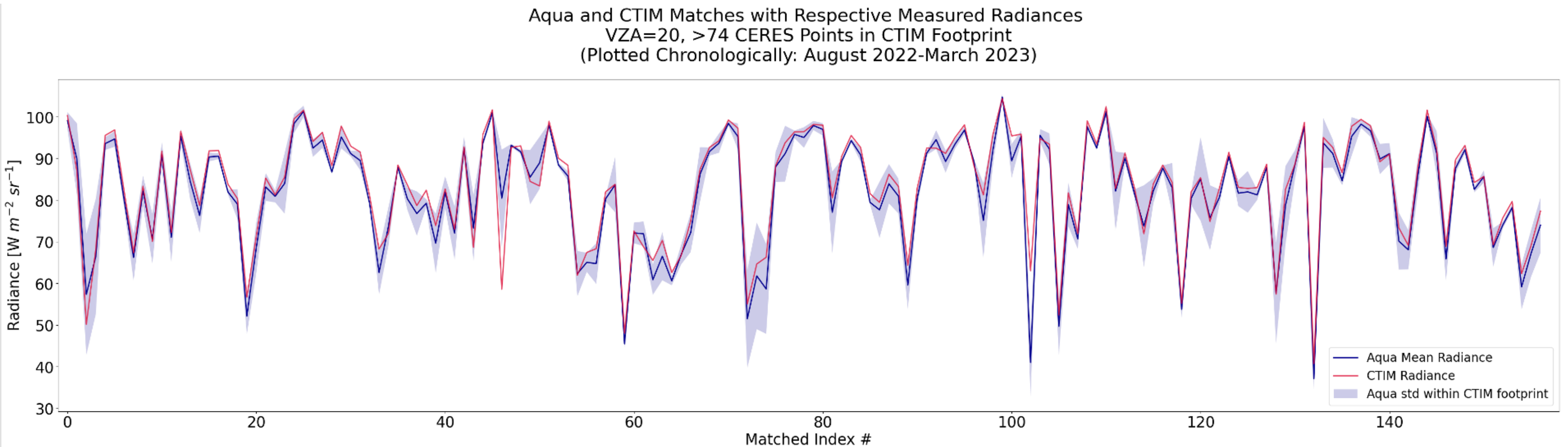
193 matches between CTIM and NOAA-20 CERES



Analysis from McKenzie Hawkins

CTIM vs CERES Aqua Radiance

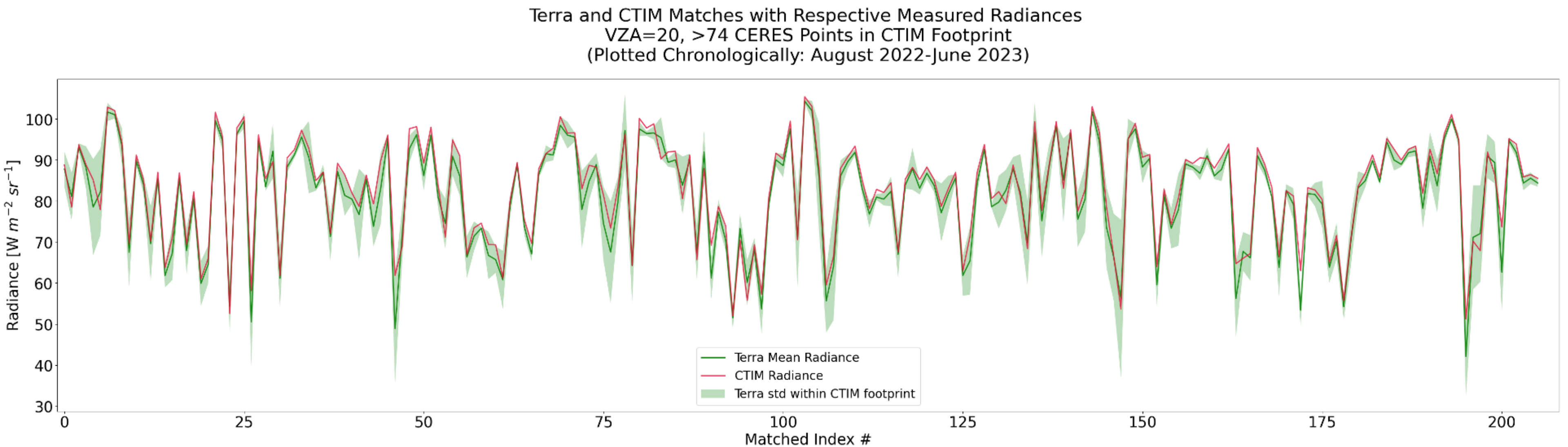
157 matches between CTIM and Aqua CERES



Analysis from McKenzie Hawkins

CTIM vs CERES Terra Radiance

206 matches between CTIM and Terra CERES

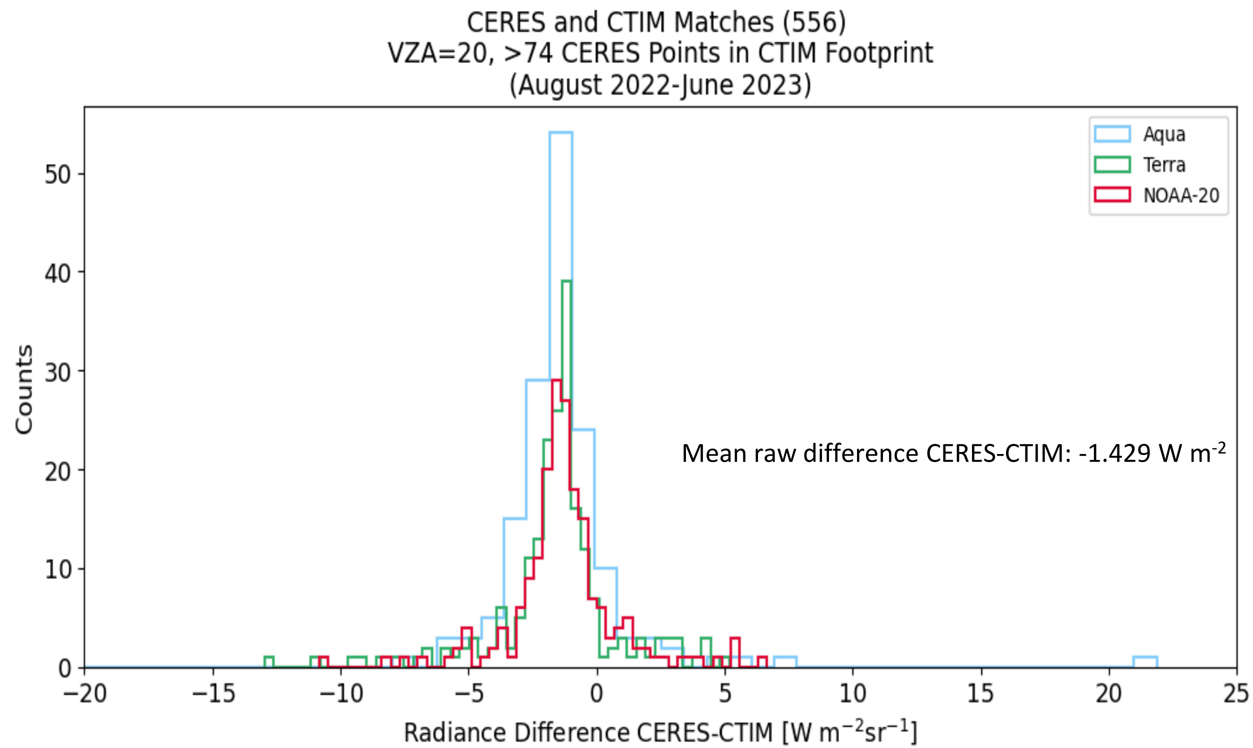


Analysis from McKenzie Hawkins

CTIM vs CERES NOAA-20, Aqua, Terra

Total of 556 matches between CTIM and NOAA-20, Aqua, and Terra CERES

Relative difference with CTIM:
NOAA-20: -1.505%
Aqua: -1.734%
Terra: -2.020%
CERES: -1.760%



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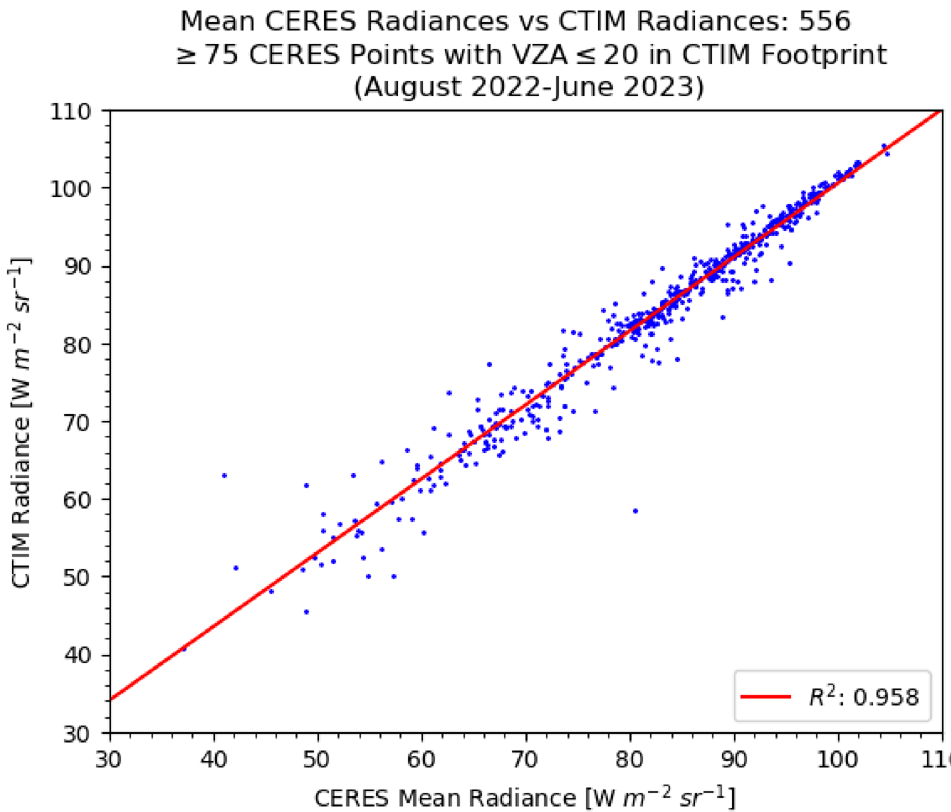
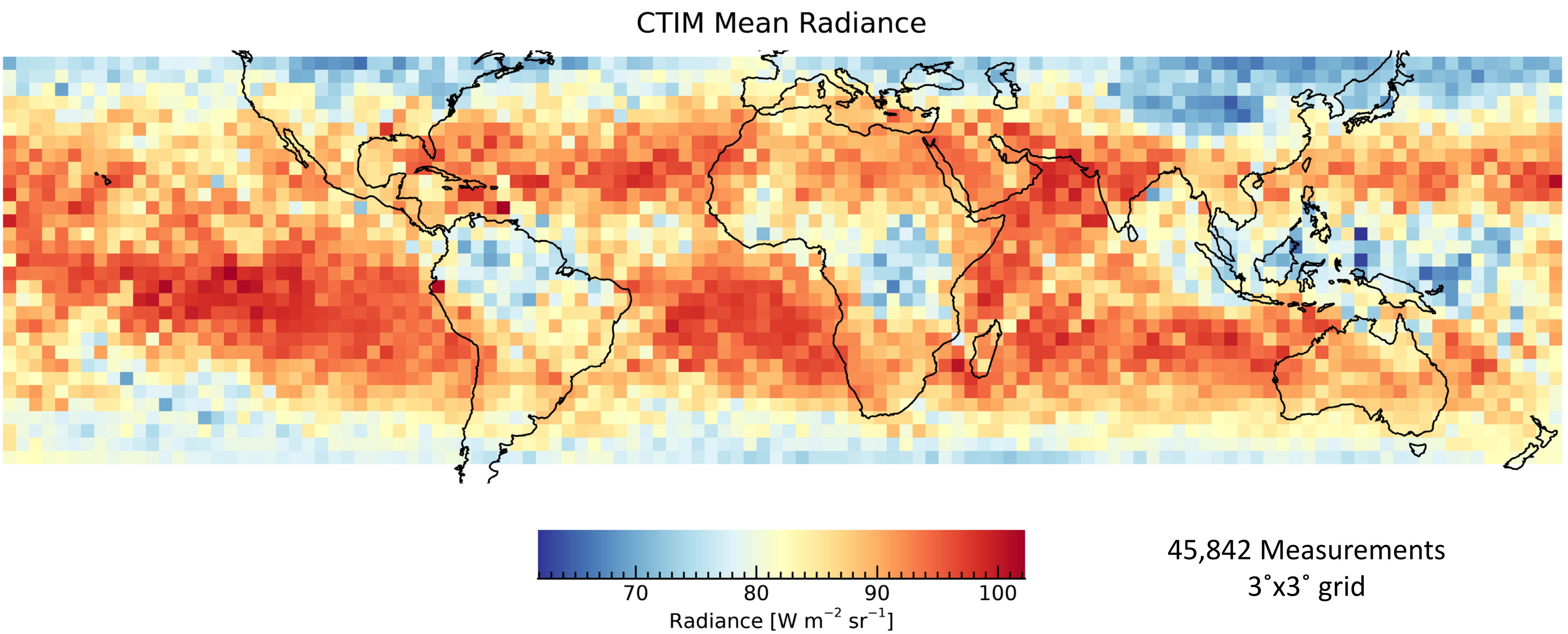


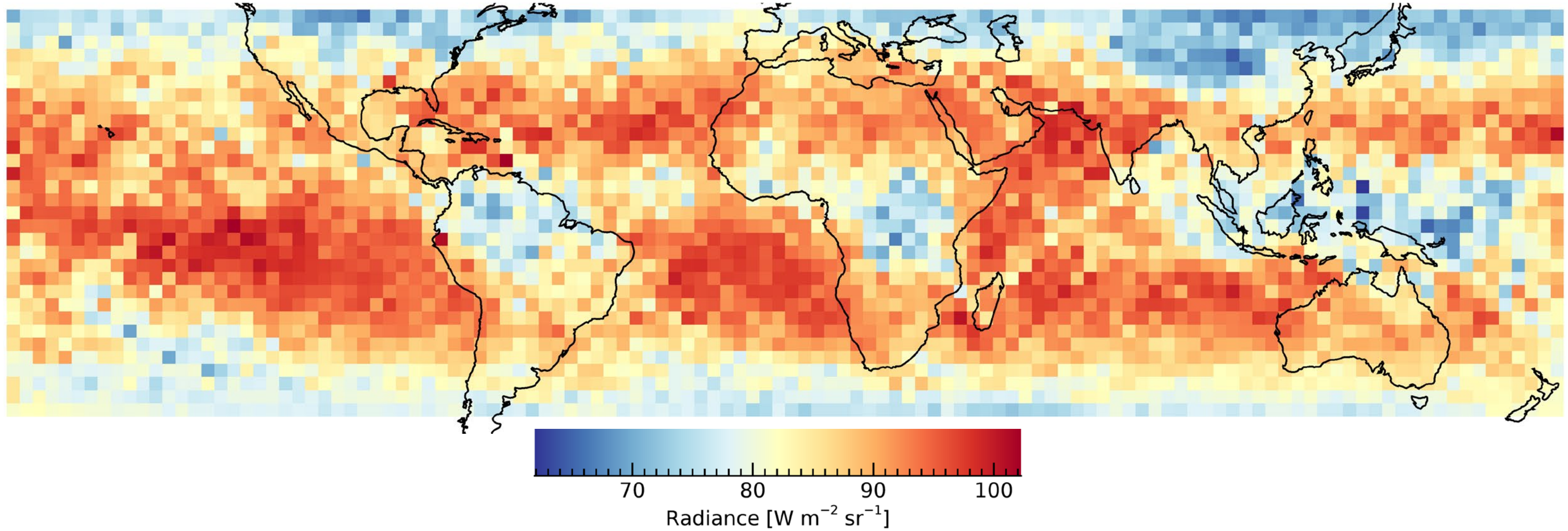
Analysis from McKenzie Hawkins

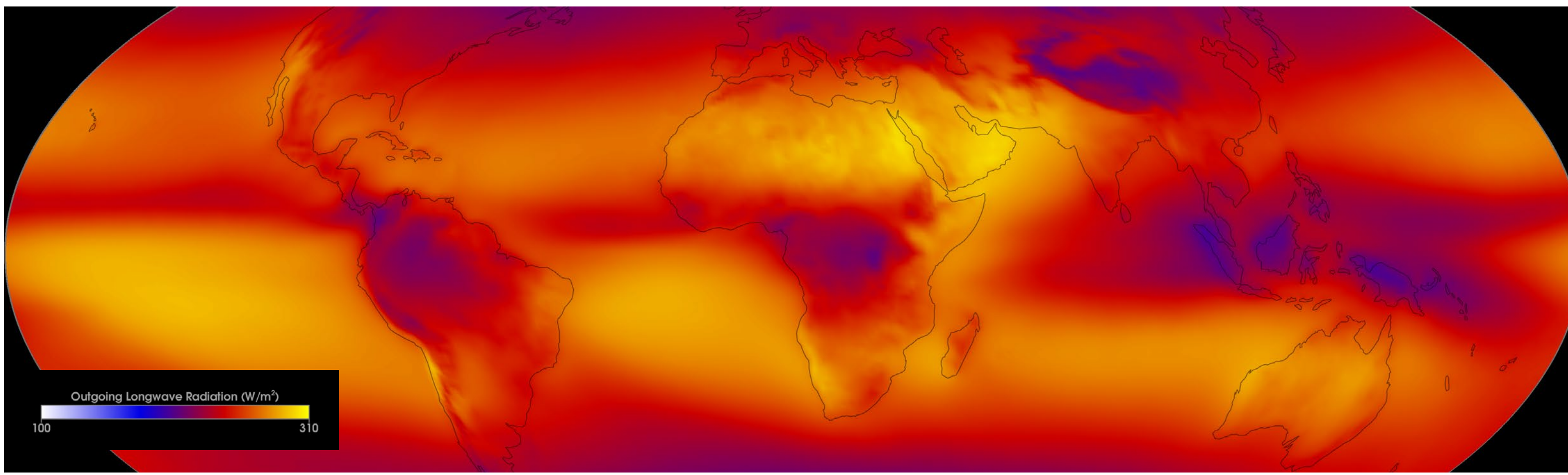
Measured Earth Radiance

Mean night side outgoing radiance from Oct 10th 2022 – Sept 19th 2023



45,842 Measurements
3˚x3˚ grid


70
80
90
100
Radiance [W m^{-2} sr^{-1}]


Outgoing Longwave Radiation (W/m²)
100
310

CTIM Earth Observation Summary

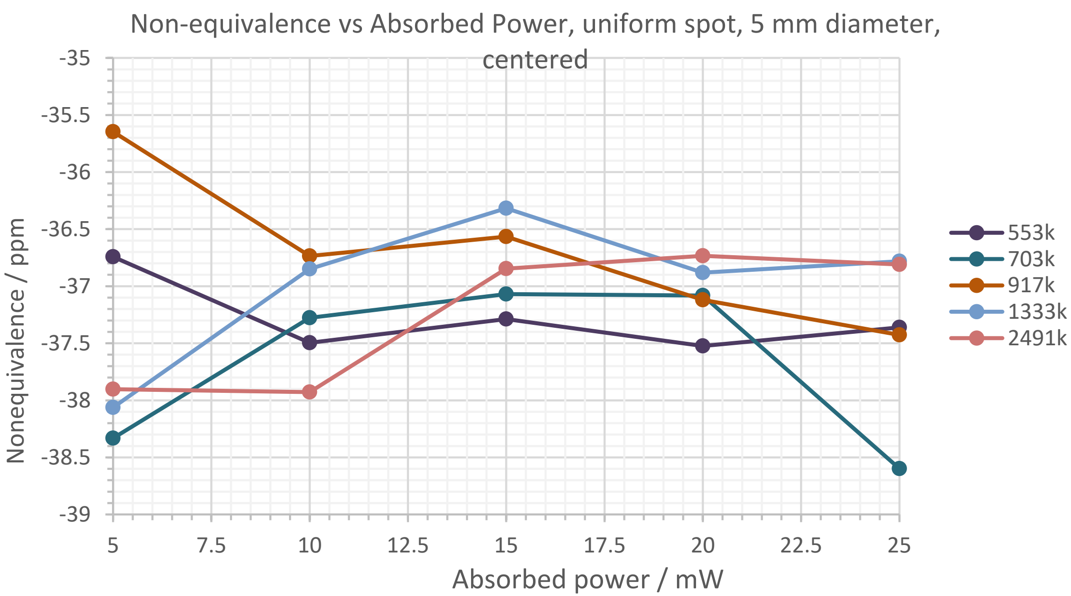
- CTIM night-side Earth radiance observations show good agreement with three CERES instruments
  - Planning on taking more day-side observations before the end of the mission
- An instrument like CTIM may have a role in future measurements of the Earth Energy Imbalance
  - Flat spectral response
  - Excellent long-term stability: <10 ppm/year
  - Potential for ~0.1% uncertainty in radiance with design optimizations

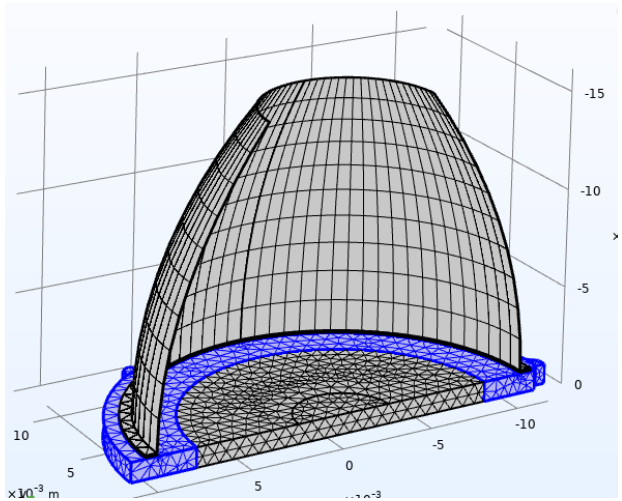
Backup Slides

NACR5 Non-Equivalence Modeling

Non-equivalence (5 mm diameter) :	**-37 ppm**
Uncertainty estimate (k = 1)	**21 ppm**
Spot size dependency up to 5 mm diameter:	11 ppm
Mounting losses dependency up to chip conductance (full range):	<5 ppm (34 ppm)
Mesh dependency:	<3 ppm
Power dependency:	<2 ppm
VACNT Thermal conductivity dependency (1 to 10 W/(m K)):	71 ppm
Silicon thermal conductivity dependency (100 to 200 W/(m K)):	2 ppm

Modeling and analysis by
Julian Gieseler





Bottom-to-top mesh