The Compact Total Irradiance Monitor: Results from the first year of on-orbit operations

Odele Coddington, Dave Harber (PI), 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, 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

Funding:

Overview

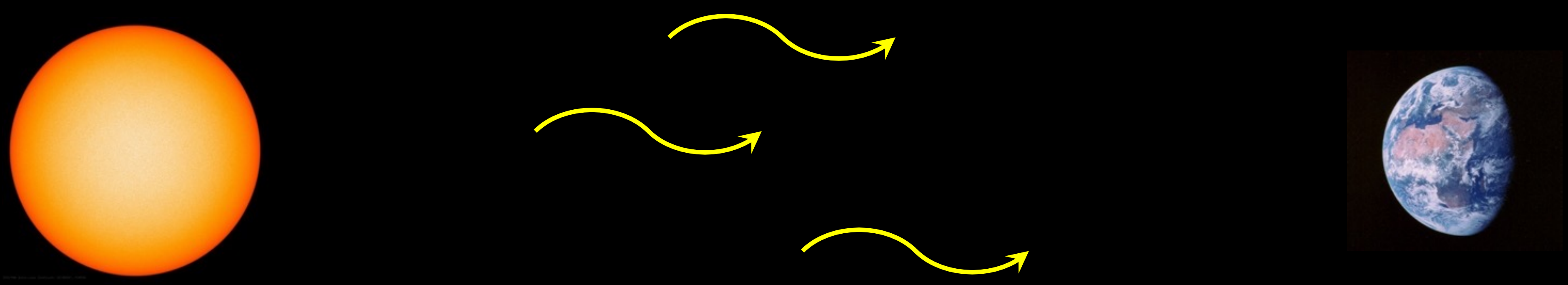
- CTIM: instrument overview and on-orbit performance
- Applicability for Earth Science
  - Observational TSI composite
  - Solar Irradiance Reference Spectra (normalization to TSI)
  - Development/Validation of solar irradiance variability models
- Summary

Total Solar Irradiance (TSI)

Total power from the sun onto the Earth

The input for Earth's climate

W m^{-2} @ 1 AU

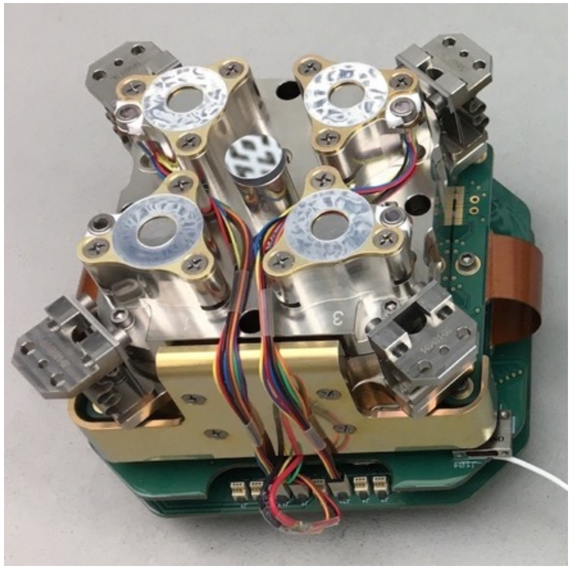


CubeSat CTIM Instrument

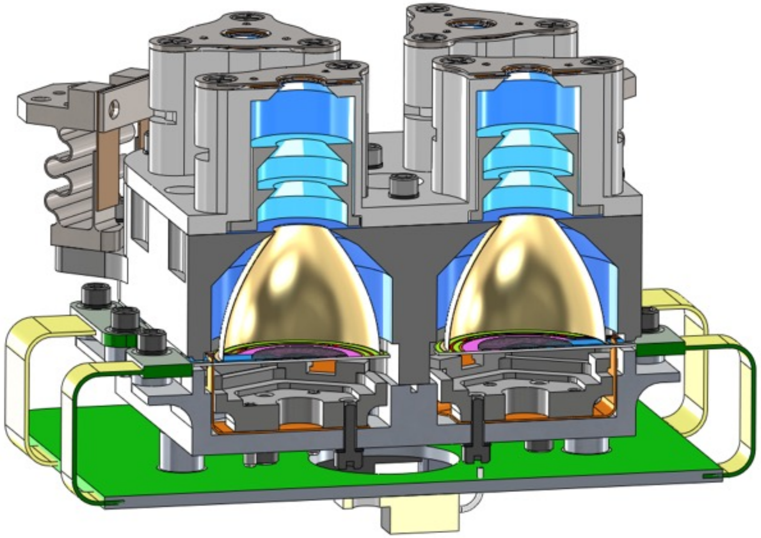
- Detectors
  - Vertically aligned carbon nanotubes on silicon substrate
    - Designed and fabricated by NIST Sources and Detectors group
    - Thermally integrated reflector bonded to silicon
      - Detector reflectance <100 ppm
- Two detector heads: total of 8 channels
  - Four detectors channels per detector head
    - Detector head size ~1U
    - Silicon precision aperture and shutter for each channel

CTIM Detector

Integrated Detector Head



Cut-Away Model of Detector Head

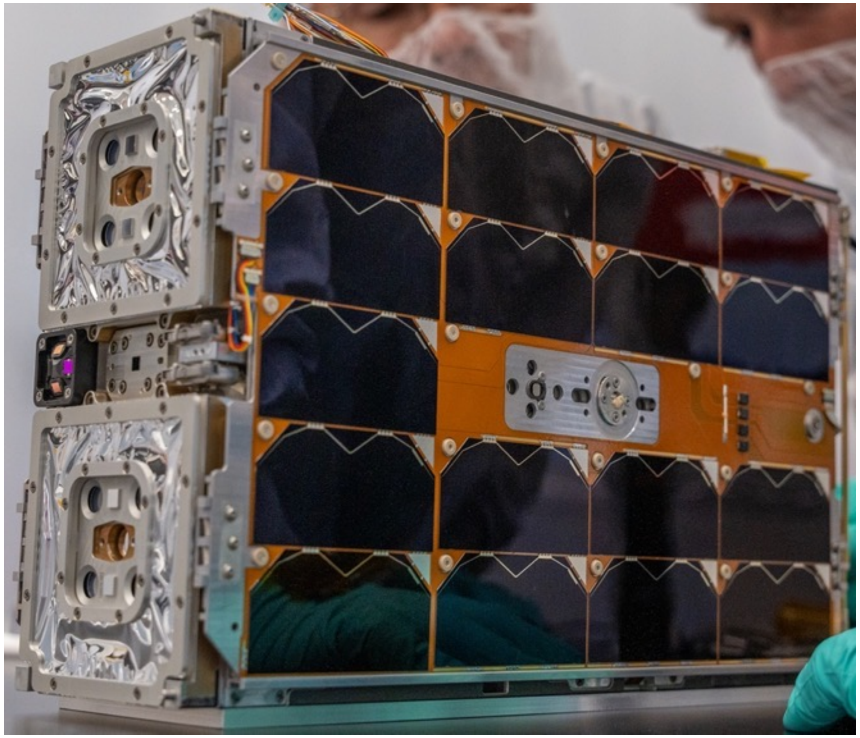


Compact Total Irradiance Monitor CubeSat

- Dual four channel heads
  - Operated as two separate TSI instruments
  - This allows us to check short and long-term stability between heads
- 6U CubeSat, planned 1 year mission
  - ~500 km orbit should allow for ~2 years of operation
- Launch:
  - Virgin Orbit launch on July 1st

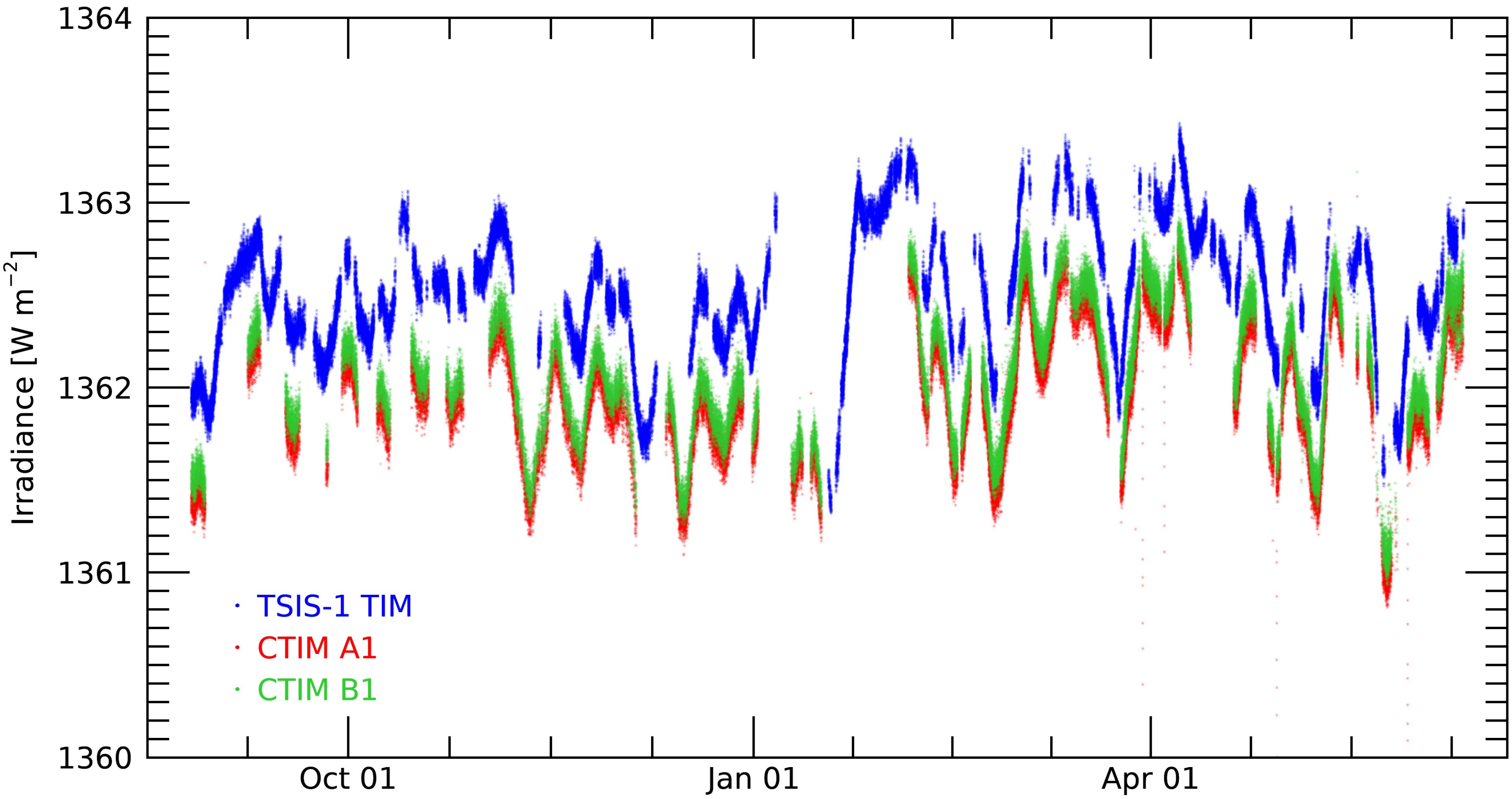
LauncherOne on Cosmic Girl

CTIM Prior to Launch Vehicle Integration



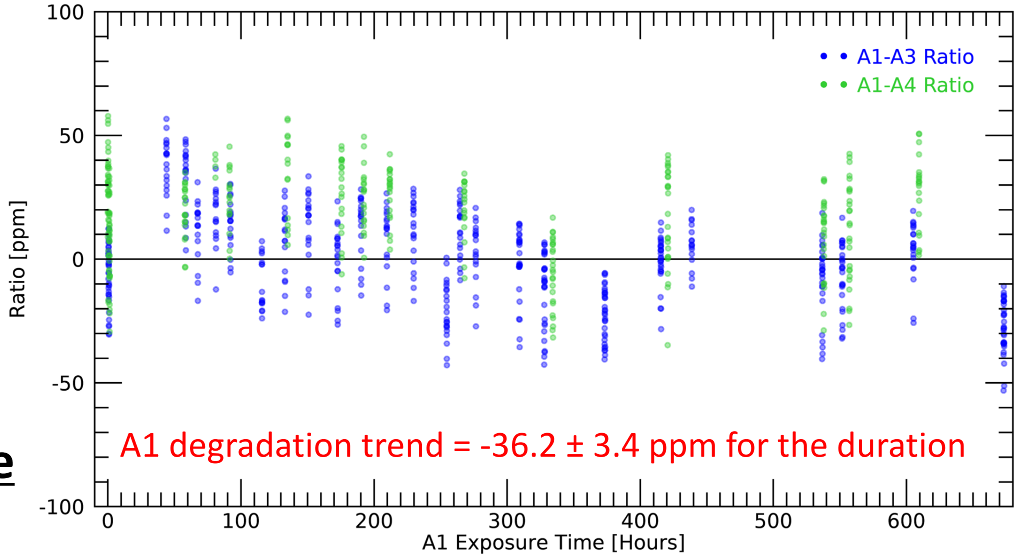
CTIM and TSIS-1 TSI Measurements

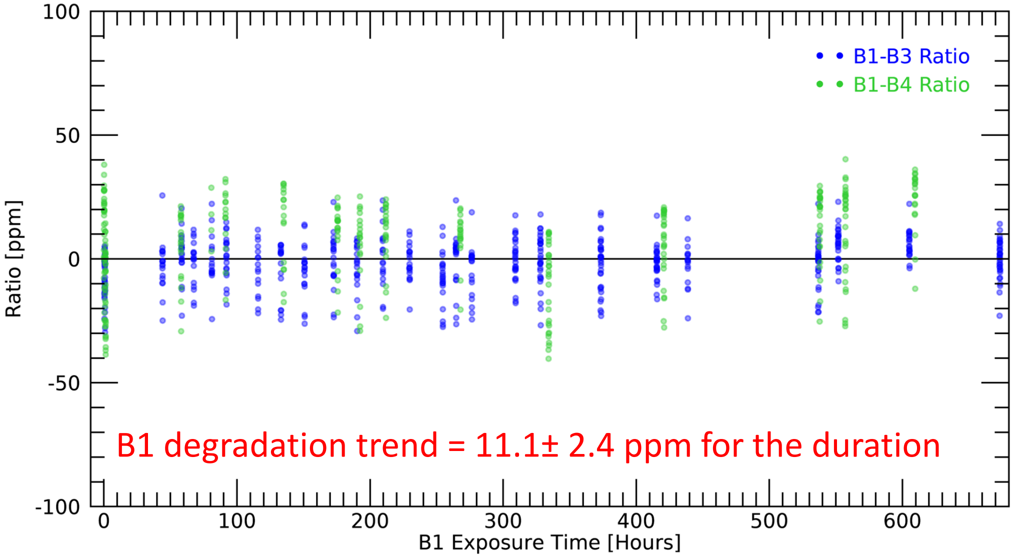
- All shown on their native scales.
- Primary channels (A1 and B1), treated as individual instruments, and adjusted to mean of their heads



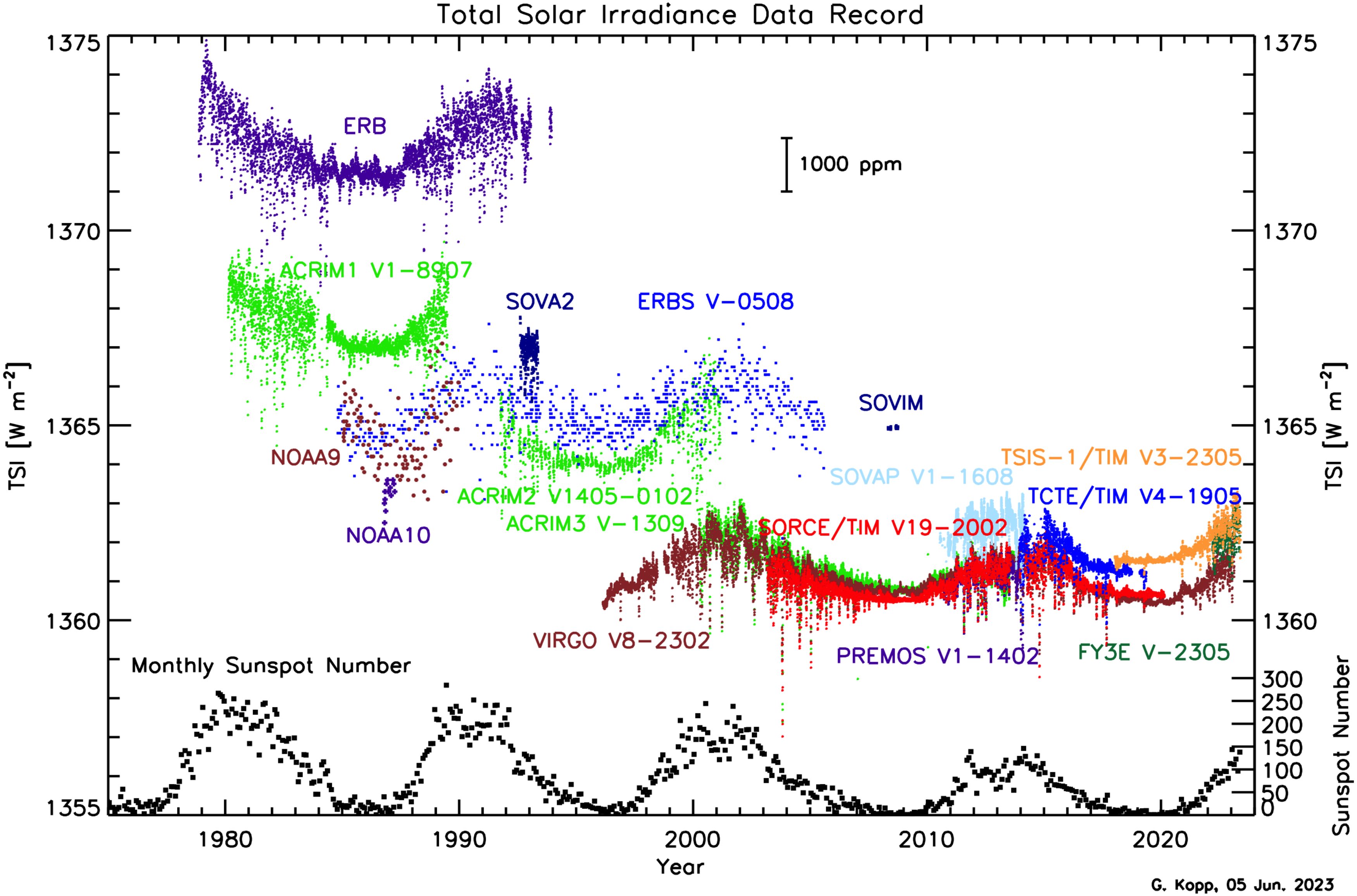
CTIM Detector Stability

- Ratios between primary (A1/B1) and secondary channels (A3, A4, B3, B4)
  - **A1/B1 Exposure = 728 hours**
  - A2/B2 Exposure = 3.1 hours
  - A3/B3 Exposure = 10.7 hours
  - A4/B4 Exposure = 6.0 hours
- **Observed <40 ppm (< 0.004%) change** in the primary channels so far
- Carbon nanotubes are showing very robust performance on-orbit with exposure to direct solar illumination





Ensemble of TSI Space-Based Measurements

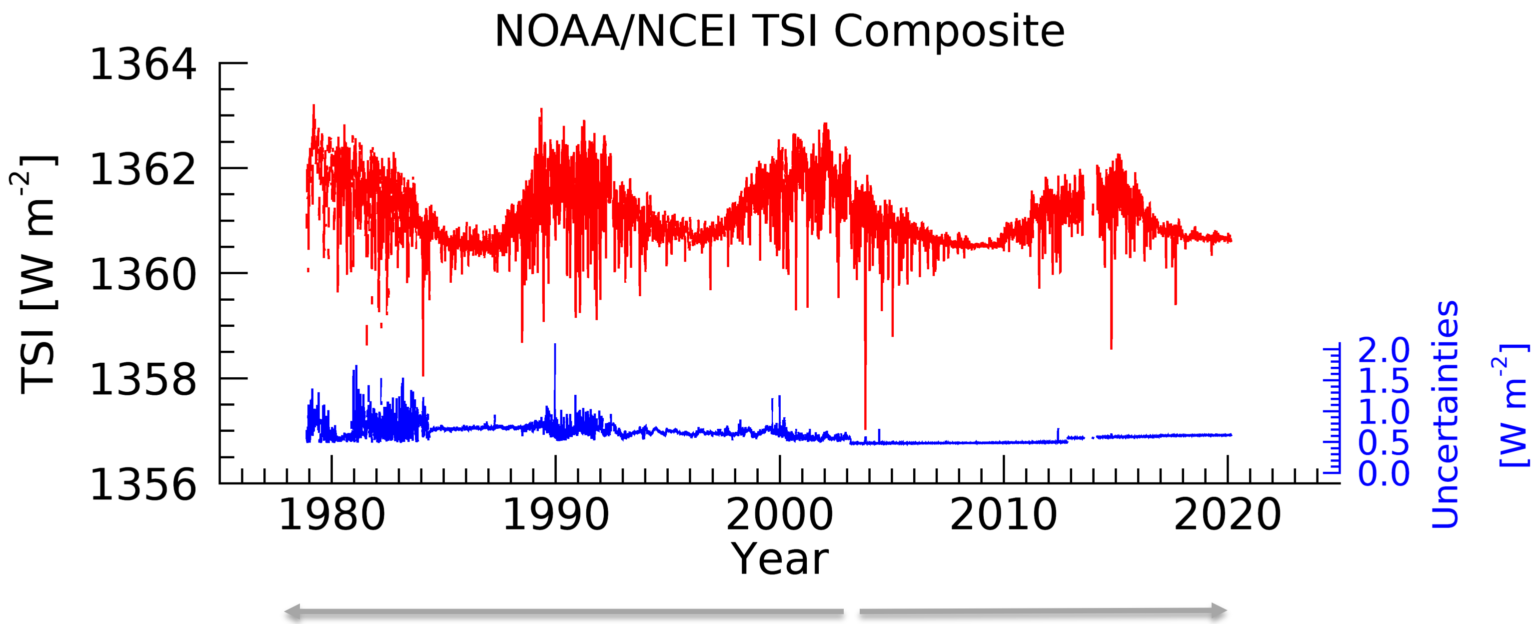


Contemporary TSI Record Including Corrections Being Applied to Select Non-TIM Instruments

NOAA/NCEI Observational TSI composite, v2r1

Coddington et al., A Solar Irradiance Climate Data Record, *BAMS*, 2016.

**at the end of the SORCE mission*



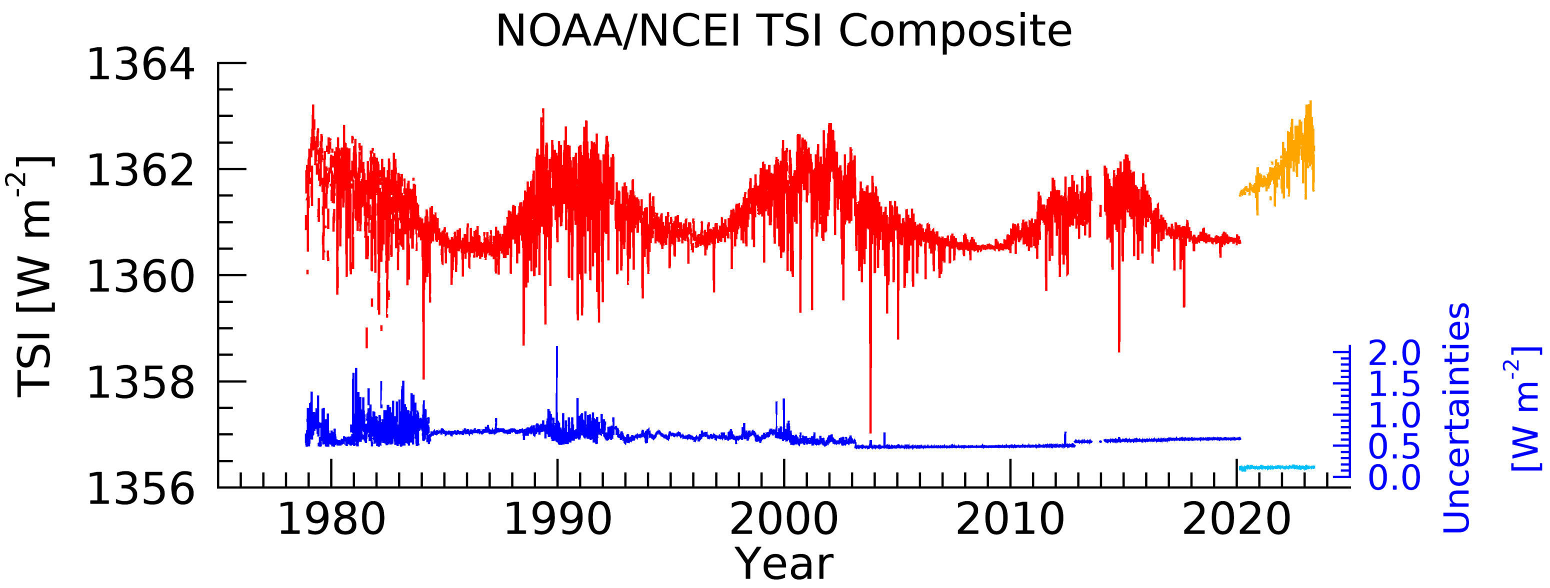
An average of three composites (ACRIM, RMIB, and PMOD) after each separately normalized to the SORCE TSI scale.

Direct SORCE TIM observations and uncertainties.

NOAA/NCEI Observational TSI composite, v2r1

Coddington et al., A Solar Irradiance Climate Data Record, *BAMS*, 2016

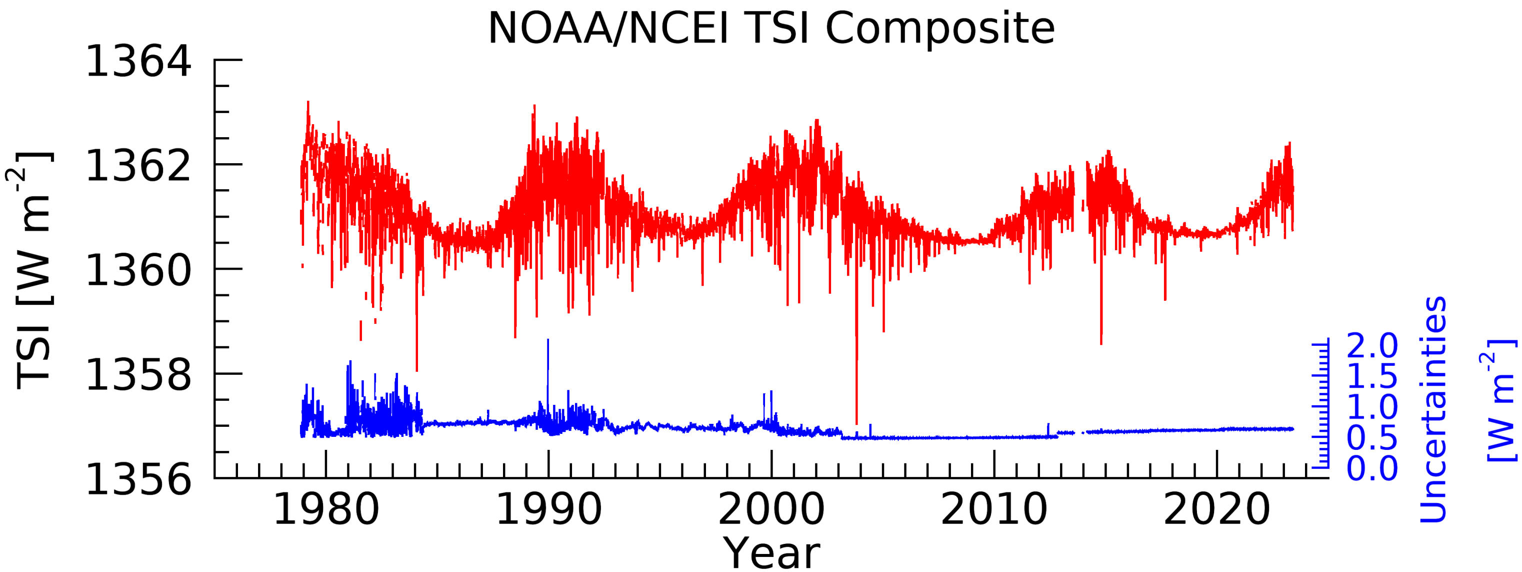
**new TSIS-1 TIM observations*



NOAA/NCEI Observational TSI composite, v2r1

Coddington et al., A Solar Irradiance Climate Data Record, *BAMS*, 2016.

**after extending with TSIS-1 TIM.*

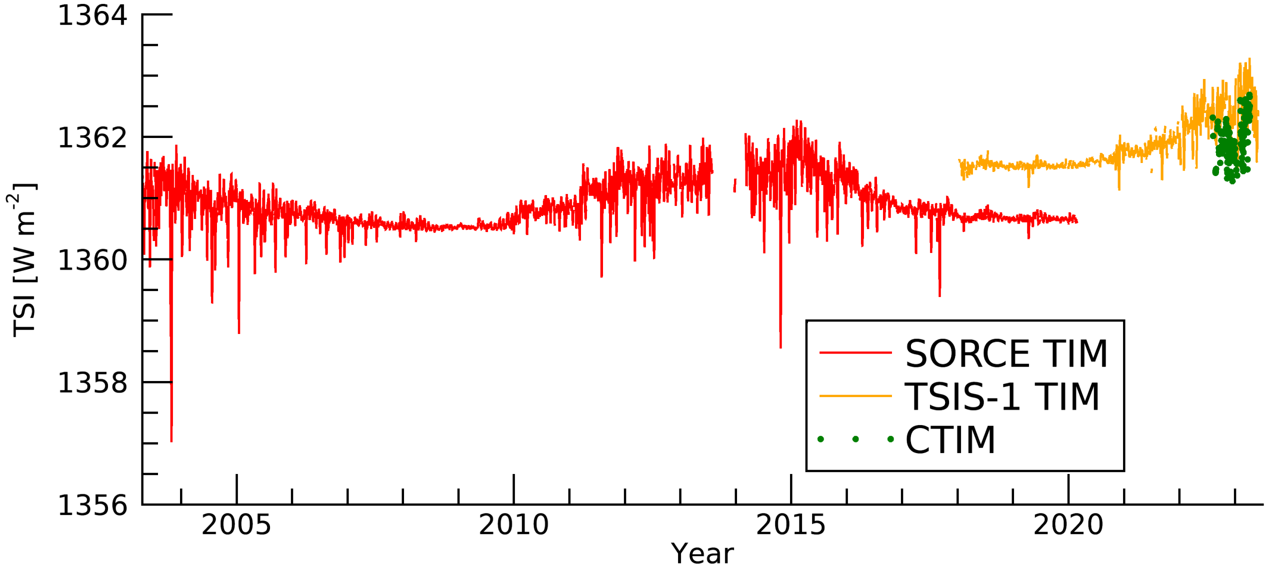


Direct TSIS-1 TIM observations (scaled) with uncertainties enhanced by SORCE TIM EOL accuracy

https://www.ncei.noaa.gov/data/total-solar-irradiance/access/ancillary-data/

NOAA/NCEI Observational Composite, v2r1

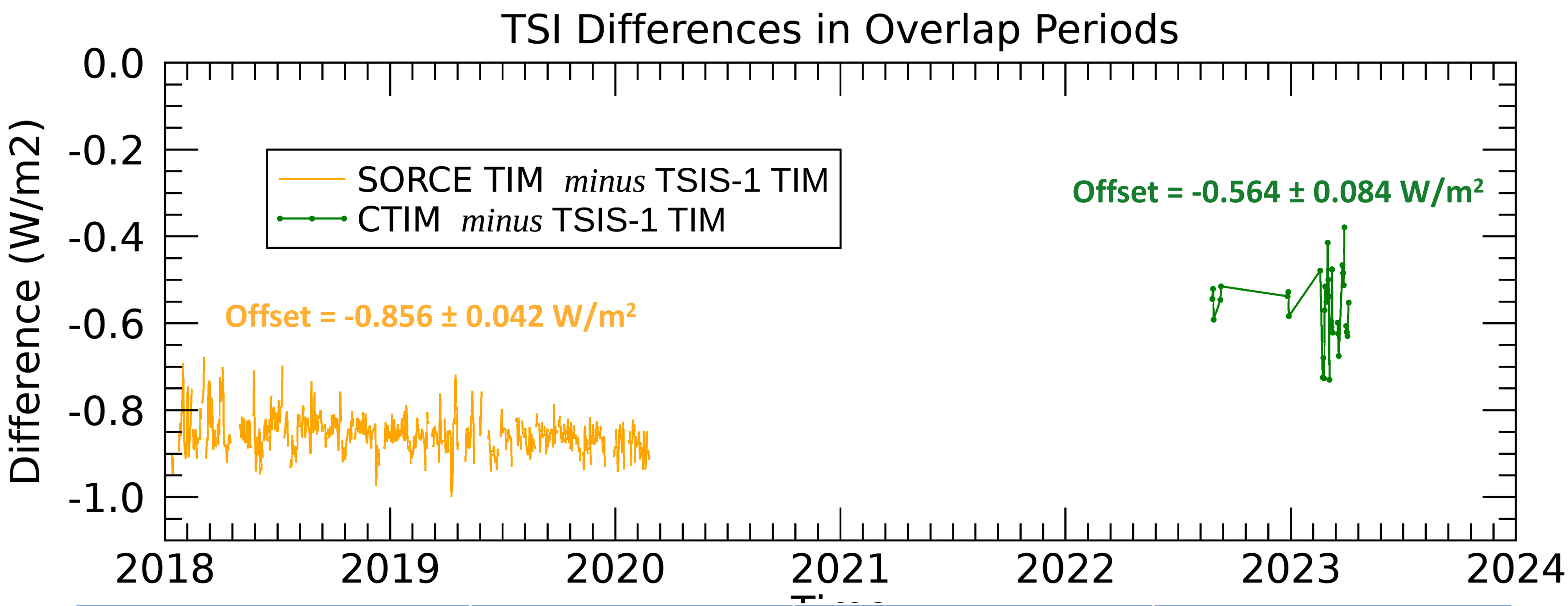
**A look at the process in the SORCE, TSIS-1 and CTIM era. Datasets shown on their native scales.*



Instrument	Total Uncertainty (ppm)	Total Uncertainty (%)	Total Uncertainty (W/m²)
SORCE TIM (EOL)	450	0.045	0.60
TSIS-1 TIM (current)	200	0.02	0.27
CTIM (first light, no time-dependence yet)	160	0.016	0.22

TSI Differences in Overlap Periods

- Differences evaluated on daily-averaged data.



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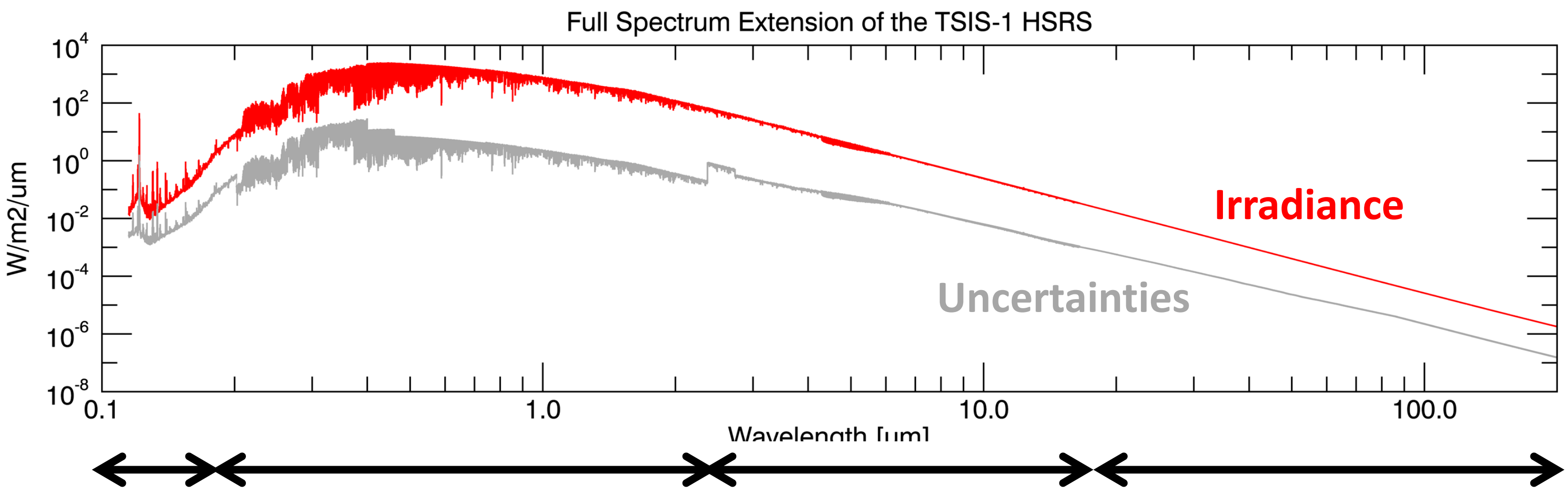
**The TSIS-1 and CTIM offset (~410 ppm) is outside their 1-σ combined uncertainties (prelim).*

The Full Spectrum TSIS-1 Hybrid Solar Reference Spectrum (HSRS)

Coddington et al., The TSIS-1 Hybrid Solar Reference Spectrum, *GRL*, 2021.
Coddington et al., Version 2 of the TSIS-1 Hybrid Solar Reference Spectrum and Extension to the Full Spectra, *E&SS*, 2023



SORCE SOLSTICE (v 18)
0.115-0.202 µm
(<0.01% of TSI)

TSIS-1 HSRS (v 2)
0.202-2.73 µm
(97.5% of TSI)

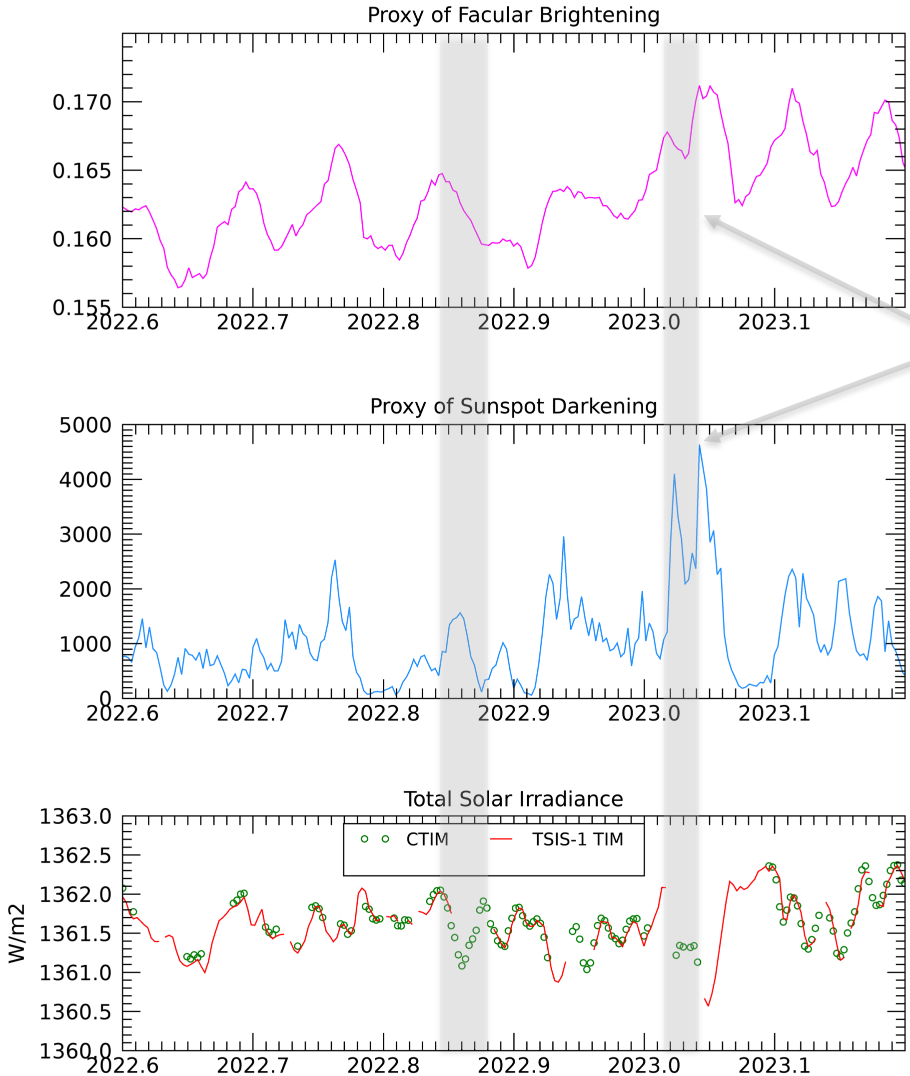
IR Extension 'A'
2.73-16.5 µm
(2.6 % of TSI)

IR Extension 'B'
16.5-200 µm
(0.01% of TSI)

∑SSI .202-2.73 µm [W/m²]	∑SSI .115-200 µm [W/m²]	TSIS-1 TSI [W/m²]	Difference from TSIS-1 TSI [%]	Implied Difference from CTIM [%]
1327.0	1362.8	1361.5	<0.1	~0.13

**Scaling factor applied to V2 published data*

CTIM Utility for TSI Gap-Filling and Irradiance Model Development



**CTIM TSI variability traceable to solar magnetic variability.*

**CTIM could be used to fill gaps in TSIS-1 TIM record.*

Summary and Future Work

- CTIM has been making TSI observations since August 2022
- CTIM has demonstrated the capability to make stable, low-noise TSI measurements from a 6U CubeSat platform
- Continued operations will further test the long-term stability of the CTIM instrument and provide supplemental TSI measurements
- Measurement scale of CTIM is tied to our ground reference detector, NACR5, so future inter-comparisons with NACR5 could further underpin the CTIM measurement scale
- CTIM measurements have utility in Earth science applications:
  - TSI composites (and data gap-filling), SSI reference spectra, TSI irradiance modeling
- CTIM data will be made publicly available here:

https://lasp.colorado.edu/home/ctim/data/

Backup Slides

CTIM Uncertainty

The current estimated CTIM standard uncertainty is 149-178 ppm:

Uncertainties in ppm (k=1)

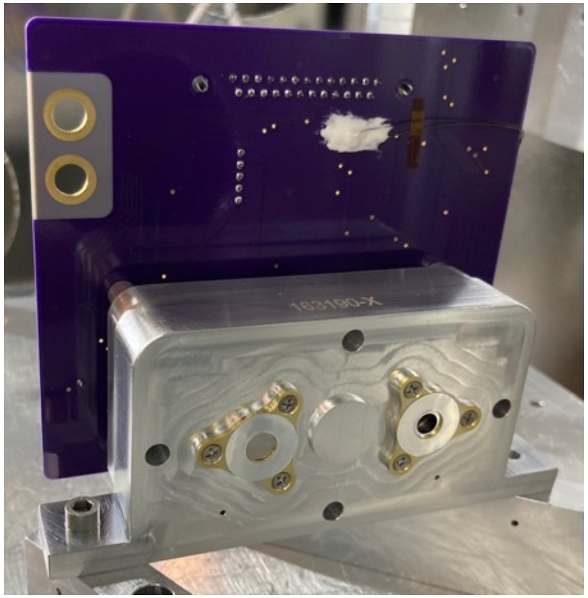
Source	**A1**	**A2**	**A3**	**A4**	**B1**	**B2**	**B3**	**B4**
Aperture Area at T0	14	14	27	12	13	13	14	14
Aperture Area Expansion	10	10	10	10	10	10	10	10
Diffraction Loss	42	42	42	42	42	42	42	42
Detector Reflectance	4	6	4	7	5	7	5	7
Reference Voltage	52	52	49	49	50	50	66	66
Top Resistor	41	41	41	41	40	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	139	155	133	134	126	139	121	113
Noise	9	9	9	9	9	9	9	9
Dark Signal	11	11	11	11	11	11	11	11
Total	*169*	*178*	*160*	*160*	*154*	*164*	*155*	*149*

CTIM was calibrated directly against a new ambient irradiance reference detector, NACR5, in the LASP TSI radiometer facility

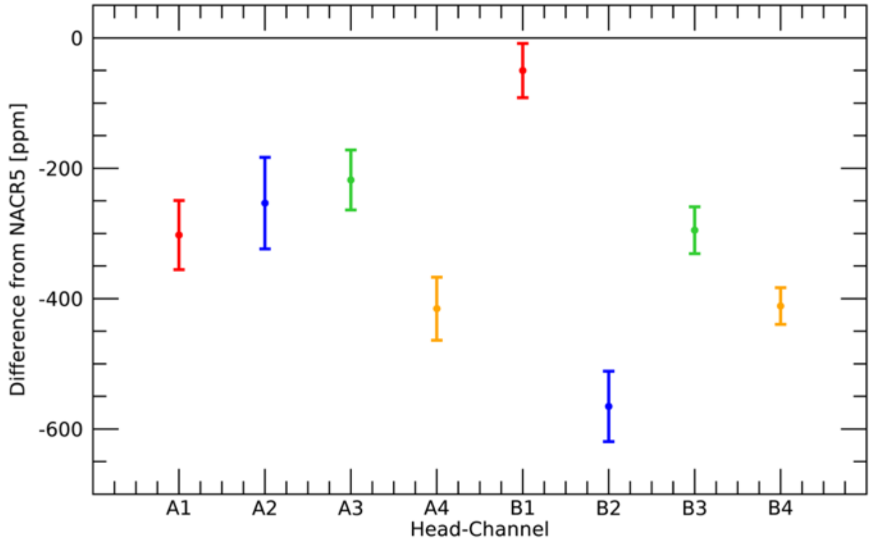
CTIM Traceability

- CTIM was calibrated directly against a new ambient irradiance reference detector, NACR5, in the LASP TSI radiometer facility
- NACR5 was compared in power mode against a a trapped photodiode calibrated by NIST POWR
  - NACR5 measured 252 +/- 257 ppm higher that POWR
- The CTIM non-equivalence correction is determined by the offset measured against NACR5 in irradiance mode

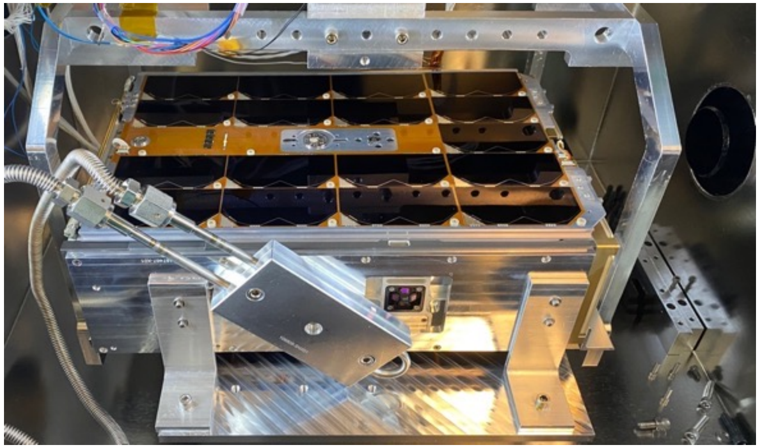
NACR5



CTIM Relative to NACR5 with no-equivalence correction applied to CTIM



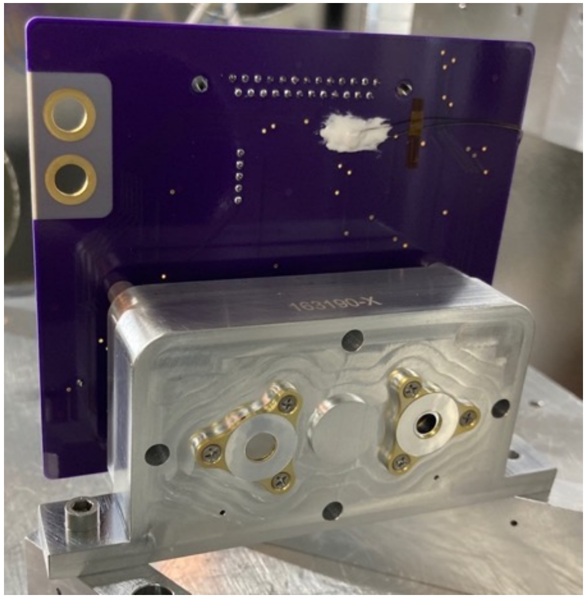
CTIM in TRF



NACR5 Uncertainty

- We are treating NACR5 as a primary standard based on component-level calibrations
- The intercomparison with the NIST trapped diode is a independent check of the NACR5 measurement scale

NACR5



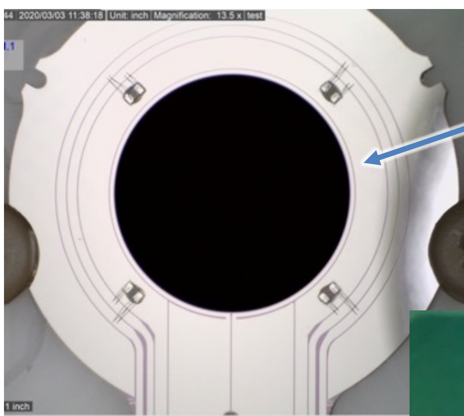
NACR5 Standard Uncertainties

Source	ppm (k=1)
Aperture Area at T0	17
Aperture Area Expansion	20
Diffraction Loss	25
Detector Reflectance	20
Non-equivalence	25
CNT IR Re-emission	48
Heater voltage	7
Sense resistor voltage	7
Frequency response	10
Wire bond resistance	49
Total	*85*

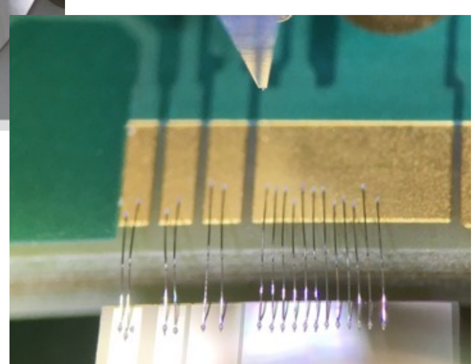
CTIM and NACR5 Non-equivalence

CTIM

- Replacement heater was 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



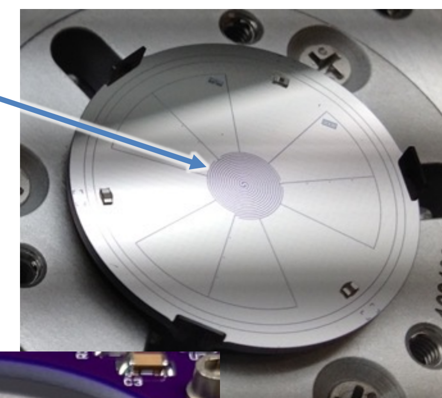
Front side annular heater



NACR5

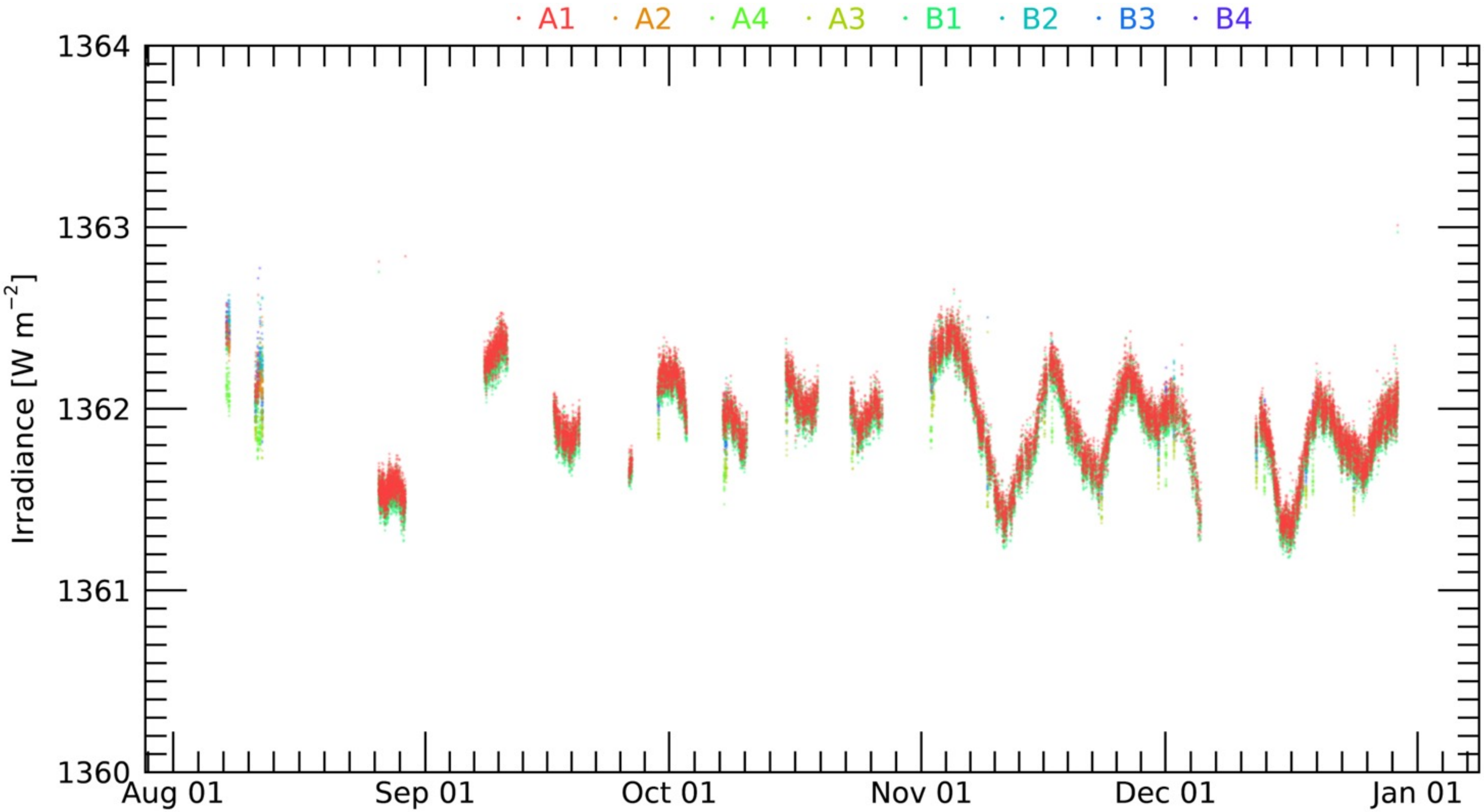
- Replacement heater on the backside of the silicon substrate and matched the illumination region
- Minimal wire bonds to optimize non-equivalence

Back side uniform circular area heater



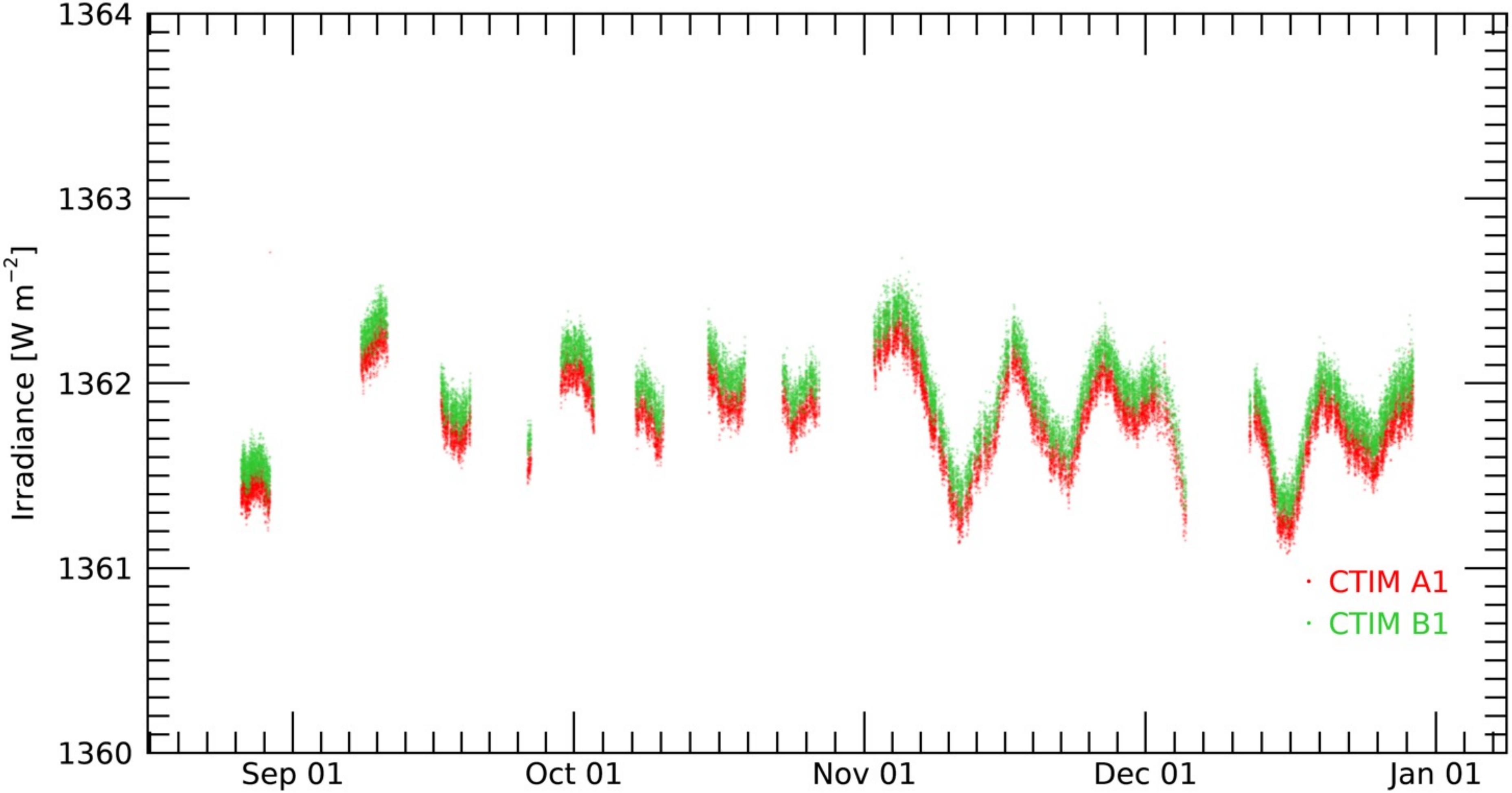
Corrected TSI Measurements

- Doppler, 1AU corrections applied, filtered for pointing

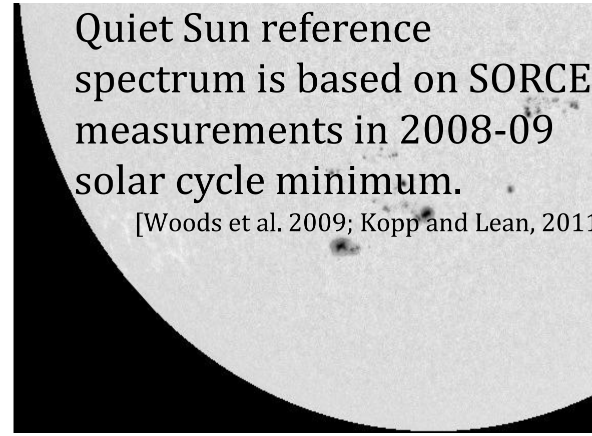


CTIM Head A/B TSI Measurements

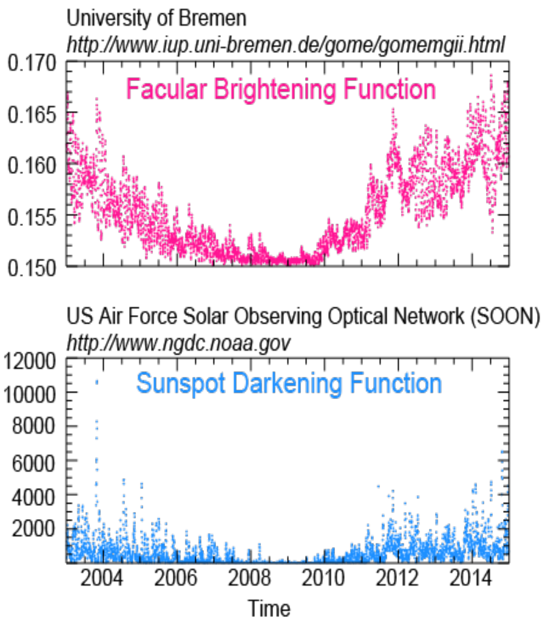
- First light data was used to determine relative offsets between all channels
- Primary channels (A1 and B1), treated as individual instruments, and adjusted to mean of their heads

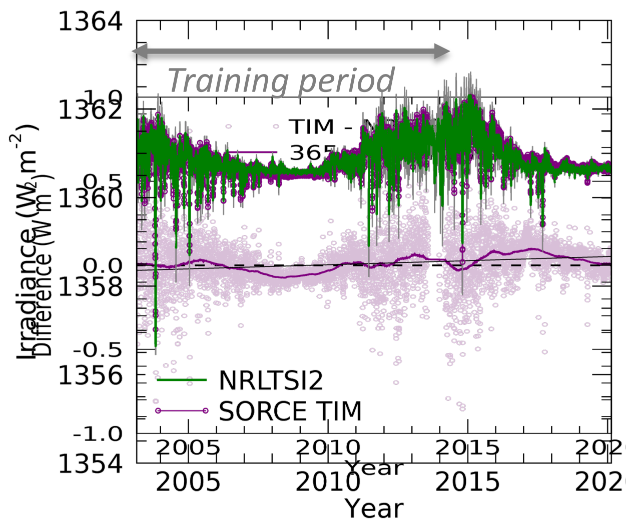


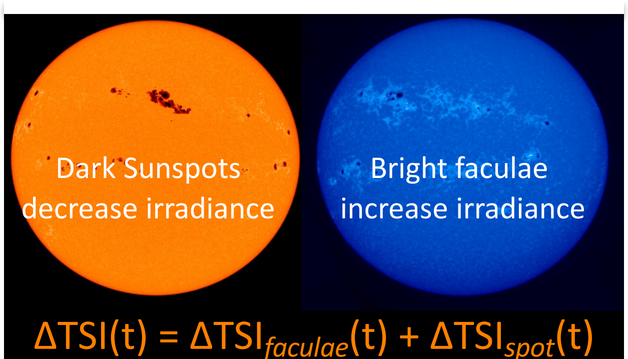
The Solar Irradiance CDR: ‘NRL V2’ Model Formulation



The magnitude of irradiance changes from “Quiet Sun” conditions is determined from multiple linear regression analysis of observations and proxy records of magnetic variability.







	Mean difference W/m2	Stdev of difference W/m2
Training period	0.009	0.149
Full SORCE era	0.010	0.137