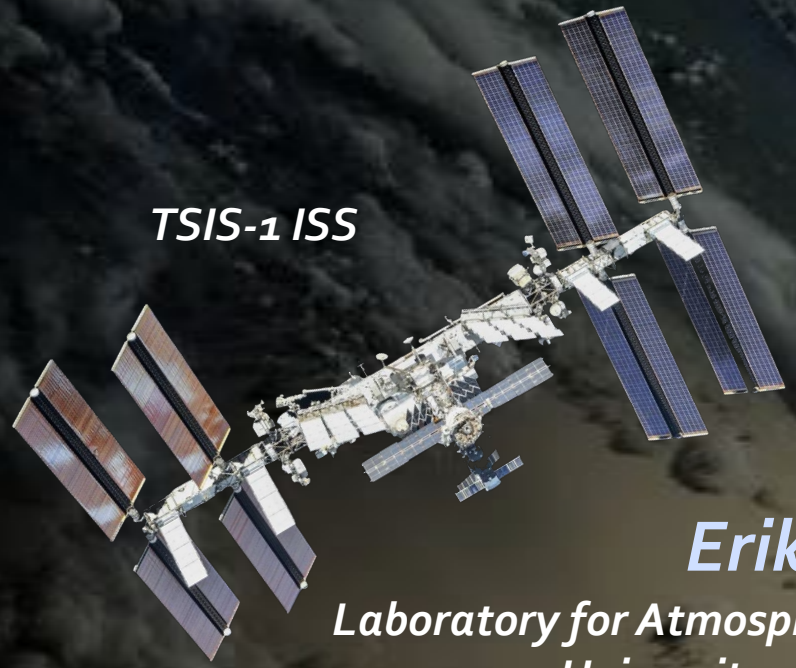
Overview of NASA Sun-Climate Missions and Research Projects

Long-term Solar Irradiance Measurements and Continuity: The TSIS-1 & 2, CSIM, and CTIM Missions

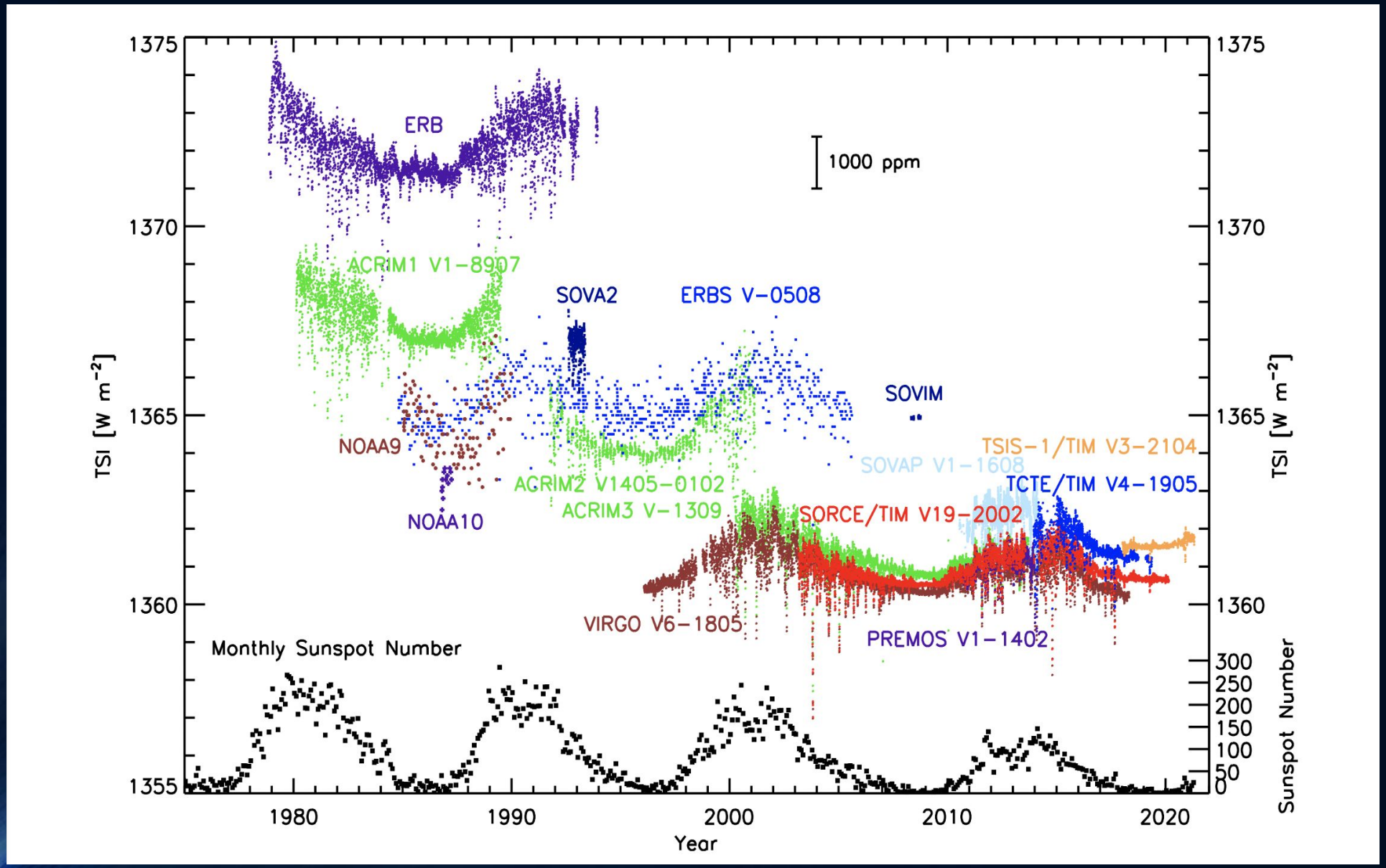


Erik Richard
Laboratory for Atmospheric and Space Physics (LASP)
University of Colorado, Boulder

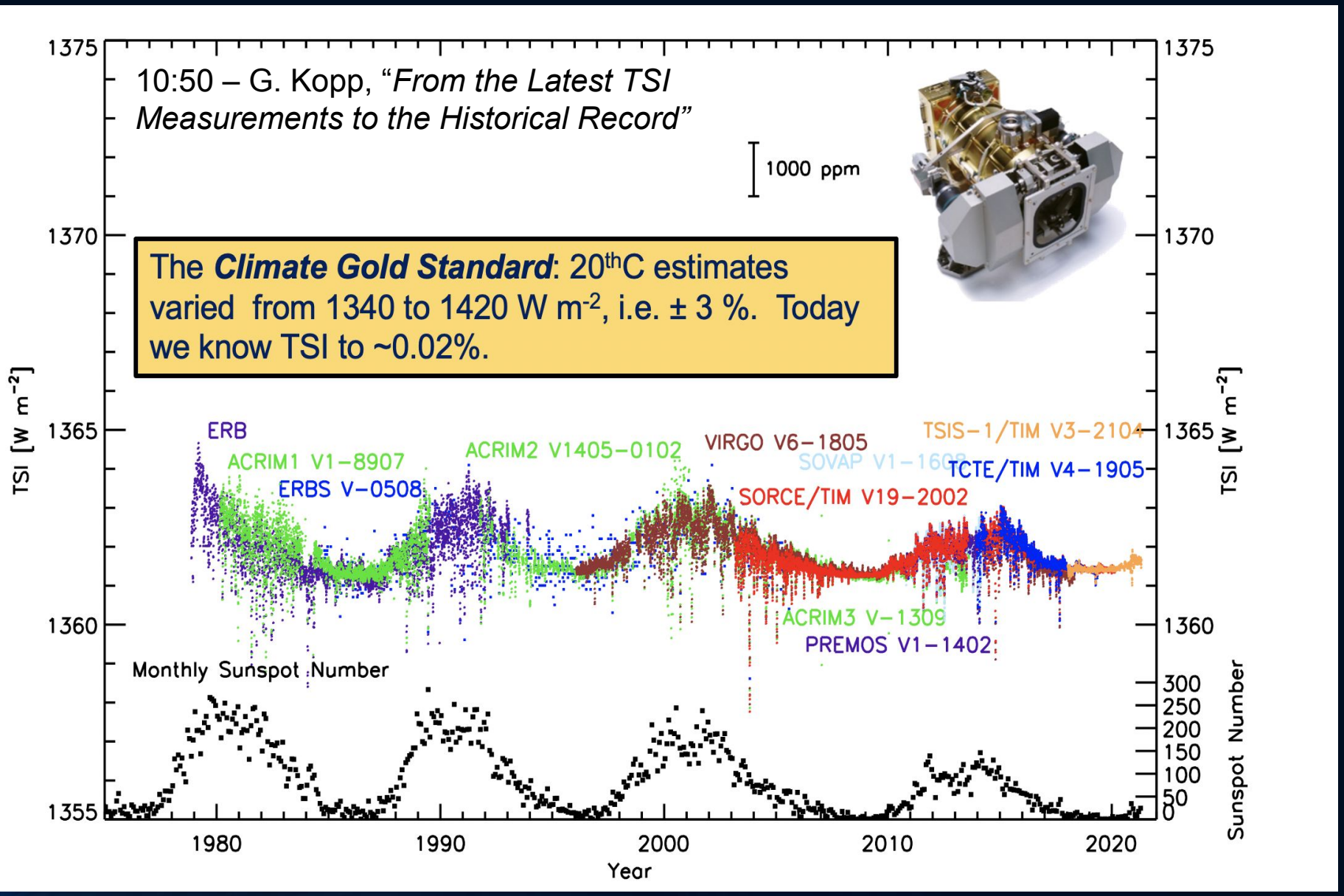
David Considine
Earth Science Division, Science Mission Directorate
NASA Headquarters

SORCE
"ave atque vale"

Total Solar Irradiance Data Record



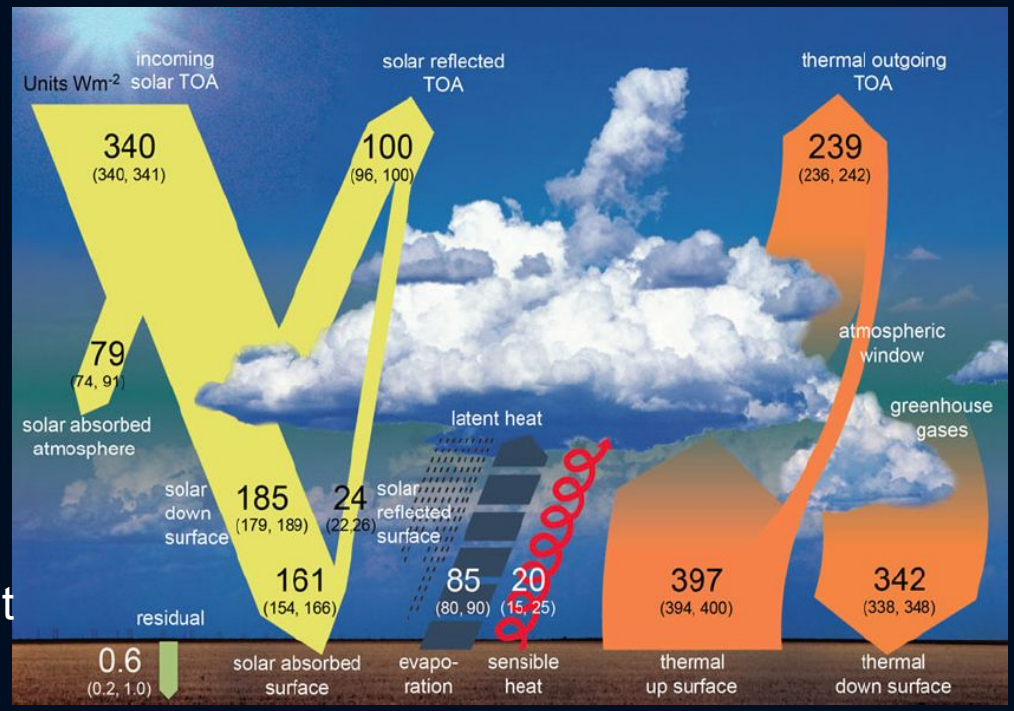
Total Solar Irradiance Composite



Justification for SSI measurement continuity

Science Justification: extending the important long-term climate record of Solar Spectral Irradiance (SSI)

- The SSI climate record extends back to 2003 (SORCE) and is critical for NASA's Sun-climate science as highlighted in the 2017 Earth Science Decadal Survey.
- SSI measurements enable in-depth research of the Sun's influence on Earth's ozone layer, atmospheric circulation, clouds, and ecosystems.
- The SSI climate record provides the spectral variability that is important for detailed understanding on how the Earth's atmosphere and surface absorb the solar energy. Model validation.



Schedule Justification: TSIS-1 needs to continue to operate until at least October 2025 in order to have a one-year overlap with TSIS-2 (Aug 2024 Launch readiness)

- The continuity of both the TSI and SSI climate records depends critically on having overlapping observations.
- The TSIS-2 mission, with the same instruments as those on TSIS-1, is planned to launch no early than August 2024 and with commissioning being completed in October 2024.
- A one-year overlap between TSIS-1 and TSIS-2 is required to ensure the continuity of the accurate SSI data records, so TSIS-1 operations need to continue to at least October 2025.

TSI & SSI focused missions & opportunities moving forward

Over 4 decades of LASP/GSFC solar irradiance measurement continuity…

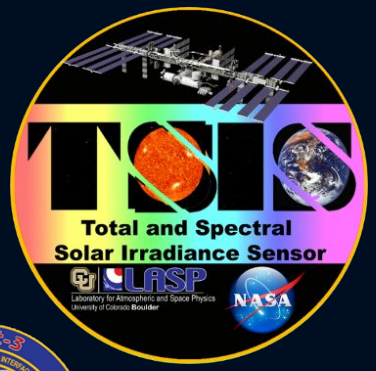
1981-1989

1991-2005

FUV & MUV SSI

2003-2020

2013-2017 (TSI)

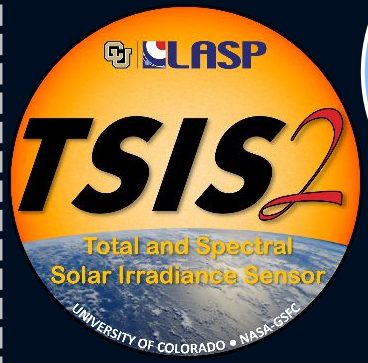


2017-present

New Tech Demo (ESTO)

2018-2022

2022 -

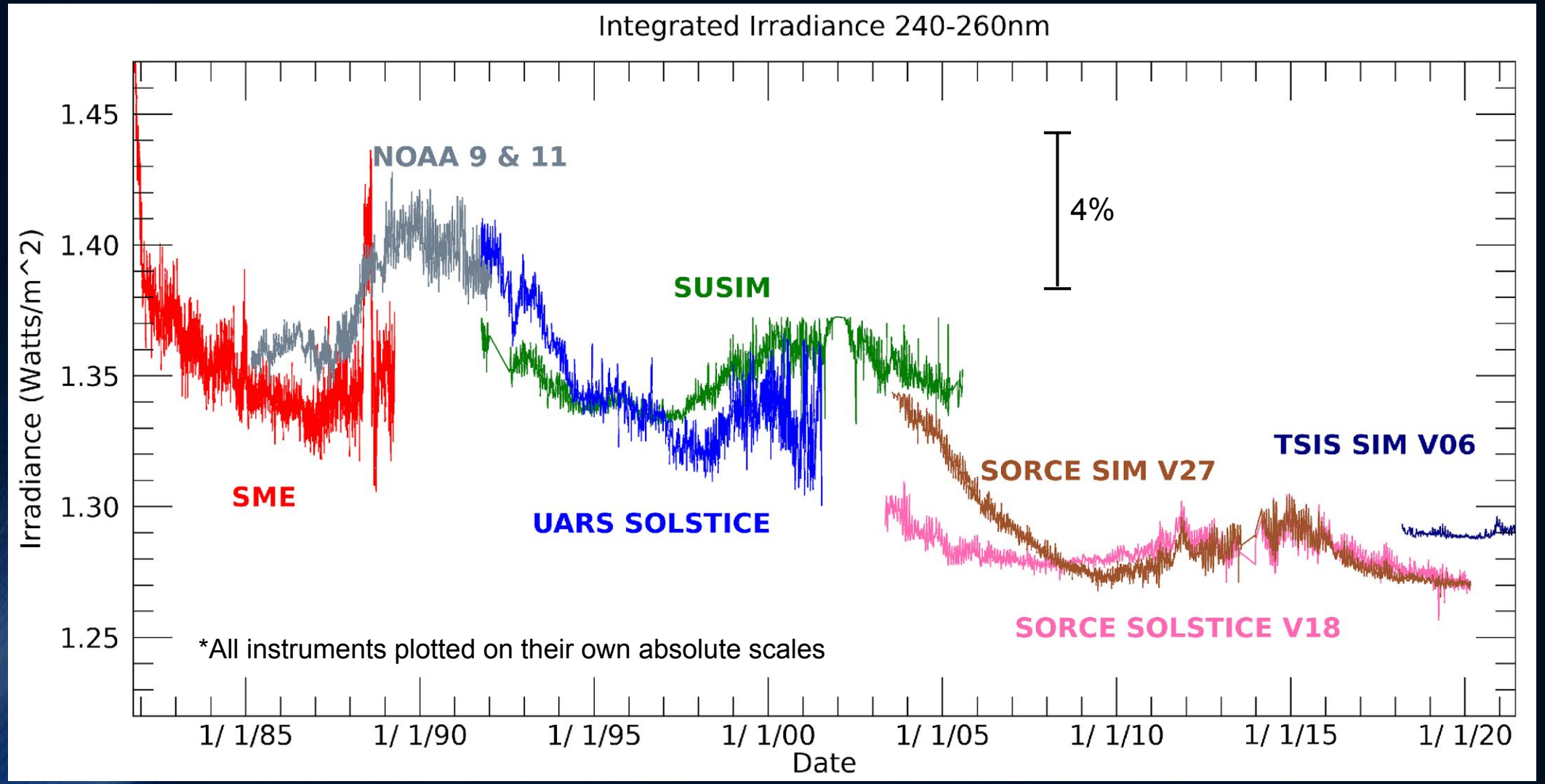


2024-

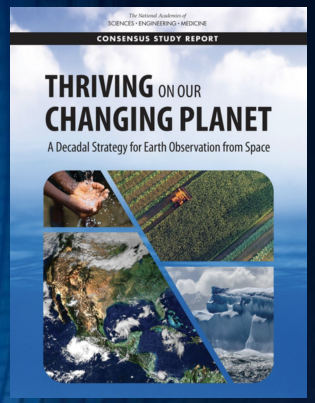
2028-

- What can we learn from past and present solar missions?
- Are the methods of observation adequate and are the results accurate enough?
- What are the observations to be continued? What are the missing ones?
- New directions? - new instrumental concepts or novel technologies, new observation strategies
- What is the best strategy for ensuring the proper observation of essential observables (dedicated missions, hosted payloads, CubeSats)?

UV SSI Data Record

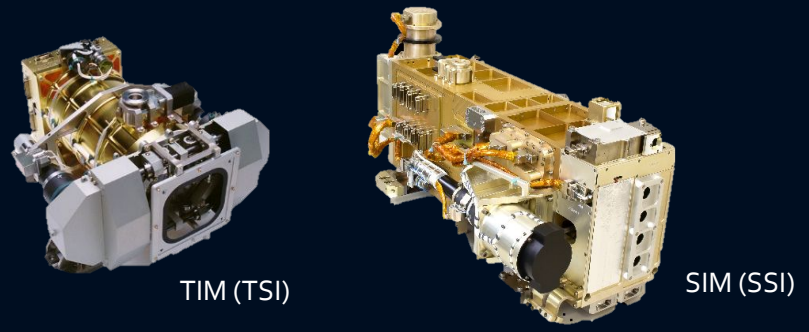


Solar Irradiance Measurement Continuity (SORCE and beyond)



2017 Earth Science Decadal Survey (Prioritized science objectives and challenges):

*"For the next decade and beyond, the measurement imperatives include ... an **emphasis on continuity** so that gaps in observations that would preclude or impair scientific understanding and societal benefits are avoided."*



***Goal: "Acquire SSI and TSI time series of measurements of sufficient length, consistency, and continuity to determine climate variability and change"**

**Climate Data Records from Environmental Satellites: Interim Report (2004)*

SORCE/TCTE/TSIS-1/CSIM Accomplishments

The 17-year SORCE mission ended on Feb. 25, 2020.

- Final data products are archived at GSFC.
- 2 years of overlap with TSIS-1 (Overlap analysis in progress – several NASA SIST efforts)
- SORCE TIM established a new TSI of 1361 W m^{-2}.

TCTE ended in June 2019.

- Over 5 years overlap with SORCE, over a year overlap with TSIS-1.

TSIS-1 normal operations on ISS started Jan 2018 (TSI) March 2018 (SSI)

TSIS-1 SIM reduces uncertainties from SORCE SIM by ~ one order of magnitude.

- TSIS-1 SIM accuracy uncertainty < 0.25% (Vis-IR). <0.5% (UV) – tied to NIST standards in irradiance
- Integrated SIM SSI (+ inferred long IR) agrees with TIM TSI to within 1 W m^{-2}
- Established absolute scale of HSRS internationally recognized SSI reference spectrum (CEOS adoption March 2022)

TSIS-1 TIM validates the SORCE and TCTE calibration scales.

- SORCE TIM reduced uncertainties from prior TSI measurements by approximately one order of magnitude.
- TSIS-1 TIM uncertainty ~ 0.012% (launch), ~0.016% (present).

CSIM Flight Demonstration first on-orbit SSI absolute validation (<1% uncertainty)

- Technology demonstration for next-generation absolute detectors
- 3 year mission (Jan 2019 – Feb 2022), contributed to extending IR of HSRS reference spectrum

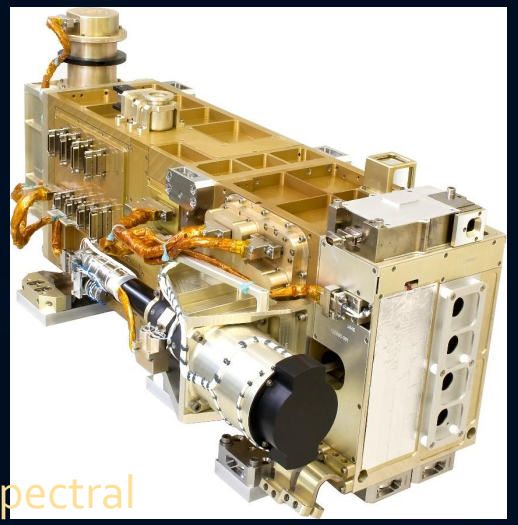
TSIS-2 TIM & SIM currently in final instrument build & calibration phase

- Scheduled launch readiness Aug. 2024, Free-flyer satellite

TSIS-2:Extending the TSI and SSI Data Record

Total and Spectral solar Irradiance Sensor – 2

- NASA GSFC Managed Mission (NASA PM: Susan Breon)
- LASP PI: Erik Richard; LASP PM: David Gathright
- Rebuild of TSIS-1 SIM and TIM instruments, flying on a dedicated spacecraft
- Payload: LASP (SIM, TIM)
- Spacecraft Bus: General Atomics
- Mission Operations: General Atomics
- Payload Operations: LASP
- Science Data Processing: LASP



Spectral Irradiance Monitor

Total Irradiance Monitor

- Payload is **[illegible] 3 delivery**
  - TSIS-2 launch readiness date: Aug 2024
  - Next milestone review: Mission KDP-C, May `22
  - TIM and SIM are in final assembly & calibration

Laboratory for Atmospheric and Space Physics
University of Colorado **Boulder**

TSIS-1 SSI Scientific Impacts

TSIS-1 HSRS Formally Recognized

March 2022: The Committee on Earth Observation Satellites (CEOS) Working Group on Calibration and Validation (WGCV) recommended the TSIS-1 HSRS as the new solar irradiance reference spectrum [https://calvalportal.ceos.org/events/].

CEOS Cal/Val Portal

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TSIS-1 HSRS Reference

SRIX4VEG 1st WS

ACIX III and CMIX II 1st WS

CEOS SAR Cal/Val WS 2021

SITSCOS WS 2019

Terms and Definitions Wiki

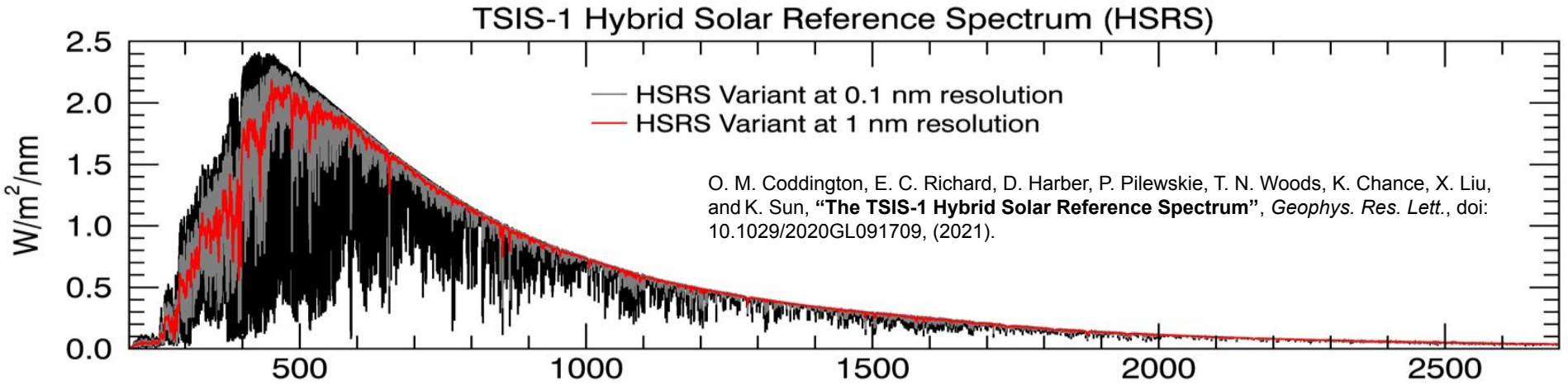
Links

TSIS-1 HSRS solar irradiance reference spectrum

TSIS-1 HSRS solar irradiance reference spectrum

CEOS WGCV recommends the Total and Spectral Solar Irradiance Sensor-1 (TSIS-1) Hybrid Solar Reference Spectrum (HSRS) as the new solar irradiance reference spectrum. This statement has been agreed during the latest WGCV#50 Plenary Meeting.

Details for TSIS-1 HSRS are available at: https://lasp.colorado.edu/lisird/data/tsis1_hsrs



O. M. Coddington, E. C. Richard, D. Harber, P. Pilewskie, T. N. Woods, K. Chance, X. Liu, and K. Sun, **"The TSIS-1 Hybrid Solar Reference Spectrum"**, *Geophys. Res. Lett.*, doi: 10.1029/2020GL091709, (2021).

Applications Using the TSIS-1 HSRS

Aerosol Optical Depth Retrievals

- Natalia Kouremeti et al 2022 Metrologia in press

Radiative Transfer Modeling

- Momoi, M. et al. Rapid, accurate computation of narrow-band sky radiance in the 940 nm gas absorption region using the correlated k-distribution method for sun-photometer observations. Prog Earth Planet Sci 9, 10 (2022).

Ozone Retrievals

- Egli, L., et al., Traceable total ozone column retrievals from direct solar spectral irradiance measurements in the ultraviolet, Atmos. Meas. Tech., 15, 1917–1930, 2022.
- Bak, J. et al., Impact of Using a New High-Resolution Solar Reference Spectrum on OMI Ozone Profile Retrievals. Remote Sens. 2022.

Airborne/Satellite Calibration & Inter-Calibration

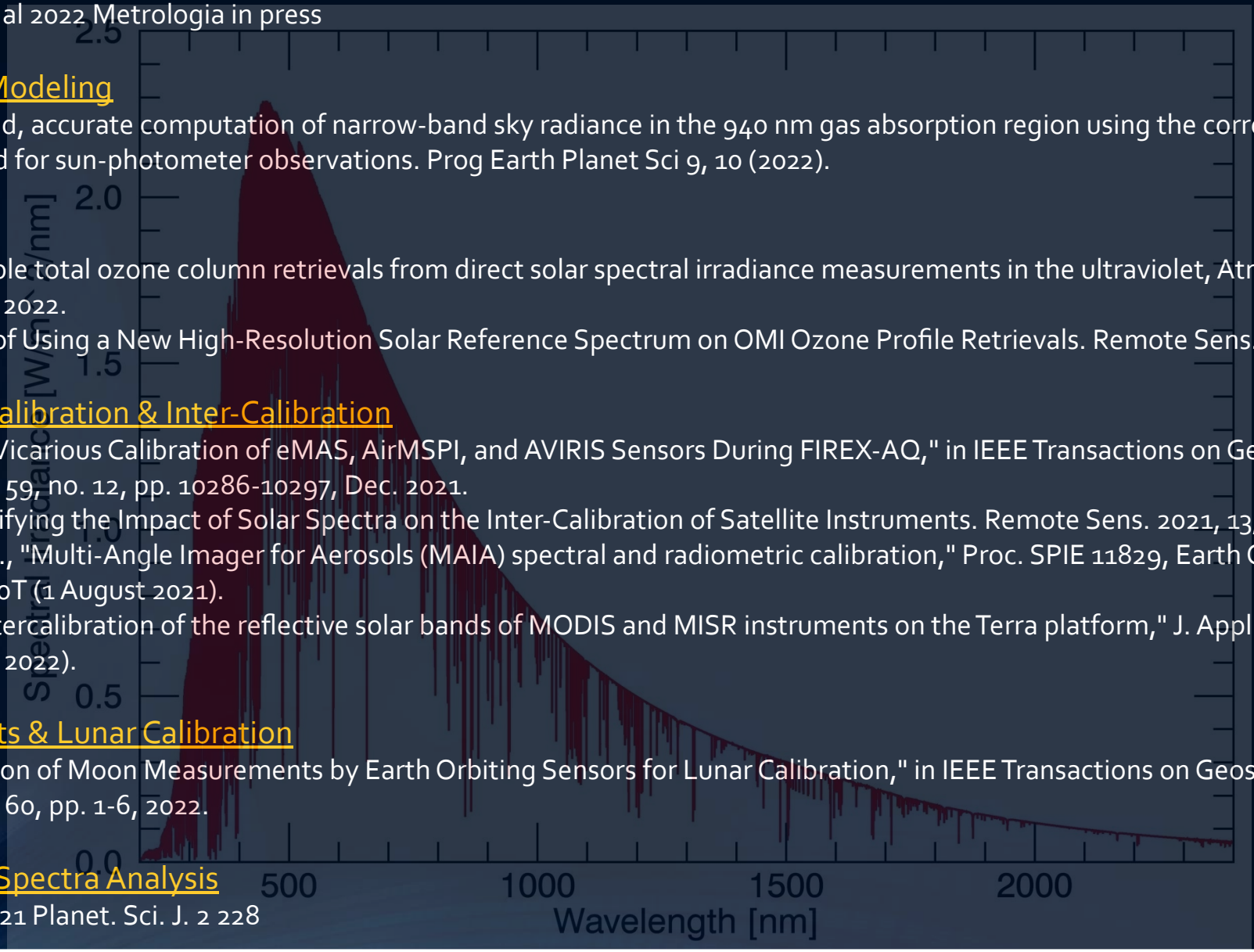
- C. J. Bruegge et al., "Vicarious Calibration of eMAS, AirMSPI, and AVIRIS Sensors During FIREX-AQ," in IEEE Transactions on Geoscience and Remote Sensing, vol. 59, no. 12, pp. 10286-10297, Dec. 2021.
- Bhatt, R et al., Quantifying the Impact of Solar Spectra on the Inter-Calibration of Satellite Instruments. Remote Sens. 2021, 13, 1438.
- Carol J. Bruegge et al., "Multi-Angle Imager for Aerosols (MAIA) spectral and radiometric calibration," Proc. SPIE 11829, Earth Observing Systems XXVI, 118290T (1 August 2021).
- Amit Angal et al., "Intercalibration of the reflective solar bands of MODIS and MISR instruments on the Terra platform," J. Appl. Rem. Sens. 16(2) 027501 (15 April 2022).

Lunar Measurements & Lunar Calibration

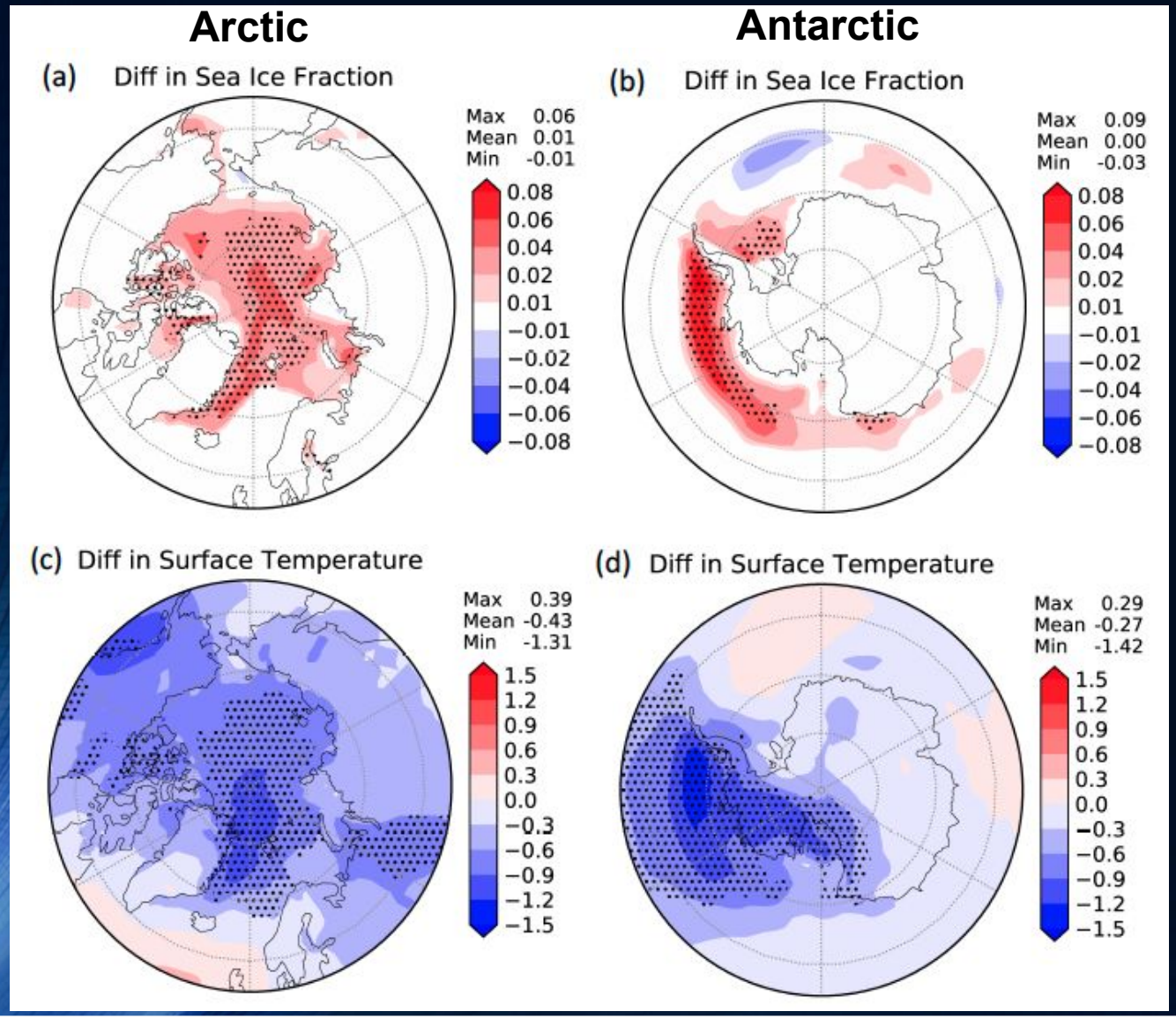
- T. C. Stone, "Acquisition of Moon Measurements by Earth Orbiting Sensors for Lunar Calibration," in IEEE Transactions on Geoscience and Remote Sensing, vol. 60, pp. 1-6, 2022.

Laboratory Atomic Spectra Analysis

- S. J. Bromley et al 2021 Planet. Sci. J. 2 228



Solar Irradiance Spectrum has Significant Impacts on Arctic Sea Ice Fraction and Surface Temperature



NCAR CESM2 Simulations

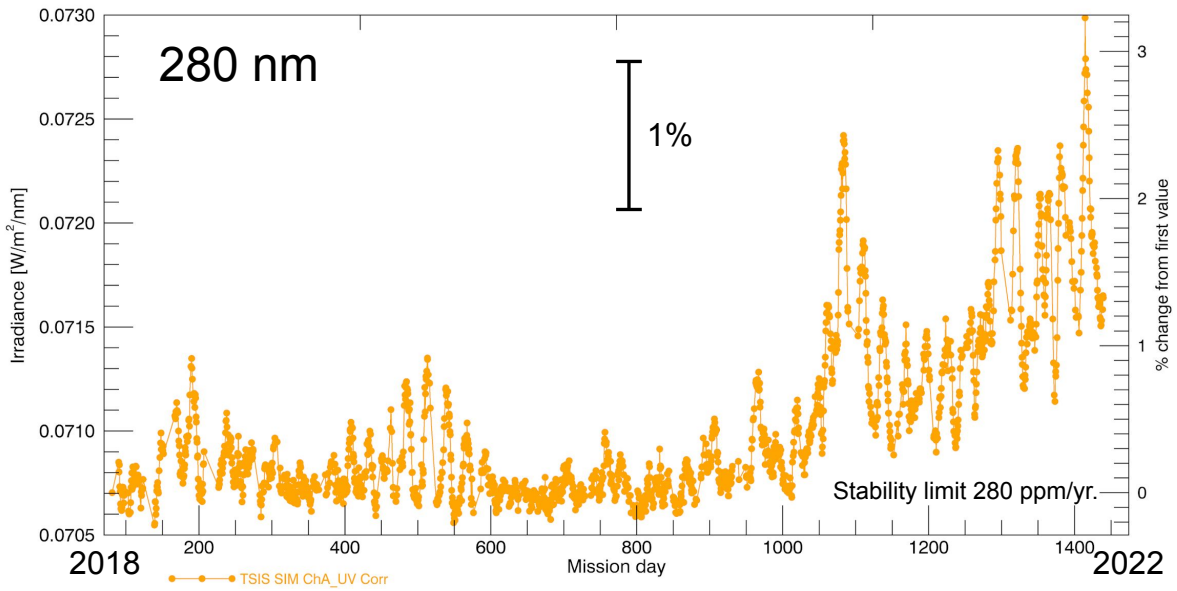
Method:
The recent TSIS-1 mission has provided more accurate SSI observations than before. The SSI difference in a given VIS or NIR band can be as large as 4 W m^{-2}.

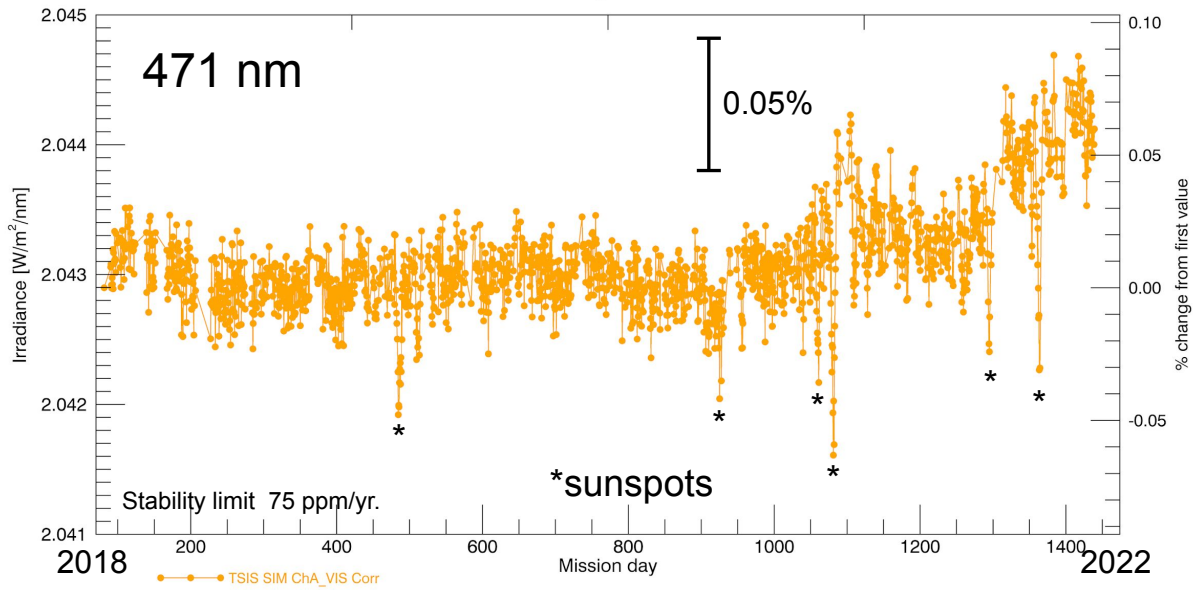
Impact:
The results show that, due to different spectral reflectance of sea ice and water surfaces in the VIS and NIR, the set of simulation with more SSI in the VIS has less solar absorption by the high-latitude surfaces, ending up with colder polar surface temperature and larger sea ice coverage.

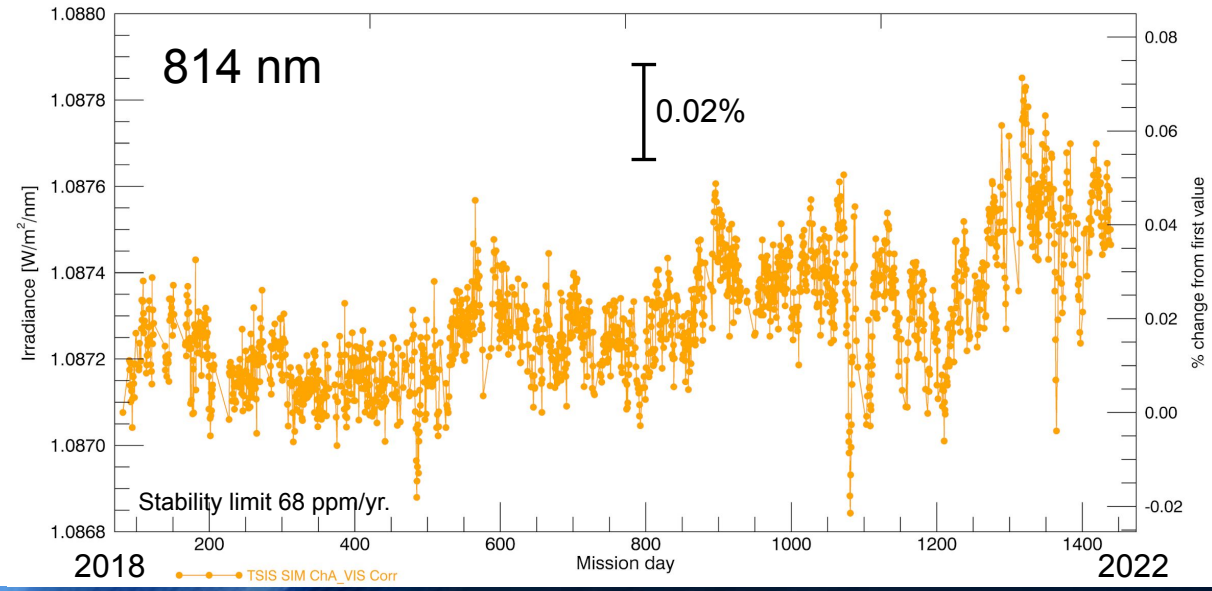
(Jing, et al., *Journal of Climate,* 2021)

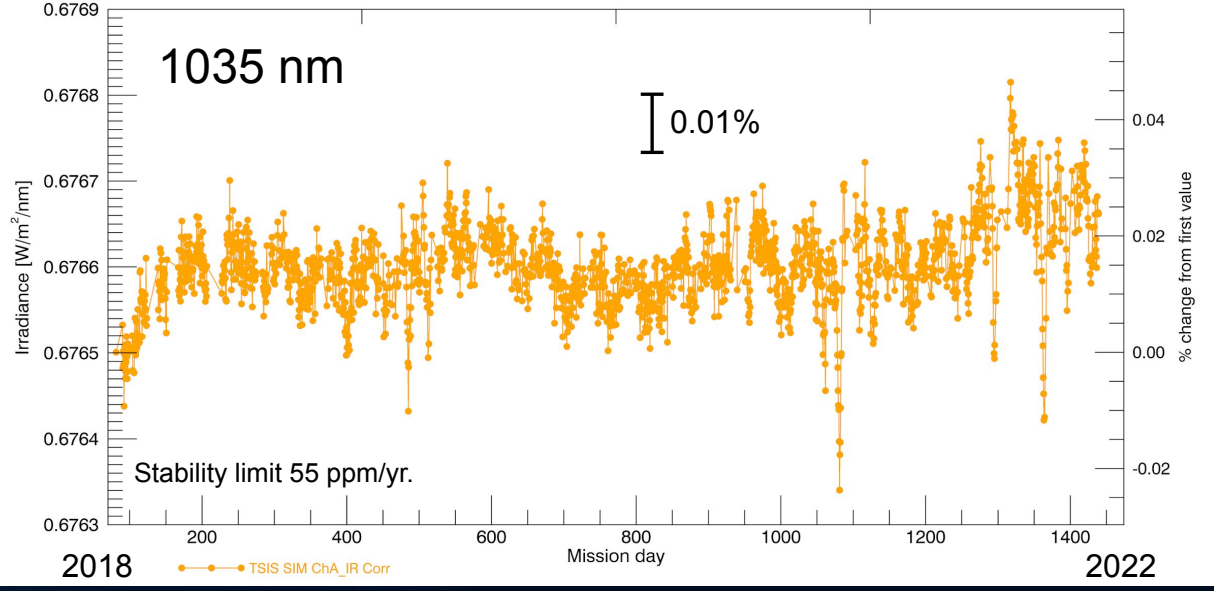
TSIS-1 Long-term SSI (from Solar Minimum into SC 25)

TSIS-1 SIM SSI Time Series (4 years)

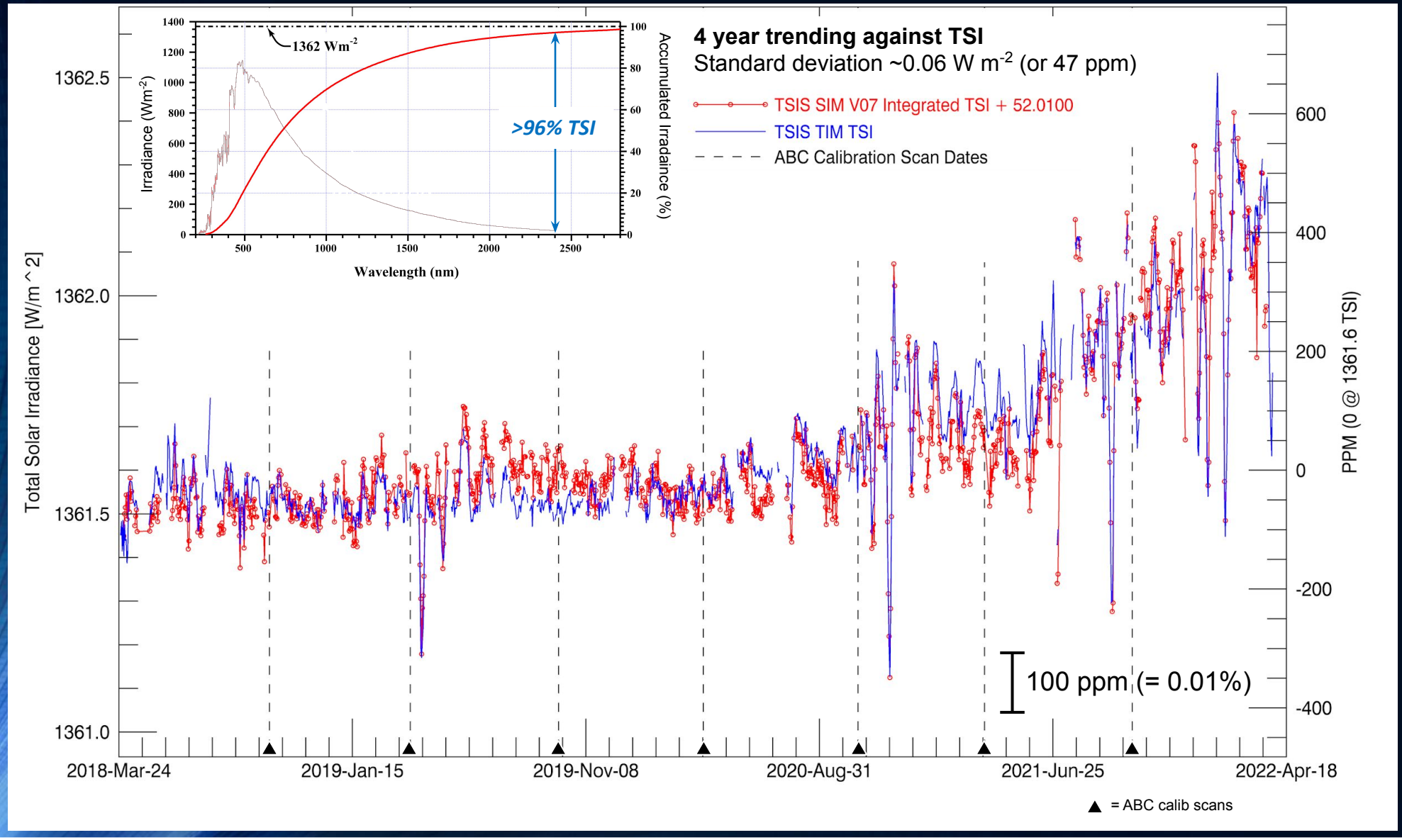


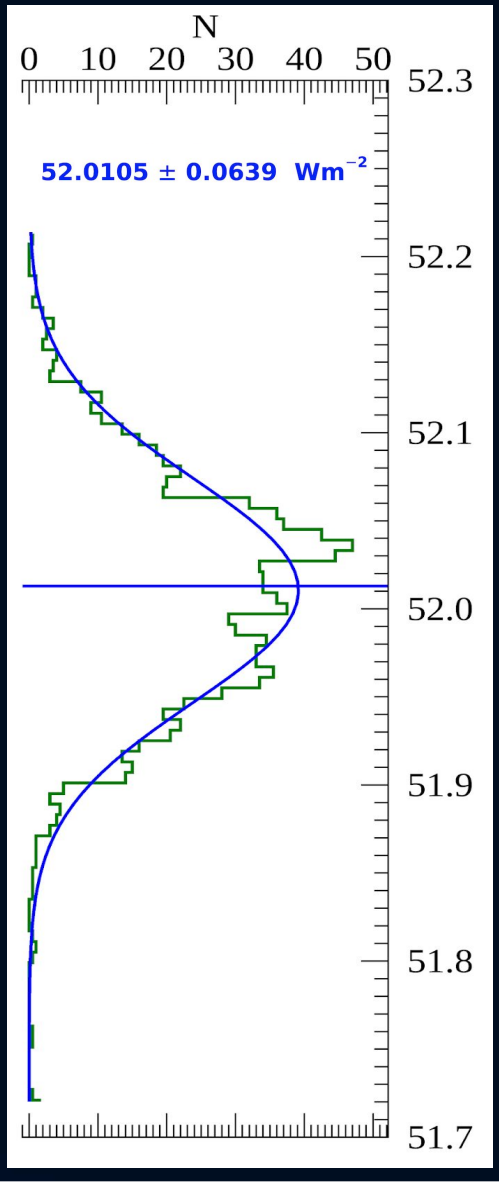






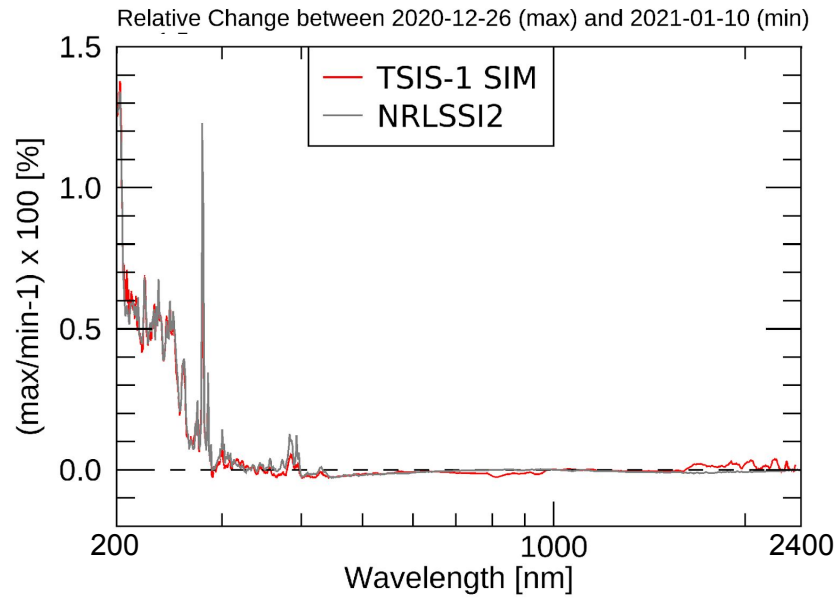
Integrated SIM to TIM TSI Comparison

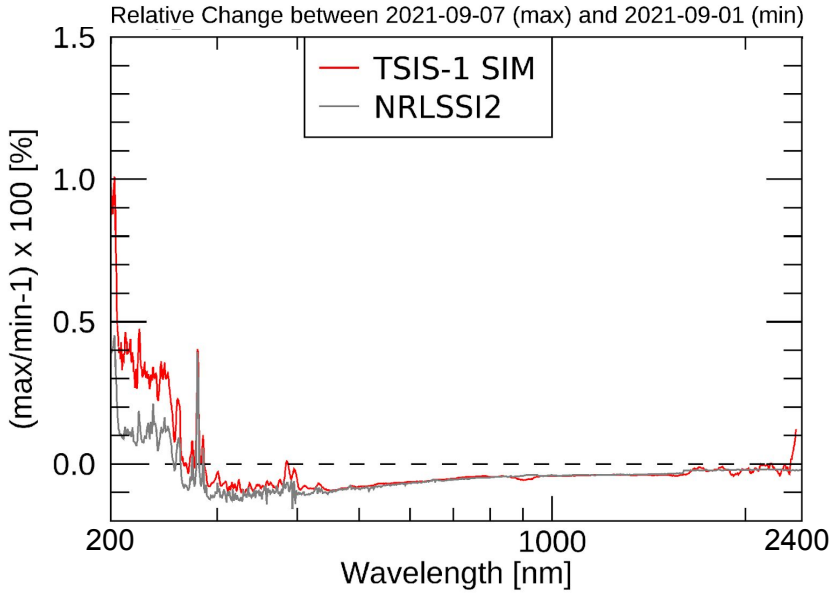




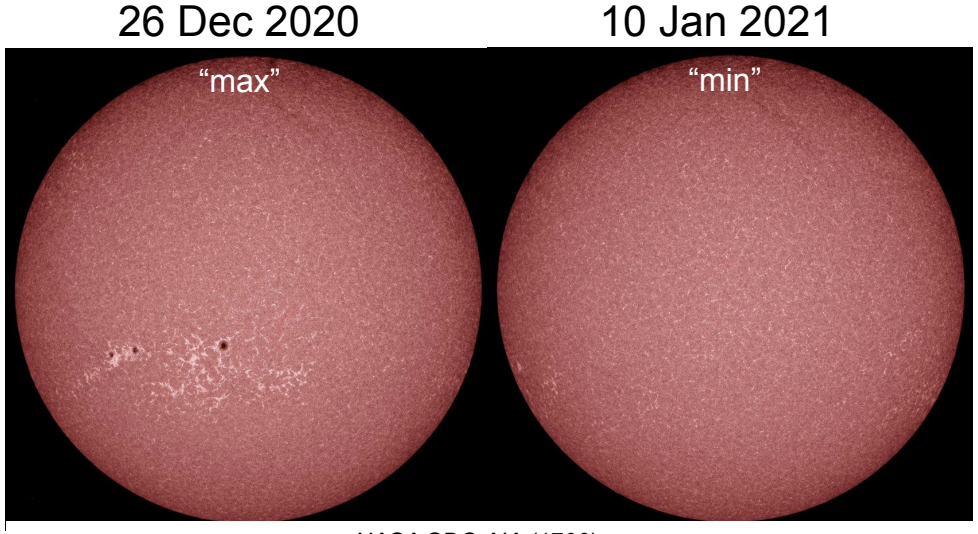
Measured vs. Model SSI Comparisons

Short-term spectral variability: Measured vs. Modeled

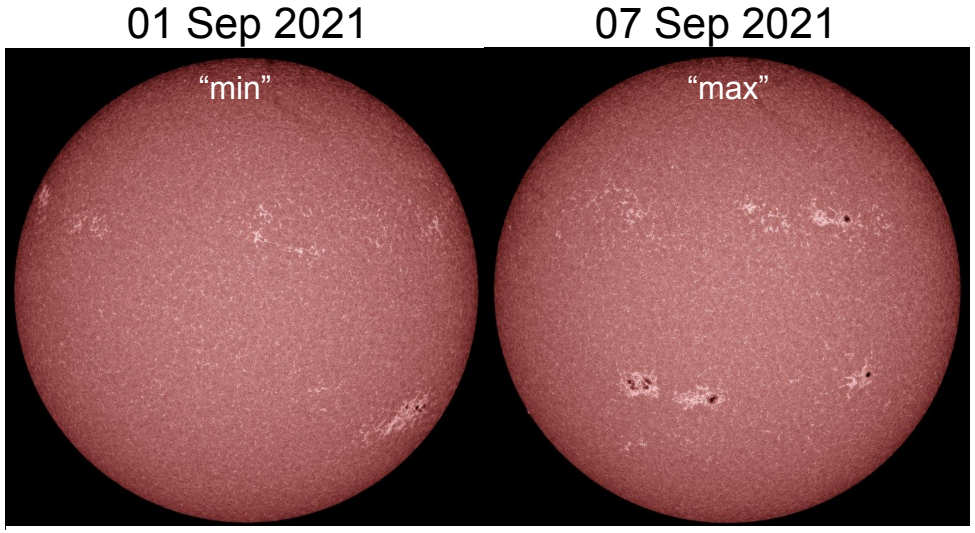




Onset of Solar Cycle 25



NASA SDO AIA (1700)

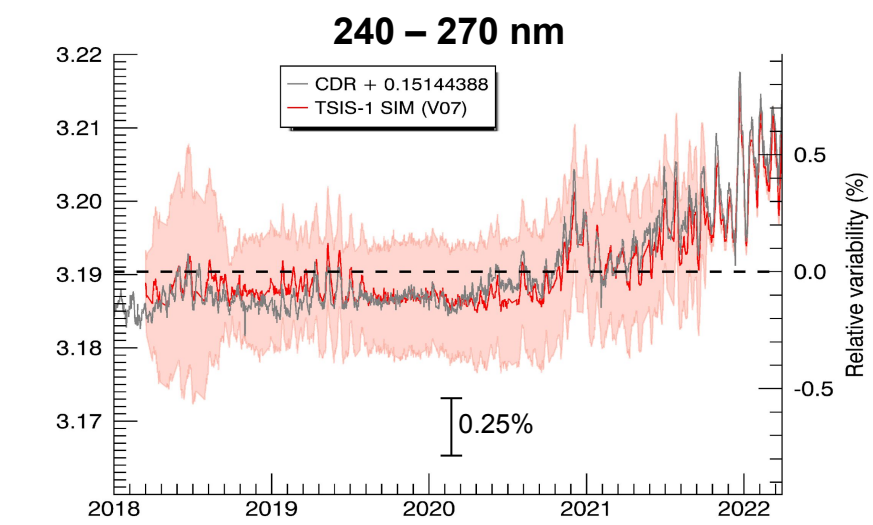


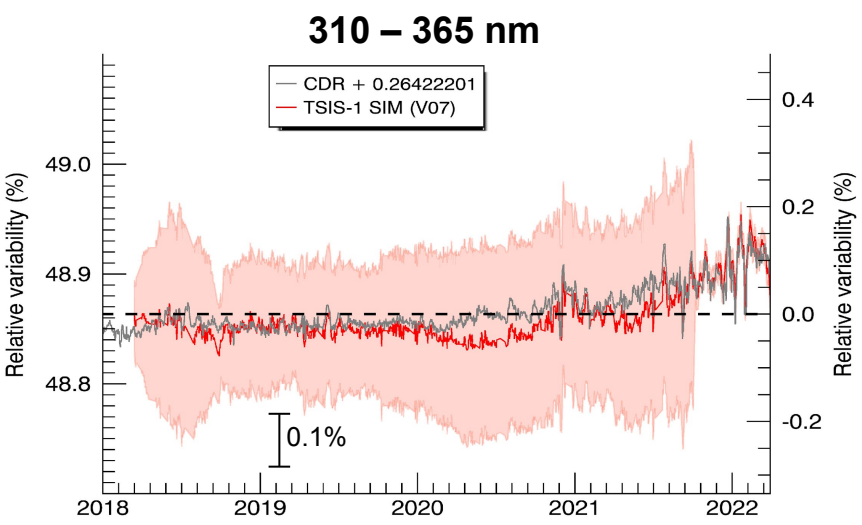
NASA SDO AIA (1700)

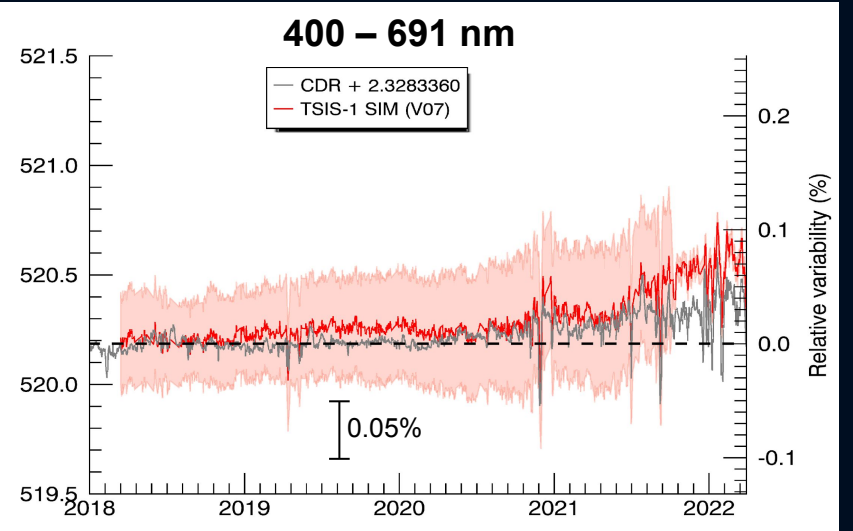
Long-term spectral variability (4 years): Measured vs. CDR

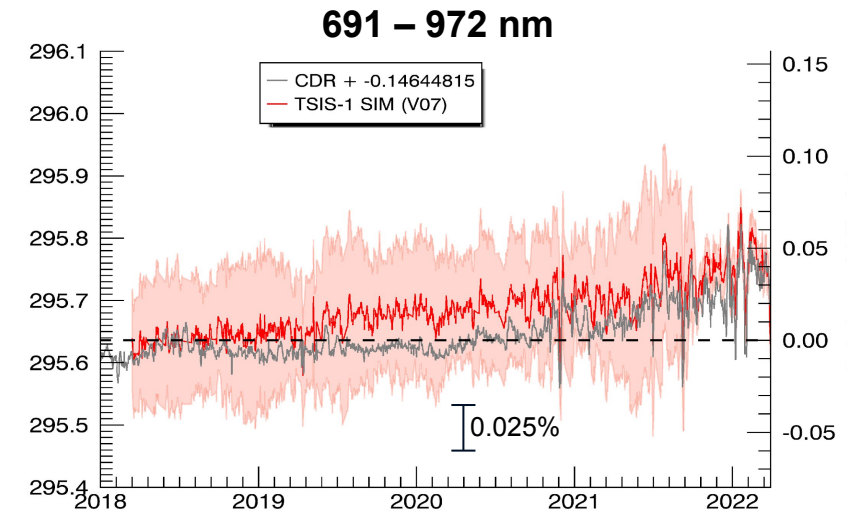
Note: CDR (Climate Data Record) is NRLSSI2 model based on SORCE reference

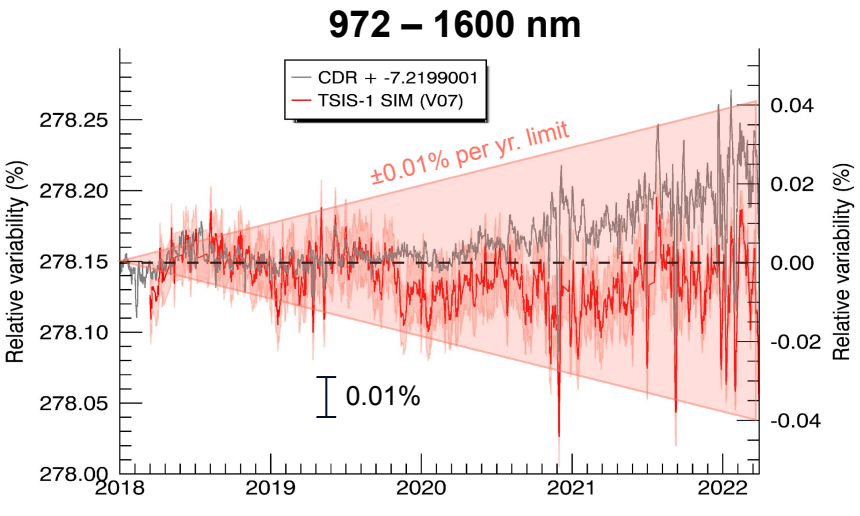
TSIS-1 SIM V07 is latest SSI data release, V08 will be in June 2022

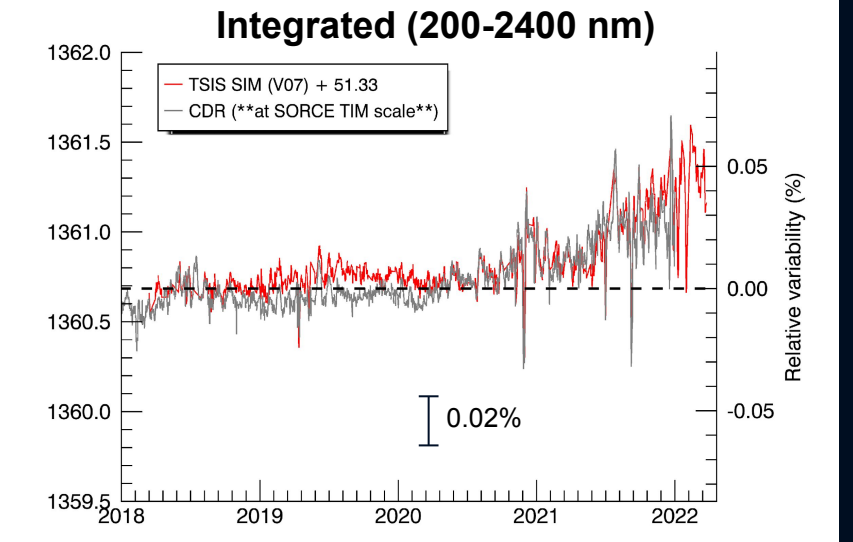












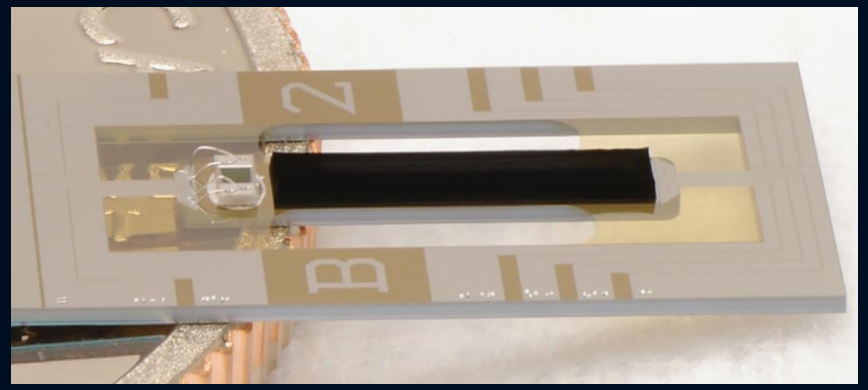
New Technology Infusion

LASP-NIST ESTO Advanced Component Technologies (ACT) Developments

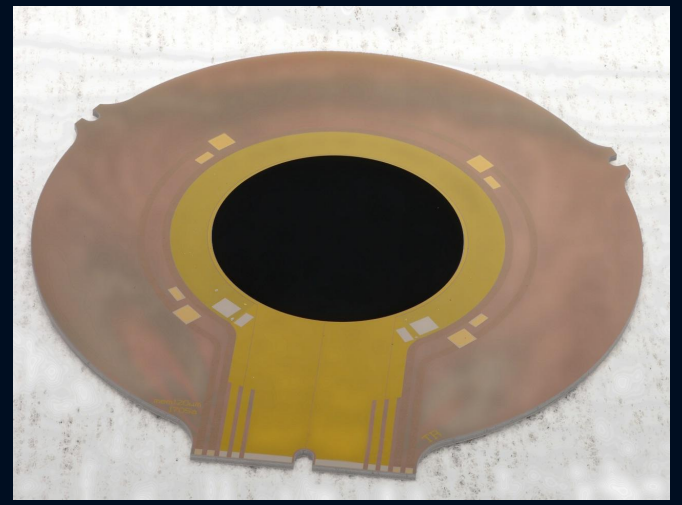
"Key Next-Generation Technologies"

- **Silicon-Based Bolometers**
  - Developed/fabricated by NIST Boulder
  - Vertically aligned carbon nanotubes (Typical absorptance >99.9%)
  - Integrated heater

CSIM Bolometer

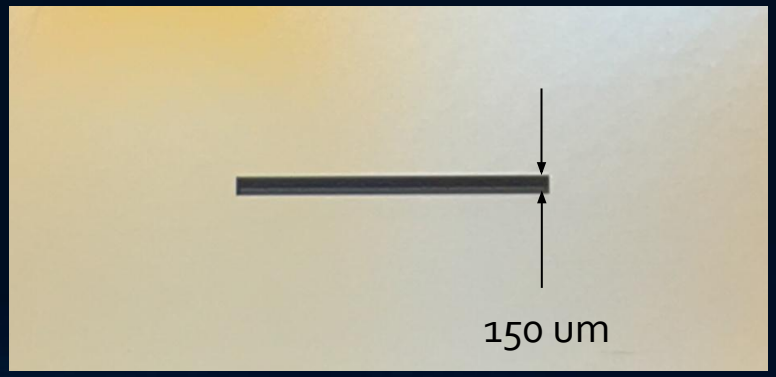


CTIM Bolometer



- **Deep Reactive-Ion Etched Apertures**
  - Fabricated by NIST Boulder
  - Fabricated to extremely high tolerances (very low area uncertainties, 10's ppm)
  - Very small CTE, High thermal stability

CSIM Precision Aperture



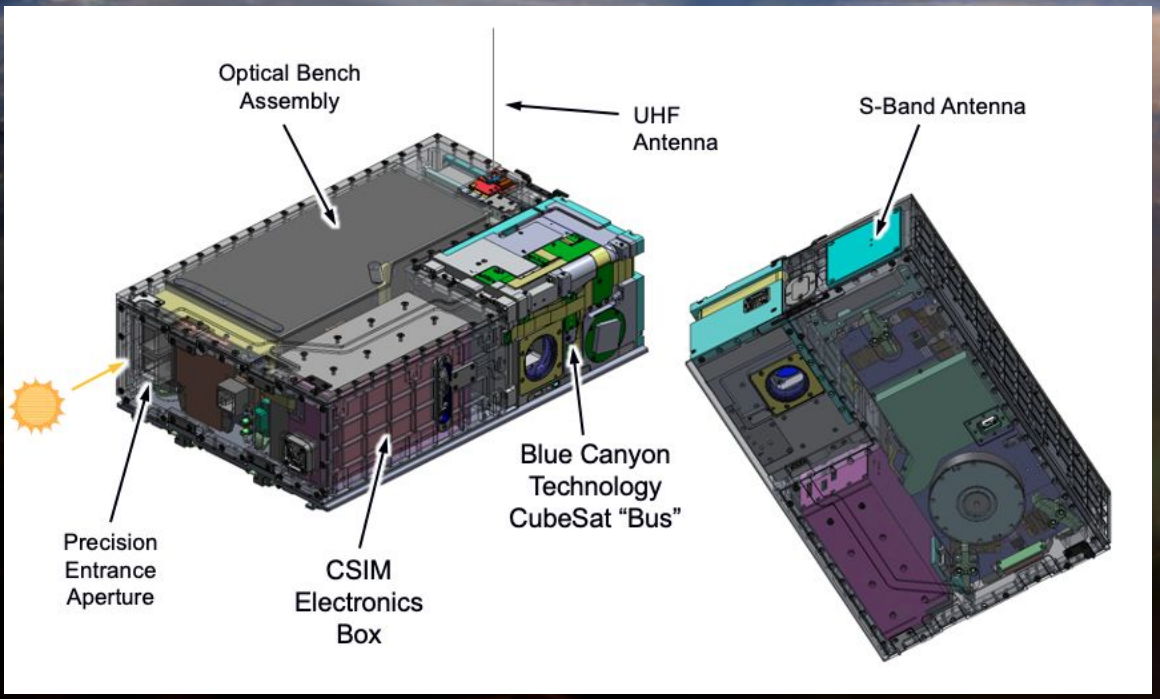
CTIM Precision Aperture

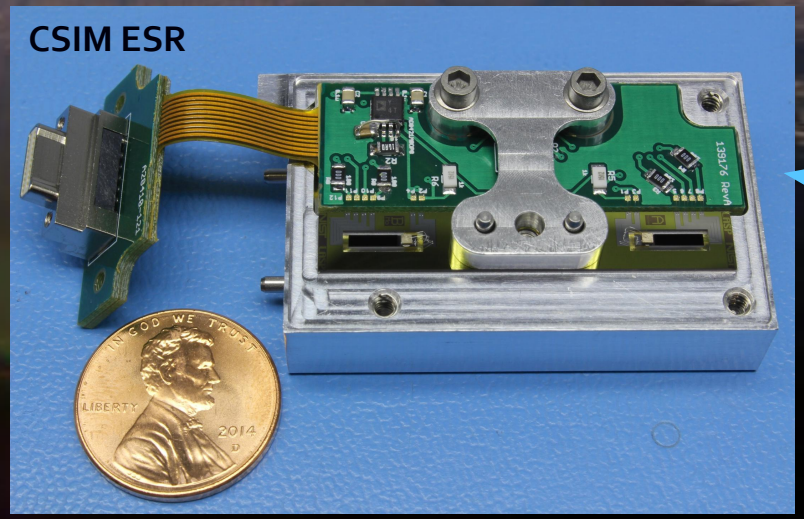
ESD IIP & InVEST: Compact Spectral Irradiance Monitor

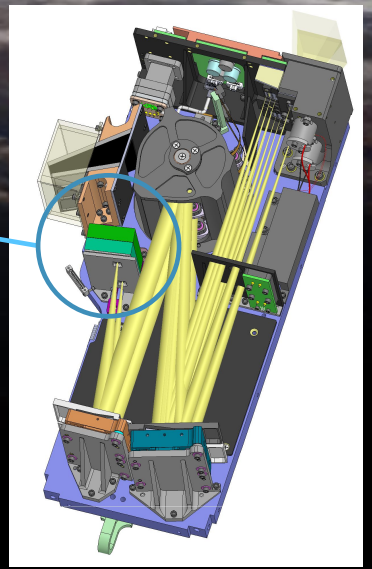
"Next Generation" SSI Measurement

CSIM is a compact solar spectral irradiance monitor that is a cost-effective and low risk alternative instrument designed for considerable implementation flexibility, high calibration accuracy and performance stability for obtaining high-priority Earth Science measurements.

Goal: Achieve **flight-qualified instrument** for LEO operational demonstration and TSIS validation. (Launched Dec 2018, EOM Feb 2022)

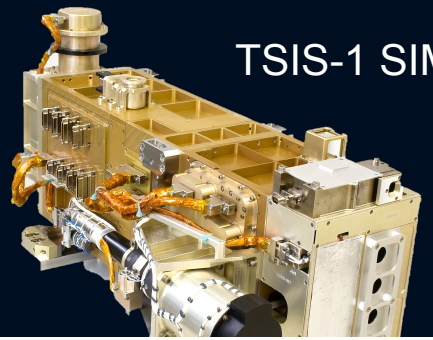






TSIS – CSIM Absolute Solar Spectrum

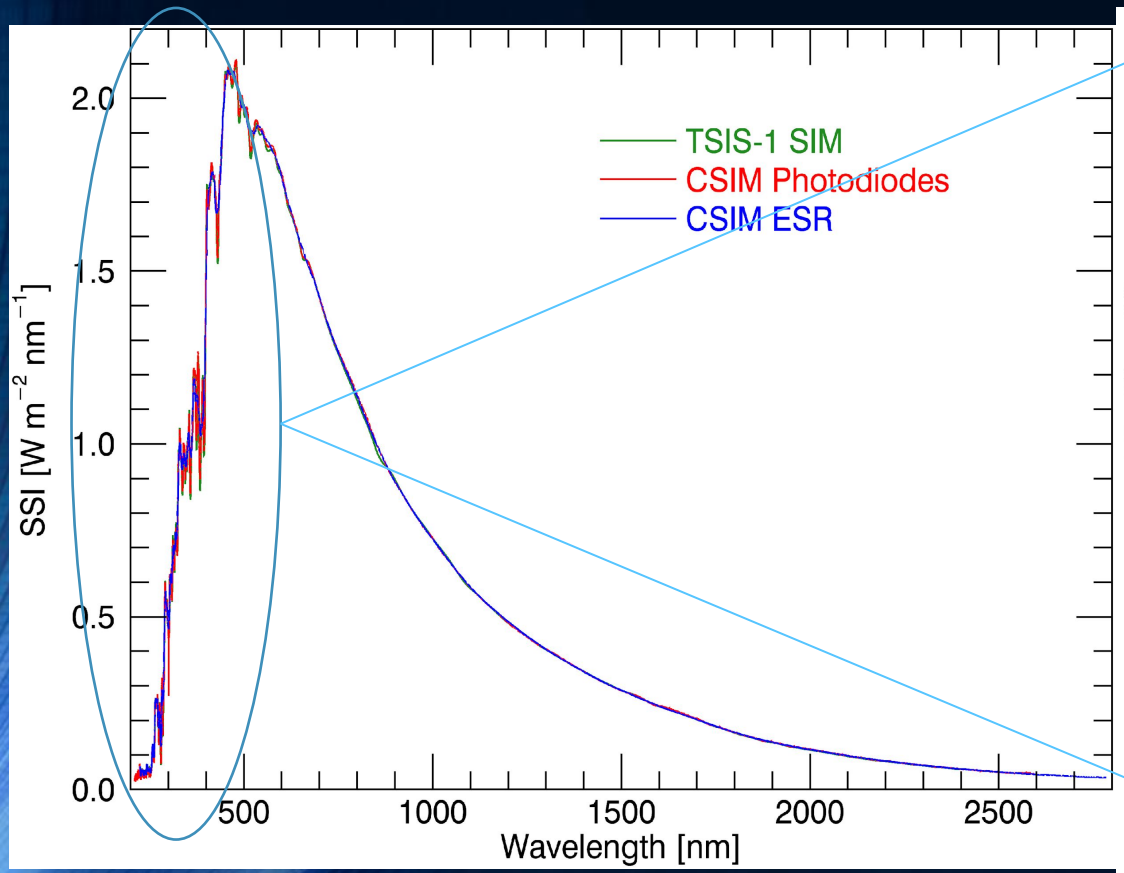
Solar Spectral Irradiance (SSI) measurements by TSIS-1 SIM and CSIM during solar minimum period resulted in a newly established SSI reference spectrum for Earth Science applications

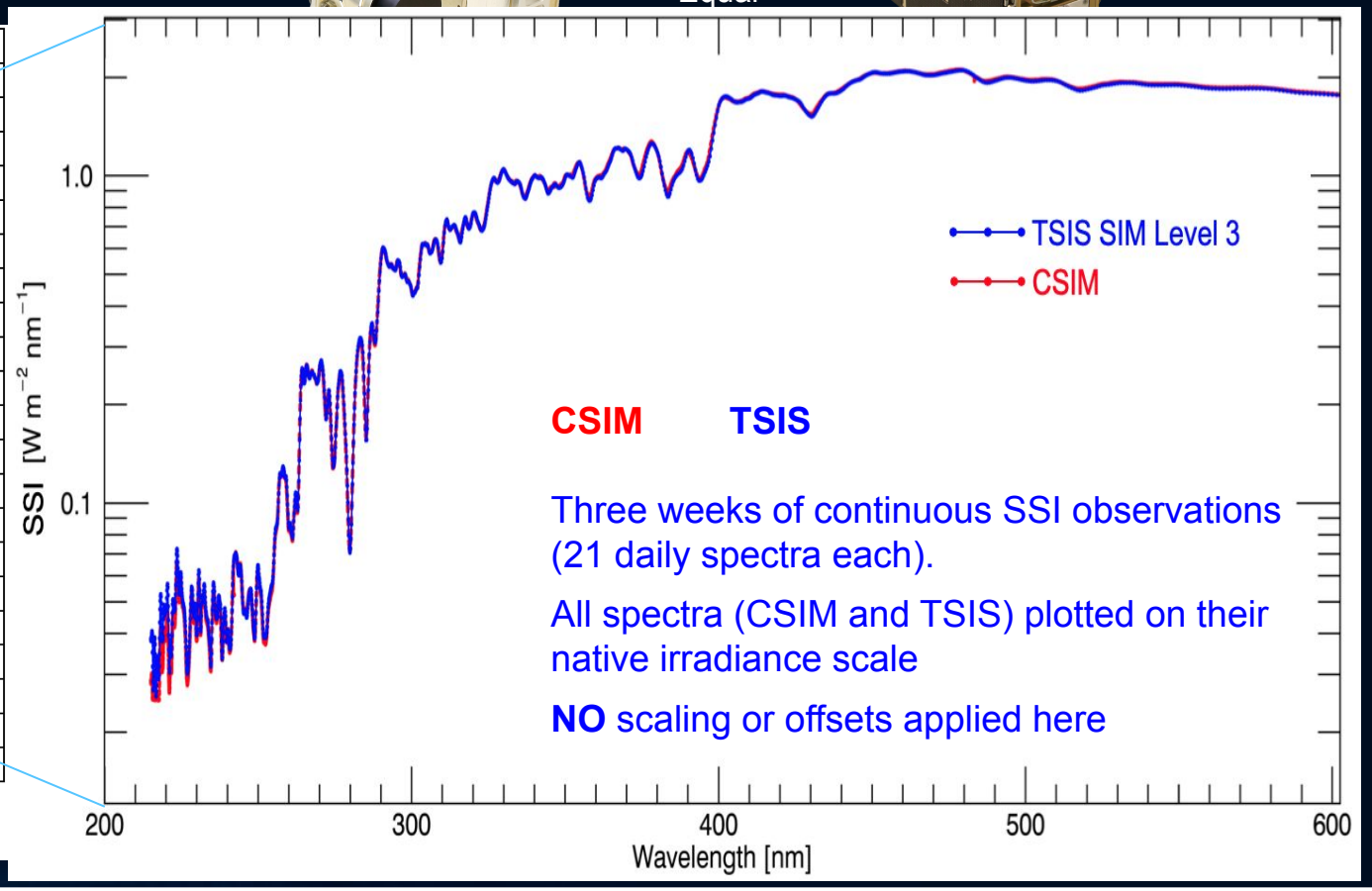


TSIS-1 SIM ($$$)

CSIM 6U CubeSat ($)

Equal





CSIM **TSIS**

Three weeks of continuous SSI observations (21 daily spectra each).

All spectra (CSIM and TSIS) plotted on their native irradiance scale

NO scaling or offsets applied here

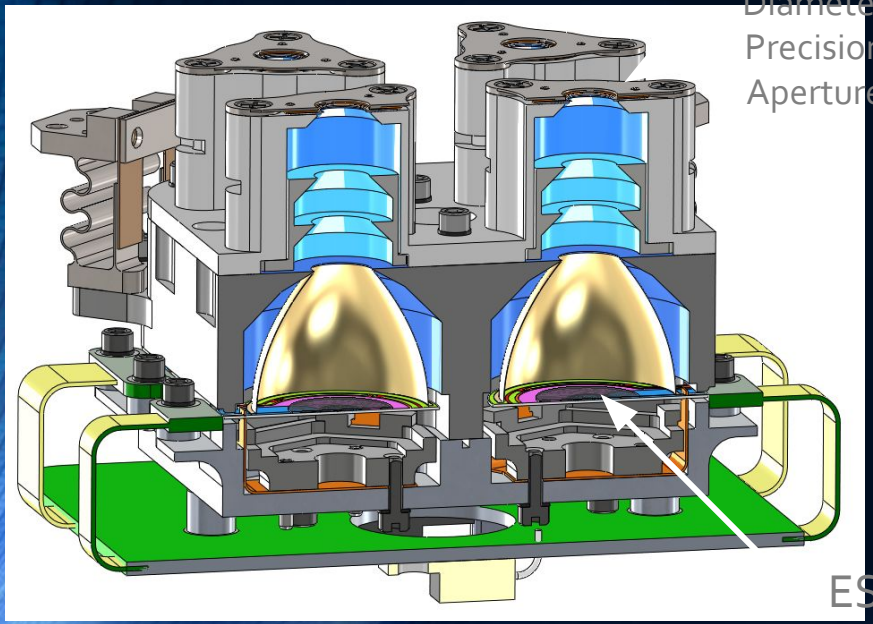
CTIM-FD IIP: Compact Total Irradiance Monitor

"Next Generation TIM"

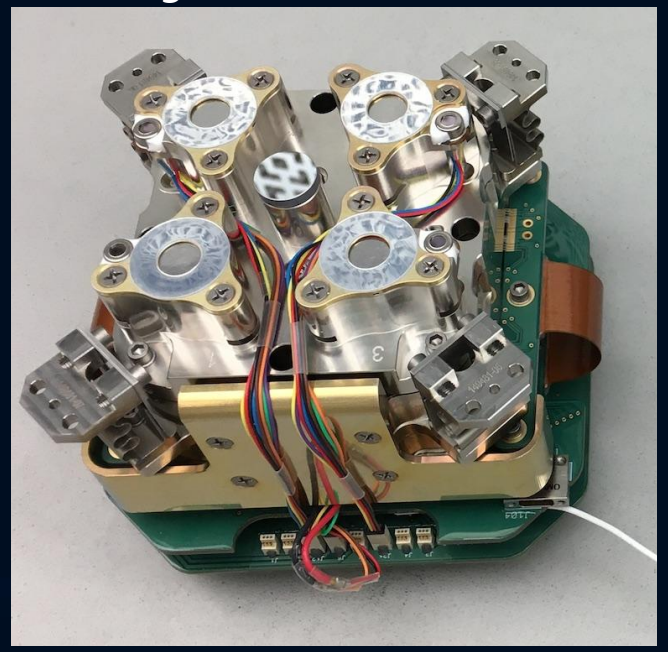
PI: Dave Harber

CTIM Detector Head

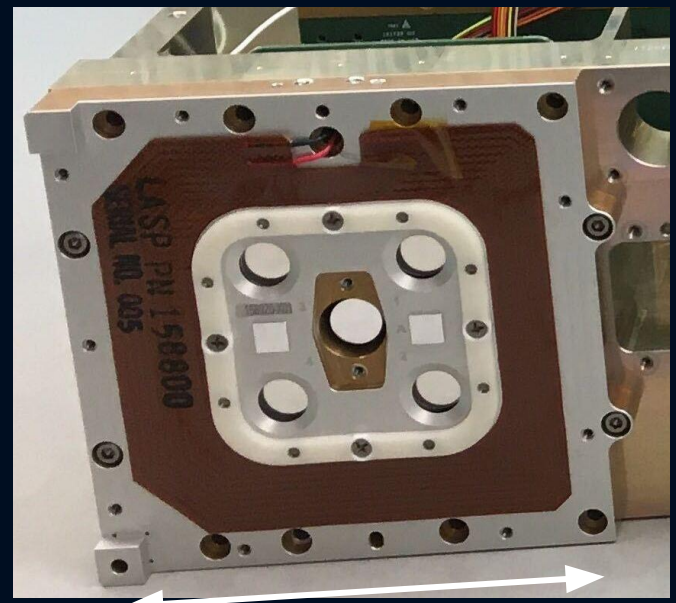
- Each detector head has four channels
  - Redundant channel degradation tracking
- Shutter for each channel



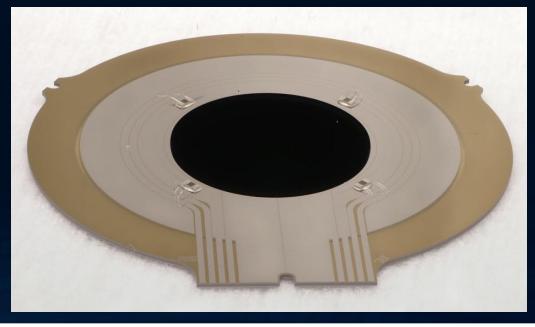
Integrated Detector Head



CTIM Detector Head



Key new technology: Silicon + Vertically Aligned Carbon Nanotubes



- Microfabrication allows 2D fabrication with micron-level precision
- Typical absorptance 99.9%
- Developed with NIST Boulder Sources and Detectors Group

New Mission Concept

C-TSIS Mission Concept

The LASP CTSIS program will address the evaluation of CSIM and CTIM as a potential low-cost alternative for a TSIS-3

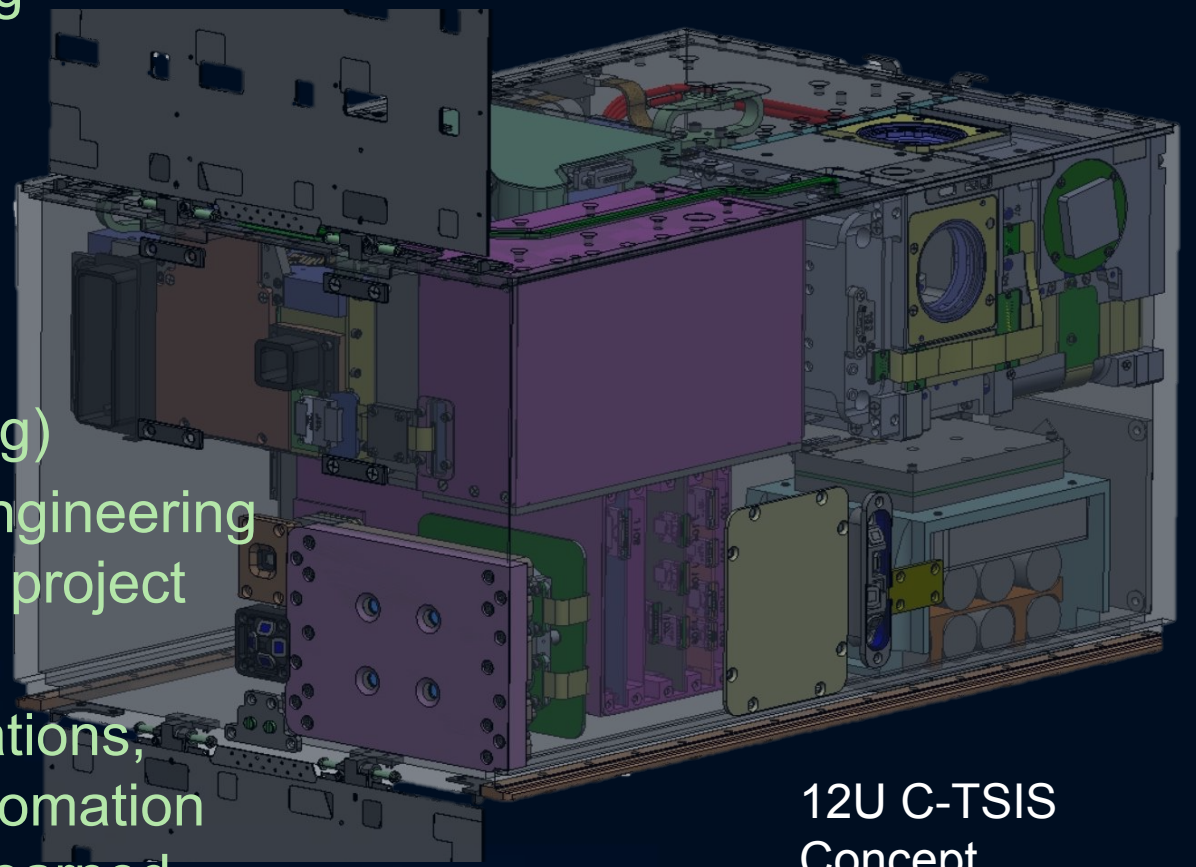
- The goal is to leverage the developments that have occurred with the SmallSat and CubeSat revolution with regard to lower-cost satellite busses and more affordable / frequent launch opportunities.

Determine the most robust and cost-effective observation system for the continued monitoring of solar irradiance.

- Evaluate a future observation system consisting of a small, continuously replenished constellation of CTSIS SmallSats for continuity of TSI and SSI measurements.

C-TSIS Mission Demonstration

- Demonstration that CSIM and CTIM can fully meet TSIS requirements in accuracy, stability, and reporting
  - Provide a 6 month overlap with TSIS-2
- Upgrade CSIM to a 3 channel instrument
- CTIM 1 Detector head (4 channels)
- Extend LASP 6U CubeSat design to 12U
- Improve parts reliability (Screening, Rad. Testing)
- Selectively move from CubeSat-class project engineering and production processes towards Class-D like project requirements (EEE parts, QA, SE, CM)
- Demonstrate regular and reliable mission operations, data capture, processing through improving automation and efficiencies from CSIM and CTIM lessons learned



12U C-TSIS Concept (for Constellation)