Overview of LASP/NASA Sun-Climate Missions and Research Projects

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LASP/NASA TSI & SSI focused missions

1981-1989

1991-2005

FUV & MUV SSI

2003-2020

2013-2017 (TSI)

2017-present

New Tech Demo (ESTO)

2018-2022

2022 -

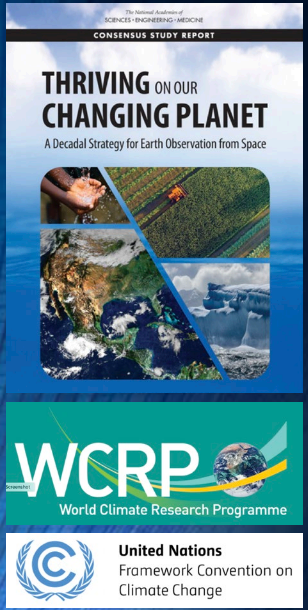
2025-

Long-term strategies

2028-

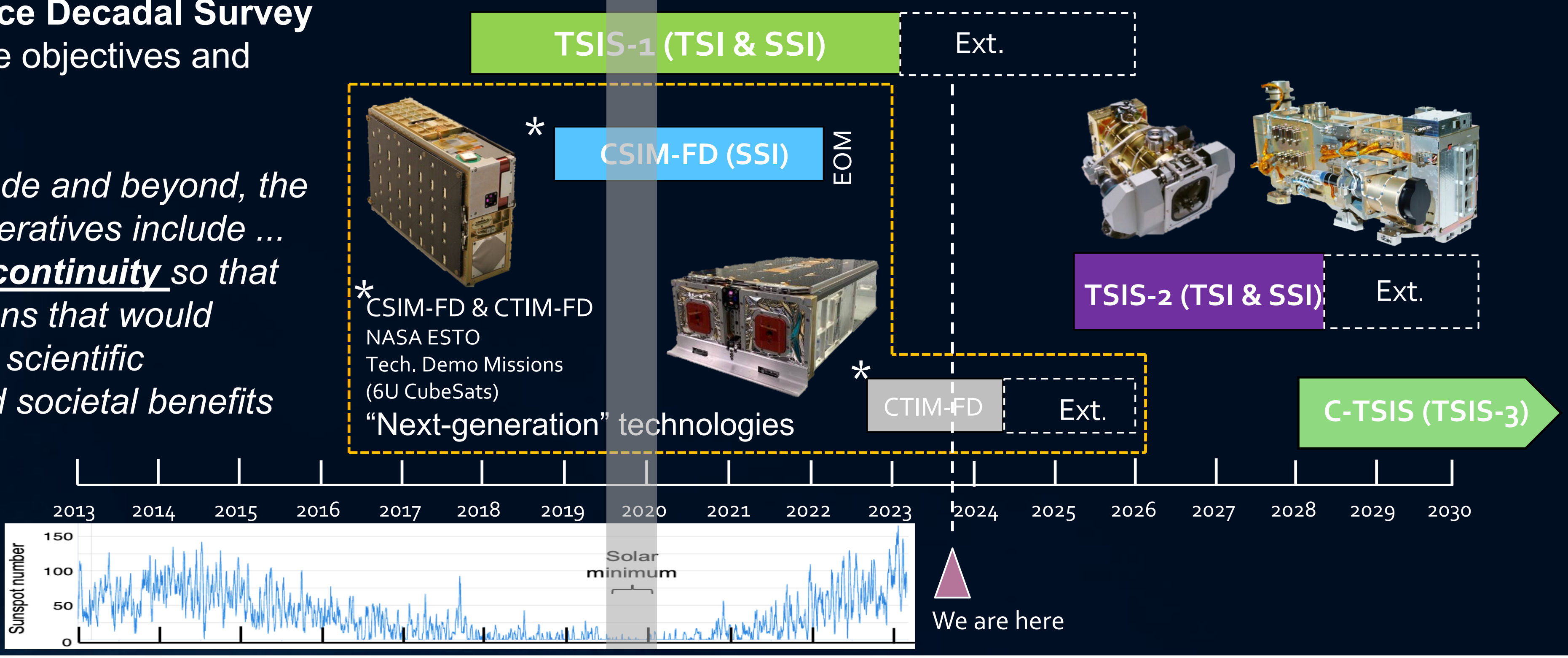
- The 17-year SORCE mission ended on February 2020 (Achieved 2 years of overlap with TSIS-1)
- TCTE ended in June 2019 (Over 5 years overlap with SORCE, over 1 year overlap with TSIS-1)
- TSIS-1 operations on ISS strated in early 2018
  - TSIS-1 TIM validates SORCE and TCTE TSI calibration scales (highest accuracy TSI monitor)
  - TSIS-1 SIM reduces uncertainties from SORCE SIM (higher accuracy by nearly order of magnitude, higher long term stability)
- CSIM & CTIM demonstraton of new, advanced SSI & TSI technology, respectively.
  - CSIM ended 3 year mission in Feb 2022 (overlapped with TSIS-1 SIM)
  - CTIM launched 2022 (currently operating overlapping with TSIS-1 TIM)
- TSIS-2 instruments built and in final calibration for S/C integration in early 2024 (early 2025 Launch readiness)

LASP/NASA TSI & SSI mission timeline



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."*



Summary of LASP Solar Irradiance Capability

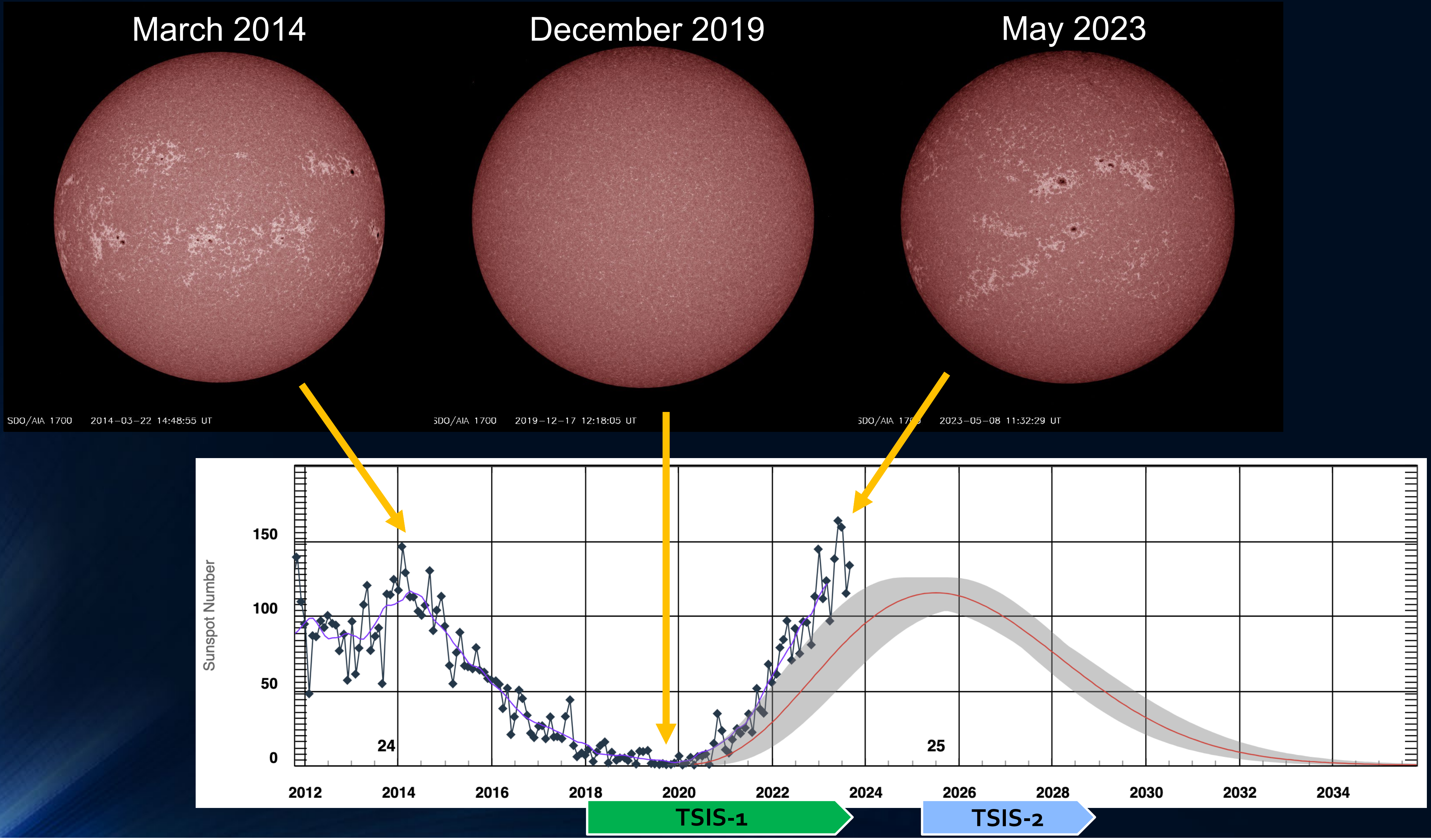
LASP Total Solar Irradiance Instrumentation (in order of mission launch date)

Mission/Instrument	Spectral Range	Spectral Resolution (nm)	Stability (%/year)	Uncertainty (%) Pre-launch
SORCE TIM (free flyer)	N/A	N/A	0.01	0.035
TCTE TIM	N/A	N/A	~0.01	0.035
TSIS-1 TIM (ISS)	N/A	N/A	<0.01	0.013
CTIM (CubeSat)	N/A	N/A	<0.01	0.011
TSIS-2 TIM (free flyer)	N/A	N/A	<0.01	0.015

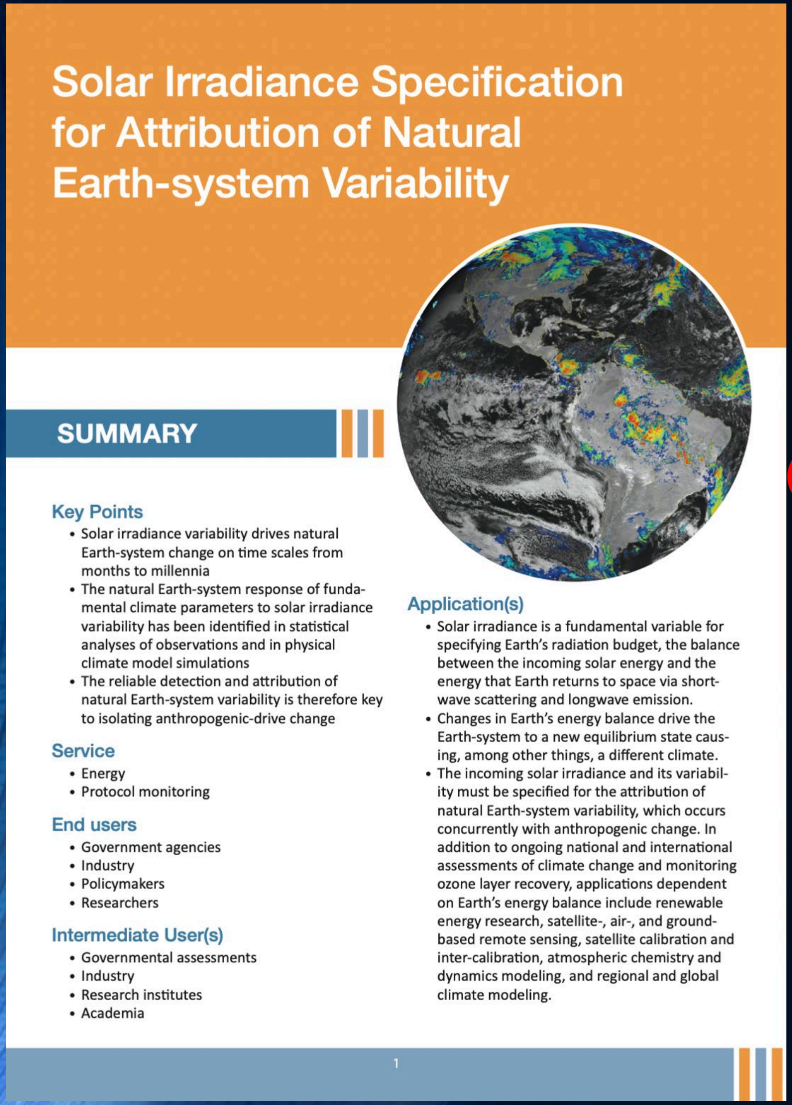
LASP Solar Spectral Irradiance Instrumentation (in order of mission launch date)

Mission/Instrument	Spectral Range	Spectral Resolution (nm)	Stability (%/year)	Uncertainty (%)
SORCE SIM (free flyer)	200 - 2400 nm	0.25 – 35	0.2	3 - 8
TSIS-1 SIM (ISS)	200 - 2400 nm	0.25 - 42	≤ 0.05	0.24 - 0.41
CSIM (CubeSat)	200 - 2800 nm	0.25 - 42	≤ 0.1	0.3 – 1.5
TSIS-2 SIM (free flyer)	200 - 2400 nm	0.25 - 42	≤ 0.05	0.3 - 0.6
OWLS (MicroSat; measures solar features, not full disk)	115 – 308 nm	1 nm	1	3-15

Solar Cycle 25 (TSIS-1 & 2)



Solar Irradiance Variability


Solar Irradiance Specification for Attribution of Natural Earth-system Variability

SUMMARY

Key Points
- Solar irradiance variability drives natural Earth-system change on time scales from months to millennia
- The natural Earth-system response of fundamental climate parameters to solar irradiance variability has been identified in statistical analyses of observations and in physical climate model simulations
- The reliable detection and attribution of natural Earth-system variability is therefore key to isolating anthropogenic-drive change

Service
- Energy
- Protocol monitoring

End users
- Government agencies
- Industry
- Policymakers
- Researchers

Intermediate User(s)
- Governmental assessments
- Industry
- Research institutes
- Academia

Application(s)
- Solar irradiance is a fundamental variable for specifying Earth's radiation budget, the balance between the incoming solar energy and the energy that Earth returns to space via shortwave scattering and longwave emission.
- Changes in Earth's energy balance drive the Earth-system to a new equilibrium state causing, among other things, a different climate.
- The incoming solar irradiance and its variability must be specified for the attribution of natural Earth-system variability, which occurs concurrently with anthropogenic change. In addition to ongoing national and international assessments of climate change and monitoring ozone layer recovery, applications dependent on Earth's energy balance include renewable energy research, satellite-, air-, and ground-based remote sensing, satellite calibration and inter-calibration, atmospheric chemistry and dynamics modeling, and regional and global climate modeling.

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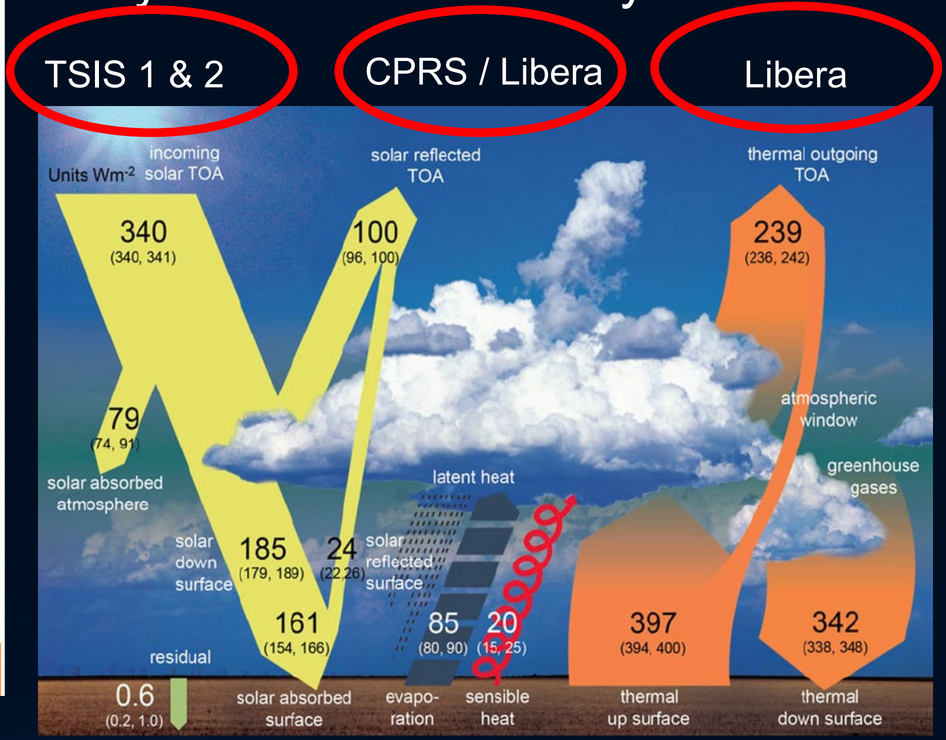
Coddington & Lean, Use Cases of Climate Monitoring from Space, https://climatemonitoring.info/use-cases/

Solar Irradiance Variability Impacts Earth in Multiple Ways

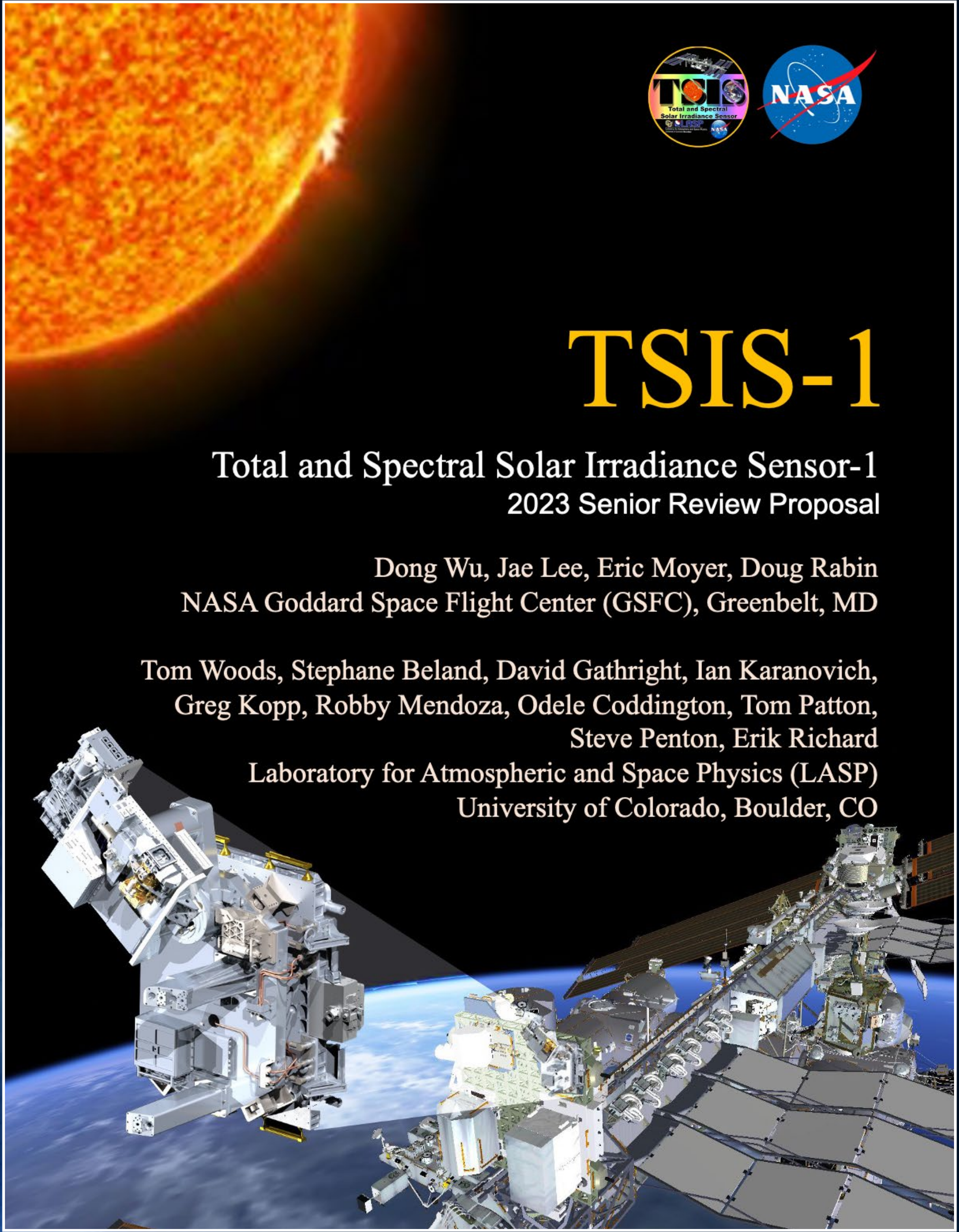
- Solar irradiance variations drive changes in the Earth system from the surface to space, on timescales of <months to >millennia.
- Statistical analyses and physical climate model simulations identify responses in climate and atmospheric parameters to solar forcing by irradiance variability.



Application → Decision Making

- Improved attribution and forecasting of natural Earth-system variability is **<u>an ongoing process of verification and validation.</u>**
- Includes analysis of multiple climate data records (solar irradiance, temperature, ozone).

TSIS-1 Mission Success



- TSIS-1 has successfully achieved its prime mission (5 years)
  - ✓ Extended Mission Appoved
  - ✓ All instruments (TIM & SIM) and the TPS pointing platform all in excellent health
    - ✗ Sept 2nd 2023 SIM anomaly, no DSP Loads
    - ✓ **Oct 14, SIM Back! Full MU rest fixed issue**
  - ✓ Continues the TSI and SSI date record for overlap with TSIS-2
  - ✓ Lifetime-limited mechanisms tested to achieve operations beyond 2028 (same mechanisms lasted 17 years on SORCE)
- Unfortunately, extended mission budget was reduced 50% (imposed on all ES Sr. Rev. proposals)

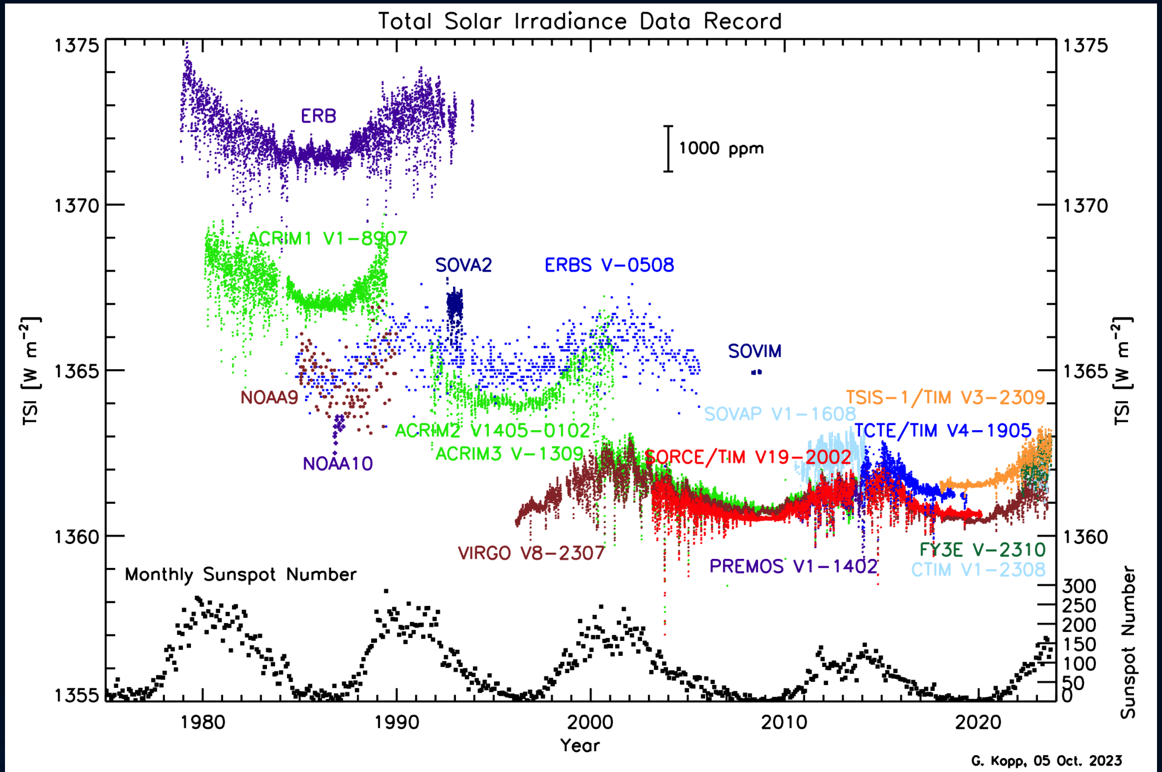
TSIS-1&2 Total Irradiance Monitor (TIM)

The TSIS-1 TIM measures the total solar irradiance (TSI)

- Earth's predominant energy source
- The TSIS-1 TIM extends the 45-year-long uninterrupted climate-data measurement record of TSI
- TSIS-1 TIM Operations began Jan 2018, continues into Solar Cycle 25
- TSIS-2 on track for launch in early 2025, will continue TSI to the end of the decade

LASP TIM

Total Solar Irradiance 45-year Data Record

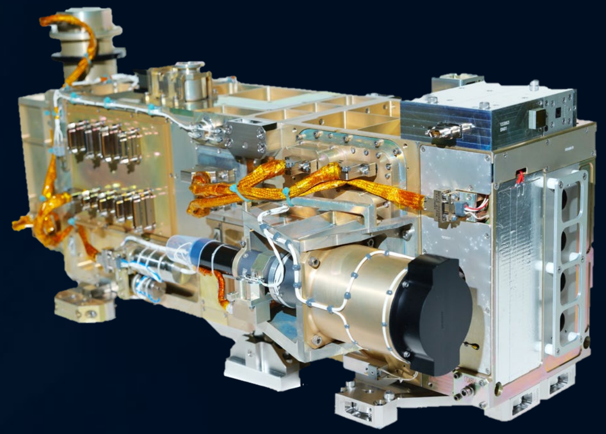


TSIS-1&2 Spectral Irradiance Monitor (SIM)

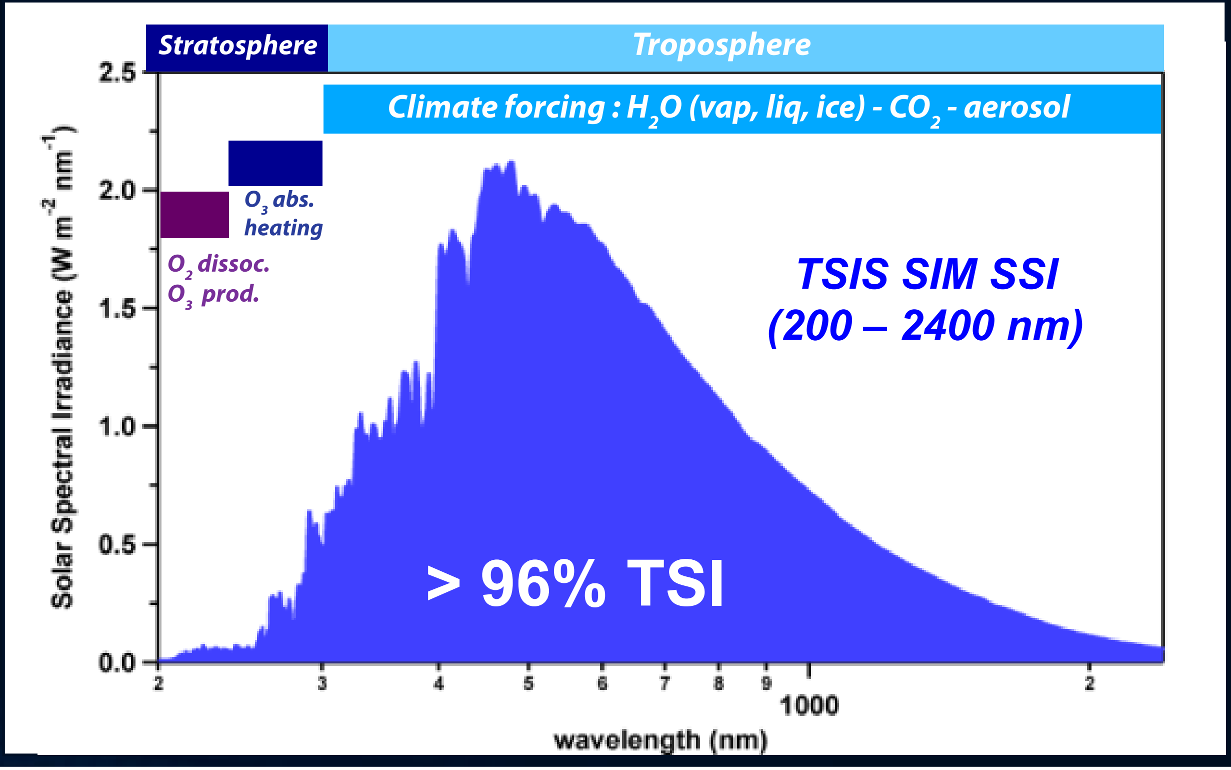
TSIS-1& 2 SIM measures by the Solar Spectral Irradiance (SSI) from the ultraviolet to the infrared (>96% TSI)

- Identifies the regions of atmosphere that are affected by solar variability and mechanisms of response
- TSIS-1 SIM Operations began Mar 2018, continues into Solar Cycle 25
- TSIS-2 on track for launch in early 2025, will continue SSI to the end of the decade

TSIS-1 SIM



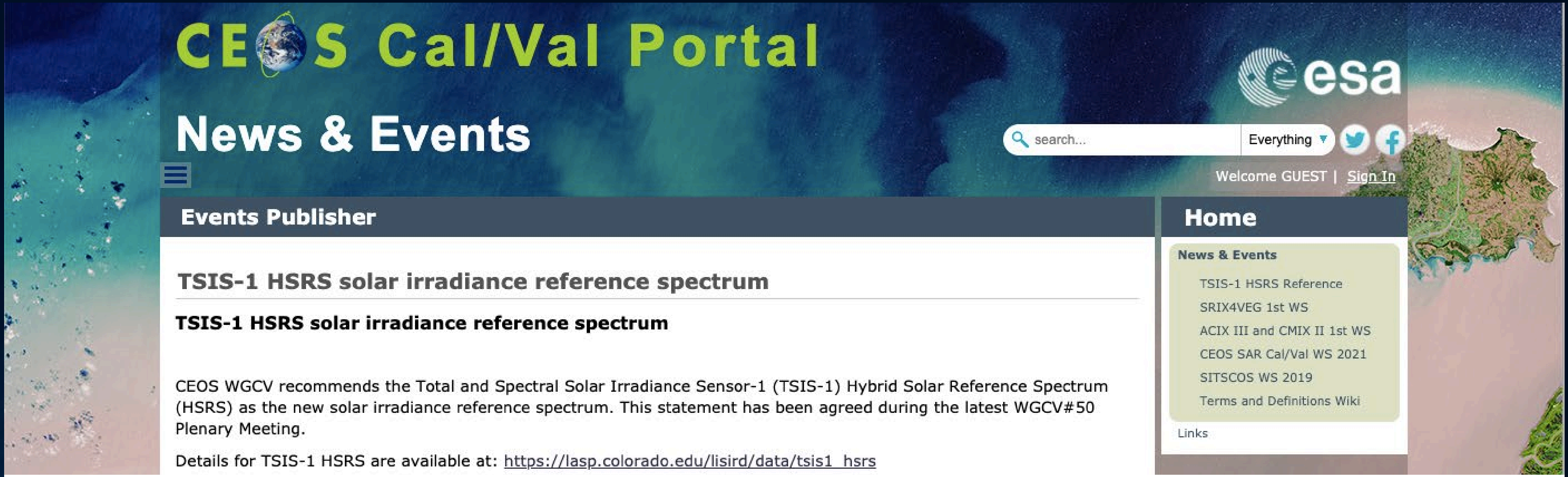
TSIS-2 SIM

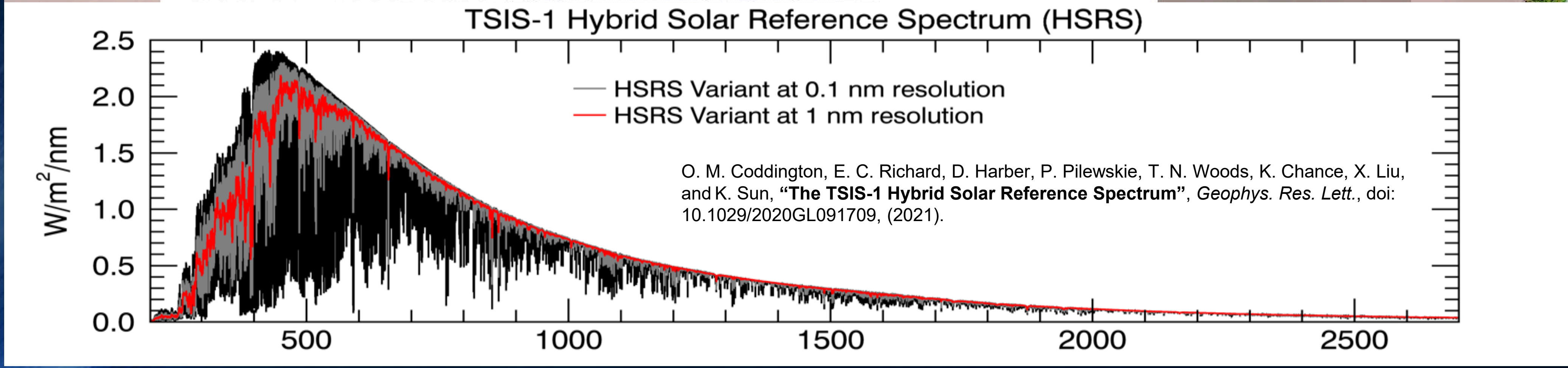


TSIS-1 SSI Scientific Impacts

TSIS-1 HSRS Formally Recognized

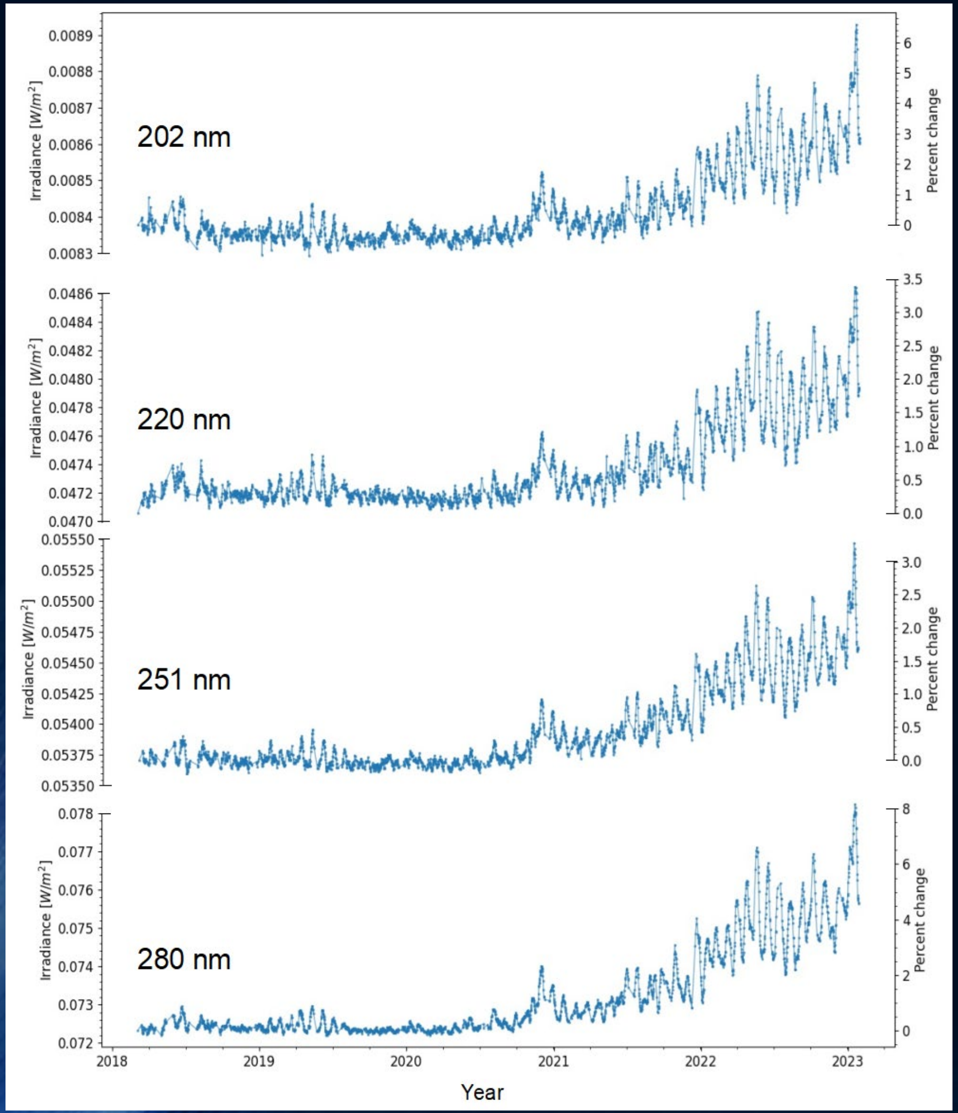
March 2022: The Committee on Earth Observation Satellites (CEOS) Working Group on Calibration and Validation (WGCV) has accepted the TSIS-1 HSRS as the new solar irradiance reference spectrum [https://calvalportal.ceos.org/events/].



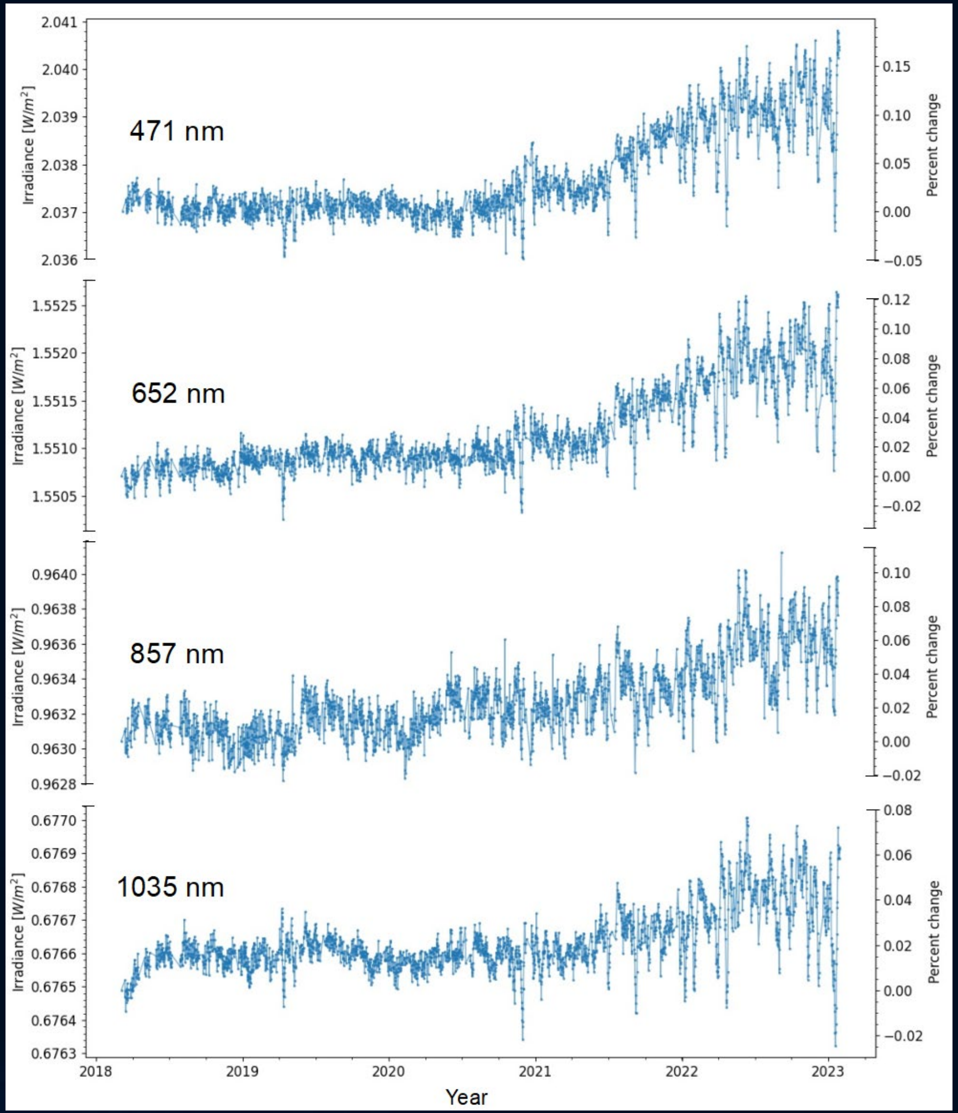


TSIS-1 SIM SSI Variability for Ascending Phase of SC25

UV

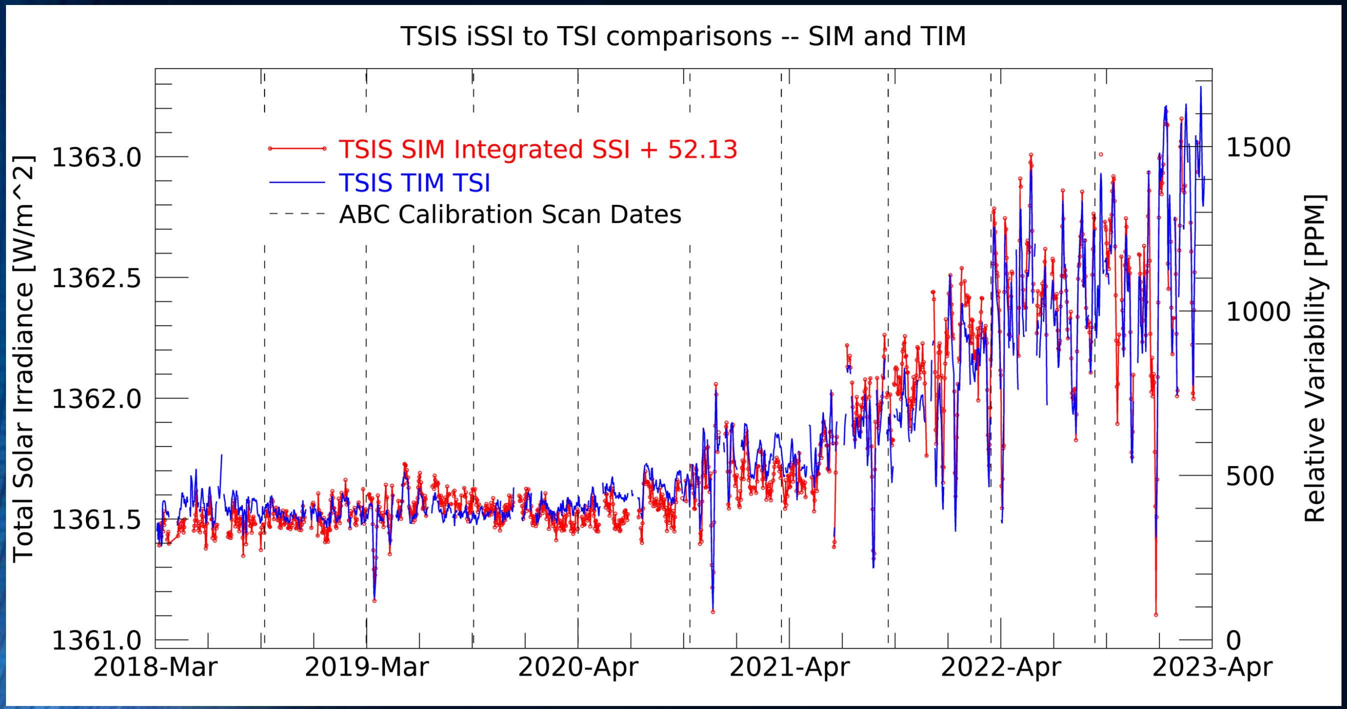


Vis - NIR

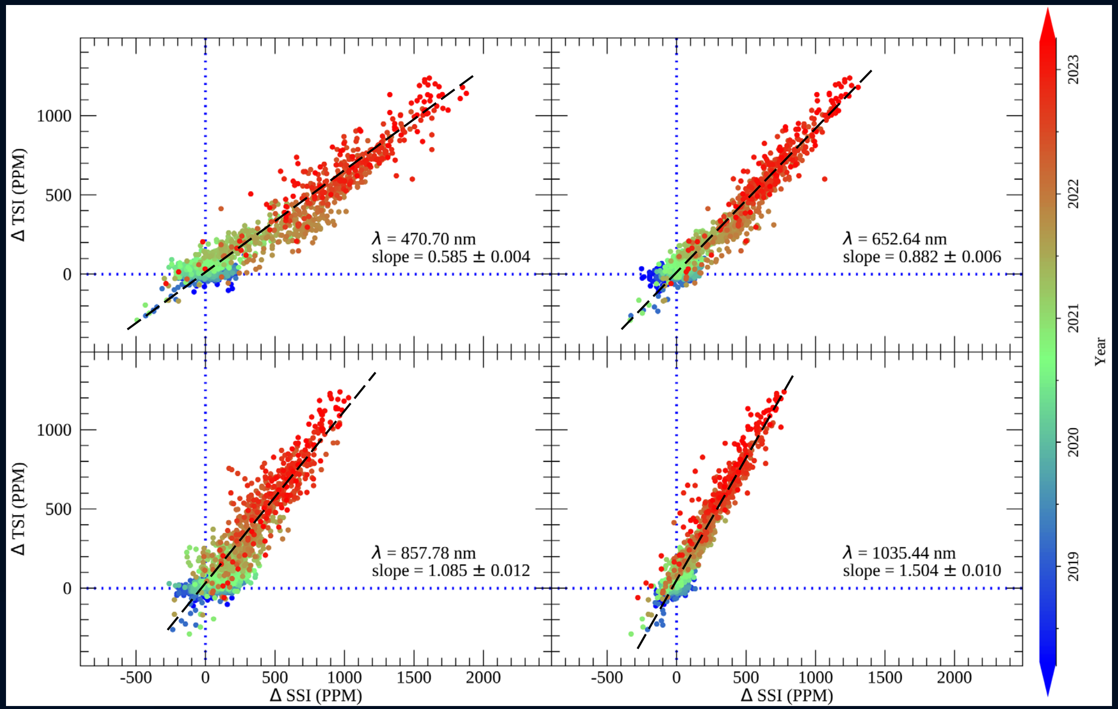


TSIS-1 SIM SSI Variability for Ascending Phase of SC25

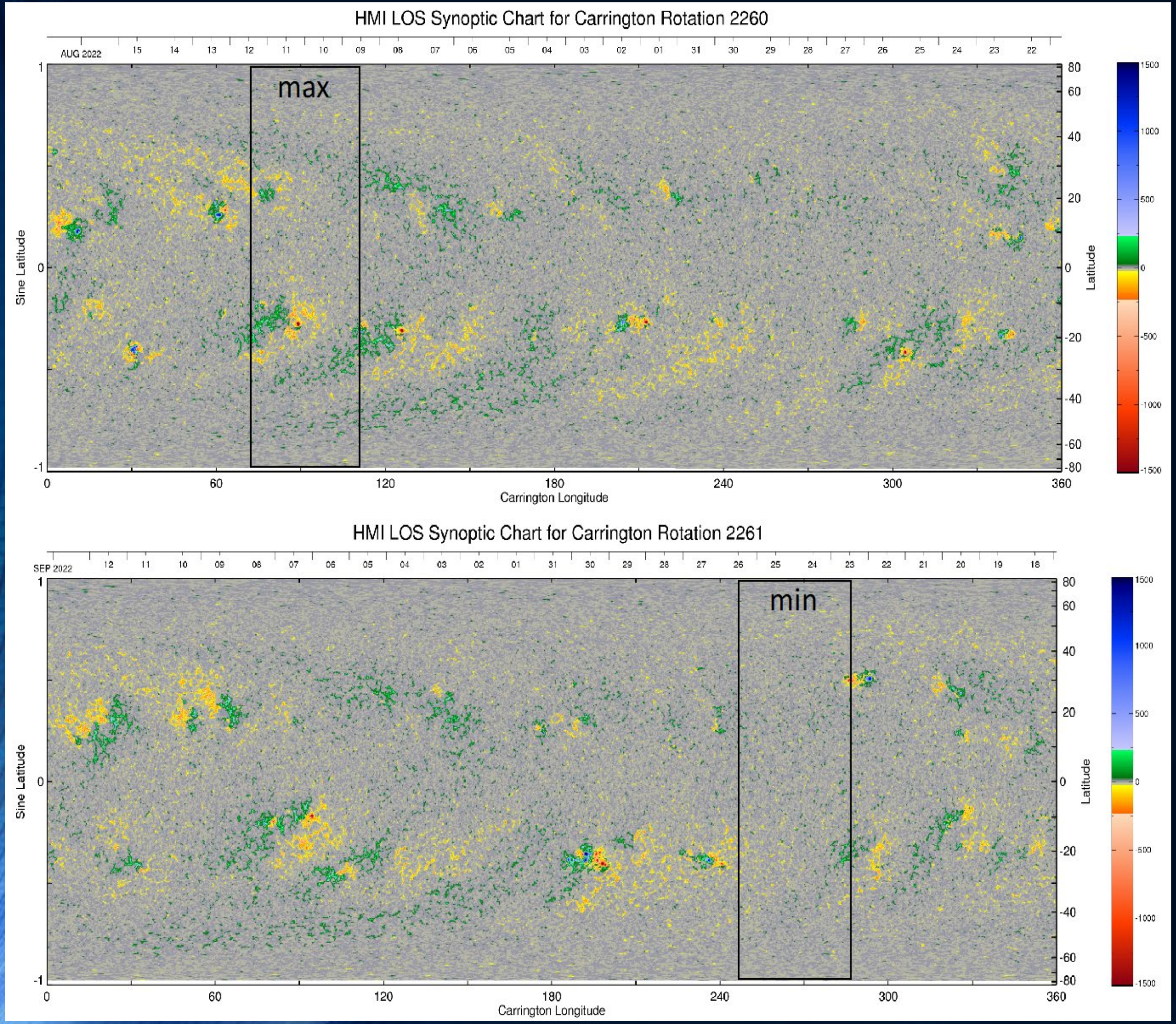
Integrated SIM SSI (200-2400 nm) vs. TIM TSI

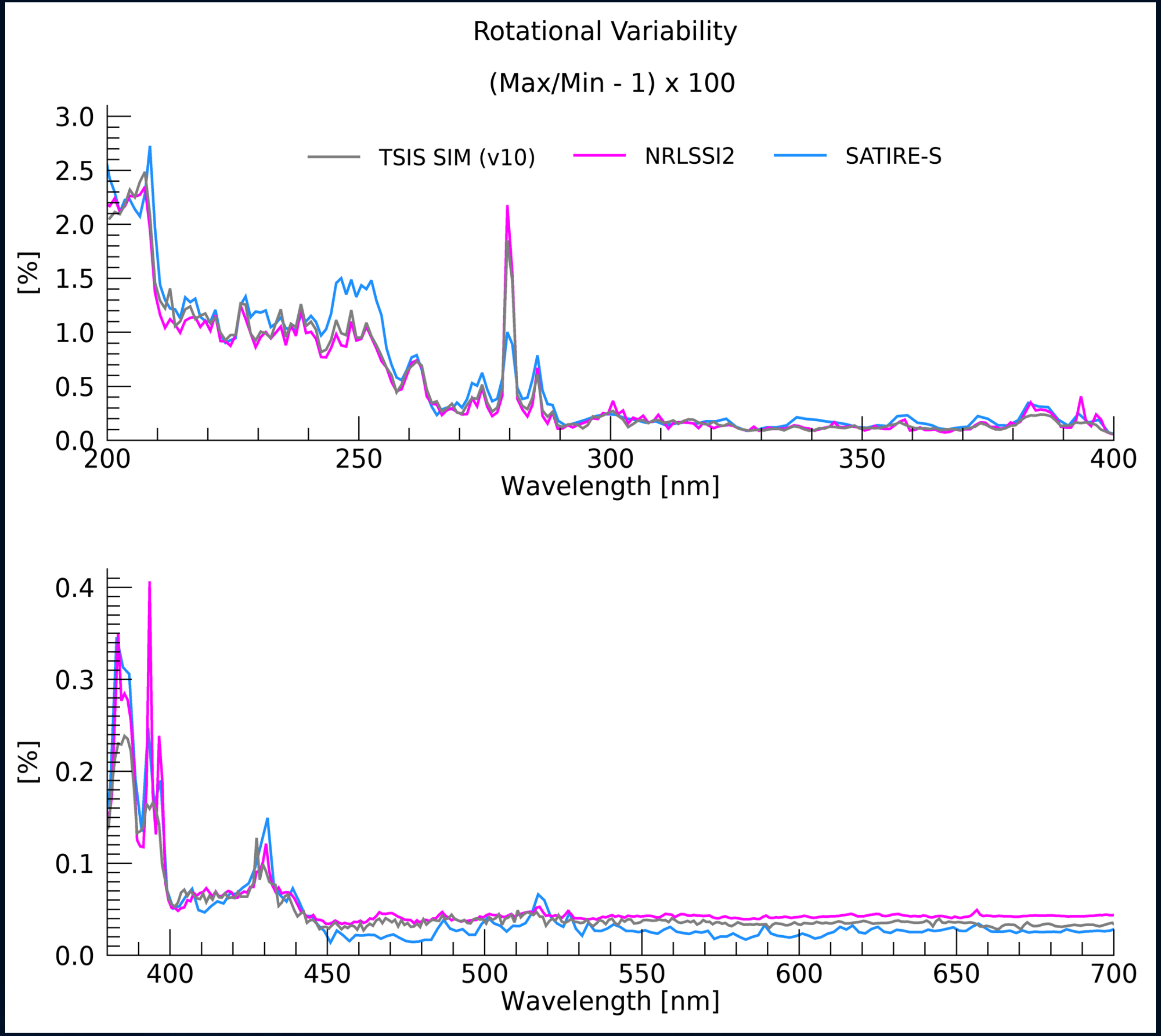


SC 25 TSI vs. SSI variability correlations

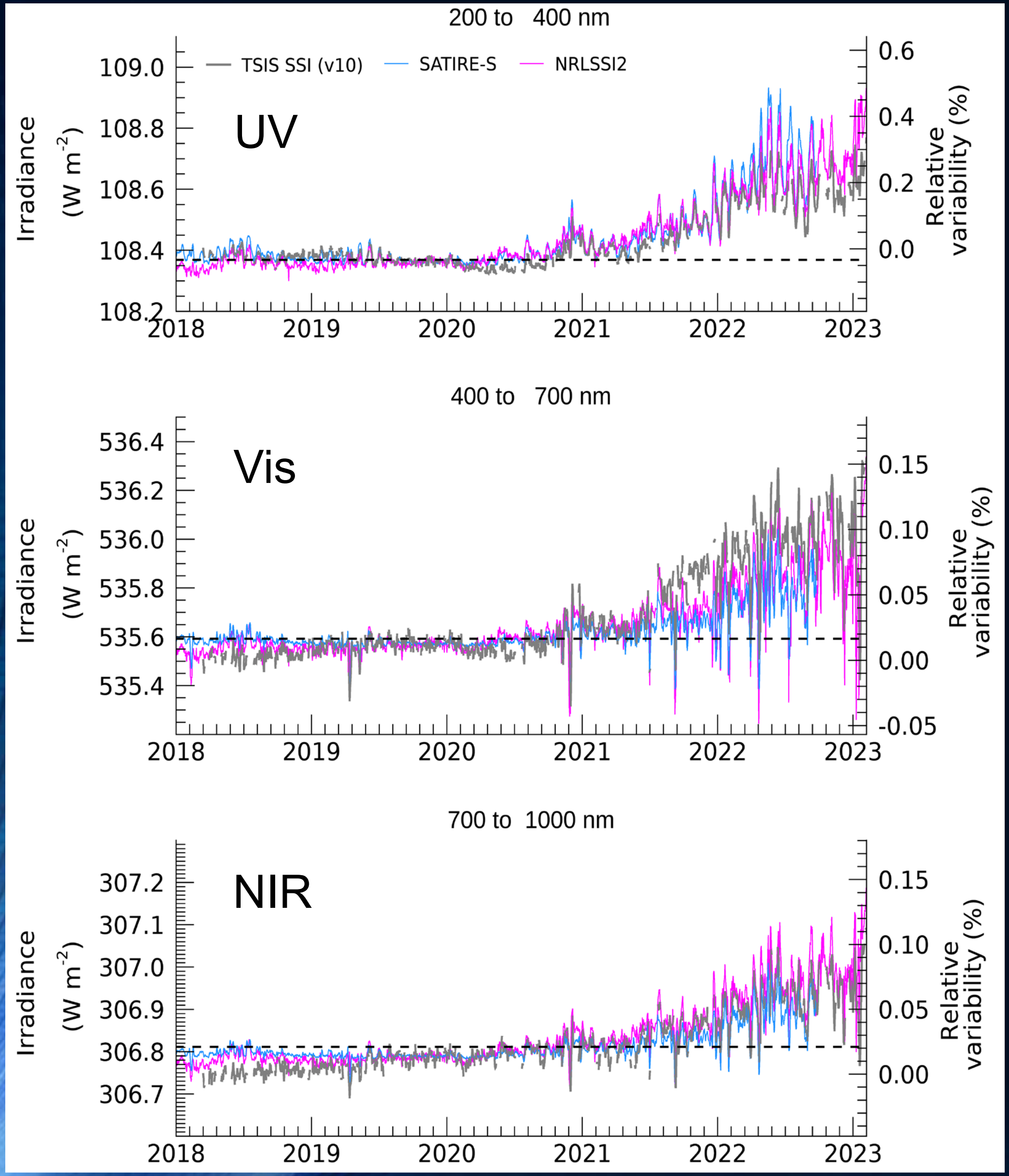


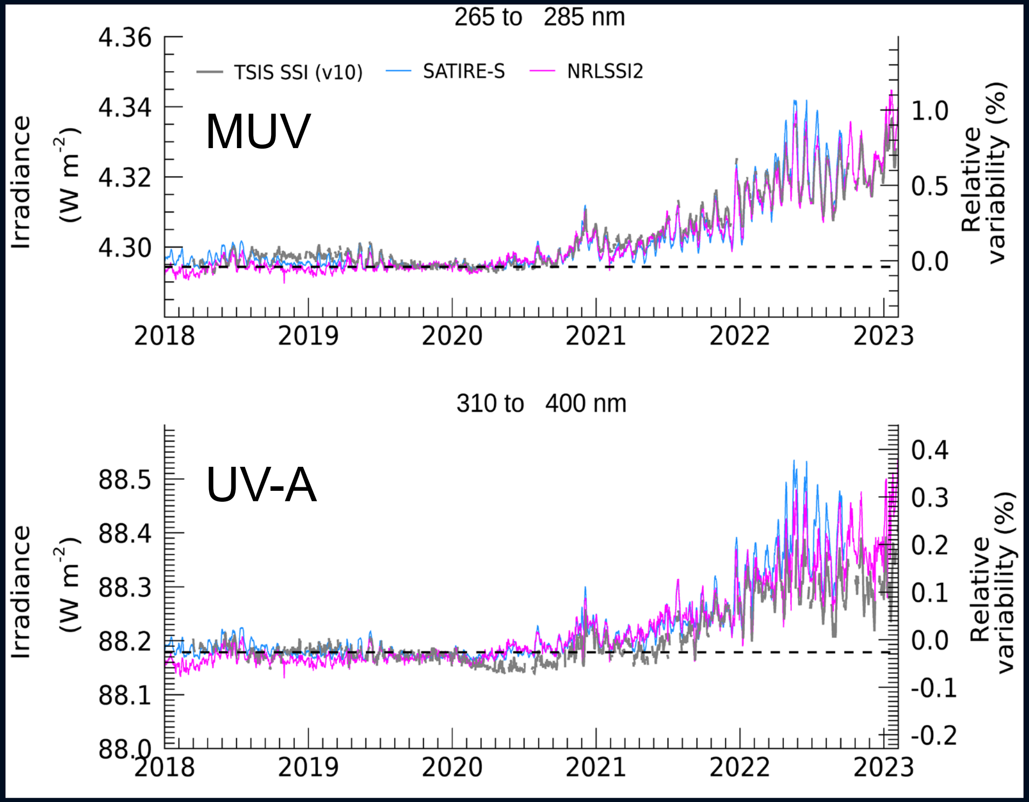
SSI Rotational Variability for Ascending Phase of SC25





Solar long-term (SC 25 solar cycle) variability

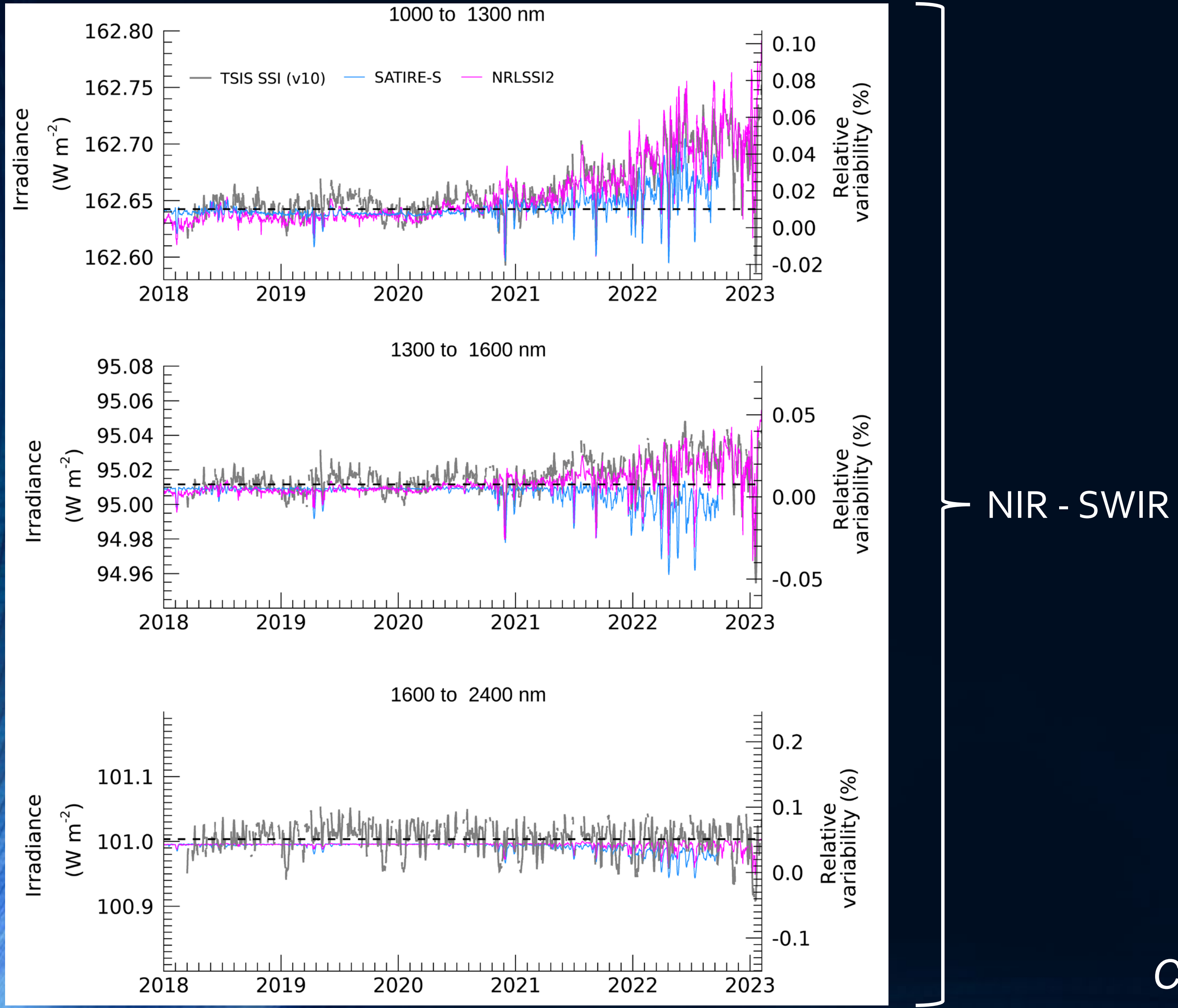




- **NRLSSI2 UV** variability tracks TSIS-1 on rotational and solar-cycle time scales, at most wavelengths.
  - *SATIRE-S UV variability exceeds TSIS-1*
- **NRLSSI2** and **SATIRE-S VIS variability** smaller than observed.
- **NRLSSI2** exceeds observed **NEAR-IR variability**.
  - *SATIRE-S NEAR-IR variability less than observed.*

Richard et al., JSWSC, 2023 (in review)

Solar long-term (SC 25 solar cycle) variability



Summary

- Ongoing analysis of multiple solar rotational epochs builds statistics of irradiance variability in faculae- and sunspot-dominated epochs.
- **TSIS-1** observations are being used to improve the **NRLSSI2** model coefficients that scale magnetic variability to irradiance changes.
  - *compare/contrast with faculae and sunspot contrast factors from theory.*
- **SATIRE-S** excess UV variability irradiance occurs at line cores and is offset by decreased VIS/NIR variability

Coddington et al., Lean et al., 2019; Lean et al., 2021

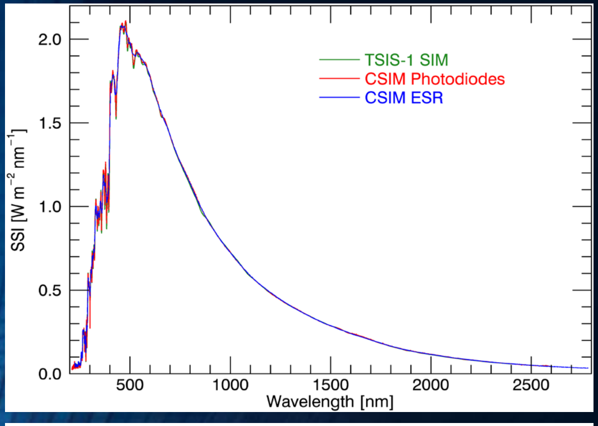
New Technology Infusion

CSIM-FD/ CTIM-FD

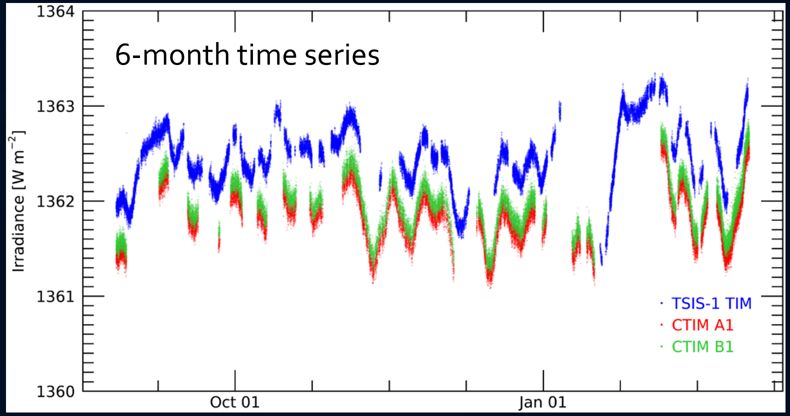
- Compact Spectral Irradiance Monitor
- Compact Total Irradiance Monitor

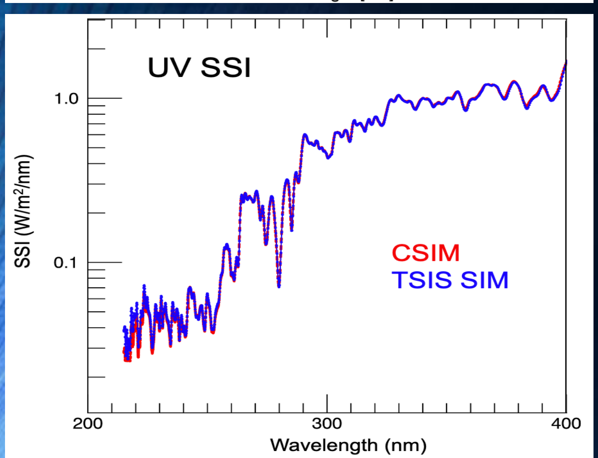
Measuring solar spectral irradiance (SSI), and monitoring Total Solar Irradiance (TSI) to explore how solar variability impacts the Earth's climate, contributing to long-term continuity measurements from SORCE SIM/TIM and TSIS SIM/TIM

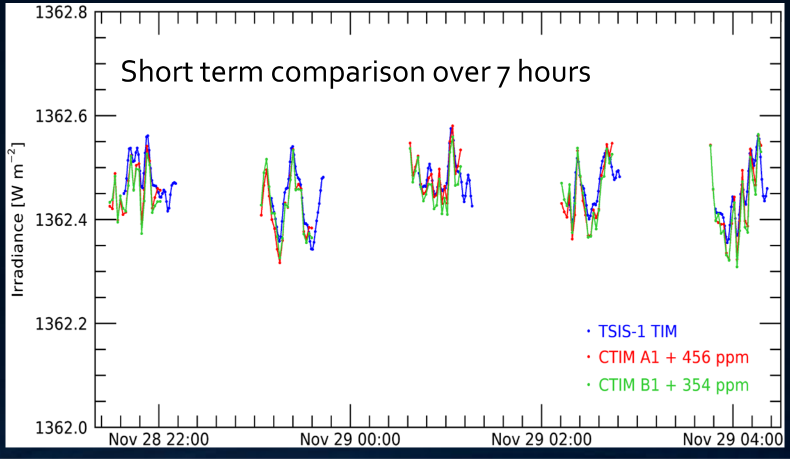
CSIM spectrum compared to TSIS spectrum



CTIM TSI measurements compared to TSIS TIM



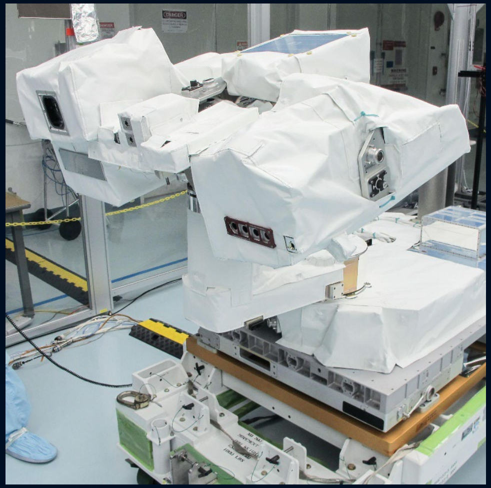




Future Technology…

CSIM (L) and CTIM (R) are 11kg CubeSats built by LASP

Prior Technology…



TSIS-1 is 363 kg built by LASP mounted to the ISS

SORCE is 290 kg based on an Orbital LEOStar-2 bus

Operations

- All mission operations, command uplink, and data downlink at LASP
  - 1 Mbps S-Band downlink, 9.6 kbps UHF uplink/downlink
- UHF and S-Band passes are fully automated
- >1.5 GB downlinked via S-Band so far

LASP 4.2m S-Band Dish

LASP UHF Antenna

New, Advanced Absolute Detector Technology…

New York Times, Nov. 11, 2019

carbon nanotube "ultra-black" that absorbs 99.9% – 99.98% of incident light engadget   Sections

This new carbon nanotube material is the darkest thing on the planet ... and in Space!

Sean Buckley
Associate Editor
Updated Fri, Jul 19, 2019 · 1 min read

Collaborations with NIST Boulder Sources and Detectors Group

...VACNT ESRs for Climate Studies

From advanced components to instruments to missions

- Carbon Absolute Electrical Substitution Radiometer (CAESR)
- Compact Spectral Irradiance Monitor (CSIM)
- Compact Total Irradiance Monitor (CTIM)
- Black Array of Broadband Absolute Radiometers (BABAR)
- Black Array of Broadband Absolute Radiometers for Imaging Earth Radiation (BABAR-ERI)
- *Libera*

NIST Sources and Detectors Group

John Lehman
Michelle Stephens
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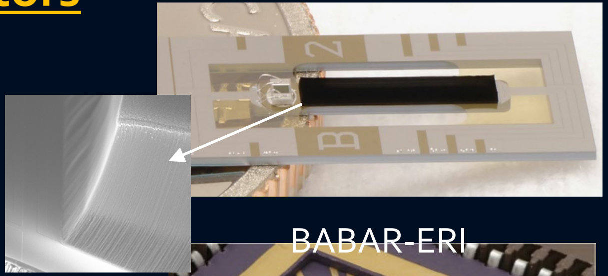
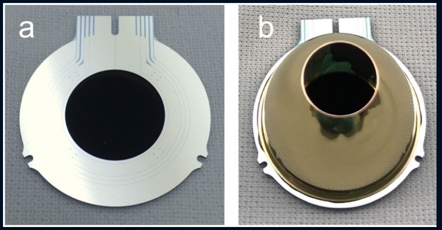
Erik Richard
Greg Kopp
Peter Pilewskie
Odele Coddington

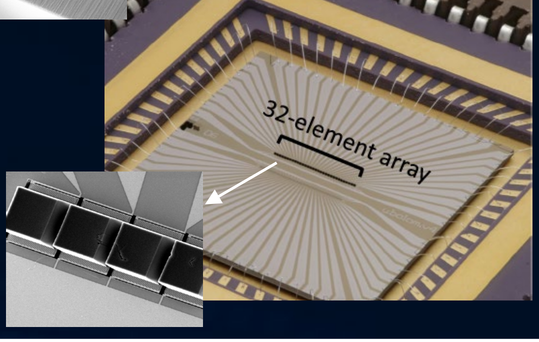
CSIM



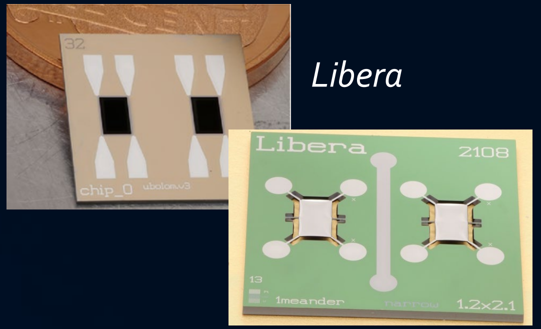
CTIM



BABAR-ERI



Libera



Compact Spectral Irradiance Monitor (CSIM)

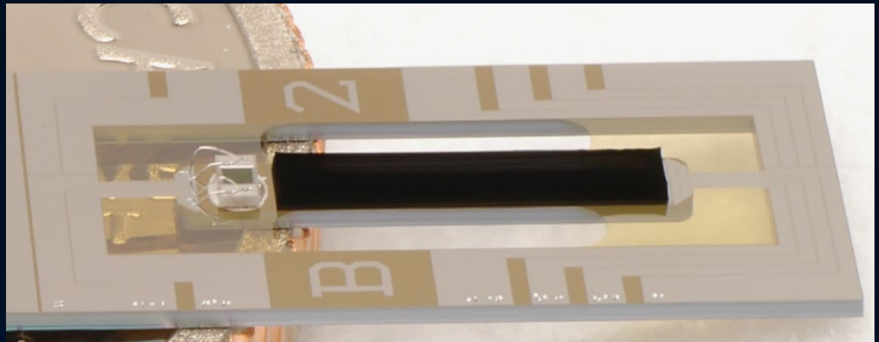
CSIM is a compact solar spectral irradiance monitor that is a cost-effective and low risk alternative instrument designed for considerable implementation flexibility, high calibration accuracy and performance stability for obtaining high-priority Earth Science measurements.

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

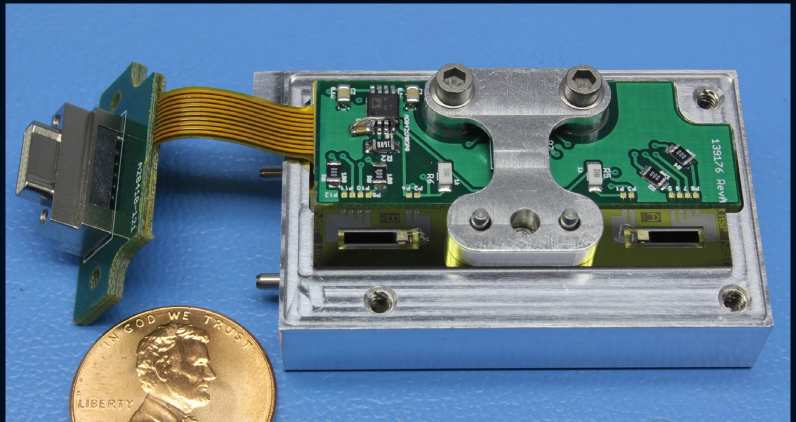
CSIM 6U CubeSat

Silicon-Based Bolometers

- Developed/fabricated by NIST Boulder
- Vertically aligned carbon nanotubes
- Integrated heater

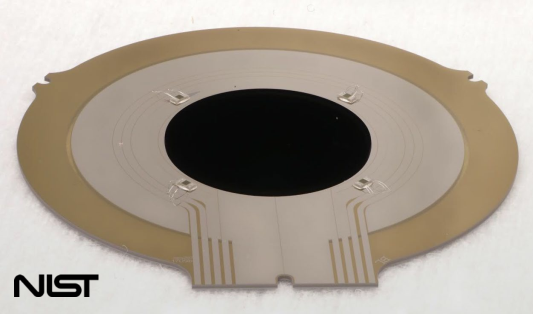


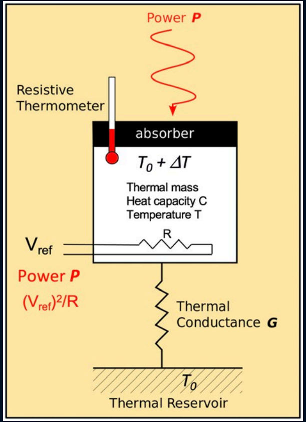
CSIM Bolometer



CSIM ESR

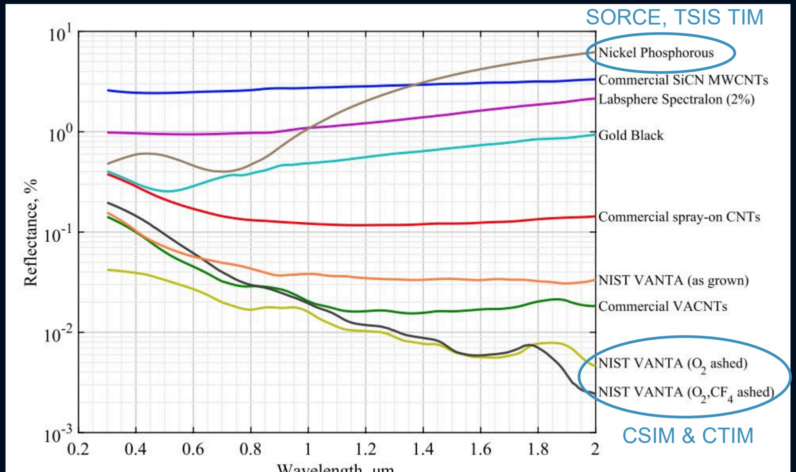
CTIM Bolometer Development





- **Detectors (ESR)**
  - Vertically aligned carbon nanotubes (VACNTs) 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

VACNTs are currently the best optical absorber



Lehman *et al.* ***Appl. Phys. Rev***. 5, 011103 (2018)

CTIM Detector

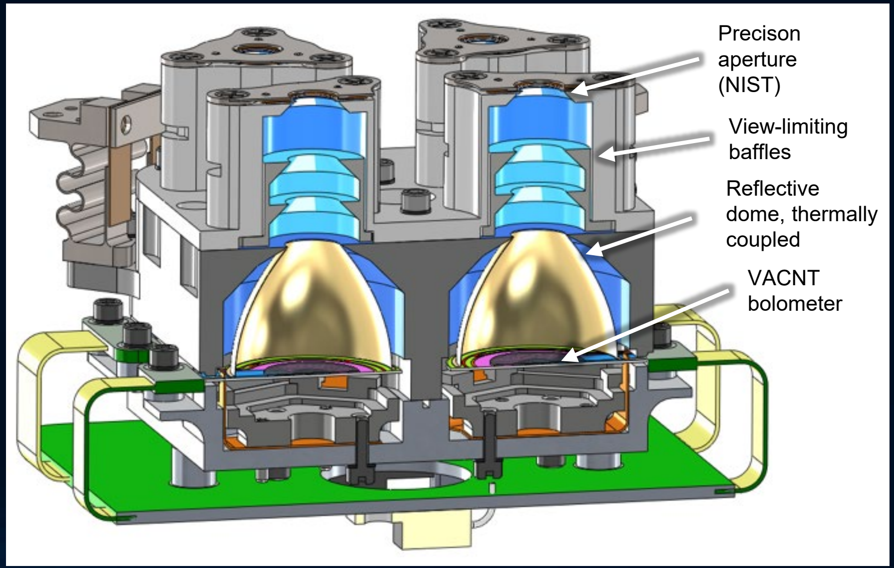
Au-plated, electroformed Cu reflector dome

(50 um thick, <0.5 gr.)

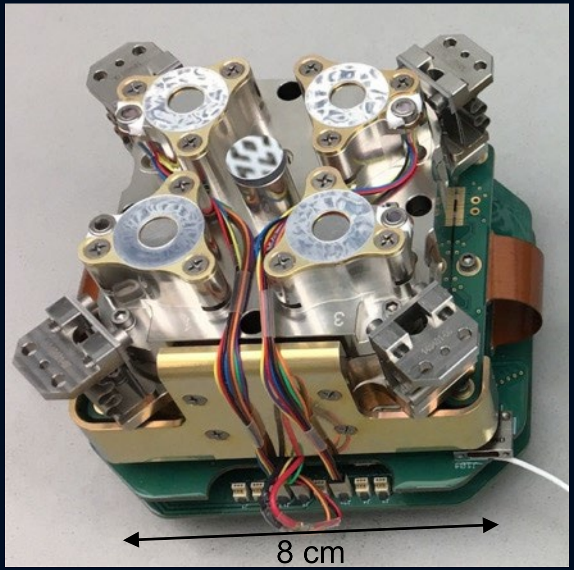
Thermally connected to bolometer.

Purpose: Increase absorptivity of VACNT and radiatively de-couple bolometer from surroundings (>90% of solid angle is dome); reduce effective emissivity of VACNT

Cut-Away Model of Detector Head



Integrated Detector Head



CTIM Uncertainty Budget

Current estimated CTIM combined standard uncertainty is 149-178 ppm:

Uncertainties in ppm (k=1)

Source	A1	A2	A3	A4	B1	B2	B3	B4
Aperture Area at T_o	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***

* NIST NACR5 Calib. → Non-Equivalence

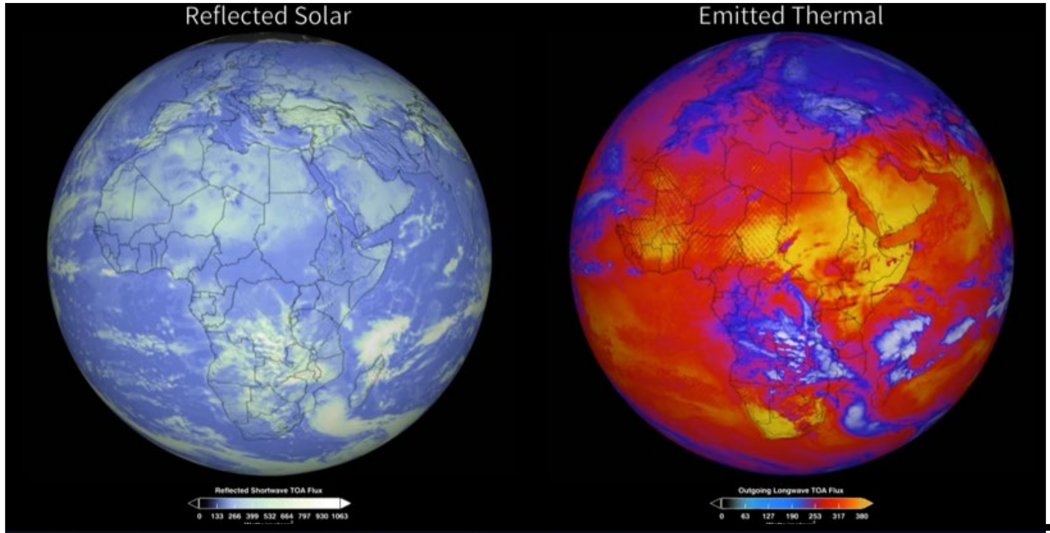
CTIM was calibrated directly against a new NIST ambient irradiance reference detector, NACR5, in the LASP TSI radiometer facility

* White, et al., 2022, "Decadal Validation of the LASP TRF Radiometer by NIST, and Establishment of a Replacement Room Temperature Standard", *Metrologia* 59, 065006, doi: 10.1088/1681-7575/ac89f5

Libera, Earth Venture Continuity-1 Mission

'Li-be-ra, named for the daughter of Ceres in Roman mythology

Outgoing Earth Radiation



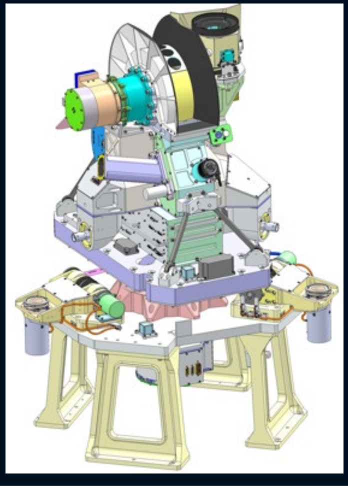
Joint Polar Satellite System-4

Libera continues the 23-year CERES Climate Data Record for the Earth Radiation Budget (ERB).

- *Measures reflected solar and emitted terrestrial radiation from Earth*
- *Provides fundamental climate information about the balance between incoming (from TSIS) and outgoing energy from Earth*
- *Continuity of this climate record over time reveals the signals of climate change – connects temperature trends to energy flow*

Libera is Innovative:

- *Uses state-of-the-art detectors with carbon nanotube technology, the blackest substance on Earth*
- *Adds a split-shortwave measurement to isolate where energy from the Sun is deposited in the Earth system*
- *Adds a wide-field-of-view camera to support split shortwave science*



Partners:

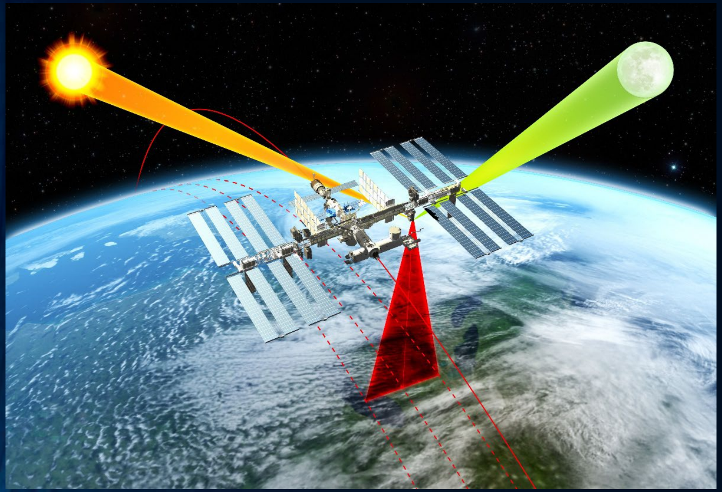
- *LASP, Ball Aerospace, NIST Boulder, Space Dynamics Lab*
- *Science Team: CU, JPL, CSU, UA, UM, LBL*

Flight:

- *JPSS-4, 2027 launch; 5-year mission*

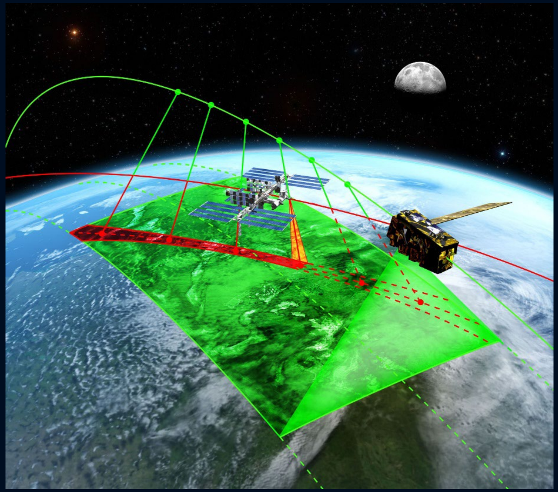
CLARREO Pathfinder

Objective 1: High Accuracy SI-Traceable Reflectance Measurements



Demonstrate on-orbit calibration ability to reduce reflectance uncertainty by a factor of ***5-10 times*** compared to the best operational sensors on orbit.

Objective 2: Inter-Calibration Capabilities



Demonstrate ability to transfer calibration other key RS satellite sensors by inter-calibrating with CERES & VIIRS.

	Objective 1	Objective 2
Uncertainty	Spectrally-resolved & broadband reflectance: ≤0.3% (1σ)	Inter-calibration Sampling Difference: ≤0.3% (1σ)
Data Product	Level 1A: Highest accuracy, best for inter-cal, lunar obs Level 1B: Approx. consistent spectral & spatial sampling, best for science studies using nadir spectra	Level 4: One each for CPF-VIIRS & CPF-CERES inter-cal. Merged data products including all required info for inter-cal analysis

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