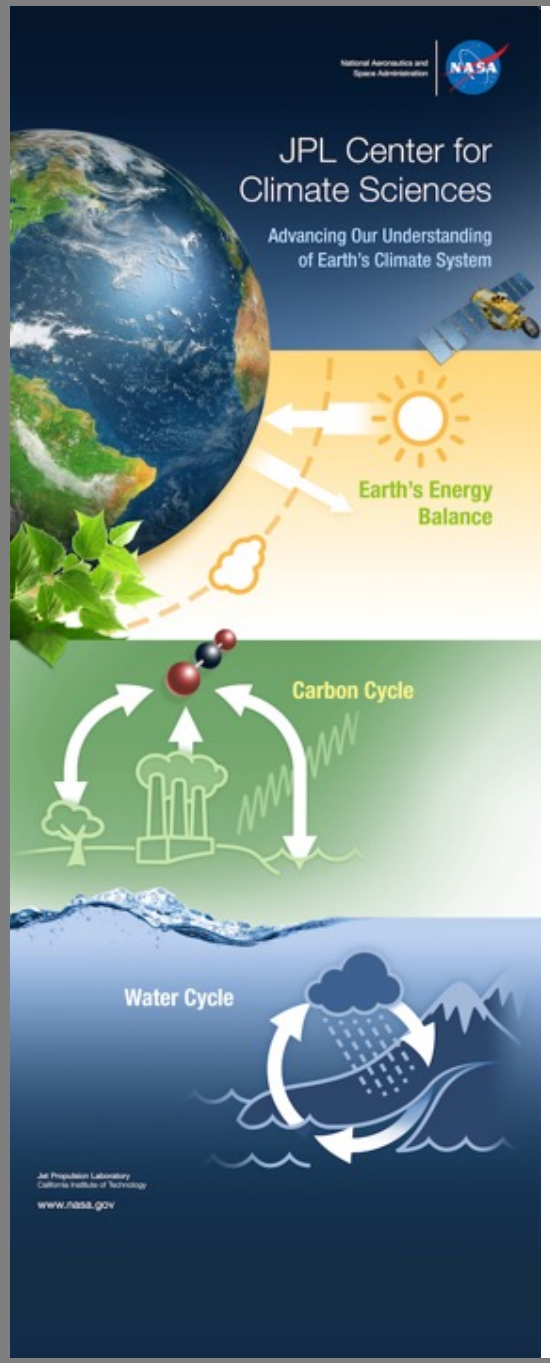
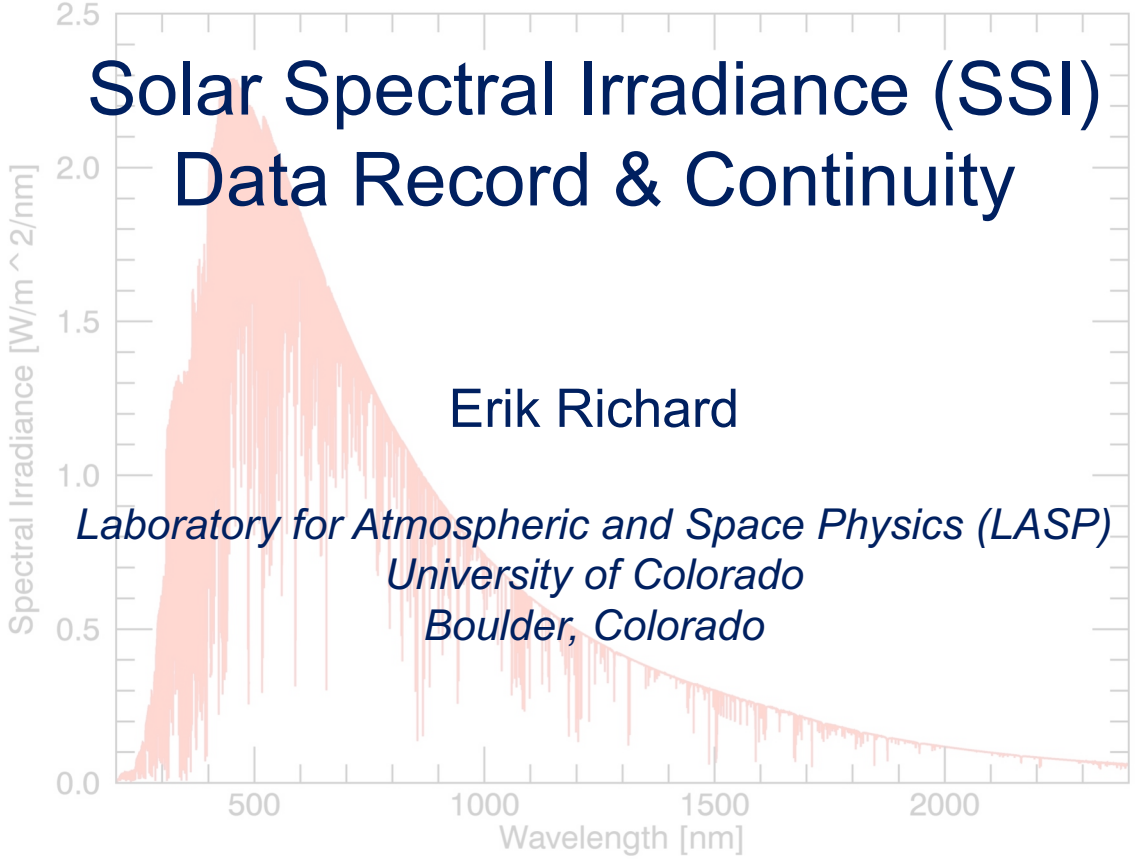



# JPL Center for Climate Sciences Virtual Mini-Symposium on Climate and Radiation Monitoring

## Solar Spectral Irradiance (SSI) Data Record & Continuity



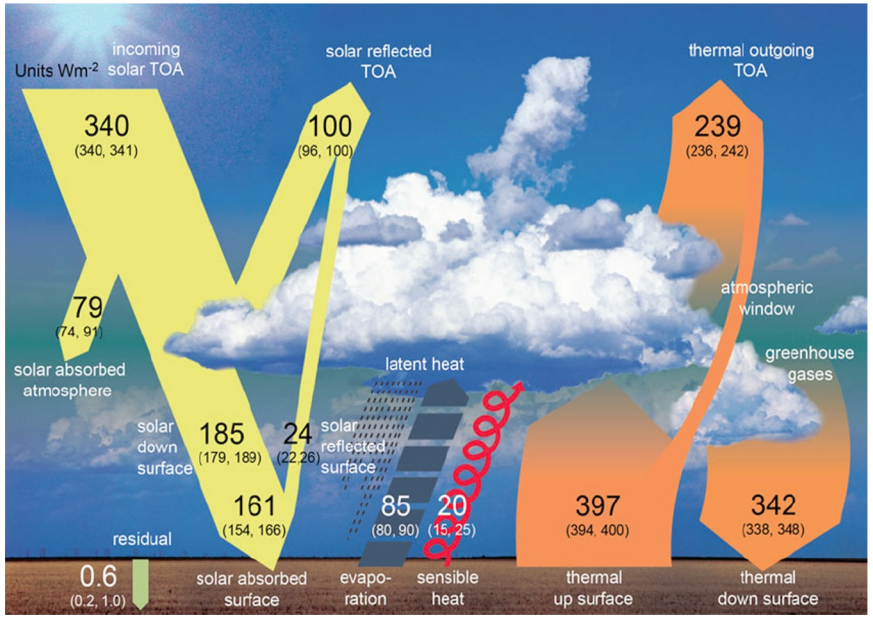

Erik Richard

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

# Justification for SSI measurement continuity

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

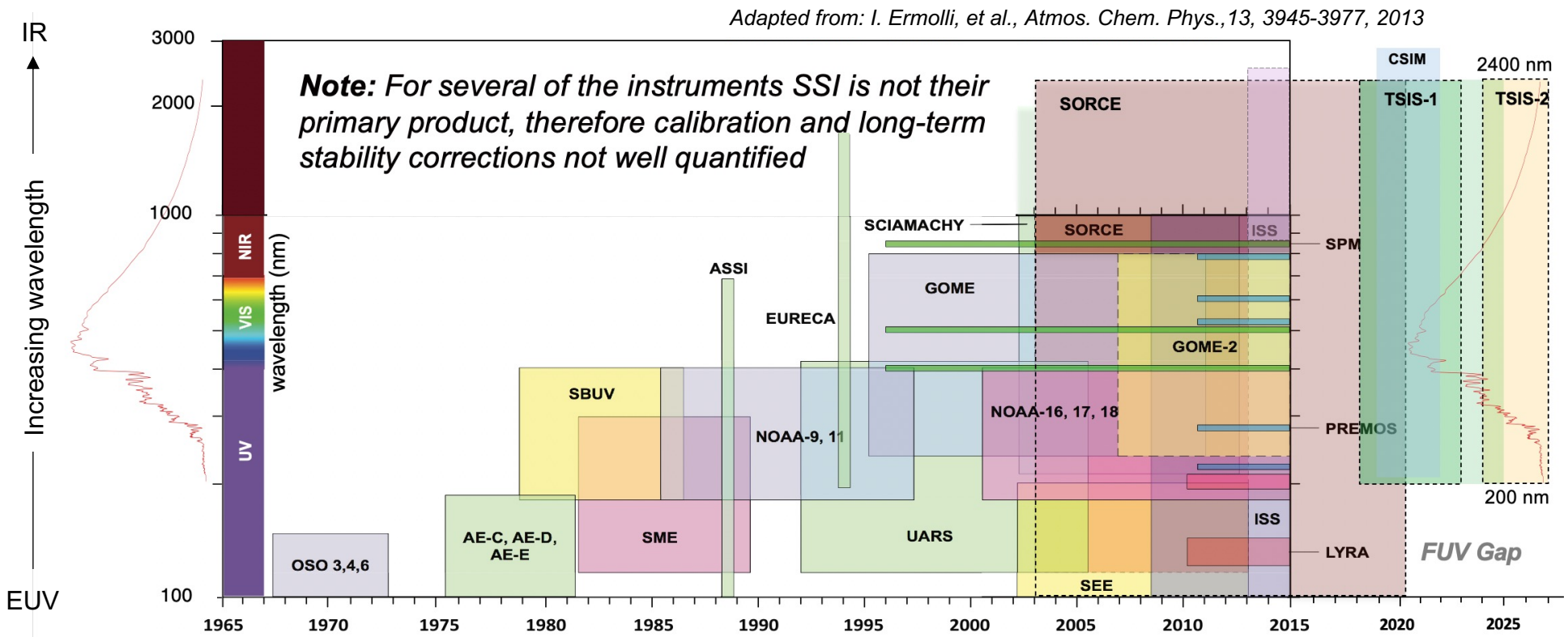
- The SSI climate record extends back to 2003 (SORCE) and is critical for NASA's Sun-climate science as highlighted in the 2017 Earth Science Decadal Survey.
- SSI measurements enable in-depth research of the Sun's influence on Earth's ozone layer, atmospheric circulation, clouds, and ecosystems.
- As climate models evolve, 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.




## 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.

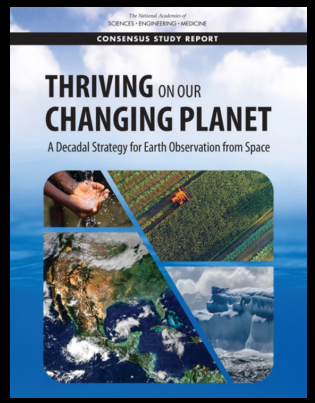
# Solar Spectral Irradiance Data Record




## SSI continuity presents a different challenge than TSI

- Requires overlap in time AND wavelength.
  - Record shows overlap in time but inconsistent overlap in spectral domain.
- Other challenges include differing absolute accuracy, long-term stability, spectral sampling, and resolution.

# Solar Irradiance Measurement Continuity (SORCE and beyond)



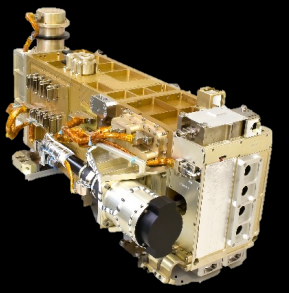

WCRP World Climate Research Programme

United Nations Framework Convention on Climate Change

**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."*


TIM (TSI)


SIM (SSI)


* CSIM-FD & CTIM-FD
NASA ESTO
Tech. Demo Missions
(6U CubeSats)
"Next-generation" technologies

BOM 2003

SORCE (TSI & SSI) — EOM

TCTE (TSI) — EOM

TSIS-1 (TSI & SSI) — Ext.

* CSIM-FD (SSI) — EOM

TSIS-2 (TSI & SSI) — Ext.

* CTIM-FD (TSI) — Ext.

2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030

We are here

08/24

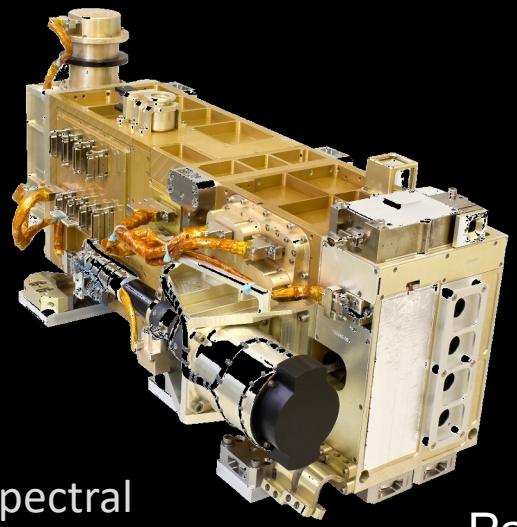
***Goal: "Acquire SSI and TSI time series of measurements of sufficient length, consistency, and continuity to determine climate variability and change"***

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

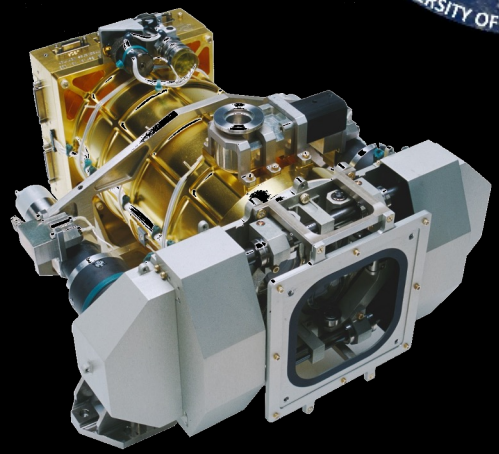
# TSIS-2: Extending the TSI and SSI Data Record

## Total and Spectral solar Irradiance Sensor – 2

- NASA GSFC Managed Mission
- 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 on track for a **Feb 2023 delivery**
- TSIS-2 launch readiness date: Aug. 2024
- Next milestone review: Mission KDP-C, May `22
- TIM and SIM instruments are in final calibration

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

# SSI focused missions & questions moving forward

*4 decades of LASP SSI measurement continuity…*


*1981-1989*


*1991-2005*


*2003-2020*


*2017-present*


*2018-2022*
*(New Tech Demo)*


*2024-*

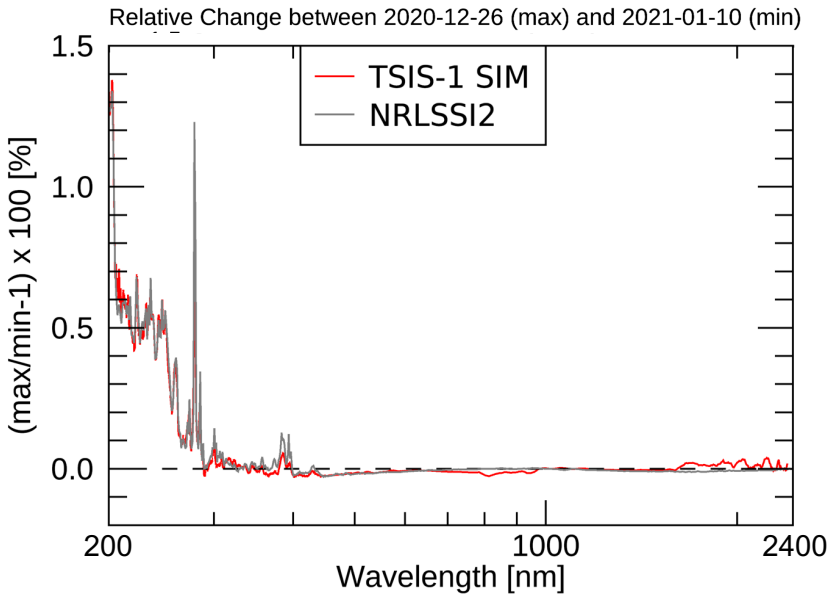
Long-term strategies

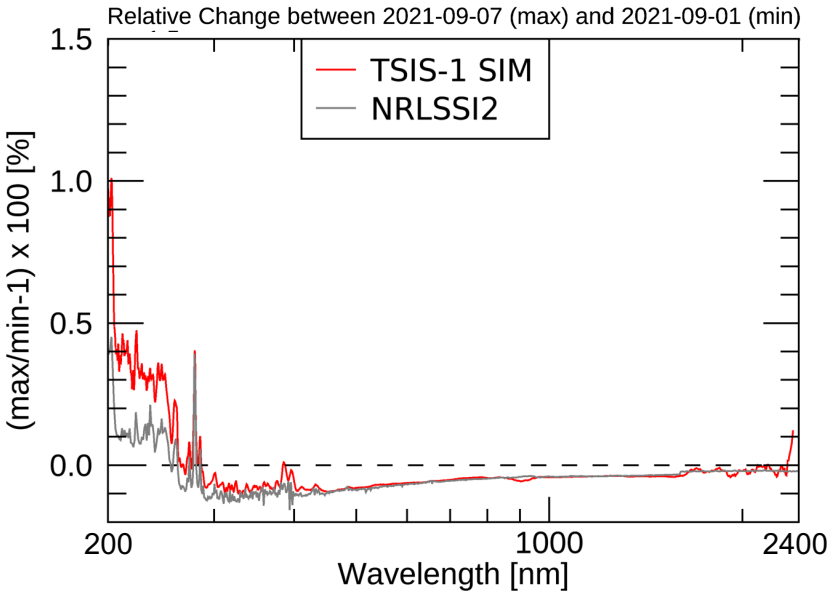
Continuity?
Constellations?
Class C, D?

*2030-*

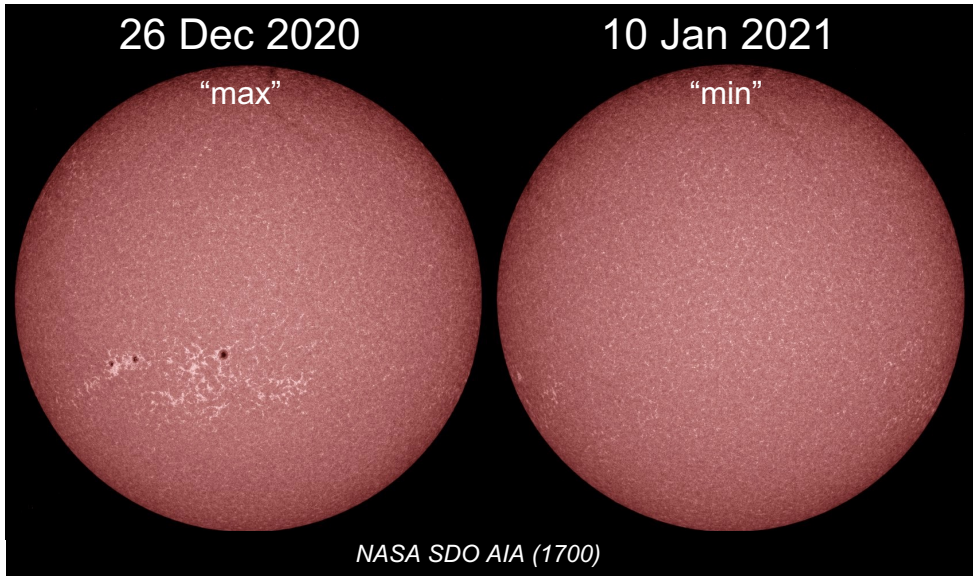
- What can we learn from past and present solar missions?
  - Are the methods of observation adequate and are the results accurate enough?
- What are the observations to be continued? What are the missing ones?
- ✓ New directions: new instrumental concepts or novel technologies, new observation strategies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

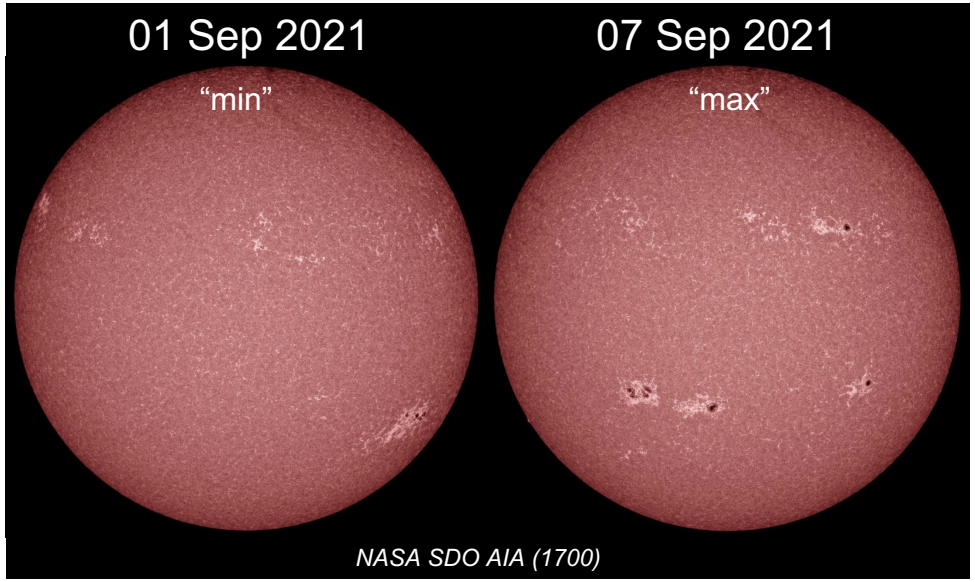
# Short-term spectral variability: Measured vs. Modeled




Onset of Solar Cycle 25

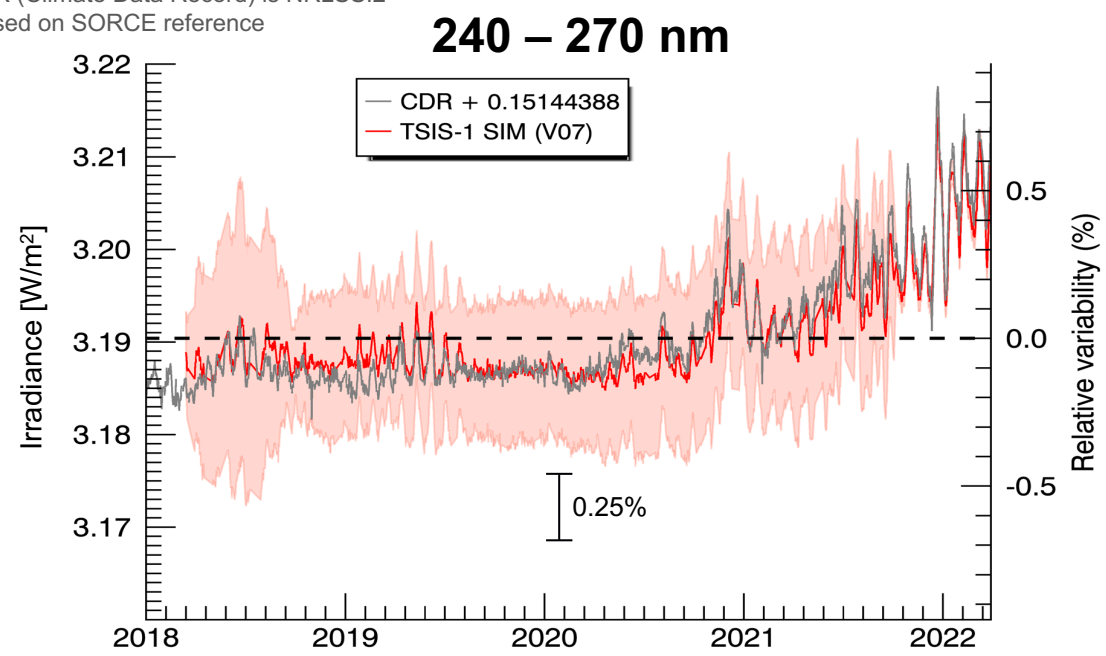


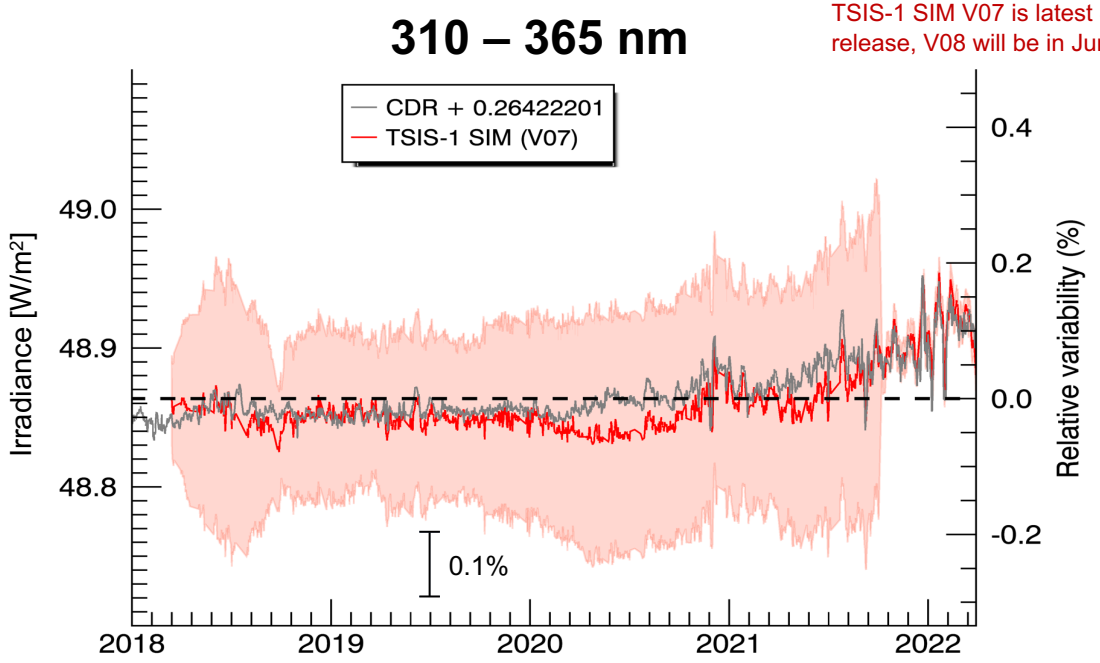



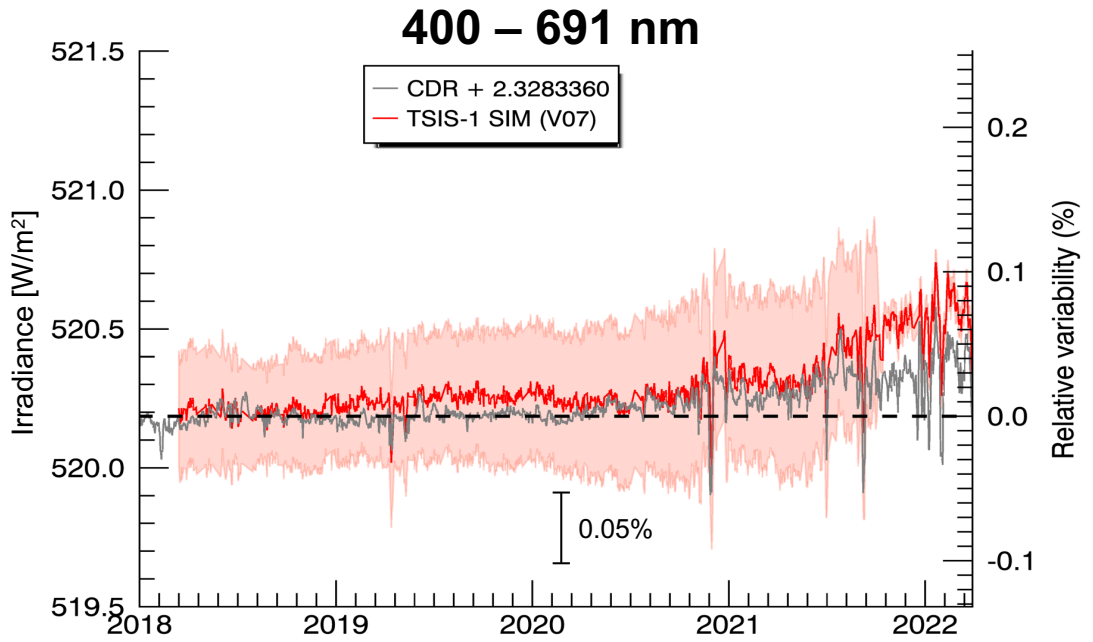
# Long-term spectral variability (4 years)

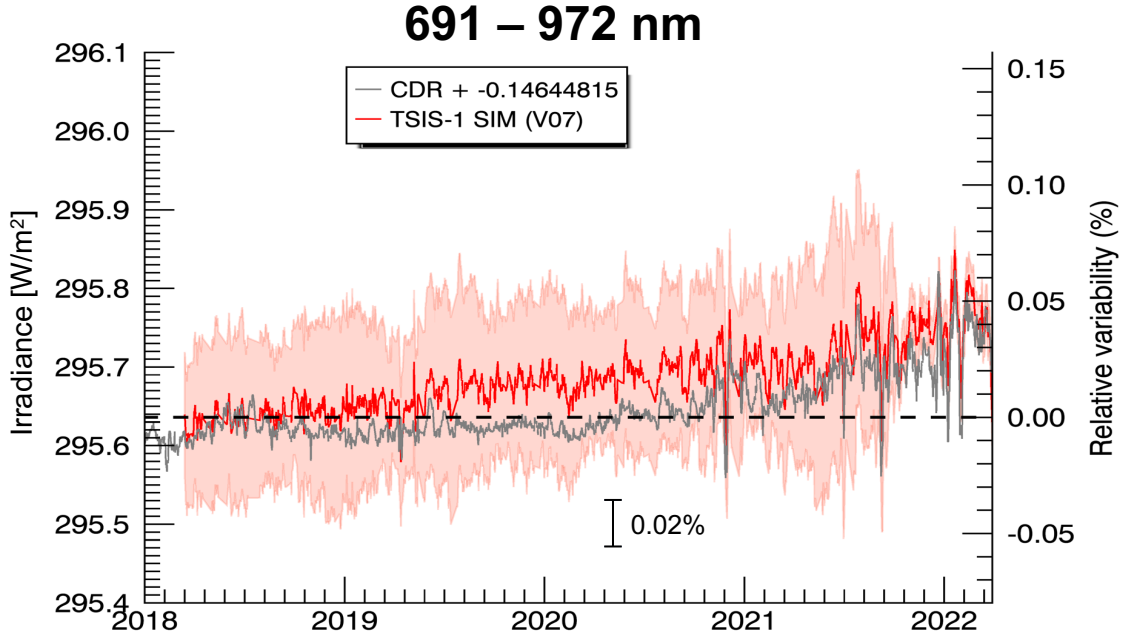
Note: CDR (Climate Data Record) is NRLSSI2 model based on SORCE reference

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

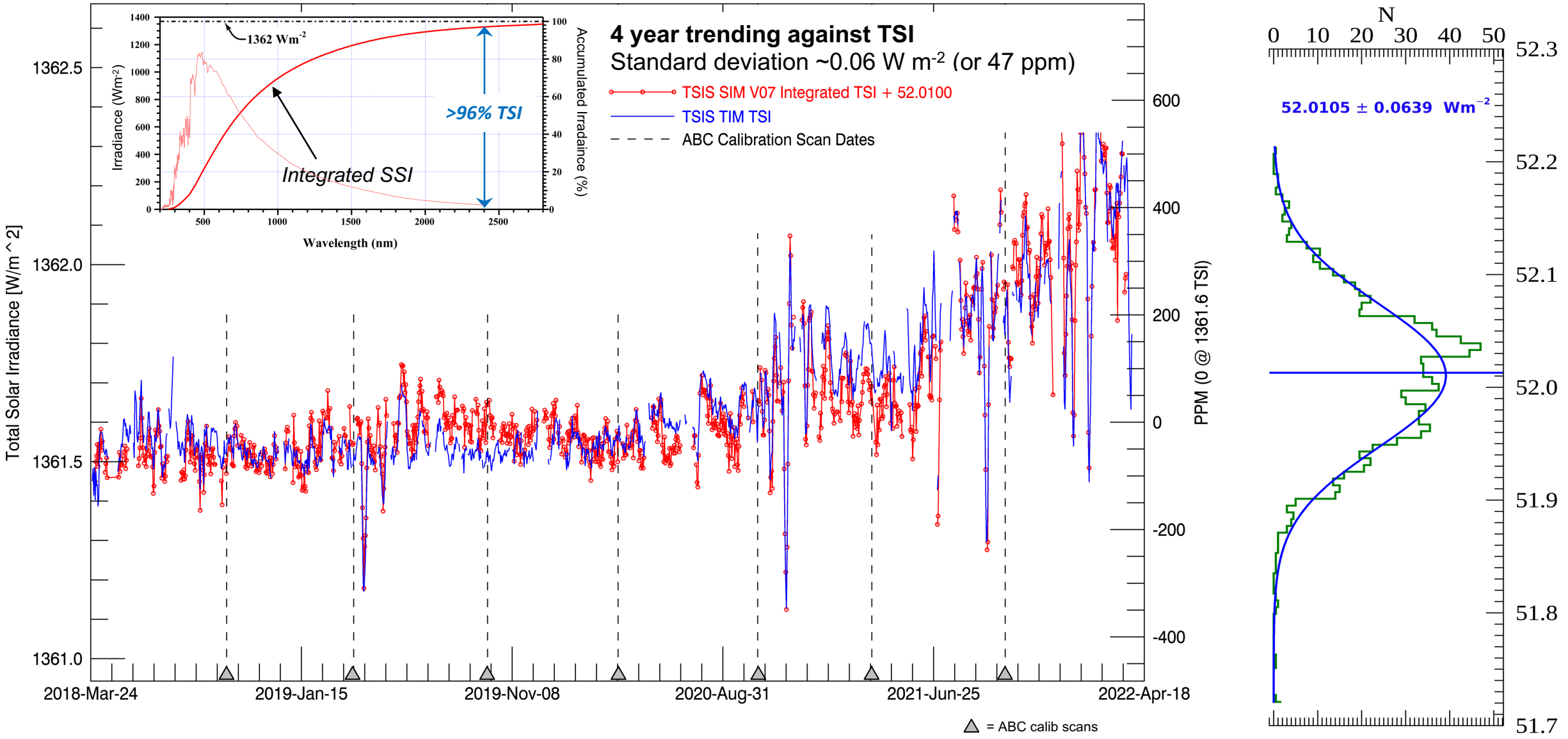


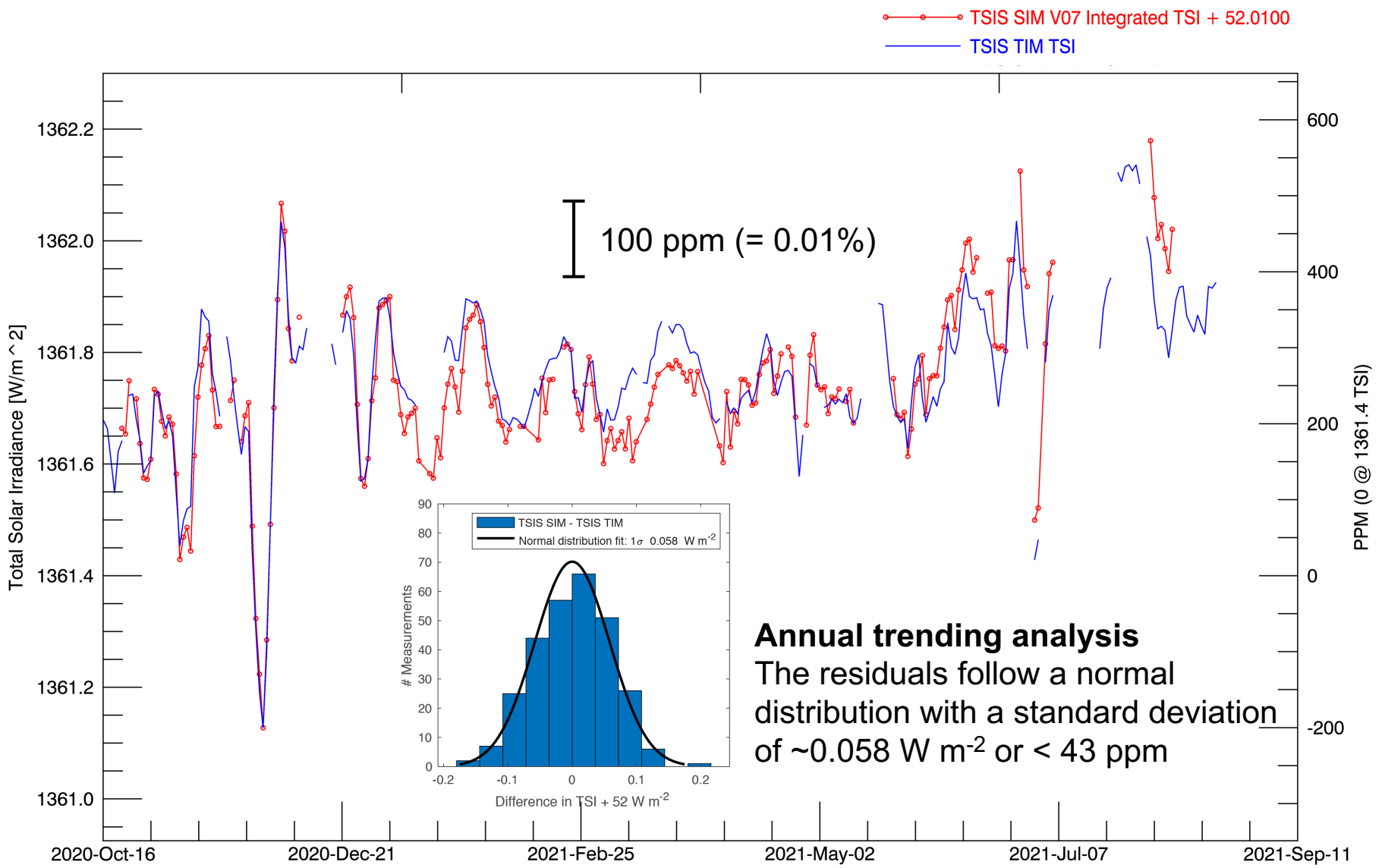



# Integrated SIM to TIM TSI Comparison



# Integrated SIM to TIM TSI Comparison



# New technologies
# &
# New mission concepts

# New Mission Concept Motivation & Benefits (concerns from last decade)

The 2012 NRC Decadal midterm assessment report[1] warns that the nation's Earth observing system is beginning a rapid decline in capability as long-running missions end (SORCE) and key new missions are delayed (TSIS), lost (Glory), or canceled.

- *Among its recommendations for opportunities to improve alignment with ES Decadal Survey priorities and mitigate losses of (or gaps in) key observational records, -* ***"new, highly flexible observing and implementation strategies should be exploited for observing the Earth system"***

A recent NAS report[2] on the role of **CubeSats** to achieve science provides an analysis of the benefits of CubeSat mission concepts with regard to Earth Science priorities, including:

- ✓ *short development cycles that allow for rapid response to targeted measurement opportunities* ***(augmenting larger missions – not necessarily replacing)***
- ✓ *providing key observational gap-fillers*
- ✓ *enabling new mission concepts not possible under present NASA large mission architectures (overlapping measurements & integratable, disaggregated new technologies)*

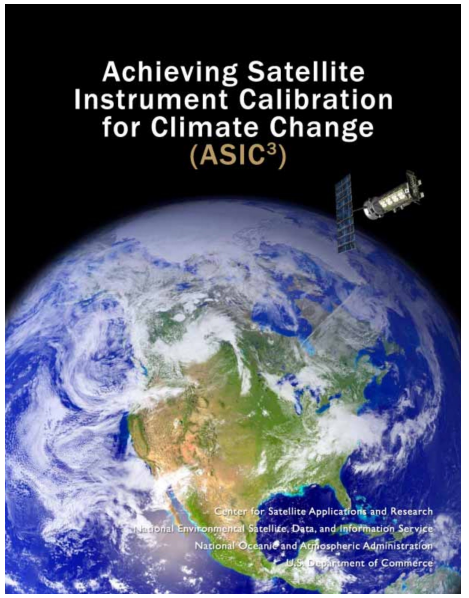
**NASA ESTO (ACT, IIP, & InVEST) programs advance instrument technologies by**

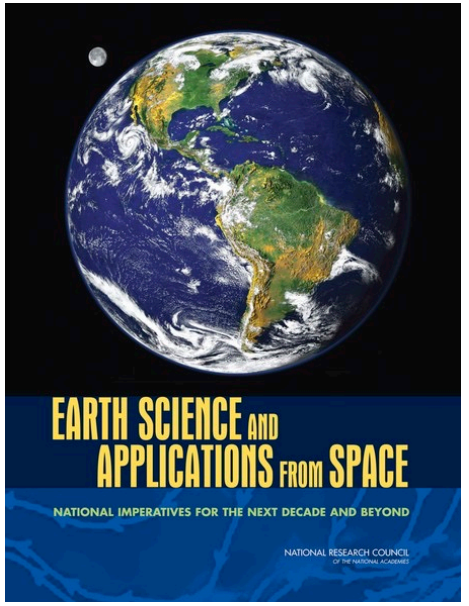
**Observation Technology**

- developing and demonstrating new measurement technologies that make significant contributions to Earth science priorities and can reduce the risk, cost, size, volume, mass and development time of Earth science instruments.

**Technology Validation**

- advance the readiness of related technologies and reduce the risks to future missions through space flight validation



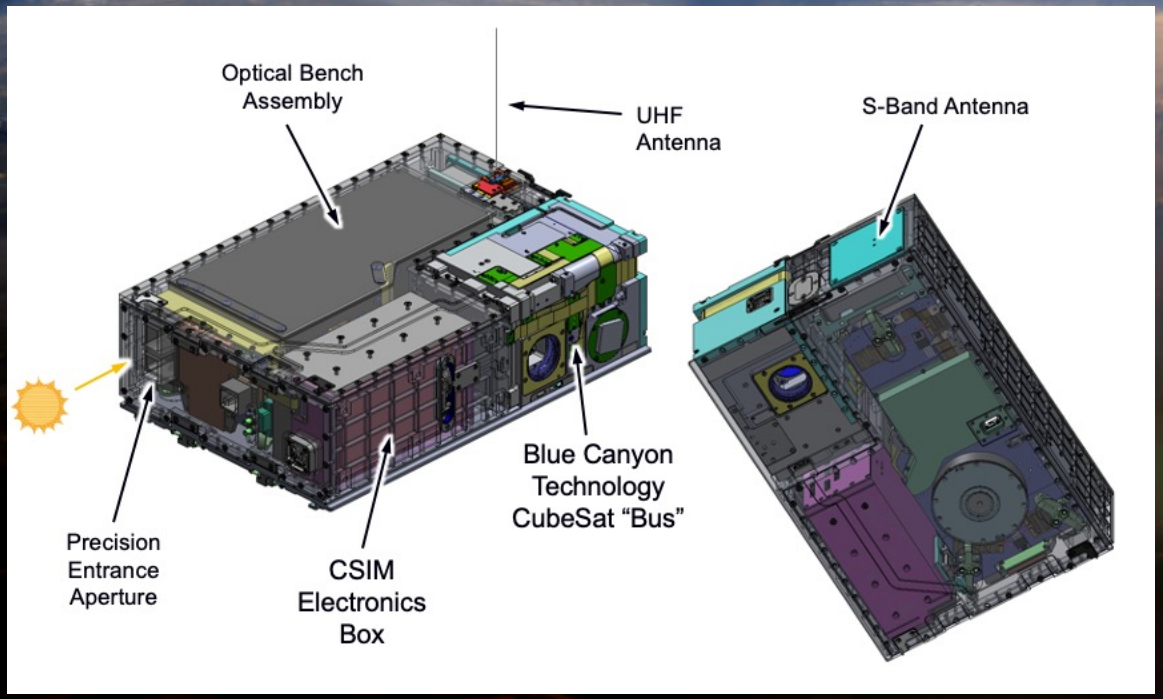

1.) Nation Research Council, *Earth Science and Applications from Space: A Midterm Assessment of NASA's Implementation of the Decadal Survey*, National Academy Press, Wash., D.C., 2012
2.) Nation Research Council, *Achieving Science with CubeSats: Thinking Inside the Box*, National Academy Press, Washington, D.C., 2016

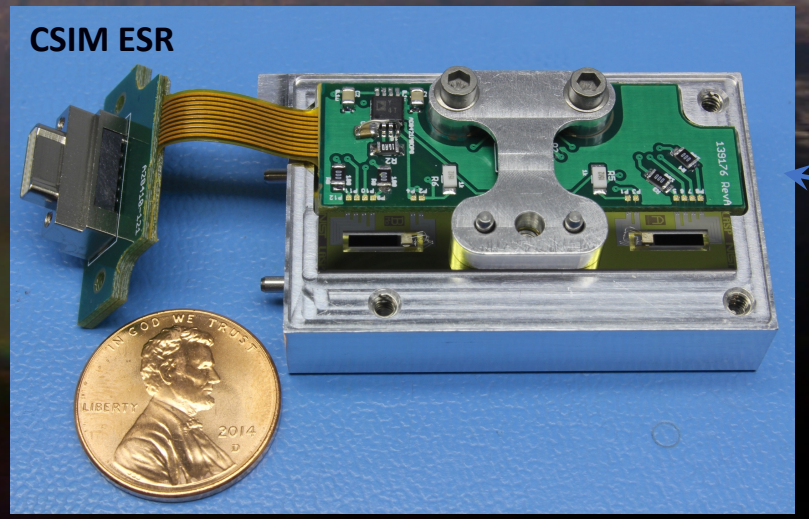
# CSIM-FD IIP & InVEST: Compact Spectral Irradiance Monitor

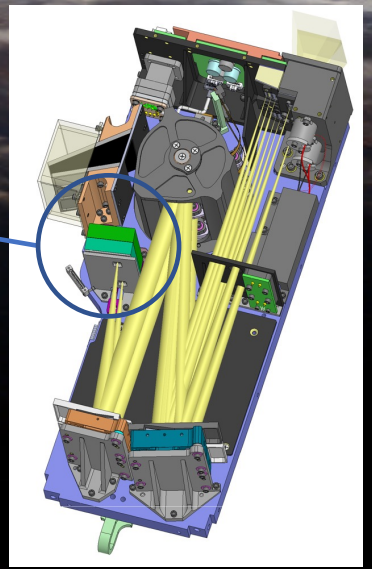
## "Next Generation" SSI Measurement

**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)



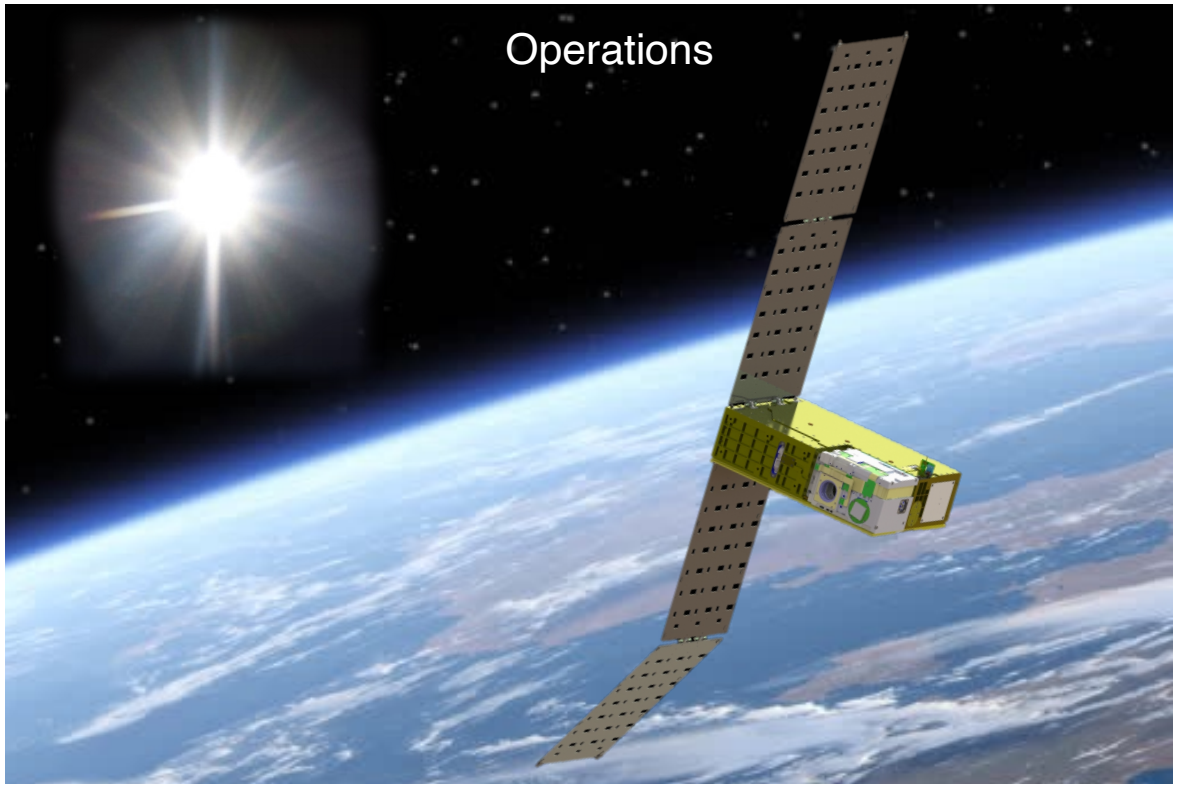
# Launch Opportunity : SSO-A SmallSat Express (SpaceX Falcon 9)

**The largest single rideshare mission from a US-based launch vehicle to date.**

Spaceflight contracted with 64 spacecraft from 34 different organizations for the mission to a Sun-Synchronous Low Earth Orbit.

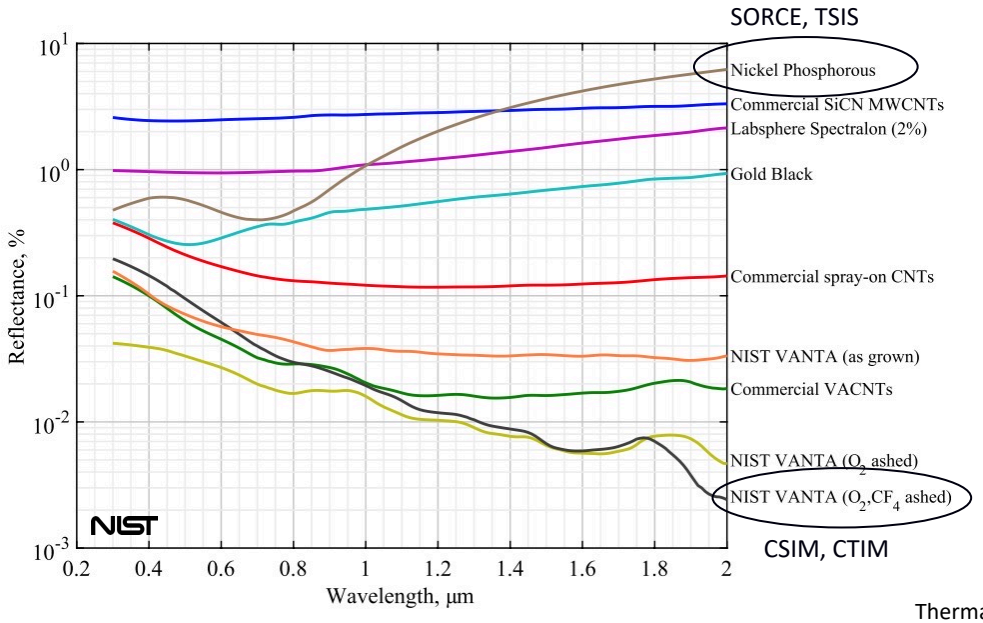
- 15 microsats
- 49 cubesats
- 25 are from international organizations from 17 countries: United States, Australia, Italy, Netherlands, Finland, South Korea, Spain, Switzerland, UK, Germany, Jordan, Kazakhstan, Thailand, Poland, Canada, Brazil, and India.



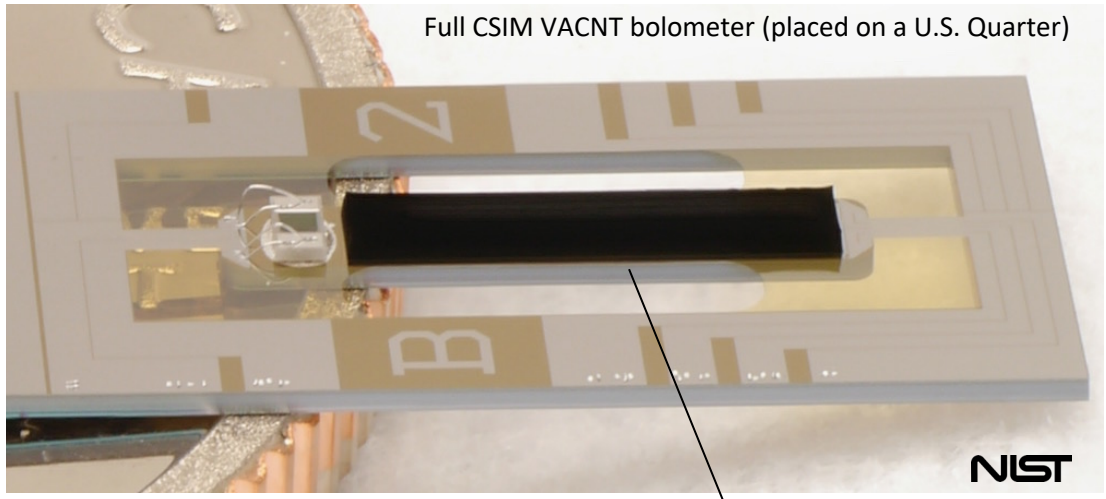



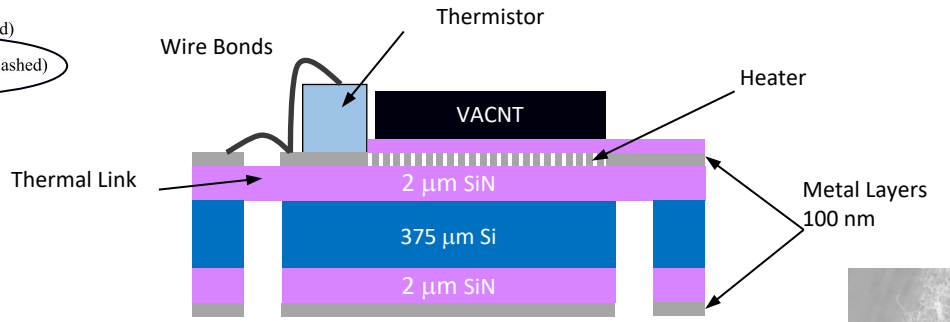
# Silicon + Vertically Aligned Carbon Nanotube Bolometers

*VACNTs are currently the best optical absorber*

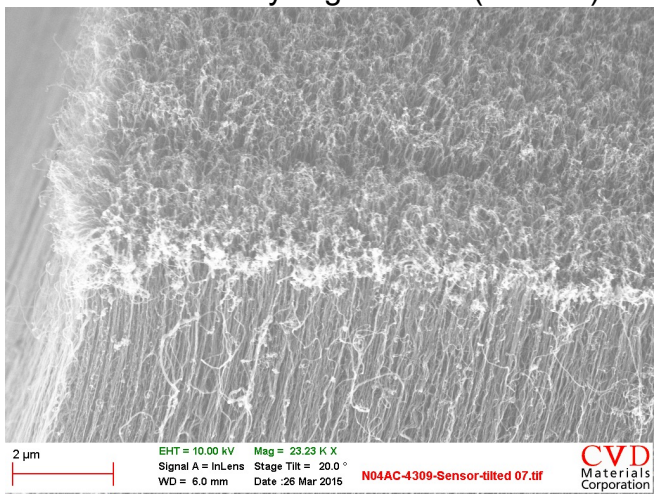



Lehman *et al.* ***Appl. Phys. Rev***. 5, 011103 (2018)



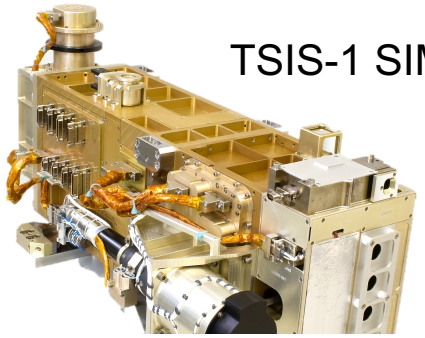

Vertically aligned CnT (VACNT)



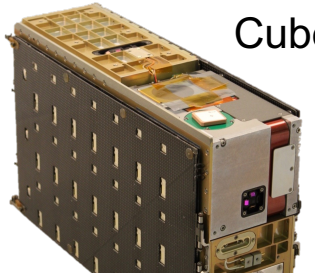

- Developed with NIST Boulder
- Silicon micro fabrication allows a nearly arbitrary 2D geometry to be fabricated with micron-level precision
- Conductive traces and integrated heaters can be fabricated on silicon
- Weak thermal links can utilize integrated thin SiN films

# 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

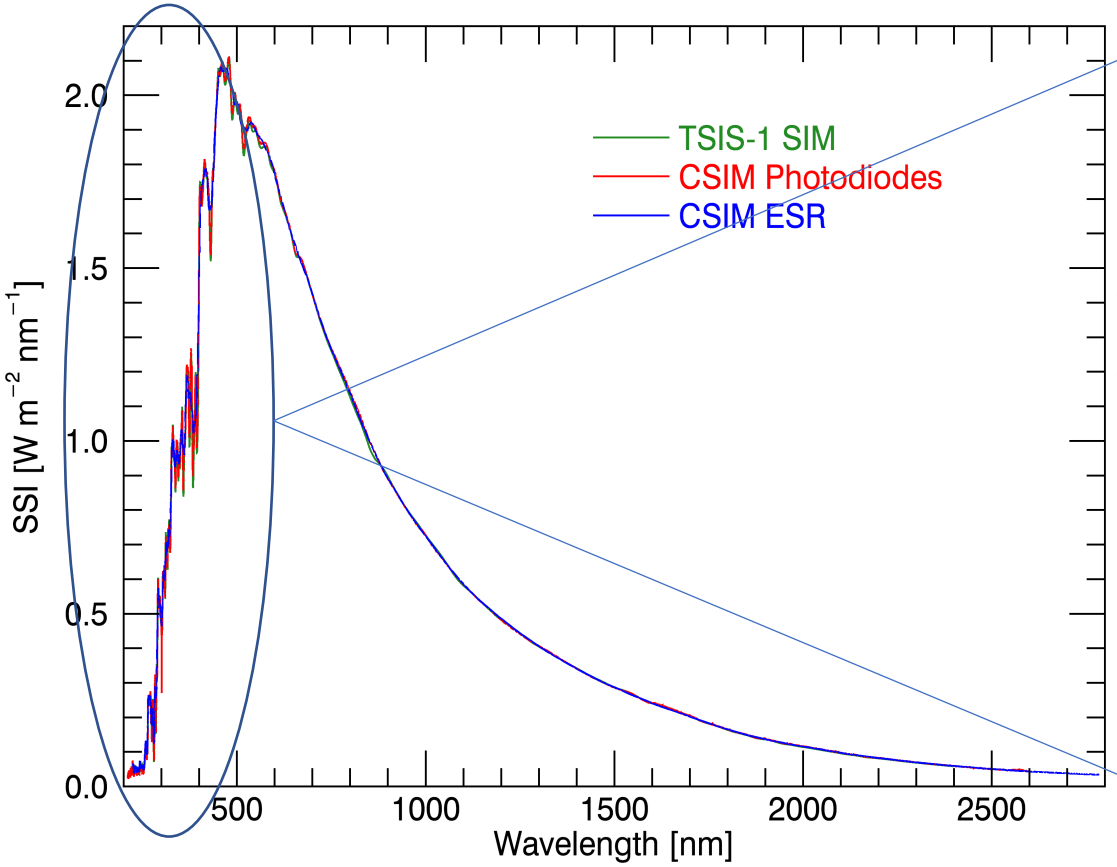


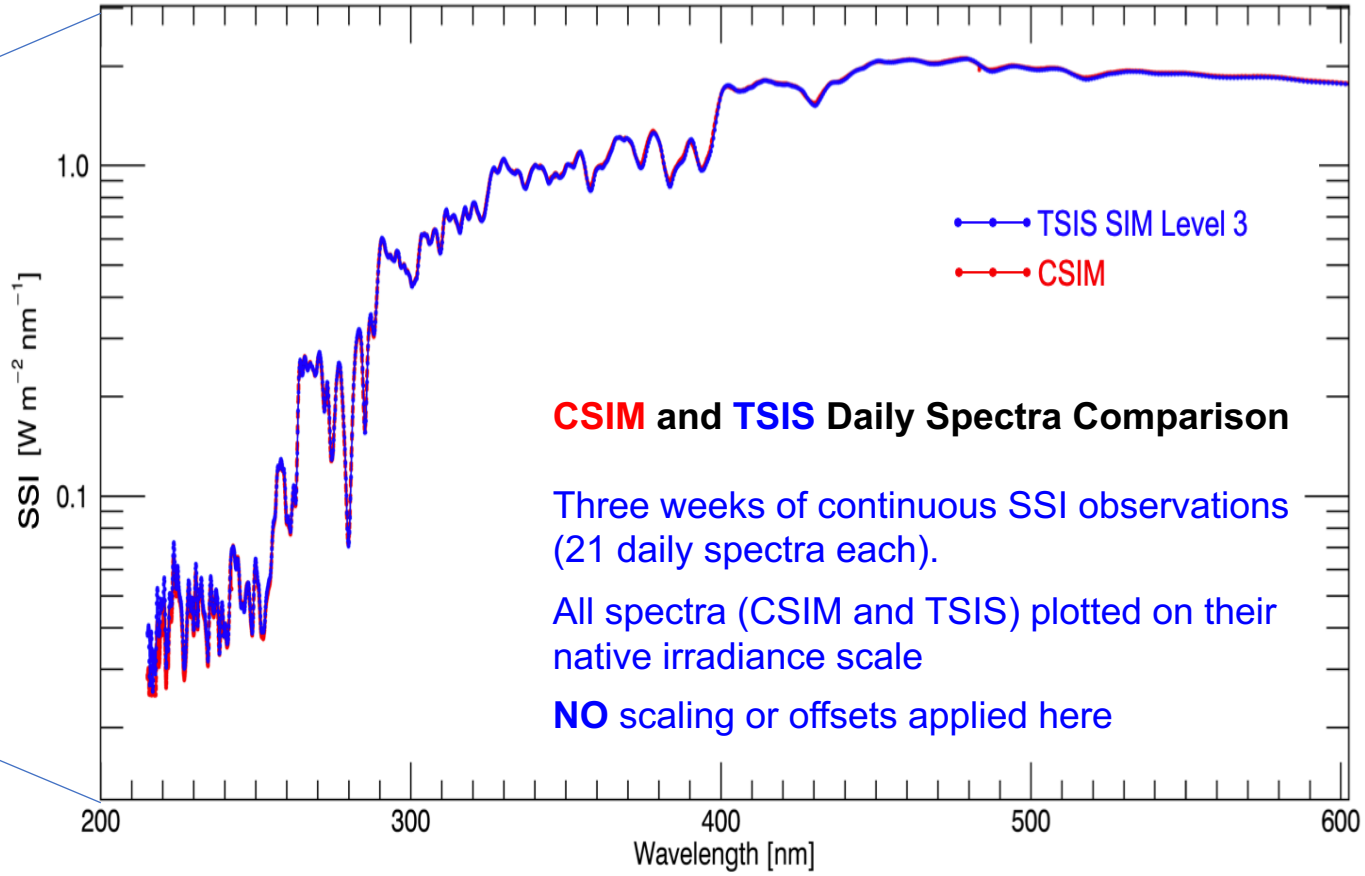
TSIS-1 SIM ($$$)



CSIM 6U CubeSat ($)

Equal




**CSIM and TSIS Daily Spectra Comparison**

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

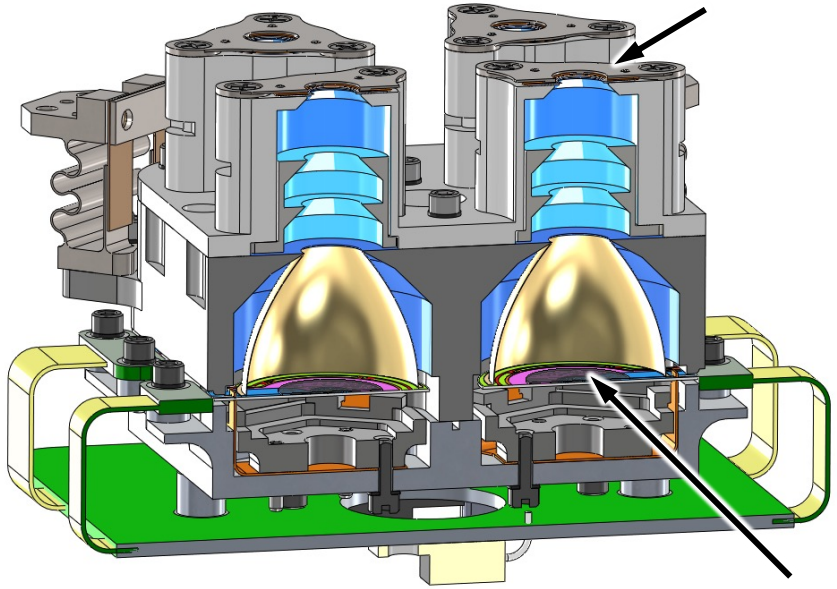
# CTIM-FD IIP: Compact Total Irradiance Monitor

## ”Next Generation” TSI Monitor

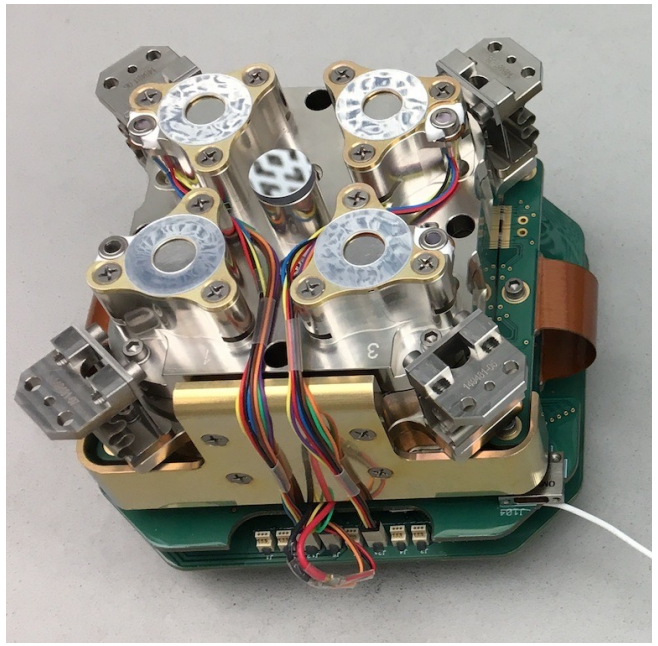
PI: Dave Harber

## CTIM Detector Head

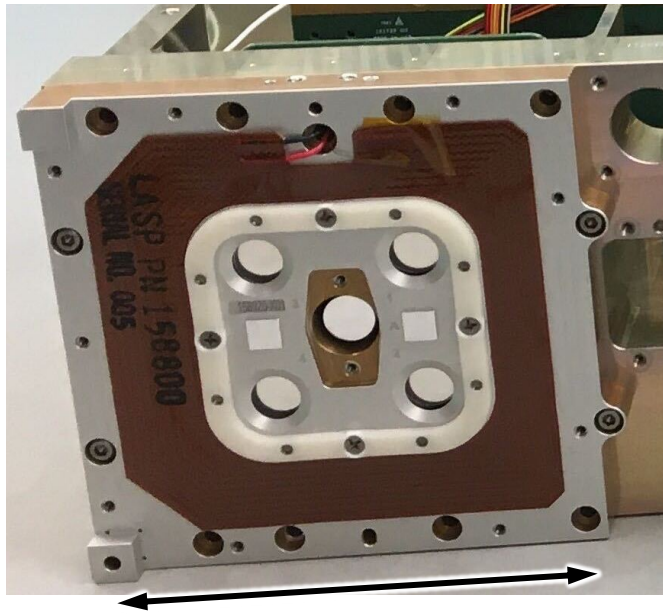
- Each detector head has four channels
  - Redundant channel degradation tracking
- Shutter for each channel



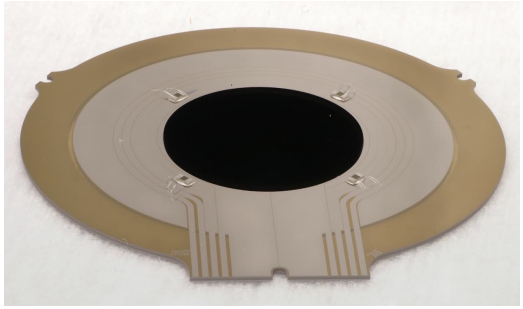
Integrated Detector Head



CTIM Detector Head



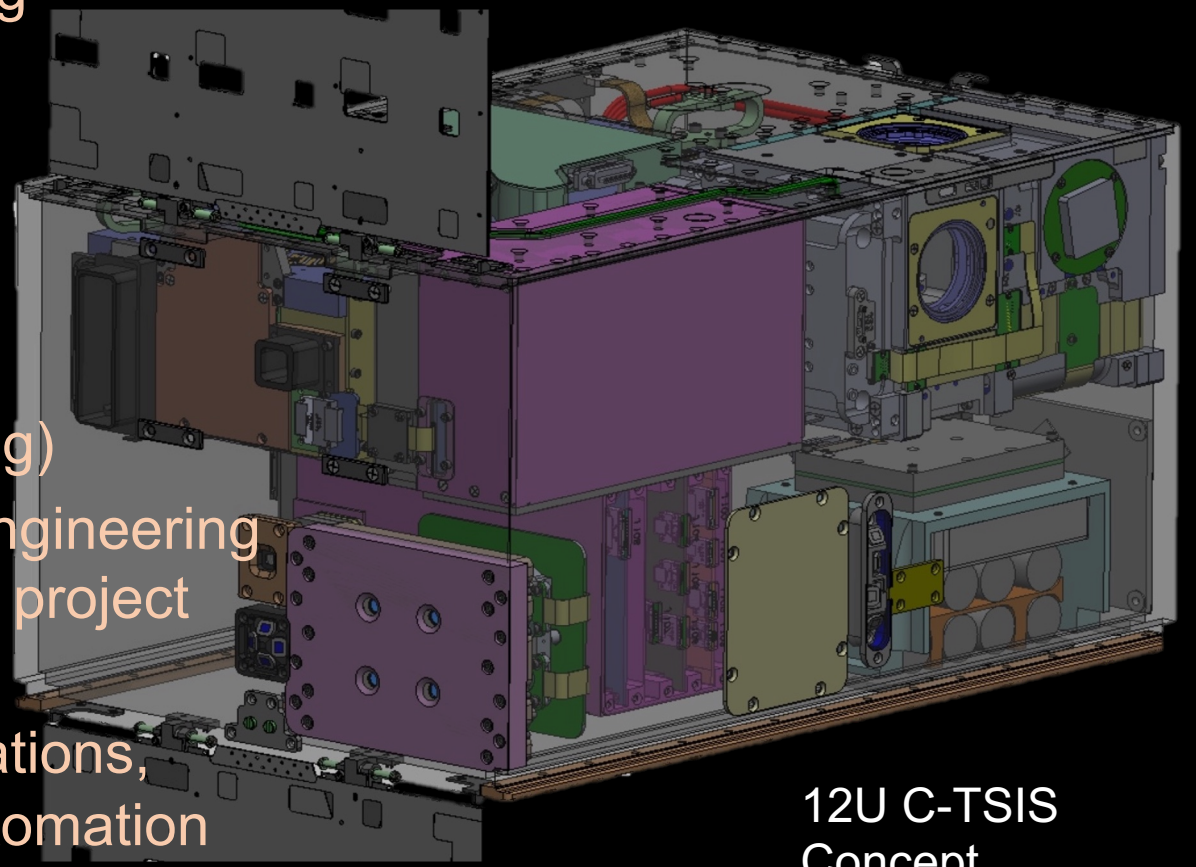

Key new technology: Silicon + Vertically Aligned Carbon Nanotubes



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

# C-TSIS Mission Demonstration

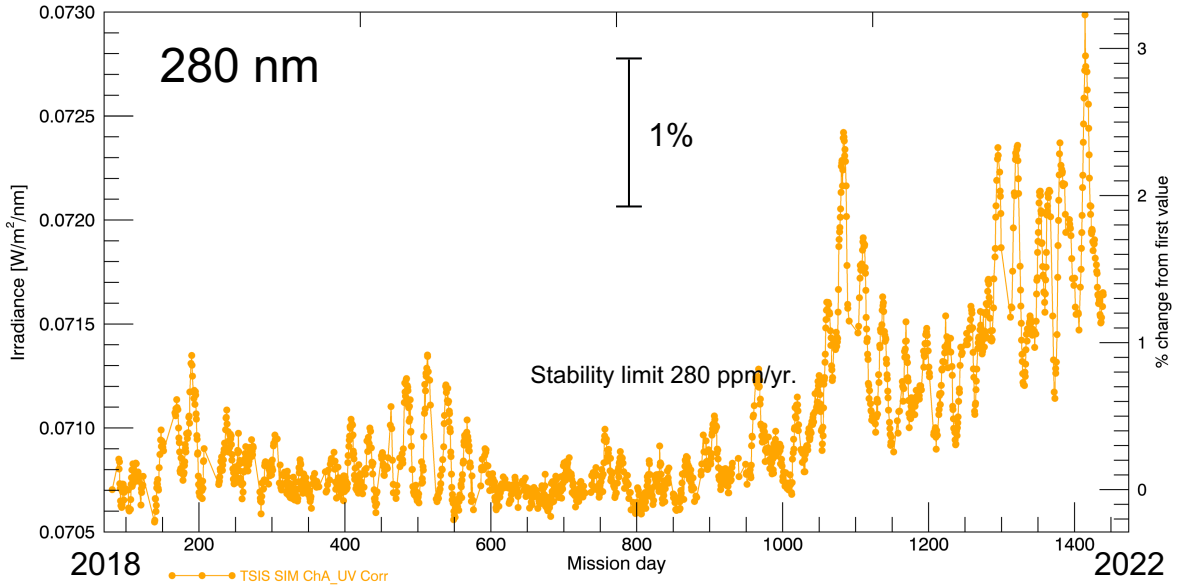
- Demonstration that CSIM and CTIM can fully meet TSIS requirements in accuracy, stability, and reporting
  - Provide a 6 month overlap with TSIS-2
- Upgrade CSIM to a 3 channel instrument
- CTIM 1 Detector head (4 channels)
- Extend LASP 6U CubeSat design to 12U
- Improve parts reliability (Screening, 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

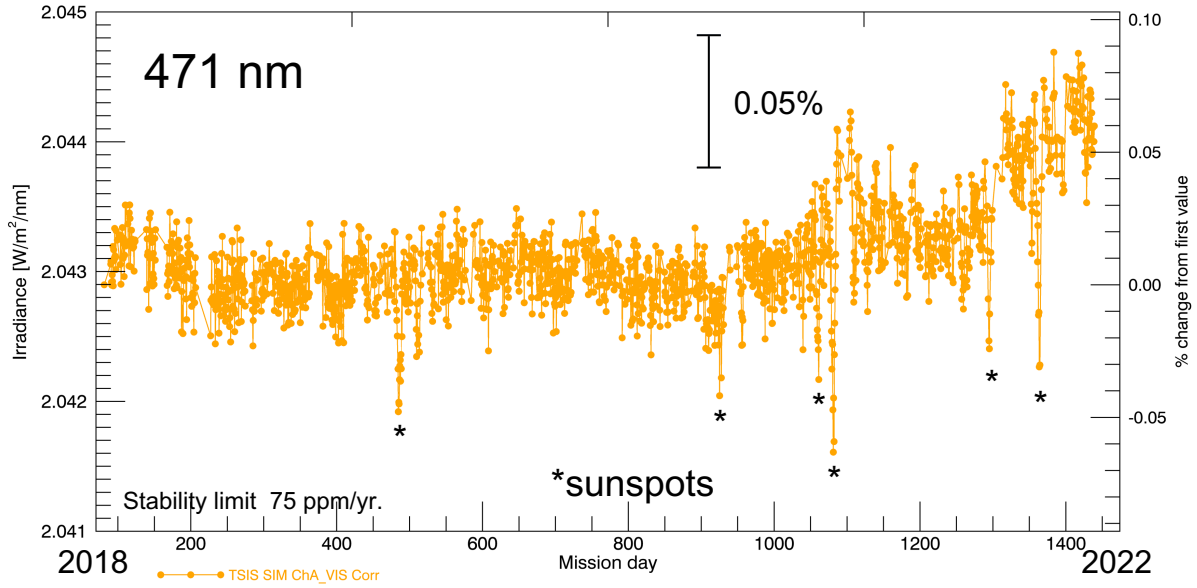


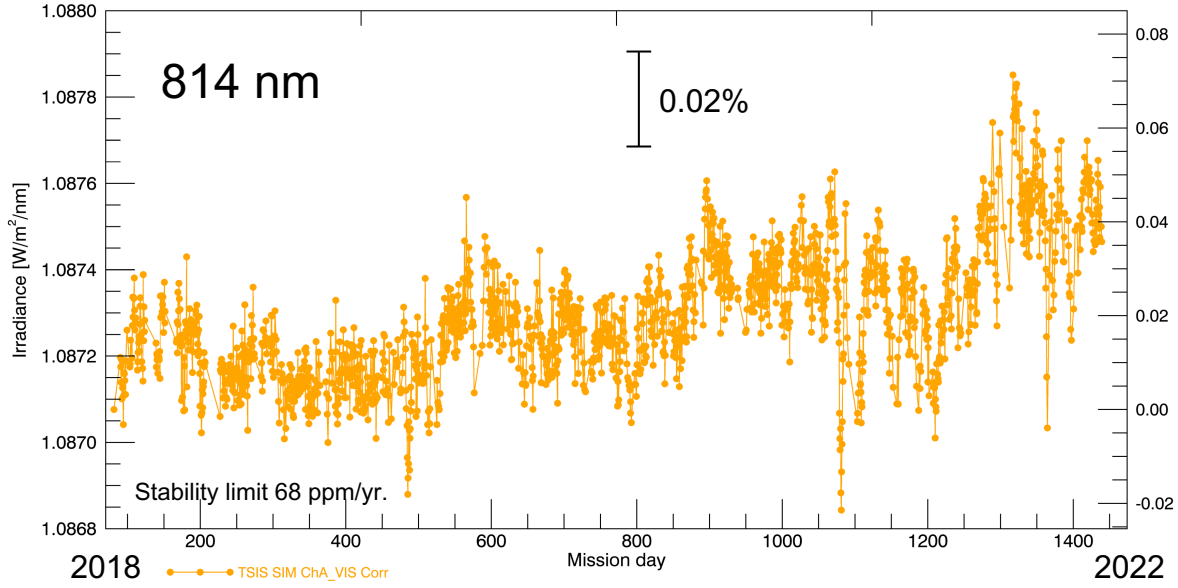
12U C-TSIS Concept (for Constellation)

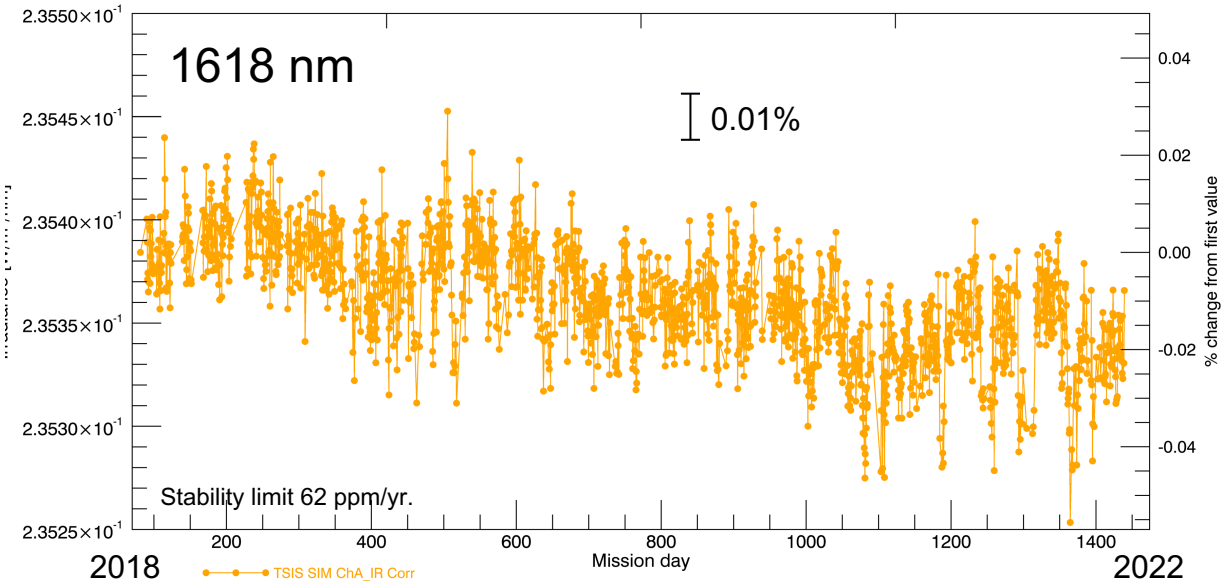
# Back up Slides

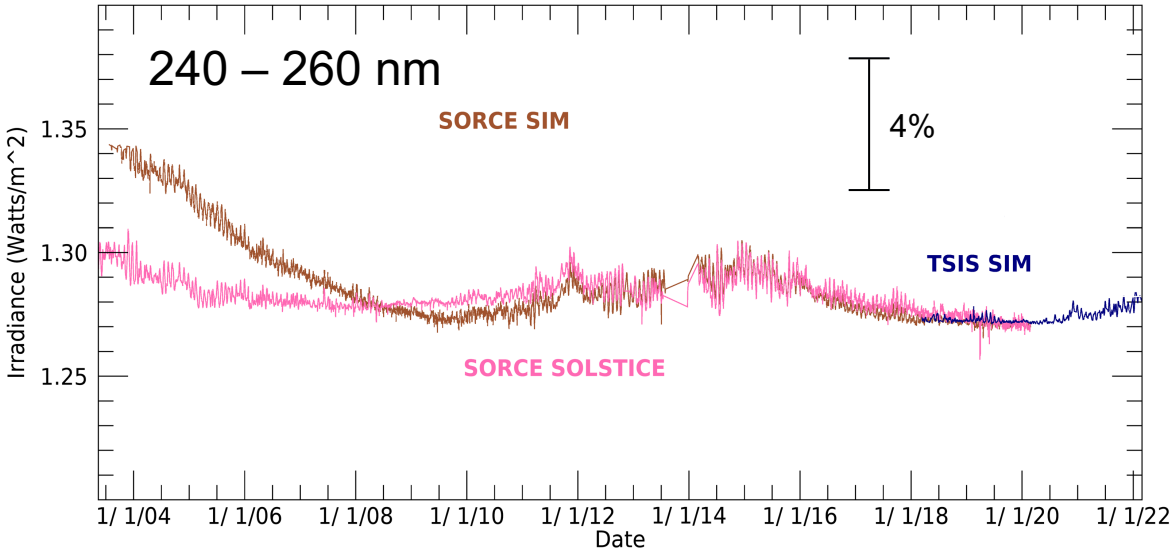
# TSIS-1 SIM SSI Time Series (4 years)

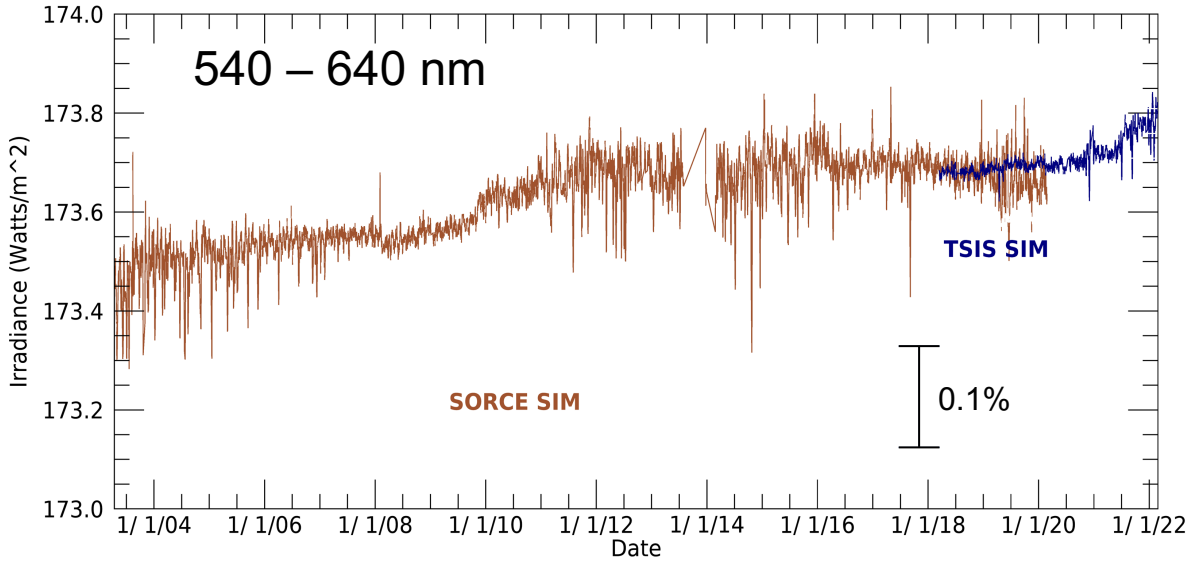


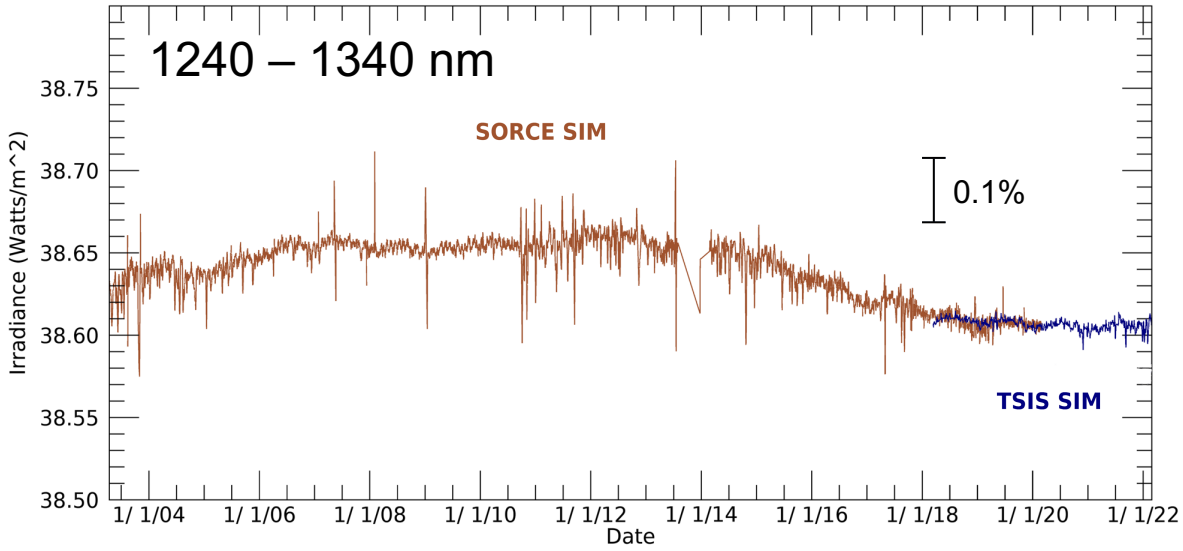



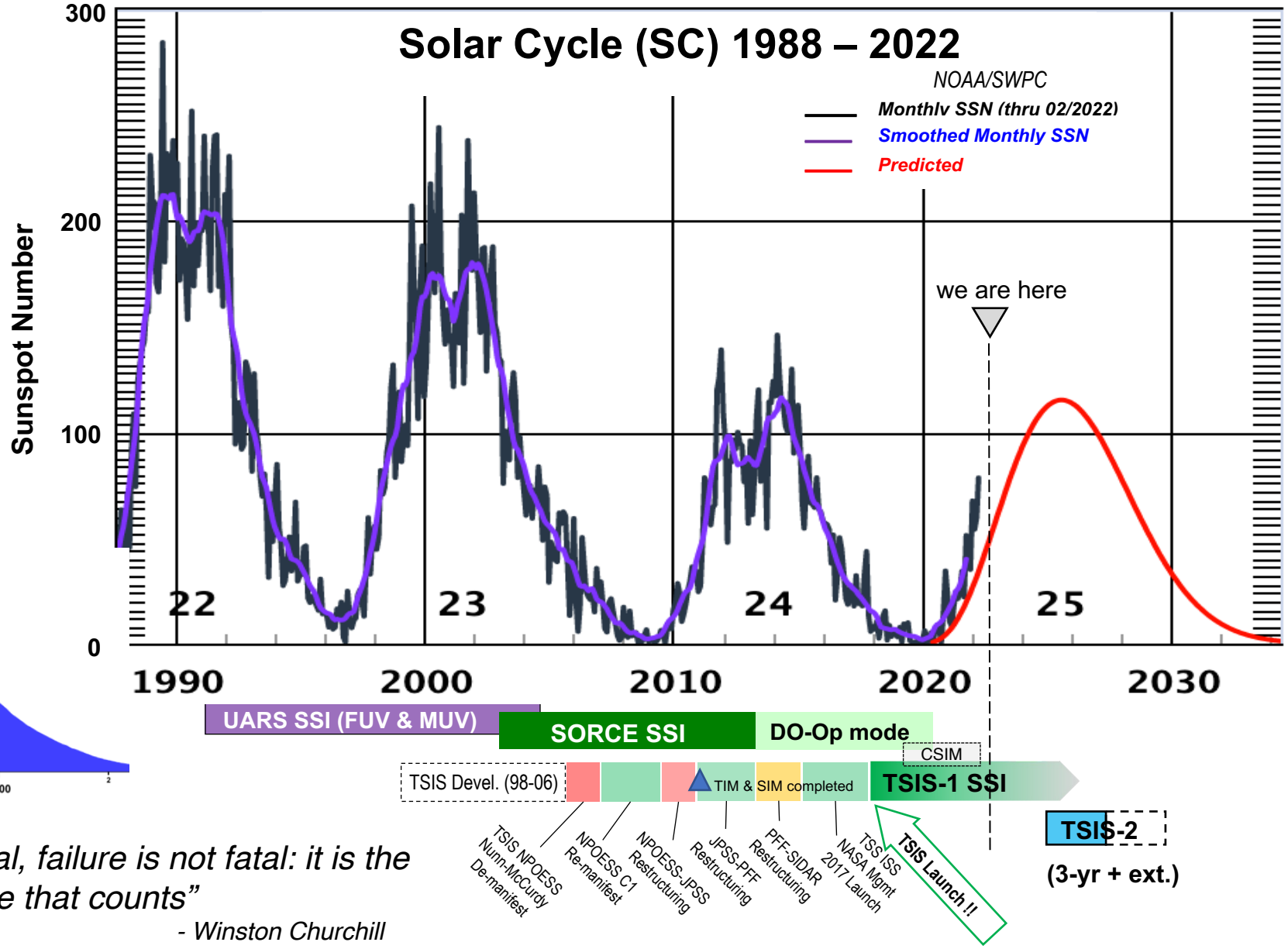



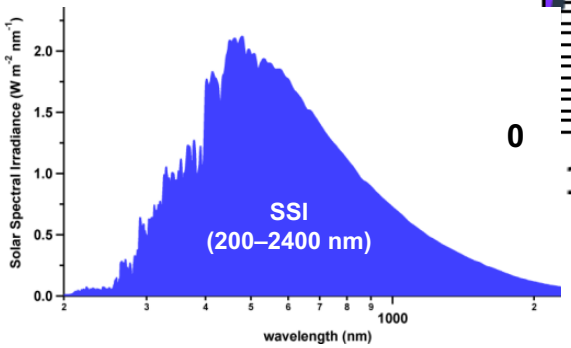

240 – 260 nm
SORCE SIM
4%
TSIS SIM
SORCE SOLSTICE
Irradiance (Watts/m^2)
1.35
1.30
1.25
1/ 1/04
1/ 1/06
1/ 1/08
1/ 1/10
1/ 1/12
1/ 1/14
1/ 1/16
1/ 1/18
1/ 1/20
1/ 1/22
Date


540 – 640 nm
TSIS SIM
SORCE SIM
0.1%
Irradiance (Watts/m^2)
174.0
173.8
173.6
173.4
173.2
173.0
1/ 1/04
1/ 1/06
1/ 1/08
1/ 1/10
1/ 1/12
1/ 1/14
1/ 1/16
1/ 1/18
1/ 1/20
1/ 1/22
Date


1240 – 1340 nm
SORCE SIM
0.1%
TSIS SIM
Irradiance (Watts/m^2)
38.75
38.70
38.65
38.60
38.55
38.50
1/ 1/04
1/ 1/06
1/ 1/08
1/ 1/10
1/ 1/12
1/ 1/14
1/ 1/16
1/ 1/18
1/ 1/20
1/ 1/22
Date

# After a full solar cycle of delays – the TSIS era begins

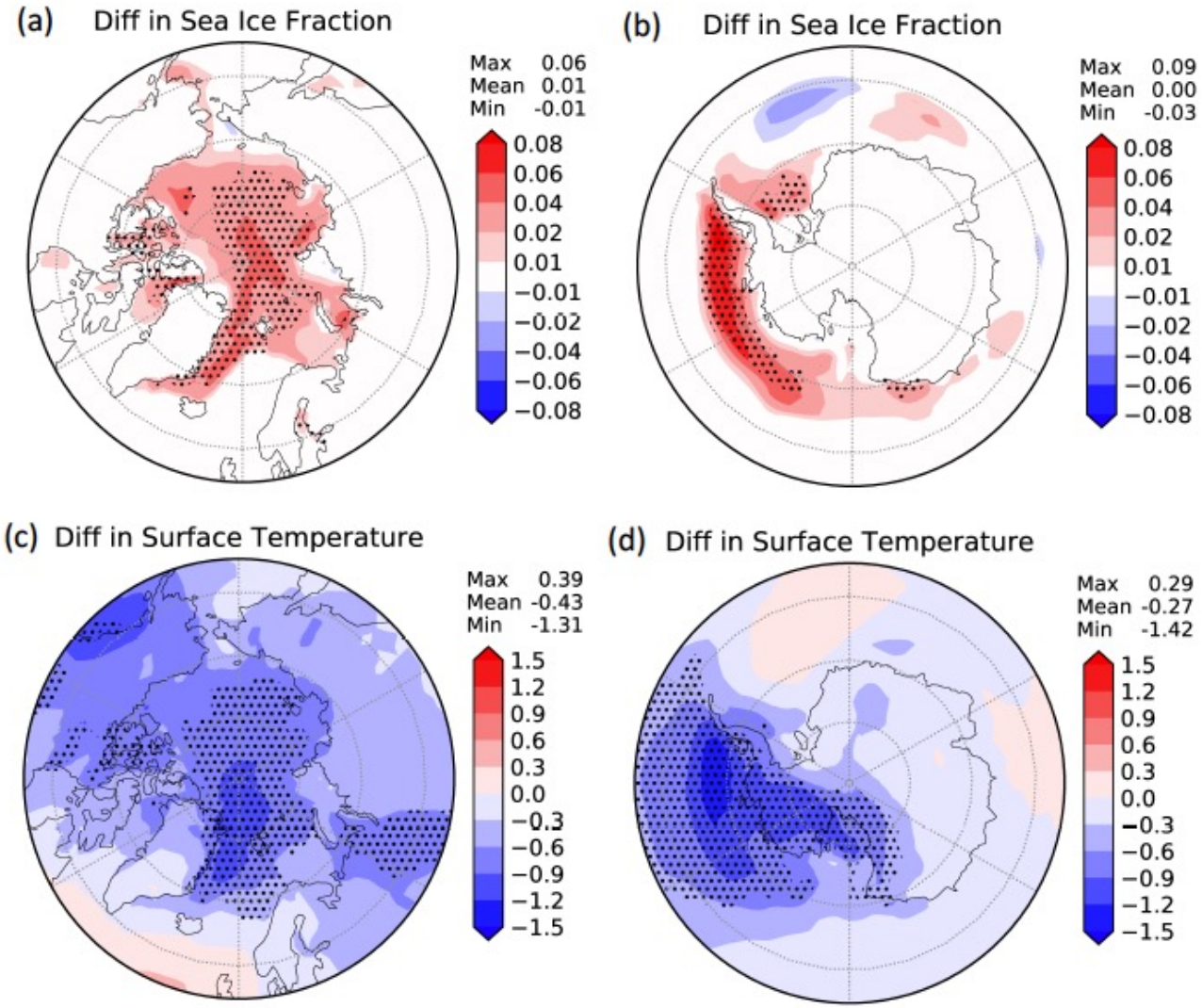



*"Success is not final, failure is not fatal: it is the courage to continue that counts"*

*- Winston Churchill*

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

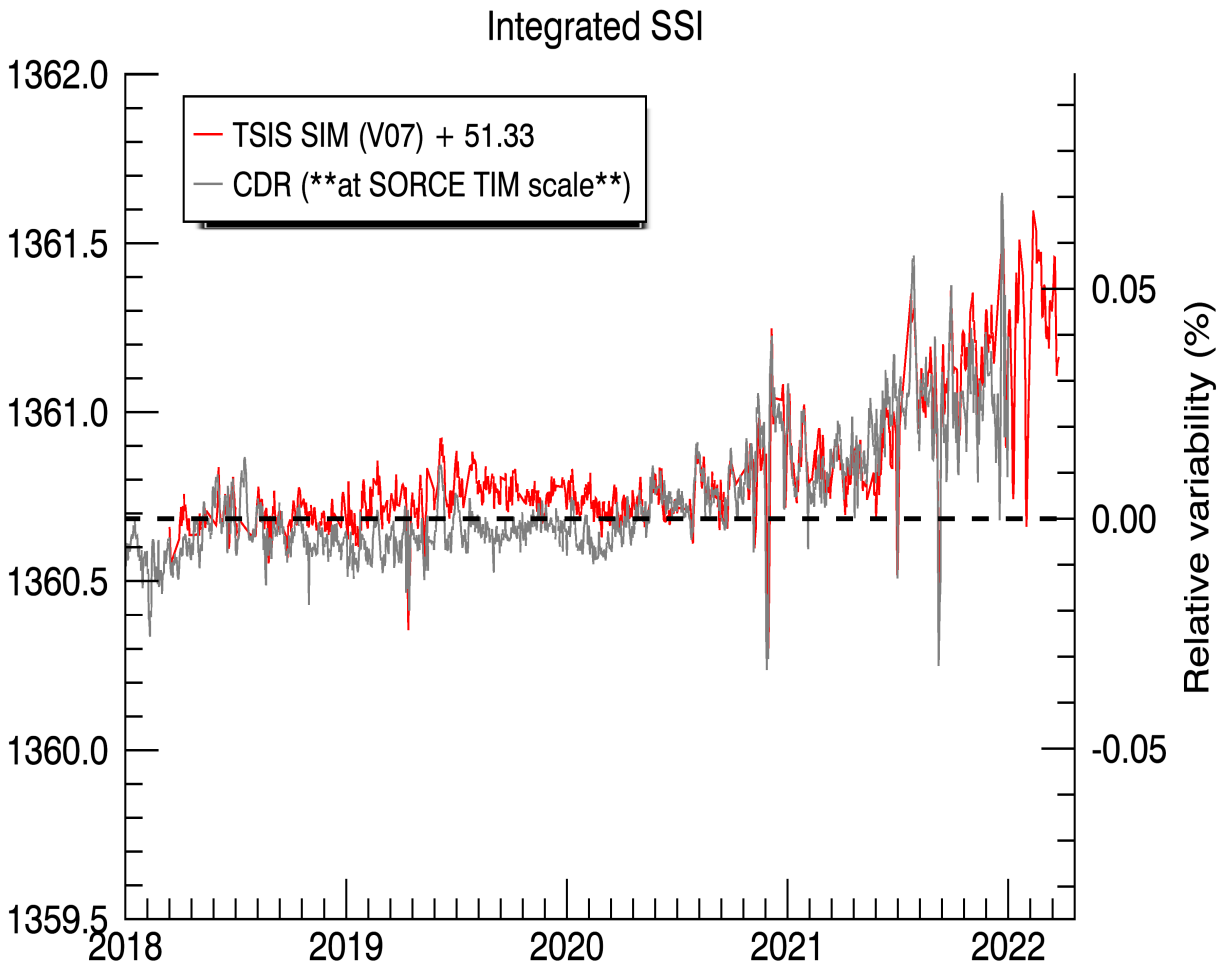


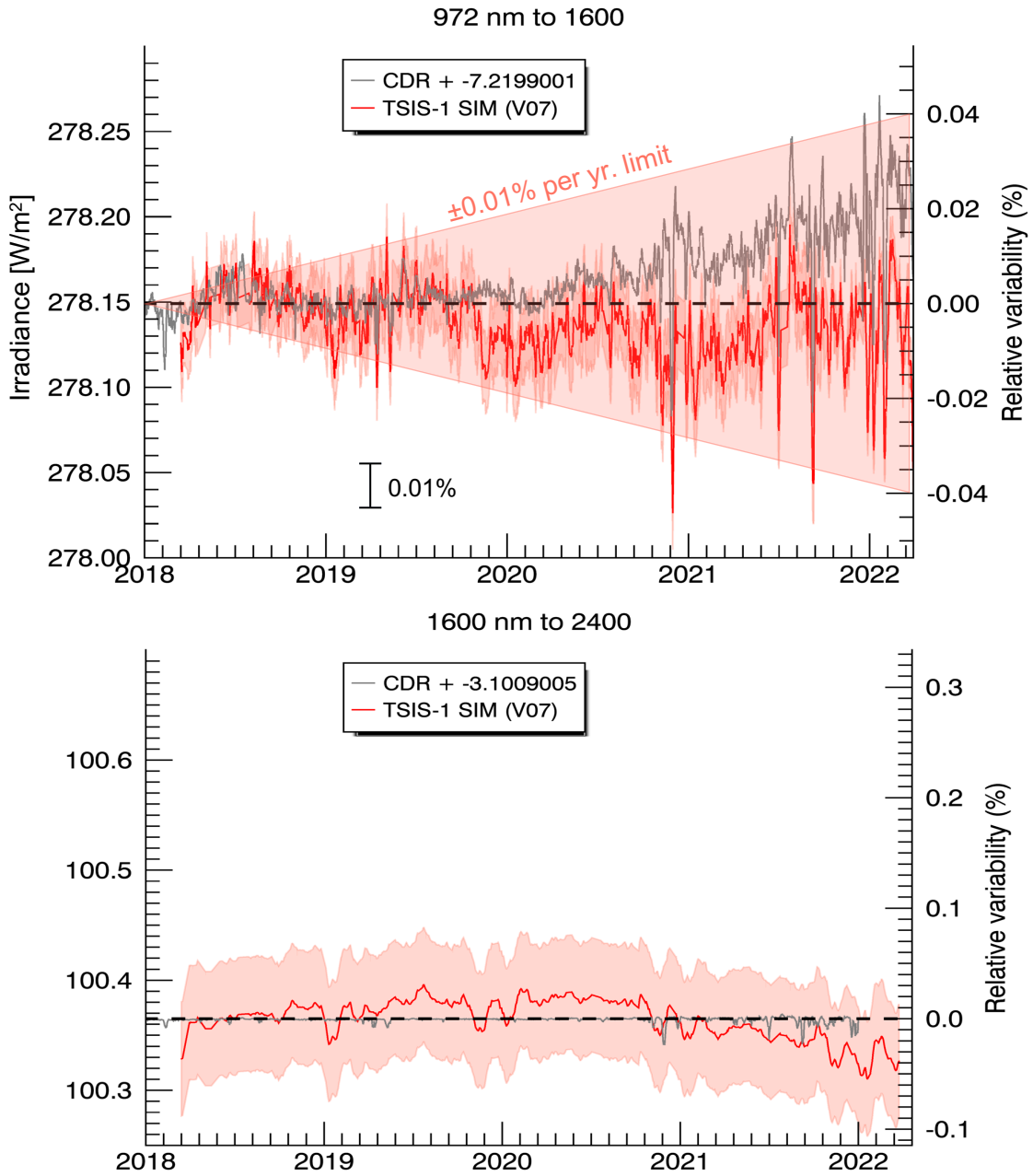

## NCAR CESM2 Simulations

**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.

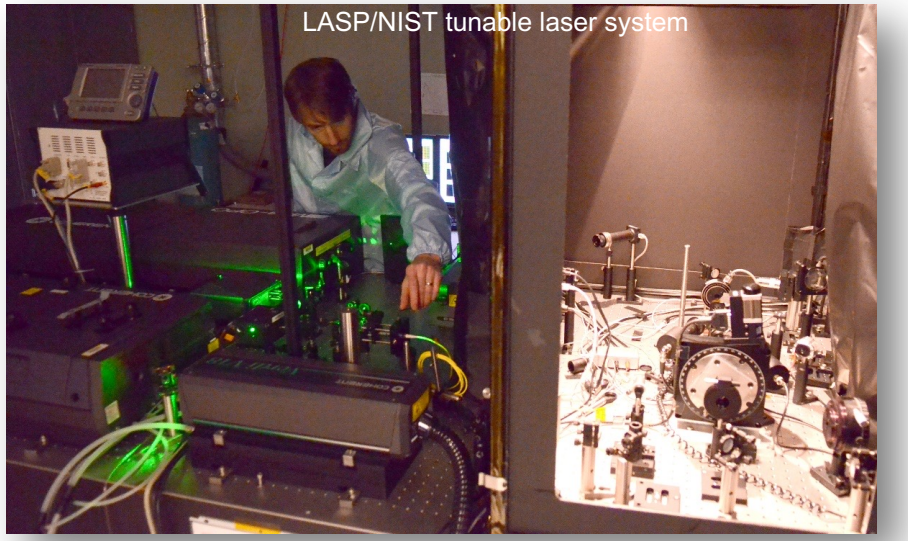
(Jing, et al., *Journal of Climate,* 2021)


Integrated SSI
TSIS SIM (V07) + 51.33
CDR (**at SORCE TIM scale**)
1362.0
1361.5
1361.0
1360.5
1360.0
1359.5
2018
2019
2020
2021
2022
0.05
0.00
-0.05
Relative variability (%)

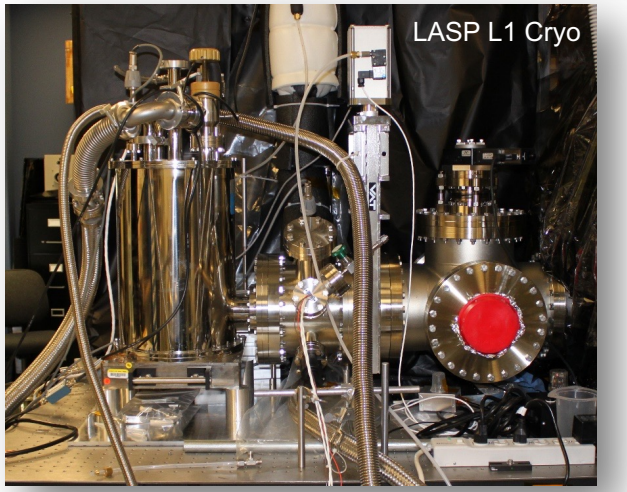

972 nm to 1600
CDR + -7.2199001
TSIS-1 SIM (V07)
±0.01% per yr. limit
0.01%
Irradiance [W/m²]
278.25
278.20
278.15
278.10
278.05
278.00
2018
2019
2020
2021
2022
0.04
0.02
0.00
-0.02
-0.04
Relative variability (%)
1600 nm to 2400
CDR + -3.1009005
TSIS-1 SIM (V07)
100.6
100.5
100.4
100.3
0.3
0.2
0.1
0.0
-0.1
Relative variability (%)

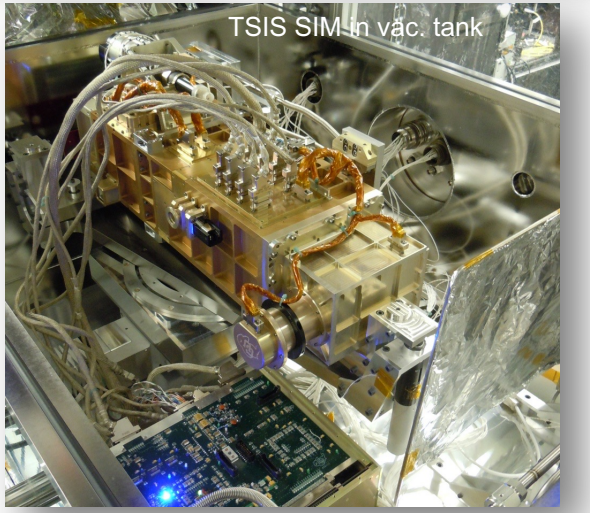
# Advances in Absolute Accuracy in Spectral Irradiance

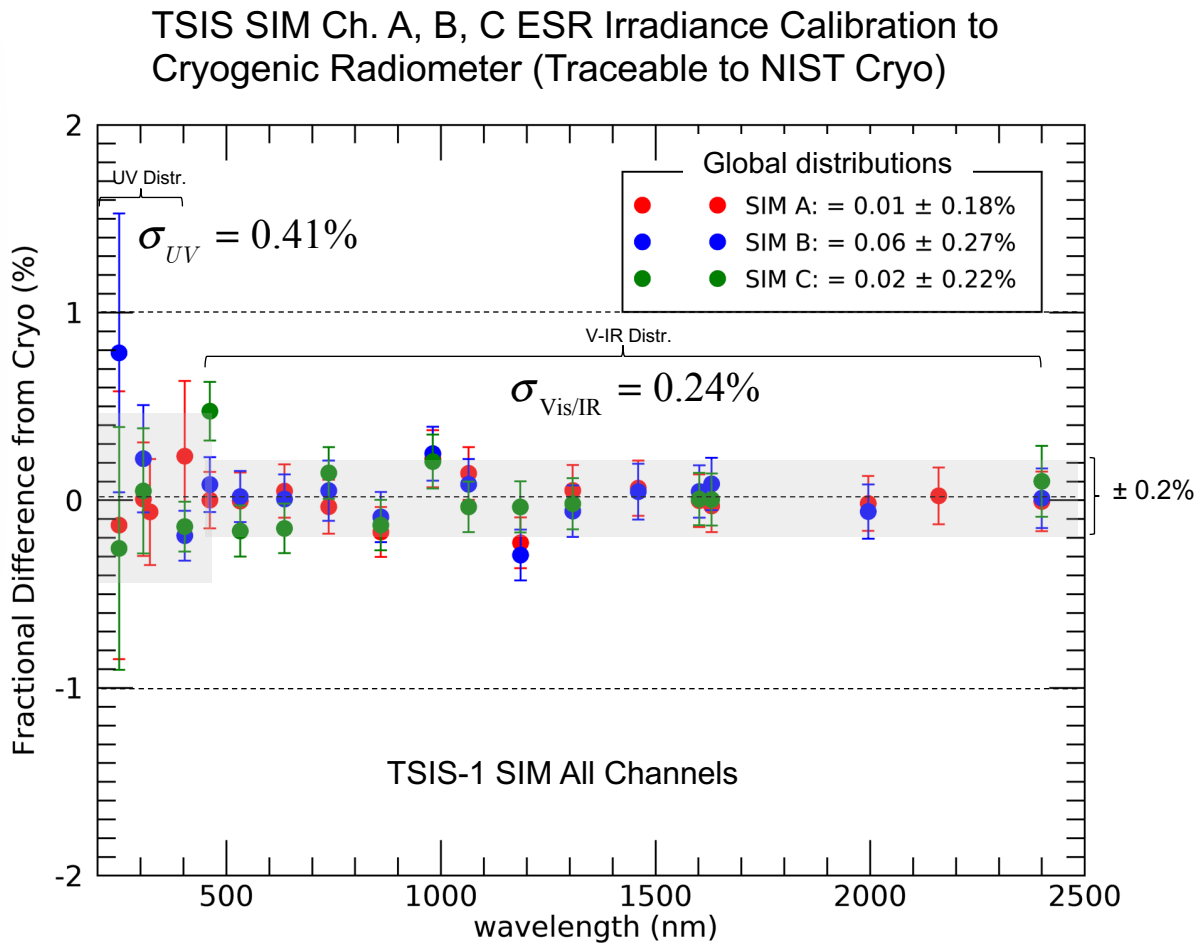
## Final full spectrum calibration of irradiance tied to NIST-traceable cryogenic radiometer





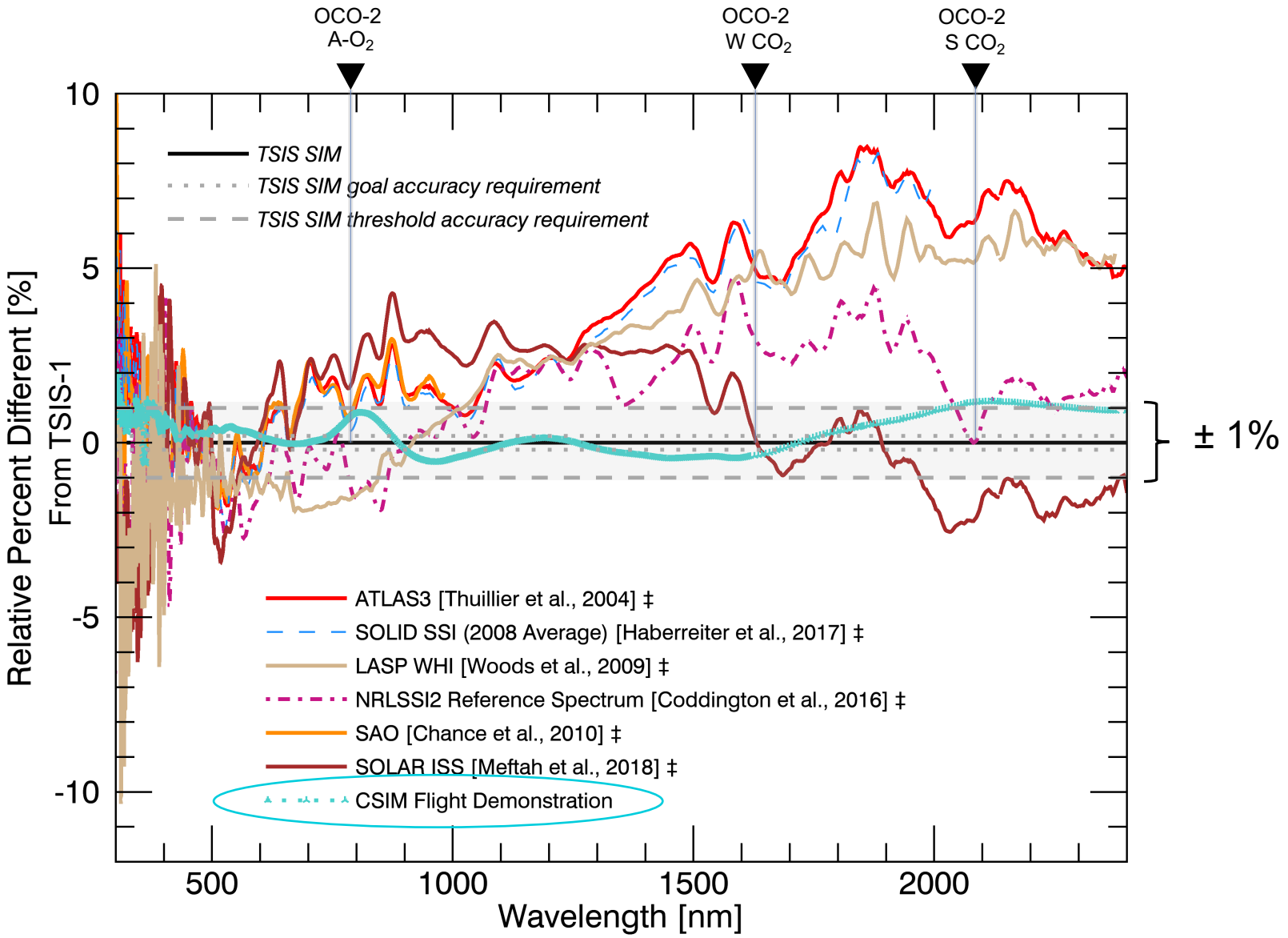



✓ *Past absolute uncertainty of spectral irradiance measurements is ~2% and recent developments during the TSIS SIM project have achieved factor of 10 improvement ~0.2% (Richard et al., 2011; Harber et al., 2013).*

# Reference Spectra Spectral Differences




*All data sets (except CSIM) have been convolved to the TSIS-1 SIM spectral resolution

# 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/].