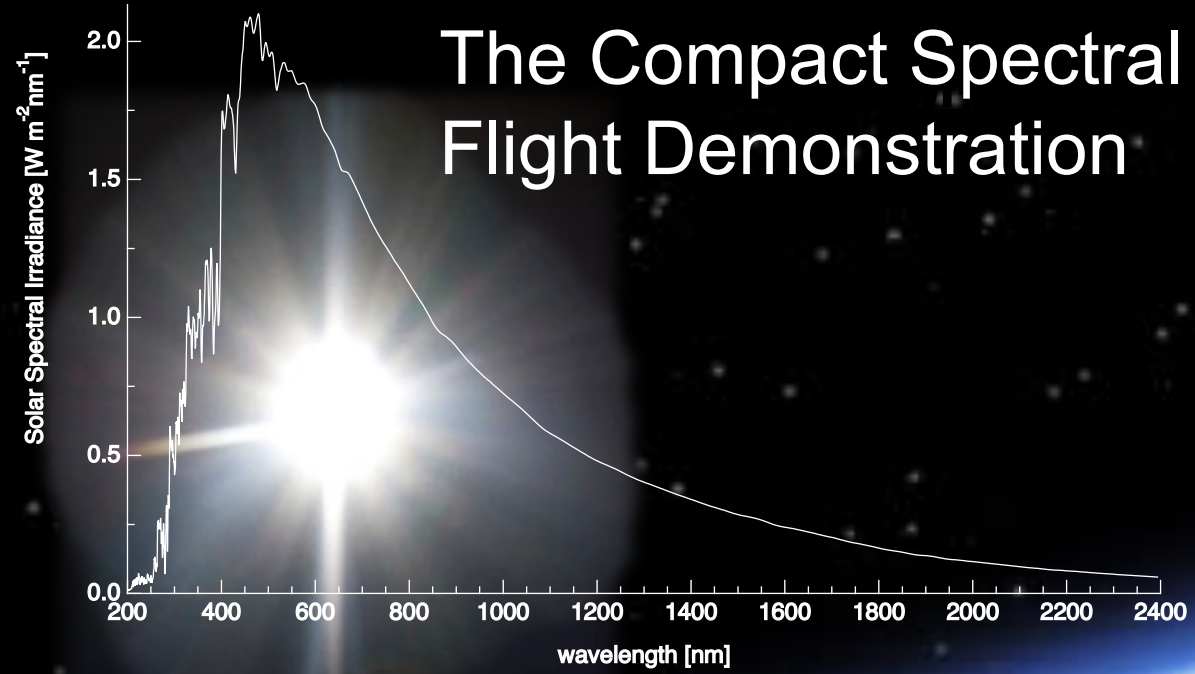
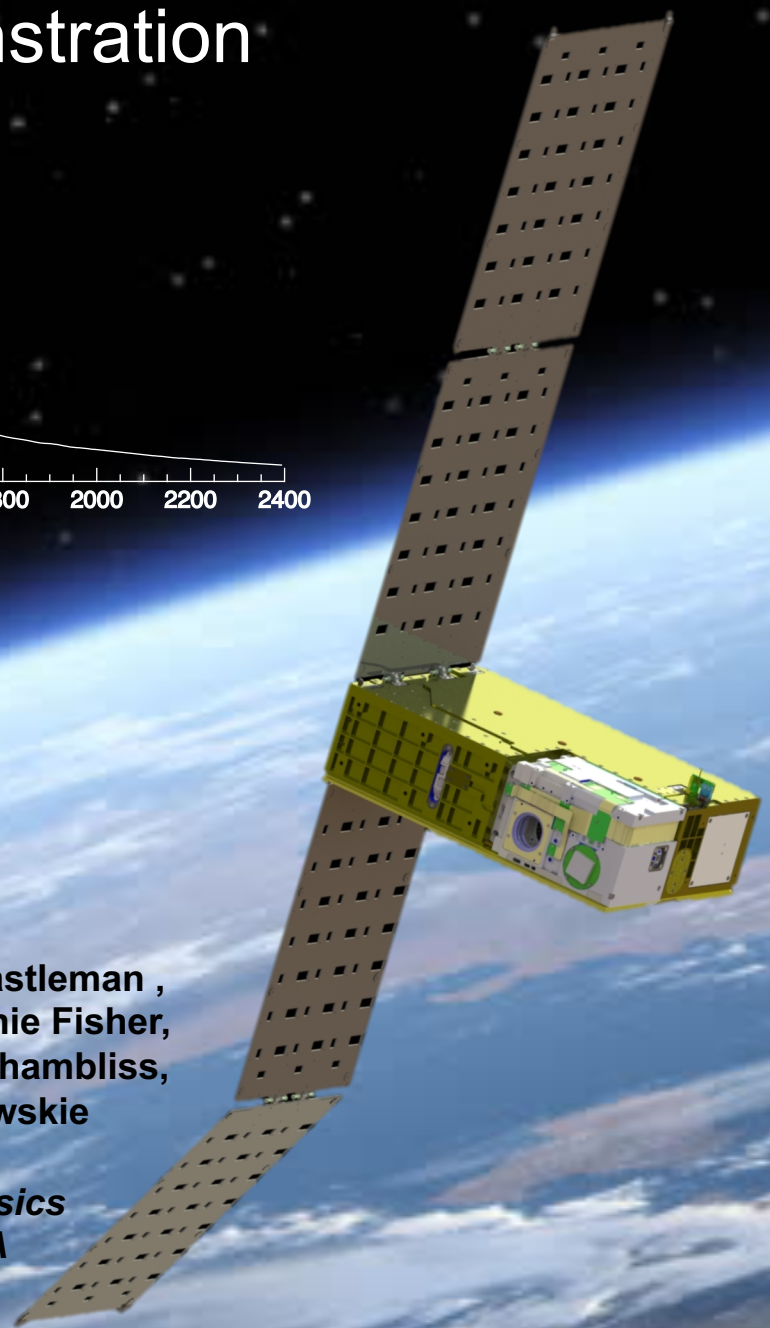
The Compact Spectral Irradiance Monitor Flight Demonstration





Erik Richard, Dave Harber, Ginger Drake, Zach Castleman , Joel Rutkowski, Maxwell Fowle, Marc Miller, Melanie Fisher, Alan Sims, Jacob Sprunck, Paul Smith, Michael Chambliss, Wengang Zheng, Tom Woods, and Peter Pilewskie

Laboratory for Atmospheric and Space Physics
University of Colorado, Boulder, CO USA

Atmospheric absorption

Photochemistry

EUV (Ionosphere)

$N_2 + hn\ (l < 80nm) \rightarrow N_2^+ + e^-$

$O_2 + hn\ (l < 103nm) \rightarrow O_2^+ + e^-$

$O + hn\ (l < 92nm) \rightarrow O^+ + e^-$

FUV (Ozone creation)

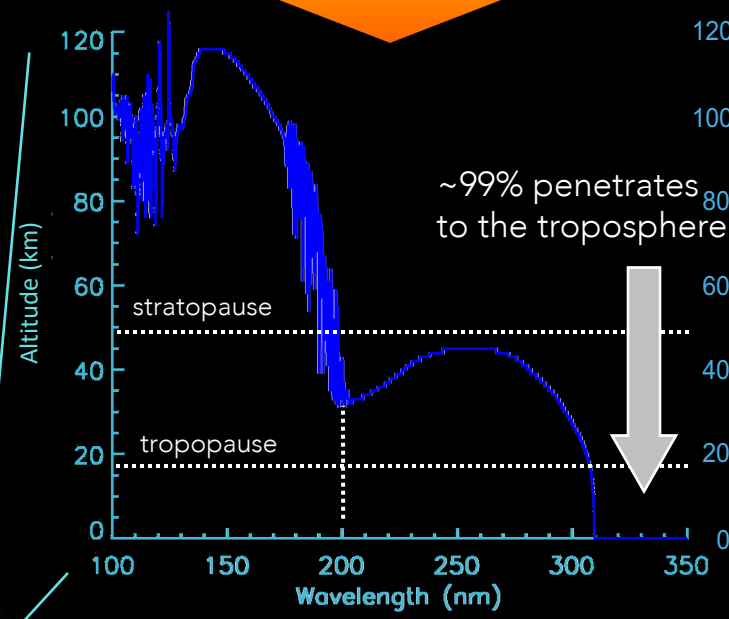
$O_2 + hn\ (l < 242nm) \rightarrow O + O$

$O + O_2\ (+M) \rightarrow O_3$

MUV (Ozone Destruction)

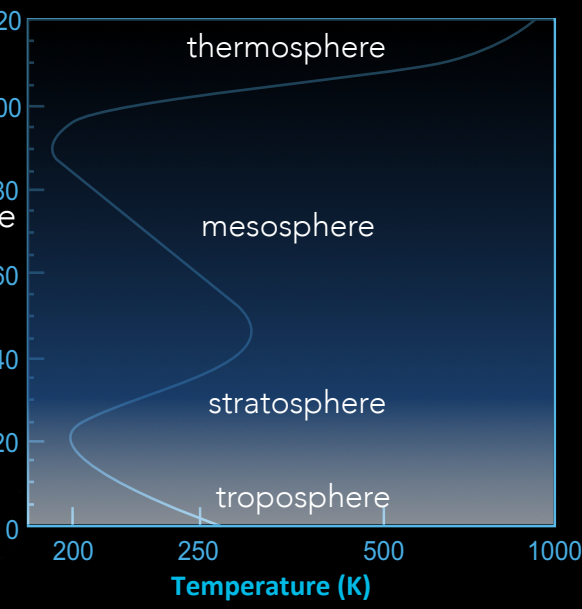
$O_3 + hn\ (l < 310nm) \rightarrow O_2 + O$

Solar Input



~99% penetrates to the troposphere

Heating



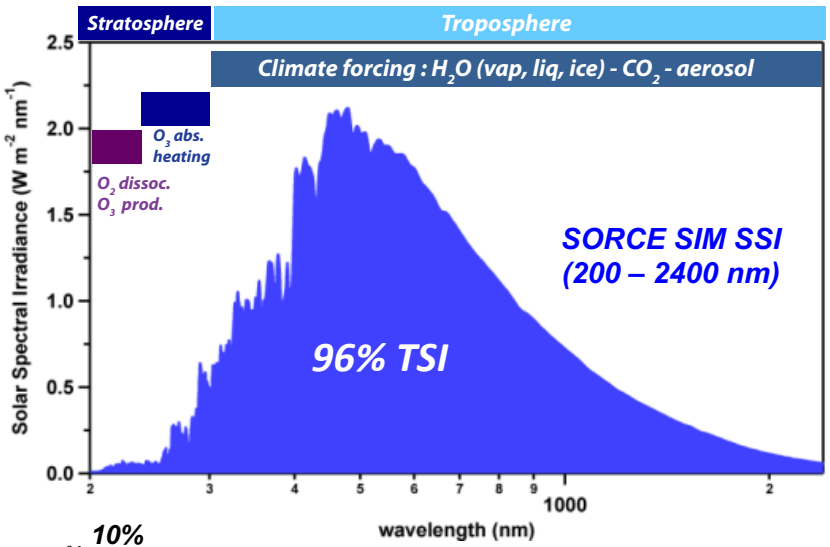
$l < 120$ nm	$= 0.003 \pm 0.001\ Wm^{-2}$		0.0002%
$120 \le l < 300$	$= 14.9 \pm 0.1\ Wm^{-2}$		~1%
$l \ge 300$	$= 1346 \pm 0.5\ Wm^{-2}$		99%

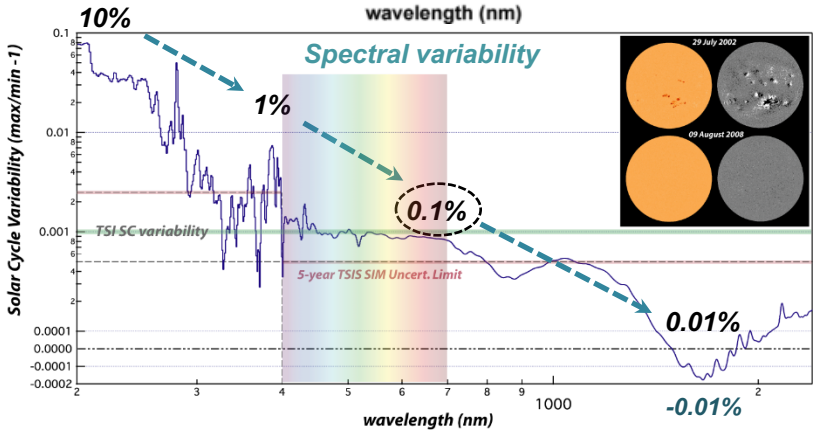
Vis-IR

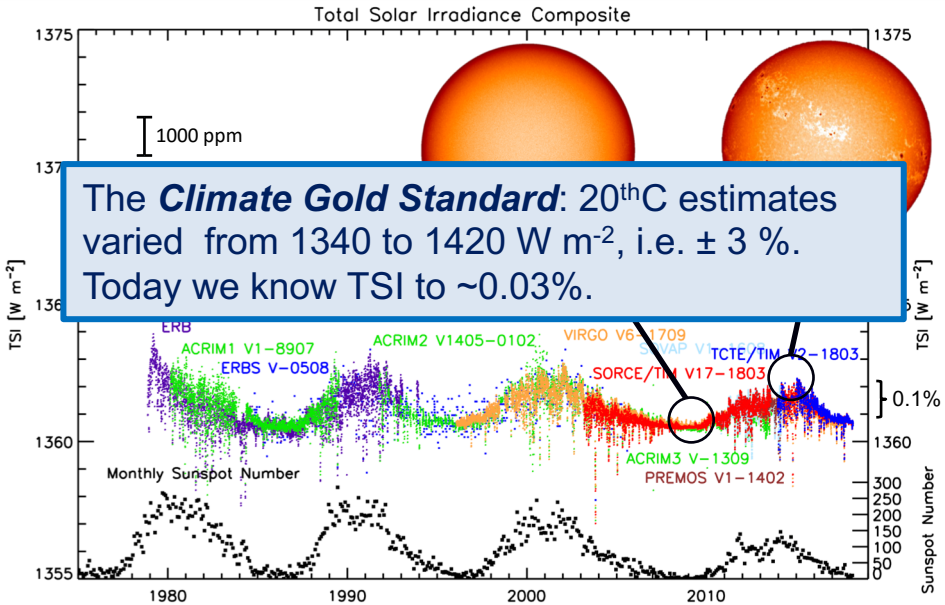
H_2O, CO_2, aerosol,

Land – Ice – Ocean

Solar Spectral Irradiance Variability







The ***Climate Gold Standard***: 20thC estimates varied from 1340 to 1420 W m^{-2}, i.e. ± 3 %. Today we know TSI to ~0.03%.

The measurement of TSI alone provides no information about the spectral content of the solar irradiance variability

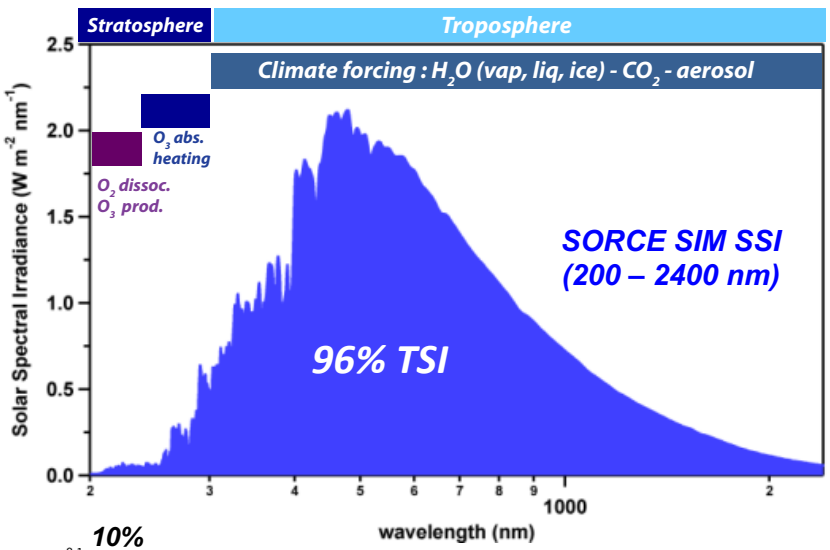
The measurement of SSI is vital for understanding how solar variability impacts climate and for validating climate model sensitivity to spectrally varying solar forcing

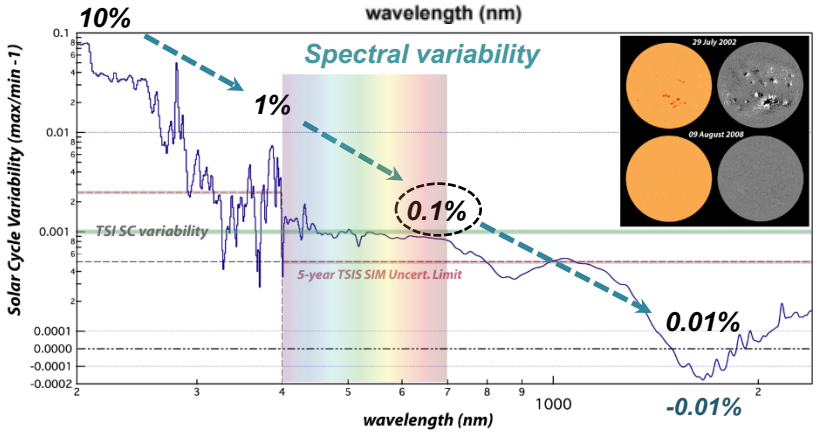
- ***Process studies seek to quantify mechanisms by which the Earth system responds to various forcings***
- ***Requires measurement of wavelength-dependent irradiance variability.***

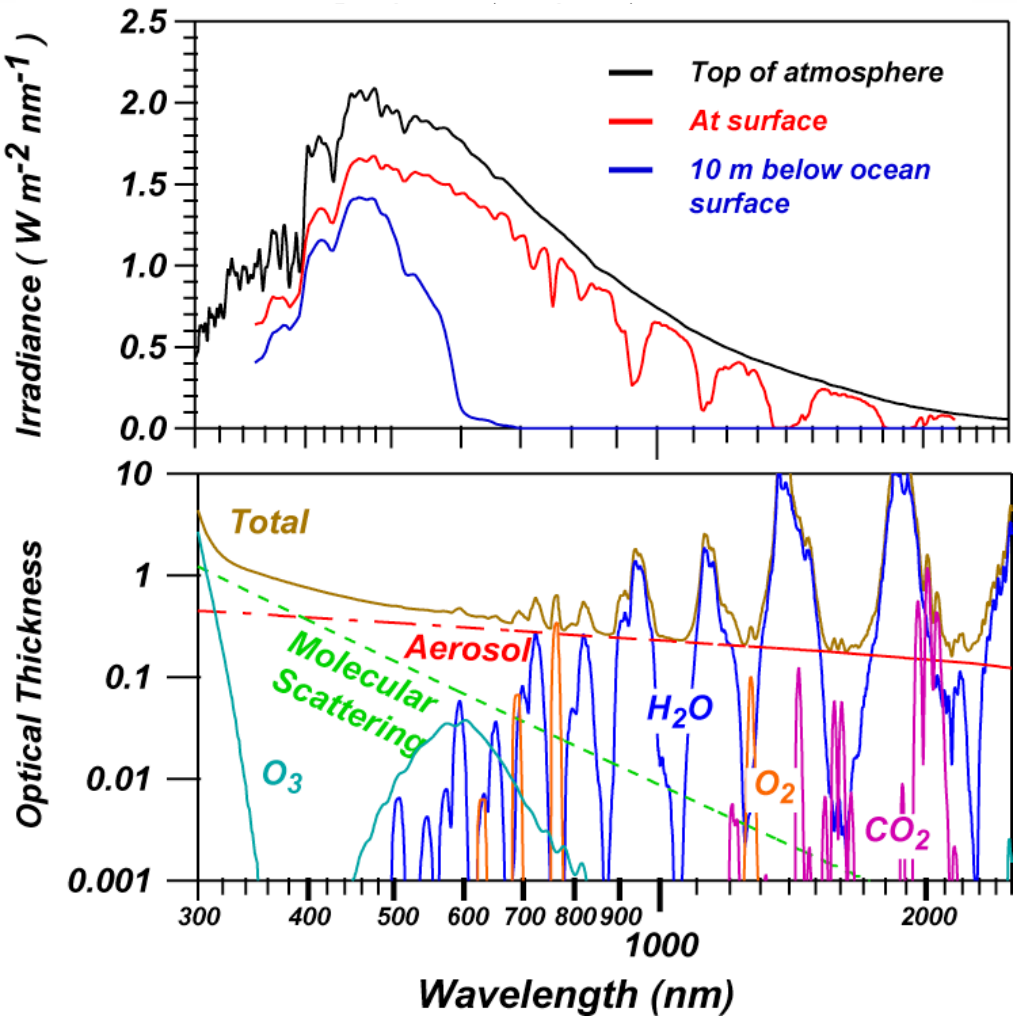
"Acquire SSI and TSI time series of measurements of sufficient length, consistency, and continuity to determine climate variability and change"

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

Solar Spectral Irradiance Variability







"Acquire SSI and TSI time series of measurements of sufficient length, consistency, and <u>continuity</u> to determine climate variability and change"

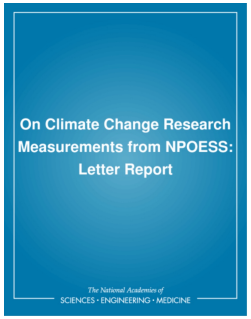
Climate Data Records from Environmental Satellites: Interim Report (2004)

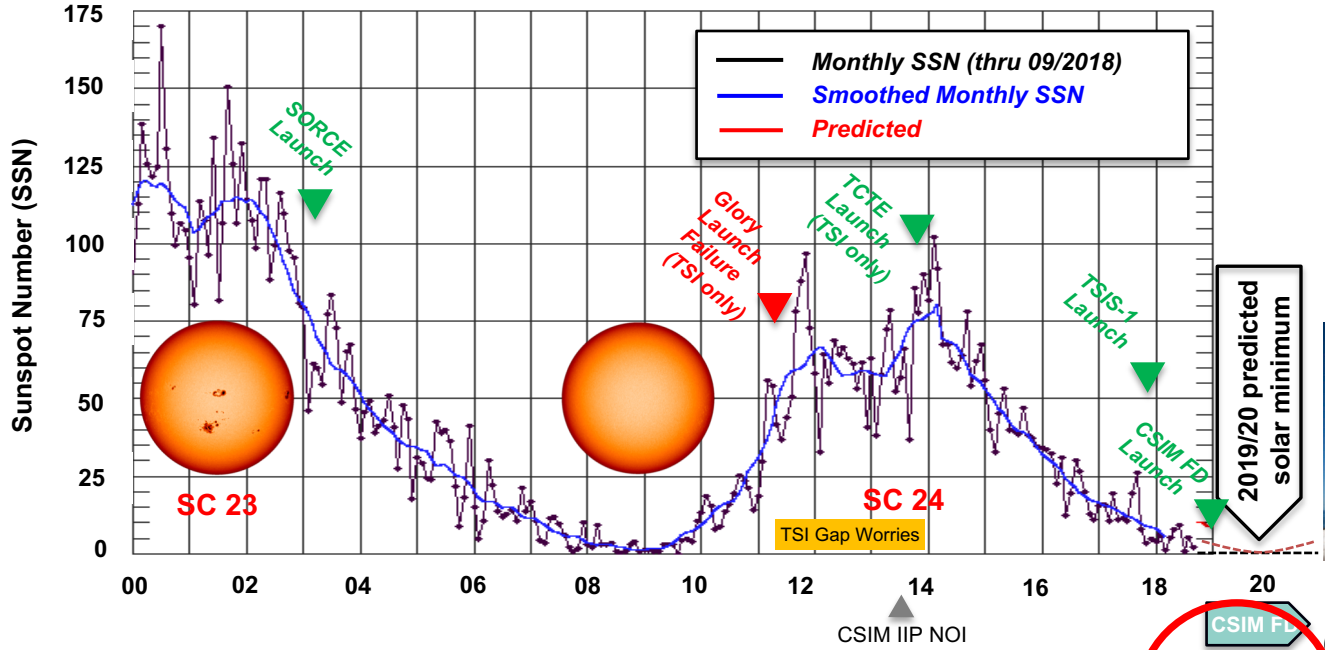
Solar Irradiance Continuity
(… or nearly lack thereof)

Solar Cycle (SC) 2000 – 2020

NOAA/SWPC

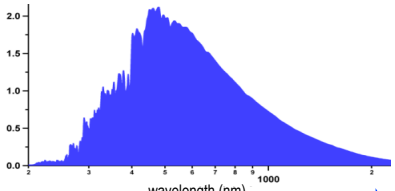
NAS 1998



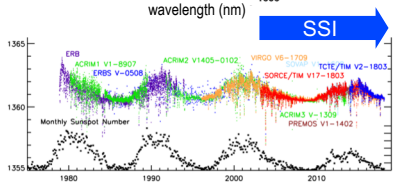


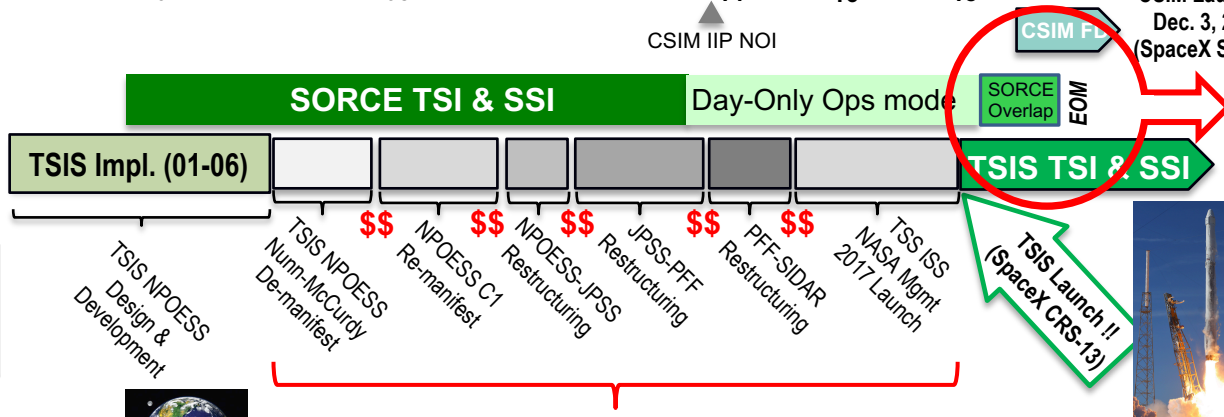
CSIM Launch !!
Dec. 3, 2018
(SpaceX SSO-A)

SSI



TSI



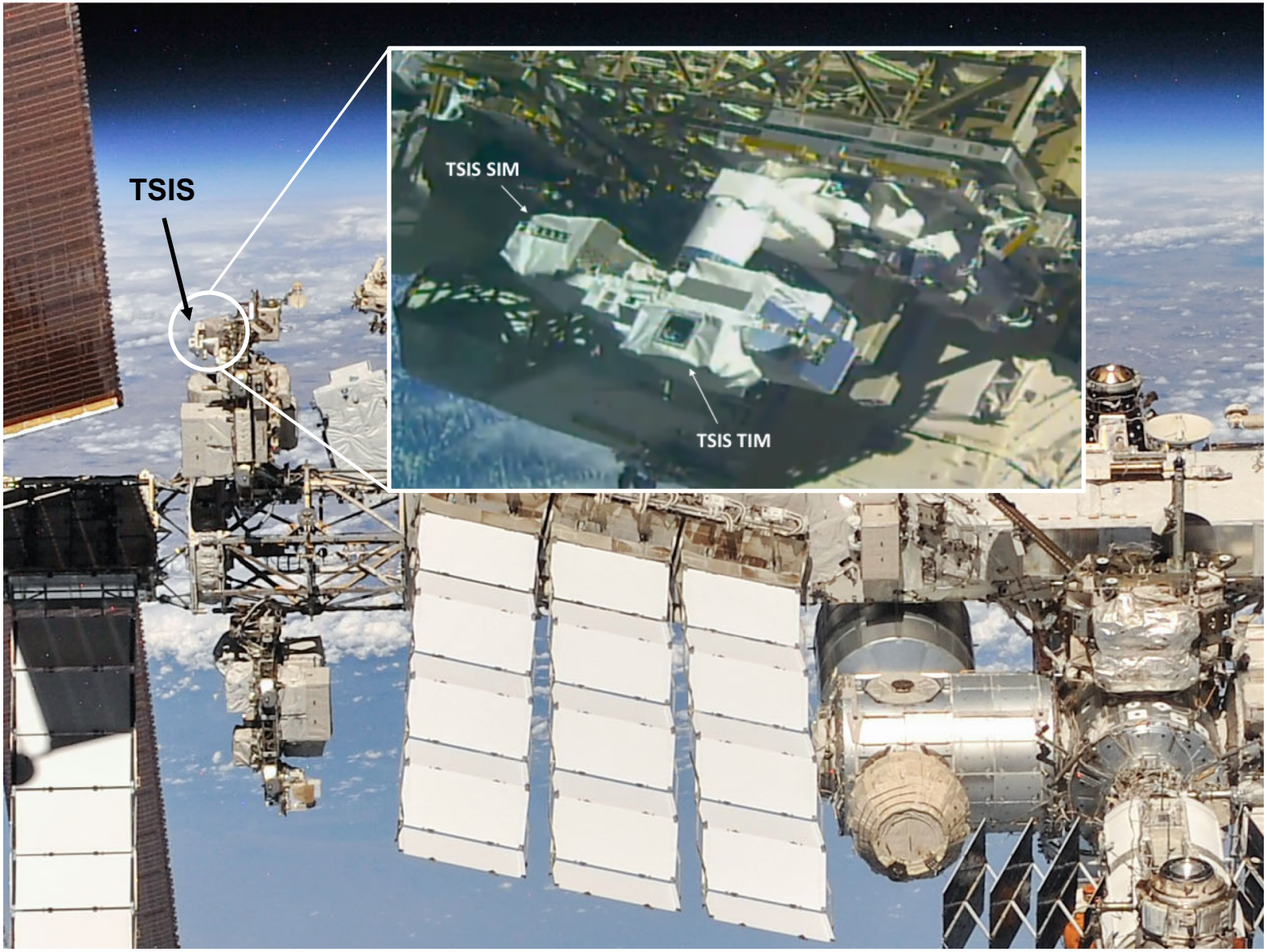


SORCE Turn-off July 2019

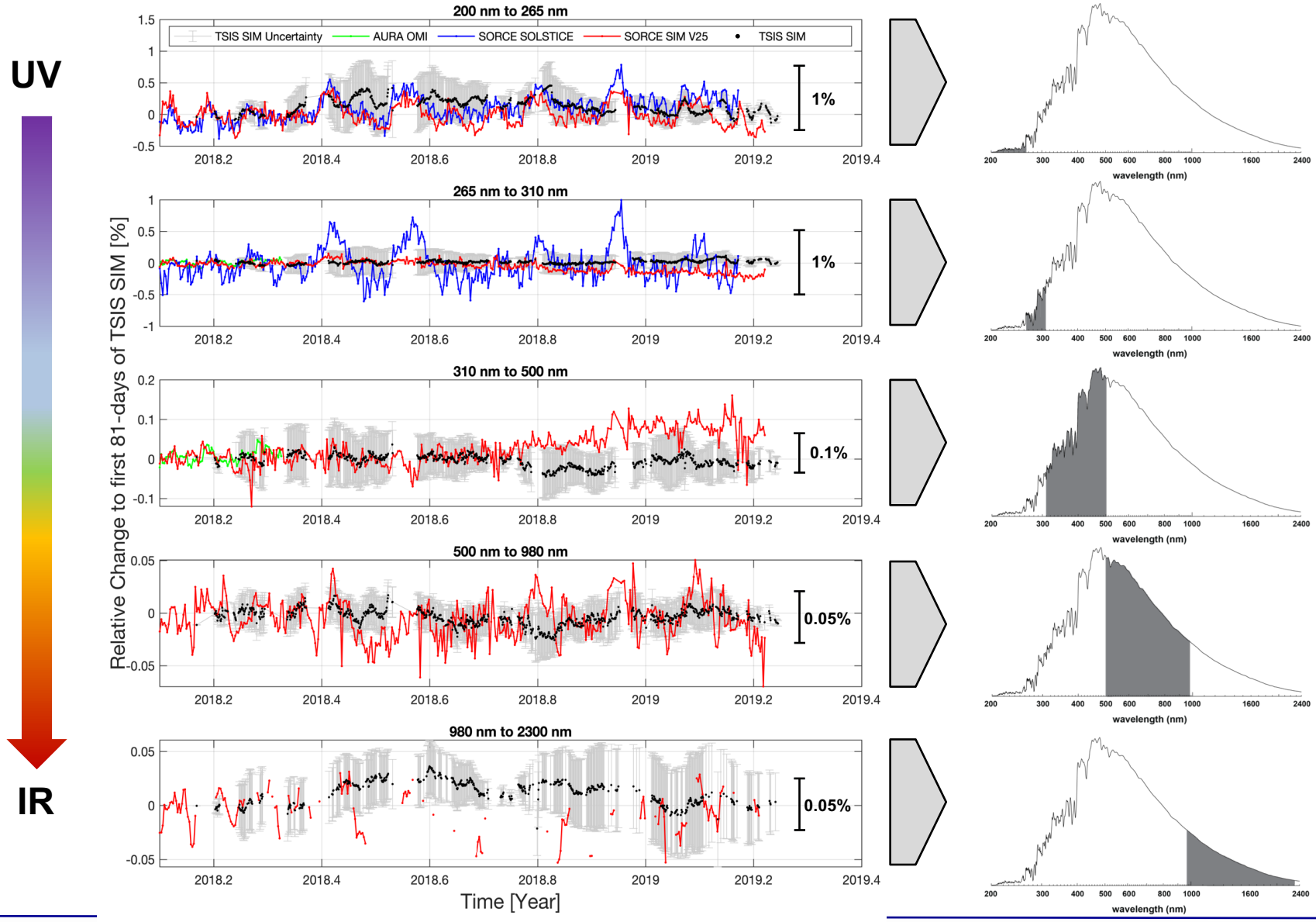
> 1 Decade !!

Covers entire 2007-2017 ES Decadal Timeline

The Total and Spectral Solar Irradiance Sensors (TSIS) on ISS



SSI Time series: 2018 Overlap



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.

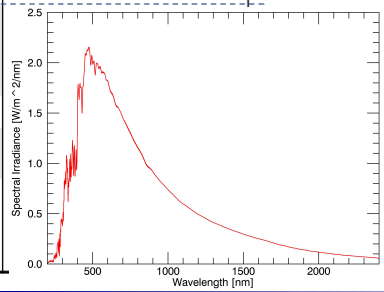
- Benefits from SORCE SIM and TSIS SIM heritage, design knowledge, and new technology advancements
- 6U envelope includes the CSIM Sensor and **ALL** control electronics along with the S/C bus

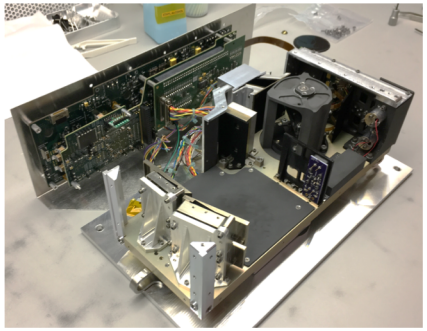
- Performance: Accuracy goal - 0.2% uncertainty (NIST-traceable 200-2400 nm), 100 – 500 ppm rel. stability
- Technologies: Straight-forward (nearly COTS) optics and proven electronic and electro-optic components and innovative new absolute ESR detector - Large cost reduction and lower risk. (ROI from ESTO ACT, IIP and InVEST investments)
- Goal: Achieve **flight-qualified instrument** for LEO operational demonstration and TSIS validation.

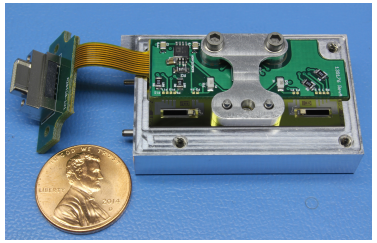
SSI Measurement Requirements

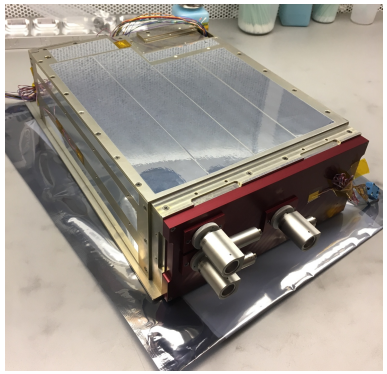
CSIM to meet TSIS

Parameters	SSI Requirements		Verification
	Baseline	Threshold	
Spectral Range	200-2400 nm		LASP SRF (SIRCUS)
Accuracy Unc.	0.2%	1%	LASP SRF (NIST Cryo Rad.)
Stability Unc.	0.05%/yr (≤0.4 μm) 0.01%/yr (>0.4 μm)	0.1%/yr (≤0.4 μm) 0.02%/yr (>0.4 μm)	On-orbit Analysis
Spectral Resolution	2 nm: (< 0.28 μm) 5 nm: (0.28 μm to 0.4 μm) 45 nm: (>0.4 μm)		LASP SRF (SIRCUS)
Reporting Frequency	2 spectra per day		On-orbit Operations
Data processing	Deliver Spectral solar irradiance data products to GES DISC (Complies with Earth Science data policy; Consistent with SORCE approach)		
Launch	Commercial Resupply Service Falcon 9 Dragon trunk		
Design Lifetime	5 years baseline		
TSIS Operations on ISS	Shall enable the TSIS-1 payload to acquire science-mode data during at least 83 percent (threshold: 66 percent) of the time the Sun is available for viewing as constrained by eclipse periods and ISS operations		

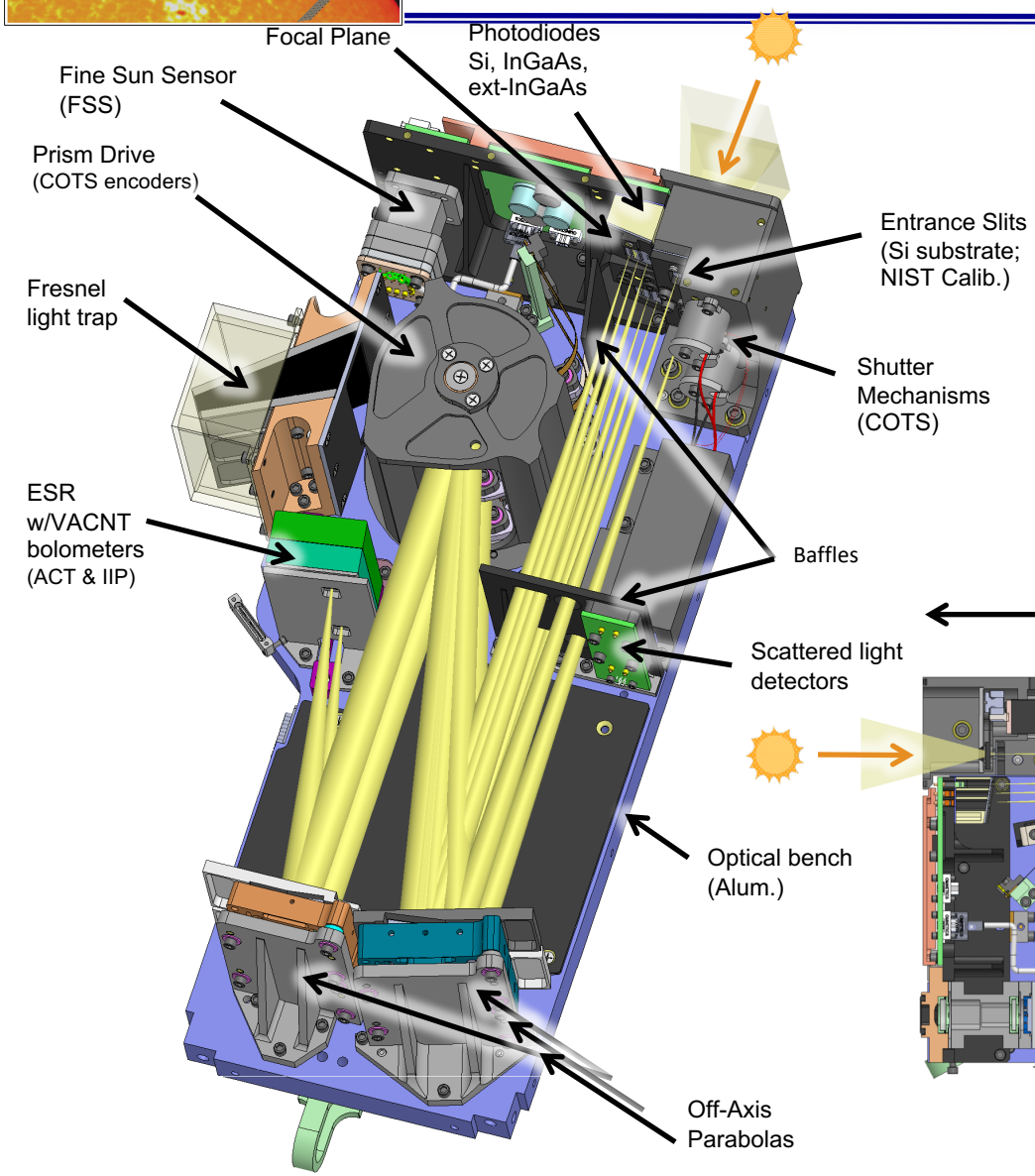




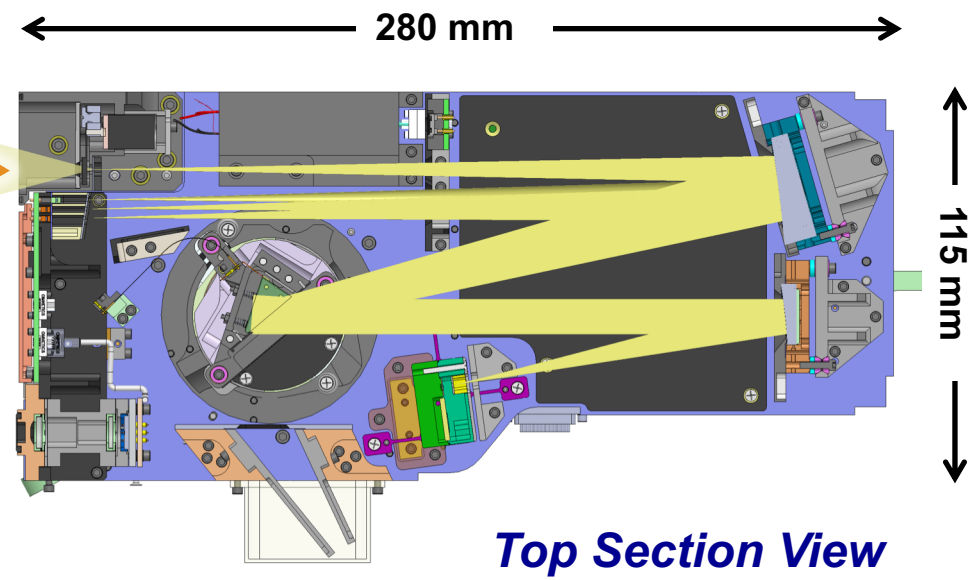




CSIM Instrument



- *Two identical, full spectral channels covering 200-2400 nm*
- *VACNT ESR for PD abs. calib. and on-orbit degradation tracking*
- *Titanium flexures interface with instrument structure (thermal isol.)*
- *Optical black aluminum enclosure for stray light and contamination control*

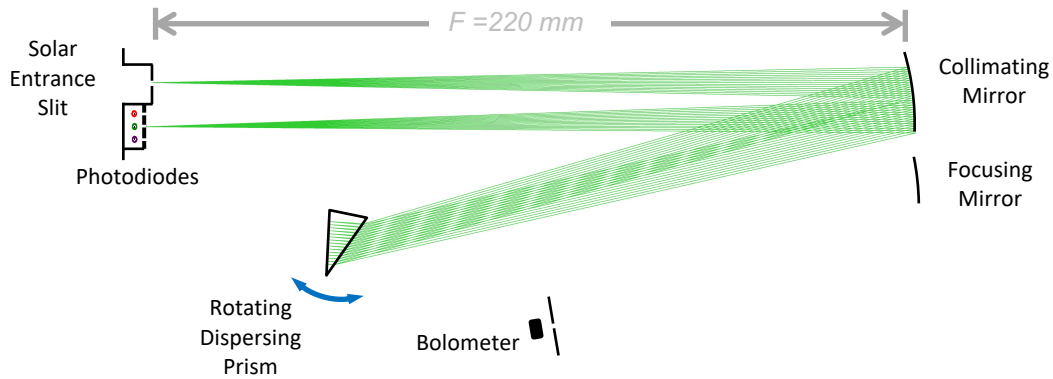


Top Section View

CSIM Optical Layout

Photodiode scan mode

Fast, high SNR detectors Full spectrum (200-2400nm) in < 30 min.

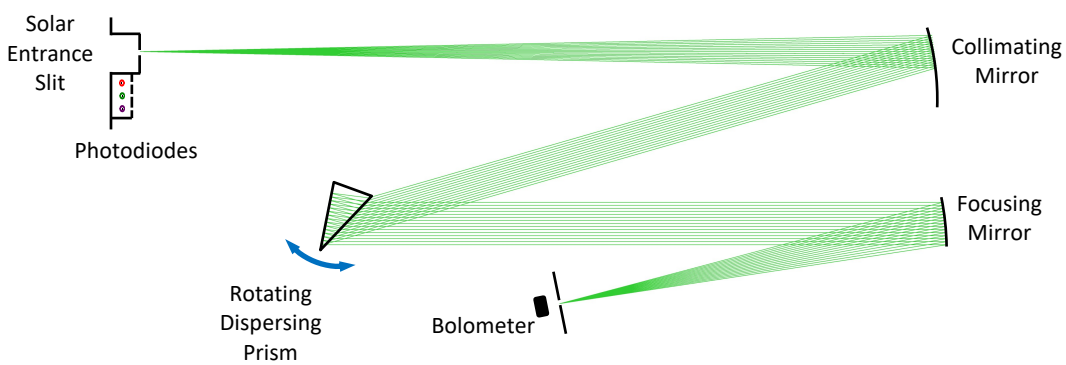


- *"Step and Stare" with the prism to take a spectra*
- *0.5 seconds per point with photodiodes*
  - **Full Spectrum in ~25 minutes**
- *10-50 Seconds per point with ESR*
  - **Full range in ~14 orbits**

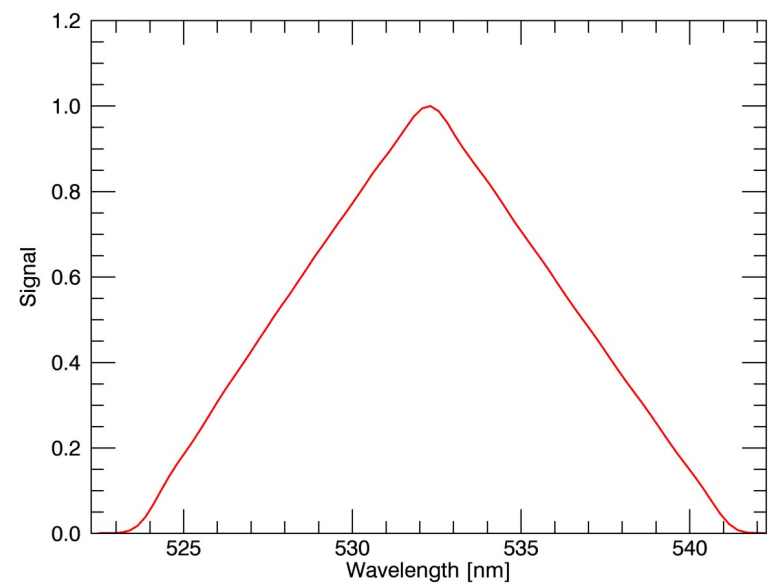
ESR scan mode

Slow, robust absolute detector

Photodiode channel irradiance calibration, degradation tracking

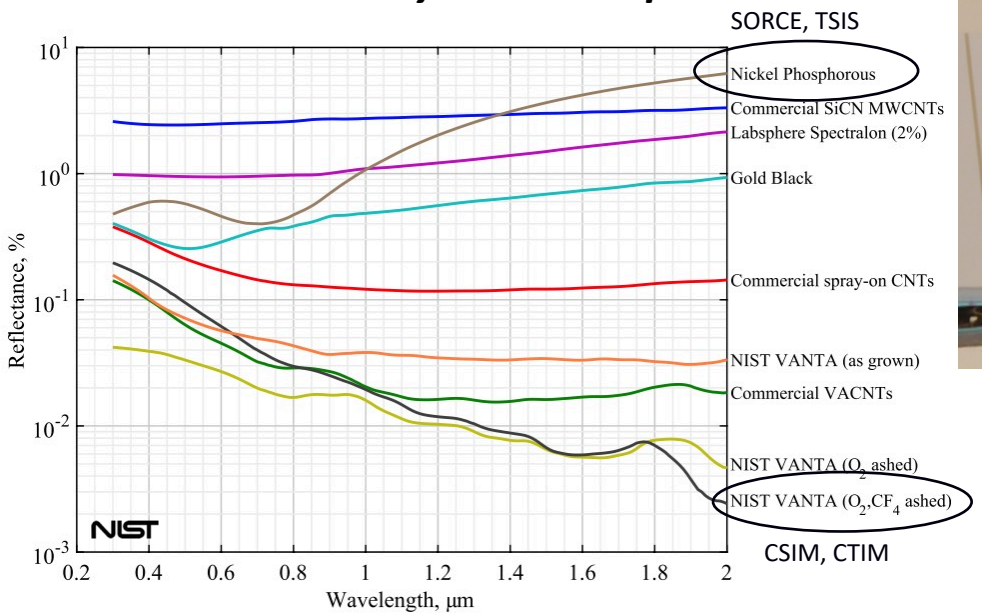


Measured Instrument Line Shape at 532 nm

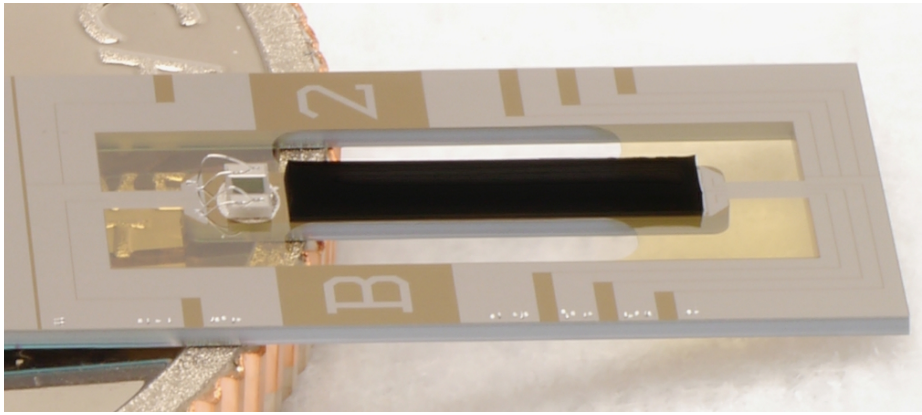


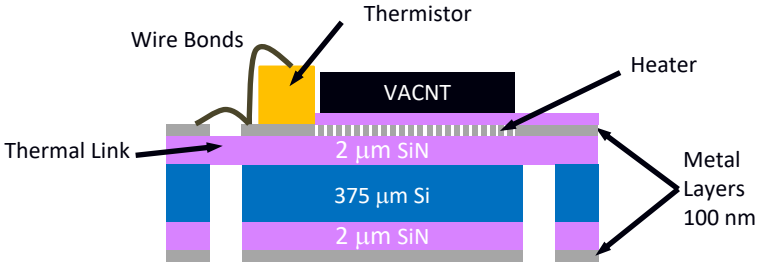
Silicon Substrate Vertically Aligned Carbon Nanotube (VACNT) Bolometers

VACNTs are currently the best optical absorber

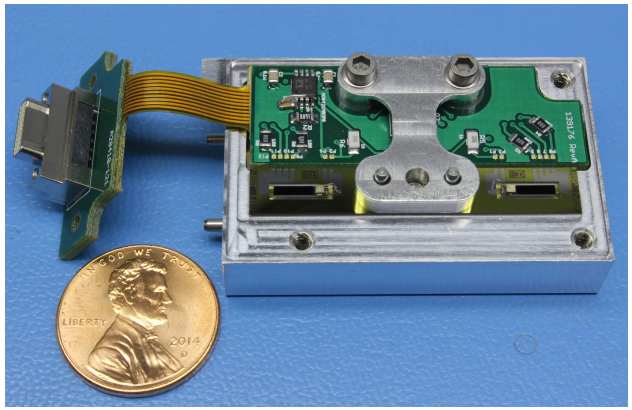


Lehman, *et al.* ***Appl. Phys. Rev***. 5, 011103 (2018)





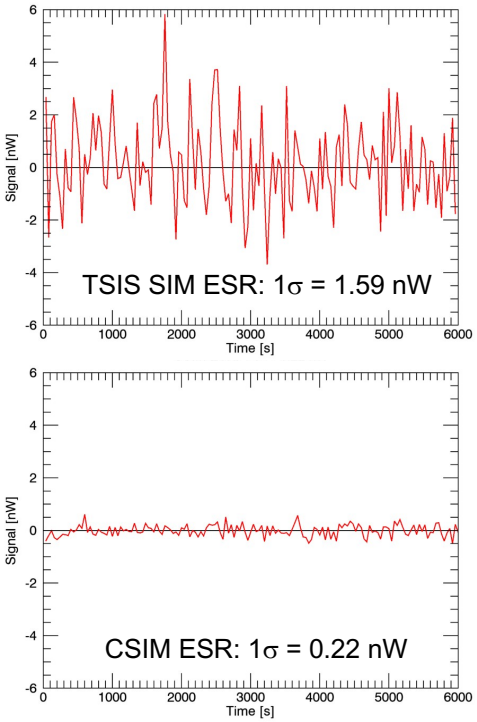
- Developed with NIST Boulder
- Silicon micro fabrication allows a nearly arbitrary 2D geometry to be fabricated with micron-level precision
- Conductive traces and integrated heaters can be fabricated on silicon
- Weak thermal links can utilize integrated thin SiN films

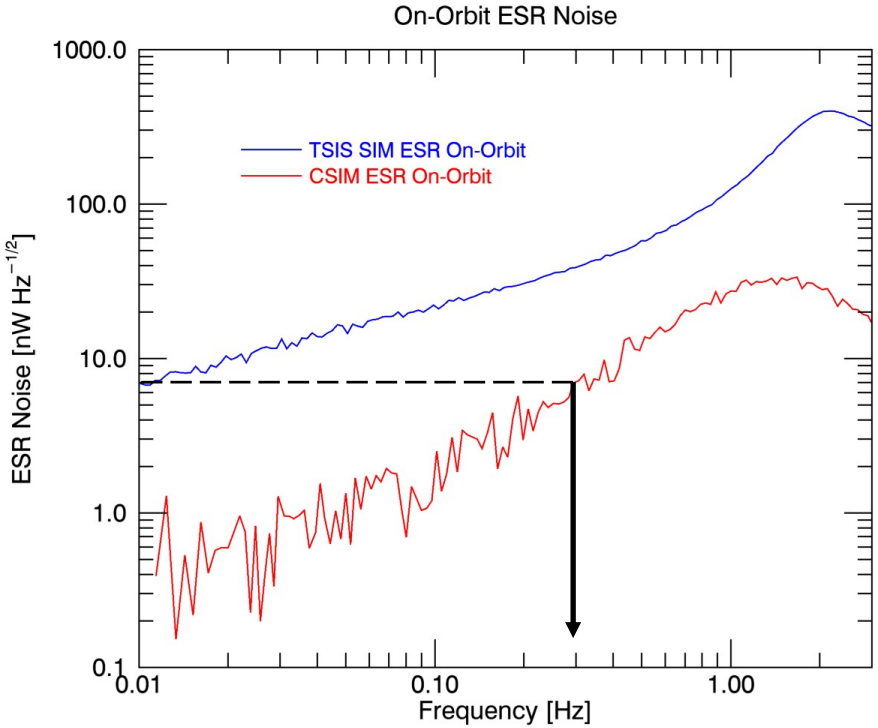


CSIM ESR Achievements

New VACNT bolometer ESR demonstrates excellent performance

- Verified noise performance of the CSIM-FD ESR and demonstrated nearly a factor of 10 improvement in noise performance over TSIS SIM ESR
  - Noise-level for 40 second signal integration: CSIM ESR has 7.2x noise reduction over TSIS SIM ESR
  - Lower noise and faster response allow ESR absolute measurements farther into the UV and faster scan rates over TSIS SIM ESR



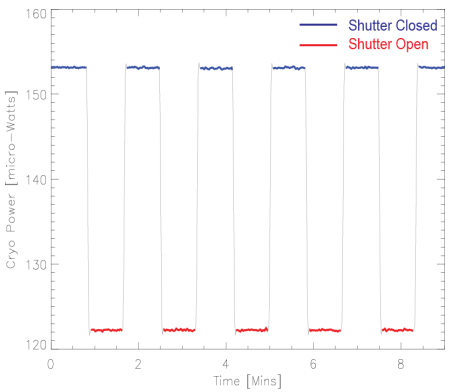


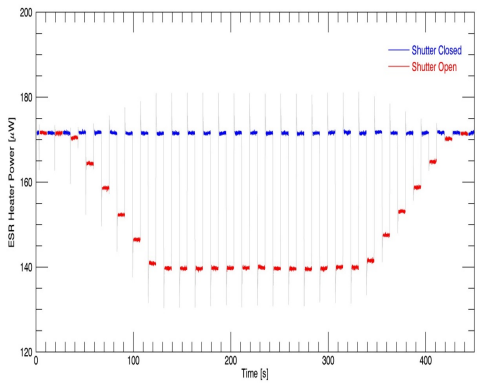
We can operate the CSIM ESR faster than the TSIS SIM ESR and achieve the same SNR. This significantly reduces reduces the prism exposure time during ESR scans

Absolute Irradiance Scale (LASP-SRF)

Cryogenic Radiometer Uncertainty Budget

Parameter	Unit	% Effect	% Unc. (k=1)
Power	W	100	0.015
Cavity Reflectance	-	0.01	0.004
Cavity Non-Equiv.	-	0	0.01
Slit Area: Measured	m^2	100	0.05
Slit Area: Contraction	-	0.04	0.01
Slit Area: Cosine effect	-	0.02	0.01
Slit Diffraction Loss	-	0.13	0.02
Total			**0.07**





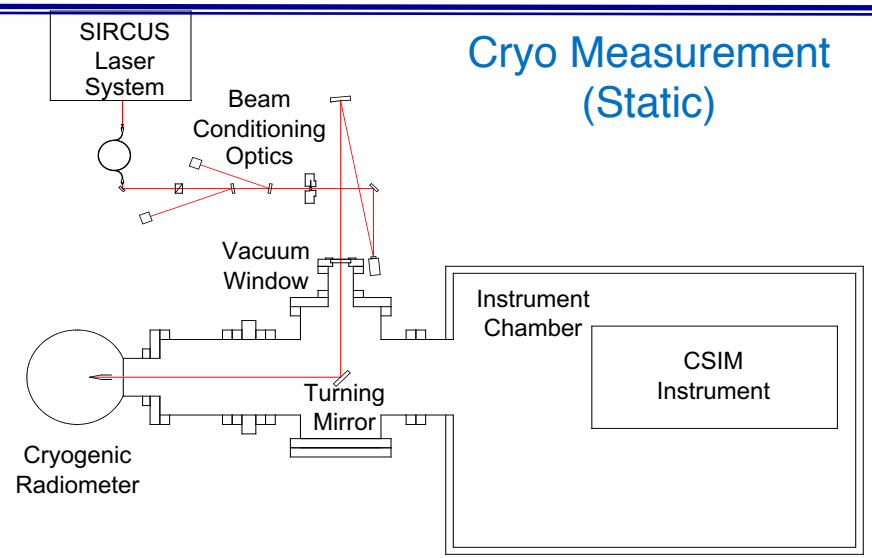
$$I_0 = \frac{DN(\lambda_0)}{AD(\lambda_0)C(\lambda_0)\bar{G}(\lambda_0, p)}$$

$$I_0 = \frac{\int DN(c)dc}{AD(\lambda_0)T(\lambda_0, p)\bar{G}(\lambda_0, p)\Delta W(c)}$$

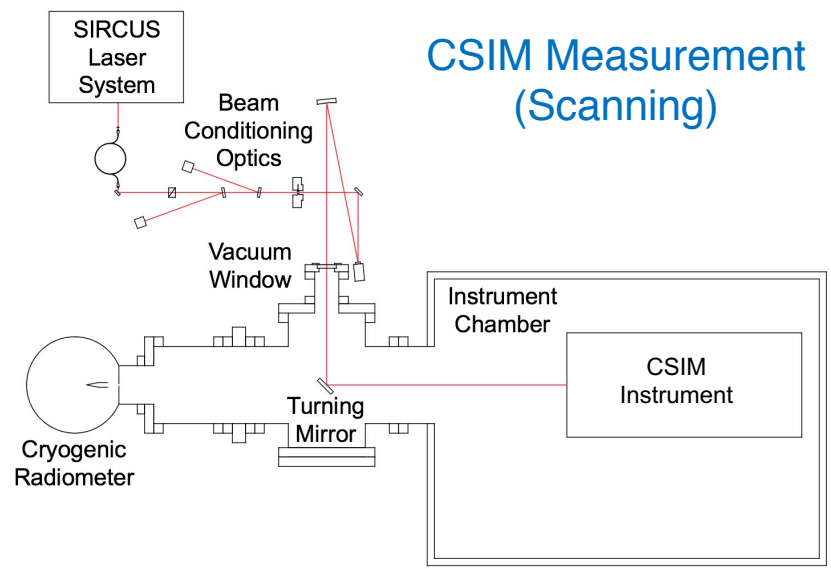
LASP SRF End-to-End Uncertainty Budget

Parameter	Unit	% Effect	% Unc. (k=1)
Cryo Measurement	W/m^2	100	0.07
Turning Mirror Repeatability	-	0	0.004
Laser: Stability	-	0	0.060
Laser: Pattern Uniformity	-	0	0.023
Path Length Correction	-	0	0.0002
CSIM Spectral Integration	W/m^2	100	0.1
Total			**0.14**

Cryo Measurement (Static)



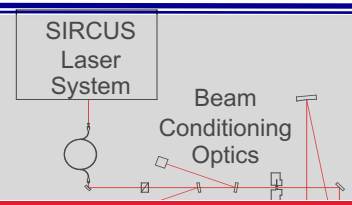
CSIM Measurement (Scanning)



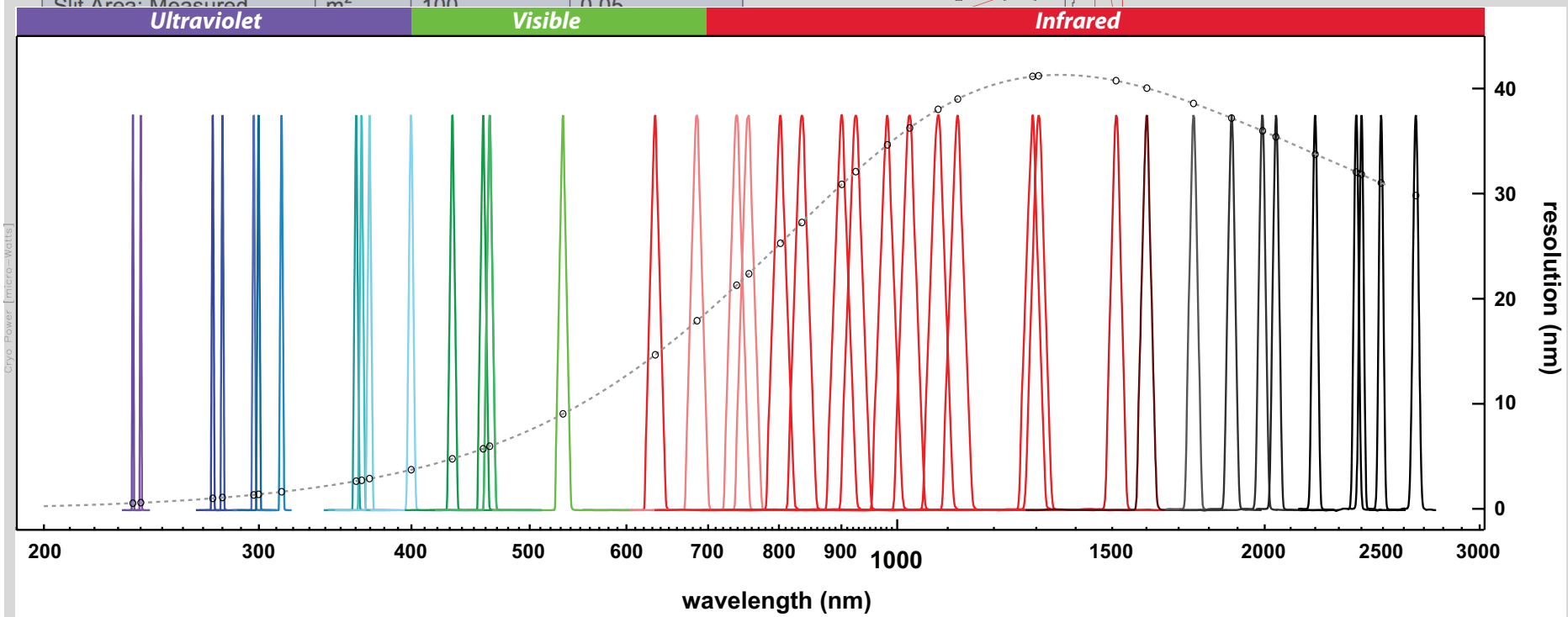
Absolute Irradiance Scale (LASP-SRF)

Cryogenic Radiometer Uncertainty Budget

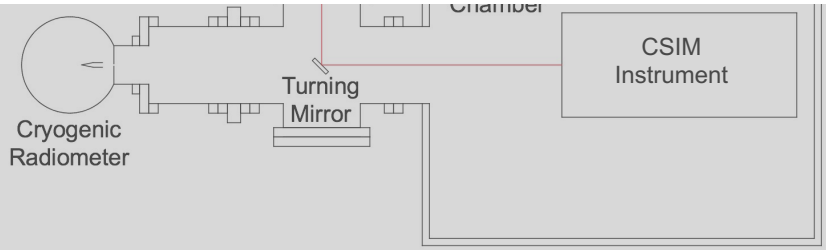
Parameter	Unit	% Effect	% Unc. (k=1)
Power	W	100	0.015
Cavity Reflectance	-	0.01	0.004
Cavity Non-Equiv.	-	0	0.01
Slit Area: Measured	m^2	100	0.05



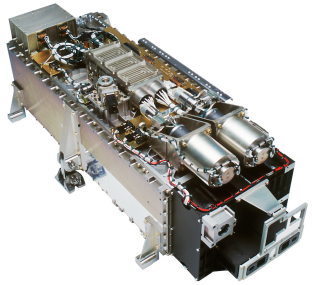
Cryo Measurement (Static)



Parameter	Unit	% Effect	% Unc. (k=1)
Cryo Measurement	W/m^2	100	0.07
Turning Mirror Repeatability	-	0	0.004
Laser: Stability	-	0	0.060
Laser: Pattern Uniformity	-	0	0.023
Path Length Correction	-	0	0.0002
CSIM Spectral Integration	W/m^2	100	0.1
Total			**0.14**

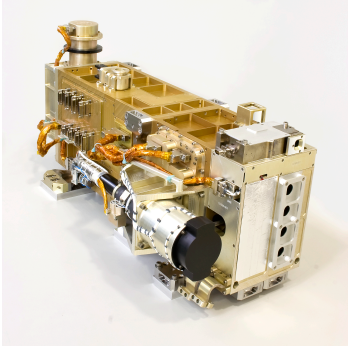


CSIM Evolution



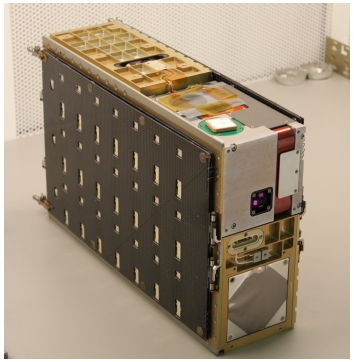
SORCE SIM (launched 15 Jan 2003)

- Two channel instrument (duty-cycled for stability corrections)
- Absolute ESR detector (NiP bolometer)
  - First generation (Noise 3 nW @ 40 sec.)
  - Diamond substrate
  - NiP black absorber
  - Kapton™ thermal link
- Abs. accuracy: 2-10% wavelength dependent (no-SI validation)



TSIS SIM (launched 15 Dec 2017)

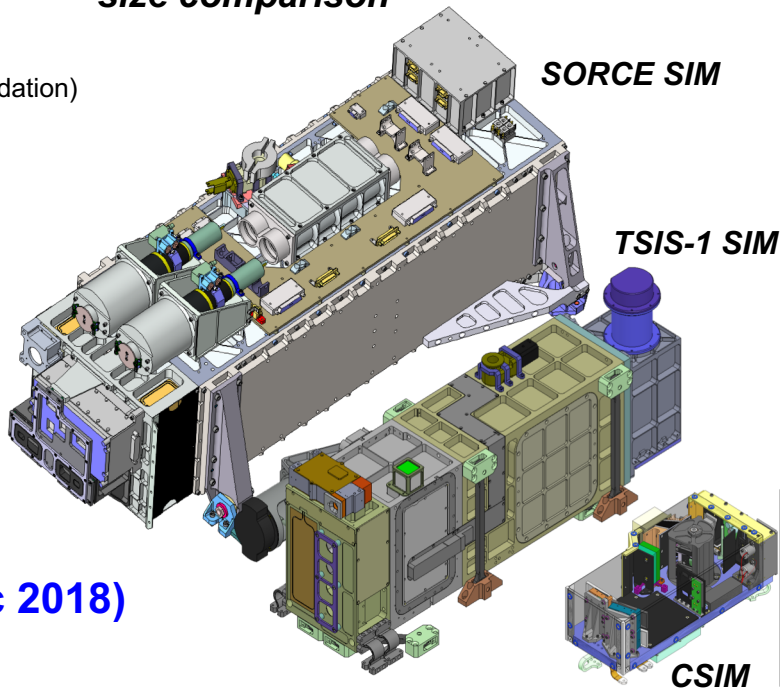
- Three channel instrument
  - For long-term stability validation of duty-cycling
- Absolute ESR detector (NiP bolometer)
  - Second gen. (Noise 1.6 nW @ 40 sec.)
  - Diamond substrate
  - NiP black absorber
  - Kapton™ thermal link
- Abs. accuracy – 0.2 % (SI-traceable validation)



CSIM 6U CubeSat (launched 3 Dec 2018)

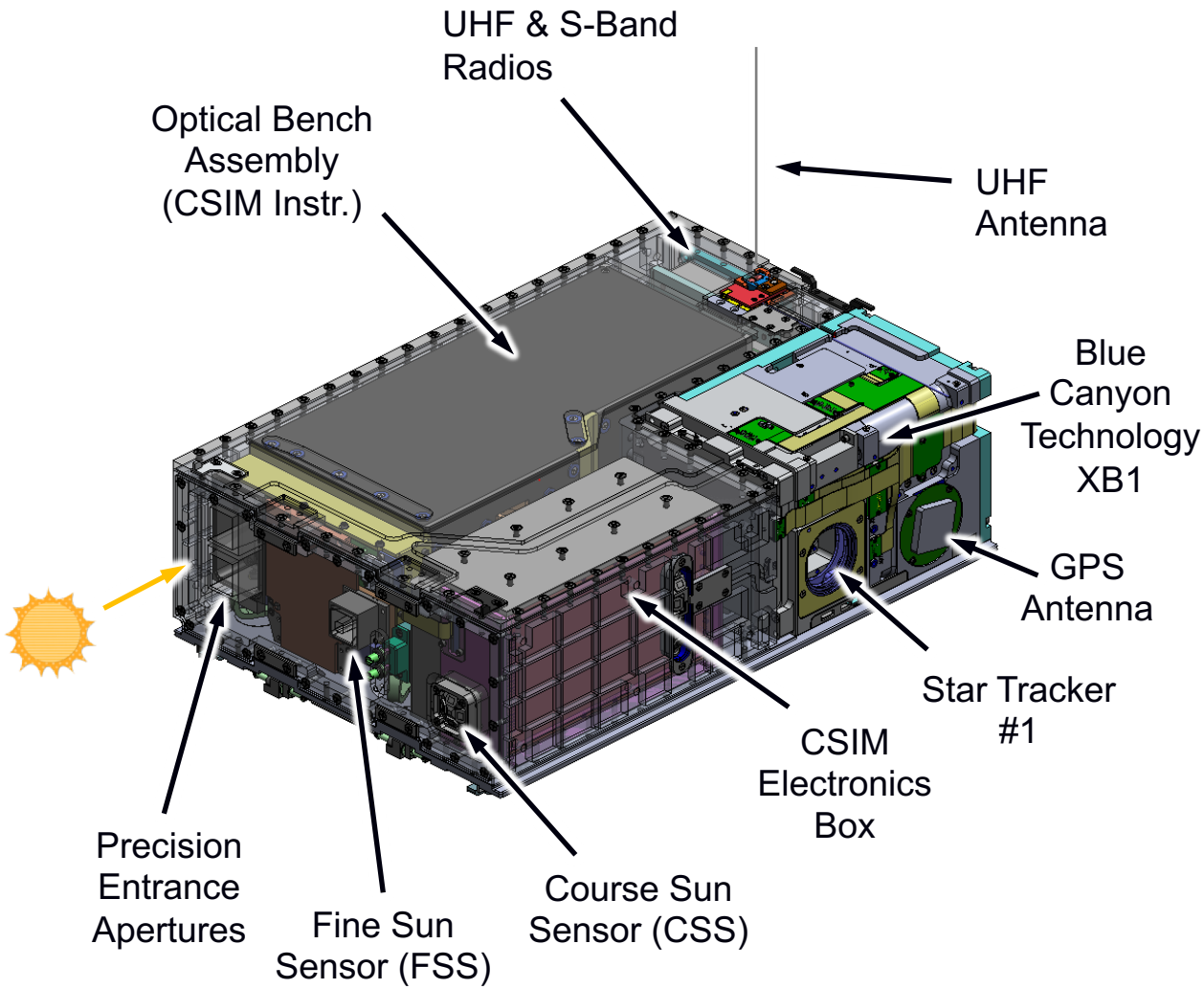
- ✓ Two channel instrument (duty-cycled)
- ✓ Absolute ESR detector (VACNT bolometer)
  - Third gen. (Noise 0.2 nW @ 40 sec.)
  - Silicon substrate
  - VACNT black absorber
  - SiNx thermal link
- ✓ 200-2400 nm (continuous)
- ✓ Abs. accuracy – 0.2 % (SI-traceable validation)

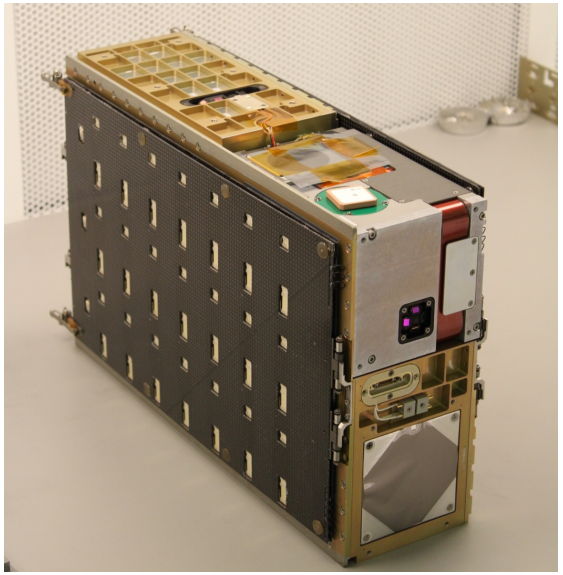
Relative instrument size comparison



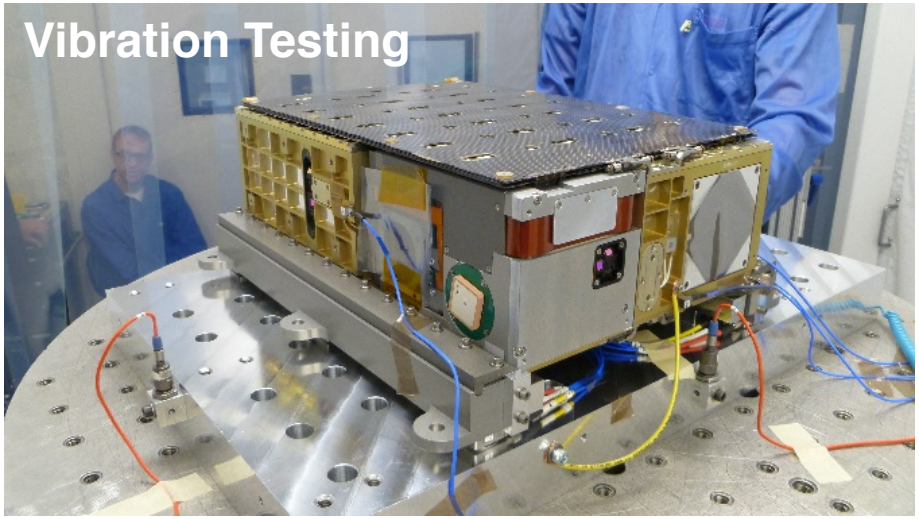
CSIM represents a significant reduction in mass (1/10th), volume (1/20th), and flight ready costs and maintains maximum performance to meet SSI measurement requirements

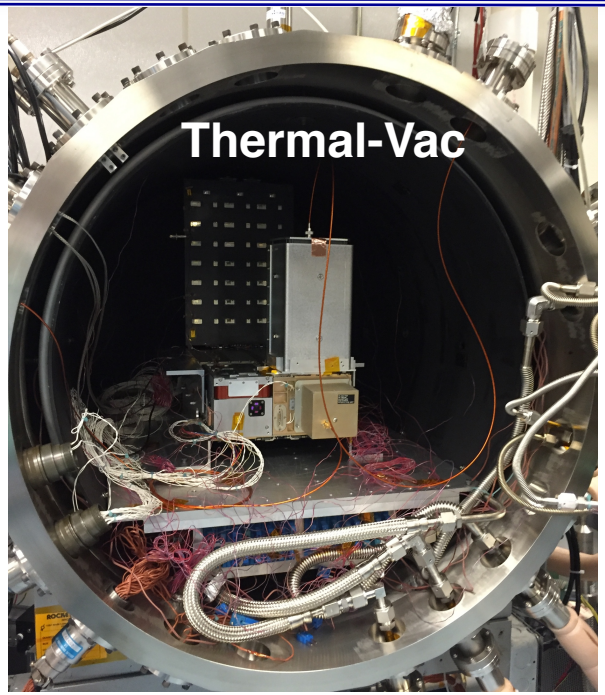
CSIM 6U CubeSat Implementation

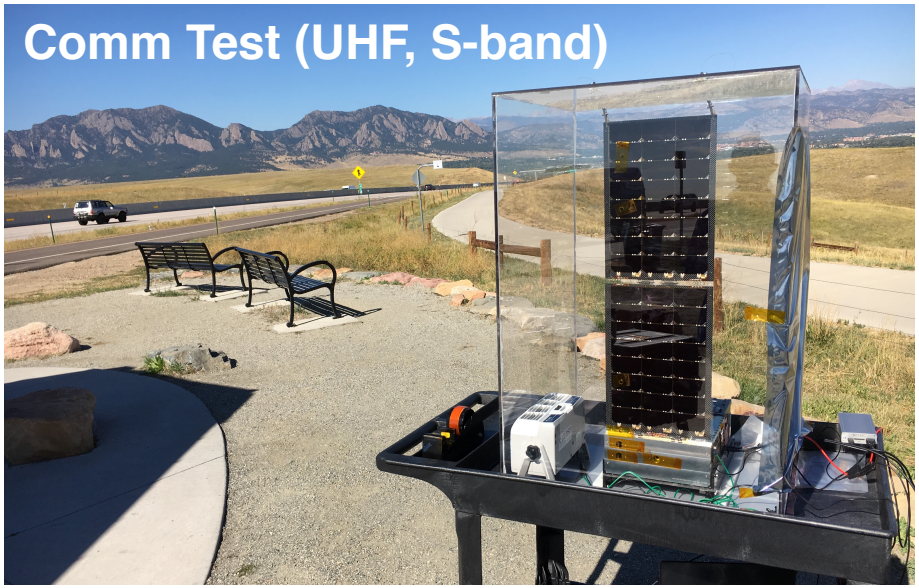


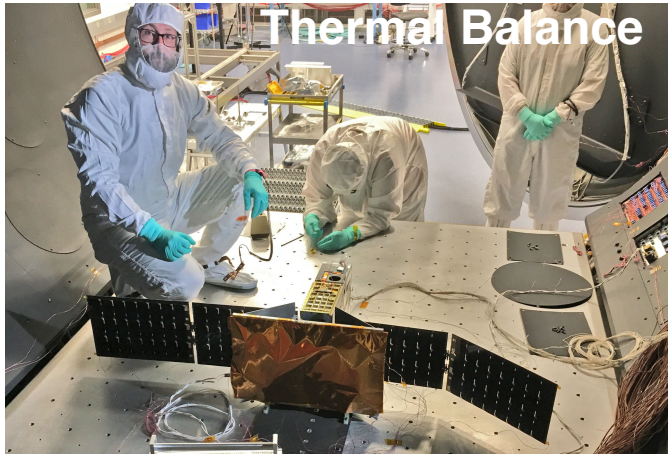


CSIM Environmental Testing





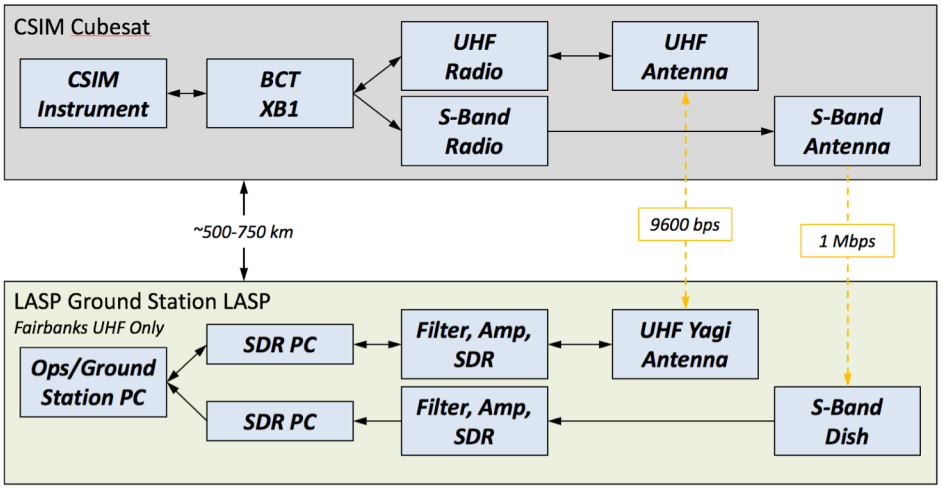




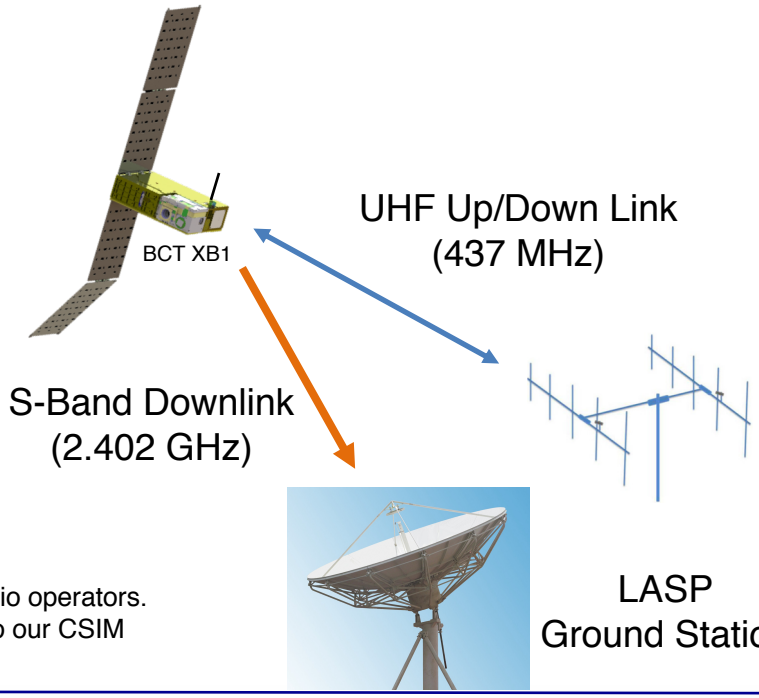
Data Rates & Mission Ops

CSIM-FD Data Rates

- **Goal: ~7 MB/day**
  - CSIM: 5 MB/day, XB1: 2 MB/day
  - >20 MB/day with 1 Mbps S-Band and one pass per day
    - Allows us to perform Ops as described
    - Get housekeeping data at 2 second rate during Ops
    - Allows for diagnostic data

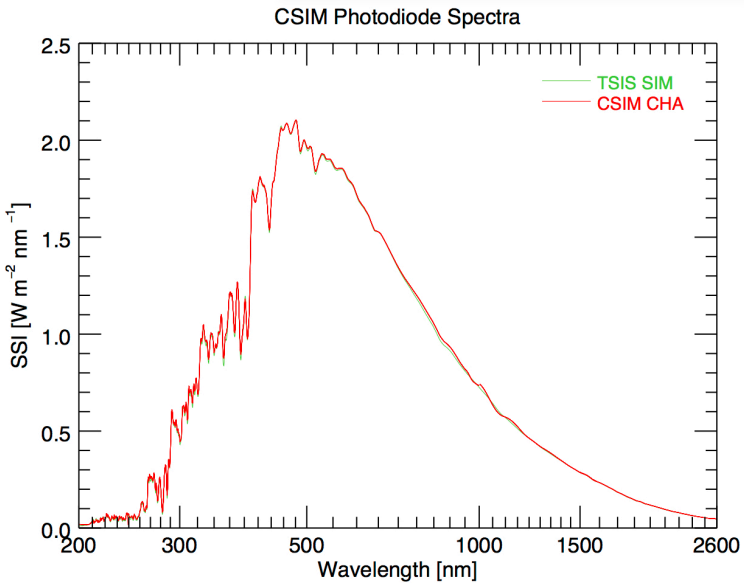


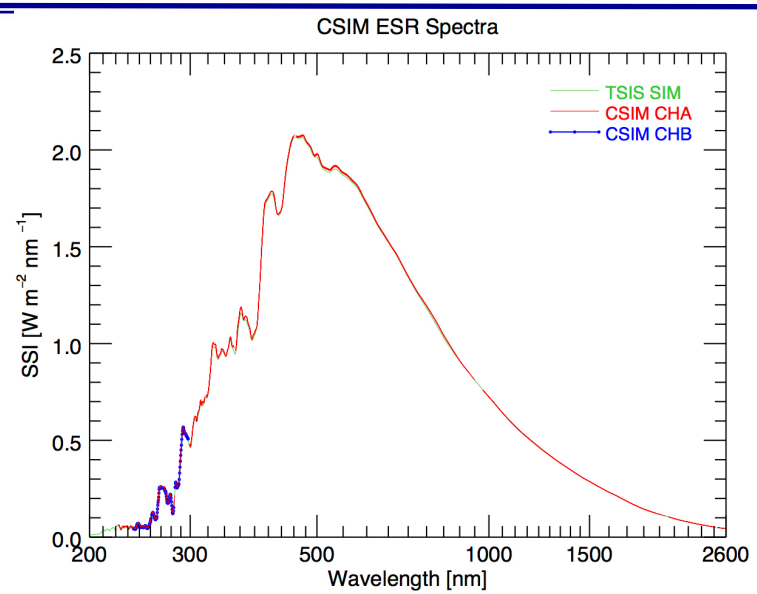
- **Threshold: 0.5 MB/day (sized for UHF link only)**
  - UHF-only operation is our backup contingency plan if we fail to establish a S-band downlink
  - CSIM: 0.3 MB/day, XB1: 0.2 MB/day
    - One full solar spectrum every two days
    - A/B comparisons occur at a lower rate
    - Housekeeping and attitude data at a low rate

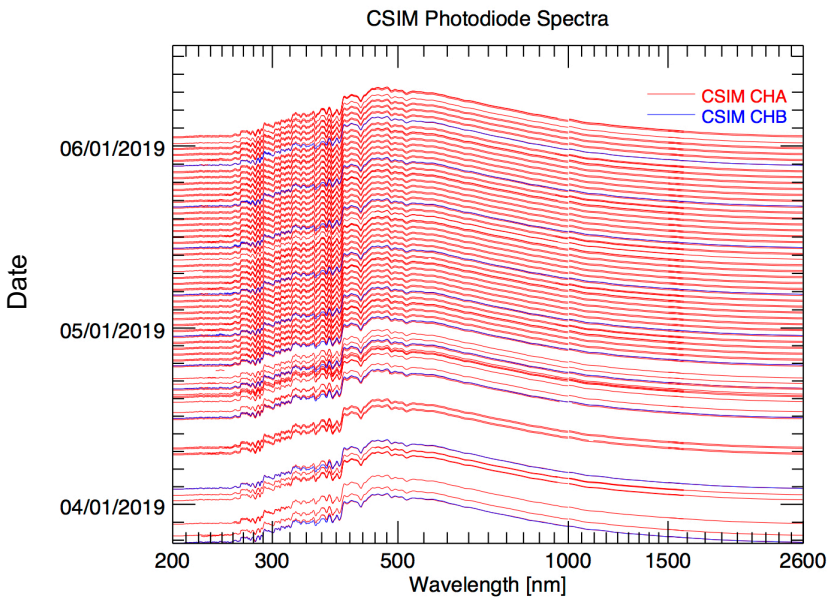


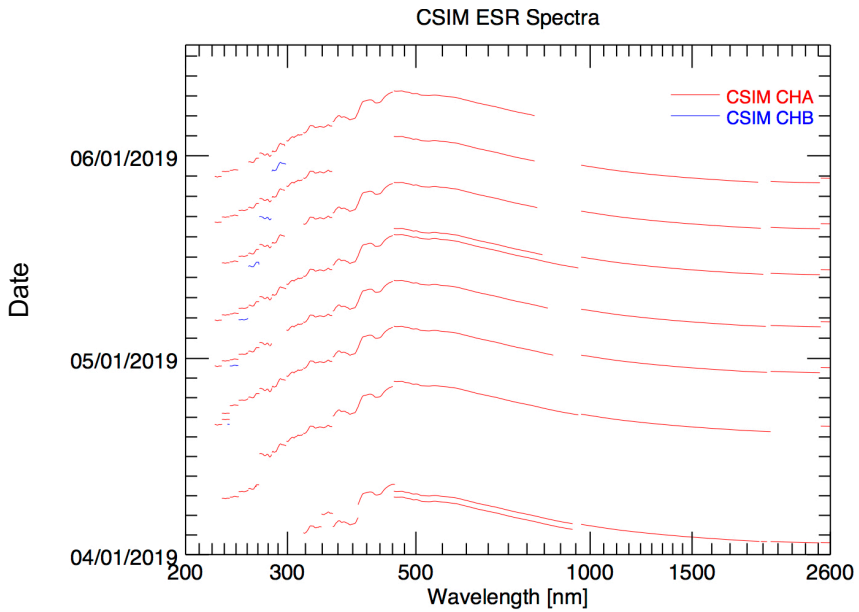
*CSIM will also transmit a periodic UHF beacon that can be received by amateur radio operators. We will provide web tools that permit those operators to upload received packets into our CSIM telemetry database.

CSIM Operational Summary





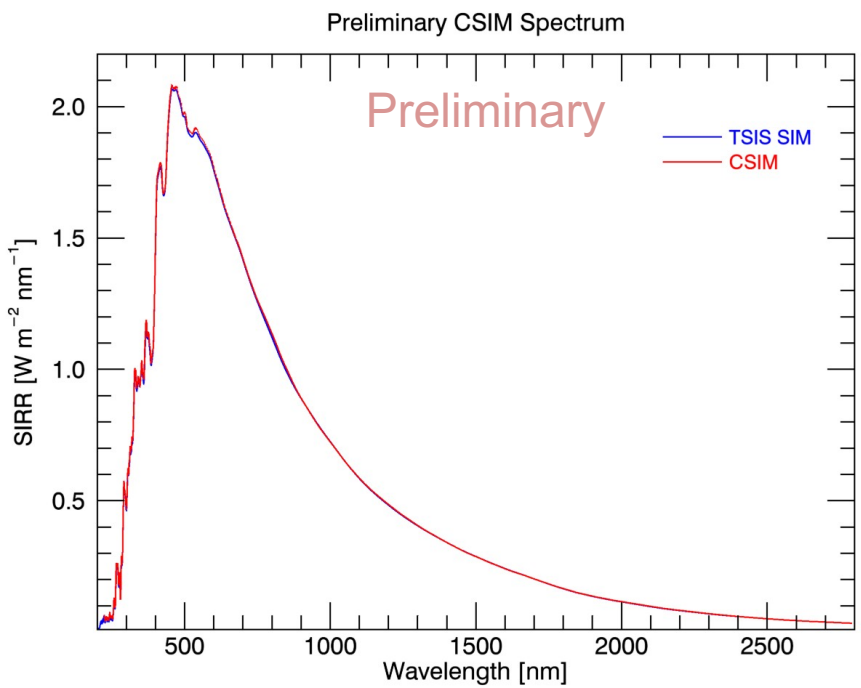


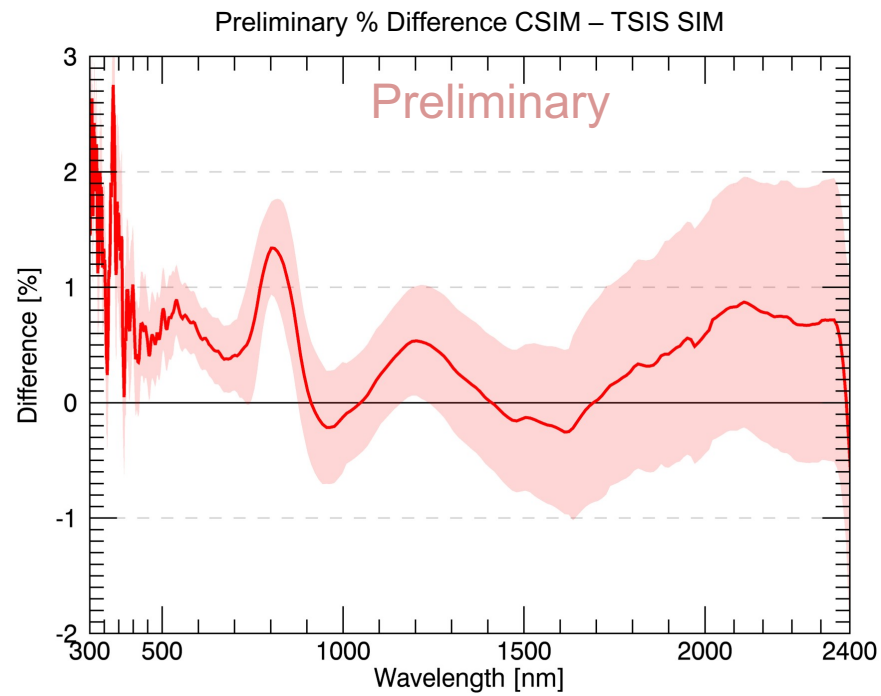


Absolute SSI Comparison

Obtained first full ESR scan covering 224 – 2800 nm

- Found excellent agreement for the CSIM ESR SSI spectrum compared to TSIS SIM (validates the TSIS SIM IR ~6% decreases over SORCE SIM)
  - Agreement <1% differences in the for visible and near IR (400 – 2400 nm)
  - Overall agreement <3% differences in the near UV (300 – 400 nm)
  - Below 300 nm agreement is poorer due to some scattered light (200 – 220) and poorer optical quality in second-surface Alum. prism coating (on-going analysis)





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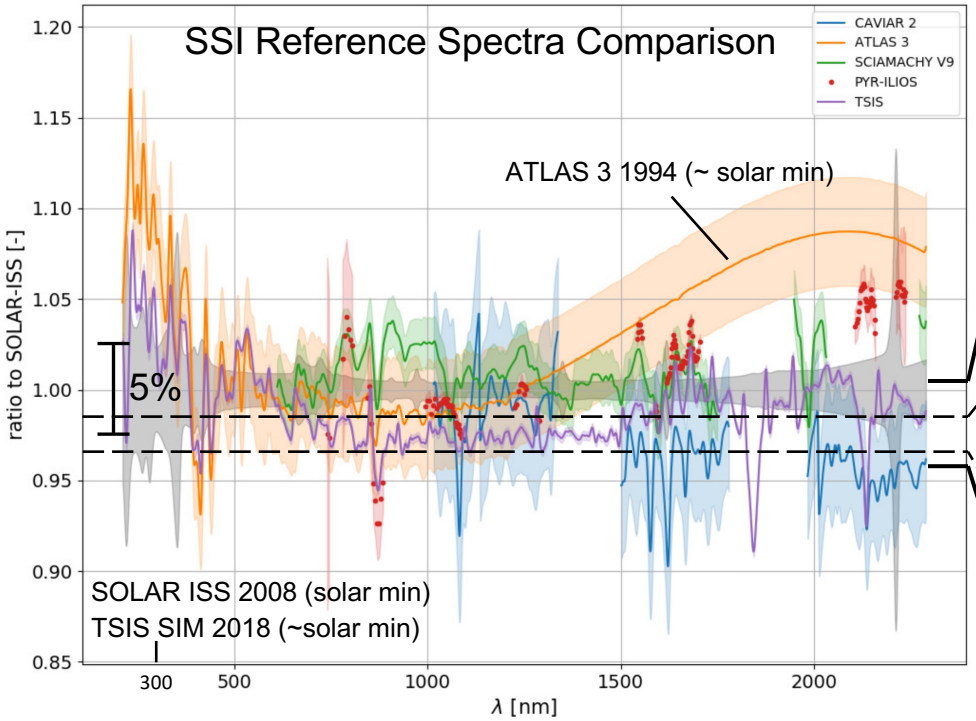

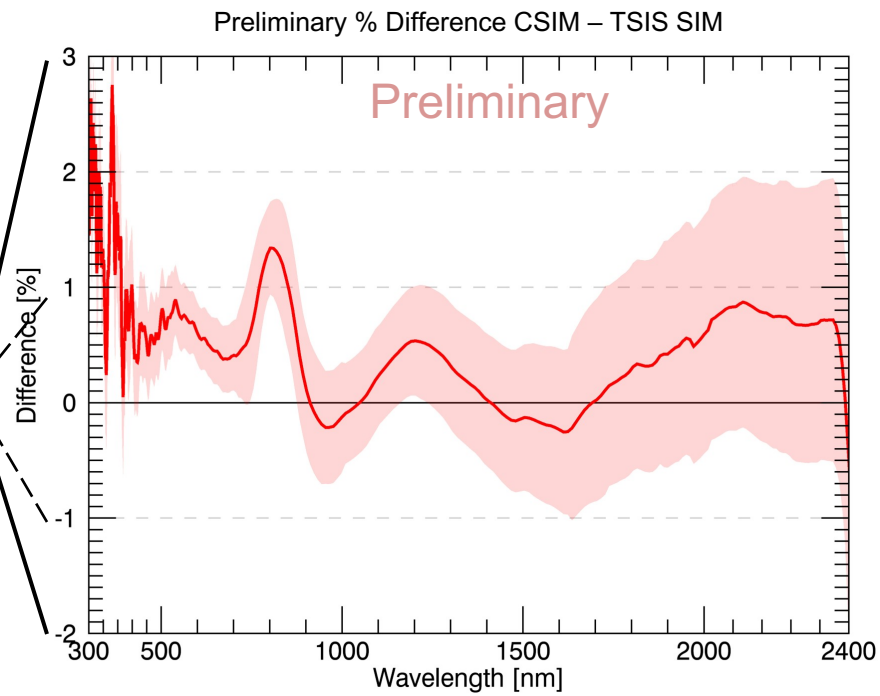

M. Meftah, et al., LATMOS, UVSQ, Université Paris Saclay, Sorbonne Université, 2019

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Earth Science Technology Office

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Laser Sources and Detectors Group, Radiation and Power Measurements (J. Lehman, Boulder, CO)