Solar Spectral Irradiance Measurements from the Total and Spectral Solar Irradiance Sensor (TSIS-1)

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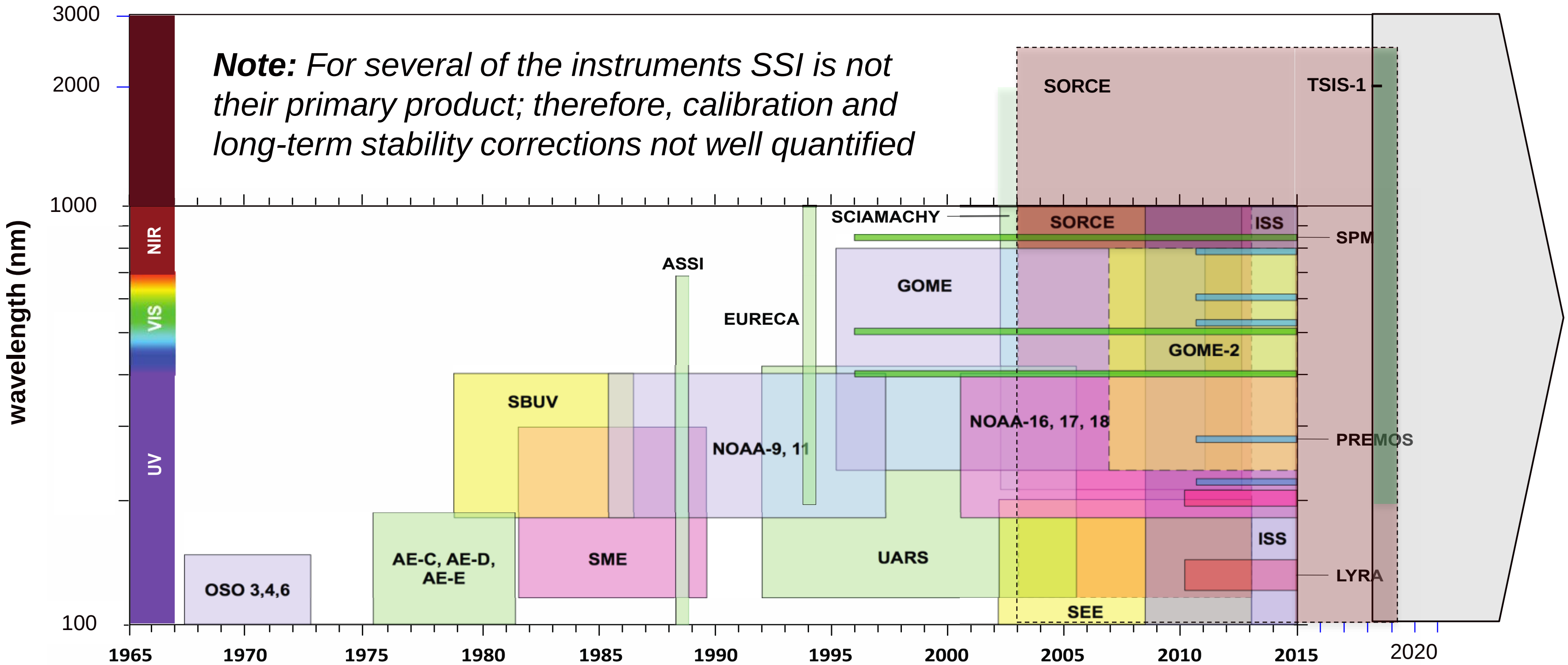
Motivation & Outline

- The **Total and Spectral Solar Irradiance Sensor (TSIS)** provides two measurements critical for understanding solar influences on Earth climate: Total Solar Irradiance (**TSI**) and Solar Spectral Irradiance (**SSI**)
  - TSI and SSI are the boundary conditions for external energy incident on Earth's atmosphere
  - SSI necessary for attribution of climate forcing, atmospheric chemistry modeling, radiative transfer modeling, & conversion of measured satellite radiances to reflectances.
  - TSIS launched to the International Space Station in December 2017 and began commissioning activities in January 2018.

TSIS SIM data is publically available: http://lasp.colorado.edu/home/tsis/data/

- In this talk we will present
  - the SSI observational record, with a focus on UV
  - TSIS SIM ***accuracy***, ***repeatability***, and ***stability***
    - Pre-launch validation in the LASP Spectral Radiometer Facility
  - Some comparisons to other SSI references

The Solar Spectral Irradiance Record



SSI validation presents a different challenge than TSI:

- Requires overlap in time and wavelength.
- Record shows overlap in time but spotty overlap in spectral domain.
- Other challenges include spectral sampling and resolution.

SSI observational composites → V1 UV composite [Deland and Cebula, 2008]; V2 in development
Full spectrum 'SOLID' composite [Haberreiter et al., 2017]

TSIS SIM Development Approach

TSIS SIM designed for long-term spectral irradiance measurements

Incorporate lessons learned from SORCE SIM (& other programs) into TSIS SIM to meet measurement requirements for long-term SSI record

Specific areas of improvement & enhancement over SORCE SIM to address both accuracy and stability

✓ *Improve uncertainty quantification in prism degradation correction to meet long-term stability requirement*

- *Ultra-clean optical environment to mitigate contamination*
- *Addition of 3rd channel to reduce degradation uncertainties*

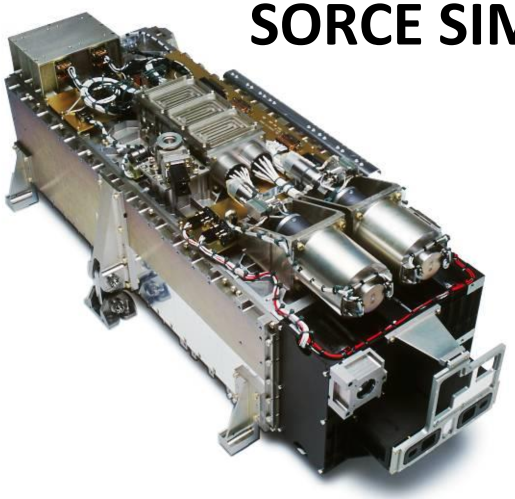
✓ *Improve noise characteristics of ESR and photodiode detectors to meet measurement precision requirement*

- *Improved ESR thermal & electrical design (sensitivity)*
- *Larger dynamic range integrating ADC's (21 bits)*

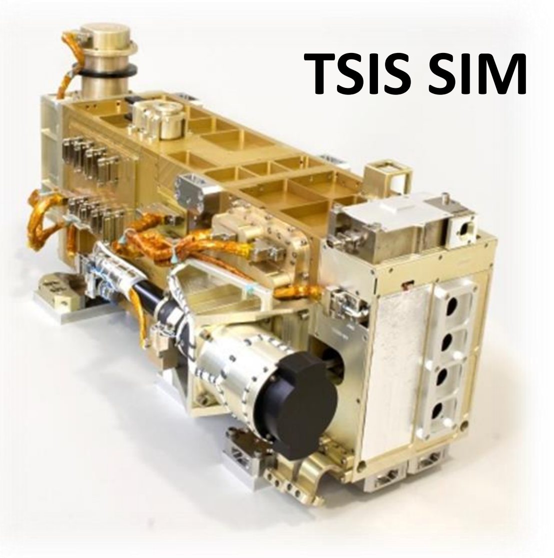
✓ *Improve absolute accuracy (pre-launch) verification*

- *SI-traceable Unit and Instrument level pre-launch spectral irradiance calibration (LASP SRF-NIST SIRCUS-L1 Cryo Rad)*

SORCE SIM

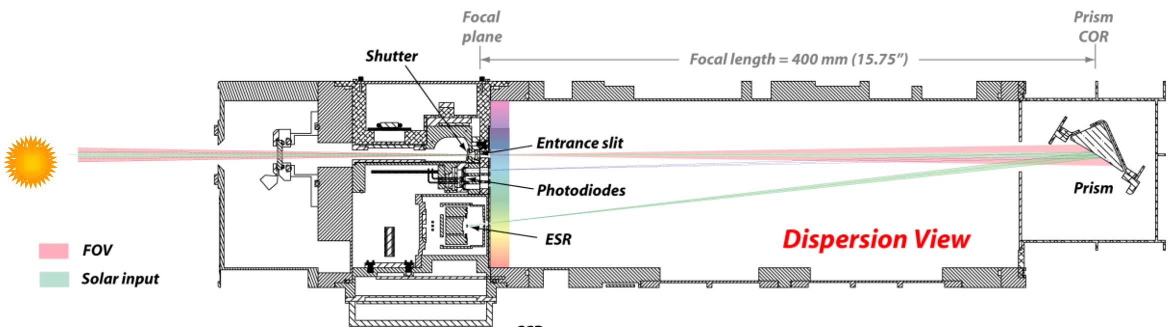


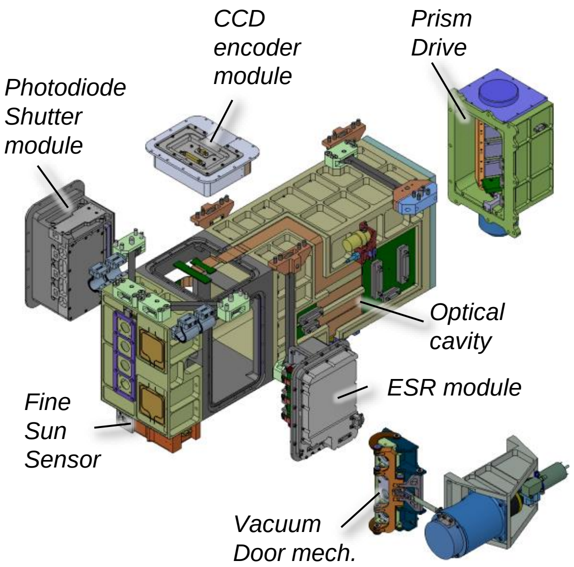
TSIS SIM



TSIS SIM Overview

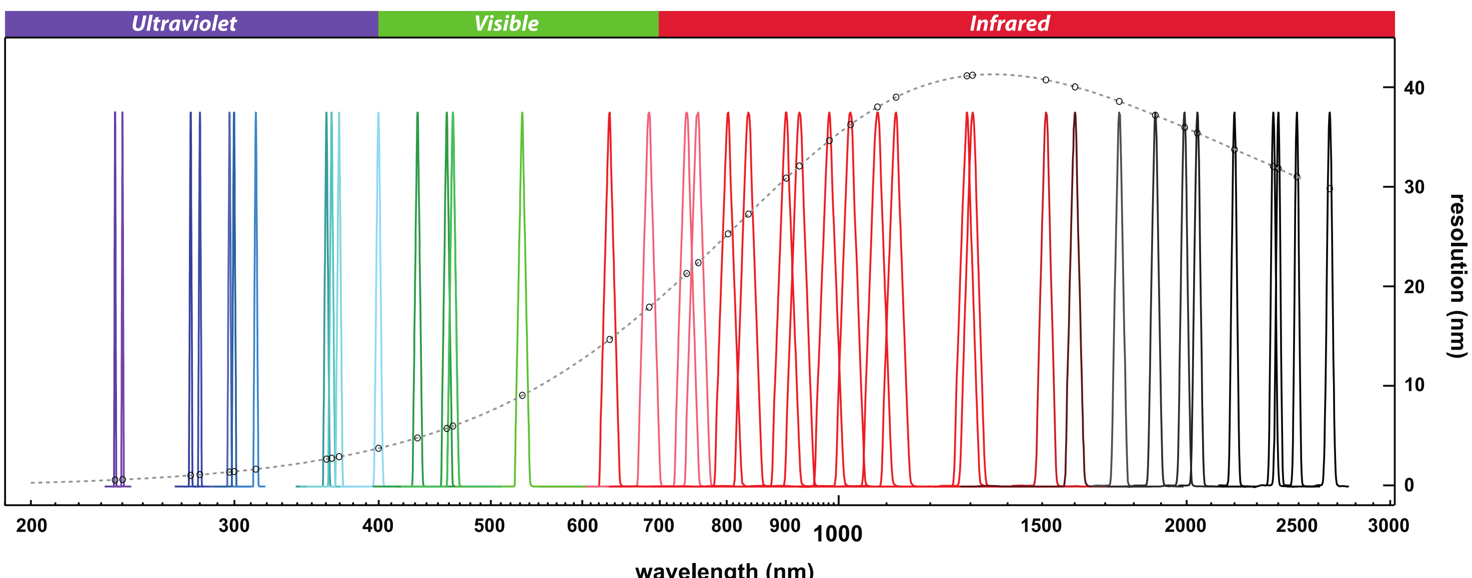
Féry prism spectrometer. Modular design.





Measurement Equation (Units: $Wm^{-2}nm^{-1}$)

$$\mathcal{E}_\lambda(\lambda_s) = \frac{\mathcal{P}_{\mathrm{ESR}}(\lambda_s)}{A_{slit} \cdot \int \alpha_\lambda \cdot T_\lambda \cdot \phi_\lambda \cdot S(\lambda, \lambda_s)\ d\lambda}$$



TSIS SIM Correction Factors

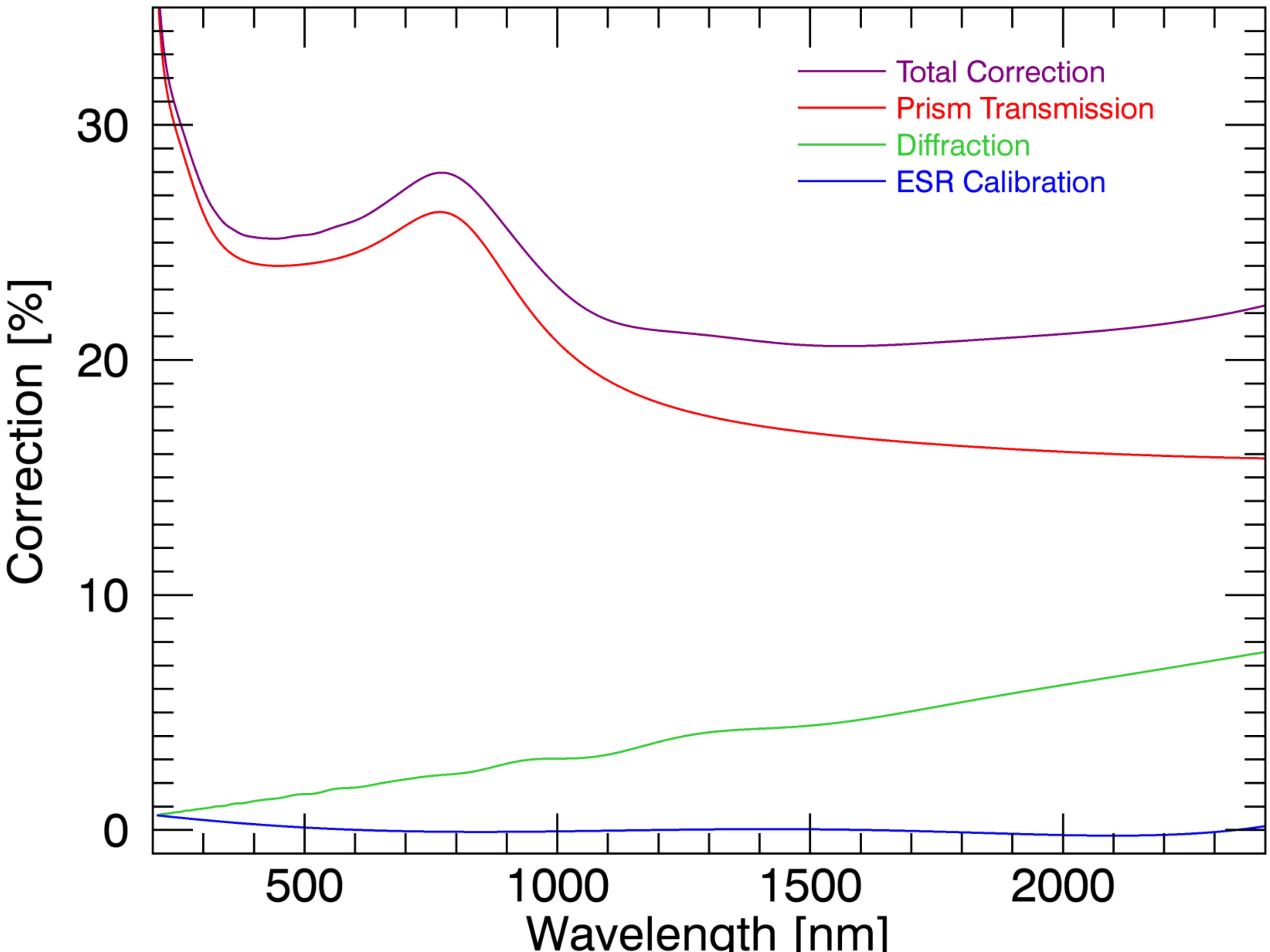
LASP — Laboratory for Atmospheric and Space Physics, University of Colorado at Boulder

Instrument uncertainties determined at the component level --> characterization of error budget

Level	Parameter	Origin	Value (ppm)	Type	Unc. (ppm) k=1	Status (532 nm)
S/C	Distance to Sun, Earth & S/C	*Analysis*	33,537		0.1	
S/C	Doppler Velocity	*Analysis*	43		1	
S/C	Pointing	*Analysis*	0		100	
Component-Level	Shutter Waveform	*Component*	100	B	10	
Component-Level	Slit Area	*Component*	1,000,000	A	300	165
Component-Level	Diffraction	*Component*	5,000-62,000	B	500	380
Component-Level	Prism Transmittance	*Component*	230,000-450,000	A	1,000	830
Component-Level	ESR Efficiency	*Component*	1,000,000	A	1,000	940
Component-Level	Standard Volt + DAC	*Component*	1,000,000	A	50	
Component-Level	Pulse Width Linearity	*Component*	0	A	50	
Component-Level	Standard Ohm + Leads	*Component*	1,000,000	A	50	
Instrument-Level	Instrument Function Area	*Instrument*	1,000,000	A	1,000	870
Instrument-Level	Wavelength	*Instrument*	1,000,000	B	750	530
Instrument-Level	Non-Equivalence, Z_H/Z_R-1	*Instrument*	2,000	B	100	
Instrument-Level	Servo Gain	*Instrument*	2,000	A	100	
Instrument-Level	Dark Signal	*Instrument*	0	B	100	
Instrument-Level	Scattered Light	*Instrument*	0	B	200	
Instrument-Level	Noise	*Instrument*	-	A	100	
	Combined Rel. Std. Unc.				***2000***	***1668***

Dominant Uncertainties are wavelength dependent (98.7% of full budget)

TSIS SIM Correction Factors



Spectral Irradiance Traceability

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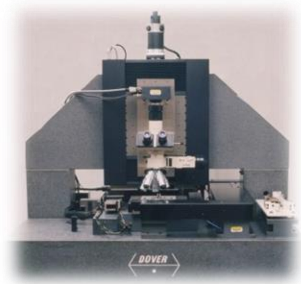
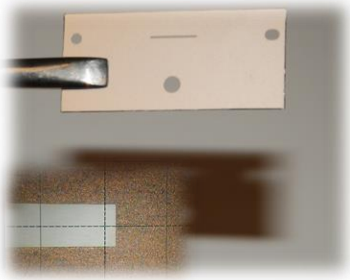
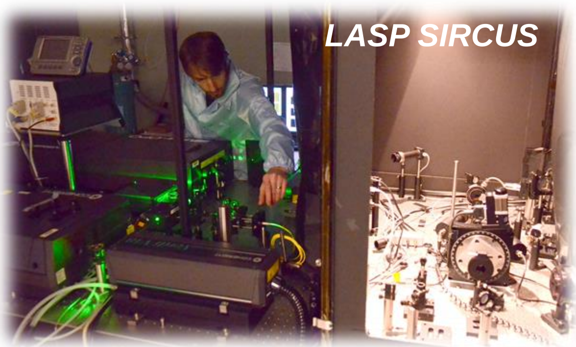
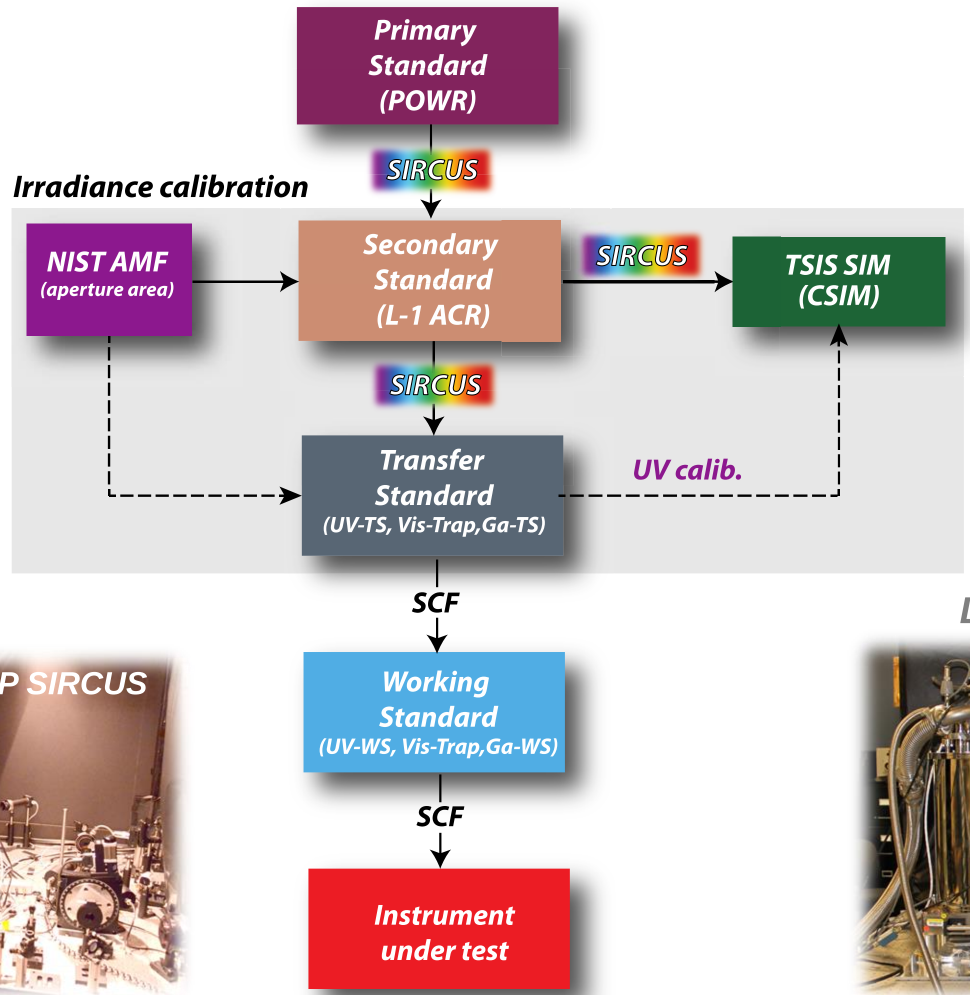
NIST AMF





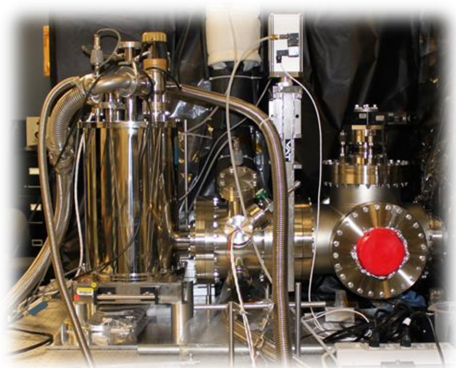


NIST Calibration Chain



NIST POWR

LASP L-1 ACR

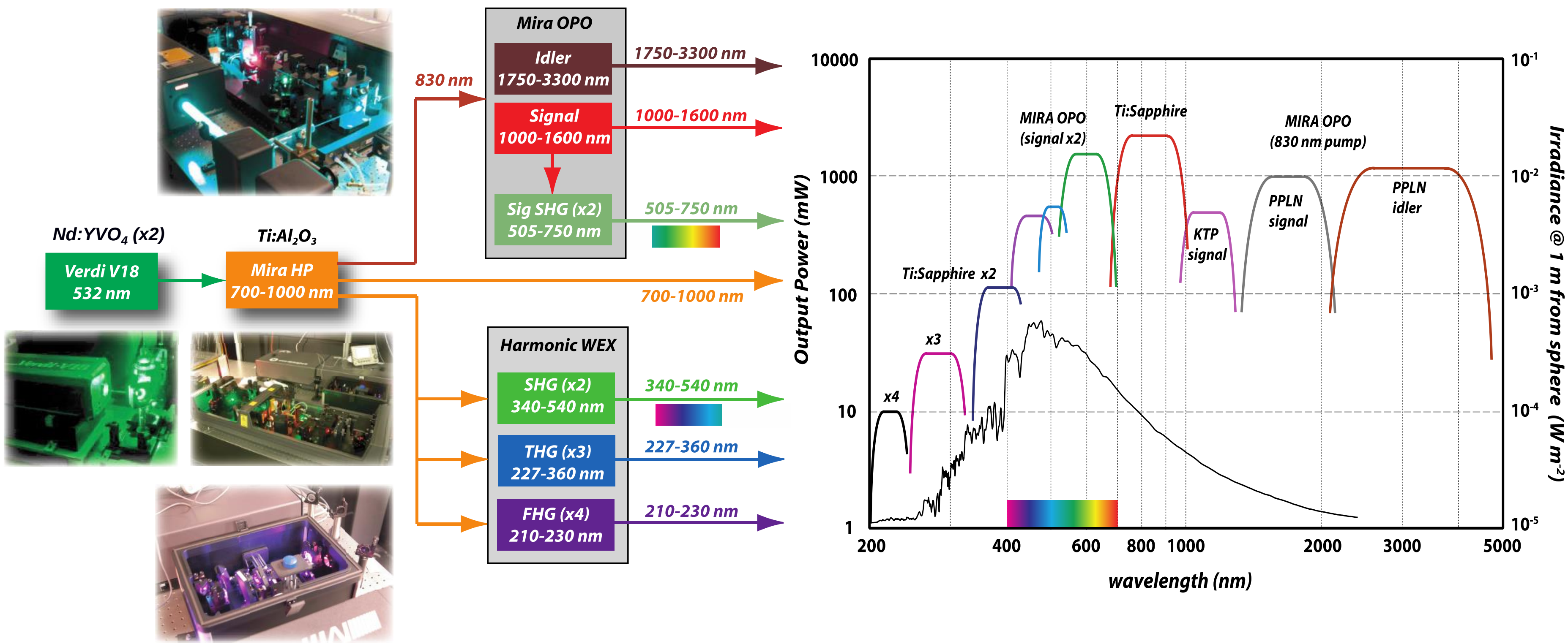


The LASP SRF uses an *L-1 Standards & Technologies* Absolute Cryogenic Radiometer with calibrated aperture to provide irradiance mode calibration

LASP Spectral Radiometry Facility (SRF)

The LASP SRF utilizes NIST SIRCUS laser sources coupled to L-1 cryogenic radiometer

The system is designed to reduce the uncertainties in spectral irradiance and power responsivity calibrations to the 0.1% level and expand the spectral range where these uncertainty levels are achievable. *(Brown et al., 2009)*



✓ ***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).***

Absolute Irradiance Scale (LASP-SRF)

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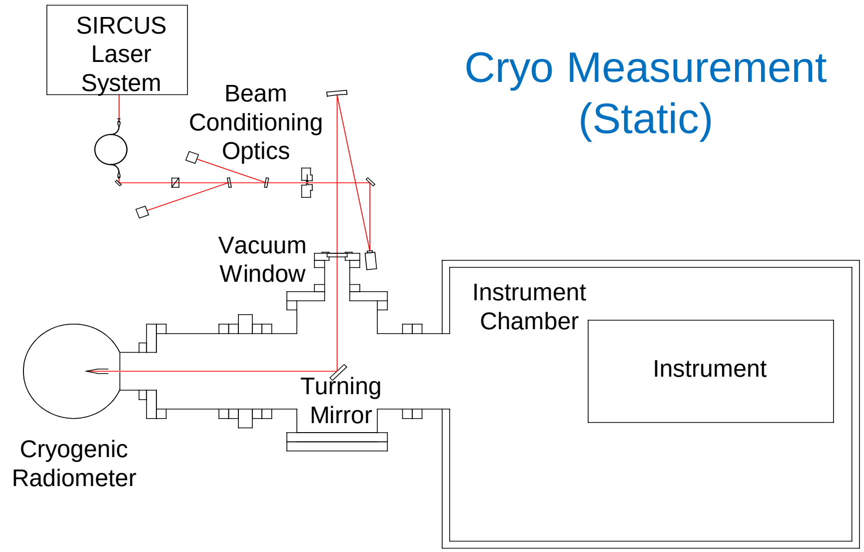
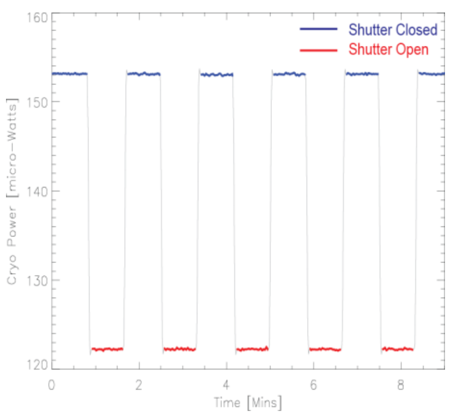
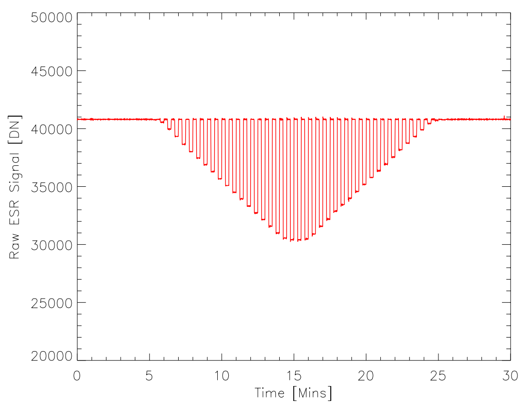
Cryogenic Radiometer Uncertainty Budget

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**





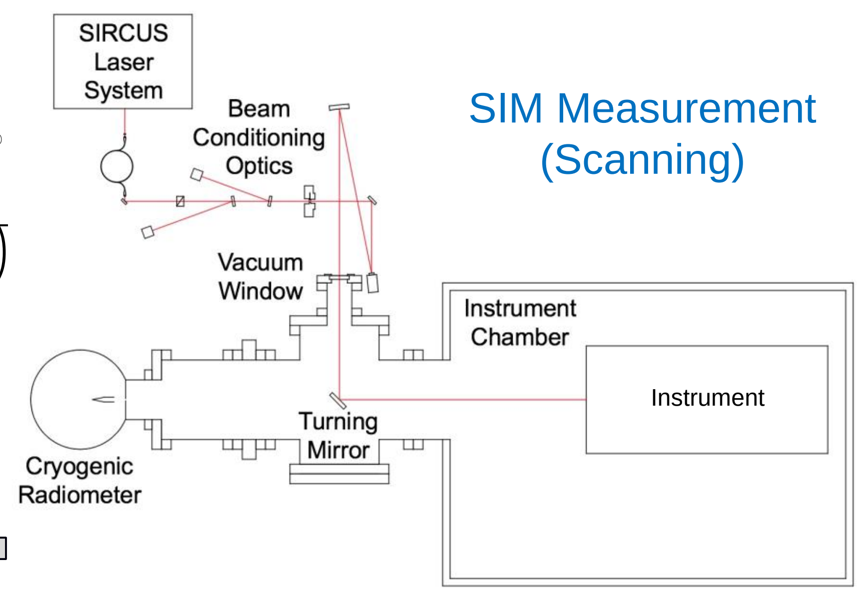


$$I_0 = \frac{DN(\lambda_0)}{AD(\lambda_0)C(\lambda_0)\bar{G}(\lambda_0,p)}$$

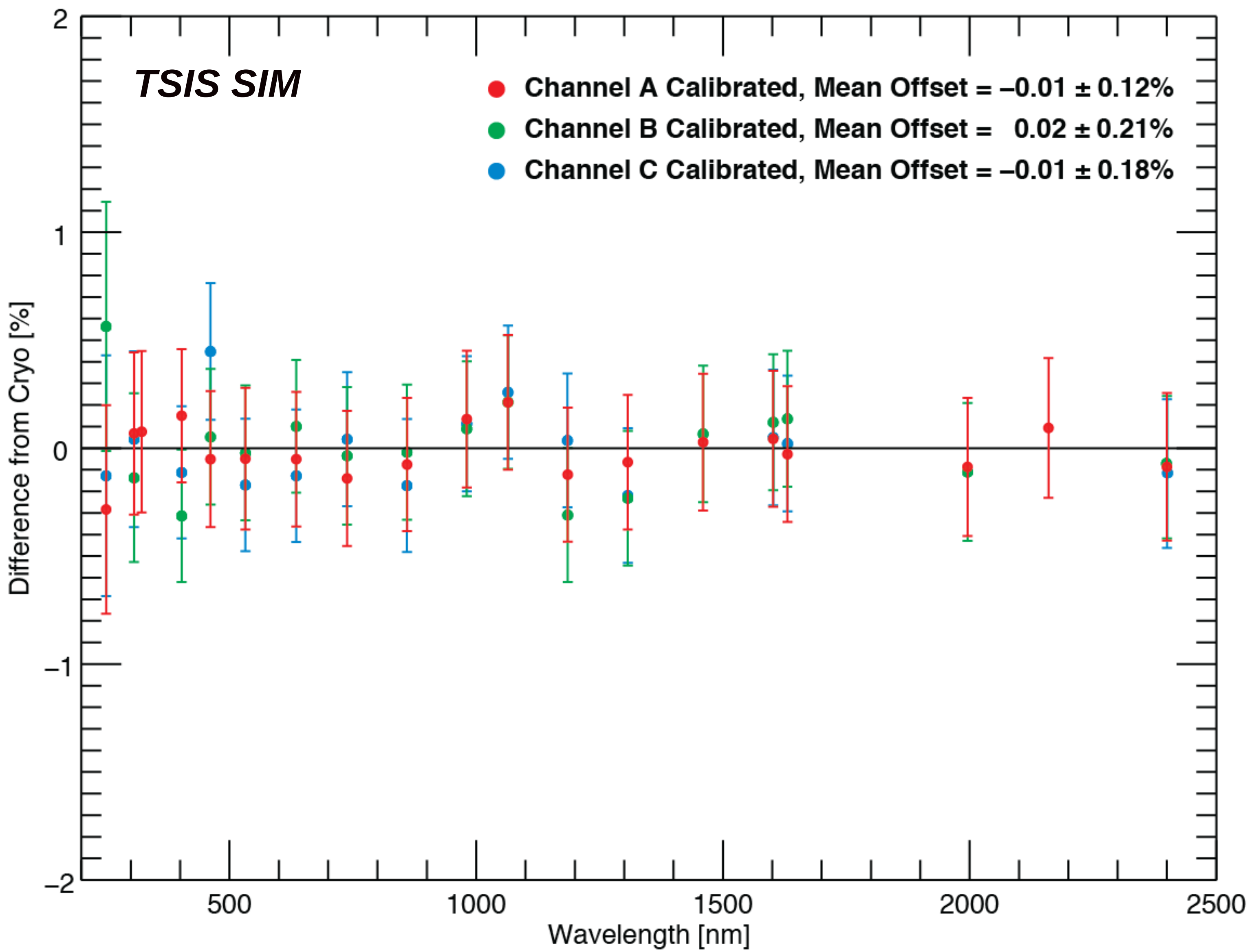
$$I_0 = \frac{\int DN(c)dc}{AD(l_0)T(l_0,p)\bar{G}(l_0,p)\mathrm{D}W(c)}$$

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**



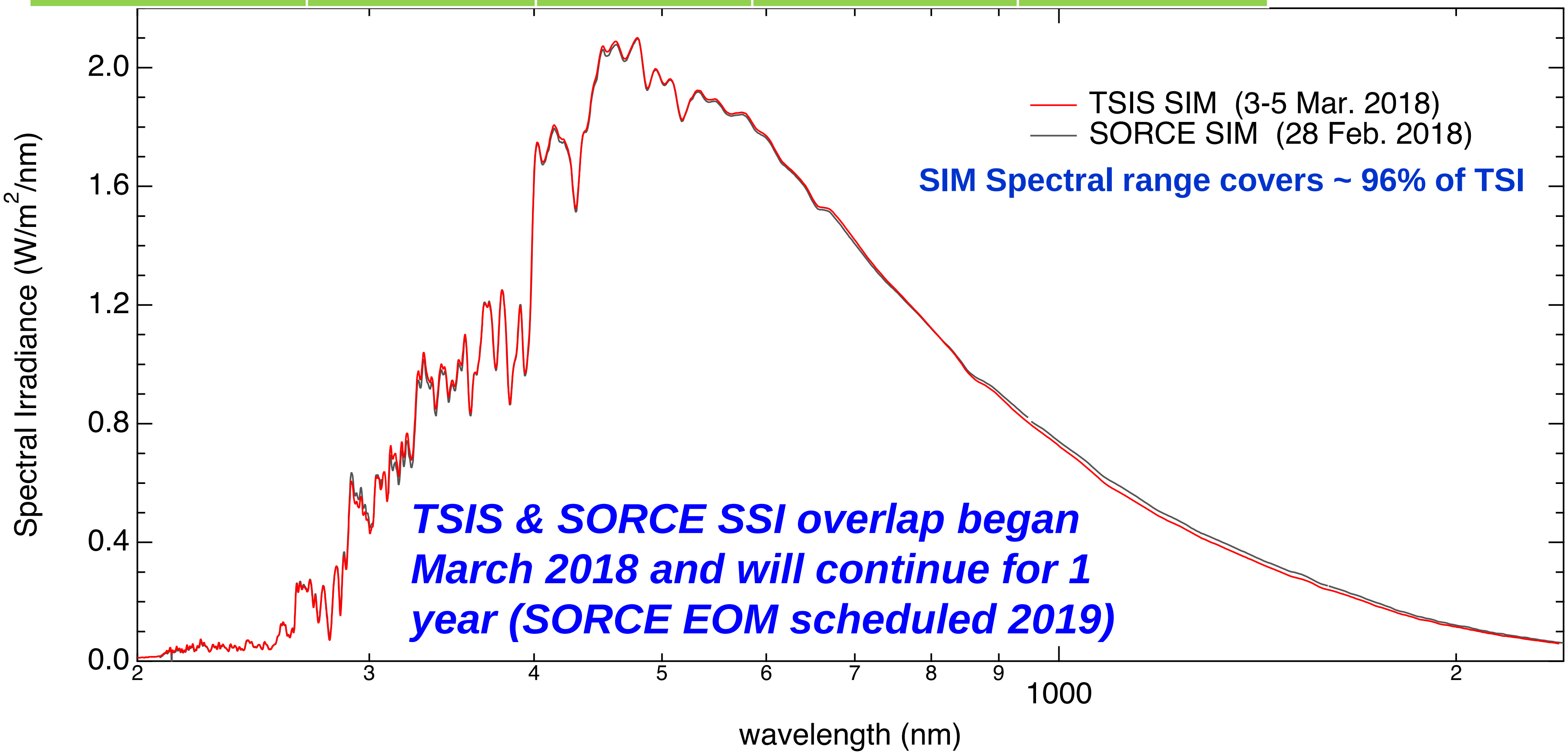
Full Spectrum Irradiance Validation



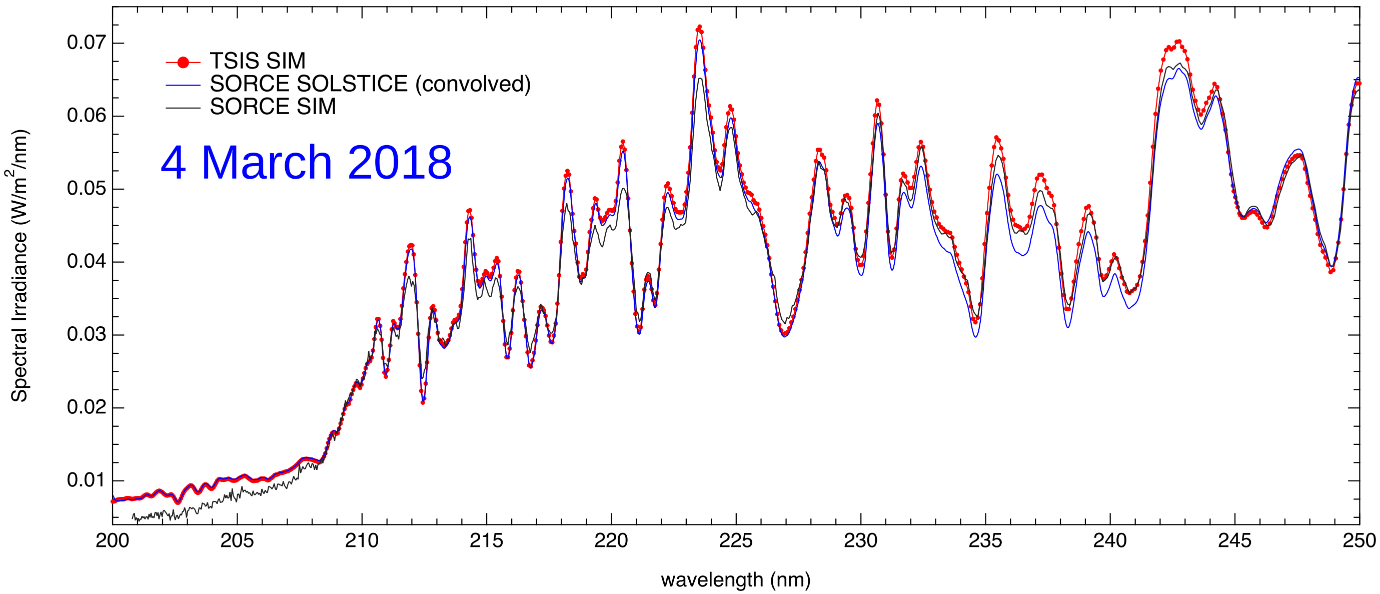
TSIS SIM First Light Comparison

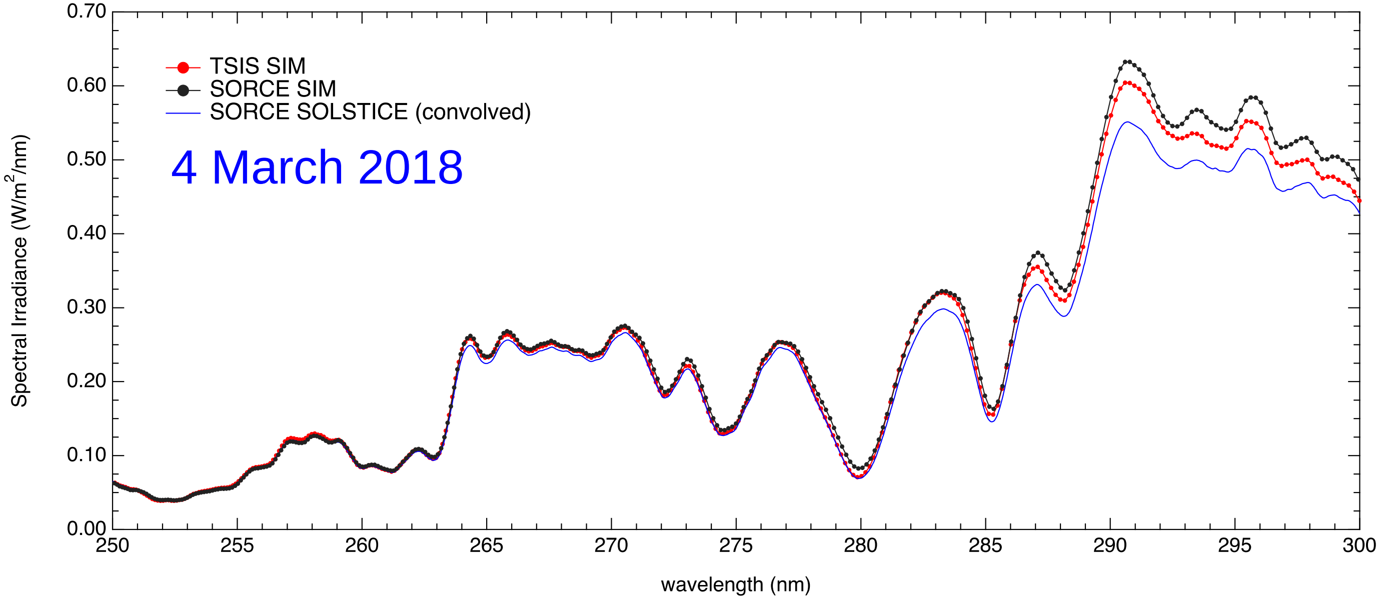
Reference Spectrum	205-2390 (W/m²) (96% TSI)	+ 52 (W/m²)*	TIM TSI (W/m²)	% Diff.
ATLAS-3	1333	1386	1362-1360	+1.76-1.88
SIRS-WHI	1323	1375	1362-1360	+0.95-1.1
TSIS SIM	**1307.6**	**1359.6**	**1360.6**	**-0.08**

***Integrated SSI contribution outside 205-2390 nm**



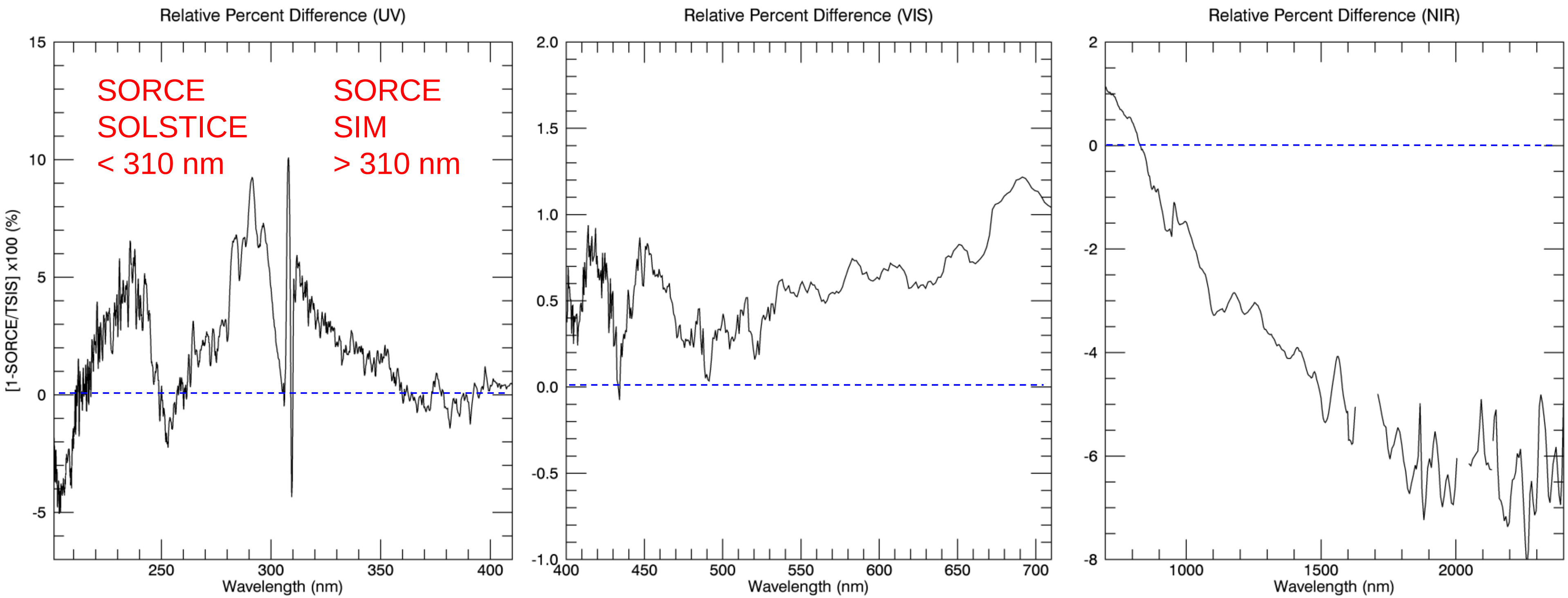
First Light Spectrum (200 - 300 nm)



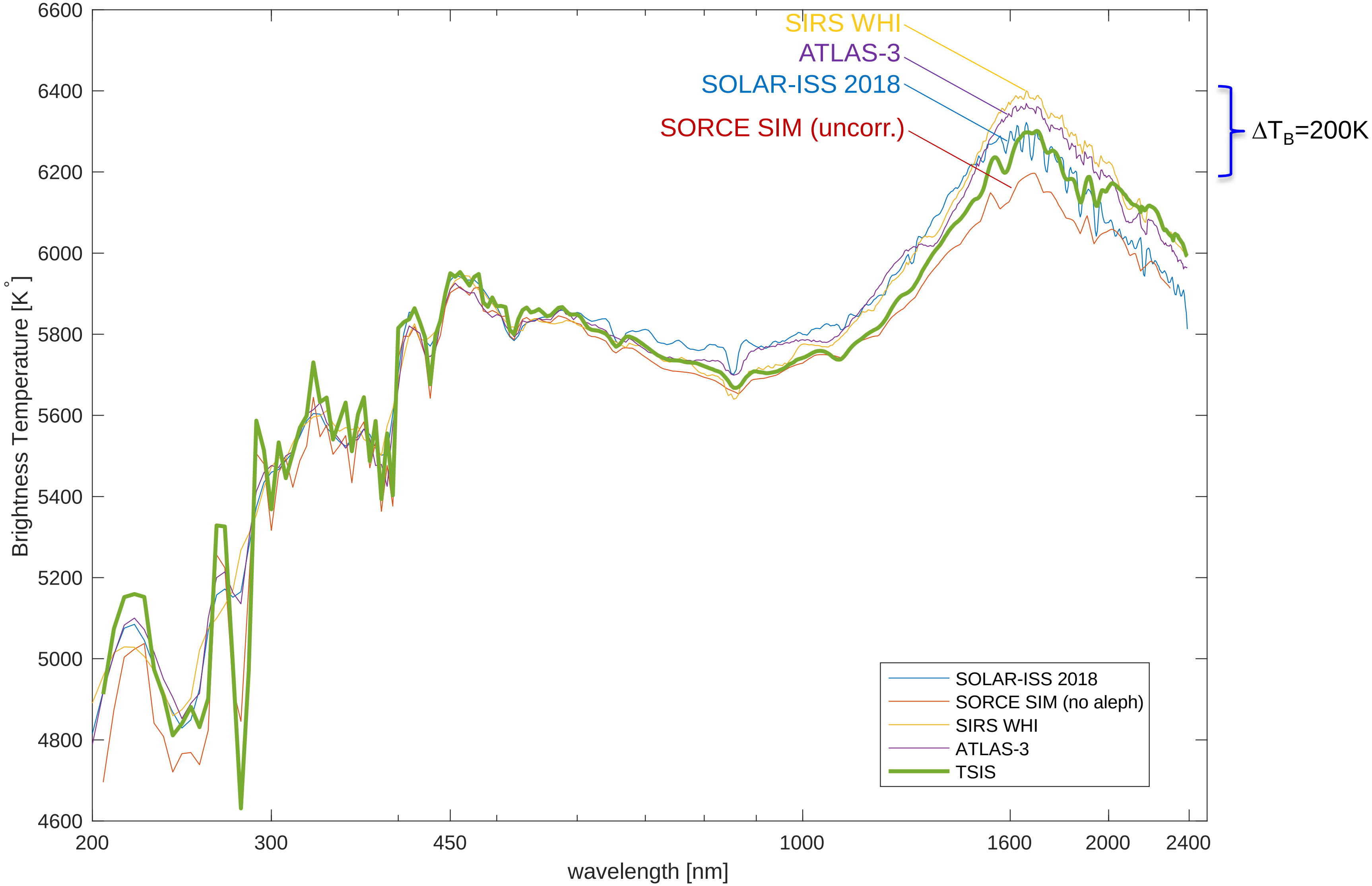


First Light: TSIS – SORCE SSI Differences

TSIS is lower in the near-IR by 2-6% (between 1000 and 2400 nm).
TSIS is higher in the VIS by ~0.5 %.
Differences from TSIS can reach +/- 5% in the UV.

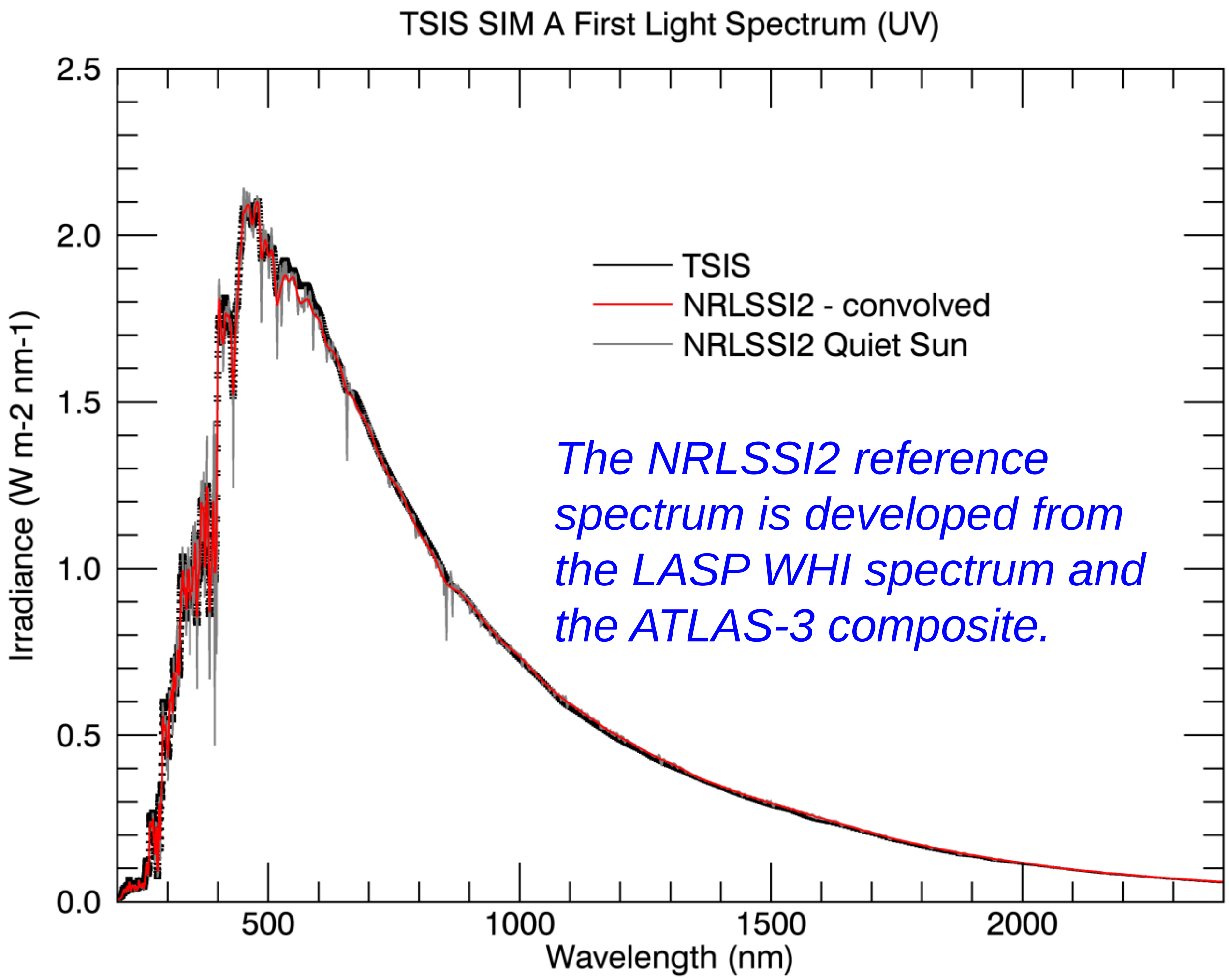


First Light: Brightness Temperature



TSIS SIM – NLRSSI2 (model) comparison

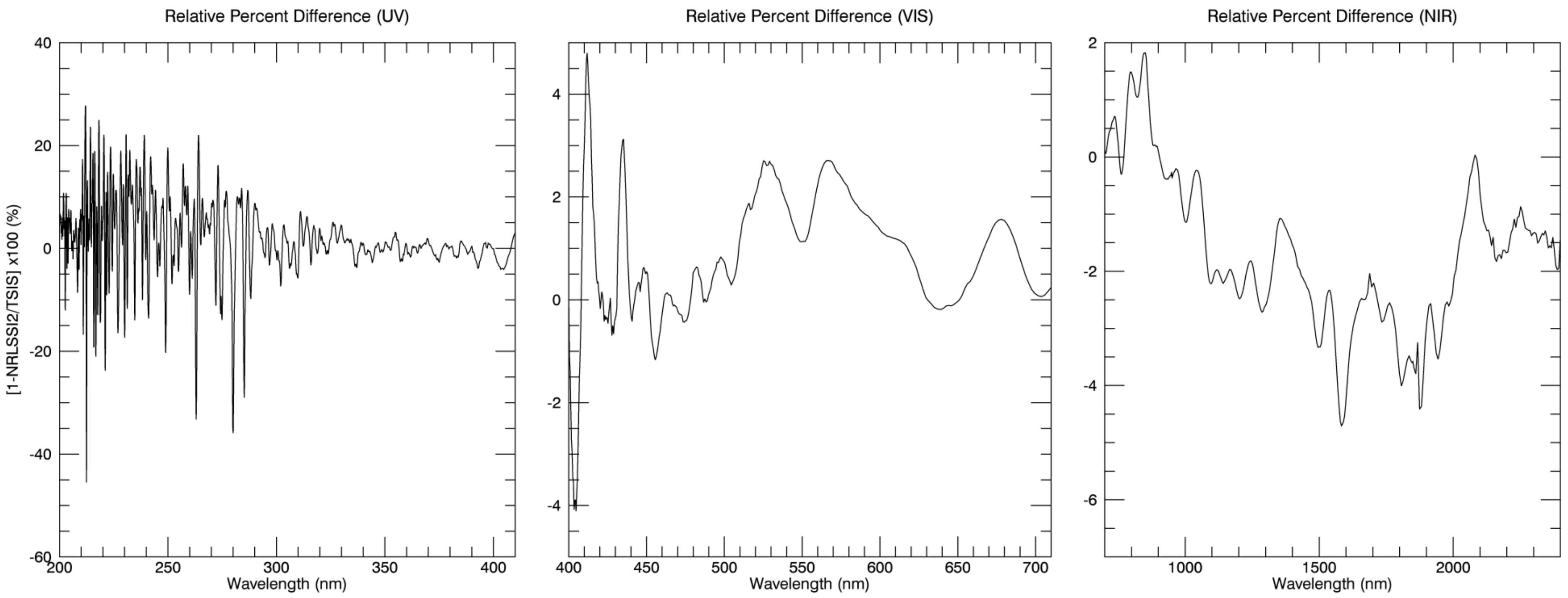
Solar irradiance variability models estimate time-dependent variability against a static, baseline, "Quiet Sun" (i.e. low solar activity) reference spectrum.



The NRLSSI2 reference spectrum is developed from the LASP WHI spectrum and the ATLAS-3 composite.

TSIS SIM – NLRSSI2 (model) comparison

Adjustments to the NRLSSI2 reference spectrum were made to within the magnitudes of the individual datasets (reported as 2-3% at wavelengths > 300 nm).
TSIS is lower in the near-IR by up to 4% (between 1500 and 2000 nm).
TSIS is higher in the VIS by ~1-2 %.
Comparison at wavelengths < 300 nm are dominated by noise (slight wavelength shifts?) in the NRLSSI2 reference as a result of the adjustment process.



Solar Exposure Degradation

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Issue:

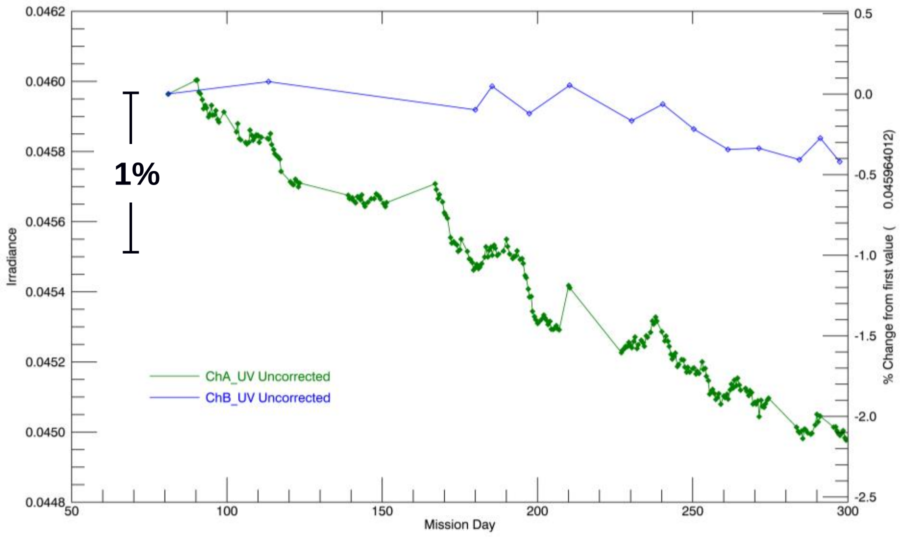
Optical degradation due to solar exposure (both wavelength and time dependent) is the largest contribution to the long-term measurement uncertainty

On-Orbit Approach:

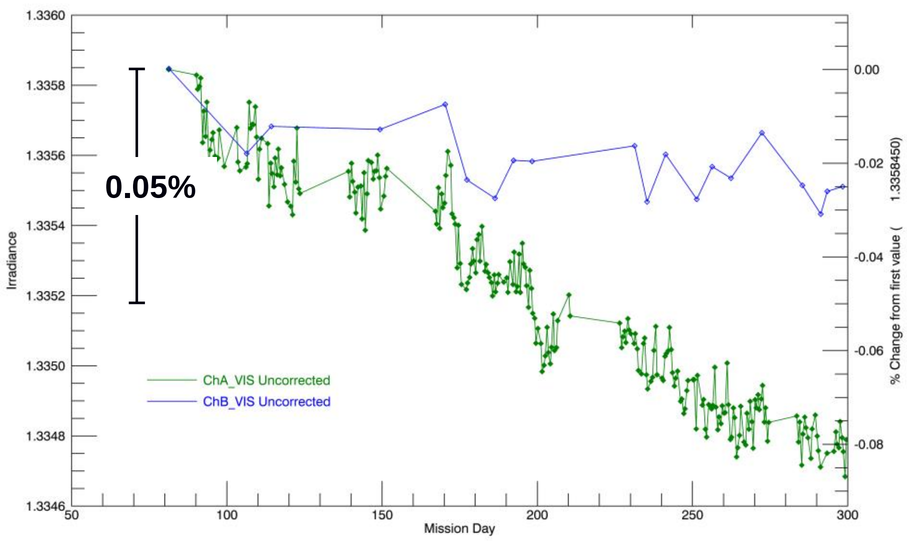
Periodic ESR & Photodiode Channel-to-Channel comparisons **(over common wavelength intervals during the same solar viewing period)** allows us to determine the optical degradation in the ESR measured irradiance.

Next Channel C exposure planned for April 2019

230-240 nm

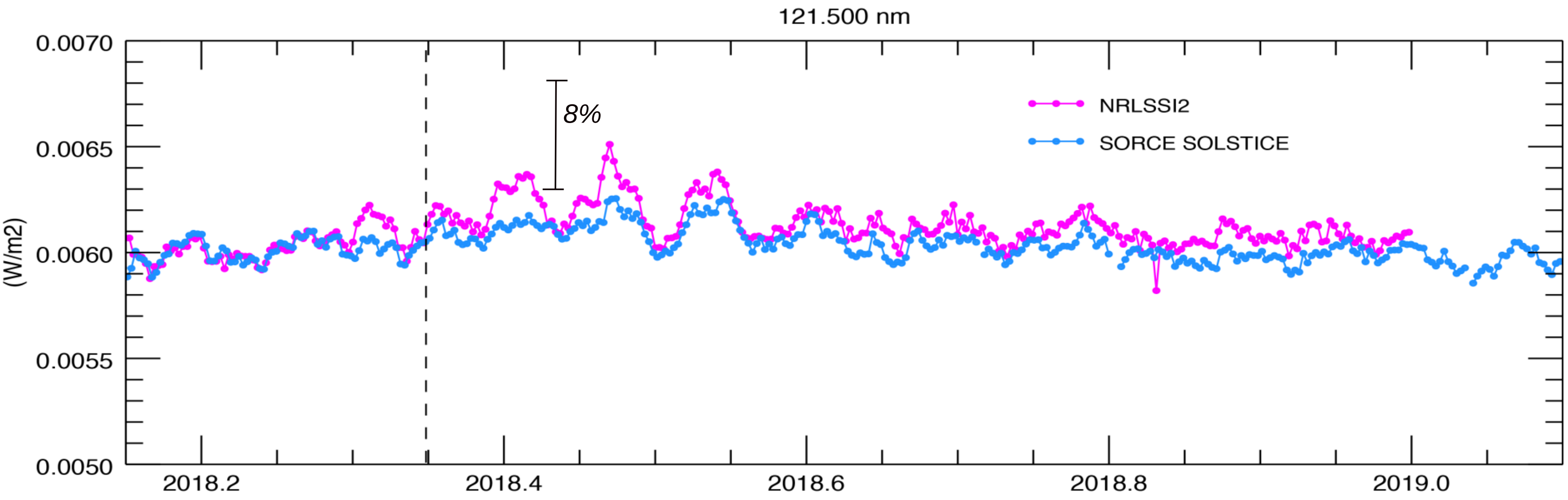


700-750 nm



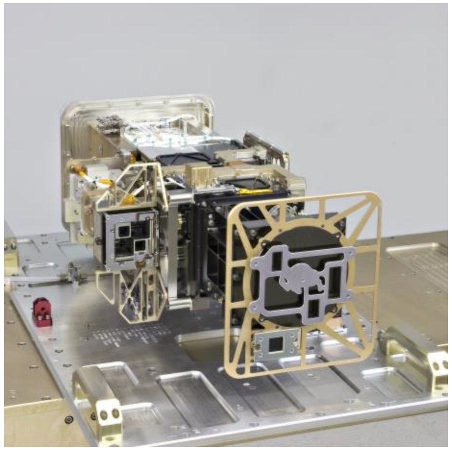
TSIS, SORCE, & model FUV comparison

After SORCE End-of-mission, there will be a gap in full-spectrum SSI measurements between 100-200 nm, necessitating the use of models, like NRLSSI2, to provide spectral & temporal variability.



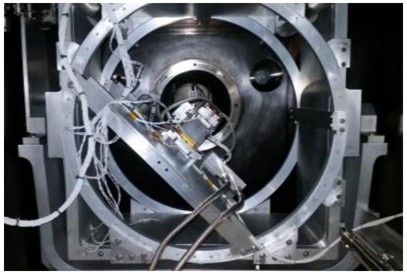
New and Future UV Datasets

Compact SIM (CSIM) 6U CubeSat
Launched December, 2018
1/10th the mass, 1/20th the volume of TSIS SIM
2 channel instrument
Absolute ESR detector (VACNT bolometer)
200-2400 nm
Absolute Accuracy 0.2% (SI-traceable validation)



GOES-R Exis (GOES-16)
Operational Lyman-alpha and Mg II index measurements
Launched Nov, 2016; data not yet publically available

GOES-17 launched March 2018



Compact SOLSTICE (CSOL) 2U CubeSat
115-310 nm
Calibration Underflight June 2018
To be mounted on INSPIRESat-3 for launch in 2021

CSIM First Light – TSIS SIM Comparison

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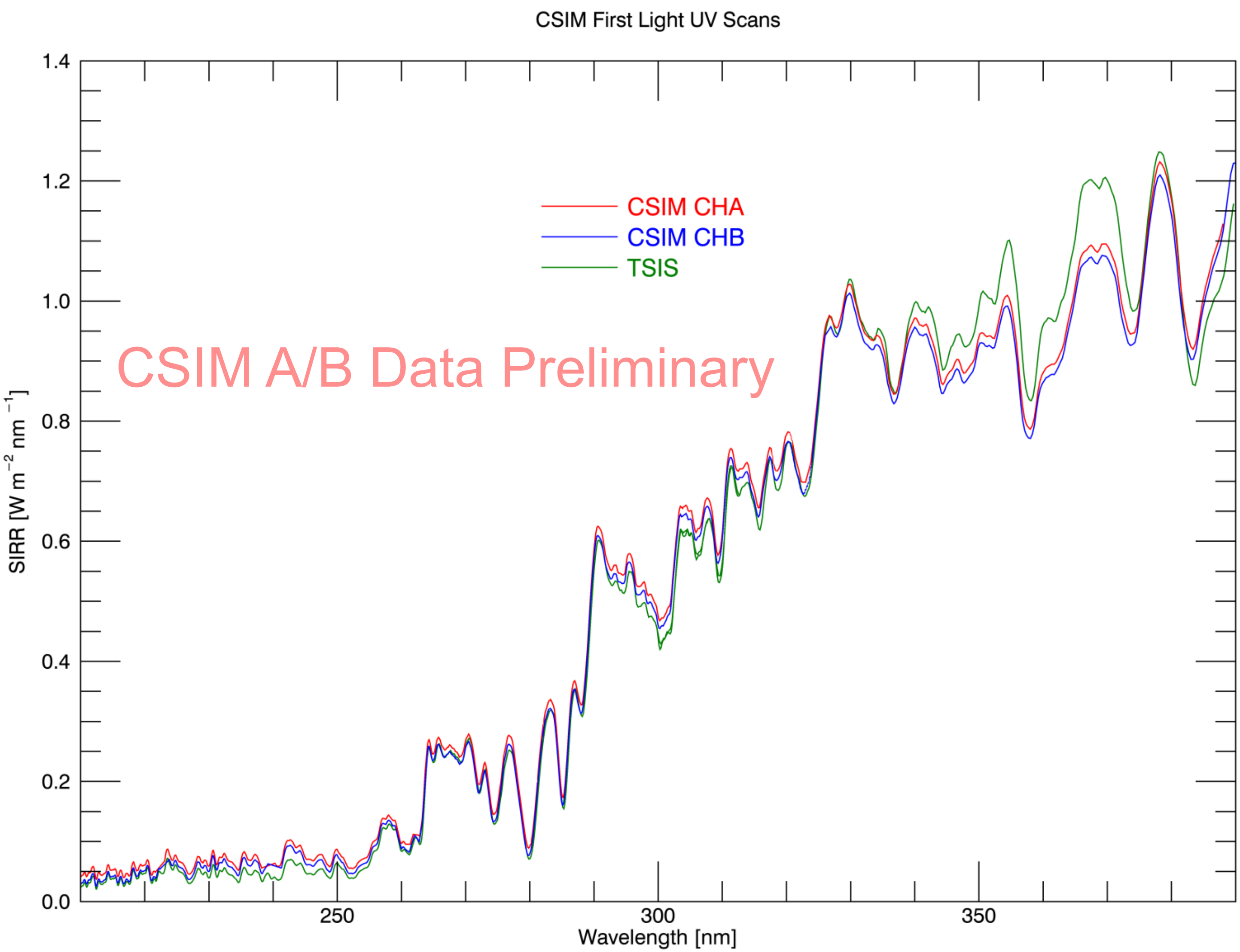

Summary

- **TSIS-1 is performing as expected thus far**.
- ***Repeatability***: TSIS SIM is measuring smaller changes in SSI than previous sensors.
- ***Accuracy***: Pre-launch measurement uncertainties validated in LASP SRF to 0.2% absolute accuracy
- ***Stability***: 2nd "C" channel measurement period in April 2019 (for degradation monitoring & correction)
- ***In development***: Time-dependent on-orbit measurement uncertainties and a TSIS SIM 'reference' spectrum.

- Continued observations beyond TSIS-1 are needed.
  - TSIS-2
  - Compact solar irradiance monitors (CSIM and a Compact TIM) being developed at LASP increase mission flexibility and increase the reliability in long-term data record.
  - After SORCE SOLSTICE, there will be a gap in full spectrum FUV (100-200 nm) observations.