

Accurate Long-term Measurements of Solar Spectral Irradiance: The TSIS-1 Spectral Irradiance Monitor on the International Space Station *...Toward an SI-Traceable SSI Data Record*

TSIS-1



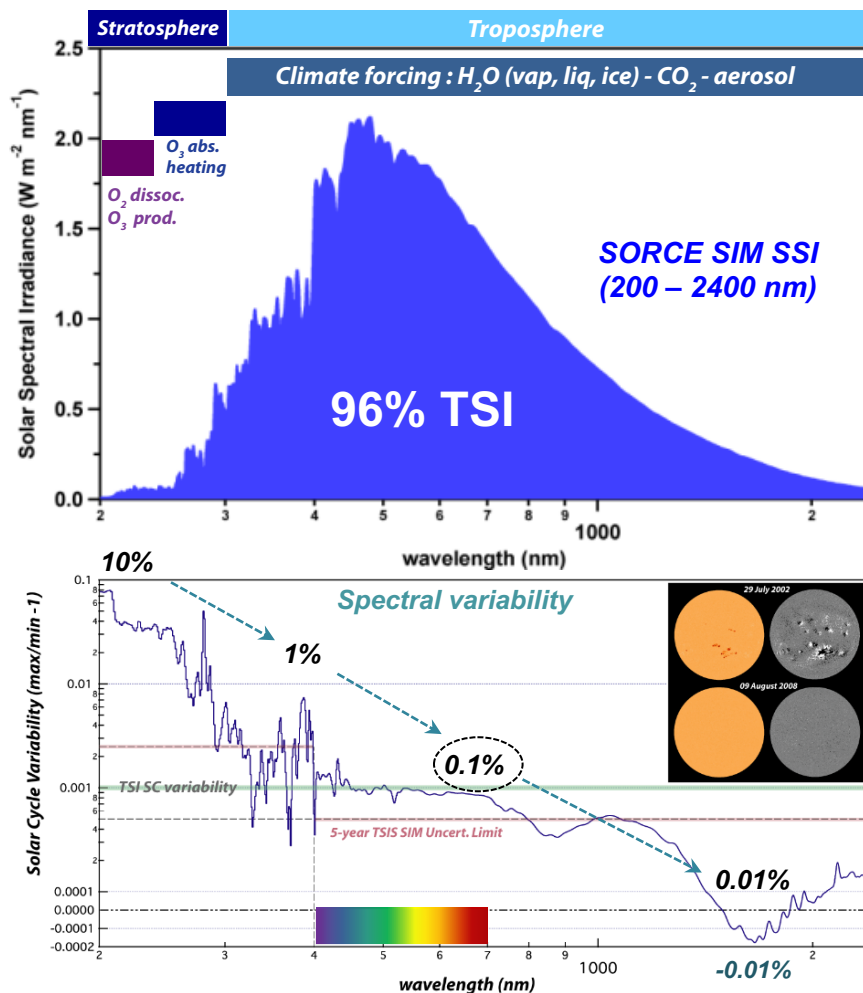
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Science Drivers for SSI Observations

SSI and its solar cycle variability



SSI necessary for attribution of climate forcing, atmospheric chemistry modeling, radiative transfer modeling, & conversion of measured satellite radiances to reflectances.

- Process studies seek to quantify mechanisms by which the Earth system responds to various forcings. (e.g. solar influence in "Top Down" and "Bottom Up" Mechanisms)
- Requires measurement of wavelength-dependent irradiance variability over decadal timescales.

The need for standard and accurate solar irradiance spectra is of critical importance for radiative transfer applications in climate research

- Present SSI absolute accuracies are in the 2-8% uncertainty range, wavelength dependent.
- SSI absolute accuracies <1% are required to enable more realistic climate model simulations for comparisons with empirical evidence and projections of future change.

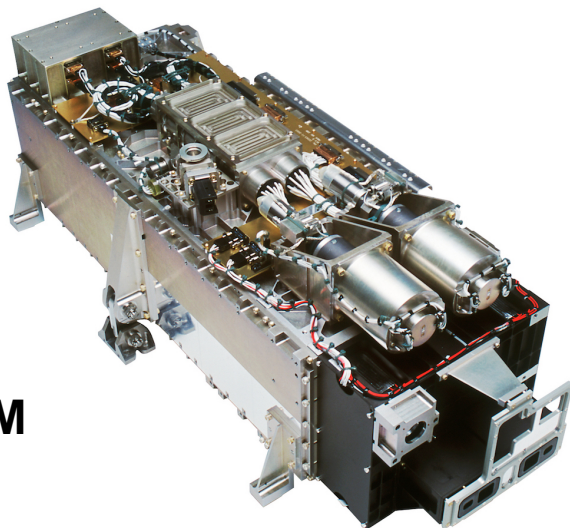
Beginning with SORCE and now continuing with TSIS-1, SIM SSI measurements represent the first continuous monitoring of variations in the UV, Visible, and near IR regions of the solar spectrum.

- Long-term SSI stabilities < 0.05% per year are required quantify the spectral partitioning of irradiance variability on solar-cycle timescales; requires overlapping measurements to validate corrections in the long-term, composite record.



200-2400 nm SSI Continuity

SORCE SIM



SORCE SIM (launched 1/25/2003)

- Two channel instrument (duty-cycled for stability corrections)
- Absolute ESR detector (NiP bolometer)
 - First generation (nominal performance, noise >3 nW @ 40 sec.)
 - Diamond substrate
 - NiP black absorber
- **Abs. accuracy unc.: 2-10% (no end-to-end SI-validation)**
 - Adjusted to match ATLAS3 reference spectrum
- Poor long term stability – not sufficient for model validation

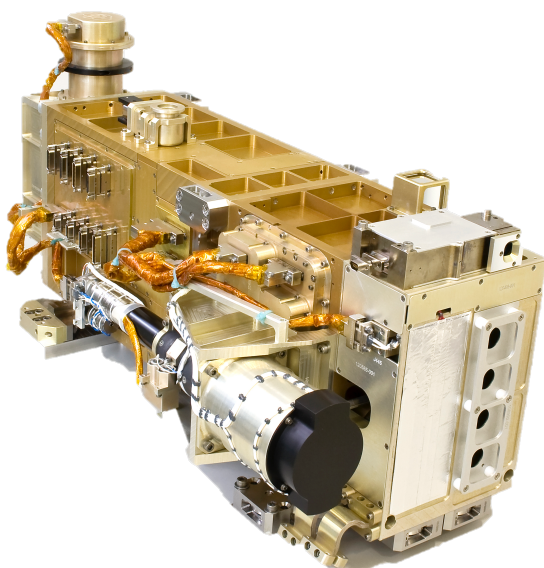
...still operating, will be turned off in early 2020.

TSIS SIM (launched 12/15/2017)

- ✓ Three channel instrument
 - For long-term stability validation of duty-cycling
- ✓ Absolute ESR detector (NiP bolometer)
 - Second gen. (improved performance, noise 1.6 nW @ 40 sec.)
 - Diamond substrate
 - NiP black absorber
- ✓ **Abs. accuracy unc.: ~0.2 % (SI-traceable validation)**
 - First SSI radiometer with detector based calib. tied to NIST cyro. rad.
- ✓ Long term stability approaching validation levels
- ✓ Full spectrum every 12 hours (...when ISS permits)

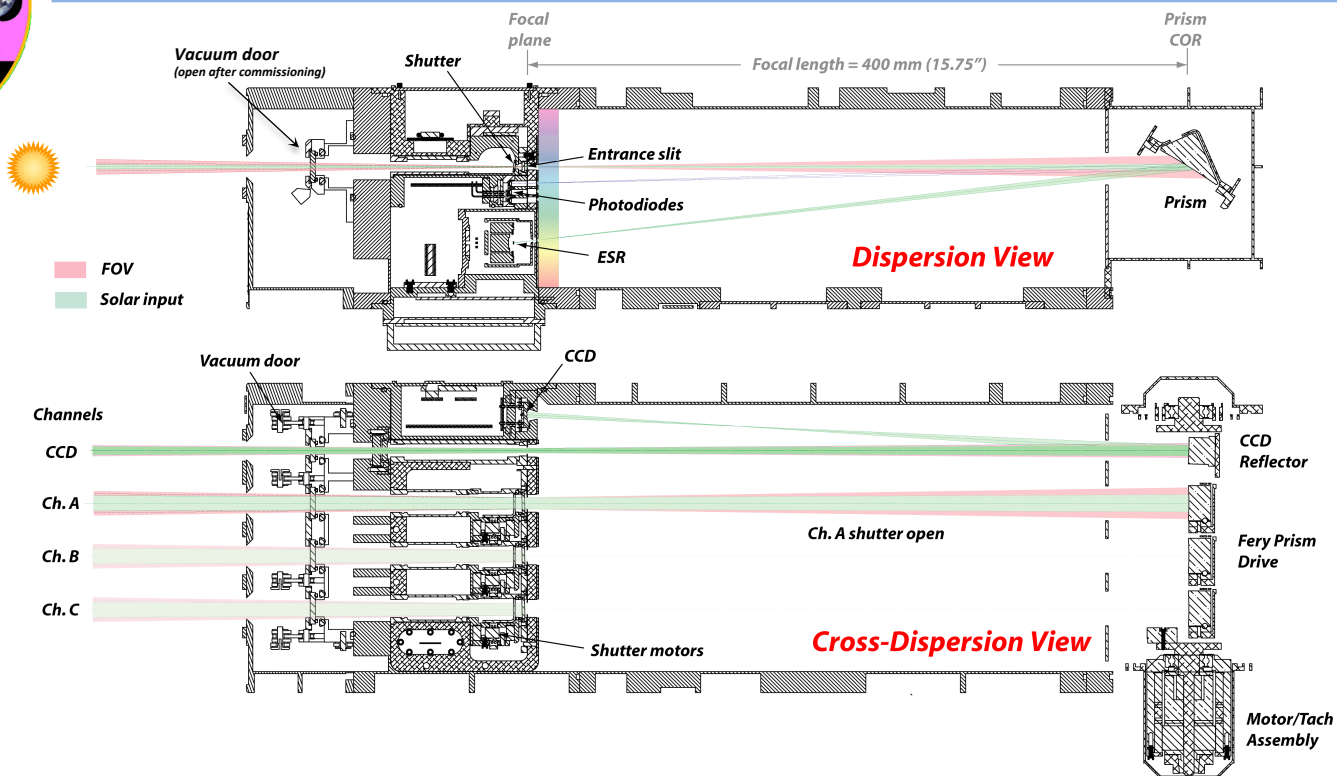
...so far, 1.5 years of overlap with SORCE SSI

TSIS-1 SIM





TSIS-1 SIM Design Overview

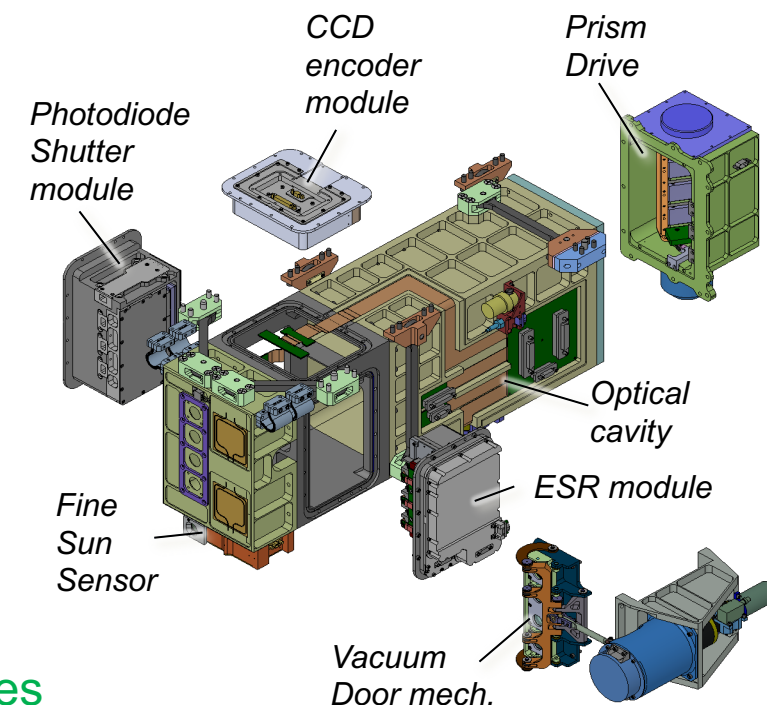


Féry prism spectrometer covering the full wavelength range from the UV to NIR (200 nm – 2400 nm) using only one optical element for spectral dispersion and image quality – characterize absolute measurement equation

Goal: Characterize as an absolute radiometer with native irradiance scale

$$\mathcal{E}_{\lambda}(\lambda_s) = \frac{\mathcal{P}_{\text{ESR}}(\lambda_s)}{A_{\text{slit}} \cdot \int \alpha_{\lambda} \cdot T_{\lambda} \cdot \phi_{\lambda} \cdot S(\lambda, \lambda_s) d\lambda} \quad (\text{W m}^{-2} \text{ nm}^{-1})$$

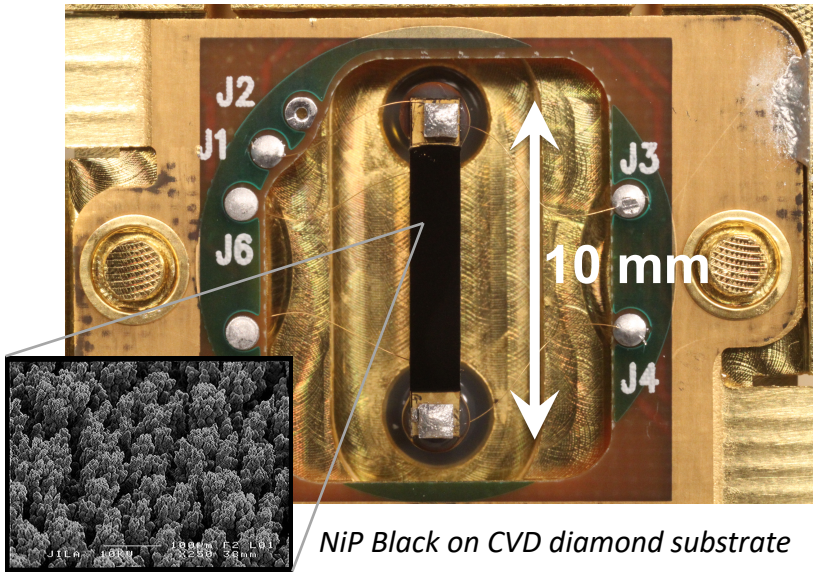
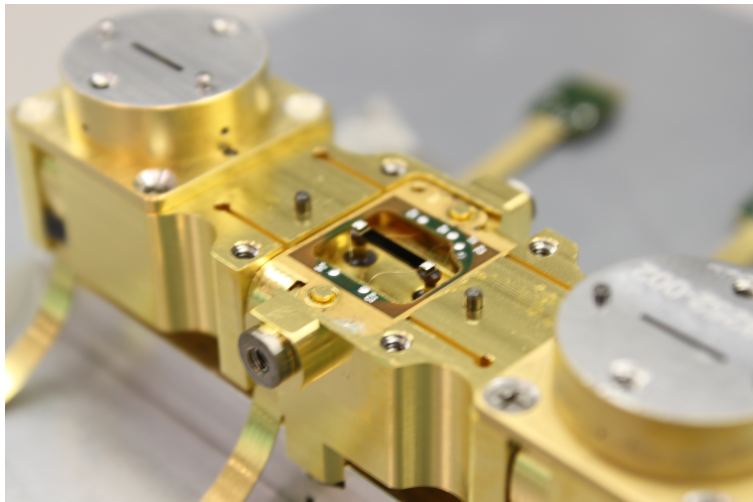
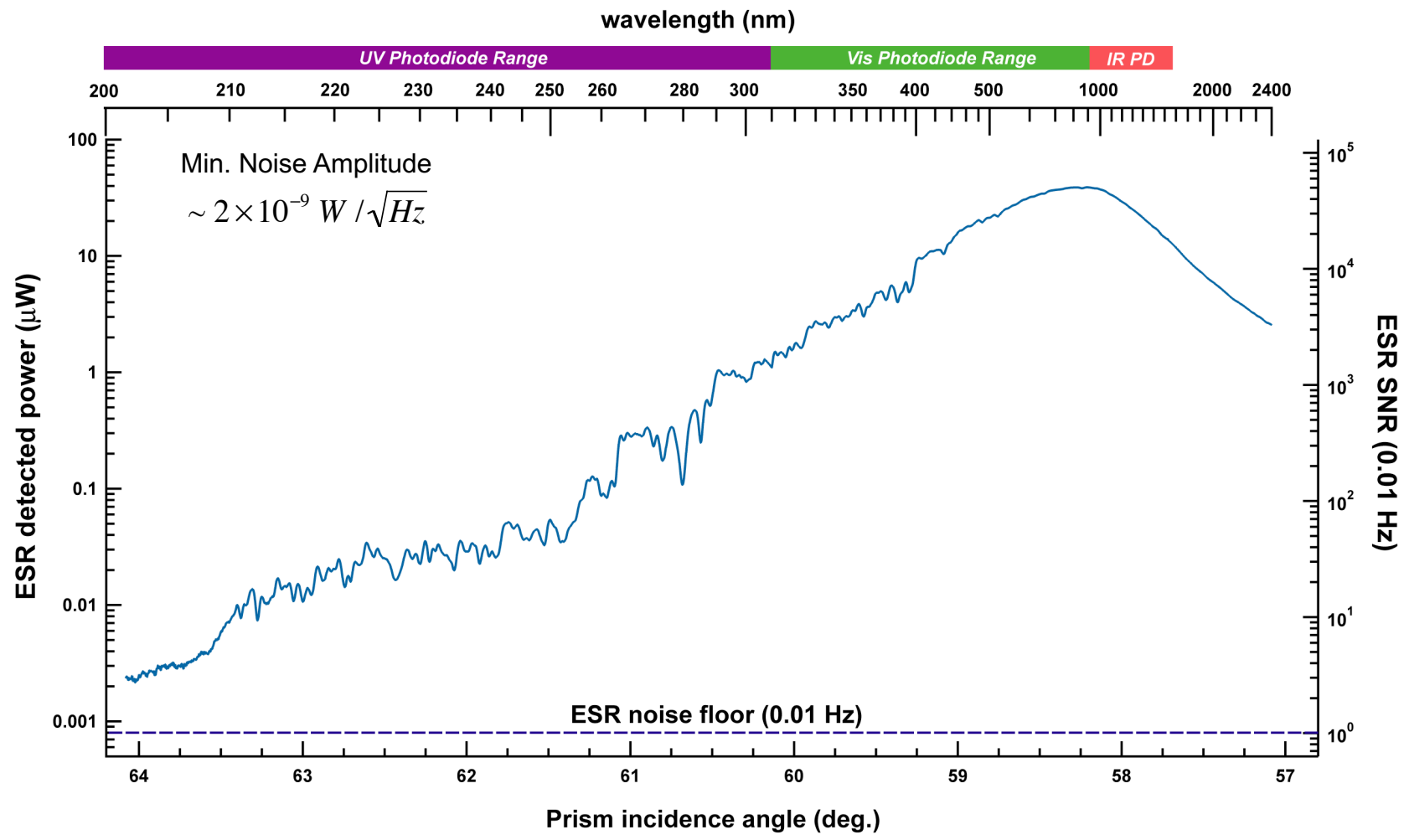
✓ Modular design that allows for unit-level and sub-system performance characterizations and calibrations, also help to mitigate contamination issues





ESR Spectral Performance

The SIM ESR is an optical power traceable, space-qualified absolute detector





Solar Attribution Measurement Accuracy

A challenging goal for TSI and SSI

“Long-term observations of the Sun’s radiation on the Earth, total and spectrally resolved, at uncertainties of 0.01 and 0.1 percent, respectively, is critical to ensure that we can fully account for the effects of all natural variability when monitoring climate and the results of any mitigation strategies. This can only be achieved through robust traceability to International System of Units (SI). The uncertainty levels required, which are commensurate with those of primary scales at NMI’s, means that we have to take instruments into orbit based on the same concepts as the terrestrial primary standards, i.e. cryogenic radiometry.”

– N. Fox, et al., “**Accurate radiometry from space: an essential tool for climate studies**”, *Philos. Trans. Roy. Soc. London A, Math. Phys. Sci.*, Vol. 369, No. 1953, pp. 4028-4063, (2011).

Recent developments in the techniques used to establish primary spectral radiometer scales make it possible to improve significantly the accuracy and traceability of spectral irradiance measurements and assure quantification of absolute measurement uncertainties near 0.1%

(Brown, et al., 2006; Richard, et al., 2011, 2015; Harber, et al. 2015)





Source-based Uncertainties

Climate benchmark missions such as CLARREO drive calibration requirements for incident and reflected solar absolute measurement uncert. to state-of-the-art levels

CLARREO Radiometric Specifications

- Spectral range: 320-2300 nm
- Radiometric calibration uncertainty $\leq 0.3\%$ ($k=2$) in reflectance
- Radiance calculated from reflectance using SSI spectrum with uncertainty $\leq 0.2\%$ ($k=1$)

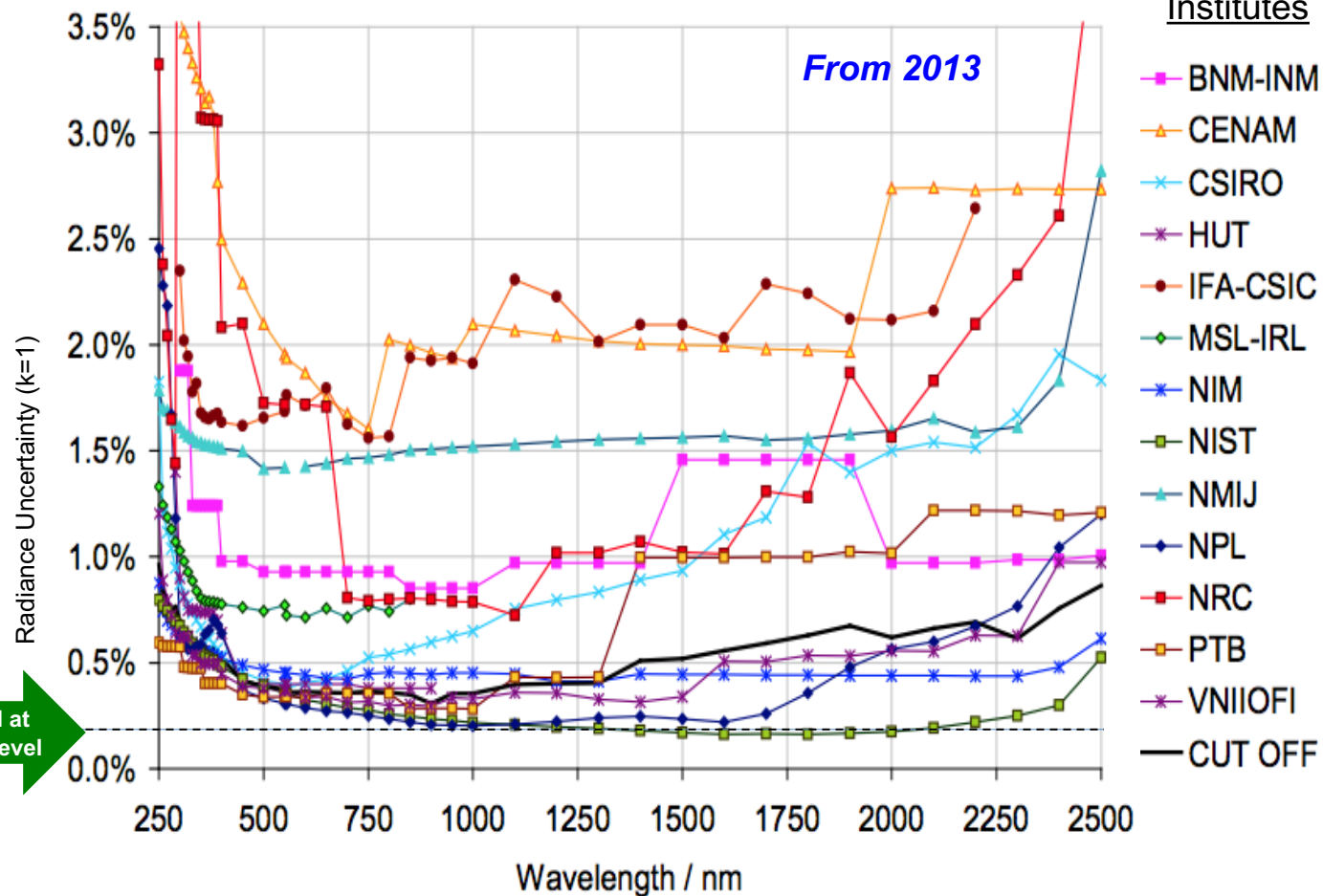


Figure courtesy: H. Yoon, NIST

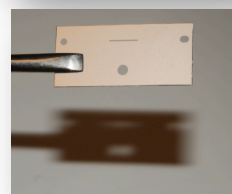
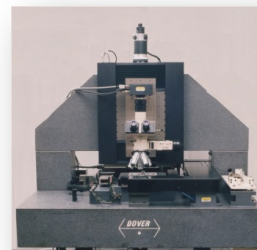
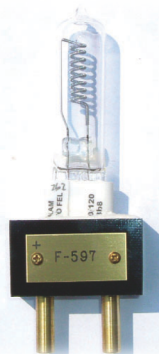


Source vs. Detector based irradiance scales

Source Based Scale

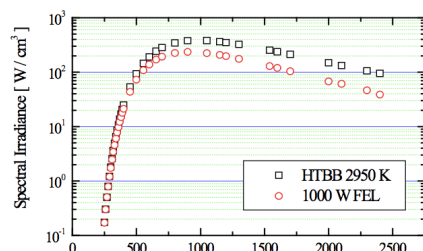
Irradiance from an extended source

- Based on radiance calibration from Planck BB (< 3000 K)
- "Lamp Plaque" Method
- Uncertainties dependent on orientation and distances (calibration at fixed distance – 50 cm)
- D₂ lamps standards for 200- 350 nm



Unc. (k=1) ~0.25%

L , Radiance [$\text{W}/\text{m}^2/\text{nm}/\text{sr}$]
 (Blackbody: Planck's law)



E , Irradiance [$\text{W}/\text{m}^2/\text{nm}$]

Detector Based Scale*

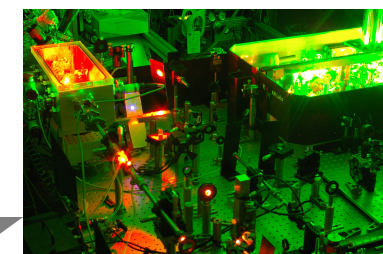
Electrical substitution radiometry

- Optical watt equivalent to electrical watt
- Cryogenic cavities and flux-stabilized lasers
- Reference standard detectors—flux responsivity
- Scale realizations in detector responsivity, spectro-radiometry, and photometry



Unc. (k=1) ~0.05%

F , Power [W]
 (ESR: Optical W = Electrical W)



Unc. (k=1) ~0.01%

A , Aperture area [m^2]

0.2%

2%

uncertainty at instrument-level

E , Irradiance [$\text{W}/\text{m}^2/\text{nm}$]

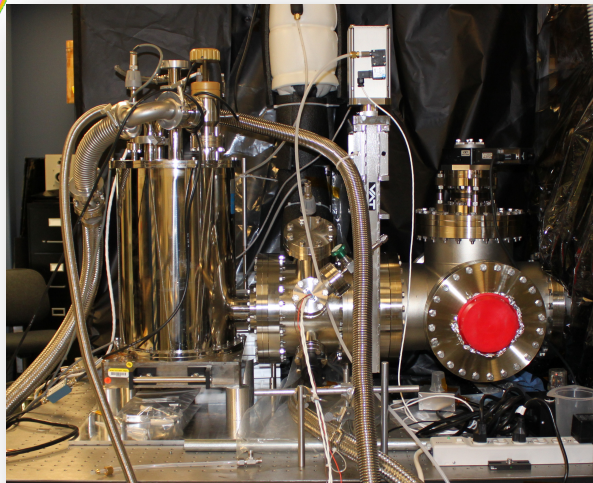
Adapted from: H.W. Yoon, et al., 2013

*Since 2001, all NIST-disseminated spectral irradiance standards have been based on the detector-based scale

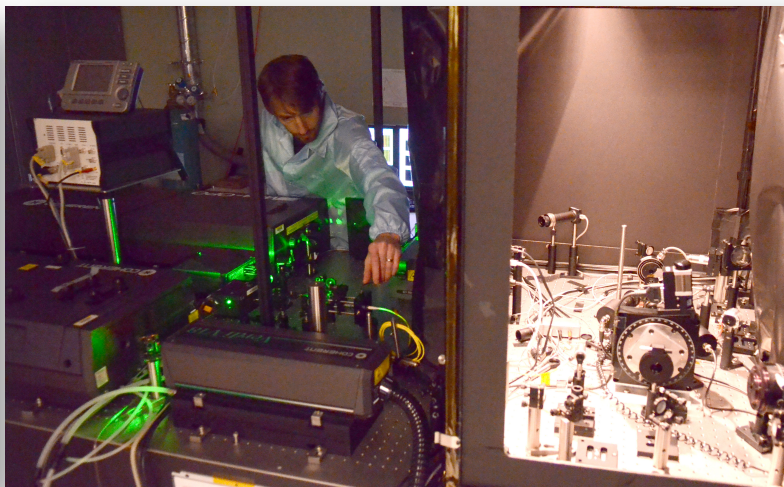


Absolute Irradiance Scale (LASP-SRF)

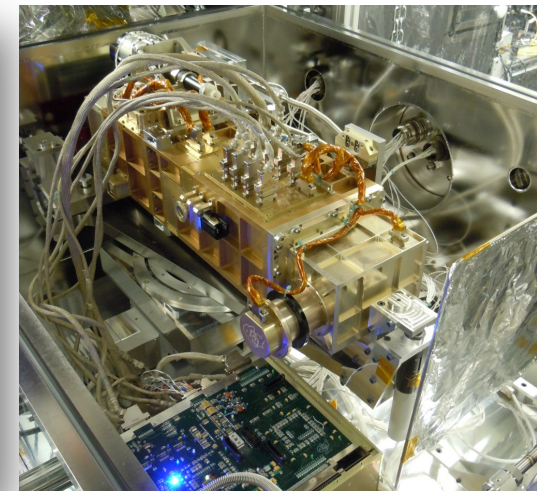
L-1 Cryogenic radiometer (NIST traceable)



SRF "SIRCUS" Laser system (206 – 3000 nm coverage)

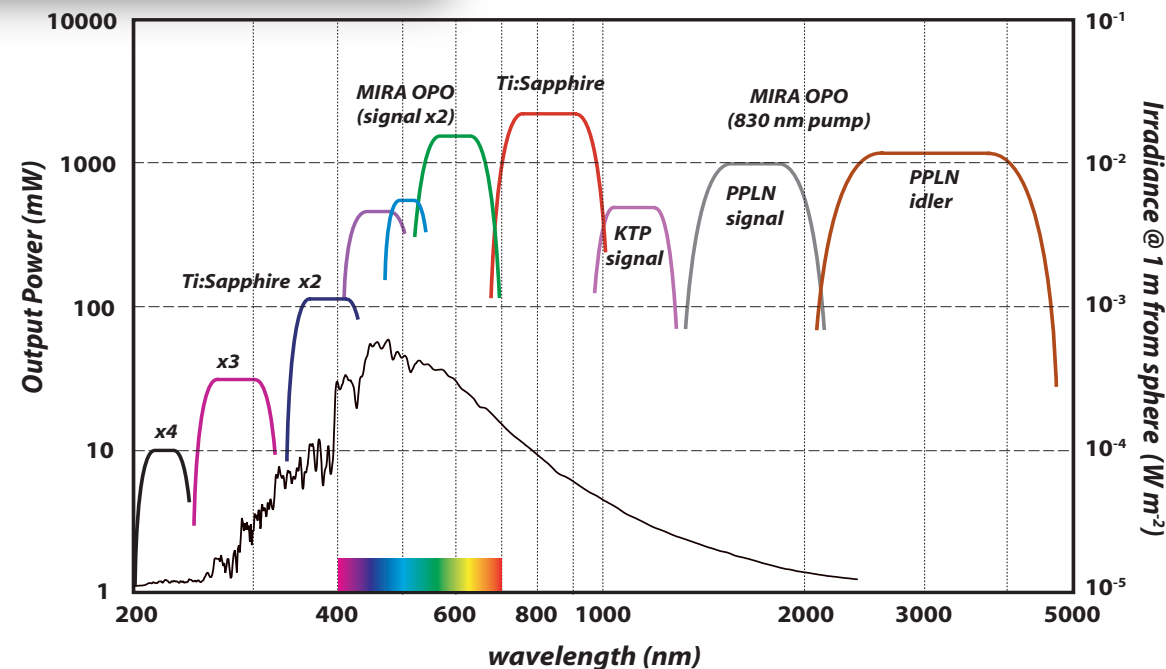


TSIS SIM in Vacuum Calib. Chamber



LASP SRF Facility

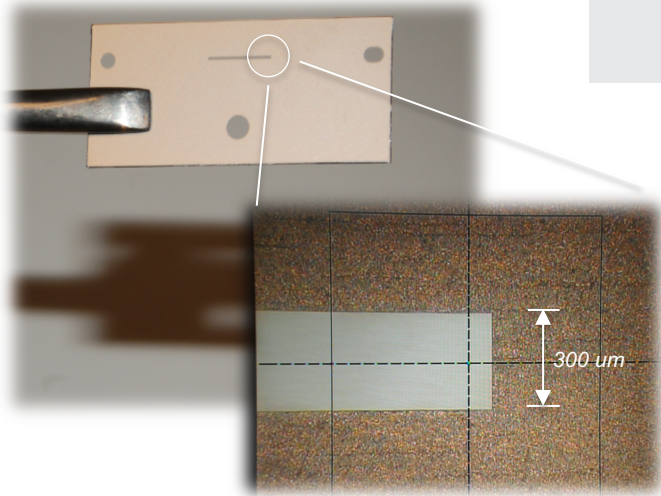
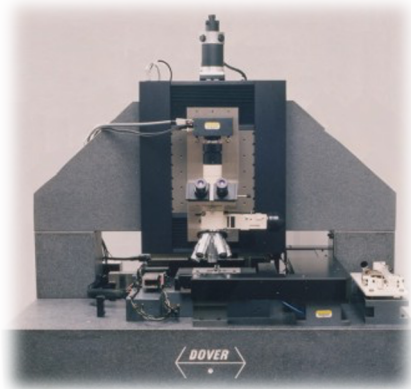
- SRF allows absolute end-to-end spectral irradiance validation of the instrument tied to a NIST traceable cryogenic radiometer and to evaluate instrument optical performance as a function of wavelength
- Direct ESR Calibration against the cryogenic radiometer (in Watts) is also part of the process as it provides the vacuum environment optimized for ESR noise testing at solar power levels
- Designed to achieve < 1% (0.2% goal) absolute accuracy uncertainty validation



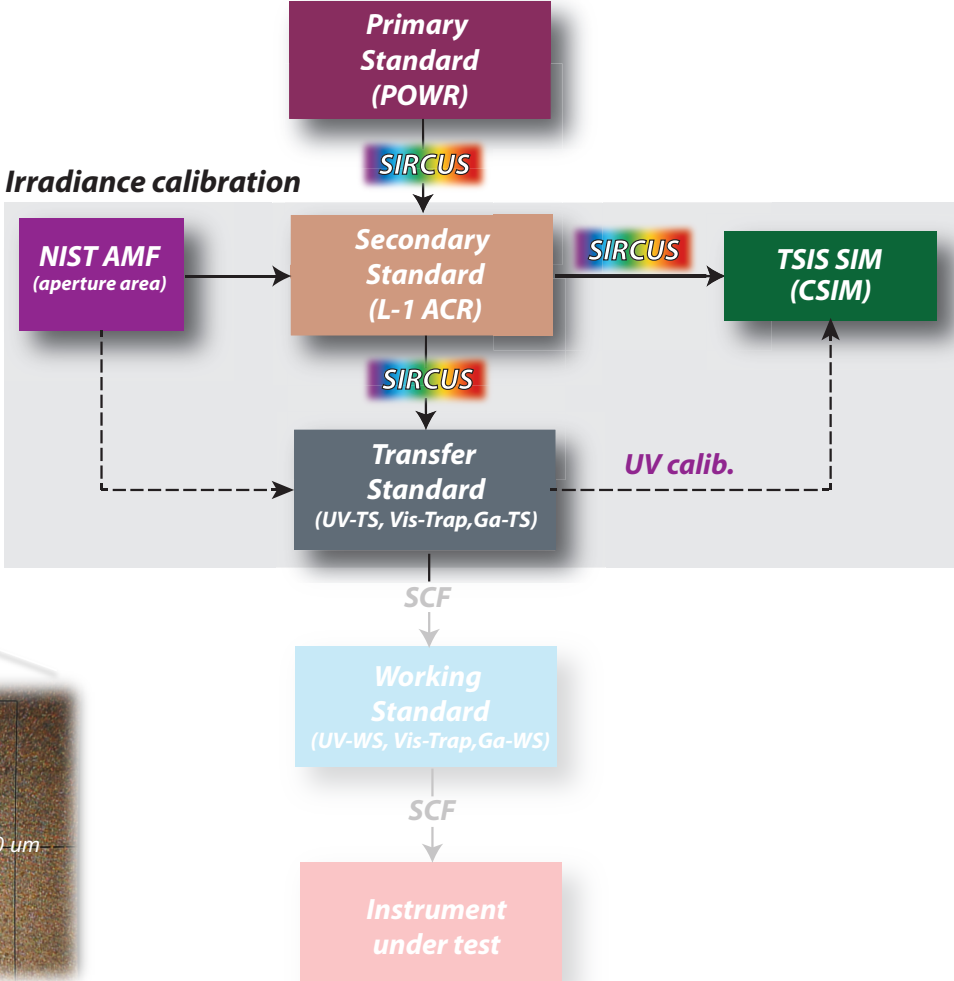


Spectral Irradiance Traceability

NIST AMF



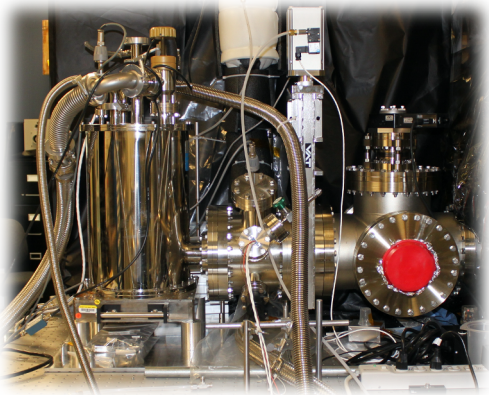
NIST Calibration Chain



NIST POWR



LASP L-1 ACR

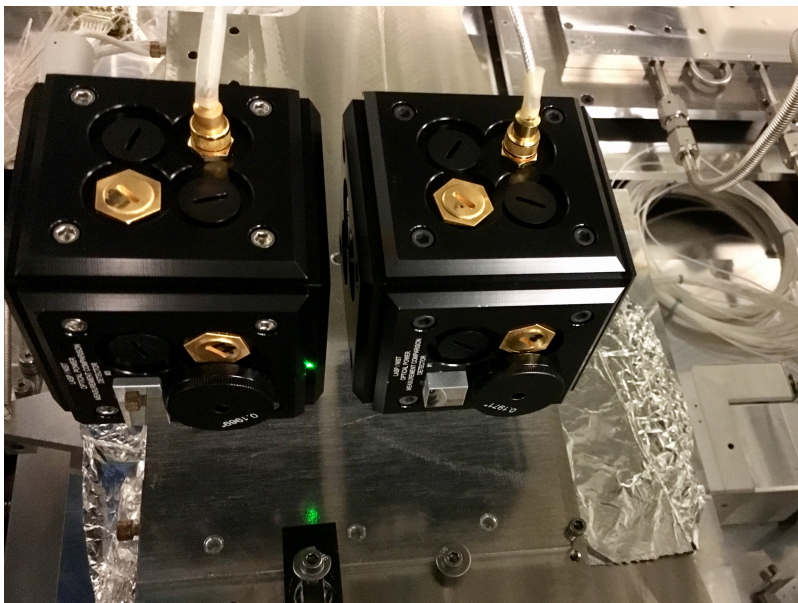


The LASP SRF uses an *L-1 Standards & Technologies Absolute Cryogenic Radiometer* with calibrated aperture to provide irradiance mode calibration



SRF Cryo to NIST Transfer Standards

SRF Cryogenic radiometer tie to NIST Stds.



Calibrated Trap Against NIST Cryo 2012

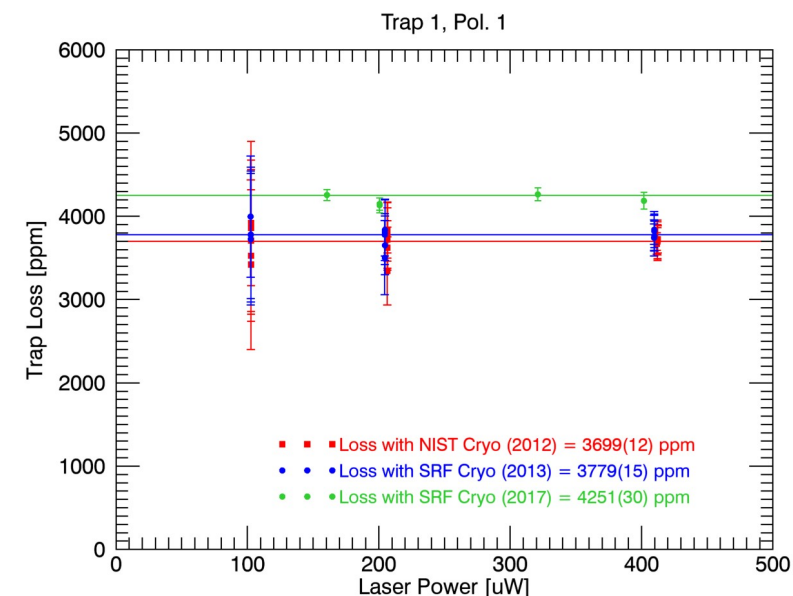
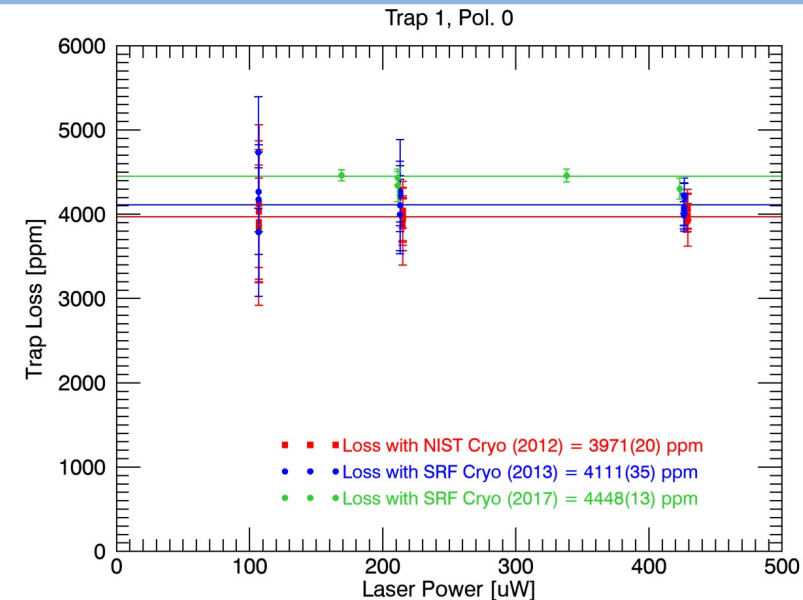
SRF Cryo-Trap Offset 2013 = -108(44) ppm

SRF Cryo-Trap Offset 2017 = -502(90) ppm

Uncertainties:

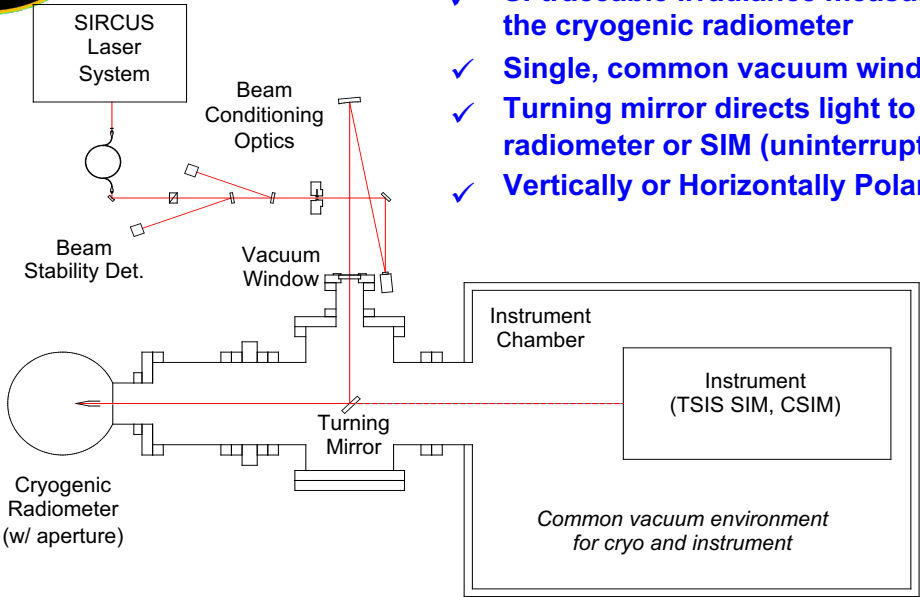
SRF Cryo-Trap Offset 2013 = $-0.011 \pm 0.004\%$

SRF Cryo-Trap Offset 2017 = $-0.050 \pm 0.009\%$





LASP-SRF Spectral Irradiance Validation



- ✓ **SIRCUS laser system: 206-3300 nm**
- ✓ **SI-traceable irradiance measurement with the cryogenic radiometer**
- ✓ **Single, common vacuum window**
- ✓ **Turning mirror directs light to cryogenic radiometer or SIM (uninterrupted)**
- ✓ **Vertically or Horizontally Polarized Light**

Entrance Aperture Measurements and Uncertainties

Slit	SN	Length	Width	Area	Uncertainties	
		[mm]	[mm]	[mm ²]	NIST (k=2) [mm ²]	NIST (k=1) [ppm]
Cryo	31	6.50021	0.29952	1.94423	1.93E-03	496
SIM A	38	6.50132	0.29904	1.94442	1.47E-03	378
SIM B	39	6.49822	0.29924	1.94431	1.30E-03	334
SIM C	42	6.50051	0.29653	1.92742	1.49E-03	387

Apertures

Cryogenic Radiometer Uncertainty Budget in Irradiance (W/m²)

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	-	0.65	0.04
Slit Area: Cosine effect	-	0.02	0.01
Slit Diffraction Loss	-	0.13	0.02
Relative combined std. uncertainty			0.07%

Cryo in irradiance

SRF Cryo Power Measurement Uncertainties
Quantified over SIM power dynamic range

Target (uW)	Cryo RC Pwr (uW)	DM3458A Pwr (uW)	Error (%)
1.00000	0.99997	1.00009	-0.0120
2.00000	2.00009	2.00035	-0.0130
5.00000	5.00075	5.00119	-0.0088
10.0000	10.0005	10.0016	-0.0110
20.0000	20.0003	20.0028	-0.0125
50.0000	50.0024	50.0091	-0.0134
100.000	100.074	100.075	-0.0010
200.000	200.019	200.050	-0.0155
500.000	500.037	500.108	-0.0142
Linear fit: Intcpt: -0.0021, Slope: 1.00015			0.015%

SRF to SIM
Validation
Limit

Full SRF End-to-End Uncertainty Budget in Irradiance (W/m²)

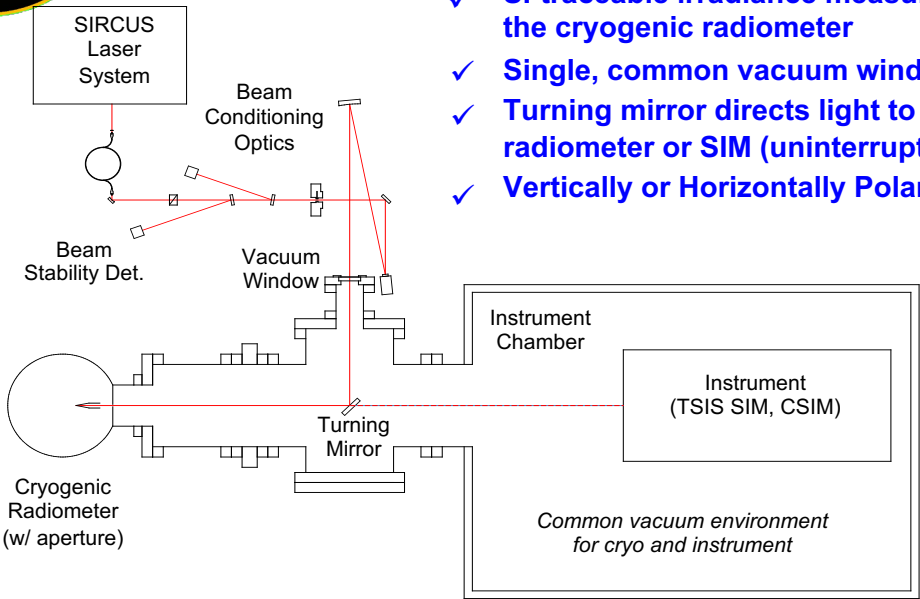
Parameter	Unit	% Effect	% Unc. (k=1)
Cryo Irradiance Measurement	W/m ²	100	0.07
Turning Mirror Repeatability	-	0	0.004
Laser Stability (relative)	-	0	0.06
Laser Pattern Uniformity	-	0	0.023
Path correction (SIM to Cryo)	-	0	0.0002
SIM Spectral PSF Integration	W/m ²	100	0.1
Relative combined std. uncertainty			0.14%

SIM-to-Cryo Valid.



LASP-SRF Spectral Irradiance Validation

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- ✓ **SI-traceable irradiance measurement with the cryogenic radiometer**
- ✓ **Single, common vacuum window**
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- ✓ **Vertically or Horizontally Polarized Light**



Entrance Aperture Measurements and Uncertainties

Slit	SN	Length	Width	Area	Uncertainties	
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SIM B	39	6.49822	0.29924	1.94431	1.30E-03	334
SIM C	42	6.50051	0.29653	1.92742	1.49E-03	387

Apertures

Cryogenic Radiometer Uncertainty Budget in Irradiance (W/m²)

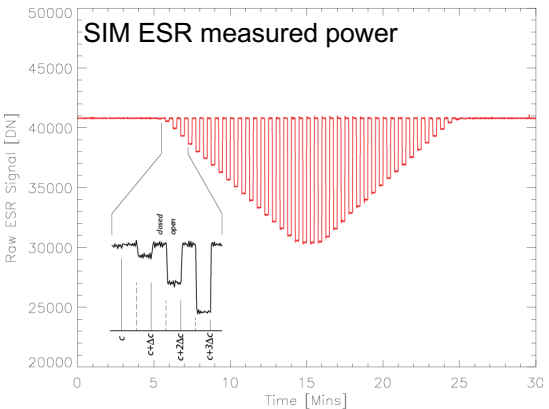
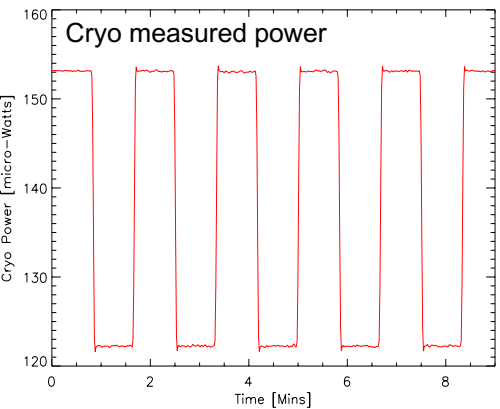
Parameter	Unit	% Effect	% Unc. (k=1)
Power	W	100	0.015
Cavity Reflectance	-	0.01	0.004
Cavity Non-Equiv.	-	0	0.01
Slit Area: Measured	m ²	100	0.05
Slit Area: Contraction	-	0.65	0.04
Slit Area: Cosine effect	-	0.02	0.01
Slit Diffraction Loss	-	0.13	0.02
Relative combined std. uncertainty			0.07%

Cryo in irradiance

Full SRF End-to-End Uncertainty Budget in Irradiance (W/m²)

Parameter	Unit	% Effect	% Unc. (k=1)
Cryo Irradiance Measurement	W/m ²	100	0.07
Turning Mirror Repeatability	-	0	0.004
Laser Stability (relative)	-	0	0.06
Laser Pattern Uniformity	-	0	0.023
Path correction (SIM to Cryo)	-	0	0.0002
SIM Spectral PSF Integration	W/m ²	100	0.1
Relative combined std. uncertainty			0.14%

SIM-to-Cryo Valid.



**SRF to SIM
Validation
Limit** →



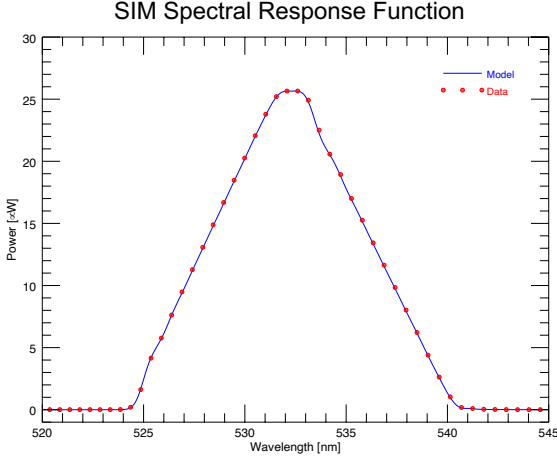
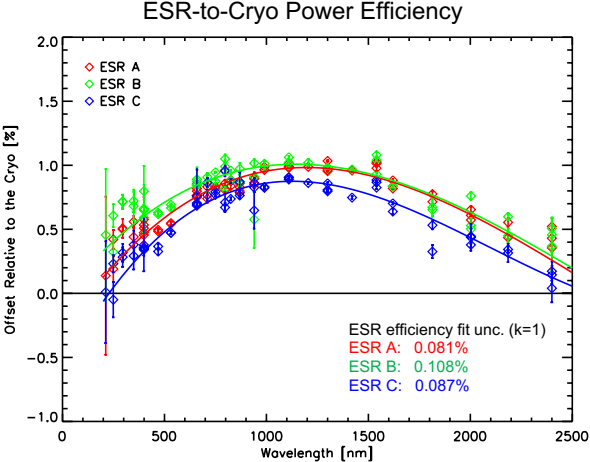
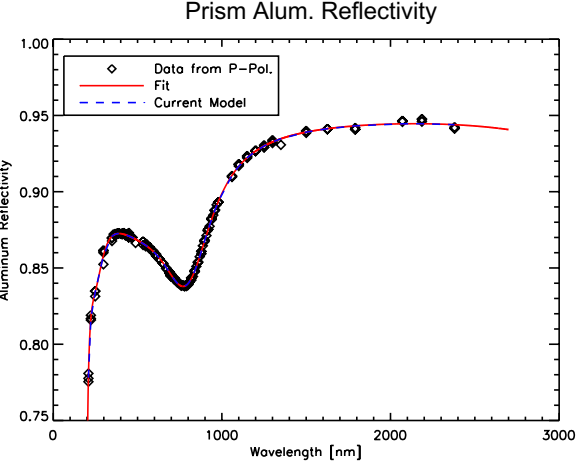
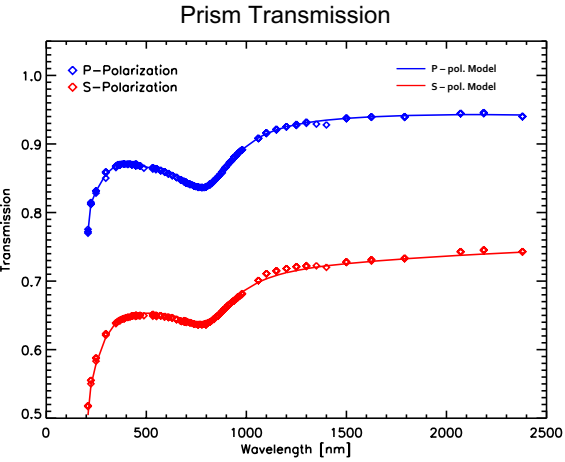
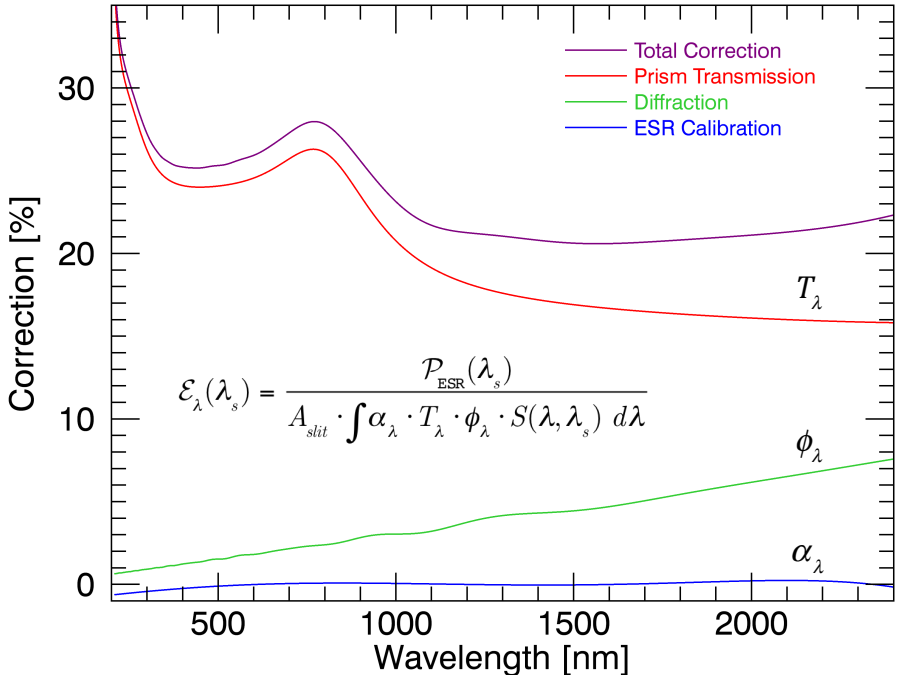
Measurement equation quantification

TSIS SIM Measurement Equation Uncertainty Budget Allocations

Parameter	Unit	Origin	% Effect in Meas. Eqn.	% Unc. (k=1) Allowable Limit
Distance (1AU correction)	m	Analysis	3.35	<0.001
Velocity (Doppler correction)	m sec ⁻¹	Analysis	0.004	<0.001
Slit Area	m ²	Component	100	0.04
Prism Transmittance	-	Component	16-45	0.1
ESR Efficiency	-	Component	1.5	0.1
Instrument Function Area	W m ⁻²	Instrument	100	0.1
Wavelength scale	nm	Instrument	100	0.08
Diffraction	-	Instrument	0.5-8.2	0.05
Dark Signal	-	Instrument	0	0.01
Scattered Light	-	Instrument	0	0.02
Noise	-	Instrument	-	0.01
Combined Rel. Std. Unc.				0.20

* % effect in measurement equation represents the error in the result if this parameter was omitted from the measurement equation. Range covers maximum contribution as a function of wavelength.

Total Spectral Corrections in Absolute Meas. Eqn.



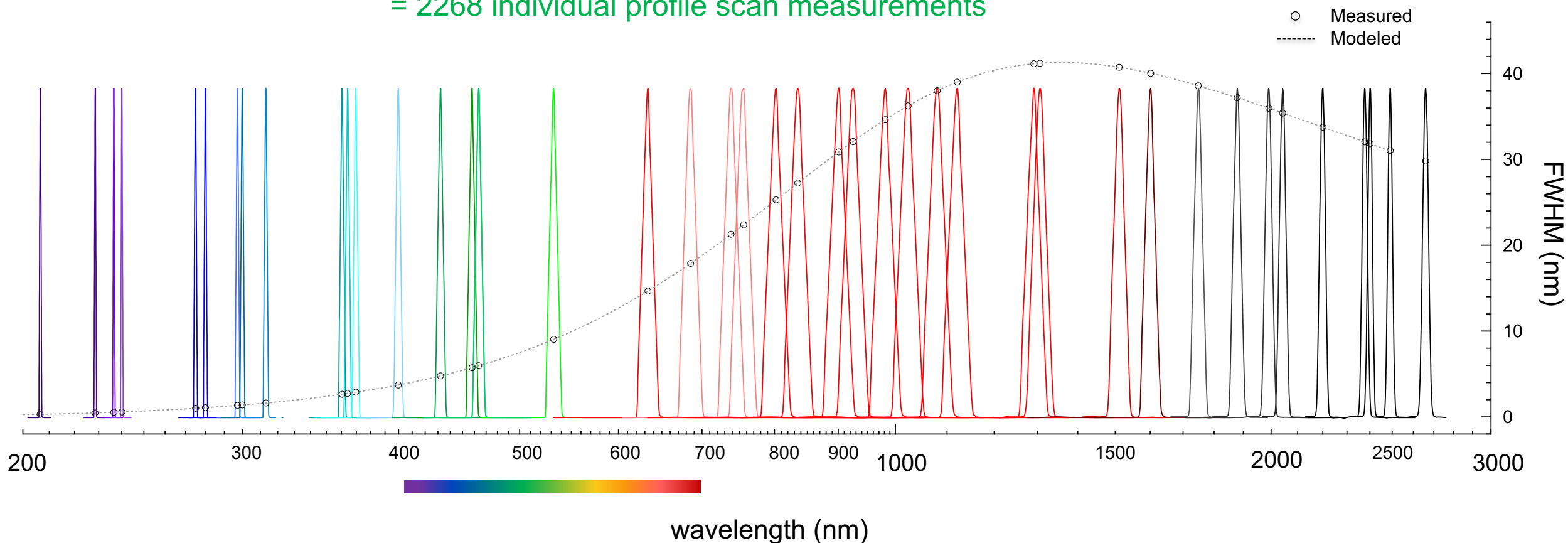


Full SRF wavelength coverage

42 wavelengths UV – NIR: 206-2700 nm

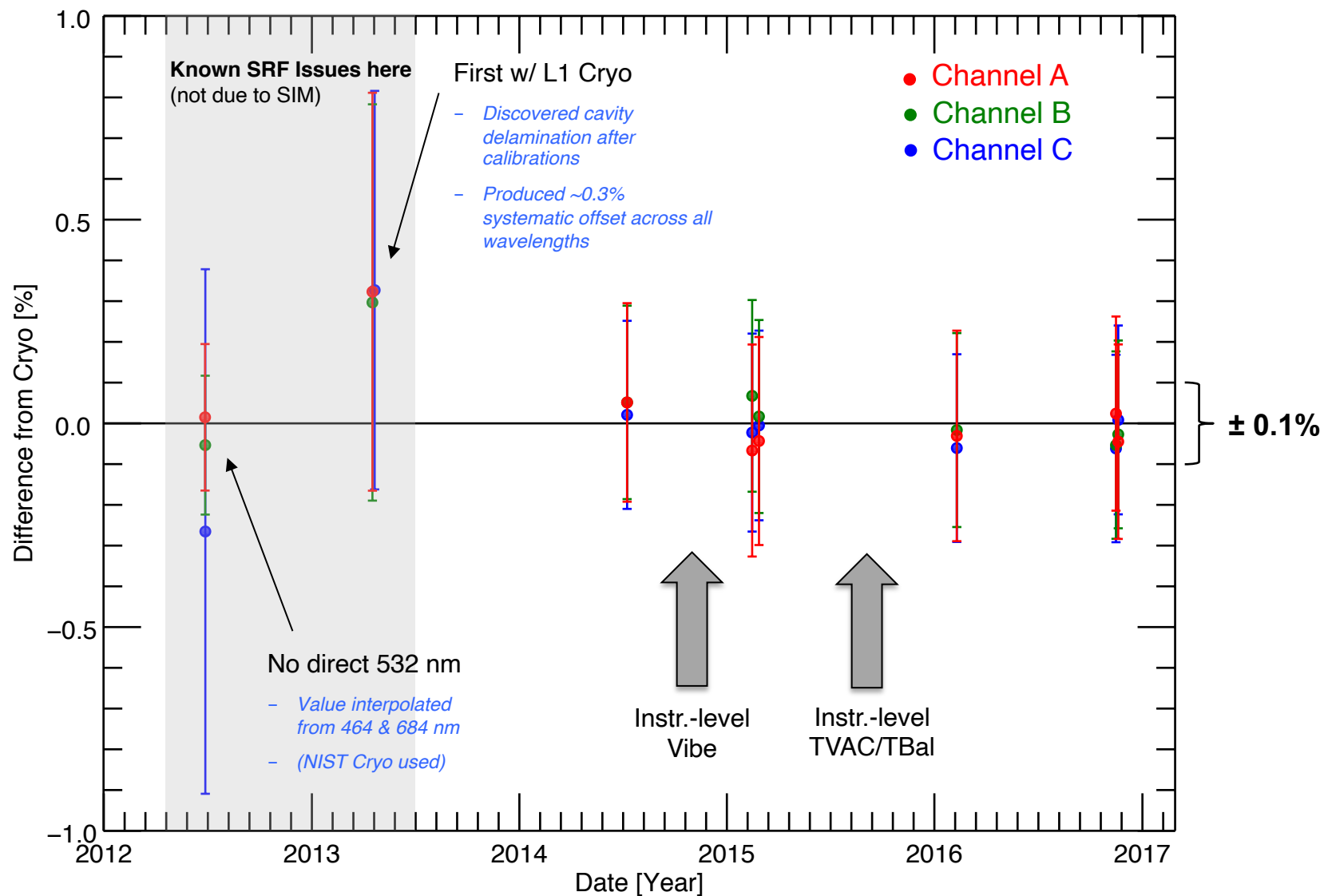
- Both s- and p-polarization
- Boresight + 8 off-axis field angles
($\pm 10'$, $\pm 20'$ disp. and cross-disp.)
- All three channels

= 2268 individual profile scan measurements





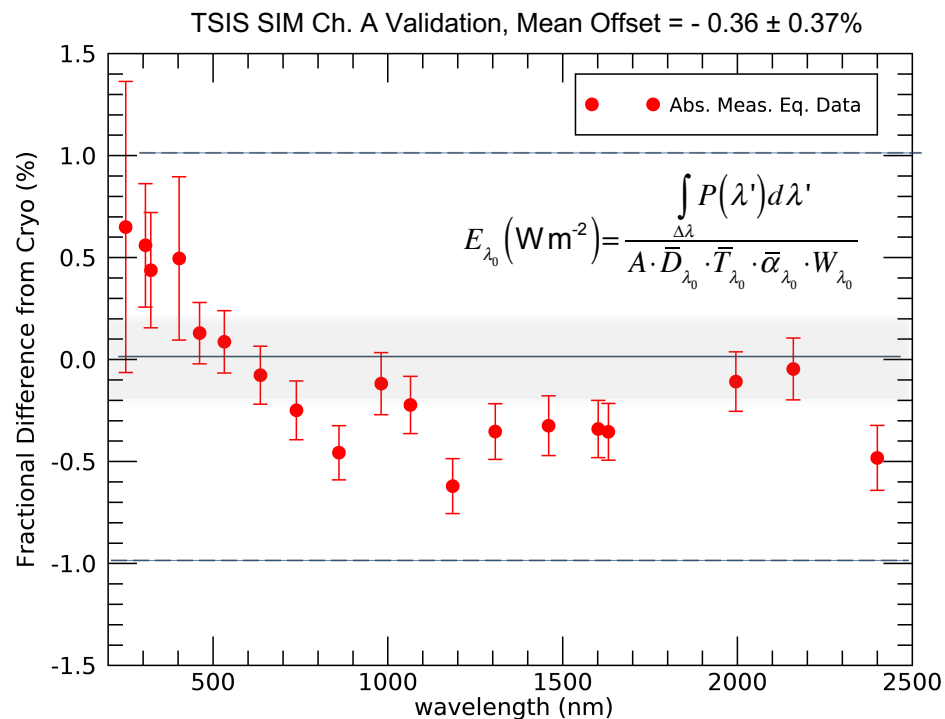
TSIS SIM Pre-Launch Stability at 532 nm





End-to-end spectral validation

Measurement equation absolute residual differences

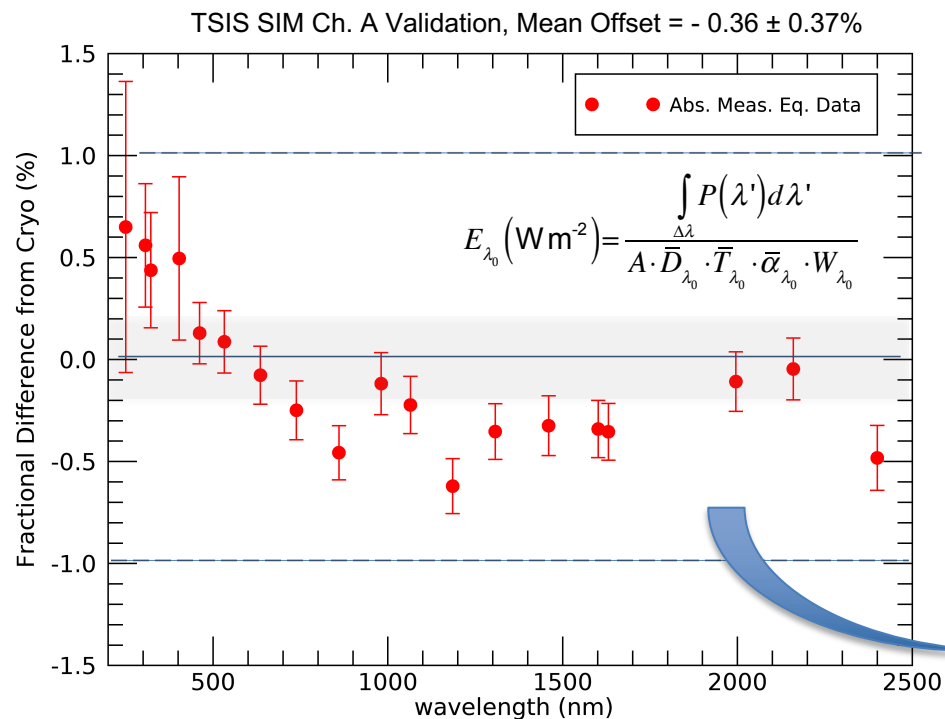


Differences here likely due to small systematic errors in prism Al-coating second surface reflection values derived from unit-level prism transmission measurements and propagated through measurement equation at instrument-level.
(On-going investigation)

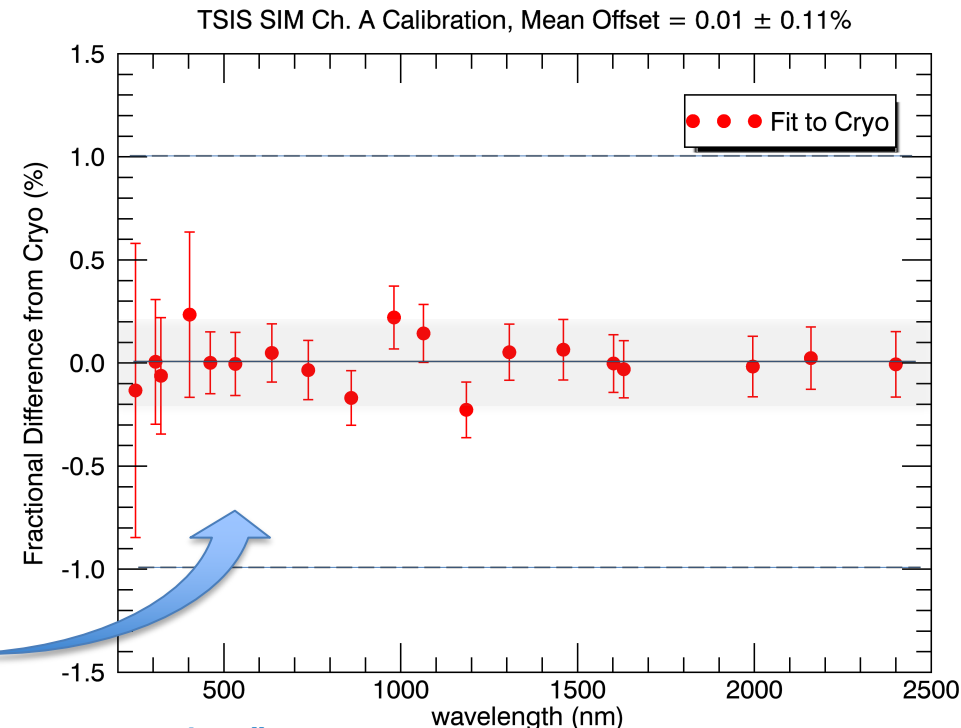


End-to-end spectral validation

Measurement equation absolute residual differences



Measurement equation absolute correction to Cryo



“functional bias correction”

Differences here likely due to small systematic errors in prism Al-coating second surface reflection values derived from unit-level prism transmission measurements and propagated through measurement equation at instrument-level.
(On-going investigation)

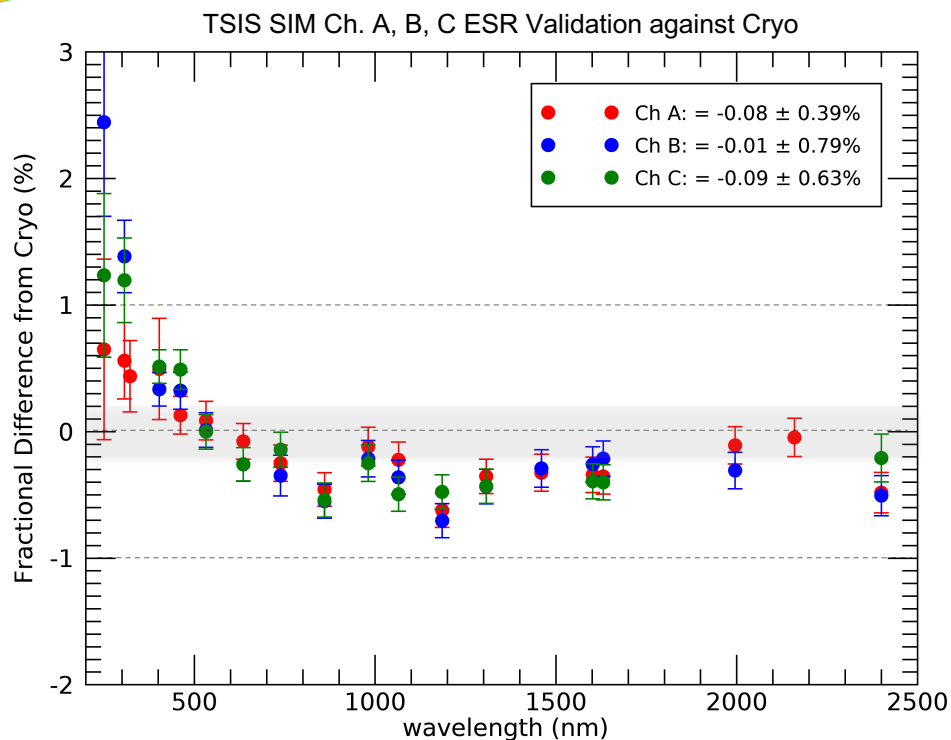
Functional fit to correct systematic offset to cryo values (Cryo has 0.14% absolute uncertainty)

$$\sigma_{Dist.} = 0.18\%$$



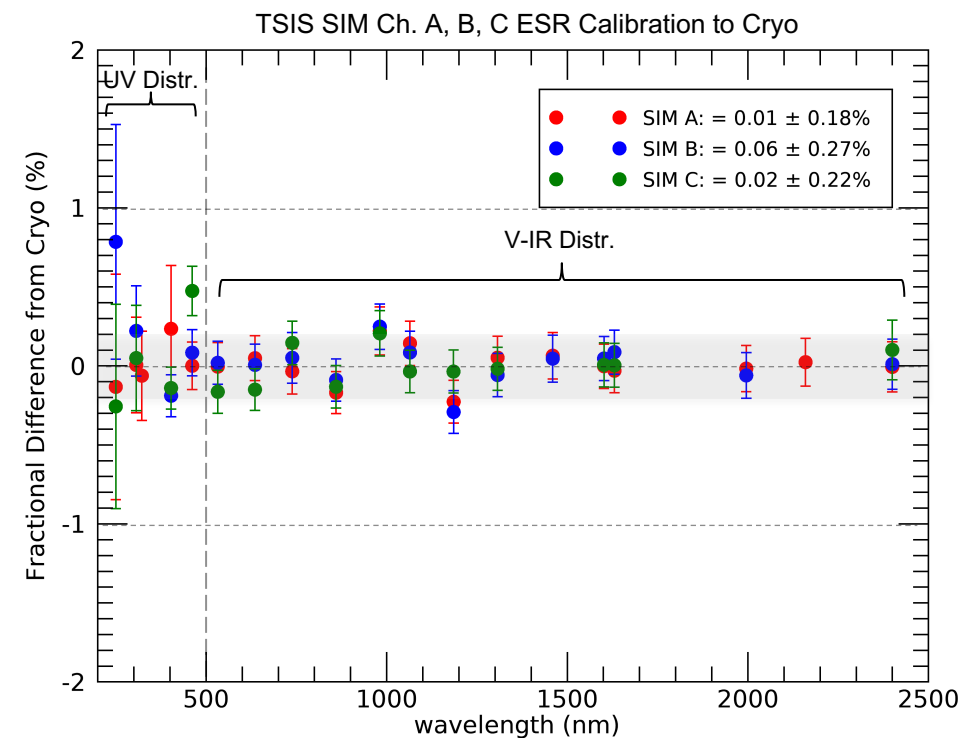
End-to-end spectral validation

All Channel Validations



Measurement equation residual differences
(systematic difference spectrally common to all channels)

All Channel Calibrations



Vis-IR Distribution

$$\sigma_{VIR}^2 = \sigma_{offset}^2 + \sigma_{dist.}^2 + \sigma_{SRF}^2$$

$$\sigma_{VIR} = \sqrt{(0.03)^2 + (0.19)^2 + (0.14)^2}$$

$$\sigma_{VIR} = 0.24 \%$$

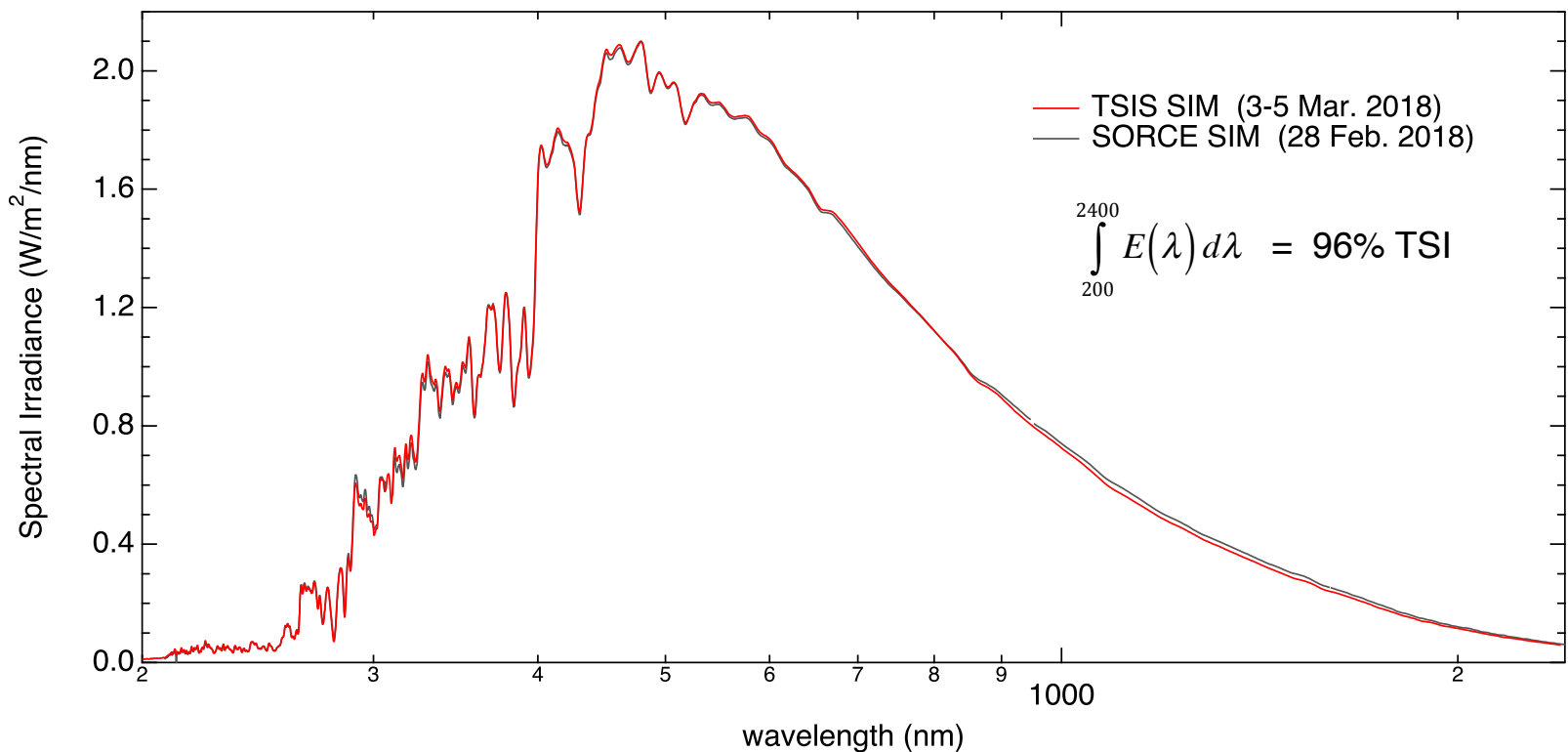
UV Distribution (<460 nm)

$$\sigma_{UV} = \sqrt{(0.31)^2 + (0.23)^2 + (0.14)^2}$$

$$\sigma_{UV} = 0.41 \%$$



SSI Reference Spectra



Spectrum	205-2390 (W/m ²)	+ 52 (W/m ²)*	TIM TSI (W/m ²)	Diff (W/m ²)	% Diff.	
ATLAS3	1333	1386	1361	+ 25	+ 1.81	← 1994
SIRS-WHI	1323	1375	1361	+ 14	+ 1.02	} 2008 S _{min}
SOLAR-ISS	1321	1373	1361	+ 12	+ 0.87	
✓ TSIS SIM	1307.6	1359.6	1360.6	- 1	- 0.08	← 2018 S _{min}

*Integrated SSI contribution outside 205-2390 nm (±0.1% variability uncertainty)



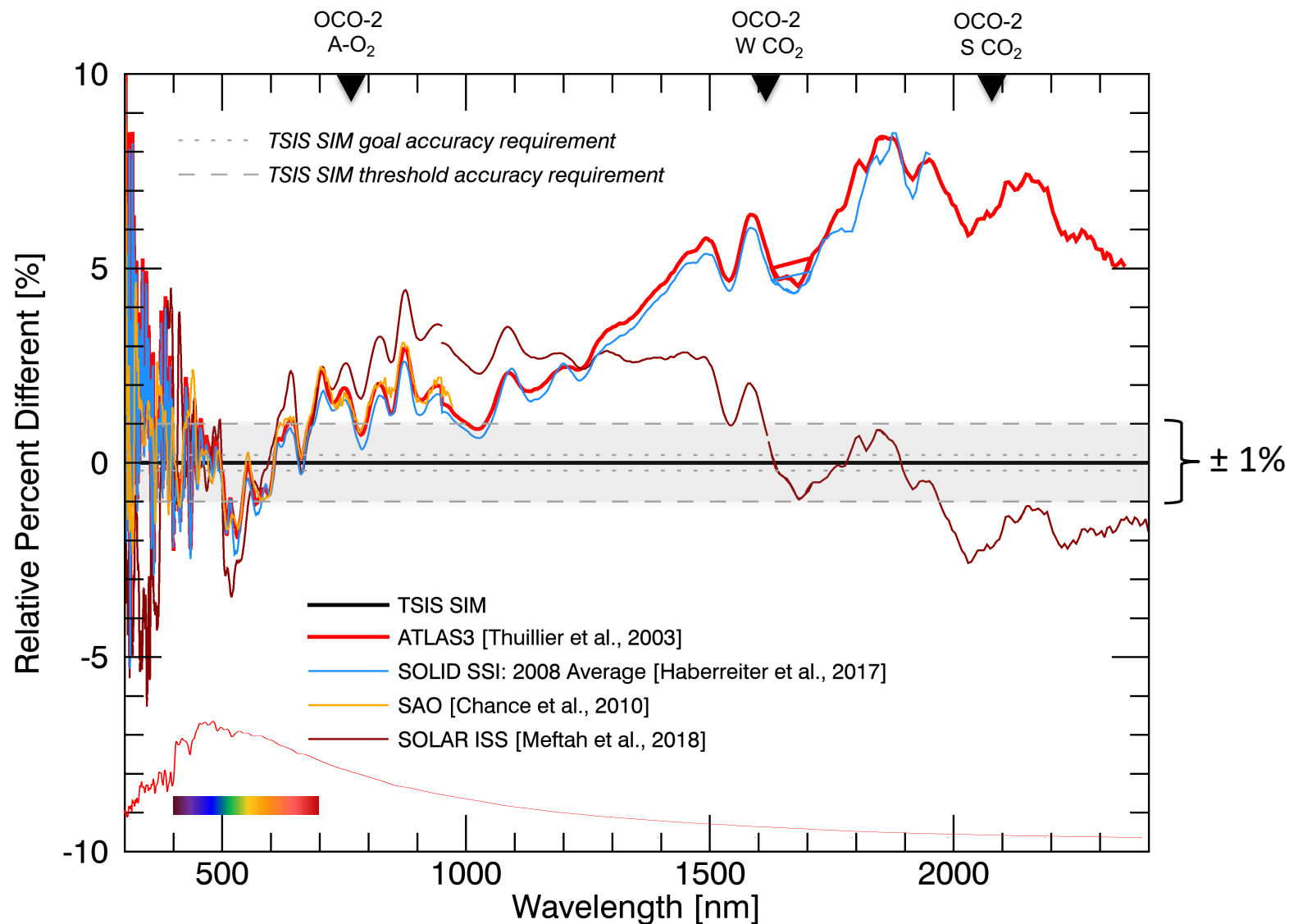
Differences from other SSI References

TSIS SIM differs from the SOLSPEC ATLAS3 reference spectrum and other SSI reference datasets.

This plot shows the relative percent difference of other solar spectral irradiance datasets from TSIS SIM.

Computed as: $\frac{'Reference\ X' - TSIS_{SIM}}{TSIS_{SIM}} * 100$

Most other reference spectra are 5-8% higher than TSIS SIM in the near-infrared.



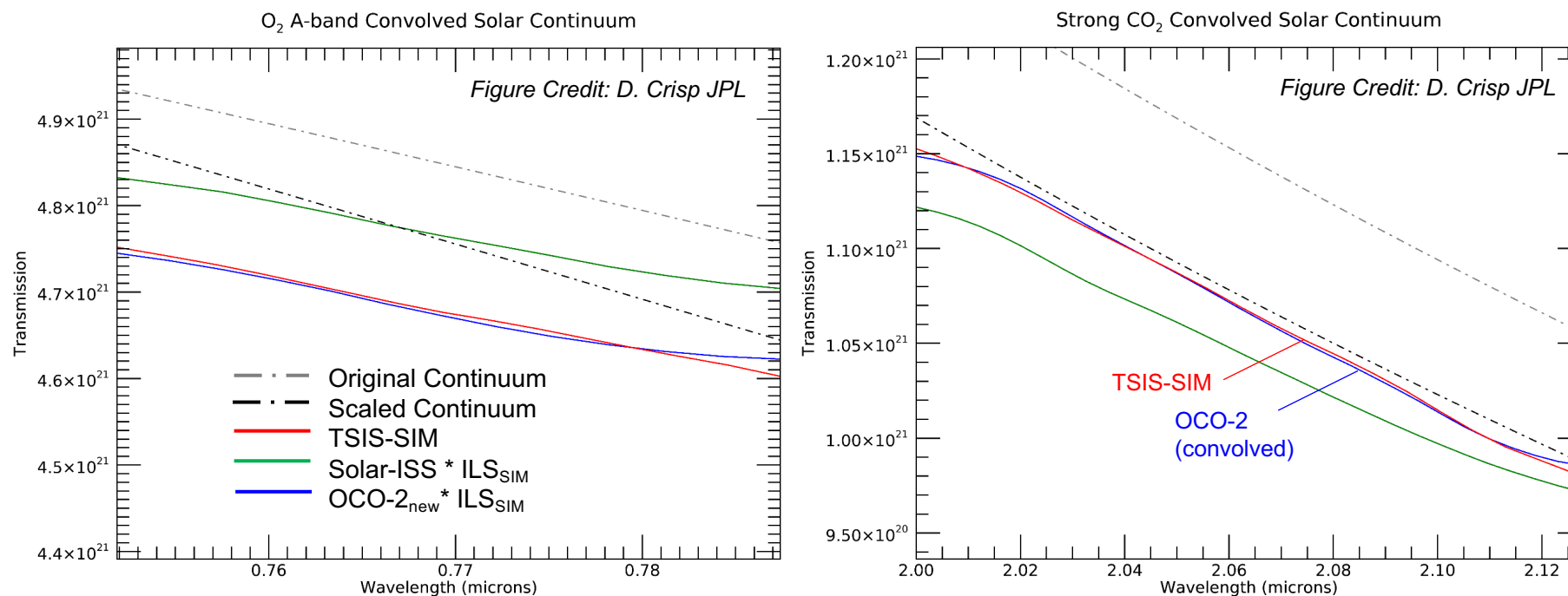
*All datasets have been convolved to the TSIS SIM spectral resolution



TSIS SIM and OCO-2 Solar Flux Scaling

TSIS SIM provides accurate TOA SSI that are critical to X_{CO_2} retrievals

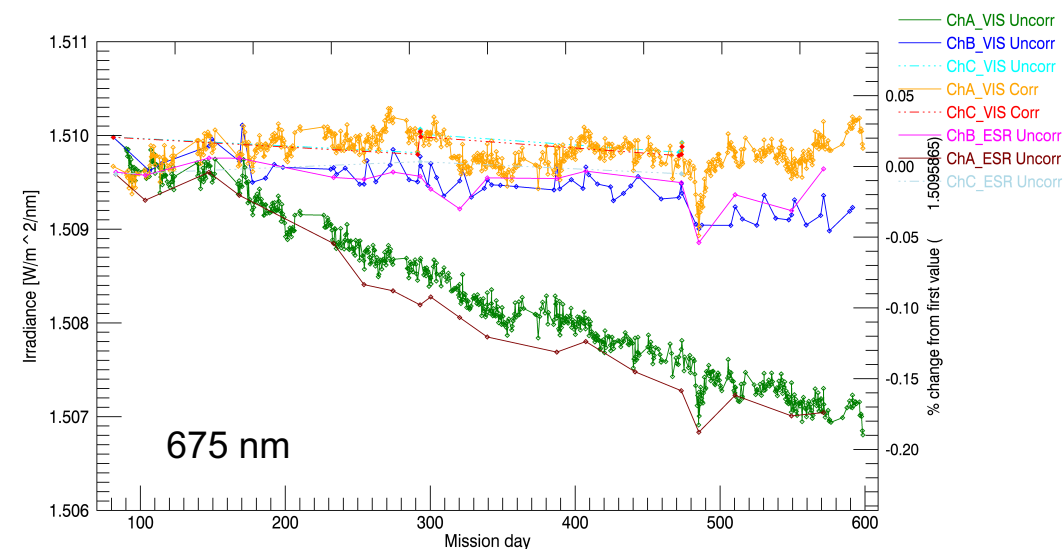
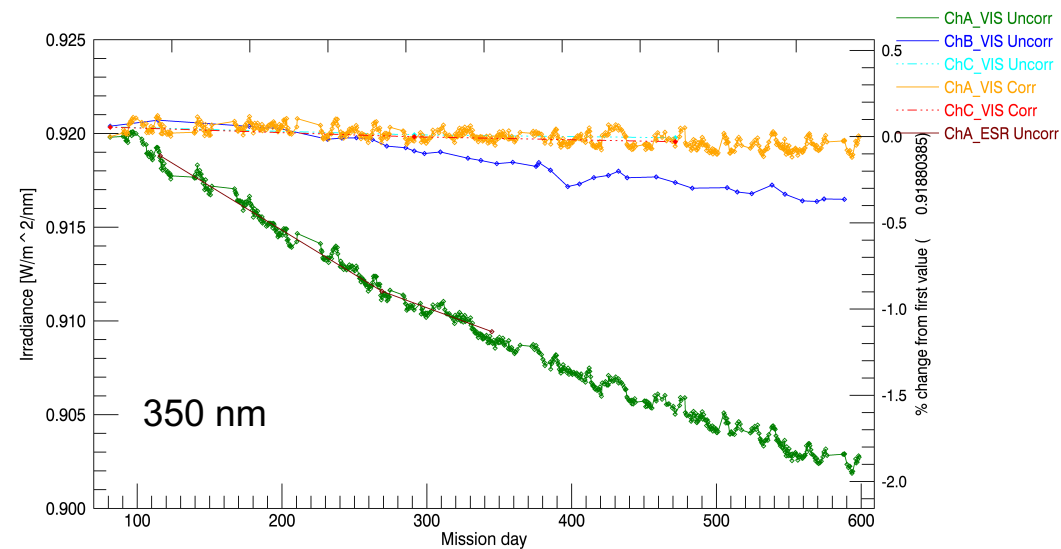
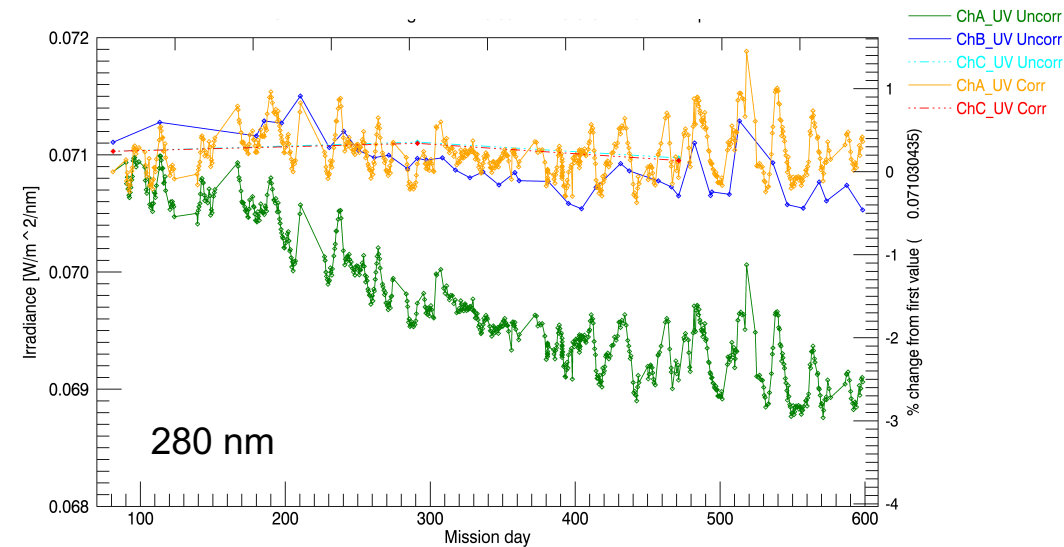
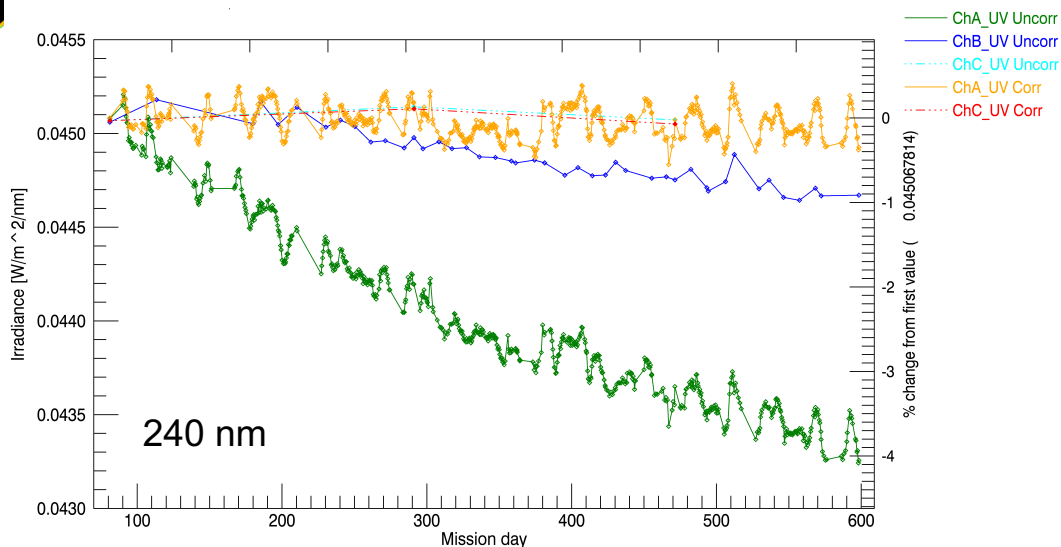
High-resolution OCO-2 A- O_2 , Weak, and Strong CO_2 band spectrum was convolved with the TSIS-SIM SRF (blue) and compared to TSIS-SIM (red) and Solar-ISS spectrum convolved with the TSIS-SIM SRF (green).



- Plots show continuum levels of the OCO-2 solar spectra using the TSIS-SIM SRF results
- Also shows comparison between the TSIS-SIM and Solar-ISS results. In general, the TSIS-SIM results are ~1.6% lower than the Solar-ISS results in the 765 nm region, about the same near 1610 nm, and about 2.6% higher at 2060 nm.



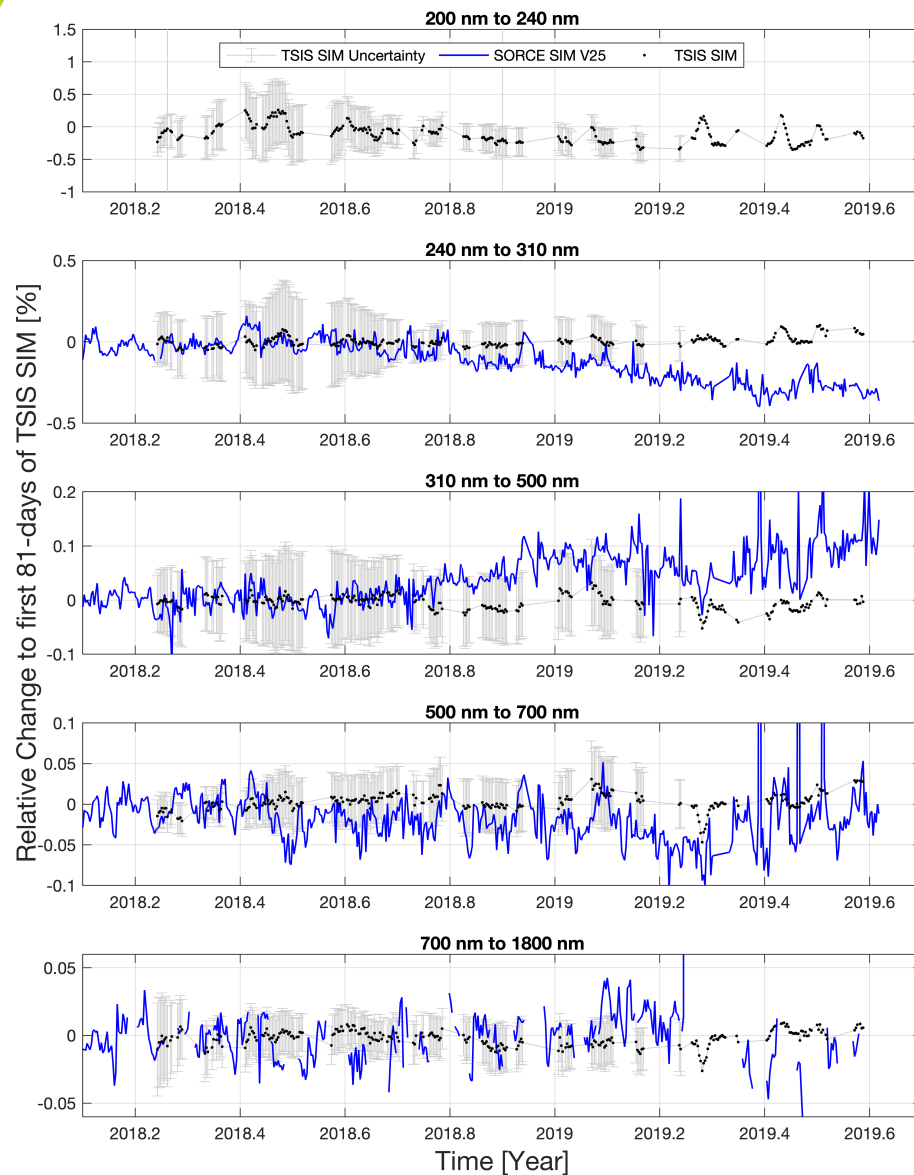
On-orbit stability correction performance



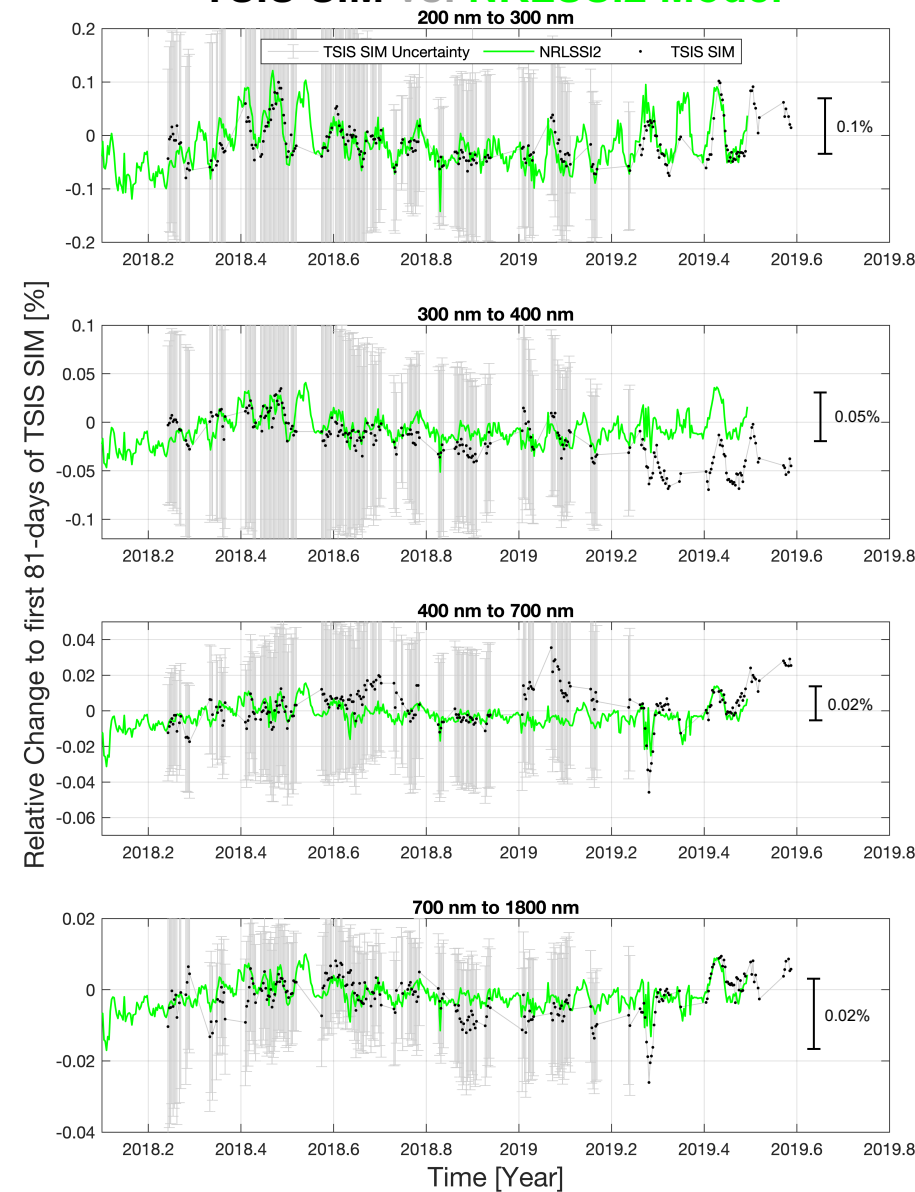


TSIS SIM Stability Comparison

TSIS SIM vs. SORCE SIM



TSIS SIM vs. NRLSSI2 Model



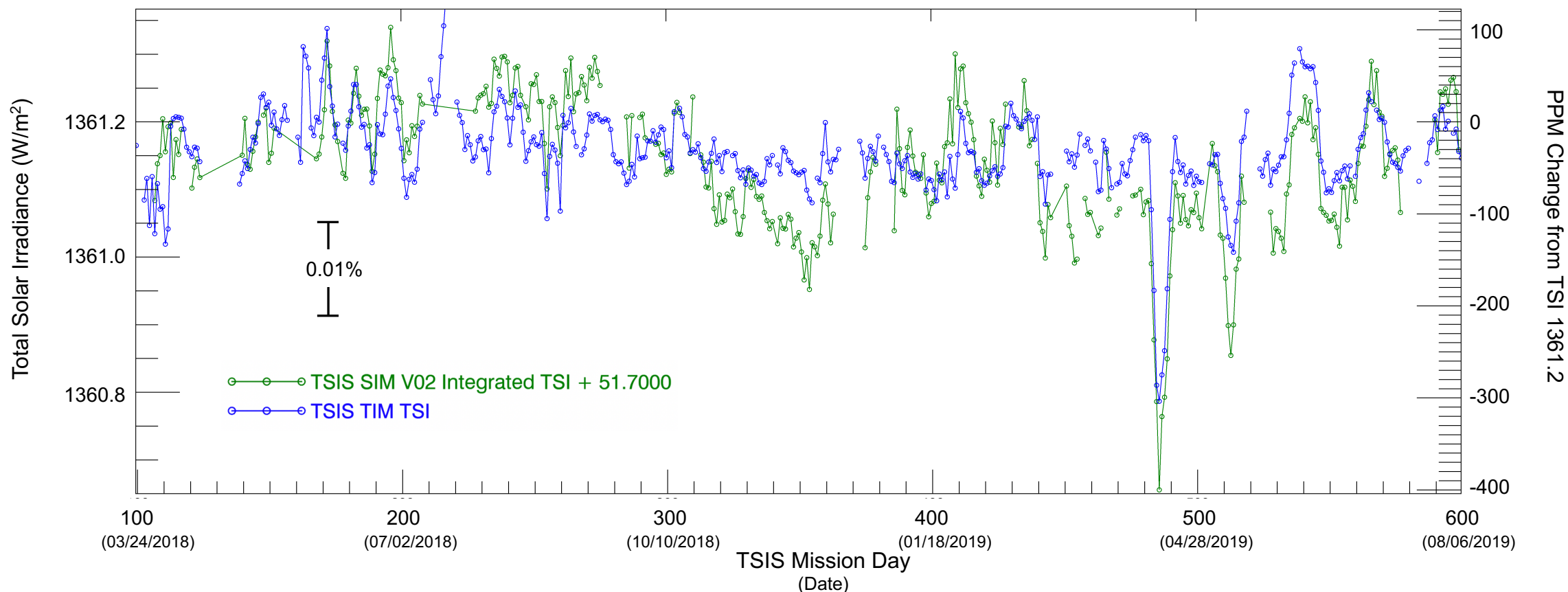


Integrated SIM stability

Comparison of the TSIS TIM TSI daily averages with the Integrated (200 – 2400 nm) spectrum TSIS SIM daily values. (TSI stability correction better than 10 ppm / yr.)

- A constant offset of 51.7 W/m^2 is added to account for the ~4% of spectral irradiance not measured by SIM (wavelengths < 200 nm and > 2400 nm)

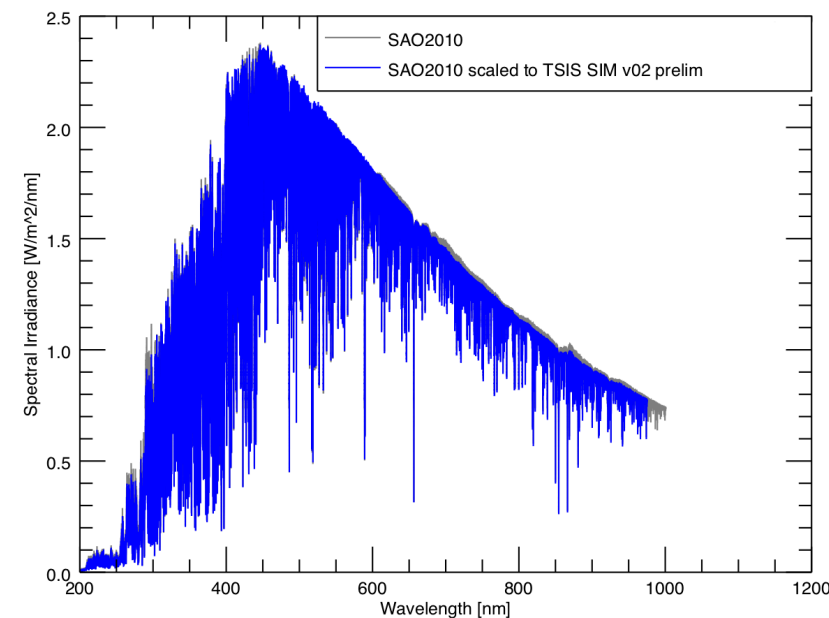
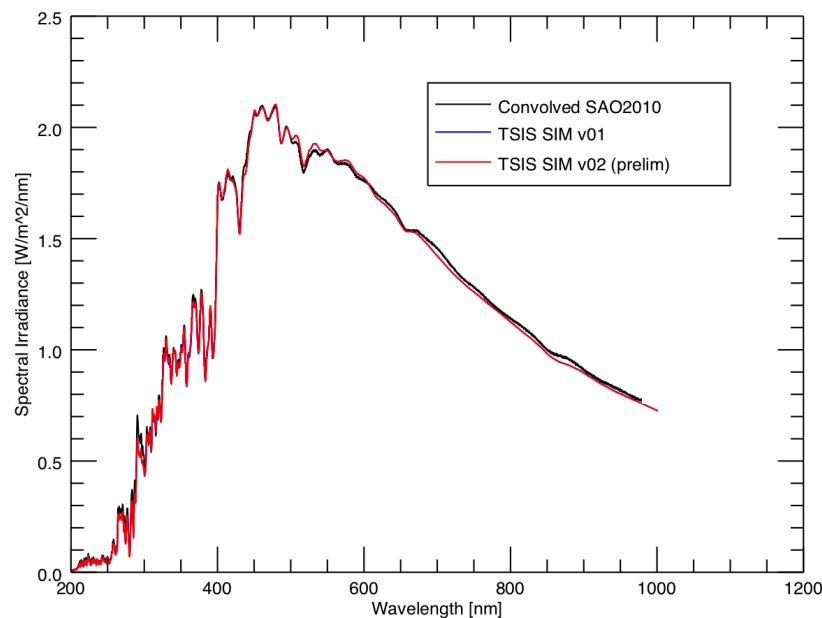
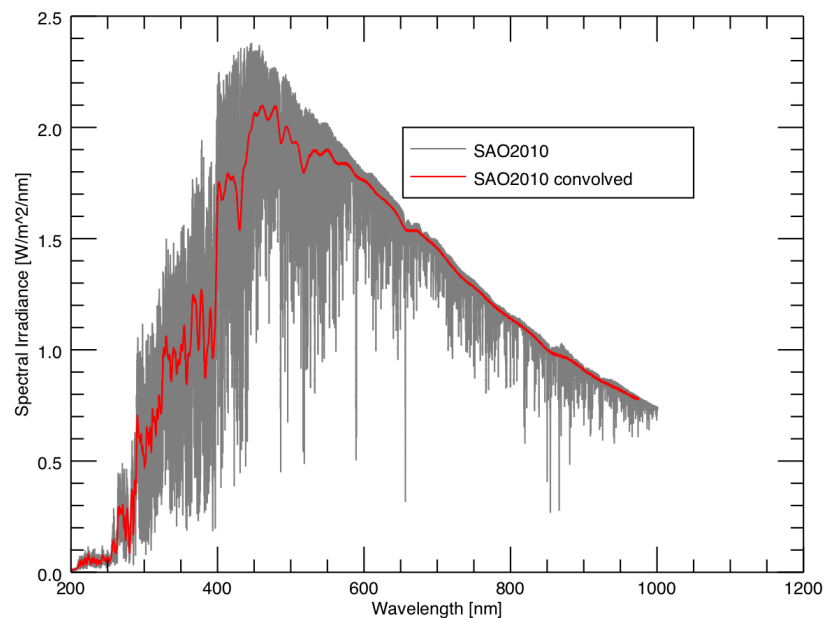
Stability agreement is seen to be better than 0.01% ppm over the whole mission to date.





TSIS Adjusted High Resolution Spectrum

- Develop an improved high-resolution solar reference spectrum from 200 nm through ~ 950 nm that combines high spectral resolution ground-based and balloon-based solar measurements with lower spectral resolution but higher accuracy irradiance information from TSIS SIM that is specific to low solar activity conditions
- Applications: atmospheric radiative transfer and remote sensing, solar irradiance modeling

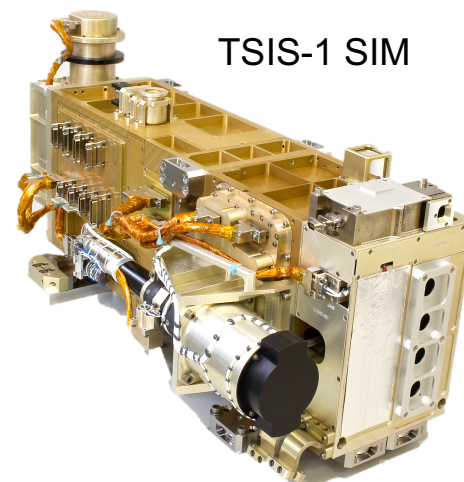




On-orbit Absolute SSI Validation

Obtained **first ever** on-orbit full SSI absolute validation.
Both TSIS-1 SIM and CSIM have calibration tied to NIST-
Standards

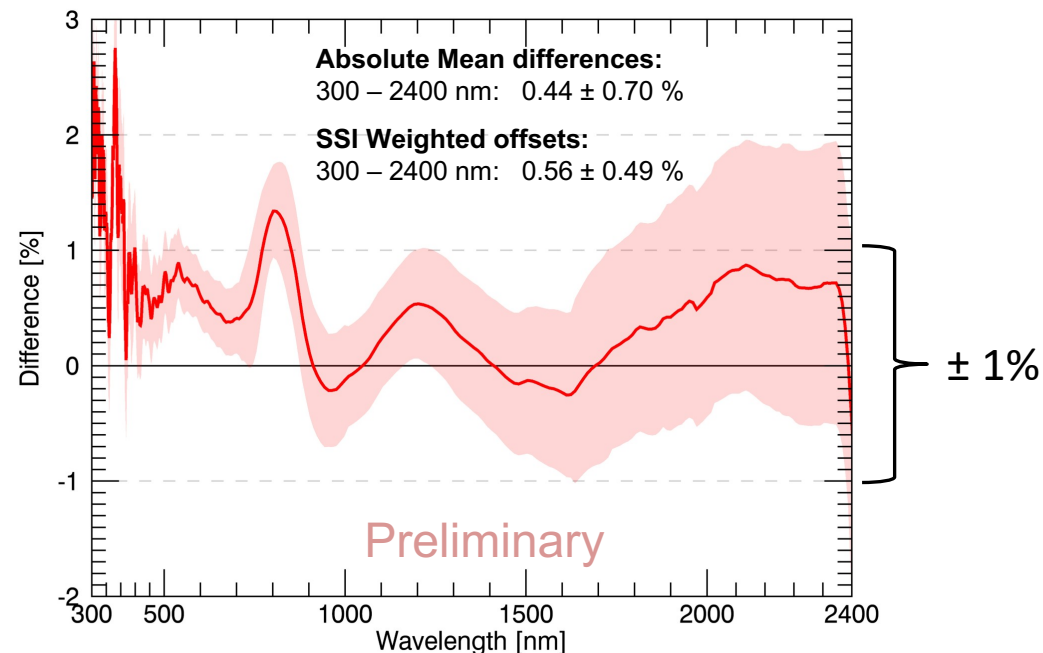
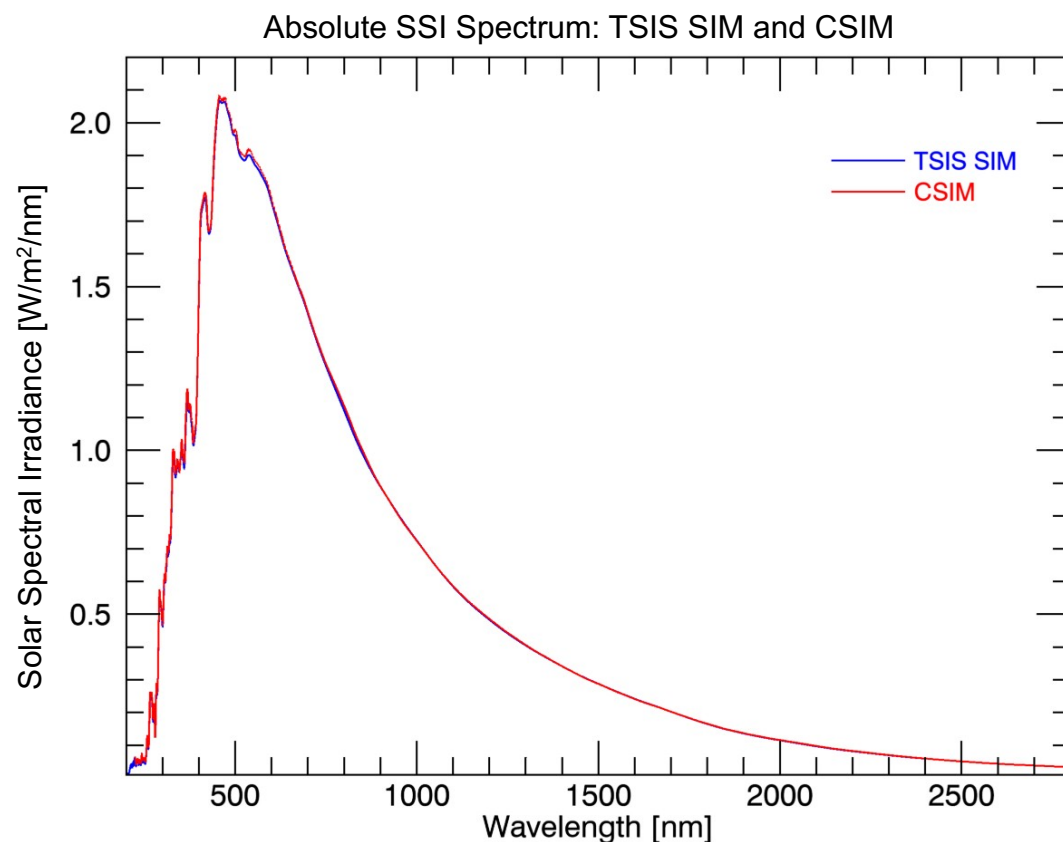
Found excellent absolute SSI agreement between the CSIM
spectrum compared to the TSIS-1 SIM 300 – 2400 nm
spectrum.



TSIS-1 SIM



CSIM 6U
CubeSat

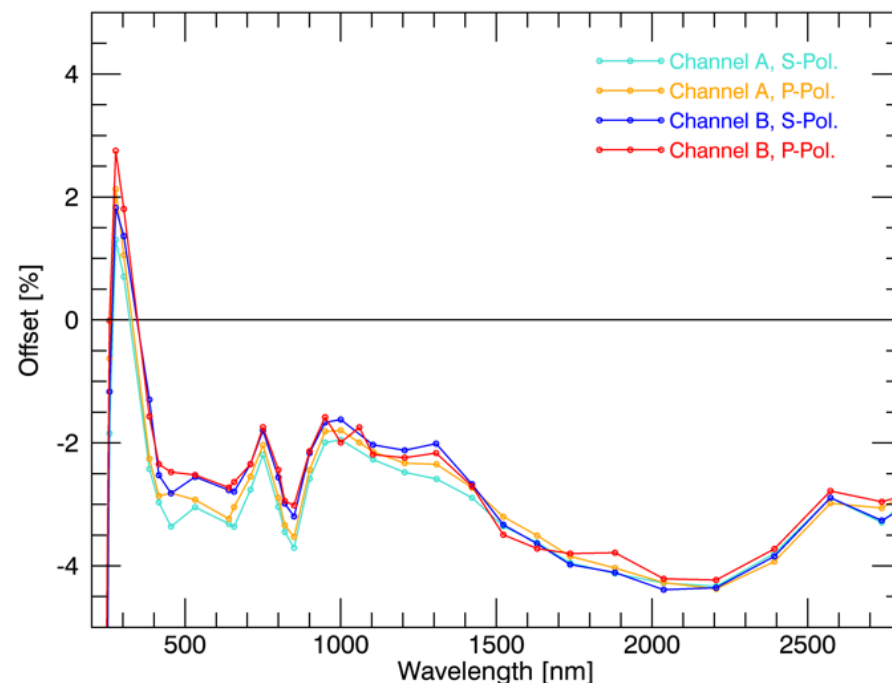




CSIM Absolute Spectral Accuracy

End-to-end Validation

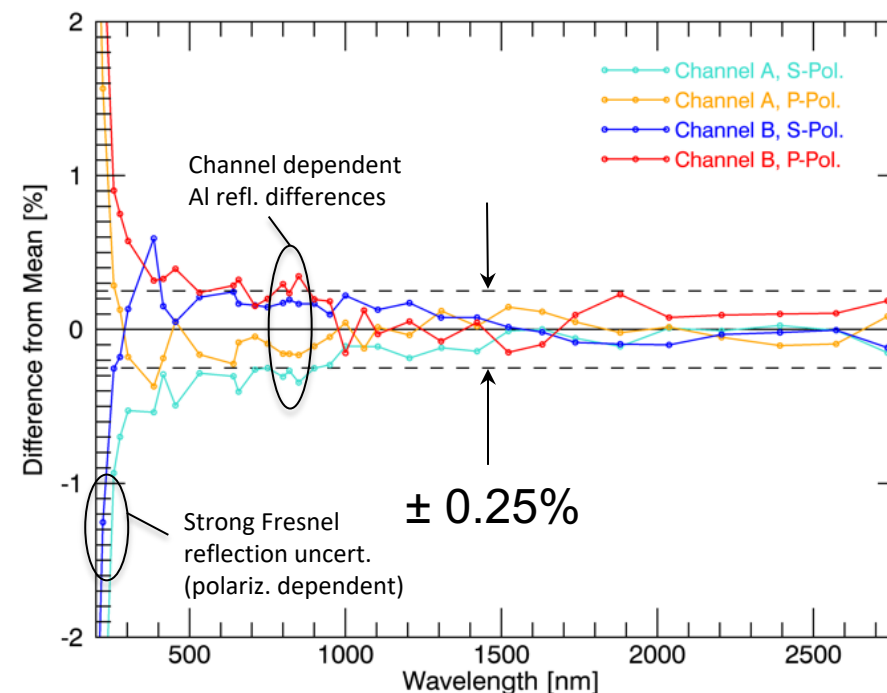
ESR Measurement equation residual differences from cryogenic radiometer measurements in LASP SRF



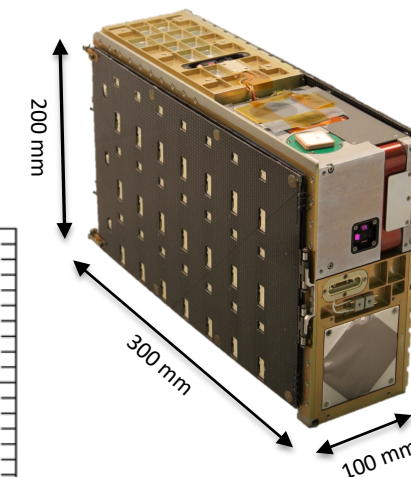
Differences here likely due to systematic error in prism Al-coating second surface reflection values derived from unit-level prism transmission measurements and propagated through measurement equation at instrument-level.
(On-going investigation)

SRF Cryo Calibration

Differences from the mean of residual error



Apply functional fit to correct systematic offset to cryo values (LASP SRF Cryo has 0.14% absolute uncertainty in irradiance)



CSIM 6U CubeSat



Summary

- TSIS SIM most accurate, highest stability SSI data record
 - Large investment in calibration/validation facilities tied to NIST (SI) standards
 - Lessons learned and improvements from SORCE SIM
- Differences from other SSI reference spectra
 - Significant decrease (5-8%) in NIR SSI from ATLAS3 (& SORCE);
 - Better agreement with SOLAR-ISS 2008 $S_{\min}$ Reference (but still 3% differences)
- Three channel, measurement-based degradation corrections significant improvement for maintaining long-term stability
 - ISS not ideal platform, but so far no major issues affecting performance
 - Present degradation rates lower than expected, spectral stability corrections meeting requirements with margin, adds confidence to corrections for full 5-7 year mission duration to maintain SSI record

TSIS SIM Data availability : NASA DAAC (GES DISC) and http://lasp.colorado.edu/data/tsis/ssi_data/

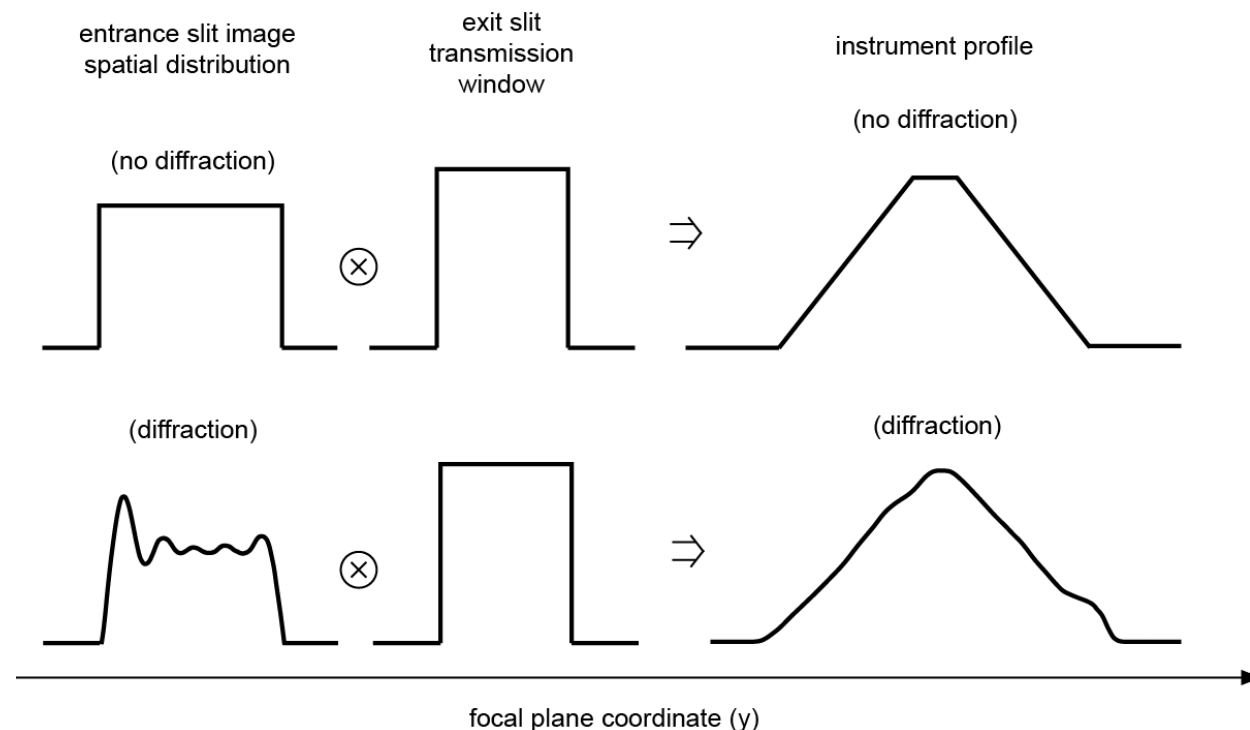
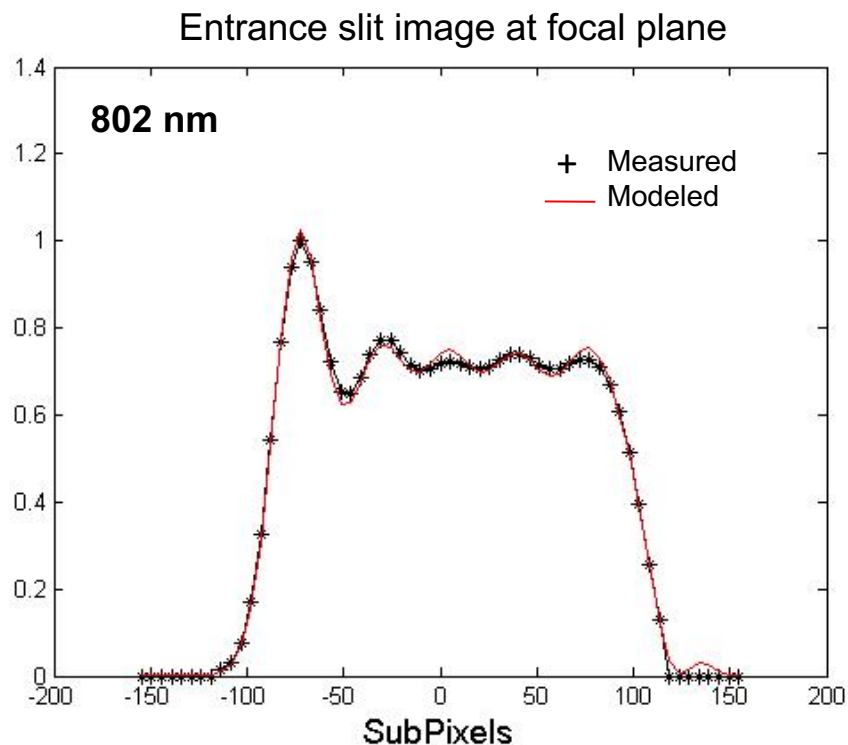


Backup Slides



SIM Spectral Response Functions (SRFs)

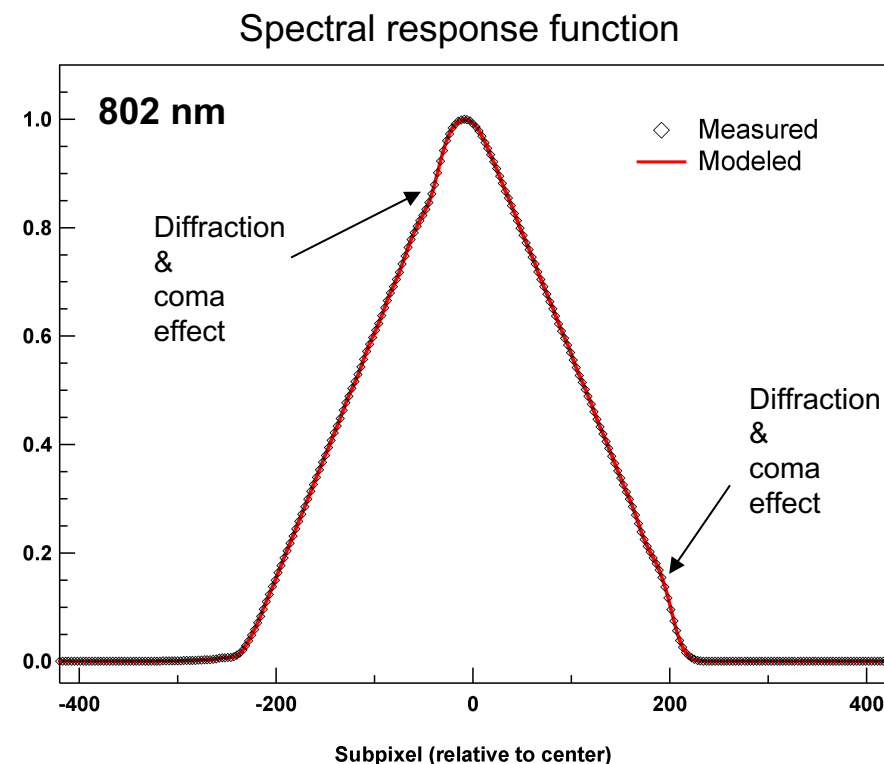
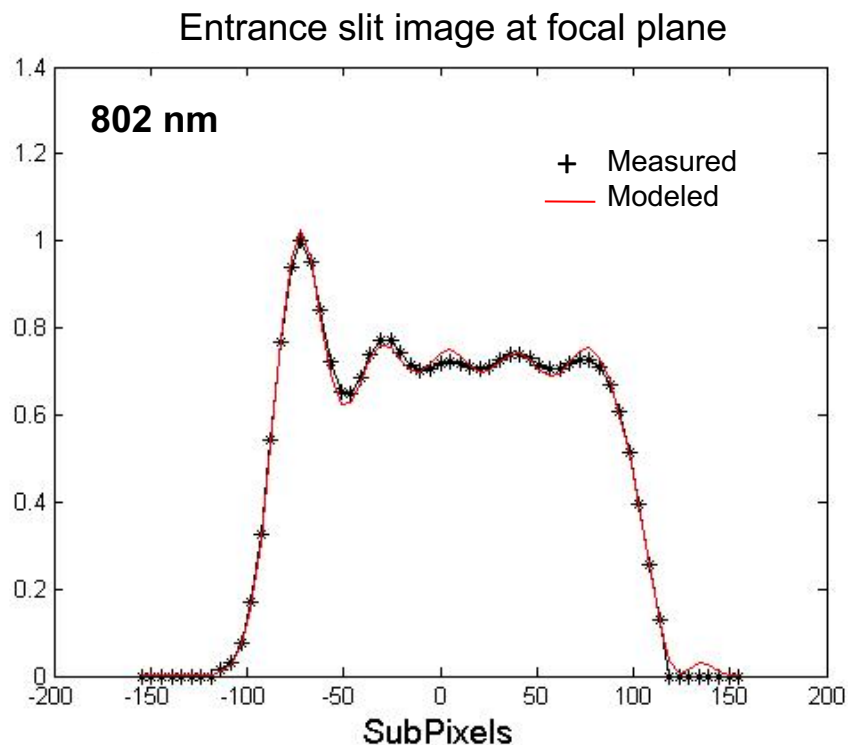
Successfully modeled the full optical path diffraction based on the measured SRF's. This model includes entrance aperture and both incoming & outgoing contributions from the prism pre-baffle as well as optical aberration effects (coma, astigmatism & defocus)





SIM Spectral Response Functions (SRFs)

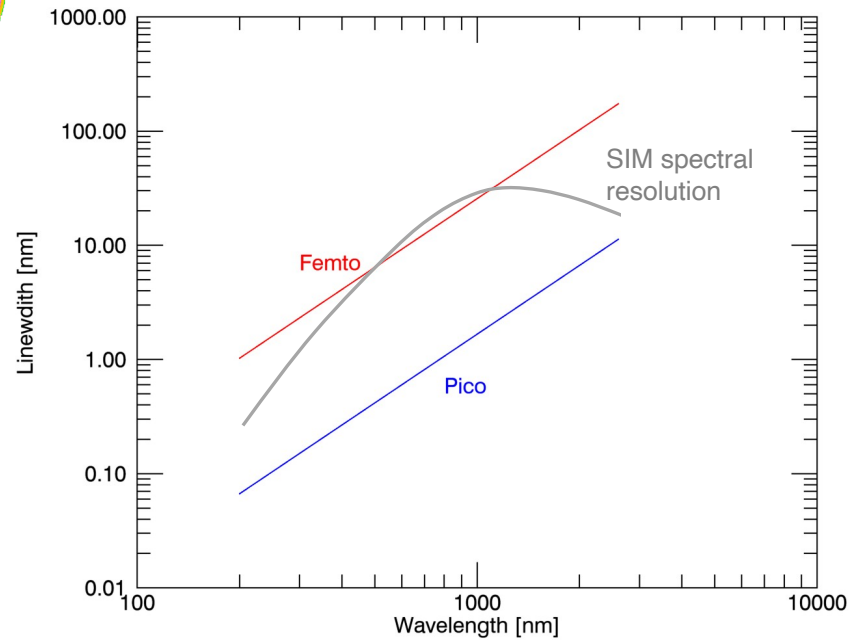
Successfully modeled the full optical path diffraction based on the measured SRF's. This model includes entrance aperture and both incoming & outgoing contributions from the prism pre-baffle as well as optical aberration effects (coma, astigmatism & defocus)



We fully quantify individual detector radiometric cut-off limits and spectral response functions (SRF's) with pointing. Cut-off limits are defined by the prism pre-baffle edges in the dispersion direction. Pre-baffle also produces diffraction effects in SRF's.



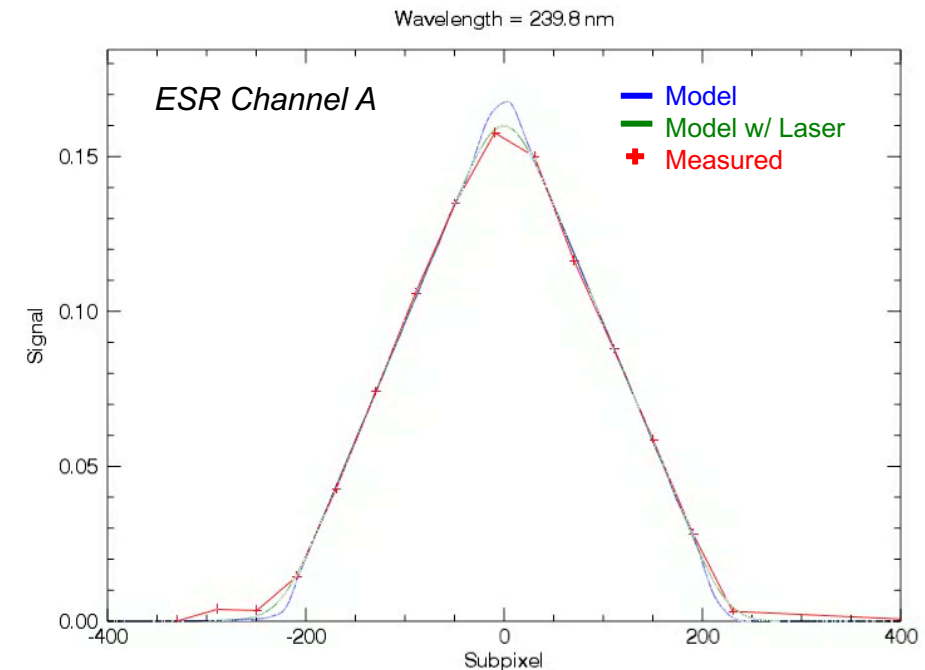
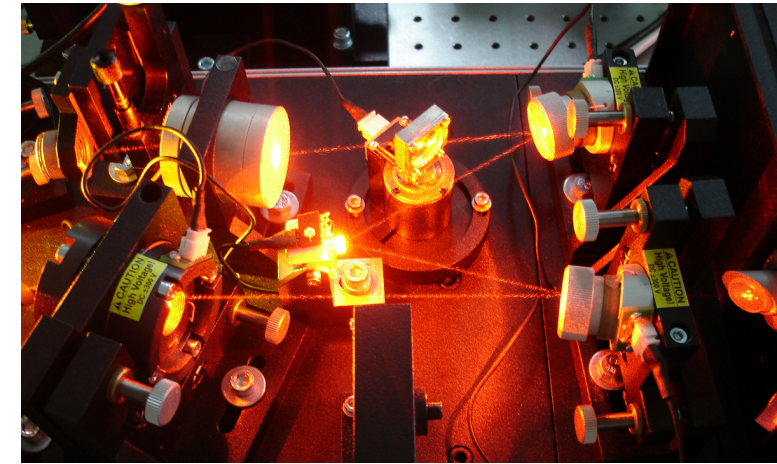
Picosecond mode-locked Ti:Sapphire Laser



- Input: 18W 532nm Laser Light (Nd:YVO₄ x2)
 - 75 MHz rep. rate
 - Femtosecond mode-locked:
 - <130 fs pulses
 - ~10 nm at 1000 nm

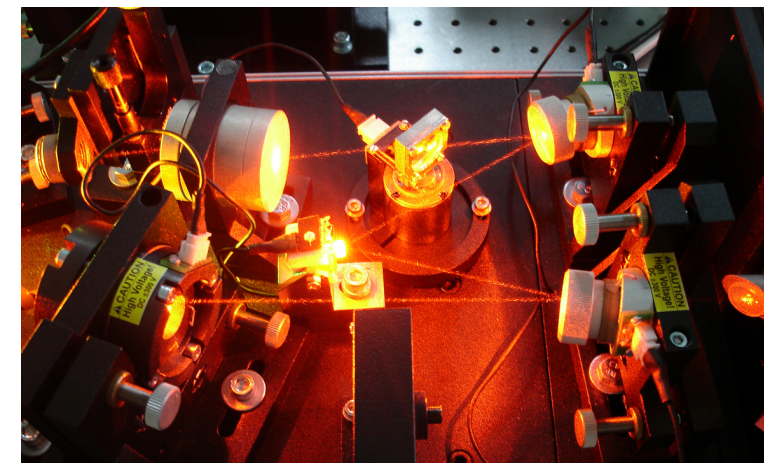
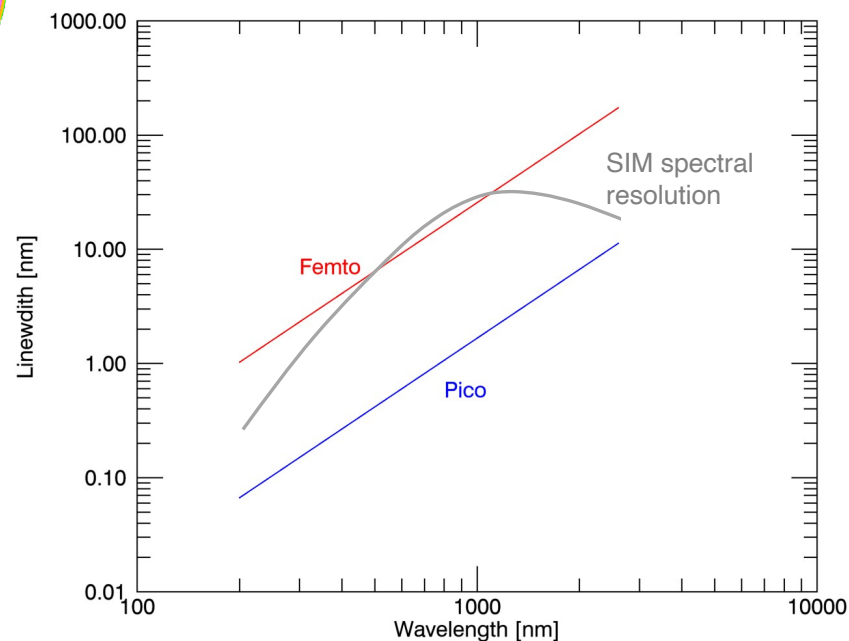
- Picosecond mode-locked:
 - <2 ps pulses (~10⁹ GW peak power)
 - ~1 nm at 1000 nm

- Closed-loop feed-back stabilized and manually tuned





Picosecond mode-locked Ti:Sapphire Laser



- Input: 18W 532nm Laser Light (Nd:YVO₄ x2)

- 75 MHz rep. rate

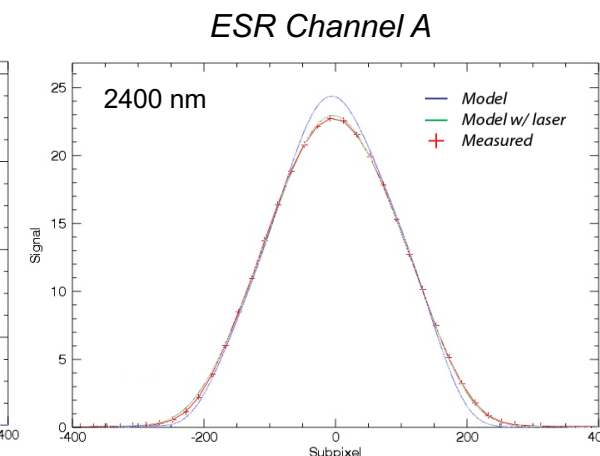
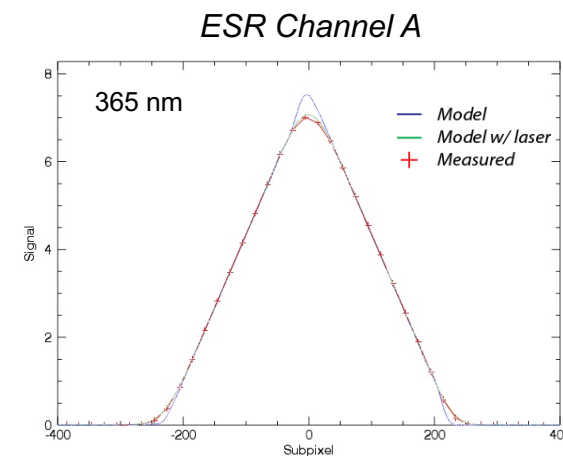
- Femtosecond mode-locked:

- <130 fs pulses
 - ~10 nm at 1000 nm

- Picosecond mode-locked:

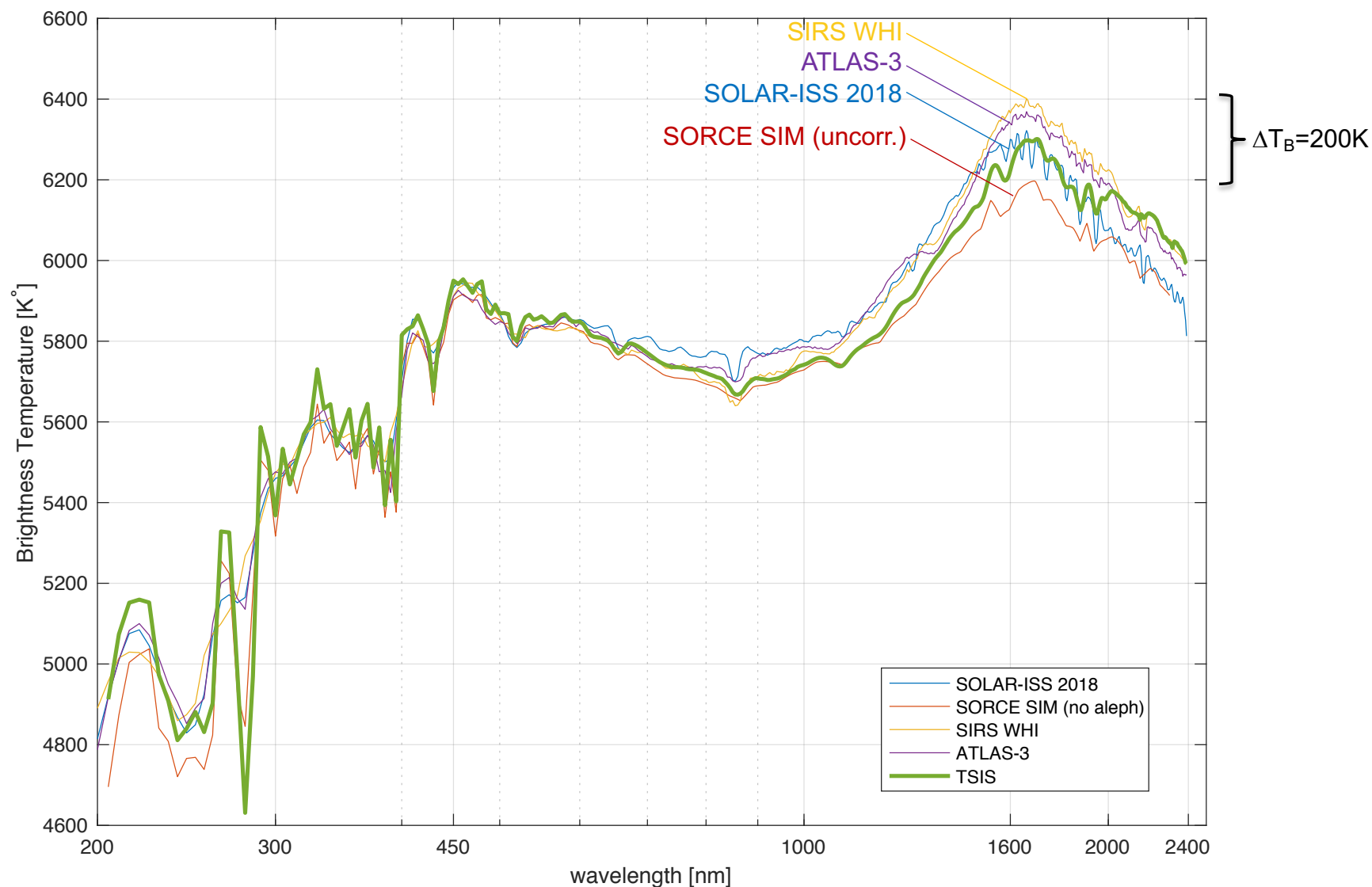
- <2 ps pulses (~10⁹ GW peak power)
 - ~1 nm at 1000 nm

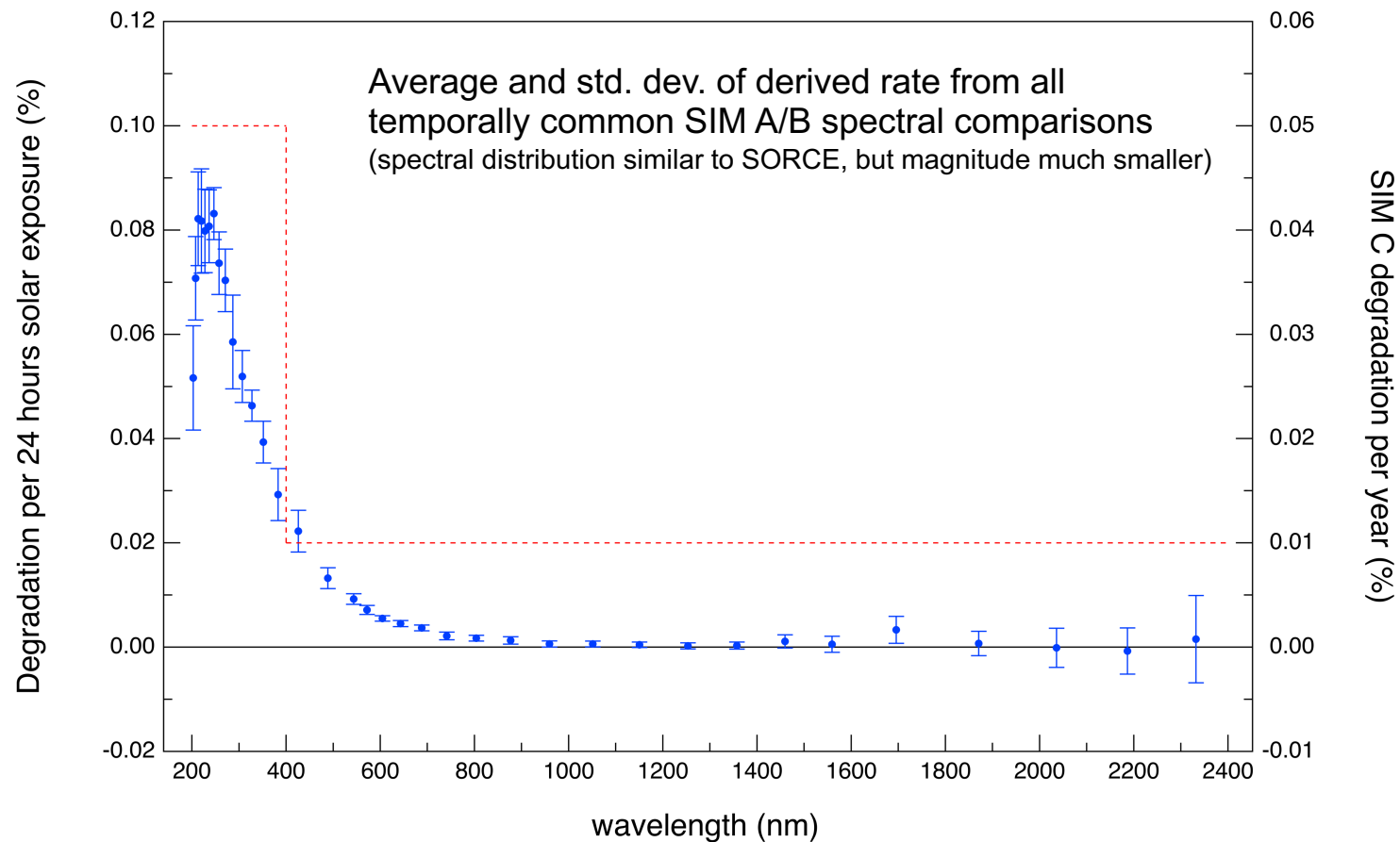
- Closed-loop feed-back stabilized and manually tuned





T_B Reference Spectra





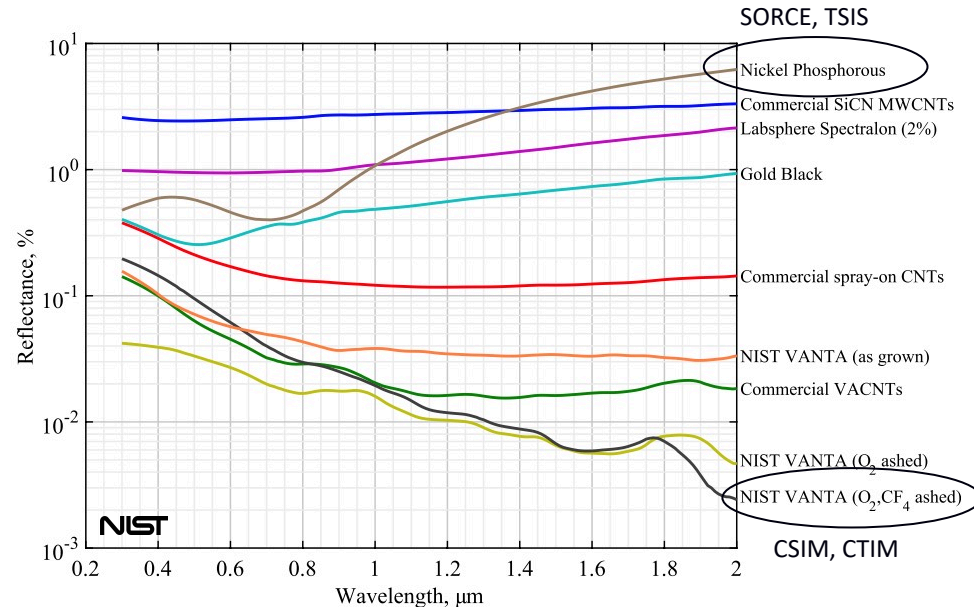
Based on present degradation rate, uncorrected SIM C meets annual L-1 stability requirement (dashed red line). Applying a SIM C degradation correction rate with exposure time will therefore meet annual stability requirements with margin.

- Based on our present operations plan, SIM C acquires only 12 hours of solar exposure per year.



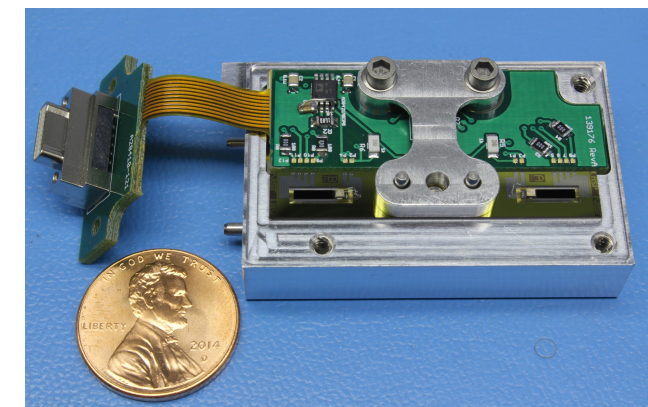
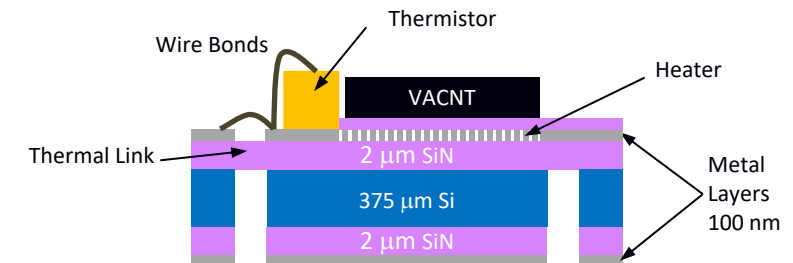
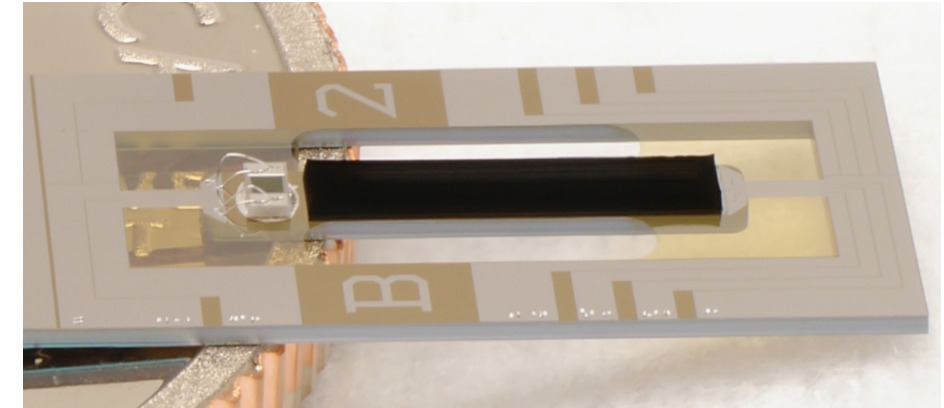
Silicon Substrate Vertically Aligned Carbon Nanotube (VACNT) Bolometers

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

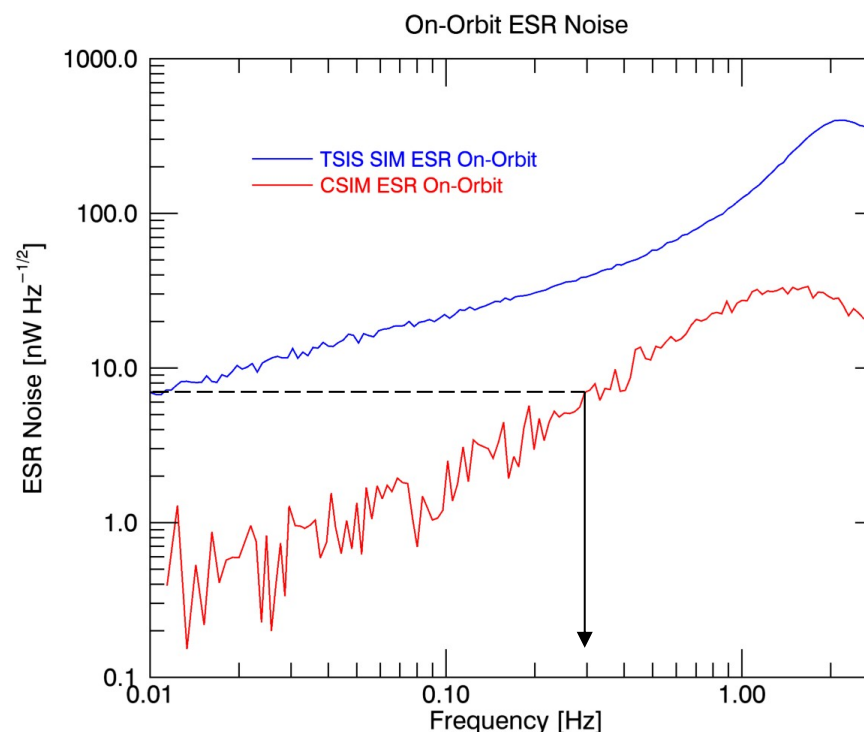
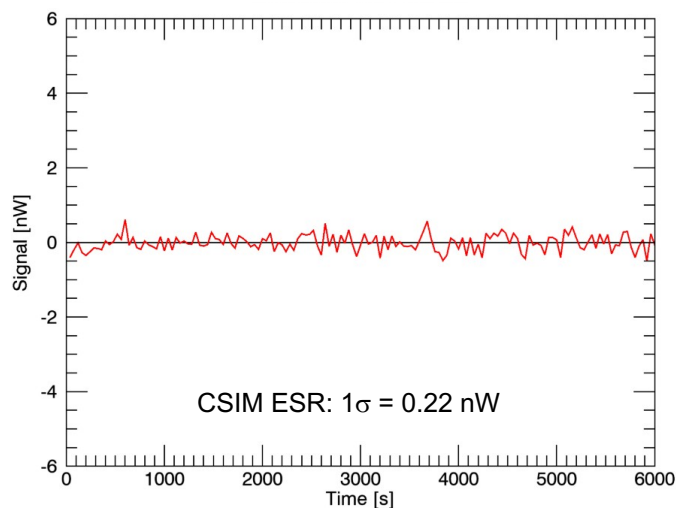
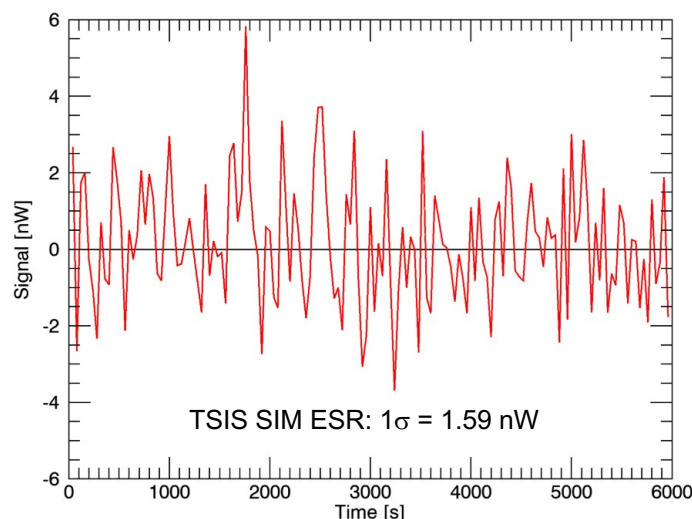




CSIM ESR Achievements

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 the prism exposure time during ESR scans