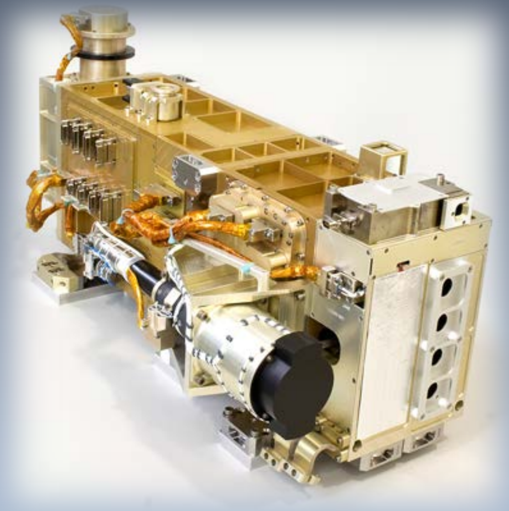
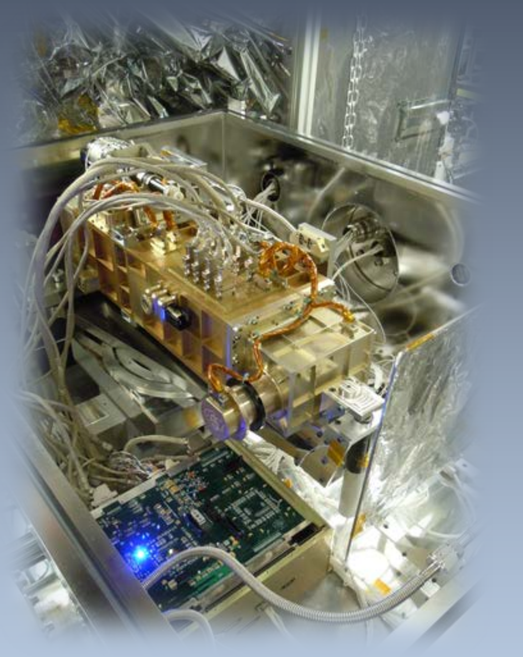
The Next Generation Solar Spectral Irradiance Monitor For the JPSS-TSIS Mission
Instrument Overview and Radiometric Performance



LASP
University of Colorado, Boulder

TSIS
Total and Spectral
Solar Irradiance Sensor



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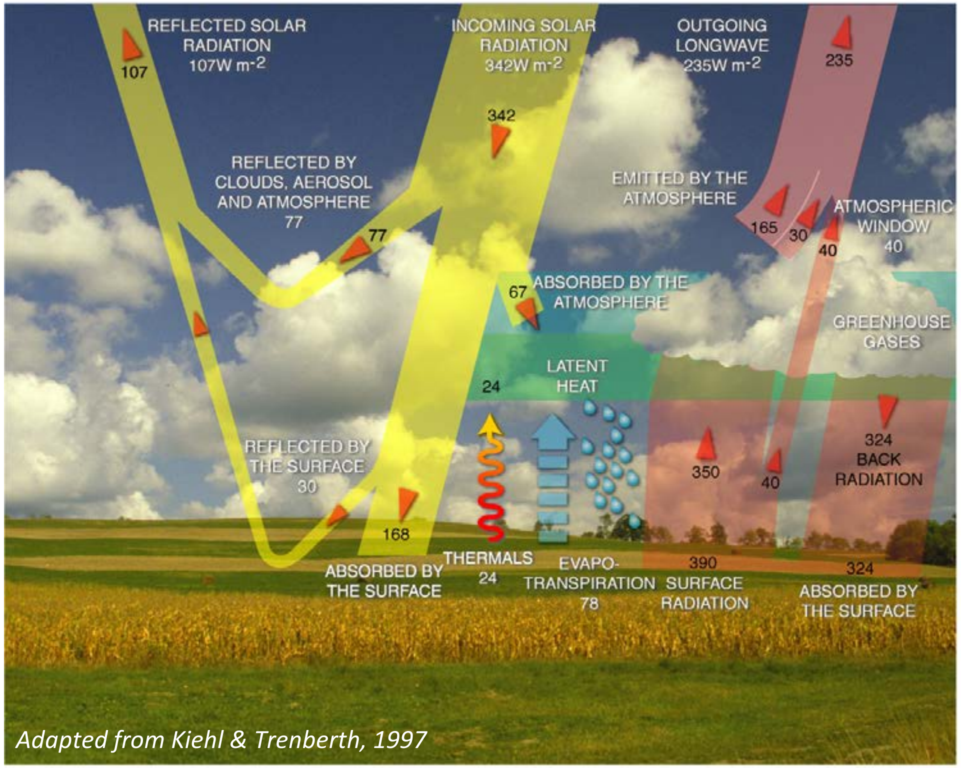
University of Colorado, Boulder, Colorado USA

Special thanks to:
Steve Brown, Keith Lykke, and Allan Smith
NIST & L-1 Standards and Technology, Inc.

Solar Spectral Irradiance (SSI) Influences on Global Change

Global Energy Budget Contributions



Adapted from Kiehl & Trenberth, 1997

SSI Radiative Forcing Questions

- ***How does the climate system respond?***

  - Process studies seek to quantify mechanisms by which the Earth system responds to various forcings

  ✓ Requires measurement of wavelength-dependent irradiance variability.

SSI observations will enable more realistic climate model simulations for comparisons with empirical evidence and ultimately projections of future change.

Measurement Goal:

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

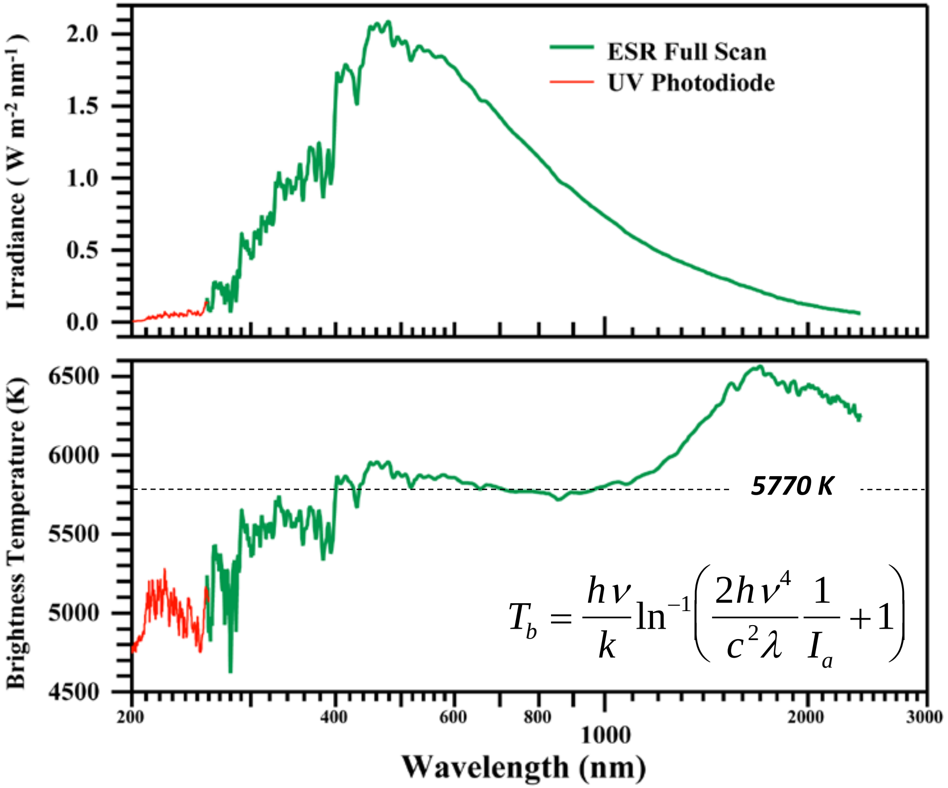
Climate Data Records from Environmental Satellites: Interim Report (2004)

SIM Measures Solar Spectral Irradiance (96% TSI)

Solar Spectral Irradiance (W m^{-2} nm^{-1})

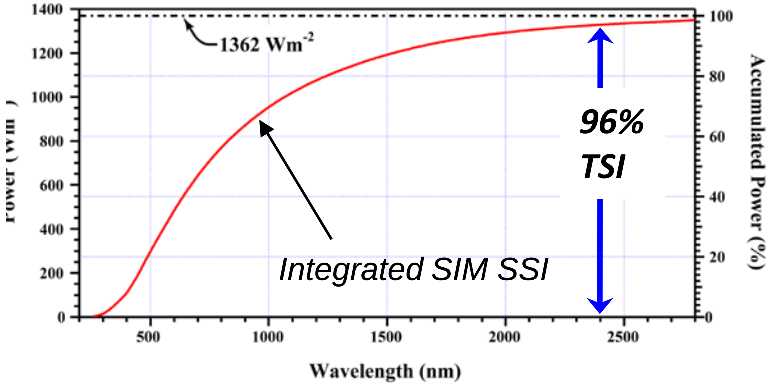
Solar Spectral Irradiance is defined as the radiant power per unit area per unit wavelength interval incident on a plane surface at the top of the atmosphere that is normal to the direction from the Sun.

SORCE SIM (200 – 2400 nm)



$$T_b = \frac{h\nu}{k}\ln^{-1}\left(\frac{2h\nu^4}{c^2\lambda}\frac{1}{I_a}+1\right)$$

SIM Integrated Power vs. Wavelength



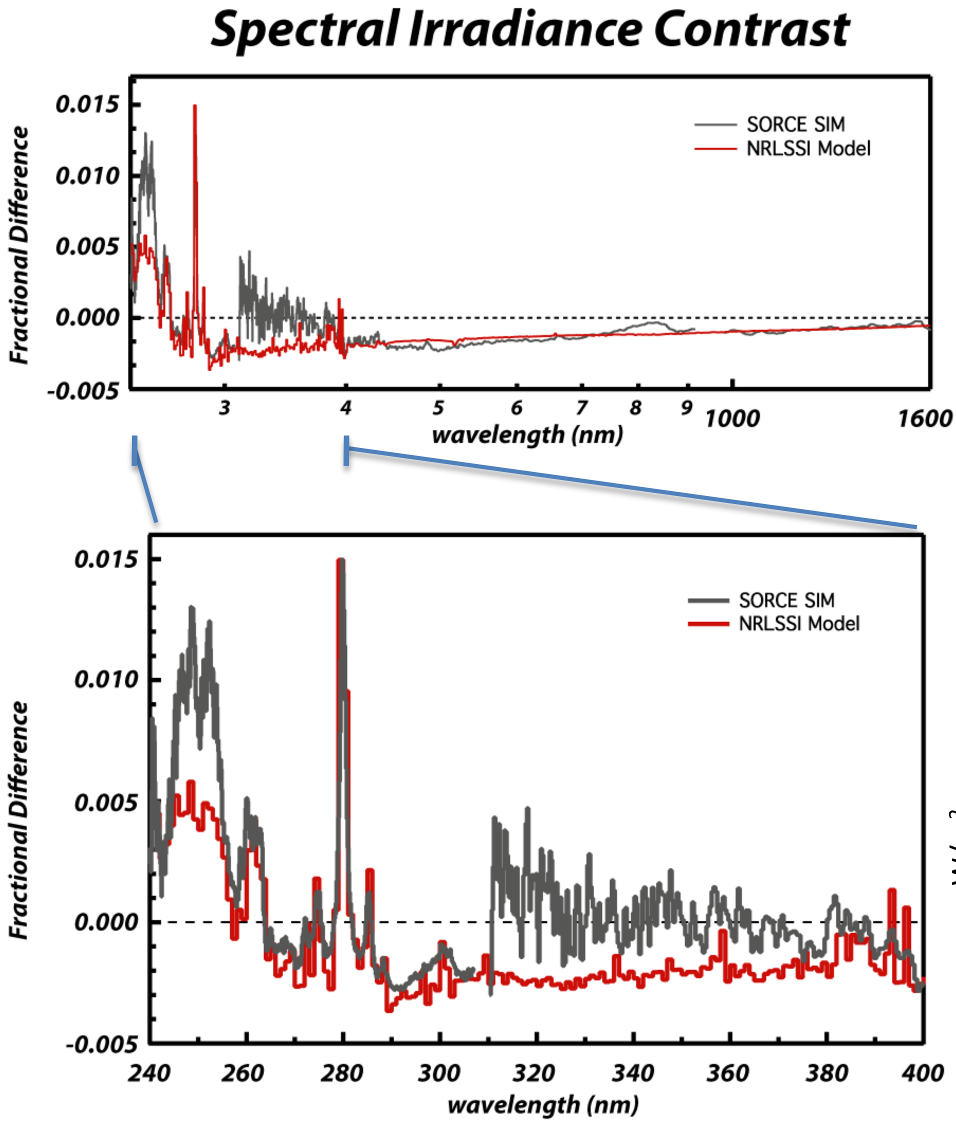
Total Solar Irradiance (TSI)

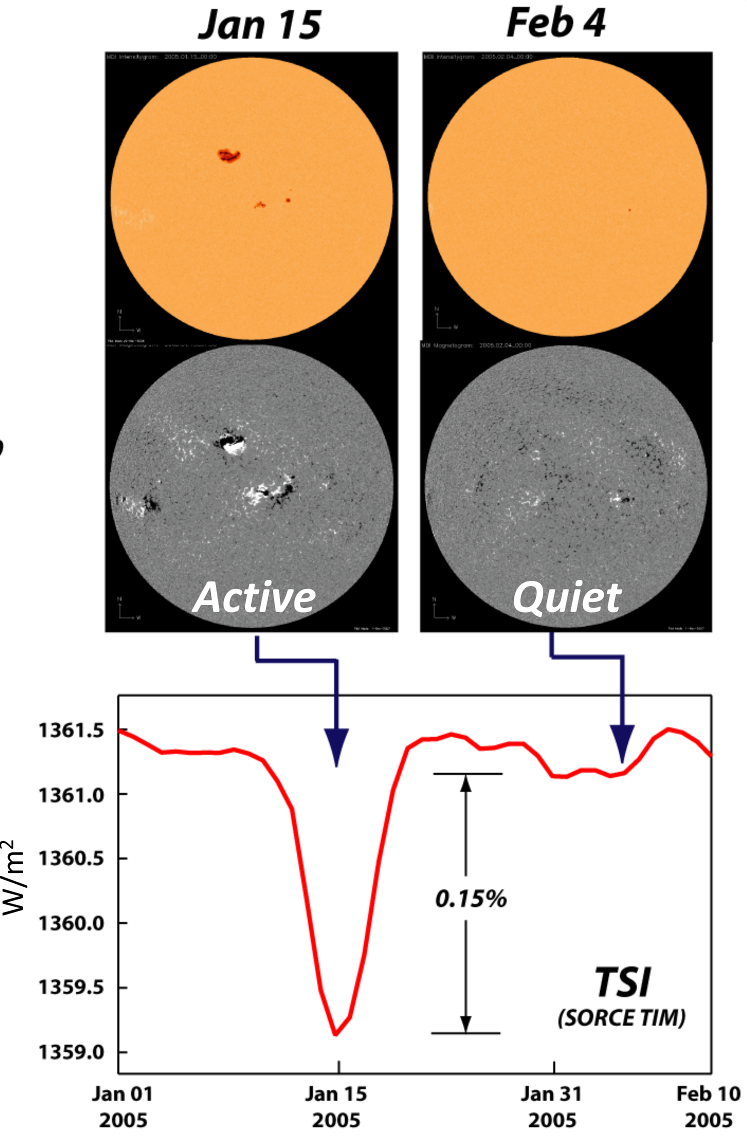
$$TSI_{TIM} = \int_{\lambda=0}^{\lambda=\infty} E_\lambda d\lambda \approx 1362 \ \mathrm{Watts}/\mathrm{m}^2$$

Spectral Solar Irradiance (SSI)

$$TSI_{SIM} = \int_{\lambda=200}^{\lambda=2400} E_\lambda d\lambda \approx 96\% \text{ of TSI}$$

Short-term (Rotational) SSI Variability



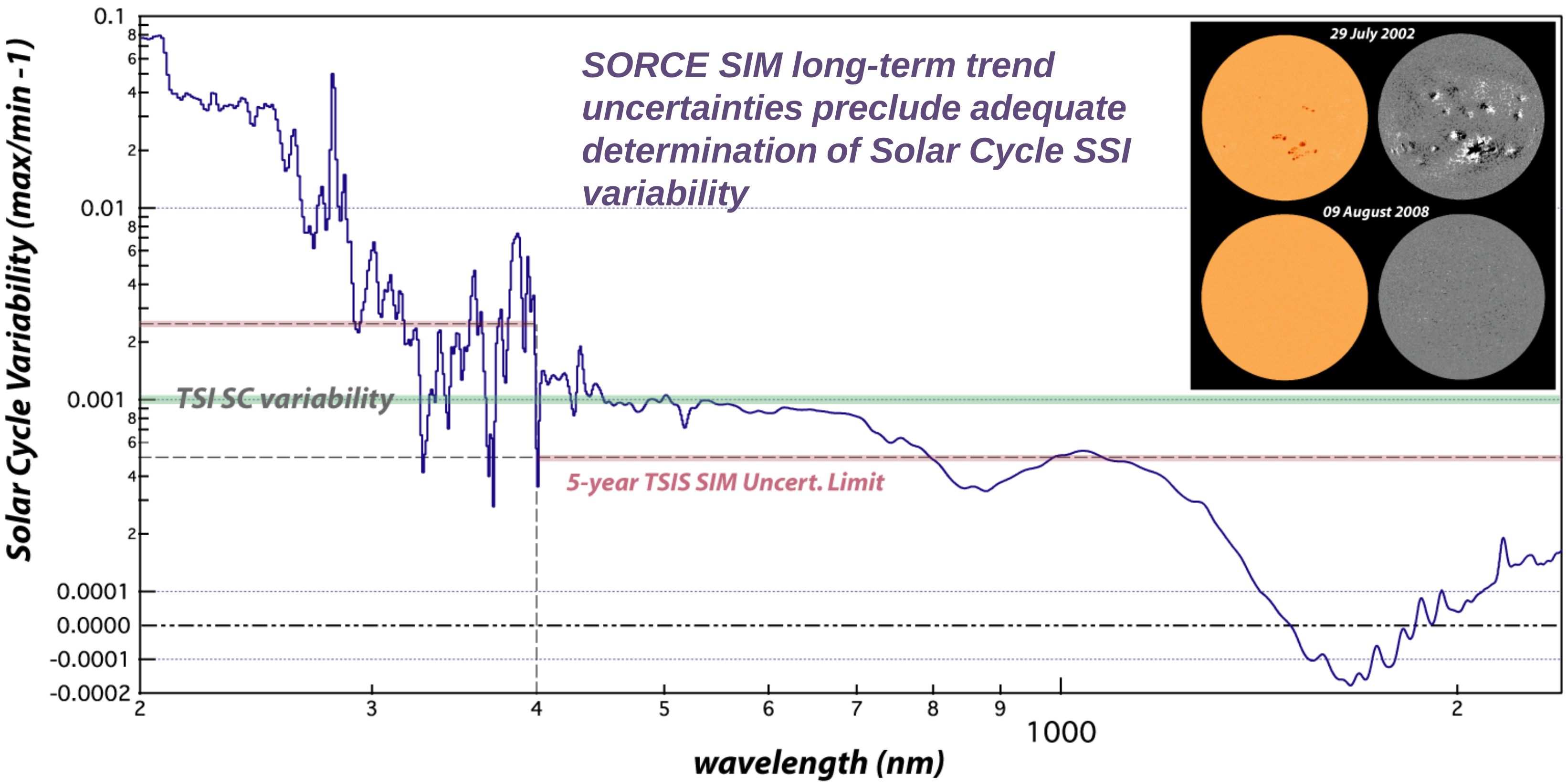


Predicted Solar Cycle SSI Variability

174-242 nm: O_2 dissociation - O_3 production (1.8 W/m^2)

242-300 nm: O_3 absorption (12 W/m^2)

300 - >2000 nm: Climate Forcing (~1355 W/m^2)



SORCE SIM long-term trend uncertainties preclude adequate determination of Solar Cycle SSI variability

NRLSSI Modeled spectral variability based on observations of UV (120-250 nm) and model of rotational modulation of plage and sunspot contrast.

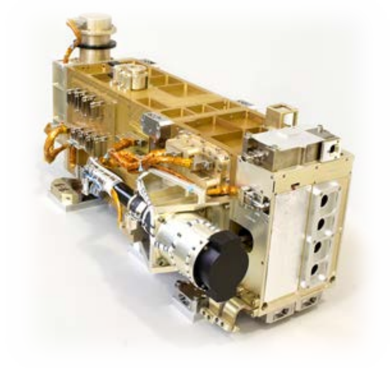
Prior to SORCE SIM (2003) no continuous measurement of variability in the 400-2400 nm region

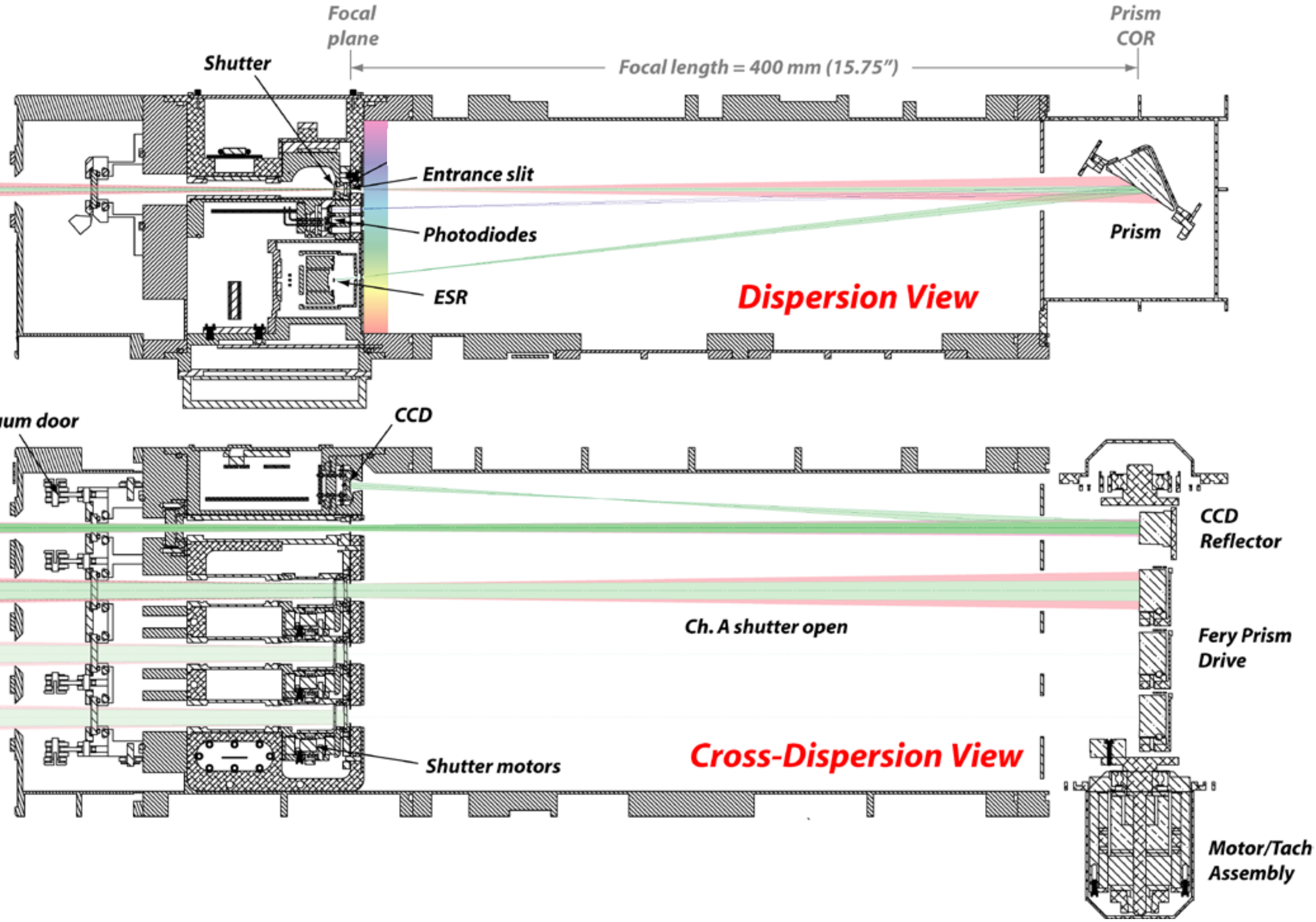
SSI Measurement Requirements

Attribute	Req't	Justification
Measurement range ($Wm^{-2}nm^{-1}$) *Spectral limits (0.2 - 2.4 μm)*	**10^{-4} - 10^{1}**	**Solar spectrum** *Full scale bounds on magnitude of SSI*
Long-term rel. stability (per year) *$0.2 \leq \lambda \leq 0.4$ μm* *$0.4 < \lambda \leq 2.4$ μm*	**0.05%** **0.01%**	**Solar cycle variability (S_{max}/S_{min})** *UV variability: 10% - 0.1% (Chromospheric)* *Vis-NIR variability: ≤ 0.05% (Photospheric)*
Measurement precision *Spectral limits (0.2 - 2.4 μm)*	**0.01%**	**Solar rotational variability** *High SNR for Vis-NIR spectral repeatability*
Measurement accuracy *Integrated spectral (0.2 - 2.4 μm)*	**0.25%**	**Climate modeling input** *Earth radiation budget: Solar attribution*
Reporting cadence (per day) *Spectral limits (0.2 - 2.4 μm)*	**2**	**Solar temporal variability** *Sample diurnal spectral variabiliy (TSI correl.)*
Spectral resolution (nm) *$\lambda \leq 0.28$ μm (Mg II)* *0.28 μm $< \lambda \leq 0.40$ μm (Ca II edge)* *$\lambda > 0.40$ μm (photosphere)*	**1** **5** **45**	**Solar wavelength variability** *Strongest λ-dependence in UV variabilty (Chromospheric origin)* *Broader λ-dependence in Vis-NIR (Photospheric origin)*

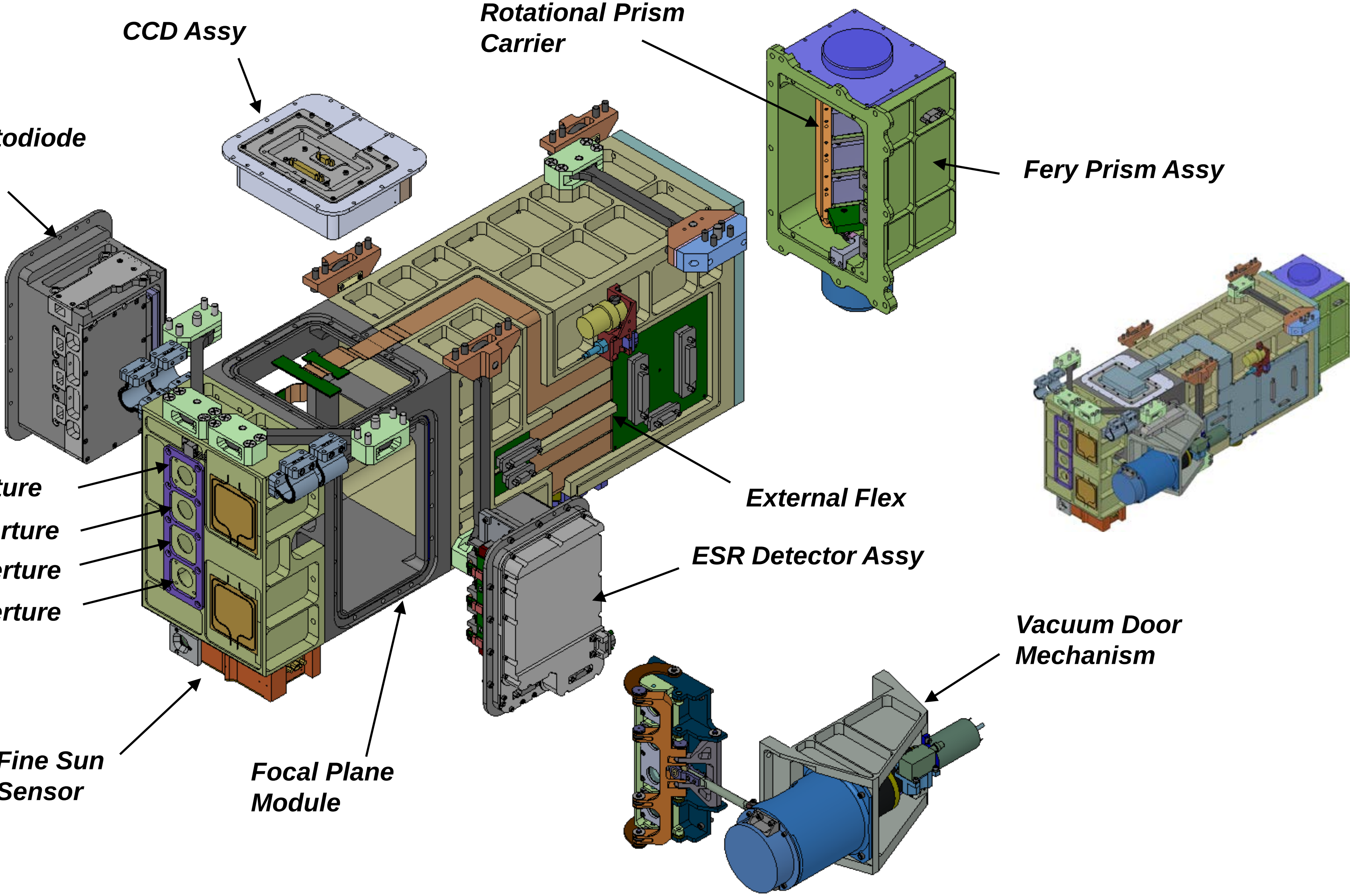
TSIS SIM Design Overview

Féry prism spectrometer (monochrometer) covering the full wavelength range from the UV to IR using <u>only one optical element</u> for spectral dispersion and image quality (3 full spectral, independent channels)





TSIS SIM Components



CCD Assy

Rotational Prism Carrier

Shutter/Photodiode Assy

Fery Prism Assy

CCD Aperture

Ch. A Aperture

Ch. B Aperture

Ch. C Aperture

External Flex

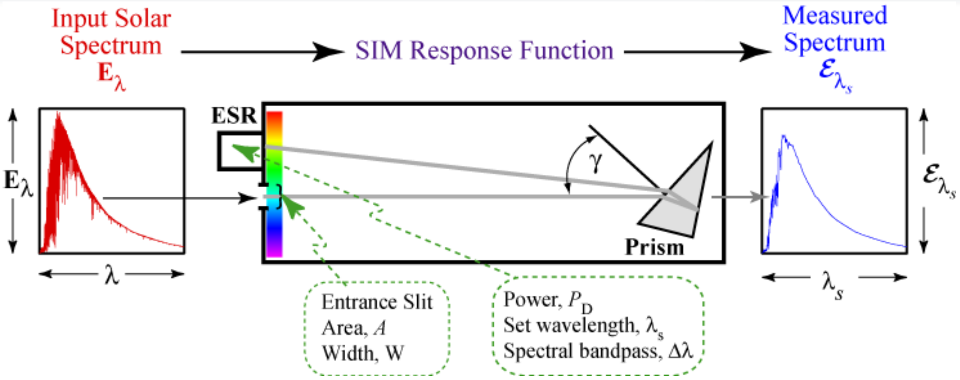
ESR Detector Assy

Vacuum Door Mechanism

Fine Sun Sensor

Focal Plane Module

Measurement Equation Overview


Input Solar Spectrum E_λ → SIM Response Function → Measured Spectrum $\mathcal{E}_{\lambda_s}$

Entrance Slit
Area, A
Width, W

Power, P_D
Set wavelength, λ_s
Spectral bandpass, $\Delta\lambda$

$$\mathcal{E}_\lambda(\lambda_s) = \frac{\mathcal{P}_{\mathrm{ESR}}(\lambda_s)}{A_{slit} \cdot \int \alpha_\lambda \cdot T_\lambda \cdot \phi_\lambda \cdot S(\lambda,\lambda_s)\ d\lambda} \qquad \left[\frac{\mathbf{W}}{\mathbf{m^2\ nm}}\right]$$

ESR detected power

Aperture area

ESR Absorptance

prism transmission

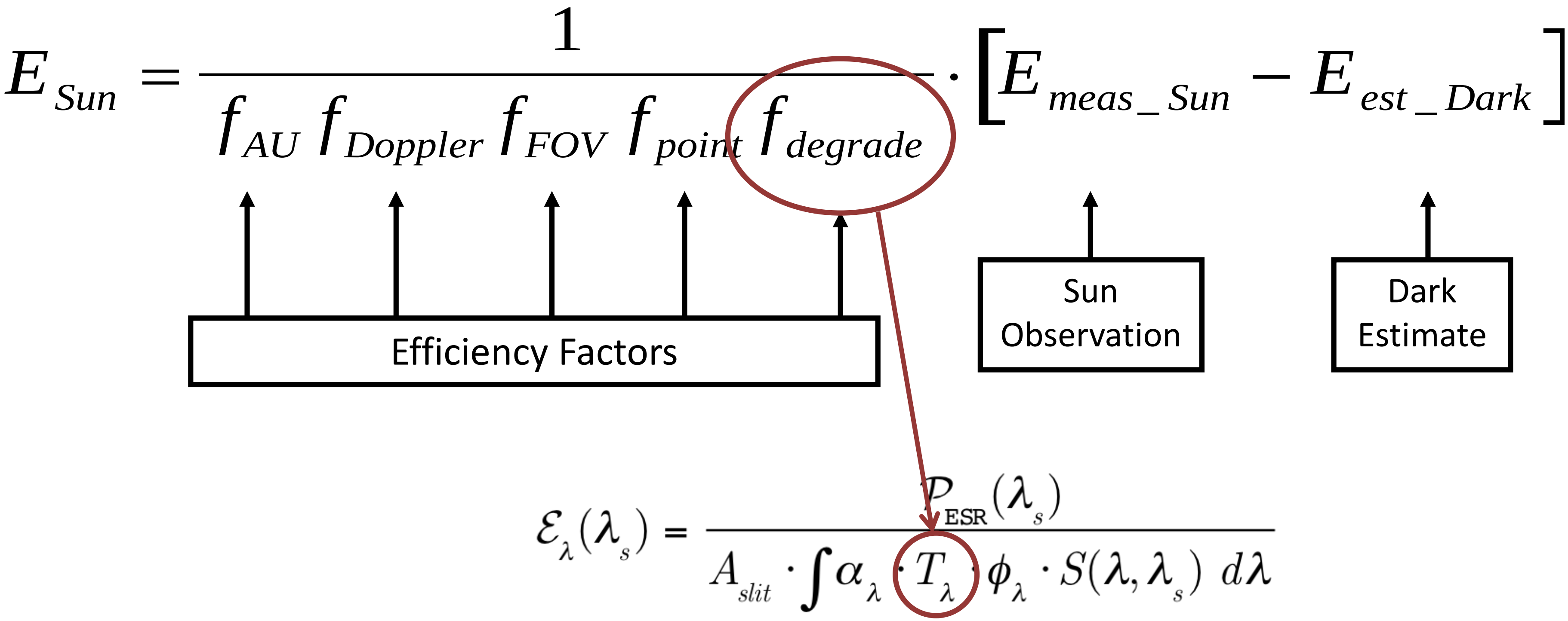
Slit diffraction

Spectral Transfer function

$$\boxed{\mathcal{E}(\lambda_s) = \frac{\mathcal{I}_{\mathrm{photodiode}}(\lambda_s)}{A_{\mathrm{slit}} \int \mathcal{R}_\lambda \mathcal{T}_\lambda \Phi_\lambda \mathrm{S}(\lambda,\lambda_s)\ d\lambda}}$$

On-orbit calibration corrections

Long-term corrections are key!



$$E_{Sun} = \frac{1}{f_{AU}\, f_{Doppler}\, f_{FOV}\, f_{point}\, \boxed{f_{degrade}}} \cdot \left[E_{meas\_Sun} - E_{est\_Dark} \right]$$

Efficiency Factors

Sun Observation

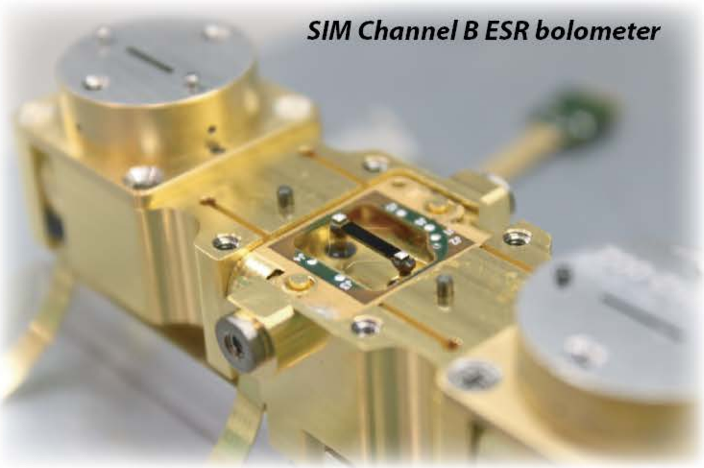
Dark Estimate

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

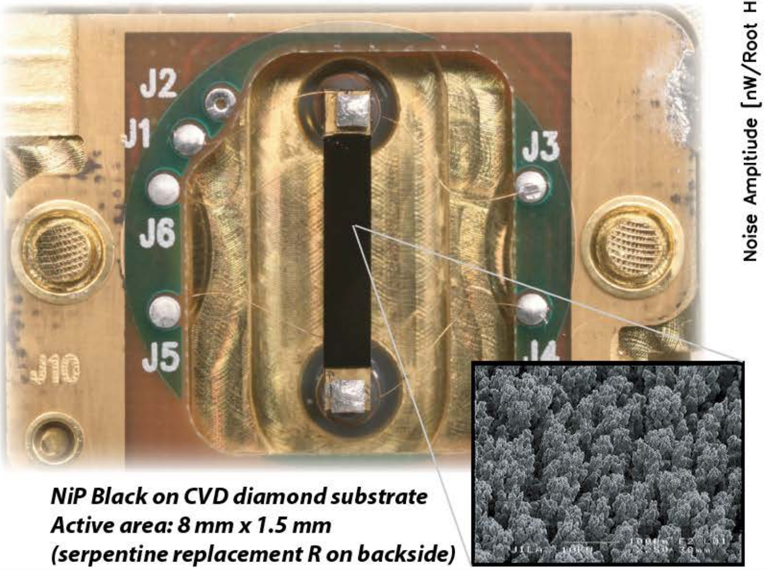
Optical degradation (both wavelength and time dependent) is the largest contribution to the long-term measurement uncertainty

SIM Electrical Substitution Radiometer (ESR)

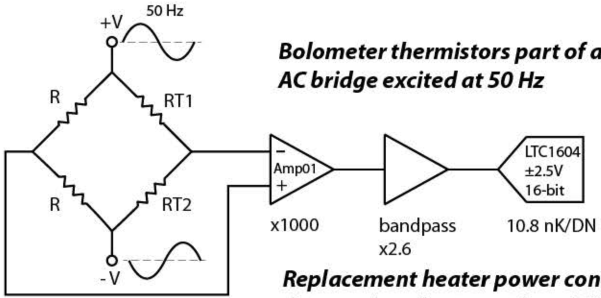
The TSIS SIM ESR serves as a NIST traceable, space-qualified absolute calibration transfer detector



SIM Channel B ESR bolometer

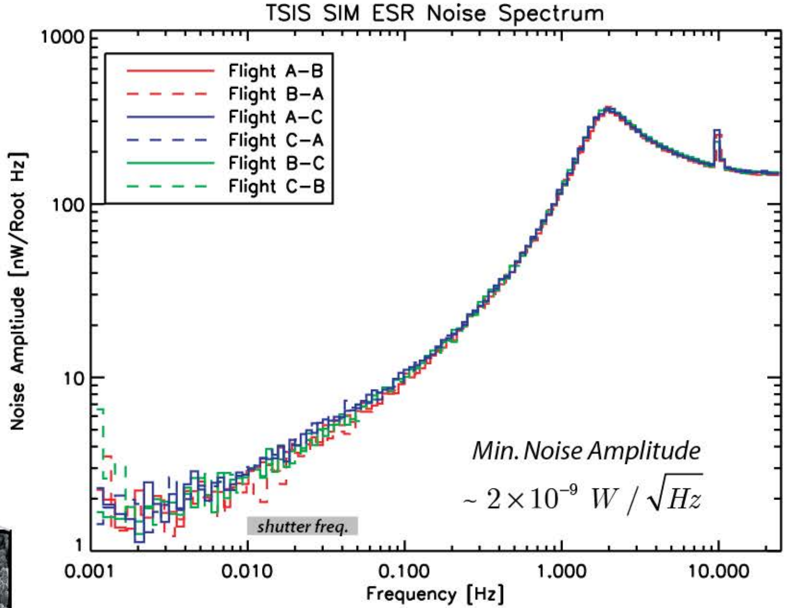


NiP Black on CVD diamond substrate
Active area: 8 mm x 1.5 mm
(serpentine replacement R on backside)



Bolometer thermistors part of a precision AC bridge excited at 50 Hz

Replacement heater power controlled by duty-cycle adjustment from PWM (100 Hz)

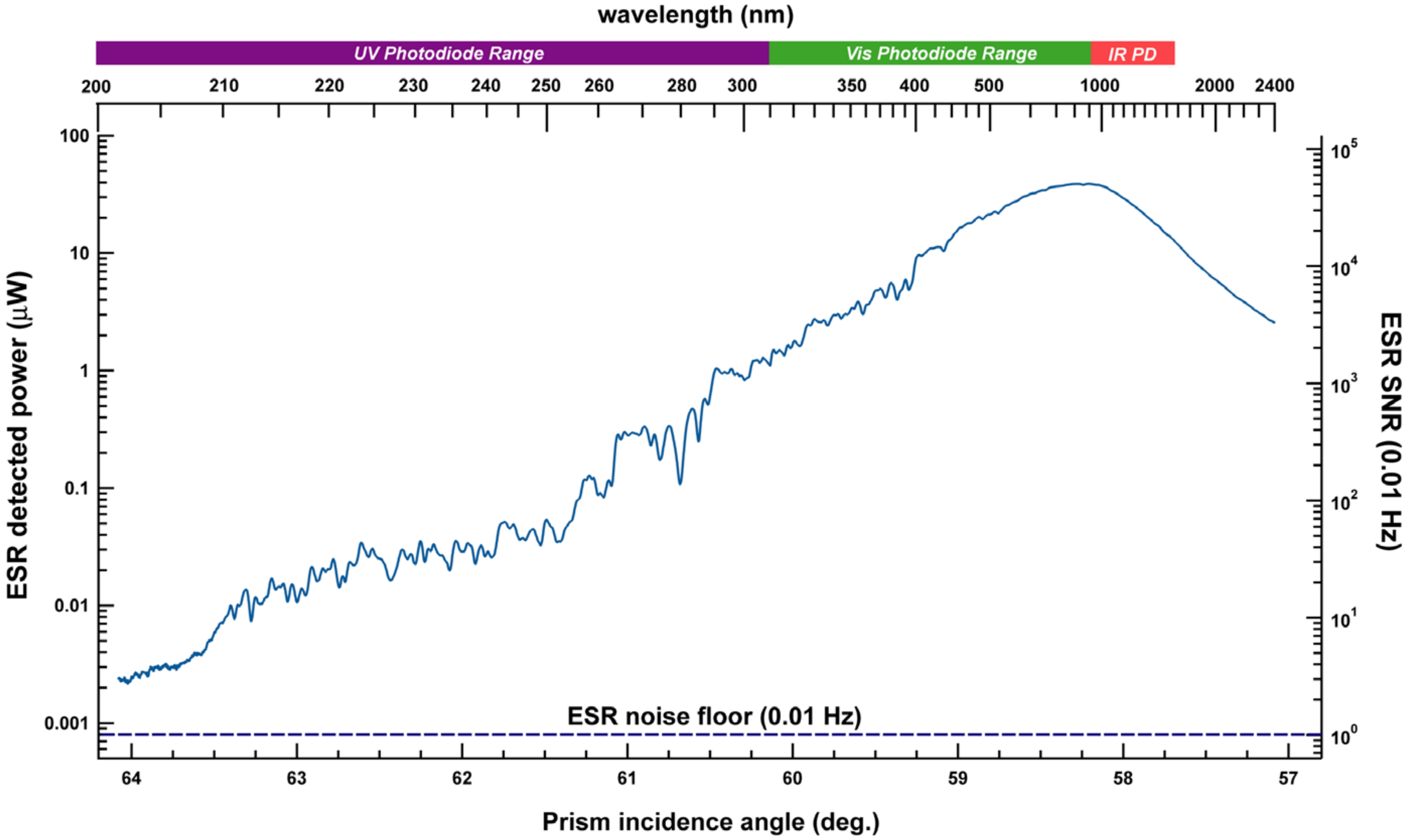


Min. Noise Amplitude

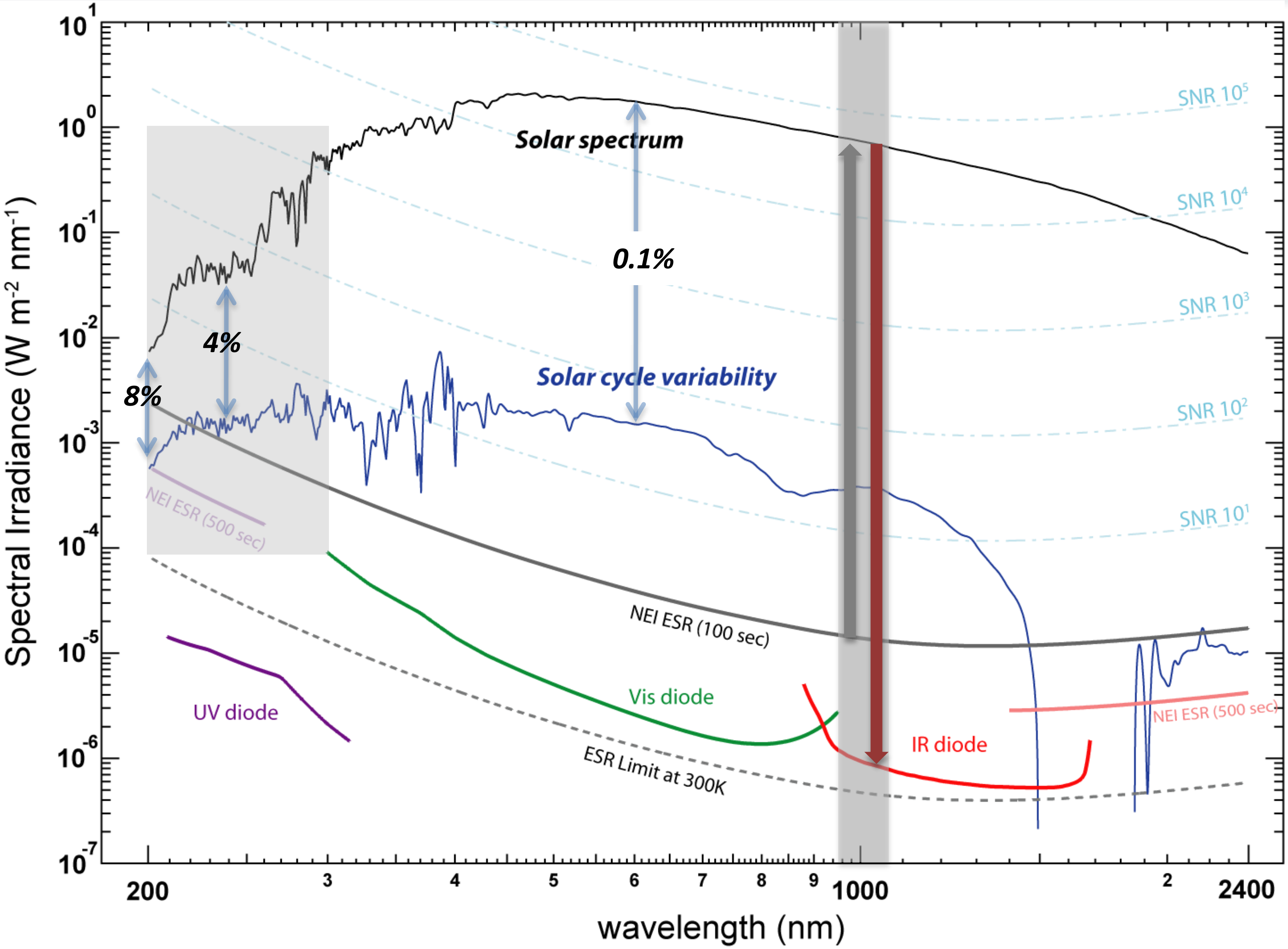
$\sim 2\times10^{-9}\ W/\sqrt{Hz}$

Phase-sensitive detection is used to analyze only changes in the applied ESR power at, and in phase with, the shutter fundamental frequency (typ. 0.01 - 0.05 Hz)

ESR Performance Meets Requirements for Solar Spectral Power

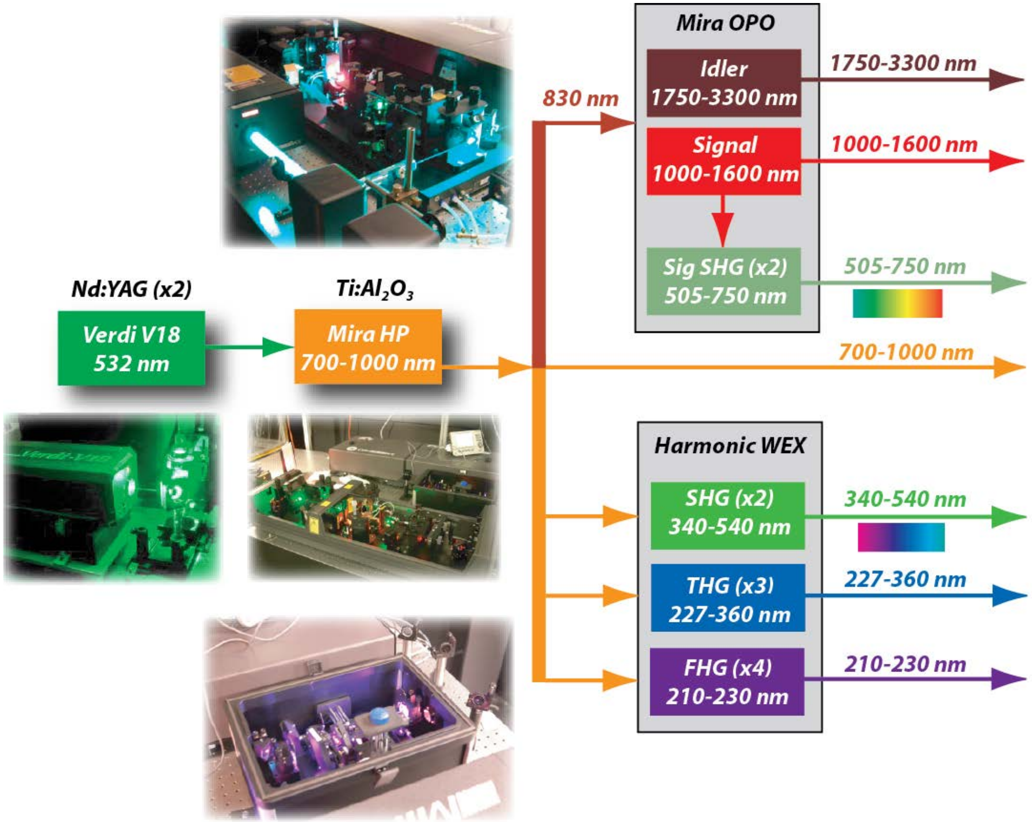


SSI Variability and SIM Measurement Capabilities

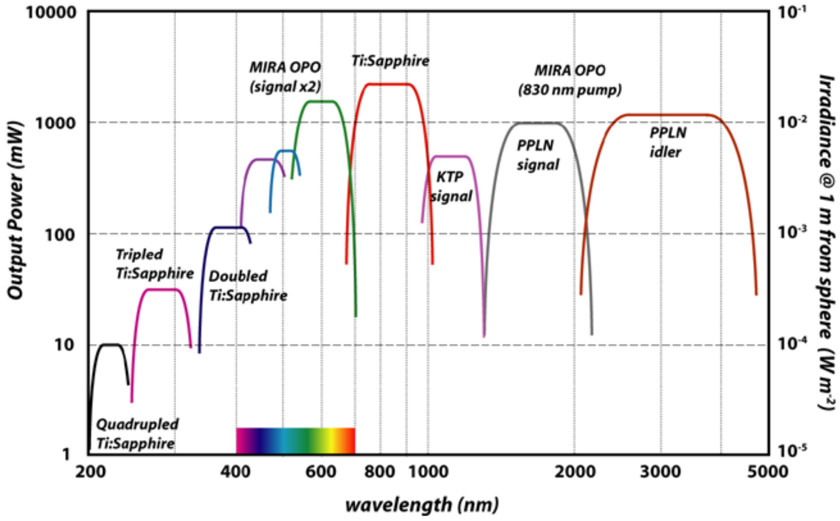


NIST SIRCUS Facility

“Spectral Irradiance and Radiance Responsivity Calibrations with Uniform Sources”



This comprehensive calibration facility provides irradiance calibration of the SIM ESR & photodiodes and the full SIM over the operational wavelength (and irradiance) range of the SIM instrument.



Designed to reduce the uncertainty in spectral irradiance and radiance responsivity calibrations at the 0.1 % level and expand the spectral range where these uncertainty levels are achievable

The current uncertainty for SSI measurements is ~3 %. Current developments are directed at reducing this to a general goal of 0.25 % (k=1)

Characterization / Calibration Flow

Component-Level Calibrations:

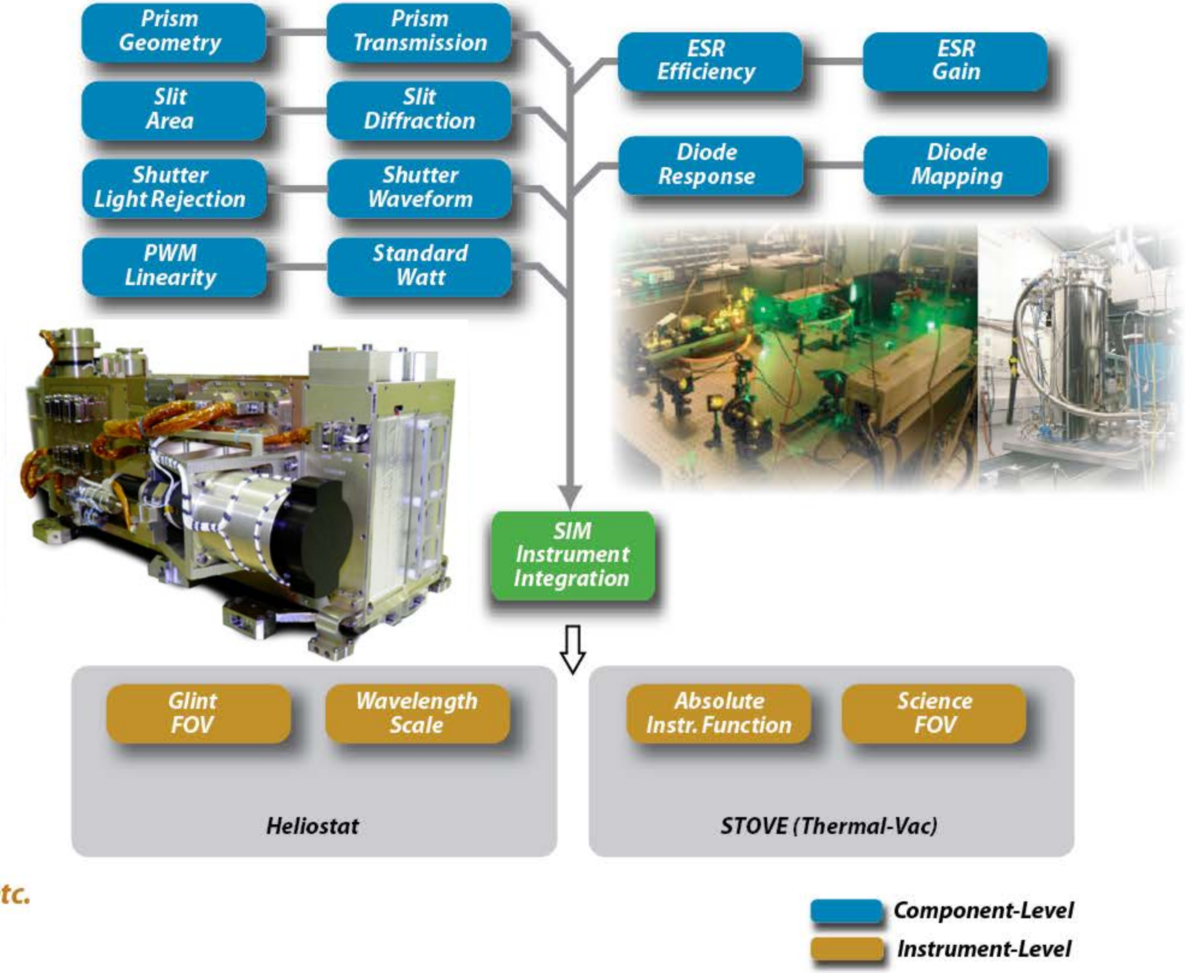
- *Slit Area*
- *Standard Watt*
- *Pulse-Width Modulation Linearity*
- *Shutter Waveform*
- *Servo Gain*

λ-dependent Calibrations:

- *Prism Geometry*
- *Prism Transmission*
- *Slit Diffraction*
- *ESR Efficiency*
- *Photodiode Sensitivity*

Instrument-Level Calibrations:

- *Glint Field of View*
- *Wavelength Scale*
- *Absolute Instrument Function Area*
- *Scattered Light*
- *Science Field of View*
- *Servo Gain, Nonequivalence, Noise, etc.*



Calibration and characterization follows a measurement equation approach at the unit-level for full validation of end-to-end performance at the instrument-level

TSIS SIM Calibration Error Budget

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

	Measurement Correction	*Origin*	*Value (ppm)*	*1σ (ppm)*
S/C	Distance to Sun, Earth & S/C	*Analysis*	33,537	0.1
	Doppler Velocity	*Analysis*	43	1
	Pointing	*Analysis*	0	100
Component-Level	Shutter Waveform	*Component*	100	10
	Slit Area	*Component*	1,000,000	300
	Diffraction	*Component*	5,000-62,000	500
	Prism Transmittance	*Component*	230,000-450,000	1,000
	ESR Efficiency (absorptance)	*Component*	1,000,000	1,000
	Standard Volt + DAC	*Component*	1,000,000	50
	Pulse Width Linearity	*Component*	0	50
	Standard Ohm + Leads	*Component*	1,000,000	50
Instrument-Level	Instrument Function Area	*Instrument*	1,000,000	1,000
	Wavelength	*Instrument*	1,000,000	750
	Non-Equivalence, Z_H/Z_R-1	*Instrument*	2,000	100
	Servo Gain	*Instrument*	2,000	100
	Dark Signal	*Instrument*	0	100
	Scattered Light	*Instrument*	0	200
	Noise	*Instrument*	-	100
	Combined Rel. Std. Uncertainty			*2000*

Dominant uncertainties are ●-dependent

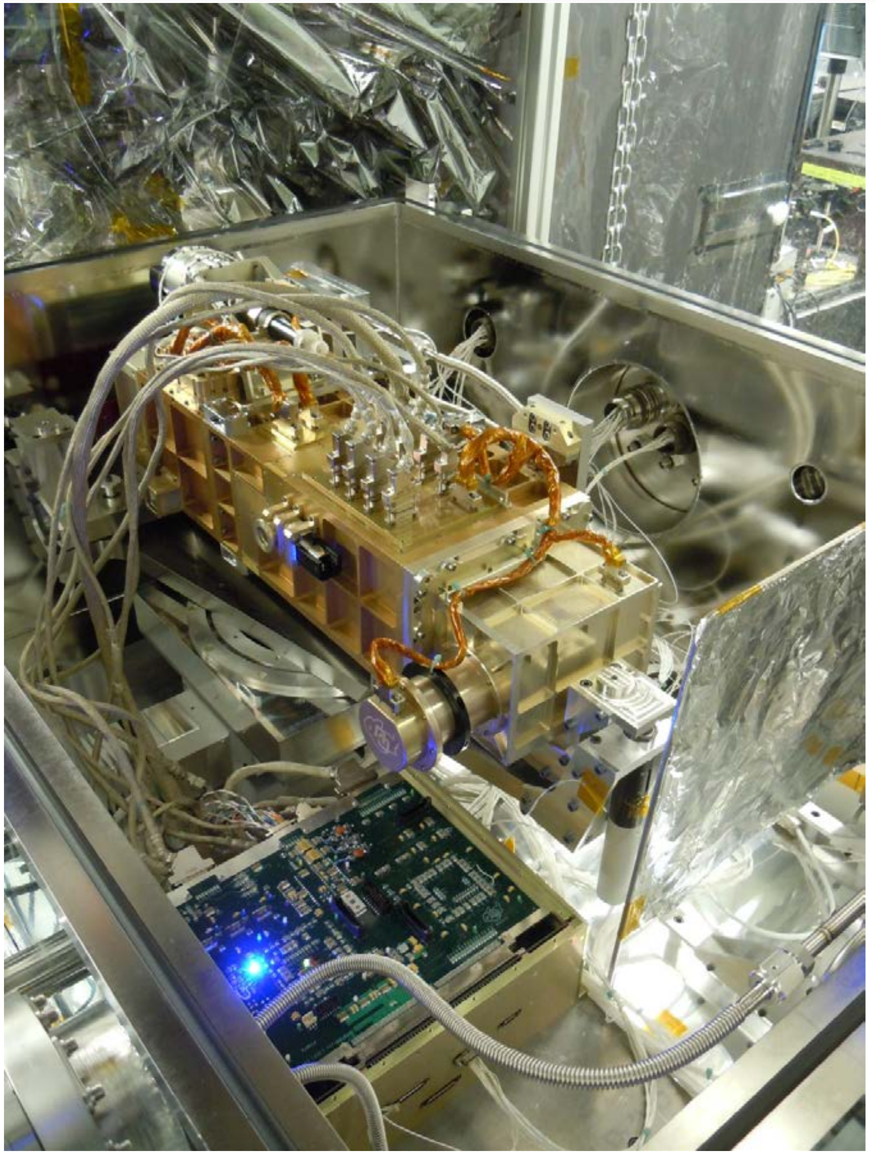
98% of full budget

Final systematic uncertainty quantification requires full end-to-end irradiance calibration

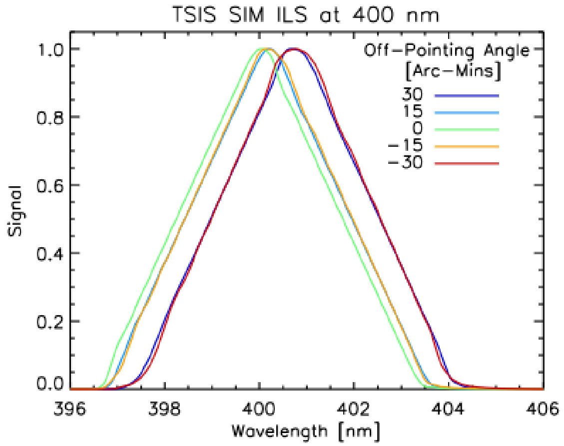
20% margin

TSIS SIM Calibration

- ***Full instrument-level calibration includes (all in vacuum):***
  - *SIRCUS laser wavelength calibration*
  - ***Spectral instrument function measurements (Spectral PSF's)***
    - ***ESR and Photodiodes (all channels)***
  - *Absolute spectral irradiance calibration tied to NIST L1 Cryo*
    - *ESR (all channels)*
  - *Channel to channel boresight alignment calibration*
  - *Pointing and FOV mapping*
    - *For all calibrations above*



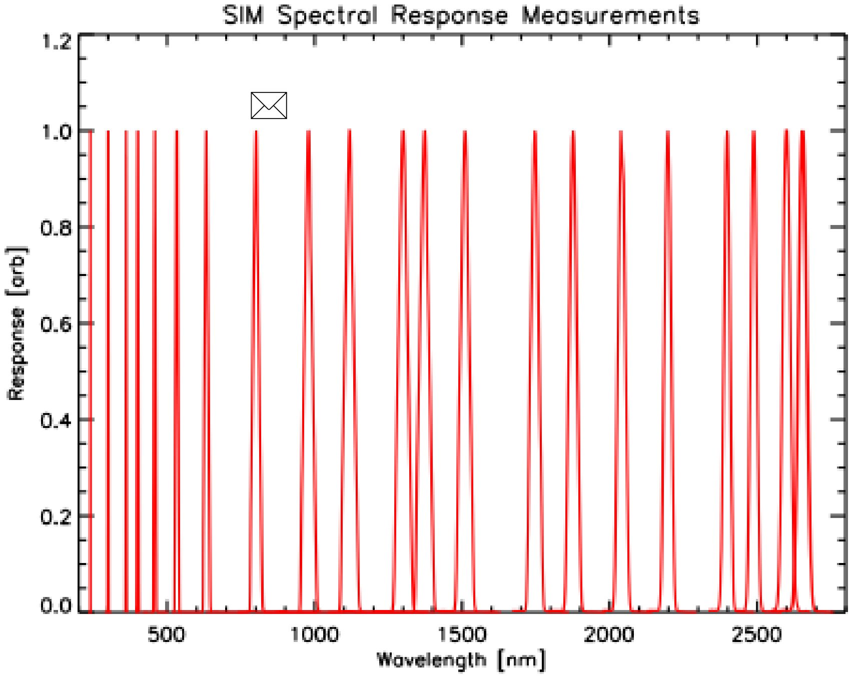
SIM Spectral Response Functions

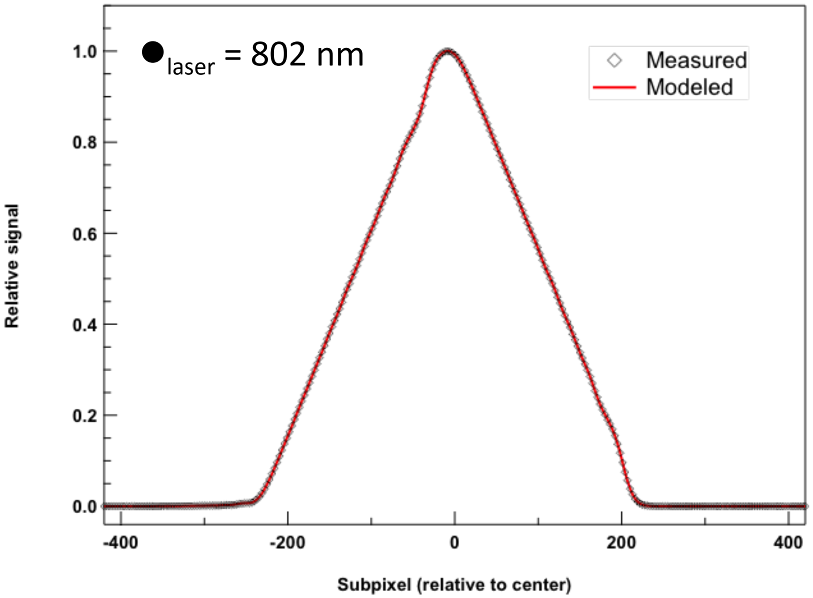


Spectral response functions are measured for each laser polarization, full FOV angles (disp. & x-disp).

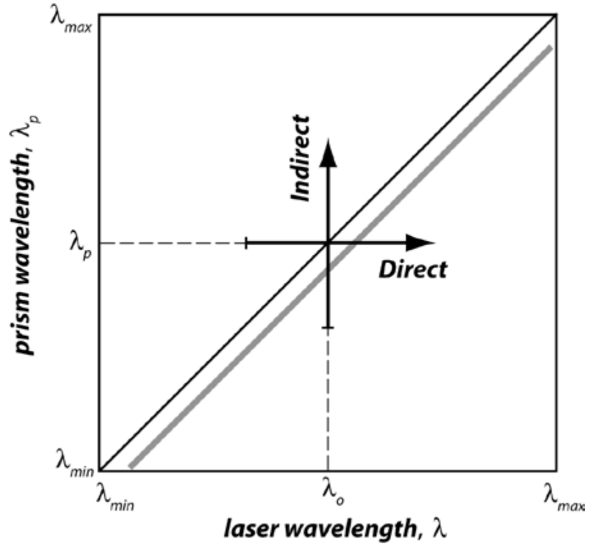
To transfer to Sun must generate "solar" SRF based on convolution of extended source including spectral center-to-limb distribution

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





SIM Spectral Response Functions



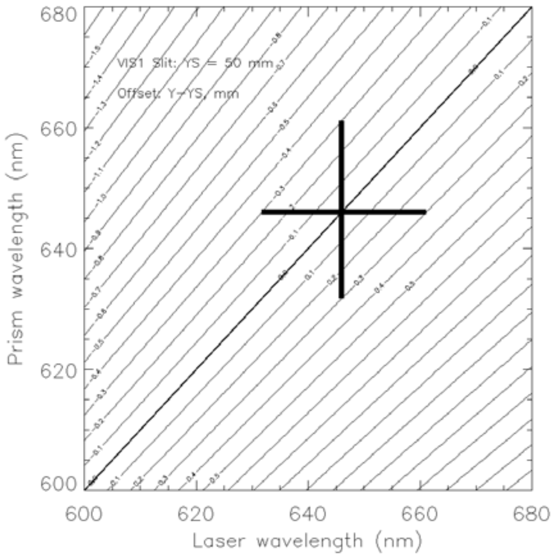
Direct determination: Fix prism, scan laser

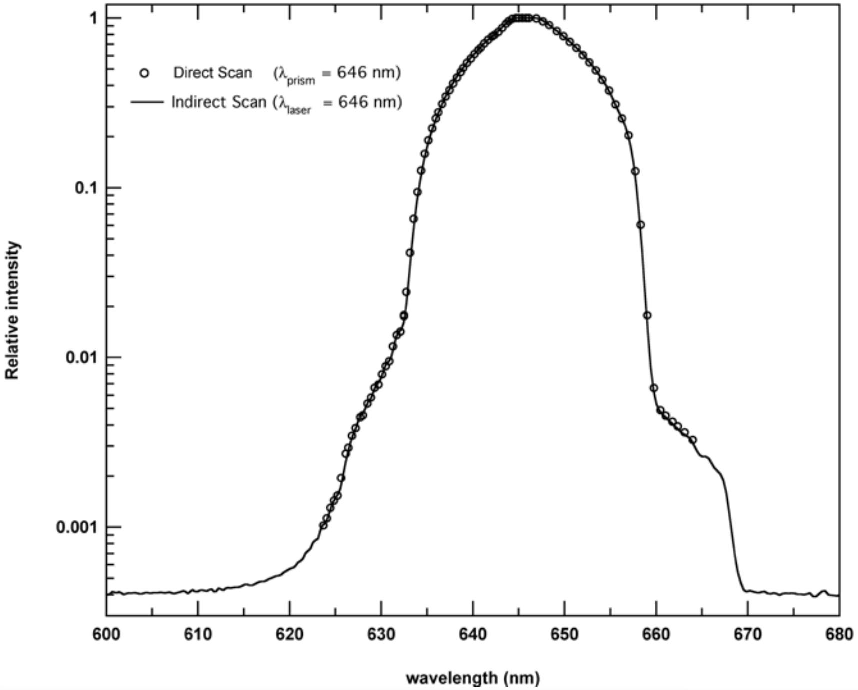
$$S(\lambda_p,\lambda) = \int_{\Delta\lambda} E_\lambda(\lambda,\lambda')R_E(\lambda_p,\lambda')d\lambda'$$

Indirect determination: Fix laser, scan prism

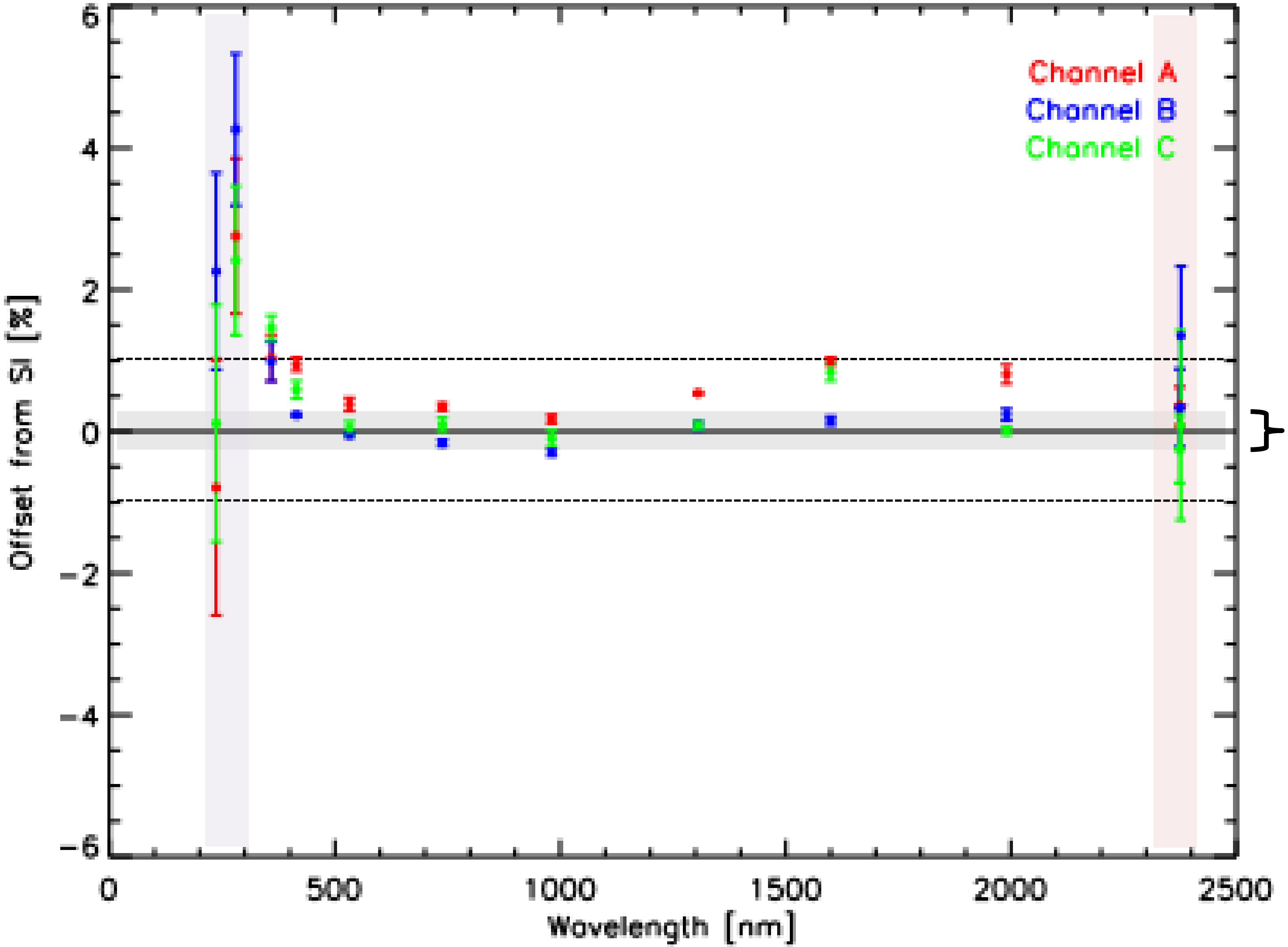
$$S(\lambda,\lambda_o) = \kappa\int_{\Delta\lambda} E(\lambda',\lambda_o)\cdot r(\lambda',\lambda_o)d\lambda'$$

$$r(\lambda',\lambda_o) = r_f(\lambda')\cdot z(\lambda'-\lambda_o)$$





Preliminary Full Validation Results



} ±0.25% !

Exposure Degradation over Mission Life

On-orbit interchannel transmission comparisons track wavelength and exposure time dependent transmission loss

$$\mathcal{T}(\lambda, t - t_0) = \mathcal{T}(\lambda, t_0)\,\mathrm{e}^{-\tau(\lambda, t - t_0)}$$

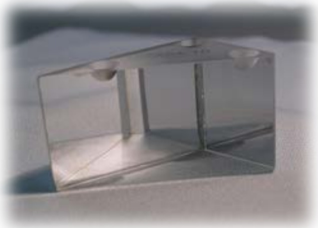
$$\tau(\lambda, t) = \kappa(\lambda) \cdot c(t)$$

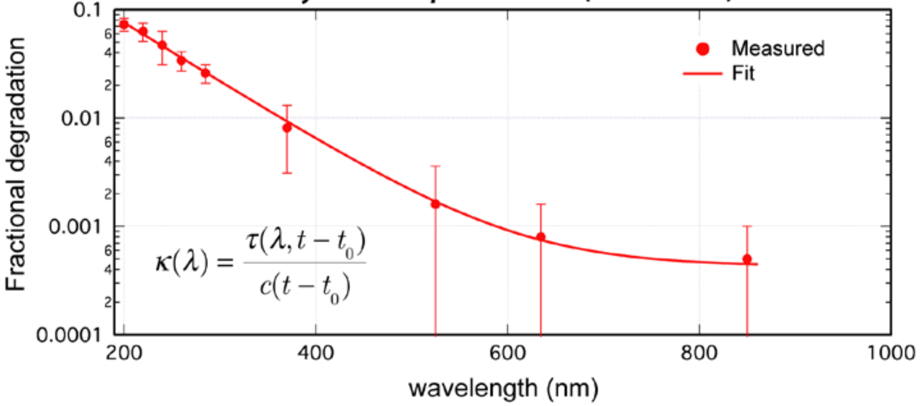
$\kappa(\lambda)$ evaluated by periodic ESR measurements between separate channels

The degradation correction determined using the Channel A to Channel B ratio data measured twice per month

The Channel A to Channel C comparison (~1 per year) verifies the degradation correction

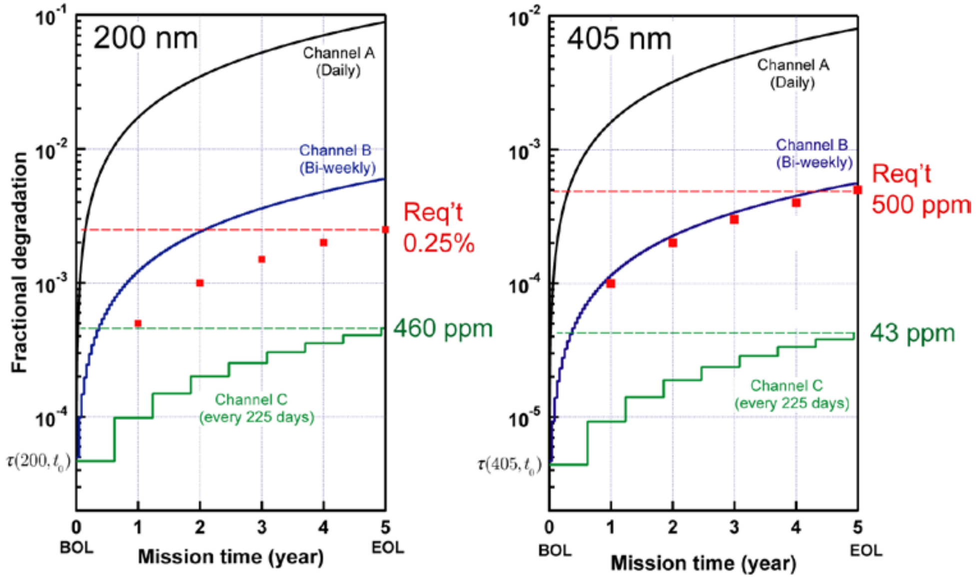
Channel C is to be used infrequently enough so that it can be considered "pristine" (less than 0.01%/year of degradation)





Fractional degradation vs. wavelength

5 year solar equivalent dose (110 - 160 nm)



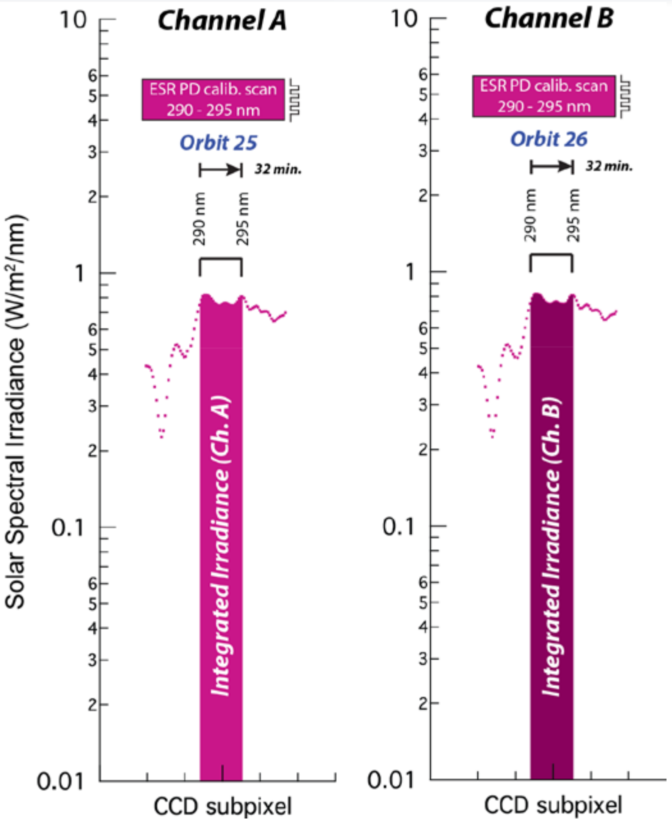
Fractional degradation vs. exposure time

Spectral degradation monitoring

ESR Channel A to Channel B comparison (over common wavelength intervals during the same solar viewing period) allows us to determine the prism degradation in the ESR measured irradiance.

For each measured wavelength interval, the ratio of the integrated A and B irradiances is proportional to the ratio of the prism degradation (within that interval) :

$$\frac{I_A}{I_B} \propto \frac{\left(\dfrac{Sun_t}{d(t_e^A)}\right)}{\left(\dfrac{Sun_t}{d(t_e^B)}\right)} = \frac{d(t_e^B)}{d(t_e^A)}$$

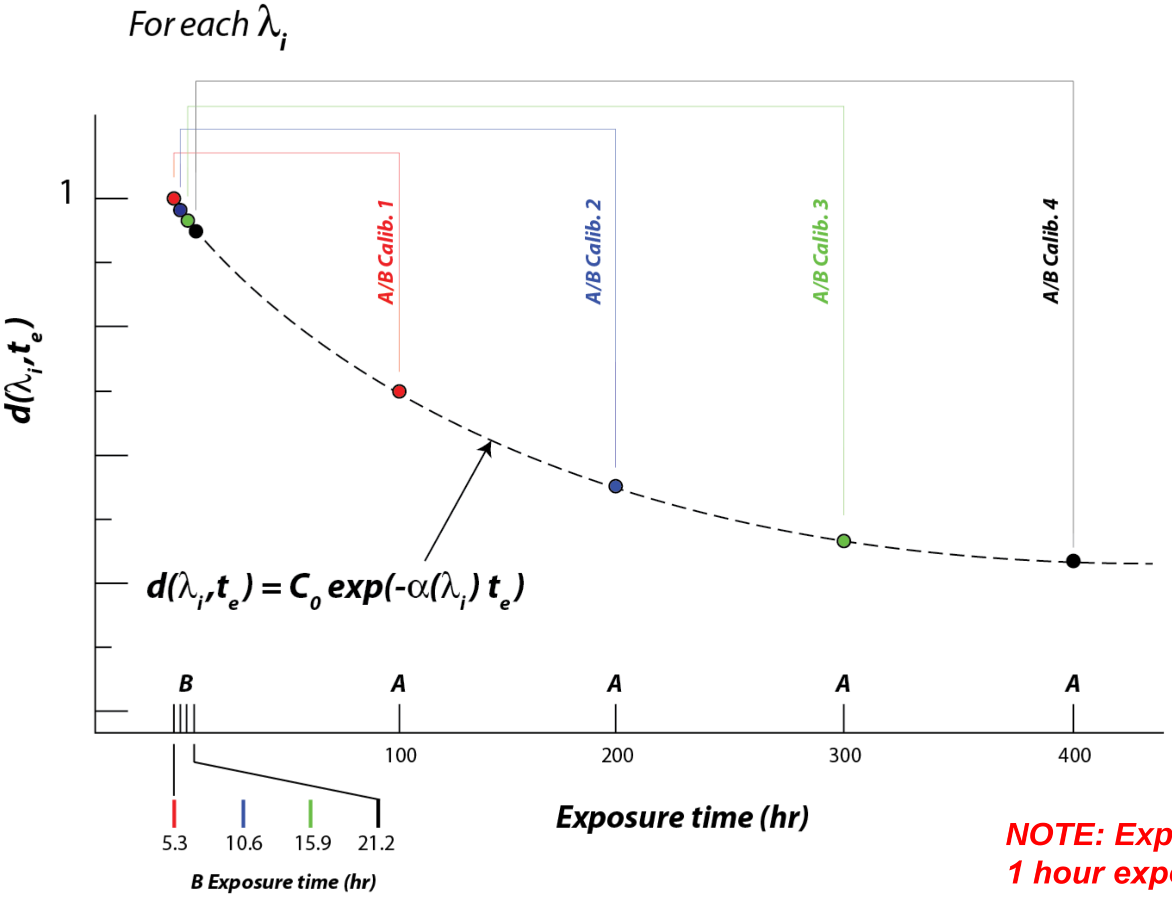


$$I_A^{292.5} = \int_{290}^{295} S_A(\lambda)d\lambda \qquad I_B^{292.5} = \int_{290}^{295} S_B(\lambda)d\lambda$$

These measured ratios constrain a functional fit of the degradation (d) with respect to cumulative exposure time for each wavelength interval

Determination of exposure time dependence

Determination of the degradation function (for each ●$_i$) is based on repeated Channel A to Channel B calibration scans. For example, we assume an exponential decay as a function of exposure time and determine a decay constant alpha (♋) for each wavelength interval



Schedule:

Every 19 days Channel A gets 100 hours of exposure, Channel B gets 5.3 hours. When Channel B reaches 100 hours exposure, we do a Channel C calibration.

When does B reach 100 hrs?

After 19 calibrations Channel B reaches 100 hour exposure:

19 day/cal x 19 cal. = 362 days

Remember,
for each cal. we know

$$\frac{d(t_e^B)}{d(t_e^A)} = R_I^{AB}(t_{cal})$$

NOTE: Exposure time is 1-AU "corrected" .
1 hour exposure (January) ≠ 1 hour exposure (July) !!

Summary

Spectral Solar Irradiance (SSI) is critical to understanding solar variability and its impact on Earth climate

- *TSIS SIM meets the JPSS measurement requirements for SSI variability, including:*
  - *High absolute irradiance accuracy (≤0.25% goal)*
  - *High measurement precision (<0.01% relative)*
  - *On-orbit capability to self-correct long-term drifts and sensitivity changes (<0.05% per year)*
    - *Channel-to-channel calibrations*
    - *Direct measurements of optical components*
    - *Detector-to-detector calibrations*
- *TSIS SIM significant improvements over SORCE SIM include:*
  - *Long-term relative stability*
    - *Improved absolute ESR detector and duty-cycling 3 independent channels provides on-orbit calibration maintenance*
  - *Measurement accuracy*
    - *NIST calibration facilities (SIRCUS/POWR) provide SI-traceable pre-launch calibration*

Back-up slides

TSIS SIM Development Approach

TSIS SIM designed for long-term spectral irradiance measurements (climate research)

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

Specific areas addressed in TSIS SIM development

✓ ***Reduce uncertainties in prism degradation correction to meet long-term stability requirement***

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

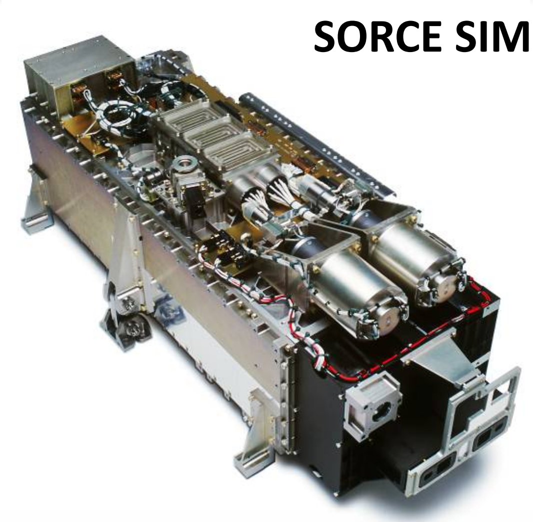
✓ ***Improve noise characteristics of ESR and photodiode detectors to meet measurement precision requirement***

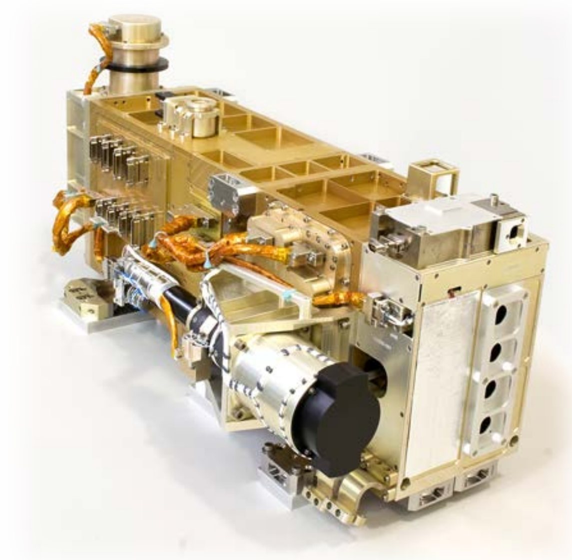
- ***ESR : Improved ESR thermal & electrical design***
- ***Photodiodes : Larger dyn. range integrating ADC's (21-bits)***

✓ ***Improve absolute accuracy pre-launch calibration***

- ***NIST SI-traceable Unit and Instrument level pre-launch spectral calibrations (SIMRF-SIRCUS)***

SORCE SIM

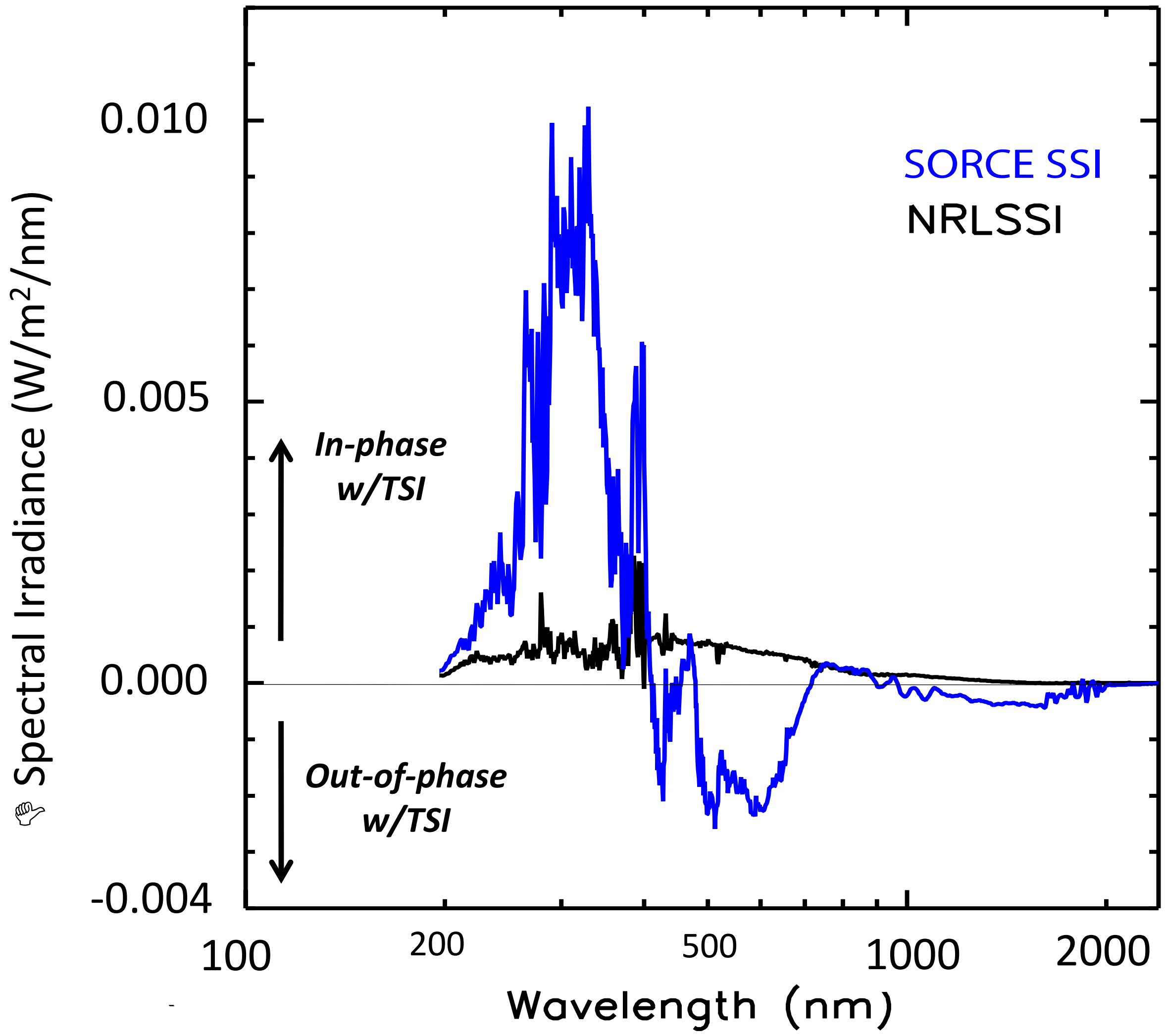




TSIS SIM

Observed "Long-term" SSI Variability

Spectral Irradiance difference between Active in mid 2004 and Quiet in late 2007

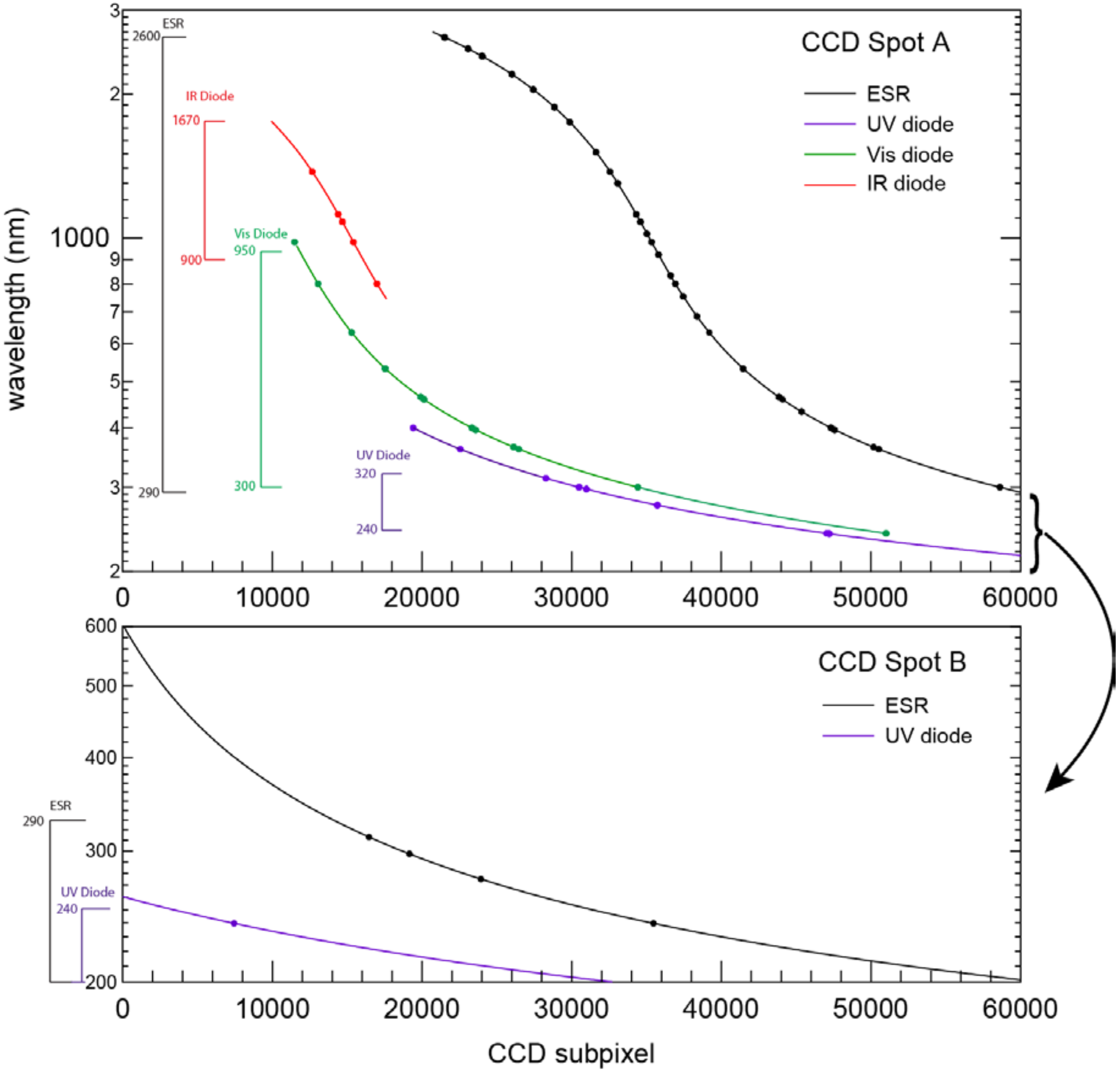


Large differences are observed between measured and modeled SSI

- ***Far more UV variability is observed (200-350 nm) than is predicted.***
- ***Strong influences on upper atm. O_3 loss/production***
- ***Observed SSI variability in the visible is out-of-phase with TSI (model follows TSI).***
- ***Dominates spectral influence since SSI maximizes in visible***

SORCE SIM long-term trend uncertainties preclude adequate determination of Solar Cycle SSI variability

Prism angle to wavelength mapping



Wavelength Calibration

Model Refinement: Fractional difference, (👎🖬☯ $\bullet_{model}/\bullet_{meas}$] - 1), between measured and modeled wavelength (238-2600 nm, both s- & p-polarizations):

Global results

On-axis:

D_{avg} = 80 ppm

$1\text{-}s_{unc}$ = 335 ppm

Full FOV

(thru ±20 arc-min in dispersion.):

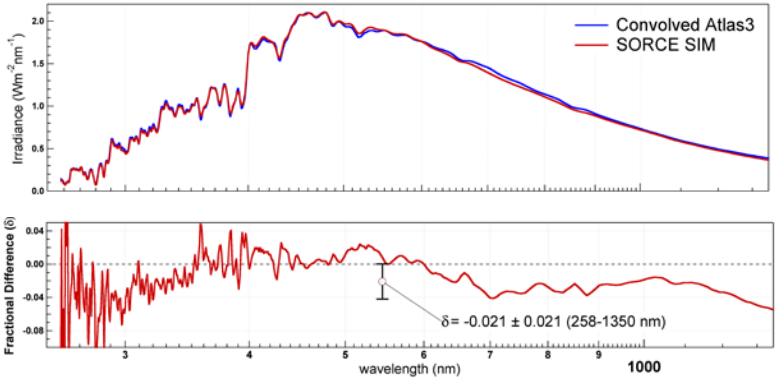
D_{avg} = 315 ppm

$1\text{-}s_{unc}$ = 547 ppm

Establishing sensor tie to SI units

Three approaches that can be adopted

- *Transfer the calibration from known “standard” instrument (1-3% unc.)*
- *Measure instrument response against an “irradiance standard” (~1% unc.)*
- *Characterize the instrument as an “absolute sensor” (<1% unc.)*
  - *Characterize each term in the measurement eqn. model (may be a unit-level calibrations or calculations based on known uncertainties)*
  - *Establish uncertainty budget: tabulate list of all individual uncertainties and propagate – (random)*
  - *Validate end-to-end performance – (systematic)*

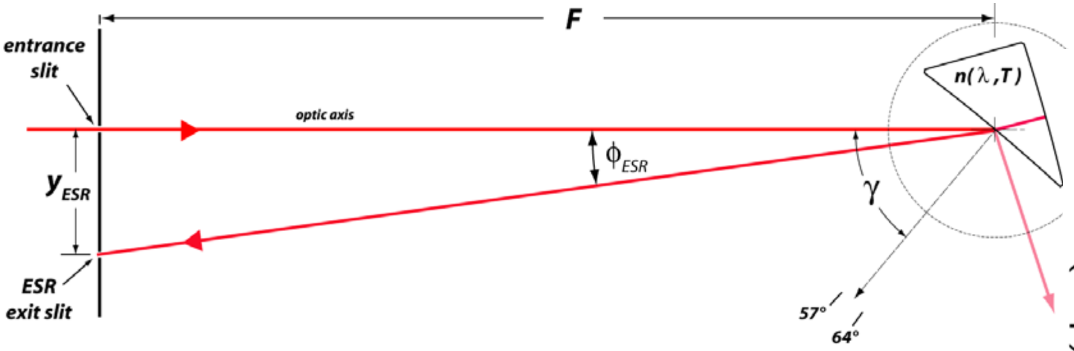


SORCE SIM and Atlas 3 Comparison (258-1350 nm)

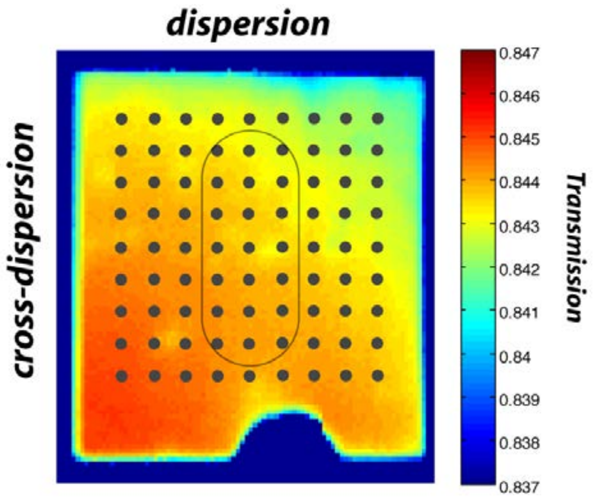
Full Spatial & Spectral Transmission Mapping

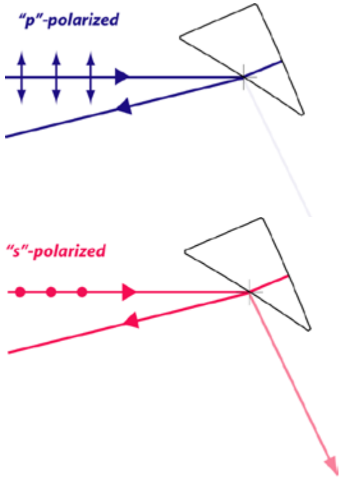
Prism measurement geometry is for ESR optical path

Stabilized SIRCUS lasers cover 210 – 2400 nm range



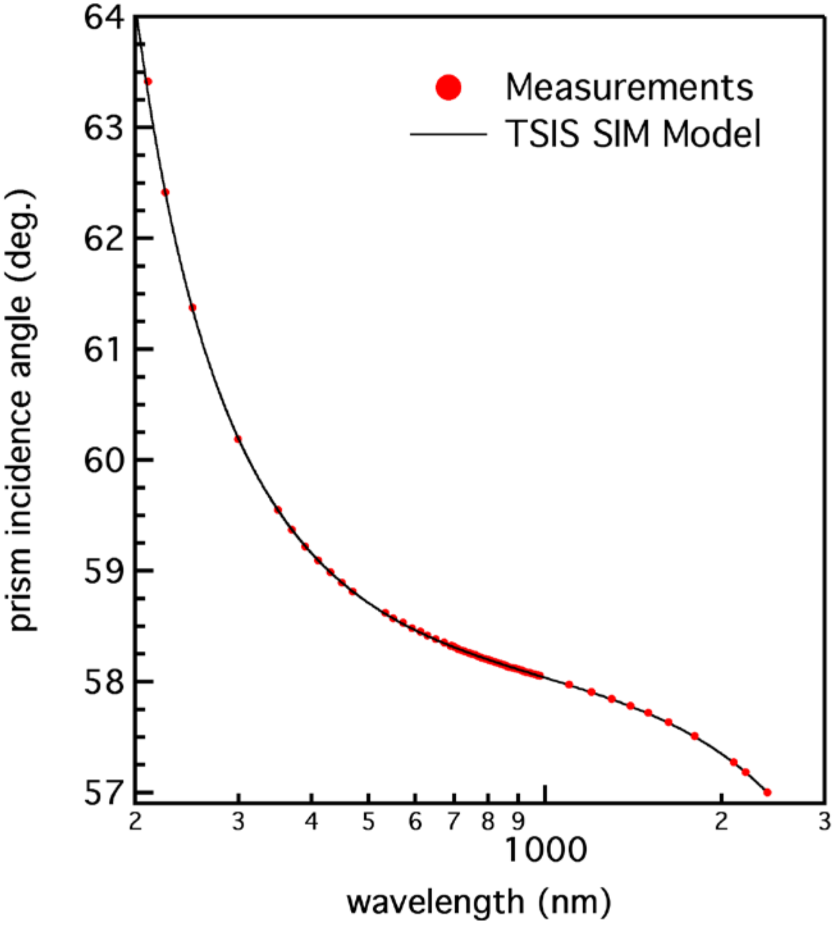
Transmission measured over 10 x 10 grid for both s and p-polarizations



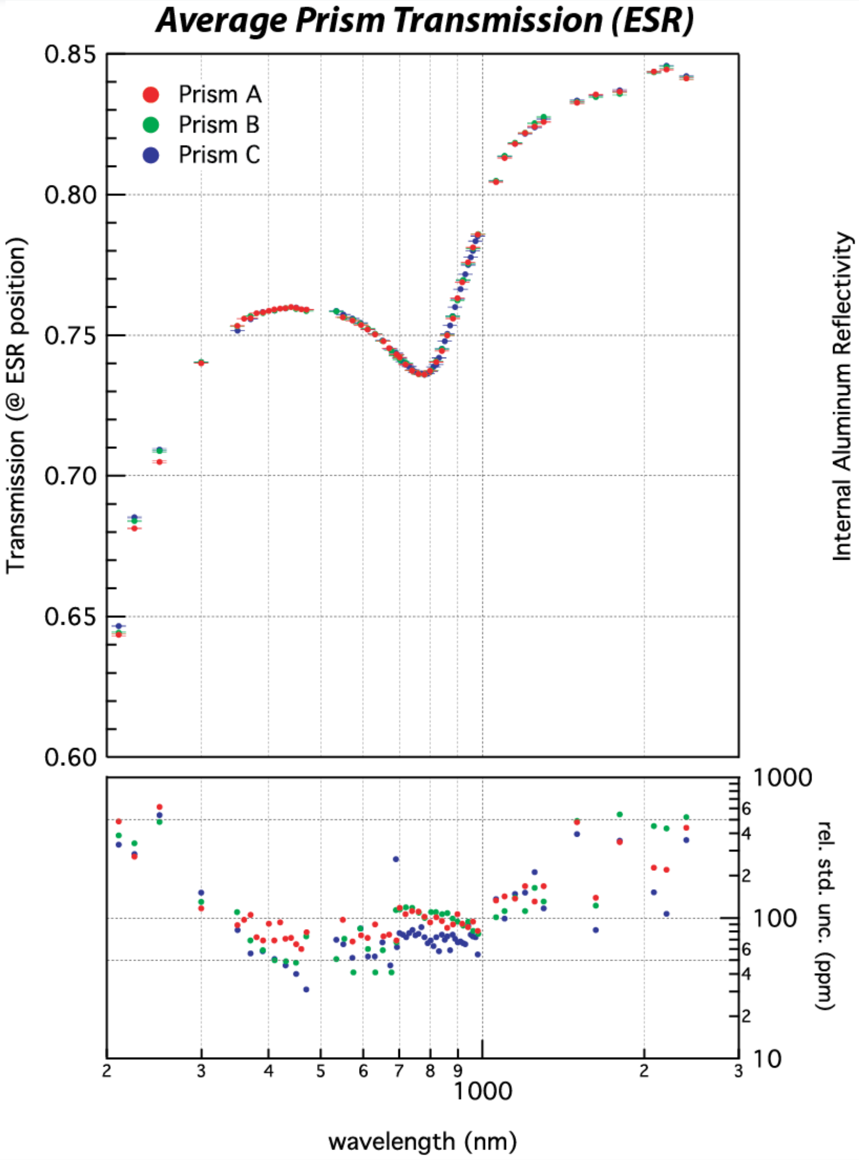


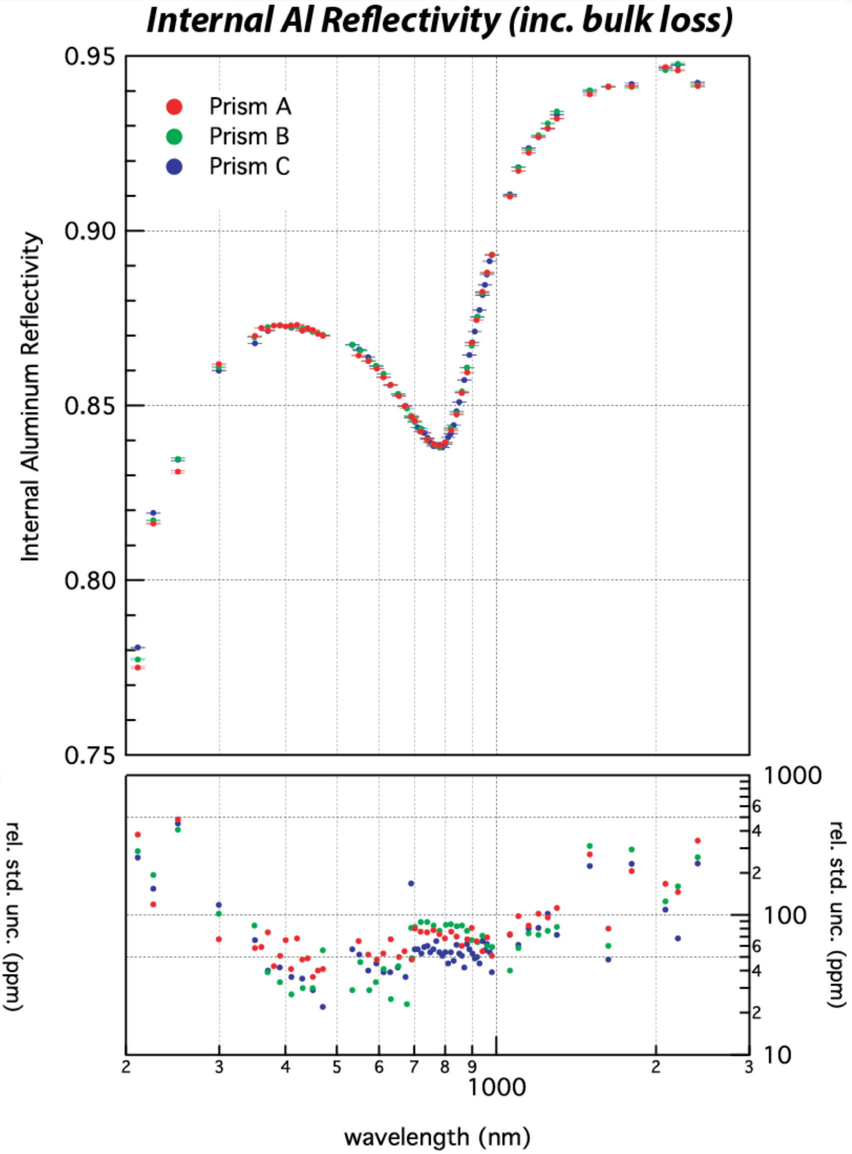
Refraction vs. wavelength

(Suprasil 3001 fused silica)



Prism Transmission


Average Prism Transmission (ESR)


Internal Al Reflectivity (inc. bulk loss)