Future Long-term Measurements of Solar Spectral Irradiance by the TSIS Spectral Irradiance Monitor:
Improvements in Measurement Accuracy and Stability

LASP
University of Colorado, Boulder

TSIS
Total and Spectral
Solar Irradiance Sensor

Erik Richard, Dave Harber, Joel Rutkowski, Ginger Drake, Jerry Harder, and Peter Pilewskie

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

Steven Brown, Allan Smith and Keith Lykke

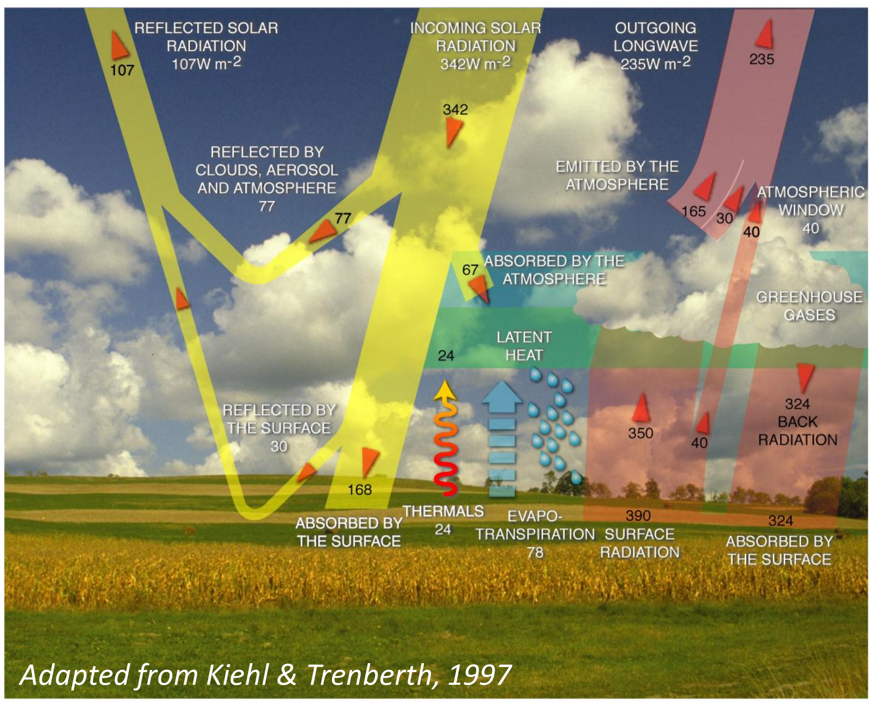
National Institute of Standards and Technology (NIST)
Gaithersburg, Maryland USA

Spectral Irradiance Contributions
Key to Climate Issues

- ***What is the solar forcing at decadal and longer timescales?***

  - Solar Irradiance Climate Data Record (CDR): time series of measurements of sufficient length, consistency, and continuity to determine climate variability and change.

Global Energy Budget Contributions



Adapted from Kiehl & Trenberth, 1997

Solar Radiative Forcing Questions

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

  ✓ ***Requires measurement of wavelength-dependent irradiance variability.***

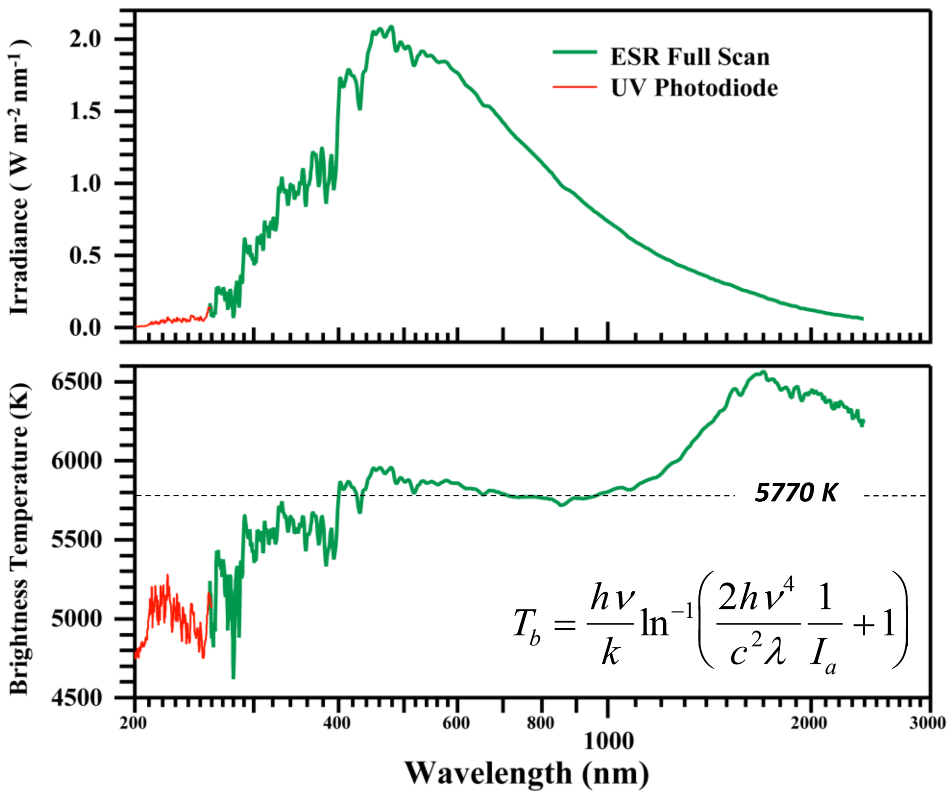
Knowledge of TOA spectral distribution of solar radiation is crucial in interpreting the highly spectrally dependent radiative processes in atmosphere and at the surface.

SIM Measures Solar Spectral Irradiance (96% TSI)

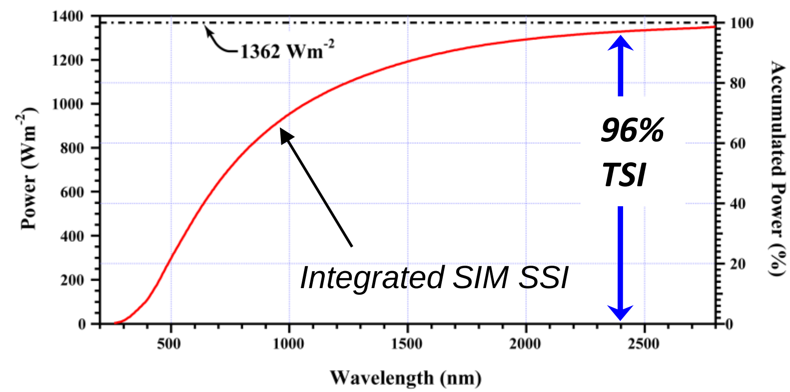
Solar Spectral Irradiance (W m^{-2} nm^{-1})

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)



SIM Integrated Power vs. Wavelength



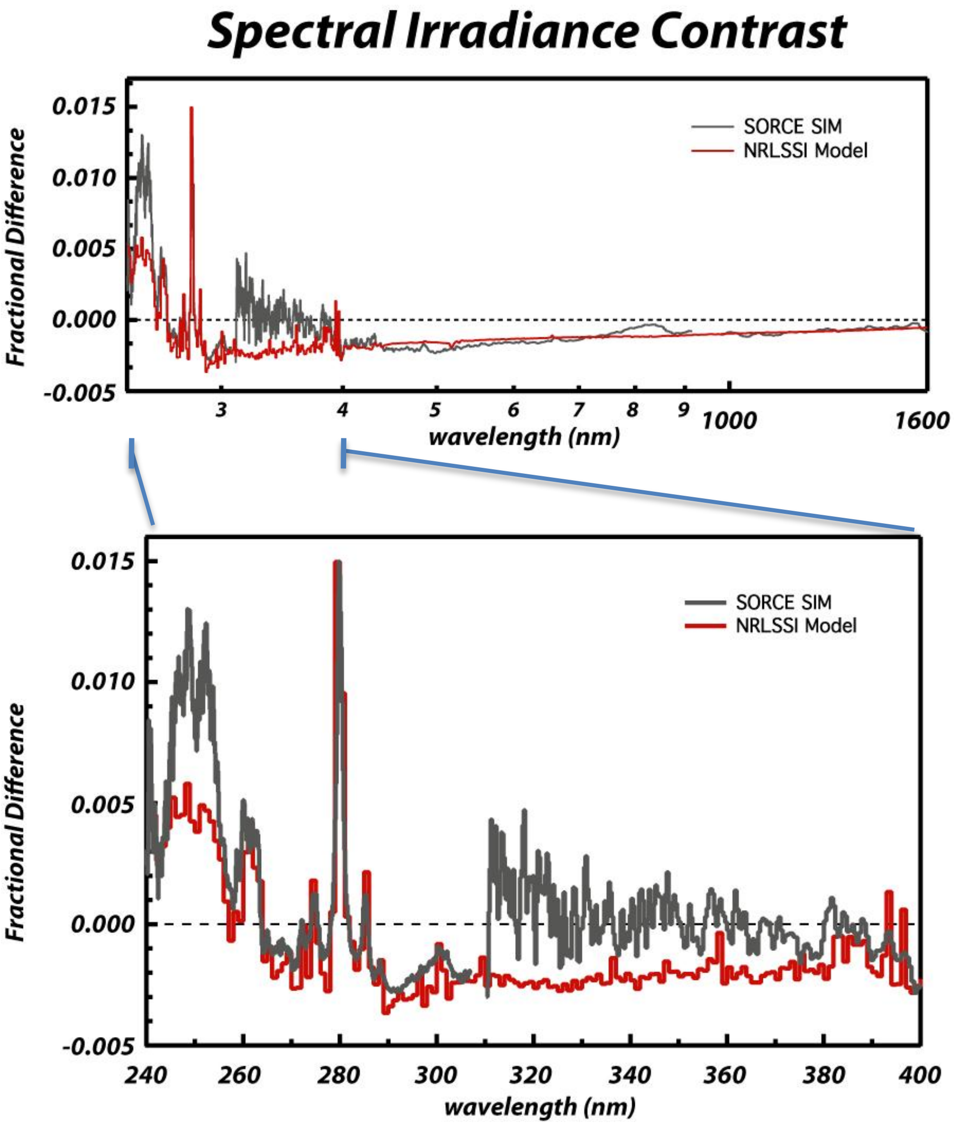
Total Solar Irradiance (TSI)

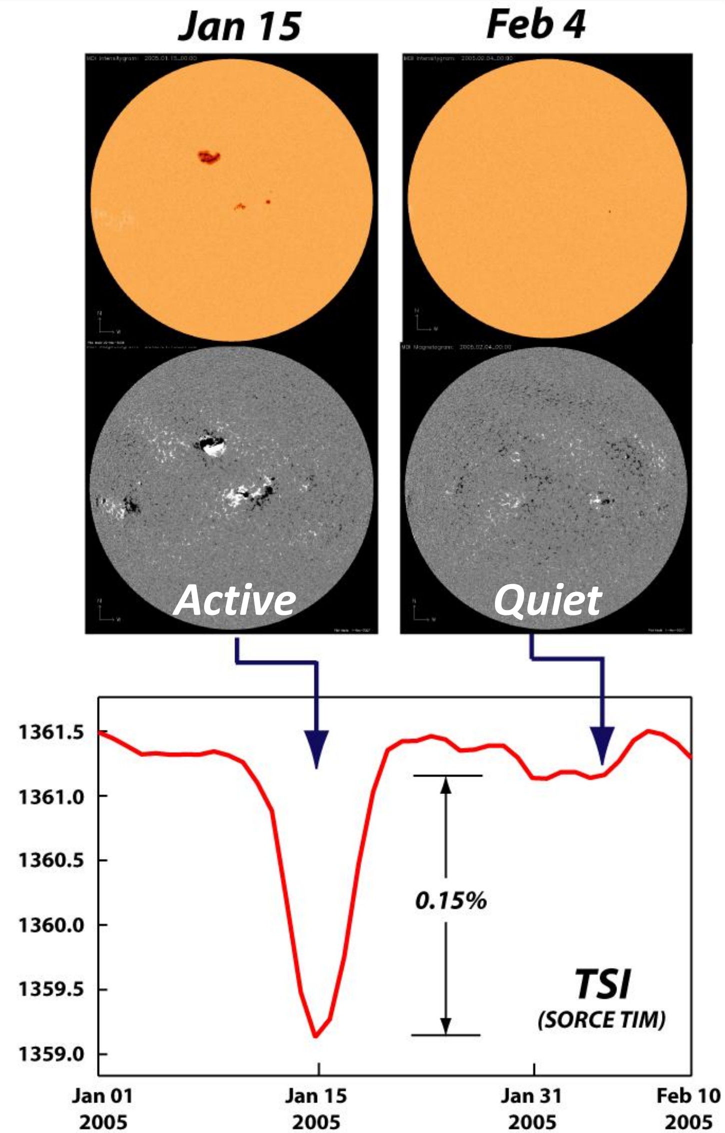
$$TSI_{TIM} = \int_{\lambda=0}^{\lambda=\infty} E_\lambda d\lambda \approx 1362 \ \text{Watts}/\text{m}^2$$

Spectral Solar Irradiance (SSI)

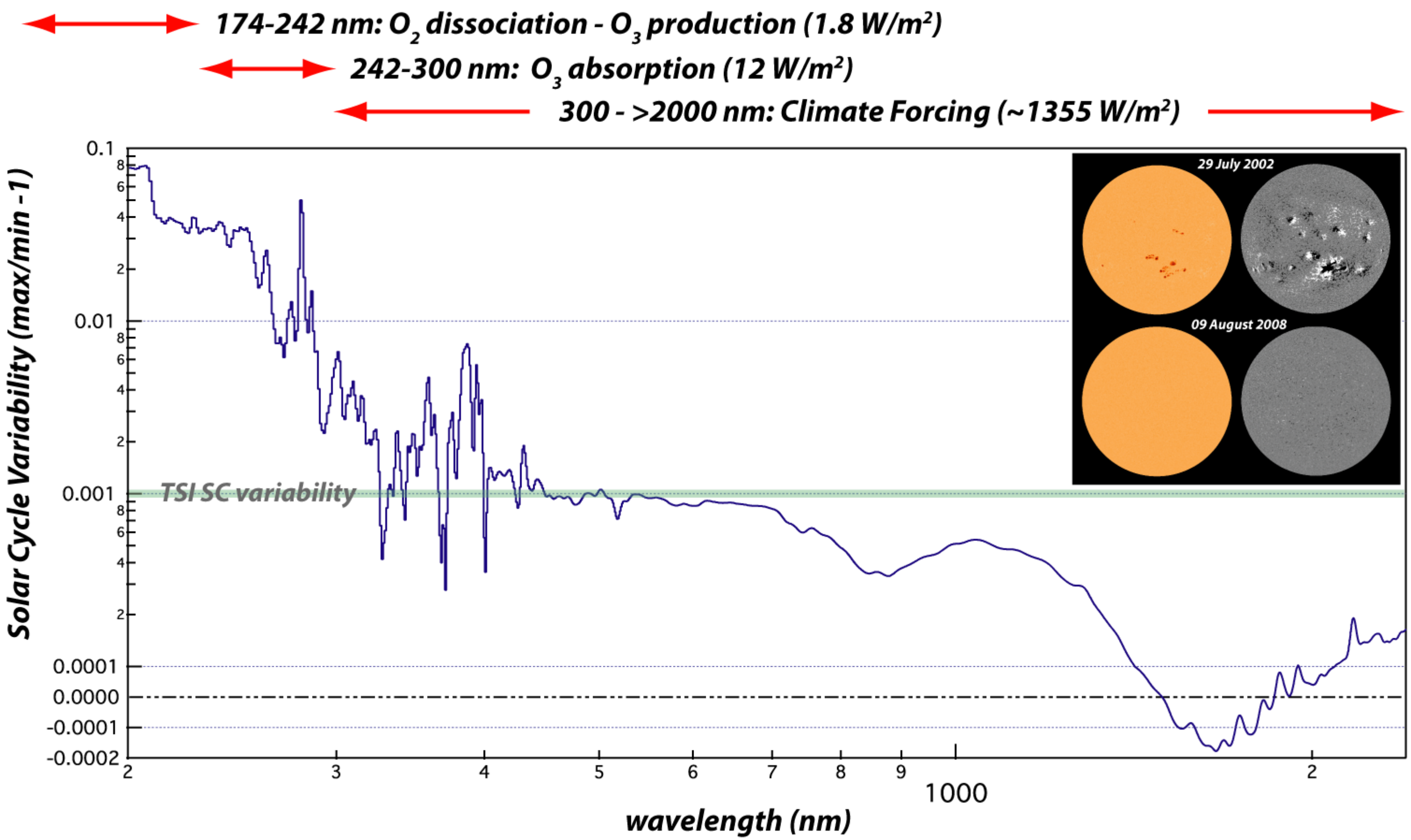
$$TSI_{SIM} = \int_{\lambda=200}^{\lambda=2400} E_\lambda d\lambda \approx 96\% \text{ of TSI}$$

Short-term (Rotational) SSI Variability





Predicted Solar Cycle SSI Variability

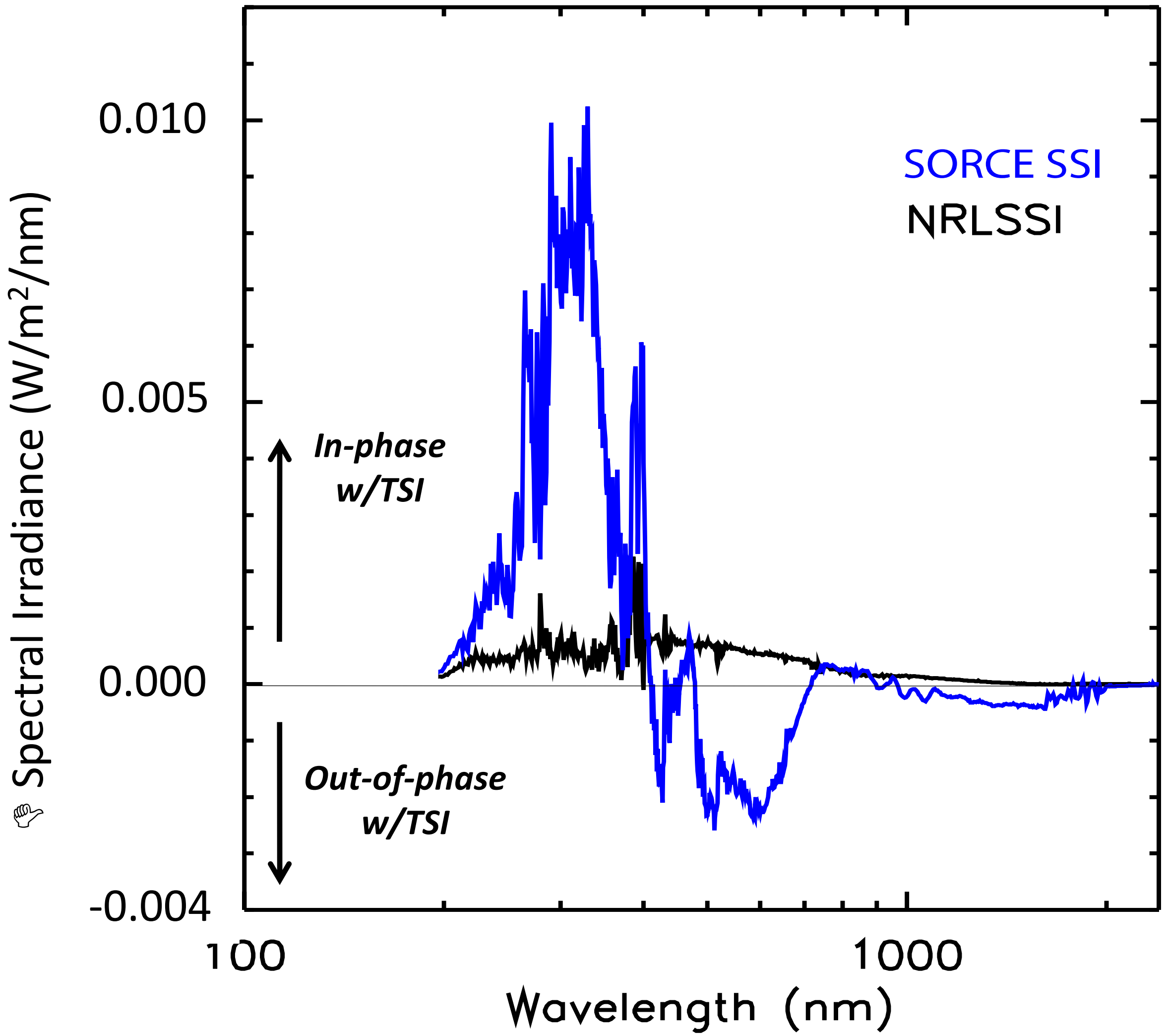


NRLSSI Modeled spectral variability based on observations of UV (120-250 nm) and model of rotational modulation of plage and sunspot contrast.

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

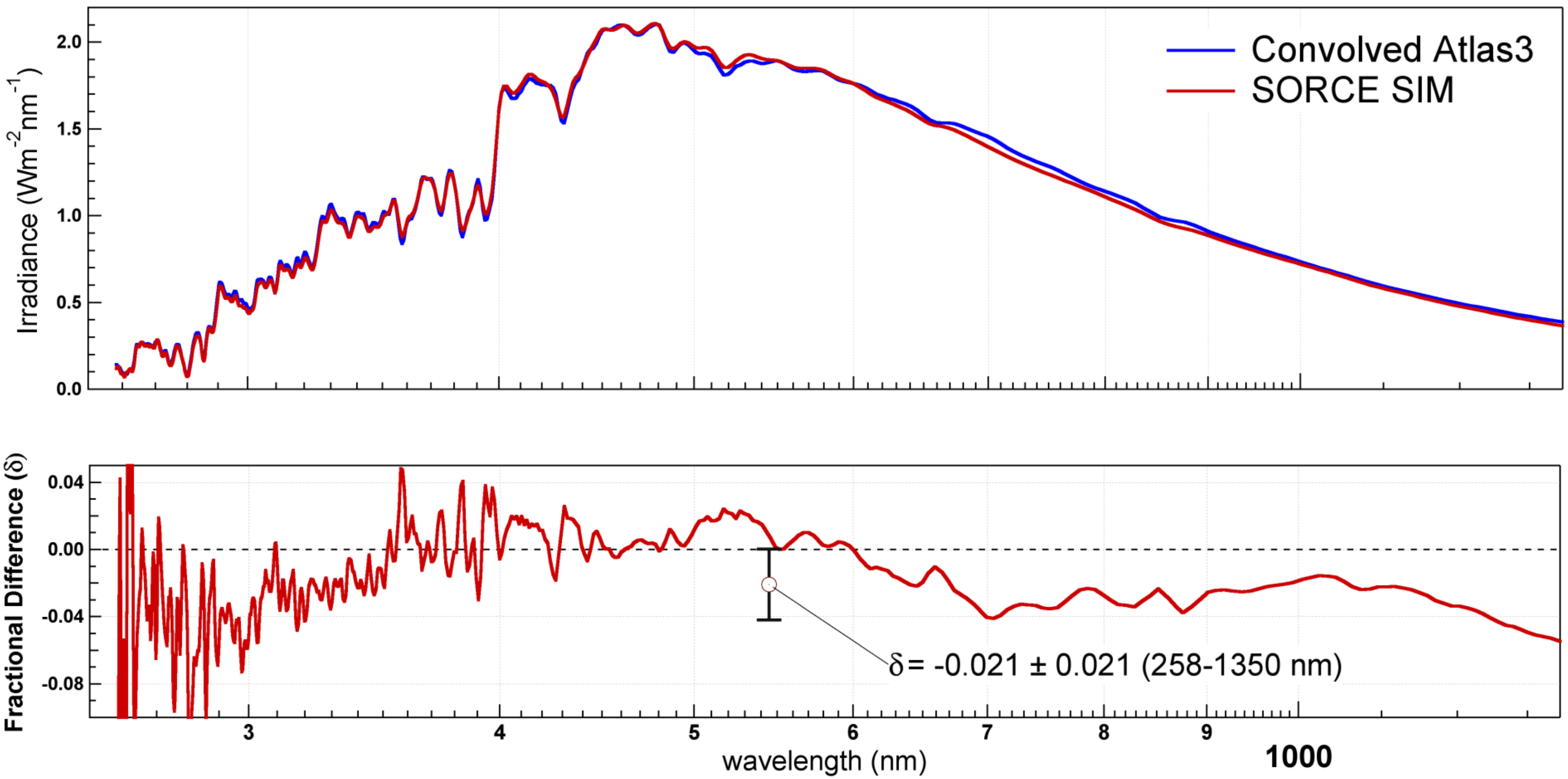
Observed "Long-term" SSI Variability

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



SSI Absolute Accuracy Issues

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



Attributes of a Climate Monitoring System

"Design of climate observing and monitoring systems must ensure the establishment of global, long-term climate records that are of <u>high accuracy, tested for systematic errors on-orbit, and tied to irrefutable international standards maintained in the U.S. by the National Institute of Standards and Technology (NIST)</u>."

- Achieving Satellite Instrument Calibration for Climate Change (ASIC^3) 2007 Final Report

JPSS SSI Measurement Requirements

Attribute	Requirement	Justification
Measurement Range ($Wm^{-2}nm^{-1}$)		**Solar Spectrum**
Spectral (0.2-2.4 µm)	10^{-4}-10^{1}	*Full scale of spectral irradiance magnitude*
Long-term rel. stability (per year)		**Interpret Solar Cycle variability**
$0.2 \le \lambda \le 0.4$ µm	0.05%	*UV variability 0.1% - 10%*
$0.4 < \lambda \le 2.4$ µm	0.01%	*Visible- Near IR variablity ≤ 0.05%*
Measurement precision		**Measure short term variability**
Spectral (0.2-2.4 µm)	0.01%	*Sufficient SNR for Vis-NIR spectral variablity*
Measurement Accuracy		**Climate modeling input**
Spectral (0.2-2.4 µm)	0.25%	*Earth radaiton budget; Processes & Mechanisms*
Reporting Frequency (per day)		**Solar temporal variability**
Spectral (0.2-2.4 µm)	2	*sample short-term spectral varaitions with TSI*
Spectral Resolution (nm)		**Solar wavelength variability**
$\lambda \le 0.28$ µm	1	*Strongest wavelength dependence of UV variability*
0.28 µm $< \lambda \le$ 0.40 µm	5	*Broader wavelength dependence of Vis-NIR var.*
$\lambda > 0.40$ µm	45	

TSIS SIM Derives Heritage from SORCE SIM

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 required capabilities over SORCE SIM

✓ **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*

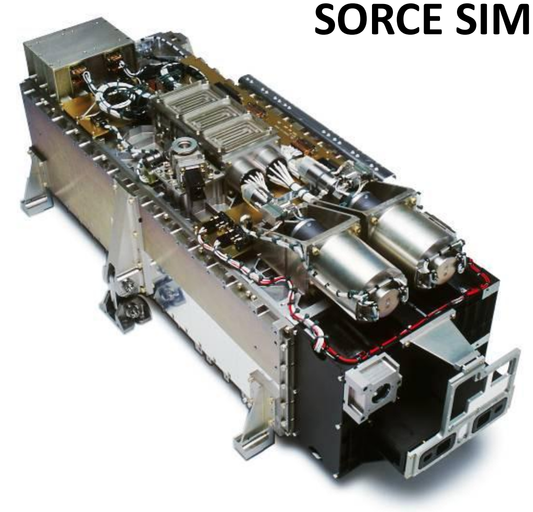
✓ **Improve noise characteristics of ESR and photodiode detectors to meet measurement precision requirement**

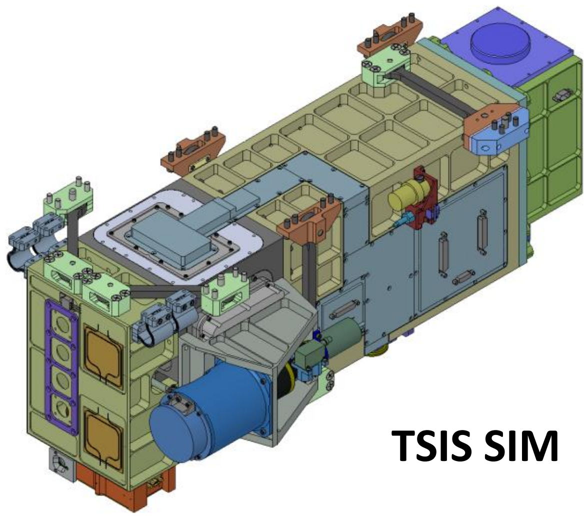
- *Improved ESR thermal & electrical design*
- *Larger dynamic range integrating ADC's (21 bits)*

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

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

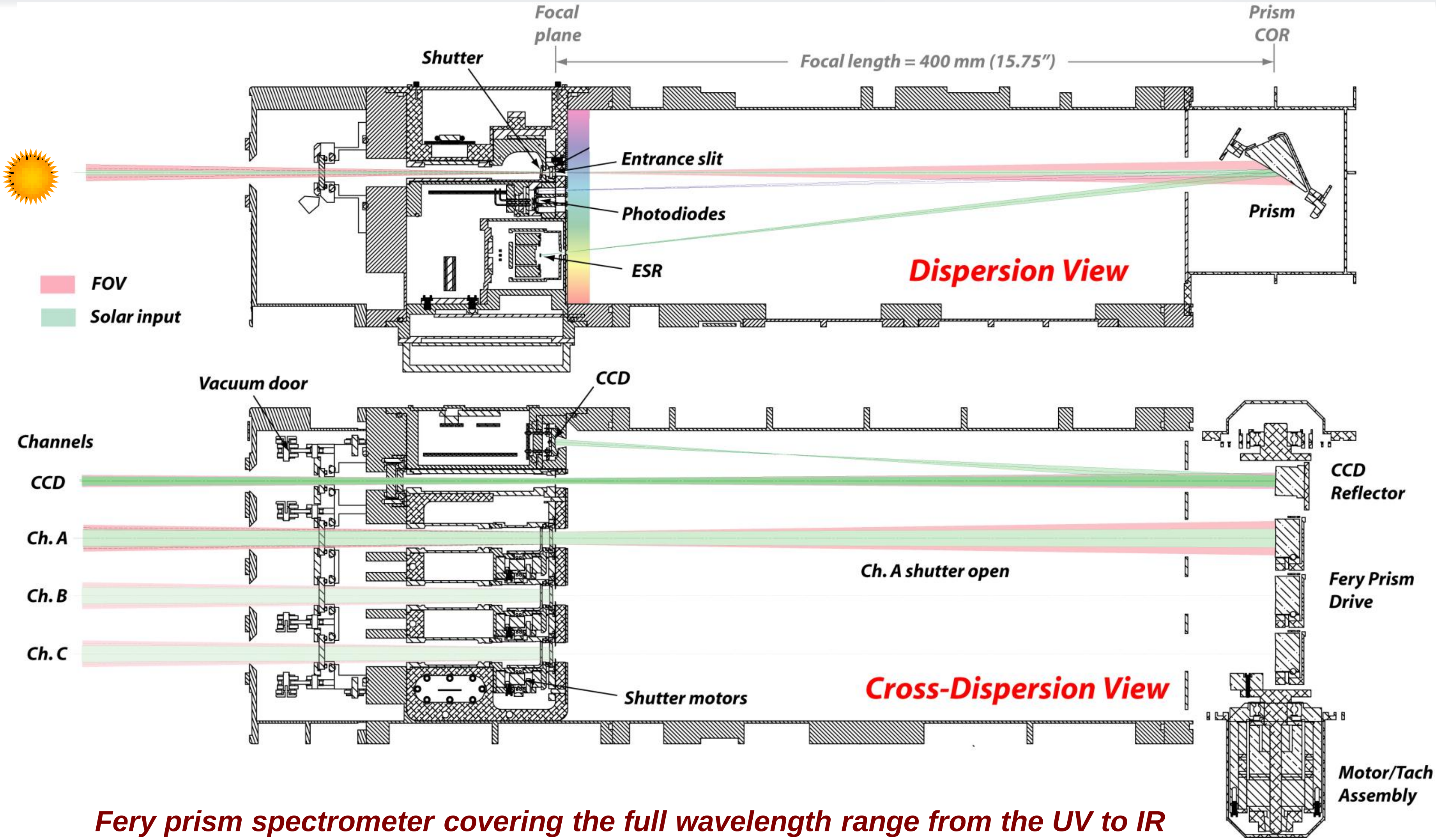
SORCE SIM





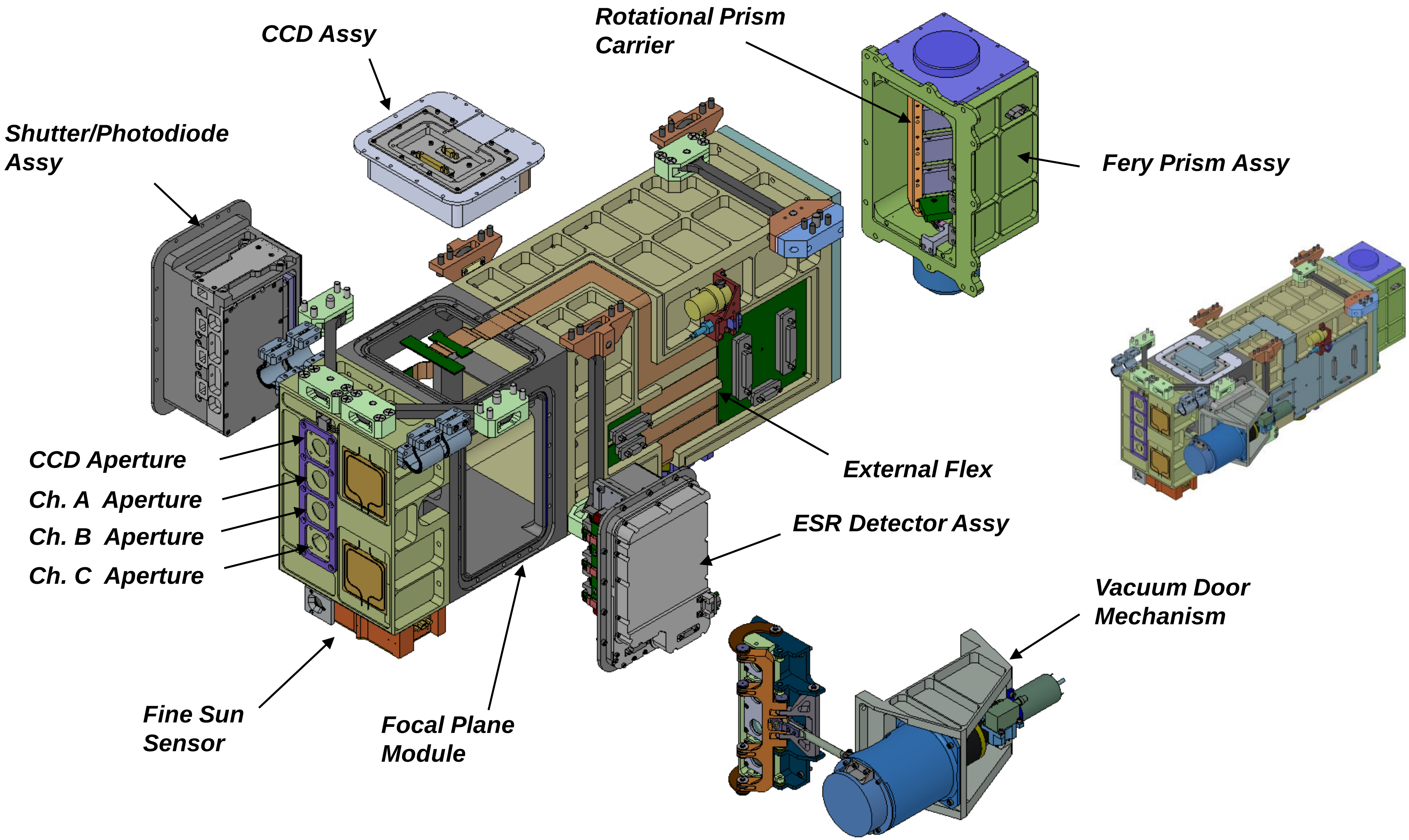
TSIS SIM

TSIS SIM Design Overview

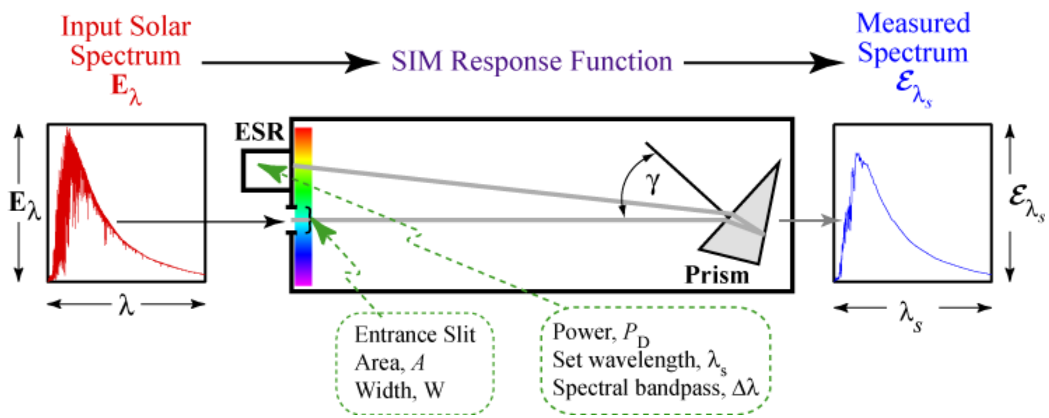


Fery prism spectrometer covering the full wavelength range from the UV to IR using <u>only one optical element</u> for spectral dispersion and image quality

Overview of TSIS SIM



Measurement Equation Overview



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

ESR detected power

Aperture area

ESR Absorptance

prism transmission

Slit diffraction

Spectral Transfer function

TSIS SIM Calibration Flow

Component-Level Calibrations:

Calibrations Common with TIM:

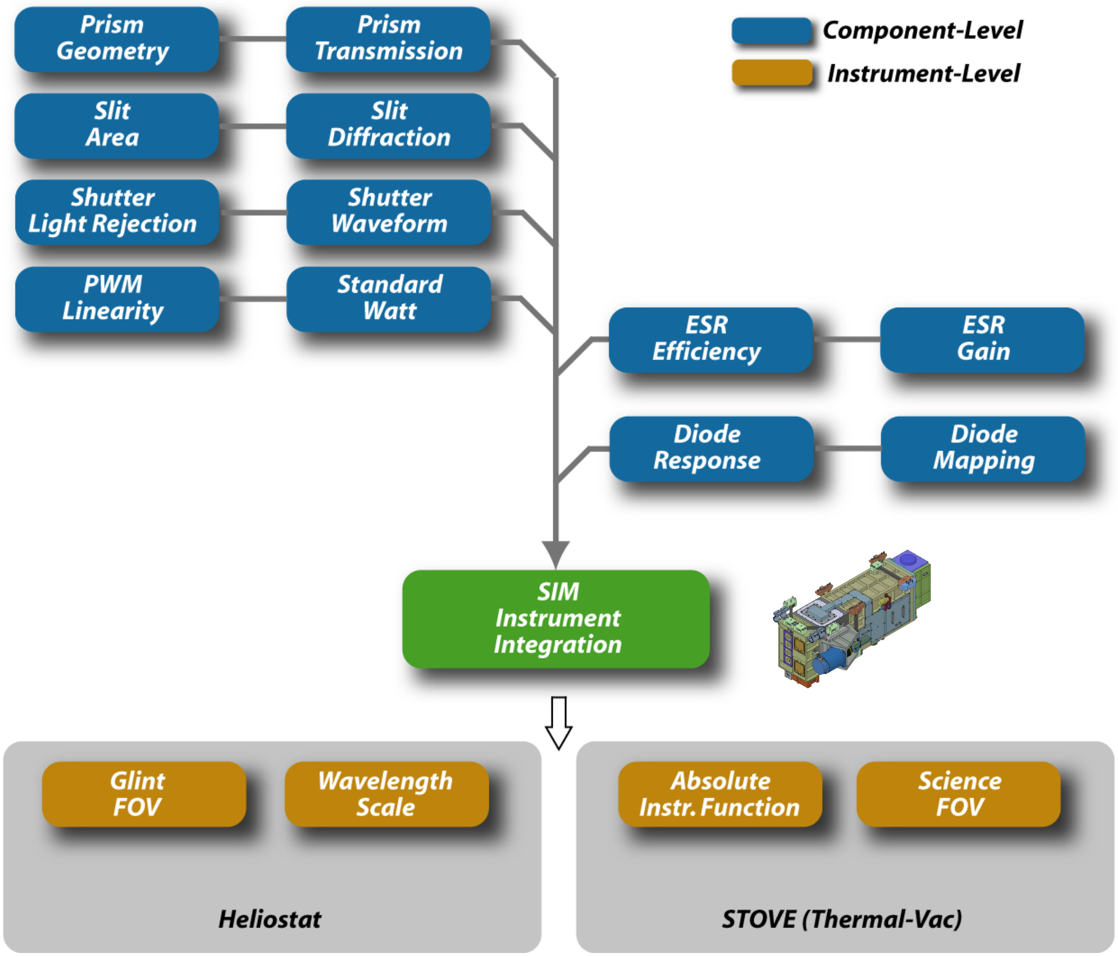
- Slit Area
- Slit Diffraction
- Standard Watt
- Pulse-Width Modulation Linearity
- Shutter Waveform
- Servo Gain

Unique SIM Calibrations:

- Prism Geometry
- Prism Transmission
- 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

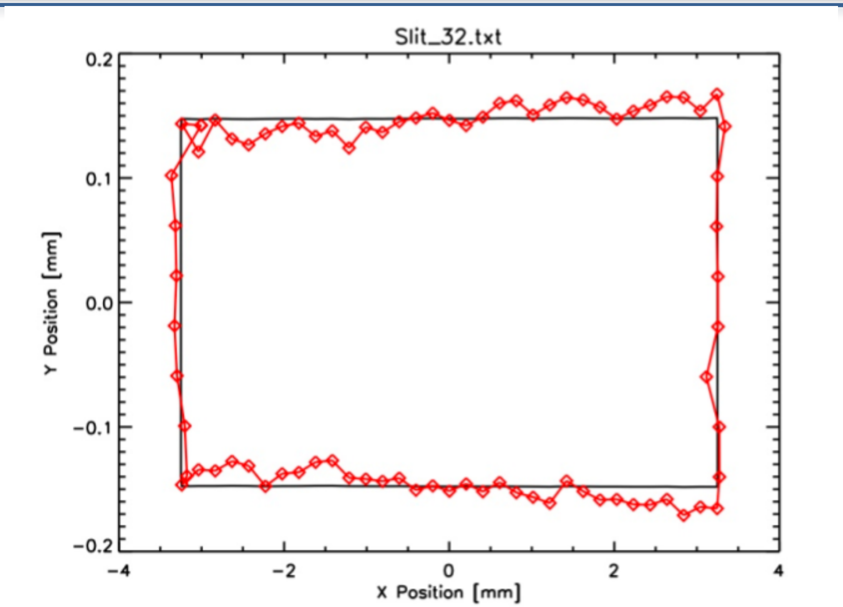


Calibration and characterization follows a measurement equation approach at the unit-level for full validation of end-to-end performance at the instrument-level

TSIS SIM Calibration Error Budget

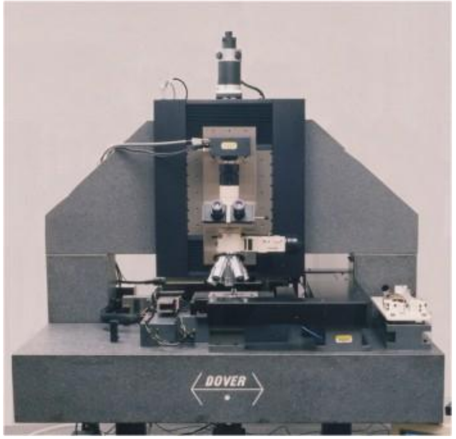
	Measurement Correction	Origin	Value (ppm)	1σ (ppm)	Status
S/C	Distance to Sun, Earth & S/C	Analysis	33,537	0.1	
	Doppler Velocity	Analysis	43	1	
	Pointing	Analysis	0	100	
Component-Level	Shutter Waveform	Component	100	10	
	Slit Area	Component	1,000,000	500	
	Diffraction	Component	5,000-62,000	500	
	Prism Transmittance	Component	230,000-450,000	1,000	
	ESR Efficiency	Component	1,000,000	1,500	
	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 ($\Delta\lambda/\lambda$ = 150 ppm)	Instrument	1,000,000	1,000	
	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			*2418*	

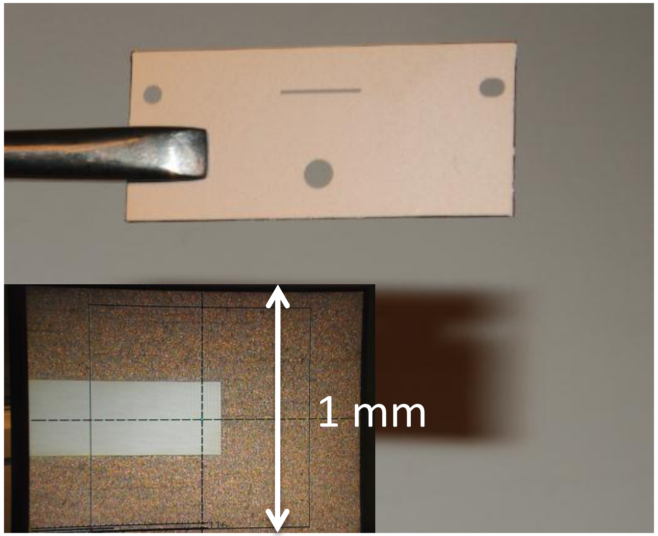
Entrance Slit Area (NIST)



Non-contact video microscopy technique

(J. Fowler & M. Litorja, *Metrologia*, **40** (2003) S9-S12)





Slit	Rectangle Fit			Polygon Fit		
	Area (mm^2)	Std. Unc (k=1)	Rel. Unc (ppm)	Area (mm^2)	Std. Unc (k=1)	Rel. Unc (ppm)
A	1.92756	1.8 $(10)^{-4}$	95	1.92756	1.8 $(10)^{-4}$	95
B	1.94450	3.1 $(10)^{-4}$	154	1.94447	2.0 $(10)^{-4}$	102
C	1.94416	3.3 $(10)^{-4}$	162	1.94414	2.4 $(10)^{-4}$	125

Calibration Budget Allocation 500 ppm - still evaluating corner issues

Component-Level

Wavelength Dependence: NIST SIRCUS

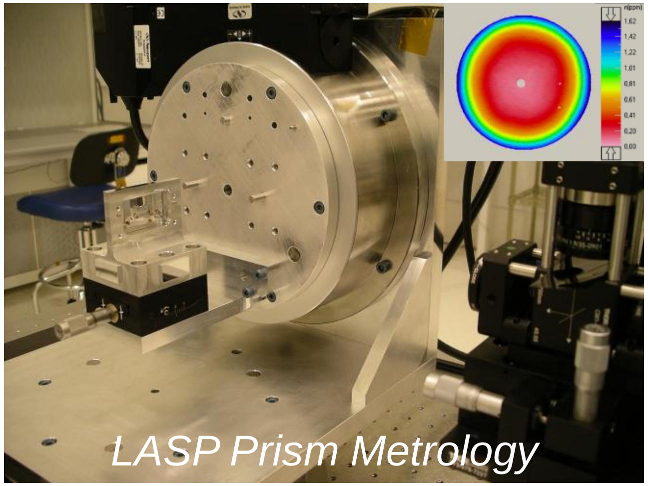
- ***We need to carefully measure the wavelength dependence of several items in the uncertainty budget:***
  - *Prism Transmission*
  - *ESR Efficiency*
  - *Photodiode Sensitivity*
  - *Wavelength Scales*
  - *Absolute Instrument Function Area*

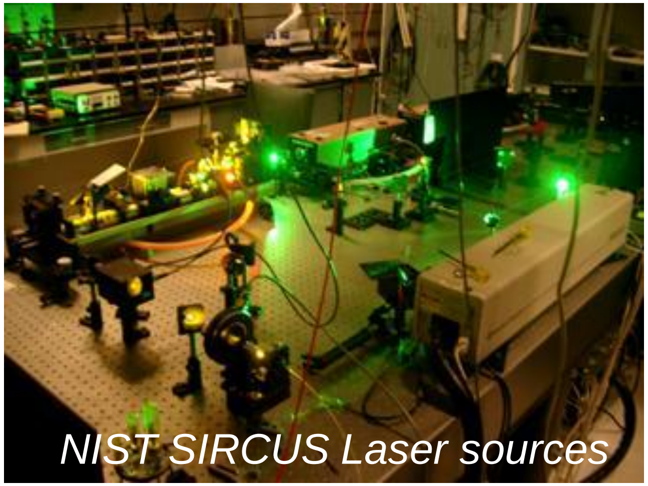
$$\mathcal{E}_\lambda(\lambda_s) = \frac{\mathcal{P}_{\mathrm{ESR}}(\lambda_s)}{A_{slit} \cdot \int \alpha_\lambda \cdot T_\lambda \cdot \phi_\lambda \cdot S(\lambda, \lambda_s)\, d\lambda}$$

- ***This wavelength dependence is always a smoothly-varying function, nonetheless calibrations must be performed at many wavelengths***

- ***We utilize NIST travelling SIRCUS* (Spectral Irradiance and Radiance Responsivity Calibrations using Uniform Sources) to generate laser light across the SIM spectrum of 210-2400 nm***

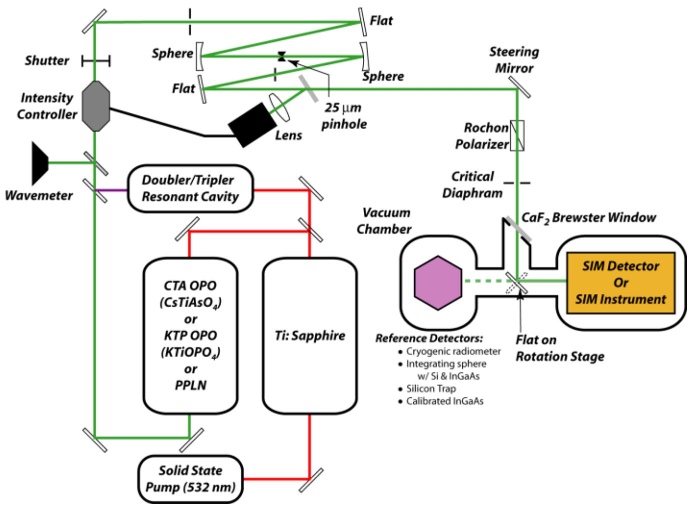
*S. Brown, et al. *Applied Optics*, **45**, (2006), 8218-8237

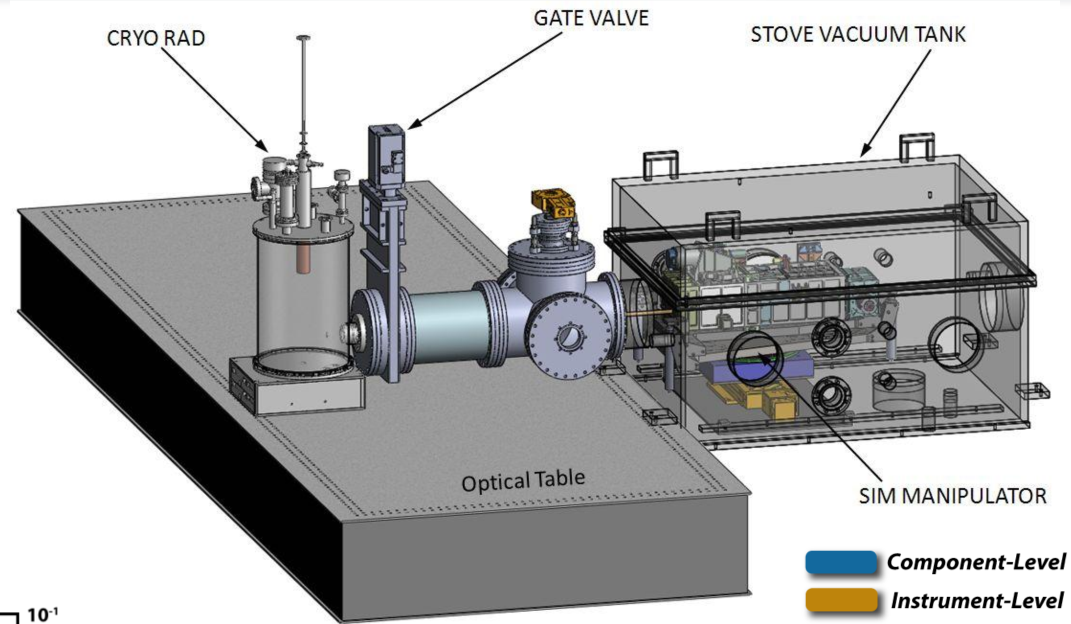




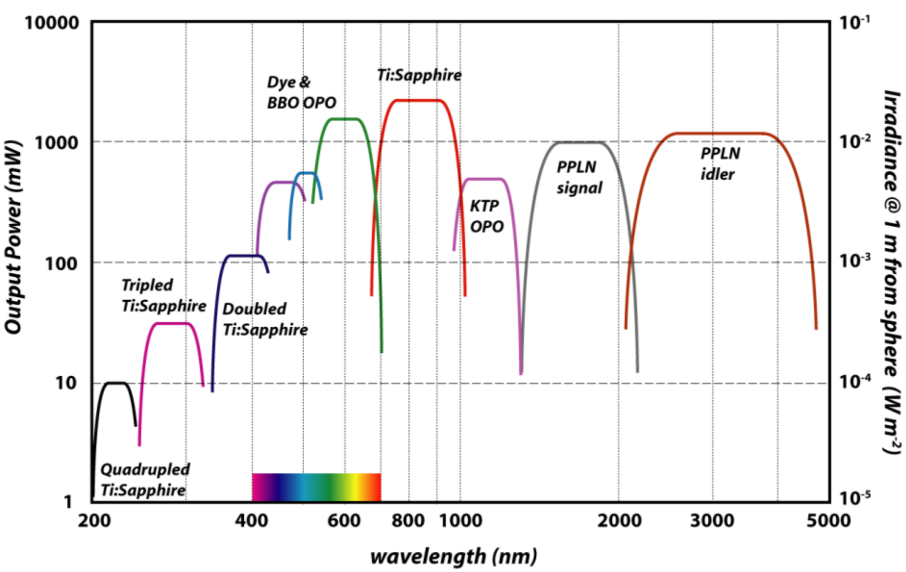
Component-Level
Instrument-Level

SIM Radiometric Facility (SIMRF) (LASP & NIST)





SIRCUS laser spectral coverage

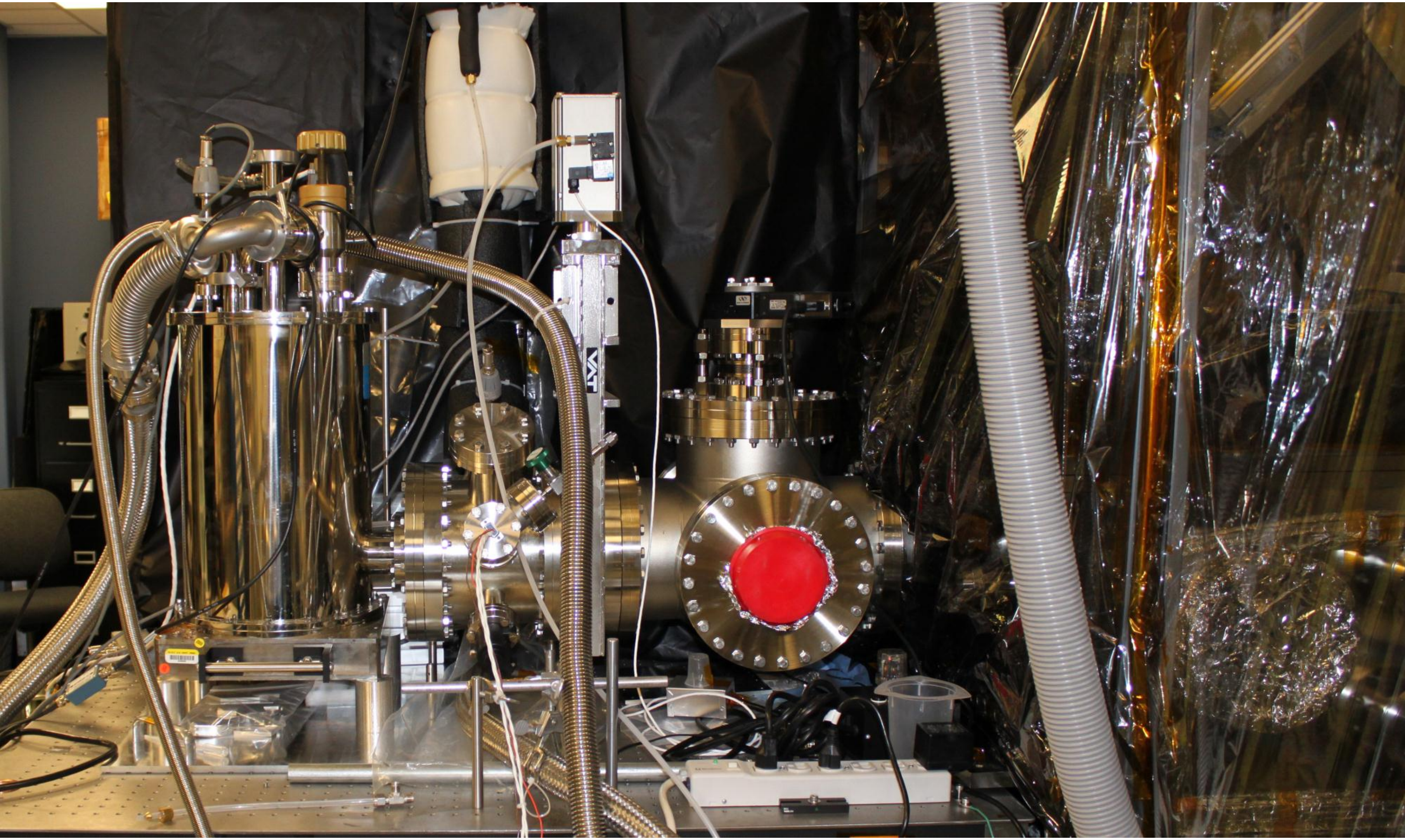


This comprehensive calibration facility provides irradiance calibration of the SIM ESR & photodiodes and the full SIM over the operation wavelength range of the SIM instrument.

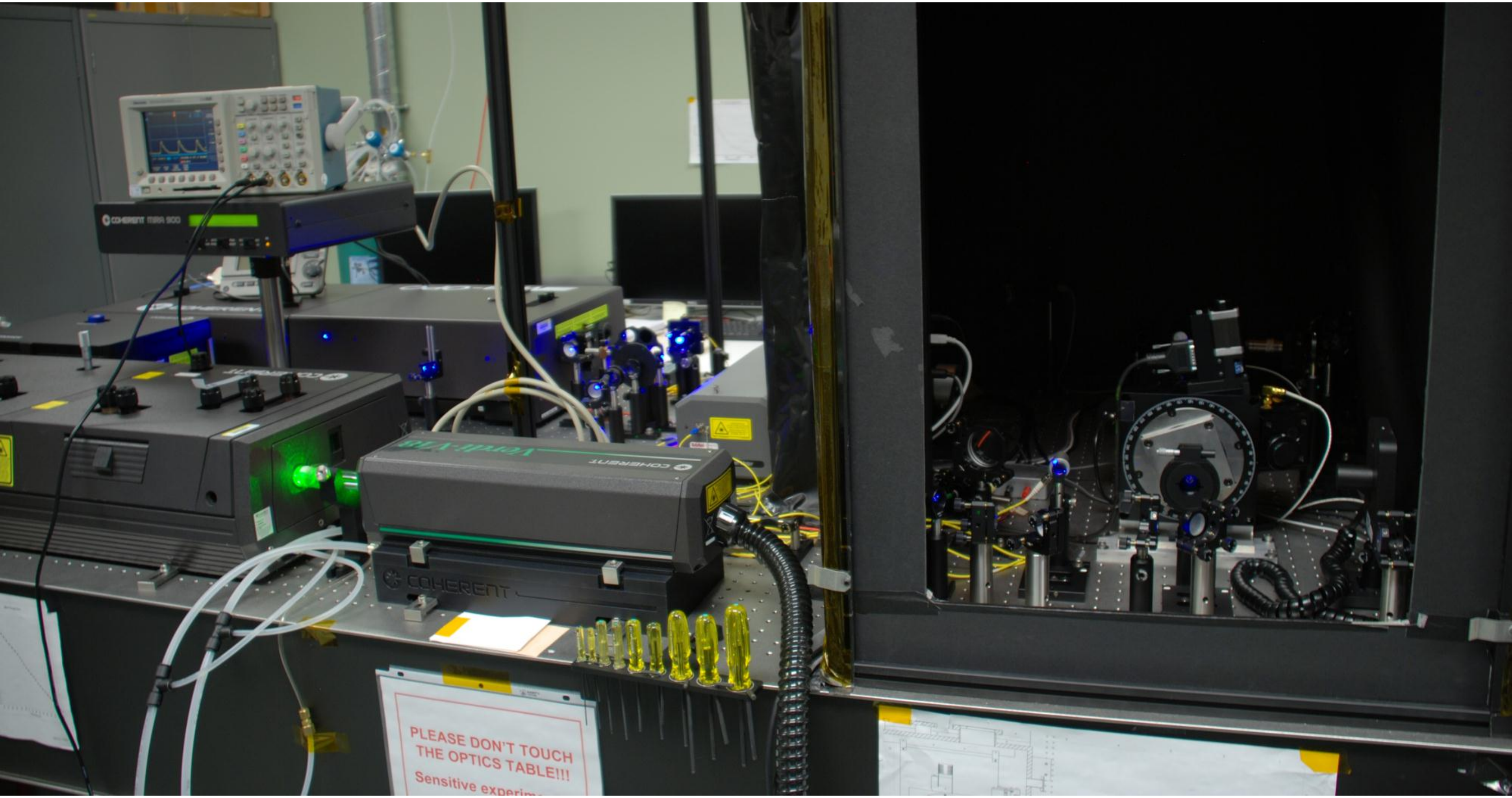
Main components of SIMRF:

- ***STOVE vacuum tank***
- ***Manipulator for SIM and ESR subassembly***
- ***Steering mirror vacuum housing***
- ***L-1 Cryogenic radiometer (NIST)***
- ***SIRCUS lasers (NIST)***

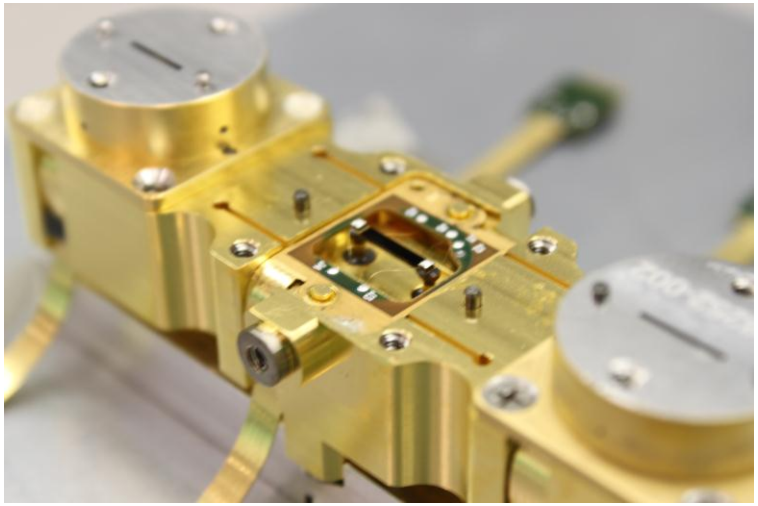
NIST L1 Cryogenic Radiometer

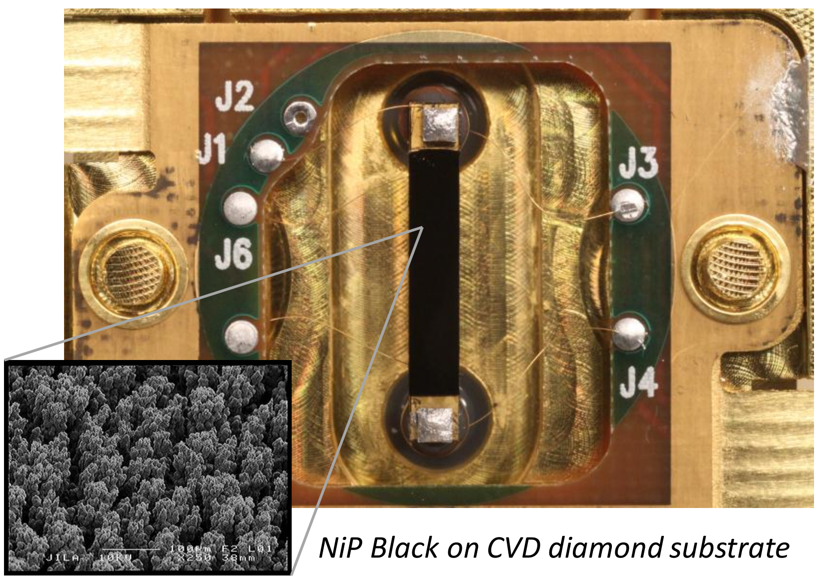


NIST Travelling SIRCUS



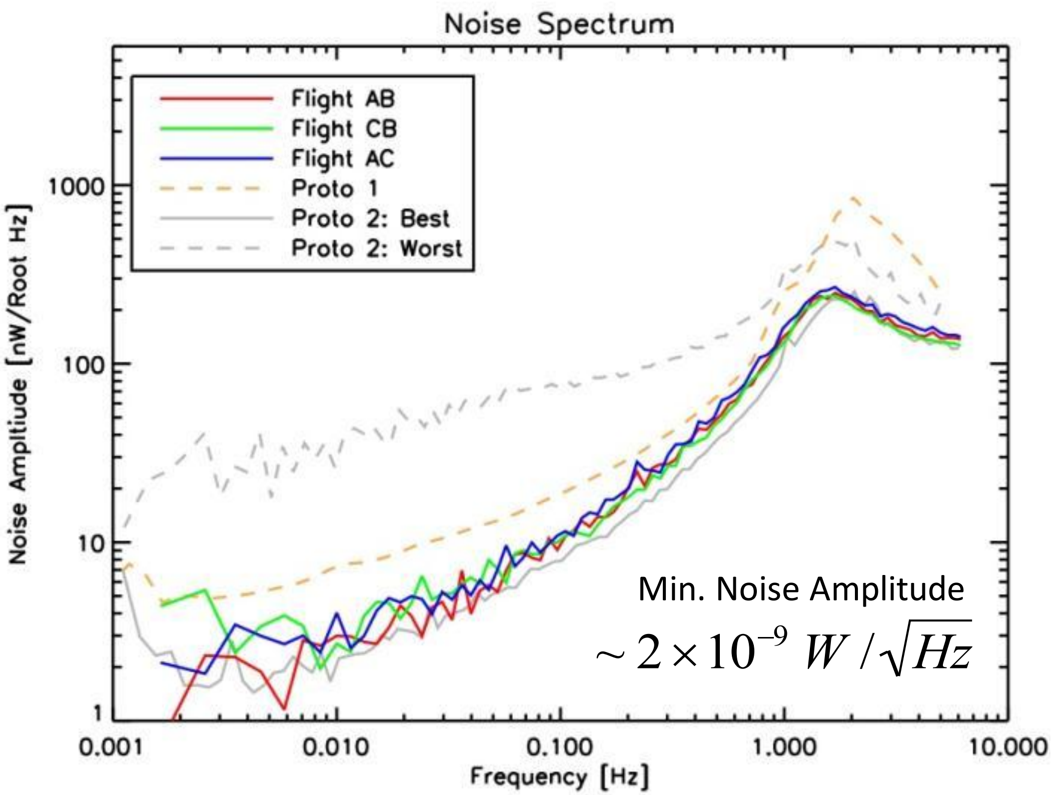
TSIS SIM ESR





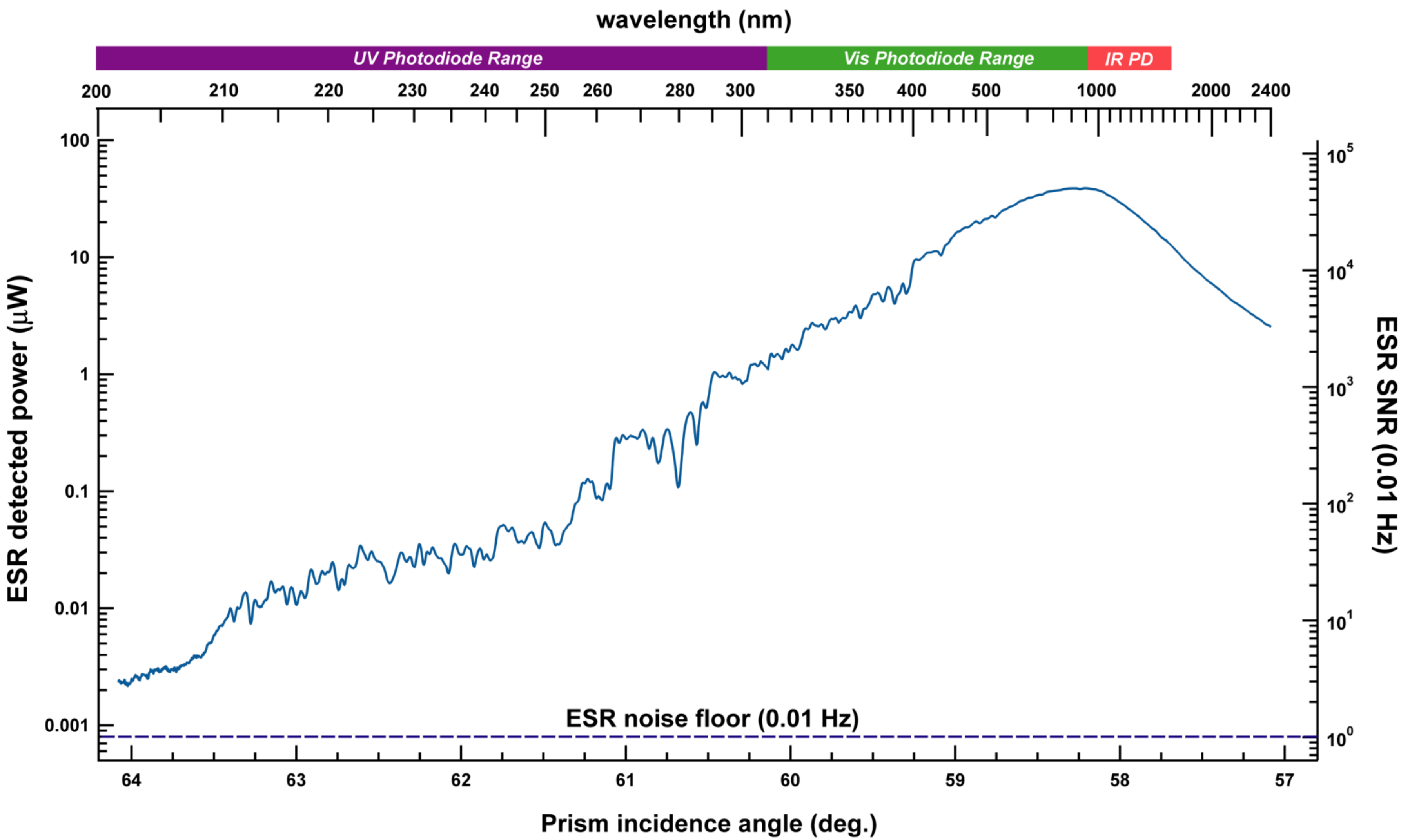
NiP Black on CVD diamond substrate

The ESR provides for a NIST traceable, space-qualified absolute calibration transfer detector



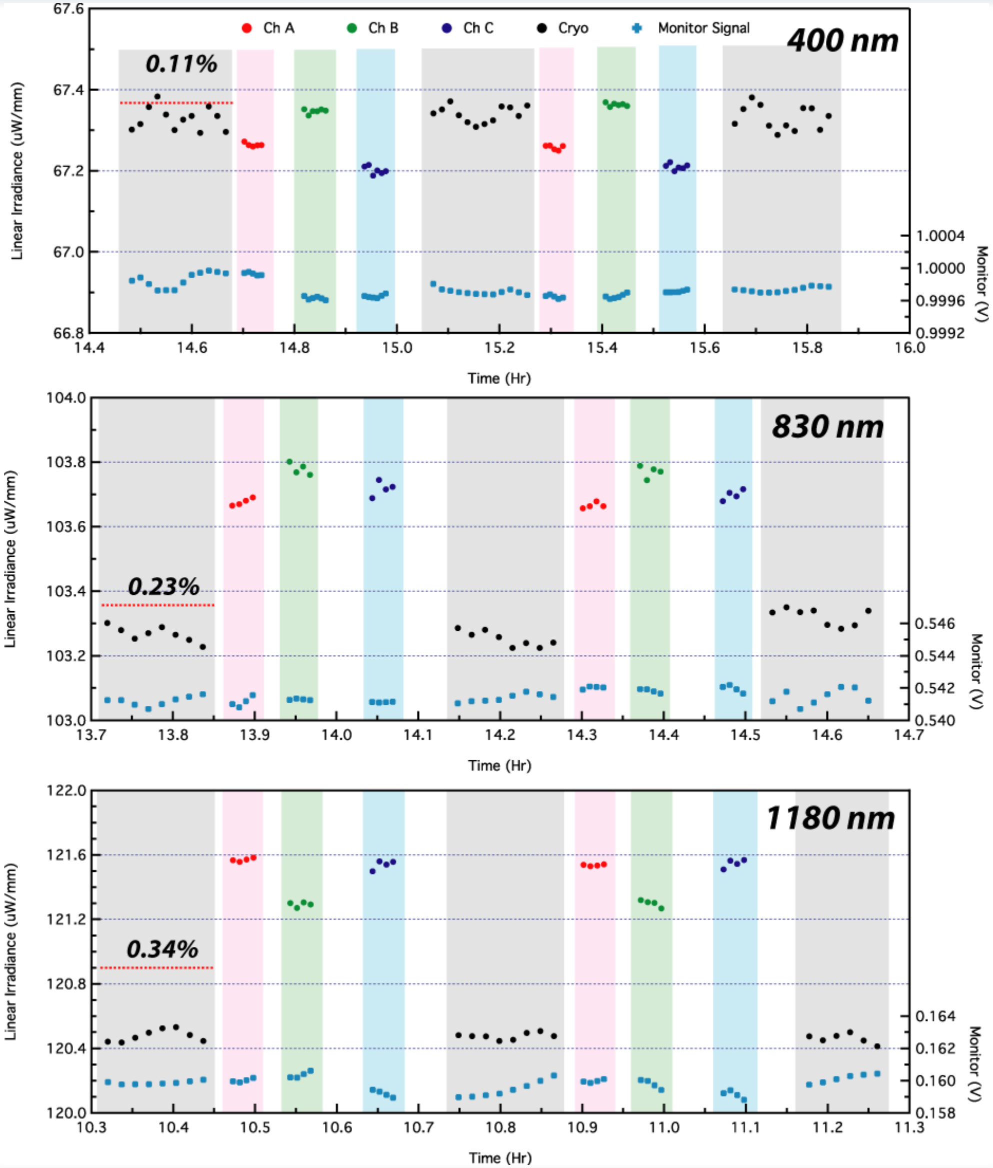
Component-Level

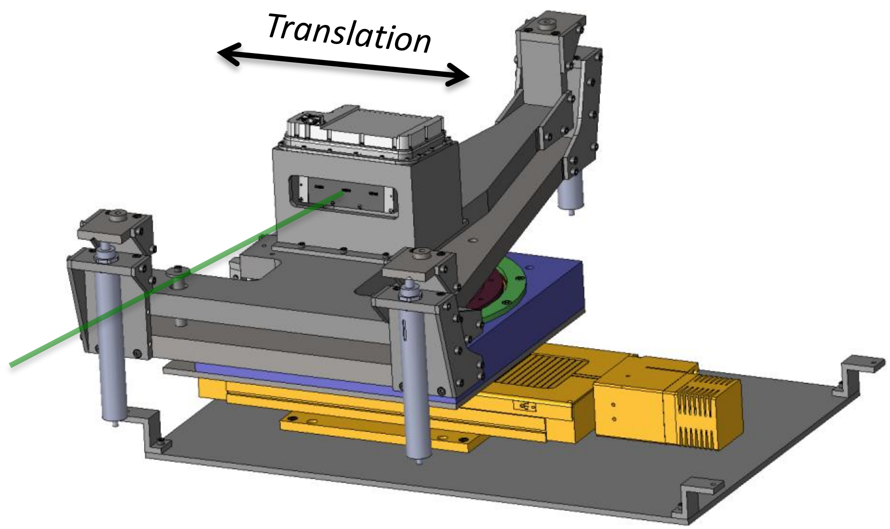
ESR Performance Meets Requirements for Solar Spectral Power



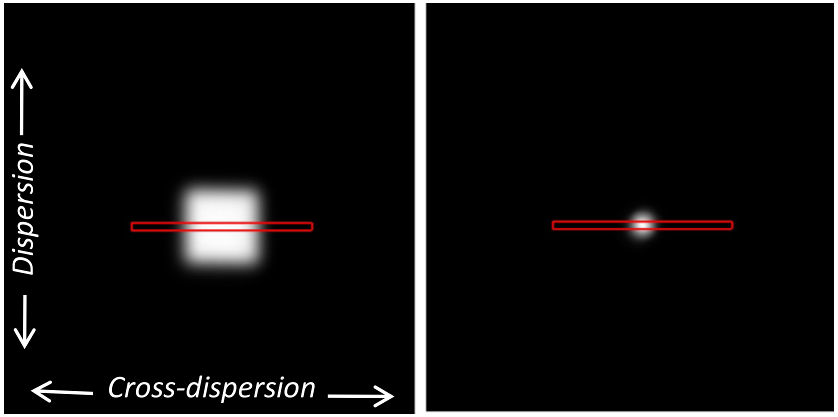
Instrument-Level

ESR – Cryo Intercomparison





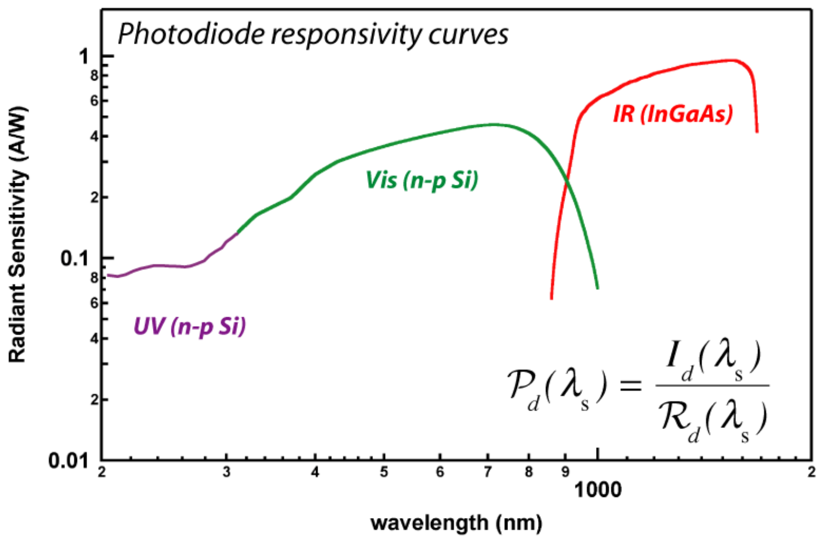
SIMRF Laser Scan Image



Component-Level

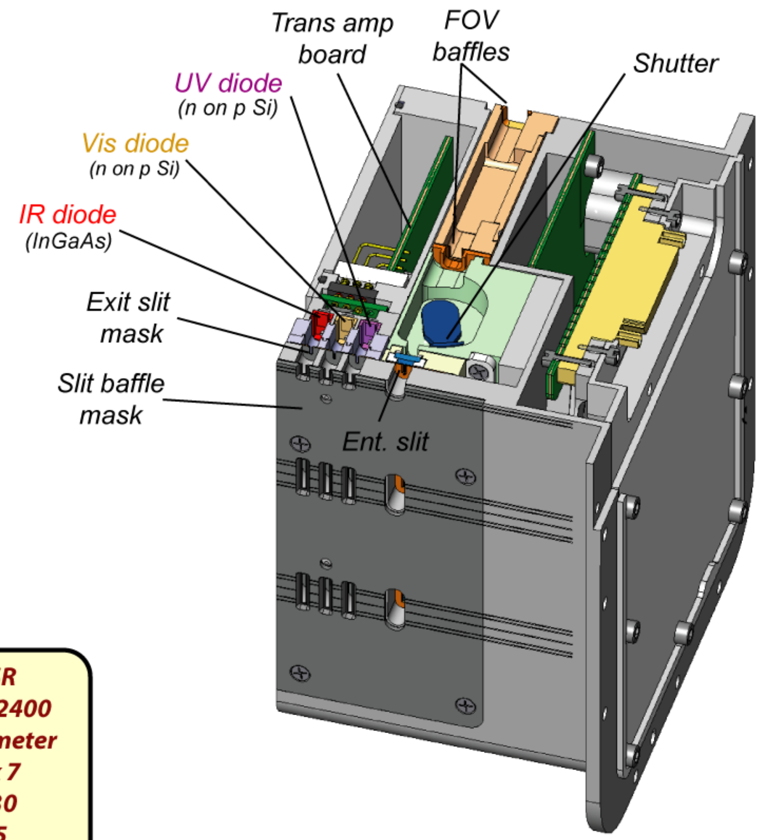
SIM Photodiode Detectors

SIM incorporates 3 photodiode detectors to cover the UV through near IR. These fast detectors are calibrated for radiant responsivity on-orbit by periodic scans with the absolute ESR detector



Detector	UV	Vis	IR	ESR
λ range (nm)	200-315	310-950	900-1655	200-2400
Material	n-p Si	n-p Si	InGaAs	bolometer
Active area (mm)	2 x 10	2 x 10	2 x 8	1.5 x 7
Exit slit width (mm)	0.34	0.30	0.30	0.30
FP position (mm)*	10	15	20	45

*relative to entrance slit

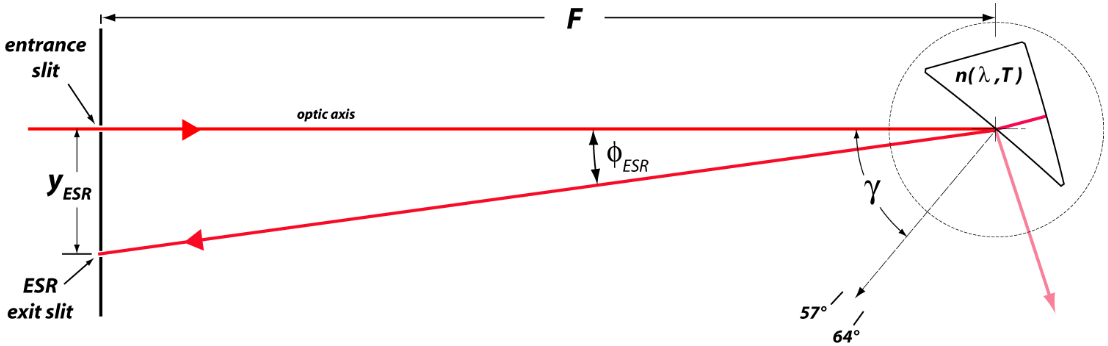


Shutter / Photodiode Assembly

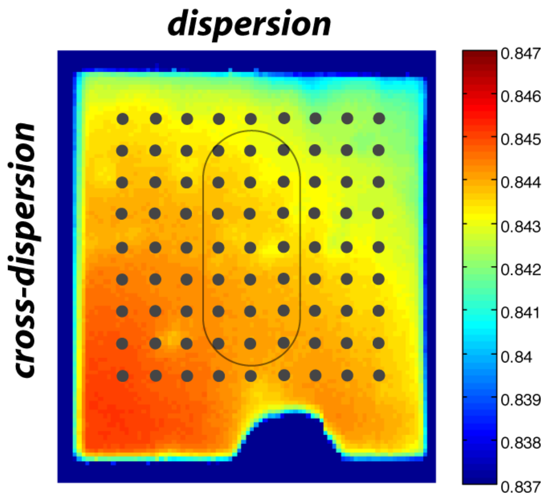
Component-Level

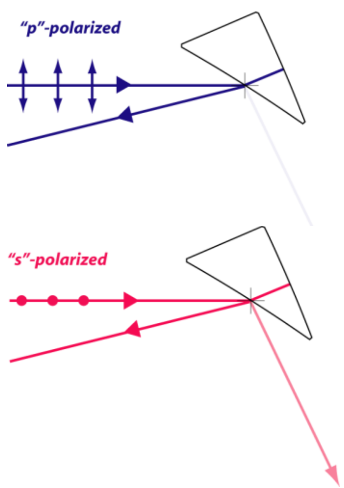
Full Spatial & Spectral Transmission Mapping

Prism measurement geometry is for ESR optical path
Stabilized SIRCUS lasers cover 210 – 2400 nm range



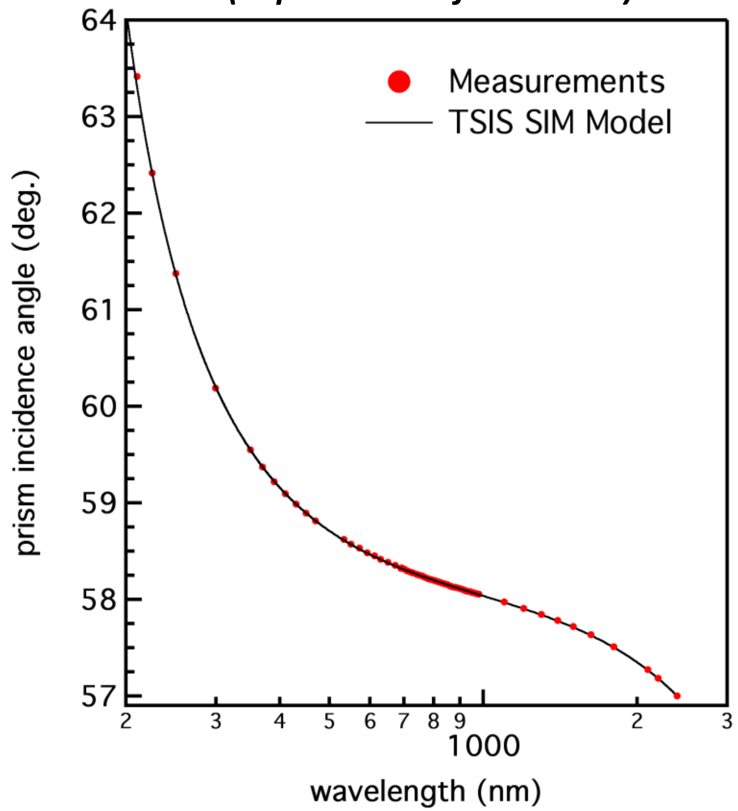
Transmission measured over 10 x 10 grid for both s and p-polarizations





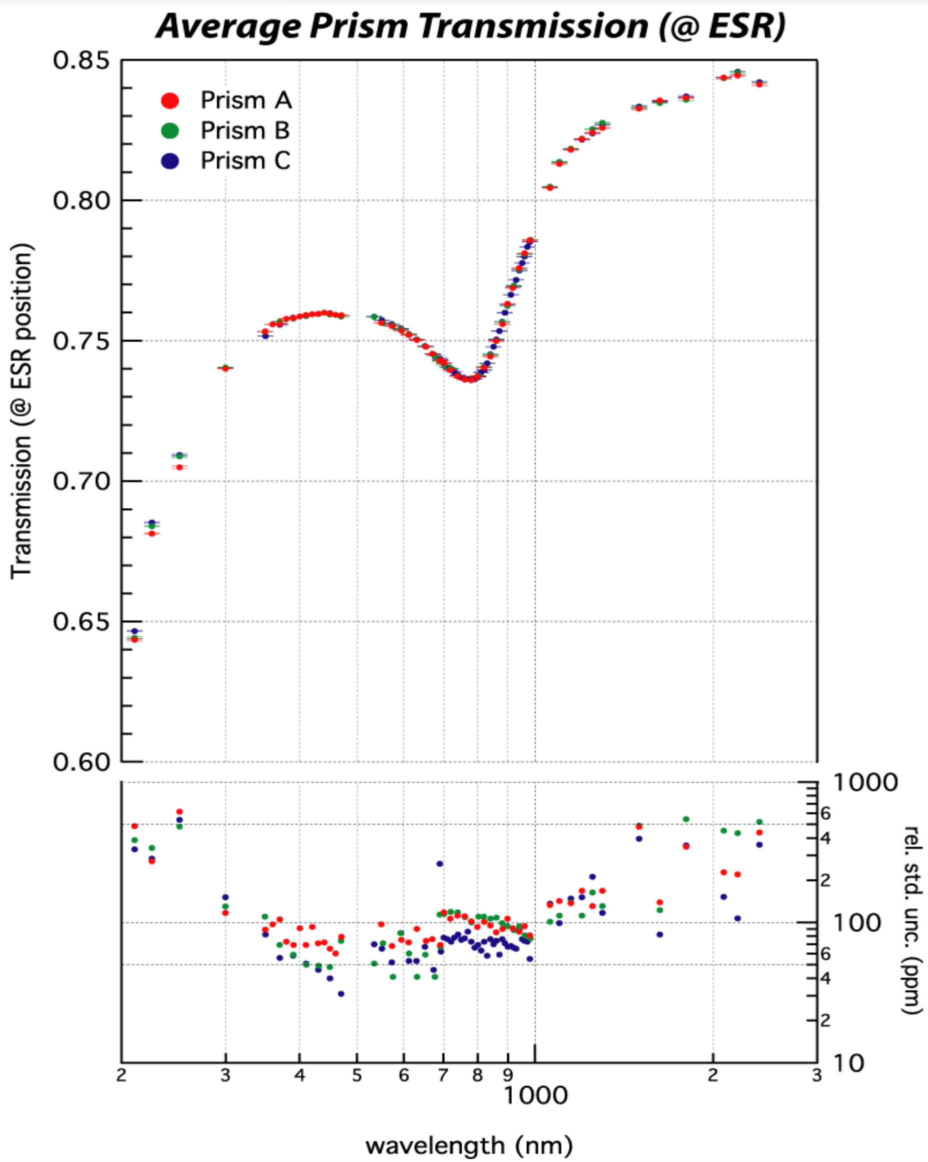
Refraction vs. wavelength

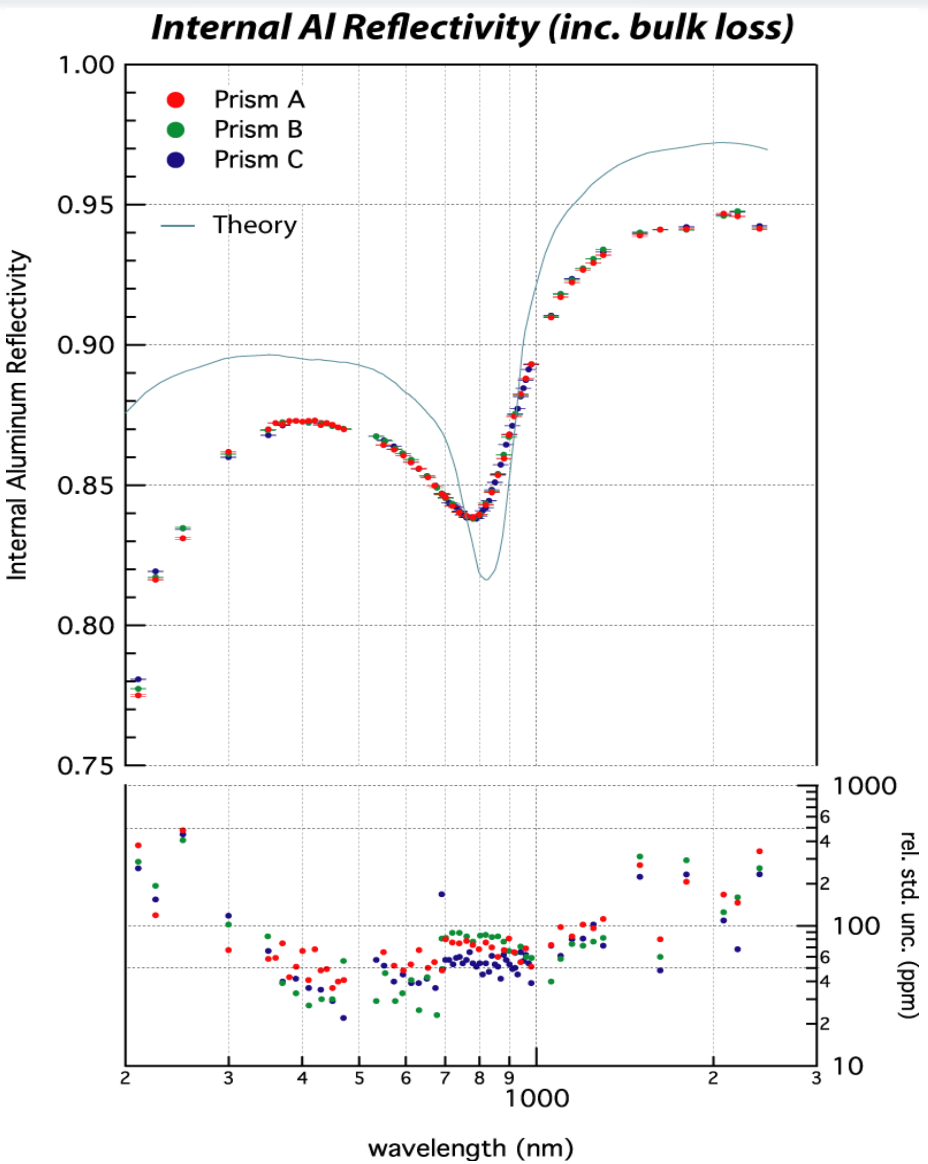
(Suprasil 3001 fused silica)



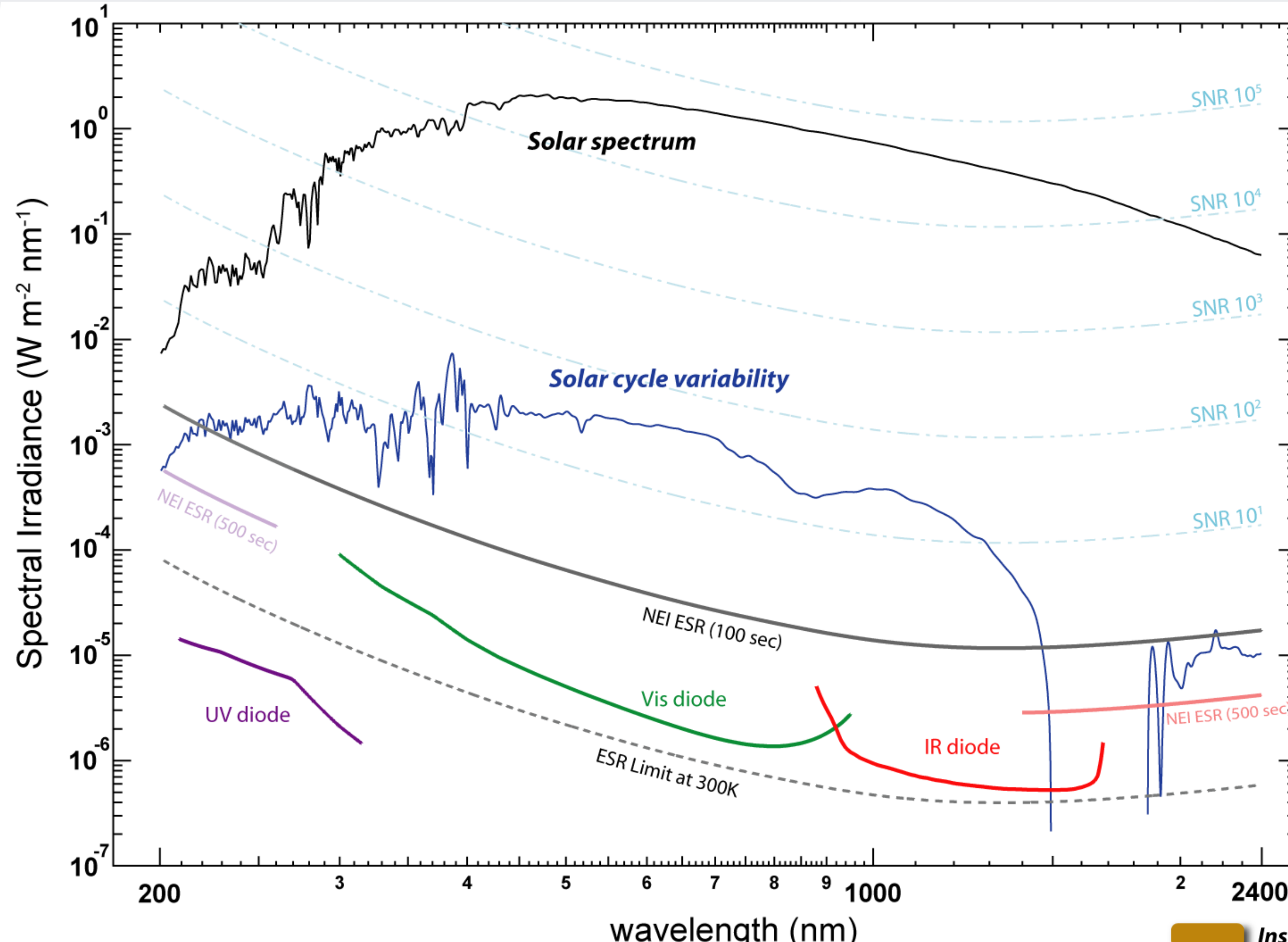
Component-Level

Prism Transmission





Spectral Variability and SIM Measurement Capabilities



Instrument-Level

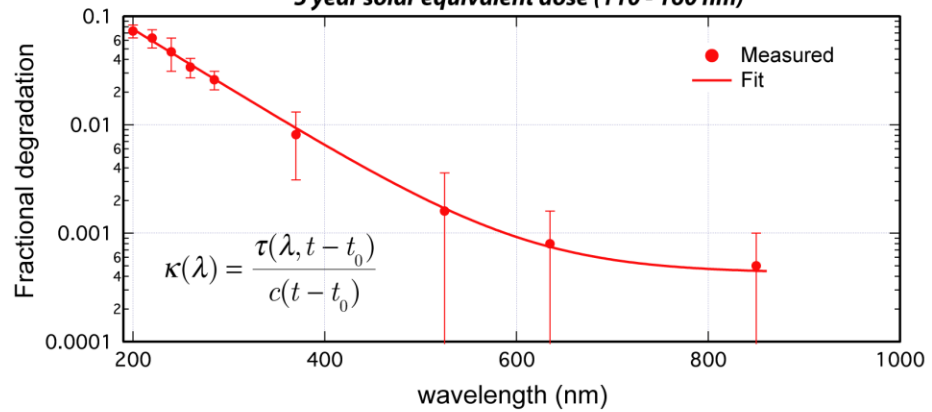
Exposure Degradation over Mission Life

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

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

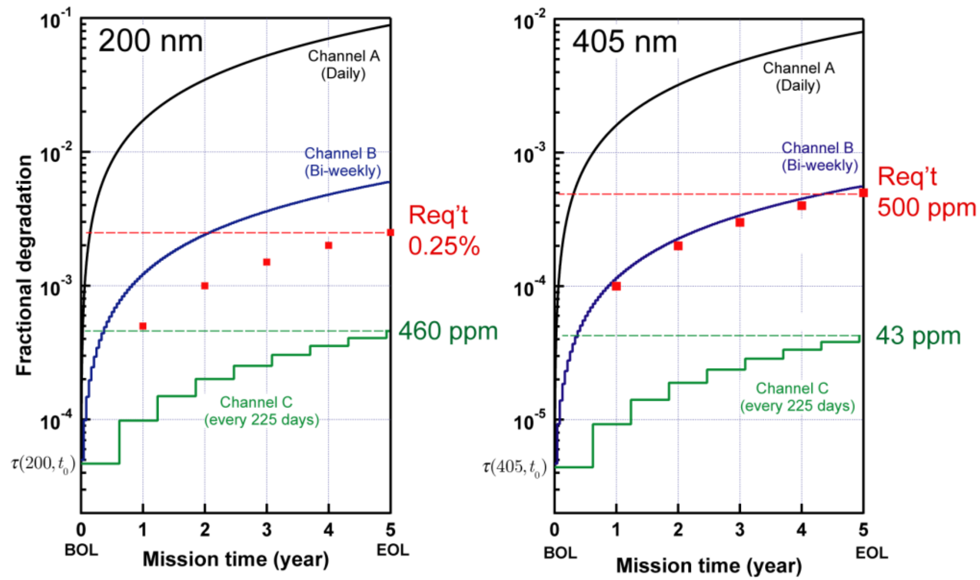
$$\tau(\lambda, t) = \kappa(\lambda) \cdot c(t)$$

Fractional degradation vs. wavelength
5 year solar equivalent dose (110 - 160 nm)



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

Fractional degradation vs. exposure time



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

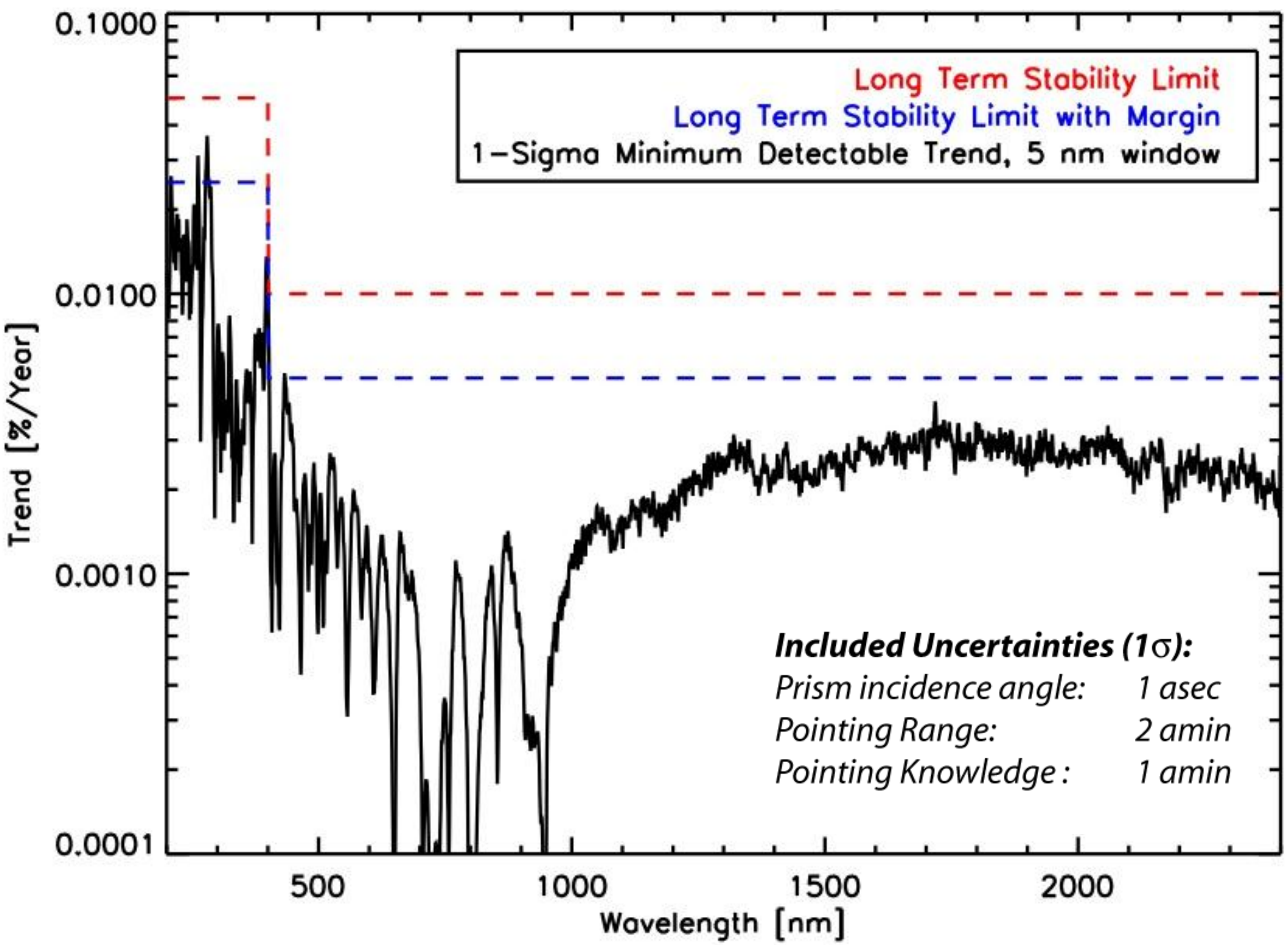
Channel C is to be used infrequently enough so that it can be considered "pristine" (less than 0.01%/year of degradation)

We must be able to measure trends < 0.01% (0.05%) / year in this Channel A to Channel C ratio data for Vis/IR (UV)

This puts a limit on the spectra to spectra repeatability

Long-term Stability Limits on SIM Noise/Repeatability

Channel A to Channel C Degradation Uncertainty



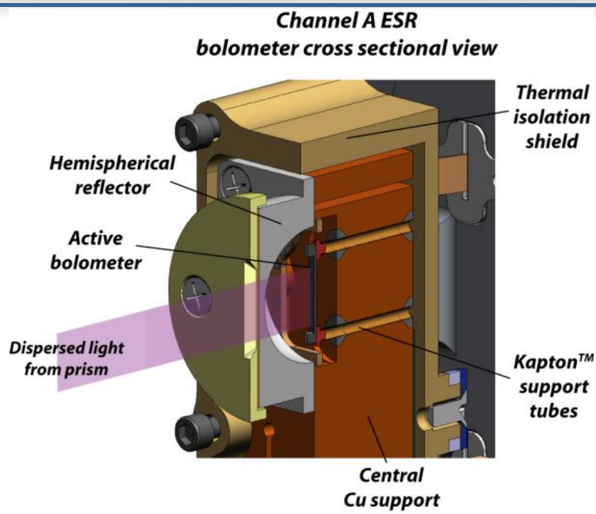
Summary

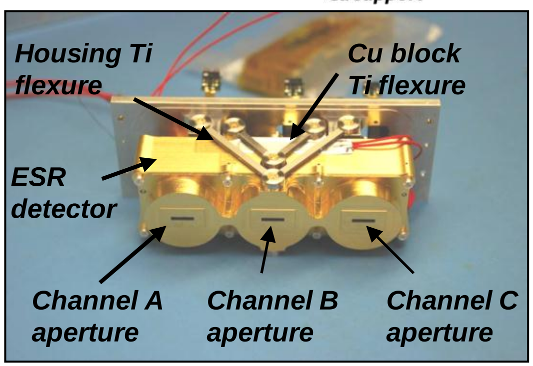
Spectral Solar Irradiance (SSI) is critical to understanding solar variability and its impact on Earth climate

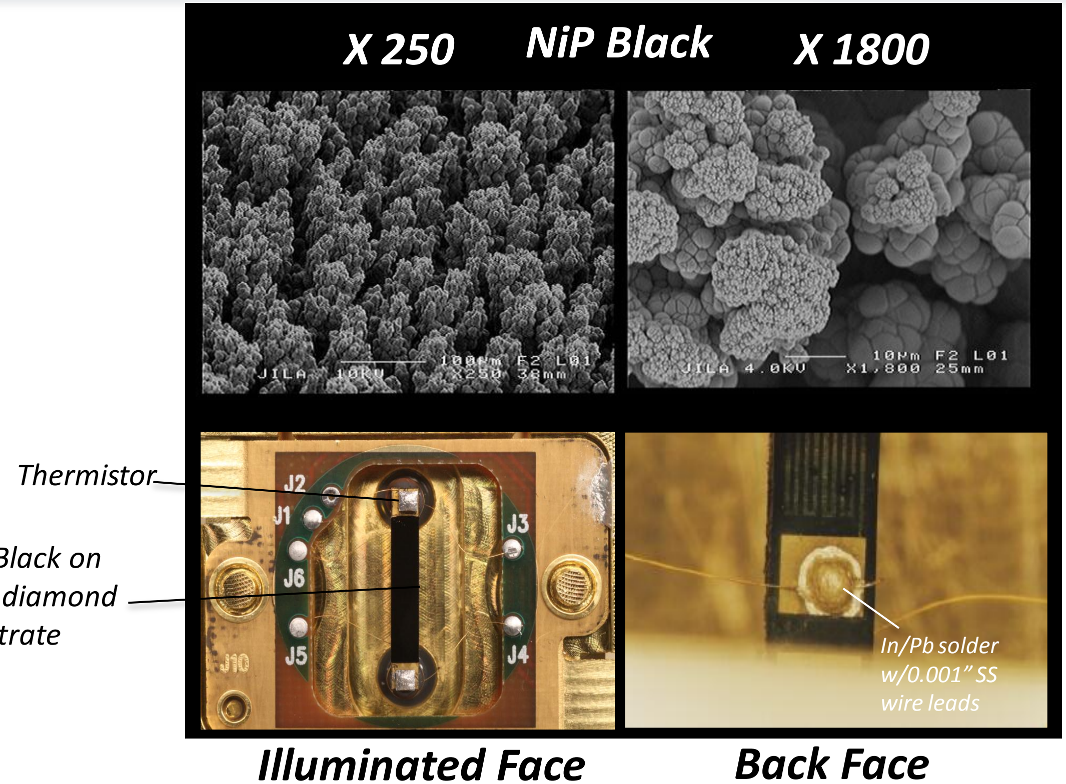
- *TSIS SIM meets the JPSS measurement requirements for SSI variability, including:*
  - *High absolute irradiance accuracy (≤0.25% over full spectrum)*
  - *High measurement precision (<0.01% relative)*
  - *On-orbit capability to self-correct long-term drifts and sensitivity changes (<0.05% per year)*
    - *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*

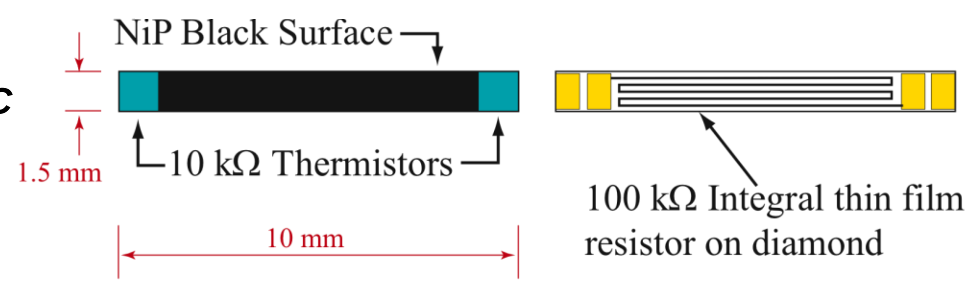
Backup Slides

ESR Detector Provides Absolute Power Measurement







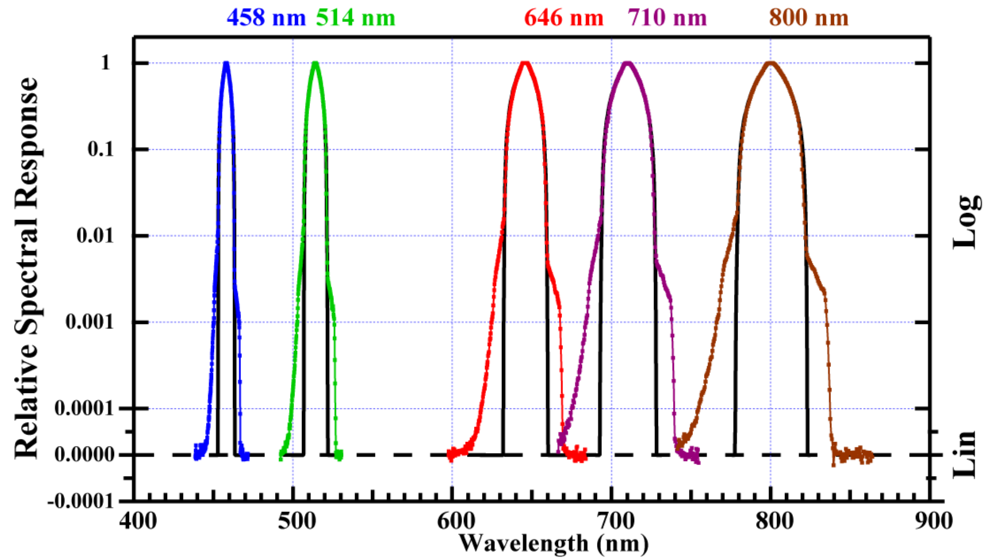


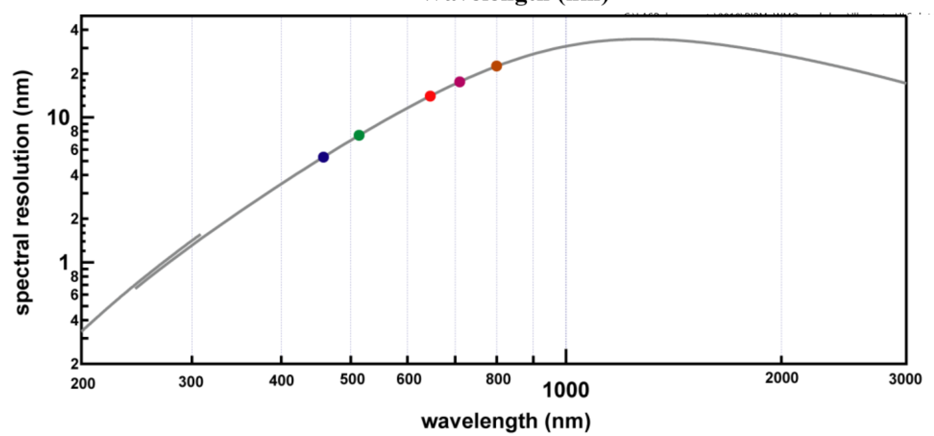
- ***Bolometer thermistors part of a precision AC bridge excited at 50 Hz***
- ***Incoming solar beam chopped by shutter at 0.01 Hz and signal detected at shutter fundamental***

Component-Level

Absolute Instrument Profile

- ***Illuminate instrument with a single wavelength and a known irradiance and measure signal vs. prism angle -*** *Irradiance is measured using the NIST Cryogenic Radiometer*





- *The resulting profile provides use in four calibrations:*
- *Instrument Function Area:*
  - *Integrated area of profile*
- *Absolute Sensitivity:*
  - *Given by the absolute height of the profile*
- *Wavelength Calibration:*
  - *Center location of profile provides wavelength calibration*
- *Scattered Light:*
  - *The background level of the profile*
- *Repeat at different wavelengths using SIRCUS to provide coverage*
- *This calibration is performed for both the ESR and diodes*

Instrument-Level