Long-term measurements of solar spectral irradiance: SSI Capabilities and Calibrations

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Sun – Climate Questions

• 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

Solar Radiative Forcing Questions

• How does the climate system respond?

  - What are the mechanisms of climate response? Requires measurement of wavelength-dependent irradiance variability.

  - Can a solar climate signal be attributed to unique mechanisms?

  - Is the climate more sensitive to solar forcing than to other forcings, for example, greenhouse gas forcing?

Adapted from Kiehl & Trenberth, 1997
Response of climate to solar variability is highly wavelength dependent:

- Direct surface heating at near-ultraviolet wavelengths and longer.
- Indirect processes through absorption of UV in the stratosphere; radiative and dynamical coupling with the troposphere.

Relative uncertainty in solar forcing is very large and must be reduced in order to separate natural from anthropogenic radiative forcing.

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

Observing the small signals of long-term global climate change places very specific requirements on satellite observing systems.

Solar irradiance variations of <0.1% per decade are typical of the kinds of signals that must be extracted from “noisy” time-series.

Measuring these signals will require much improved satellite instrument calibration and inter-comparison of similar instruments.
**Desired Characteristics of Climate Monitoring Sensors**

- High absolute accuracy in the measurement of the climate variable is vital for understanding climate processes and changes (solar irradiance ~1.5 Wm\(^{-2}\))

- High relative stability is necessary for determining long-term changes or trends (solar irradiance ~0.02% per decade)

- For flight instruments in general, accuracy is more difficult to achieve than stability
Establish the response of a flight instrument relative to SI units

Three specific approaches:

• Transfer calibration from known “standard” instrument

• Measure flight instrument response against an “irradiance standard”

• Characterize the flight instrument as an “absolute sensor”
  - characterize each term in the measurement equation (may be a unit level calibration or calc).
  - tabulate list of individual uncertainties and r.s.s. for overall measurement uncertainty.
Characterization

The measurement, over a range of instrument and environmental operating conditions, of all relevant instrument parameters; used to quantitatively understand the operation of an instrument and its response as a function of the range of operating and viewing conditions experienced by the instrument on-orbit.

Calibration

The process of quantitatively defining the system response to known, controlled signal inputs.
Calibration Mantras

- Redundant and Independent approaches
- Keep the physics of the instrument as simple as possible
- Design ground calibration instrument in parallel with flight instrument
  - ground calib. is typically last major test prior to delivery
  - cost schedule constraints typically dominate
- Capitalize on previous investments in “engineering” capital
  - don’t reinvent the wheel…at least not too much!

For climate monitoring in particular….

- Calibration is the primary instrument requirement
- Resolution (spectral & temporal) is secondary
  - however, sufficient sampling is important
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)**

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

Total Solar Irradiance (TSI)

\[
TSI_{\text{SIM}} = \int_{\lambda=0}^{\lambda=\infty} E_{\lambda} d\lambda \approx 1362 \text{ Watts/m}^2
\]

Spectral Solar Irradiance (SSI)

\[
TSI_{\text{SIM}} = \int_{\lambda=200}^{\lambda=2400} E_{\lambda} d\lambda \approx 96\% \text{ of TSI}
\]
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$^2$

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

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

S. Solanki & Y. Unruh, 1998
## SIM Measurement Requirements

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Requirement</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Measurement Range (W m(^{-2}) nm(^{-1}))</strong></td>
<td></td>
<td>Solar Spectrum</td>
</tr>
<tr>
<td>Spectral (0.2-2.4 µm)</td>
<td>10(^{-4})-10(^{1})</td>
<td>Full scale of spectral irradiance magnitude</td>
</tr>
<tr>
<td><strong>Long-term rel. stability (per year)</strong></td>
<td></td>
<td>Interpret Solar Cycle variability</td>
</tr>
<tr>
<td>0.2 ≤ λ ≤ 0.4 µm</td>
<td>0.05%</td>
<td>UV variability 0.1% - 10%</td>
</tr>
<tr>
<td>0.4 &lt; λ ≤ 2.4 µm</td>
<td>0.01%</td>
<td>Visible- Near IR variability ≤ 0.05%</td>
</tr>
<tr>
<td><strong>Measurement precision</strong></td>
<td></td>
<td>Measure short term variability</td>
</tr>
<tr>
<td>Spectral (0.2-2.4 µm)</td>
<td>0.01%</td>
<td>Sufficient SNR for Vis-NIR spectral variability</td>
</tr>
<tr>
<td><strong>Measurement Accuracy</strong></td>
<td></td>
<td>Climate modeling input</td>
</tr>
<tr>
<td>Spectral (0.2-2.4 µm)</td>
<td>0.2%</td>
<td>Earth radiation budget; Processes &amp; Mechanisms</td>
</tr>
<tr>
<td><strong>Reporting Frequency (per day)</strong></td>
<td></td>
<td>Solar temporal variability</td>
</tr>
<tr>
<td>Spectral (0.2-2.4 µm)</td>
<td>2</td>
<td>Sample short-term spectral variations with TSI</td>
</tr>
<tr>
<td><strong>Spectral Resolution (nm)</strong></td>
<td></td>
<td>Solar wavelength variability</td>
</tr>
<tr>
<td>λ ≤ 0.28 µm</td>
<td>1</td>
<td>Strongest wavelength dependence of UV variability</td>
</tr>
<tr>
<td>0.28 µm &lt; λ ≤ 0.40 µm</td>
<td>5</td>
<td>Broader wavelength dependence of Vis-NIR var.</td>
</tr>
<tr>
<td>λ &gt; 0.40 µm</td>
<td>35</td>
<td></td>
</tr>
</tbody>
</table>
SORCE SIM and Atlas 3 Comparison (258-1350 nm)

The top graph shows the comparison of irradiance between Convolved Atlas 3 and SORCE SIM over the wavelength range of 258-1350 nm. The bottom graph illustrates the fractional difference (δ) between the two datasets at the same wavelength range, with δ = -0.021 ± 0.021 (258-1350 nm).
TSIS SIM designed for long-term spectral irradiance measurements (climate research)

Incorporate lessons learned from SORCE SIM (and other LASP programs) into TSIS SIM to meet measurement requirements for long-term 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 design
  • Larger dynamic range ADC’s plus signal integration

✓ Improve absolute accuracy pre-launch calibration
  • NIST SI-traceable Unit and Instrument level pre-launch spectral calibration
5 years ago… thoughts for TSIS SIM

Long-term measurements of SSI
Expanded View of TSIS SIM

- CCD Assy
- Rotational Prism Carrier
- Fery Prism Assy
- Shutter/Photodiode Assy
- CCD Aperture
- Ch. A Aperture
- Ch. B Aperture
- Ch. C Aperture
- Fine Sun Sensor
- Focal Plane Module
- External Flex
- ESR Detector Assy
- Vacuum Door Mechanism
Fery prism spectrometer covering the full wavelength range from the UV to IR using only one optical element for spectral dispersion and image quality
SIM Measurement Equation Overview

\[
\mathcal{E}_\lambda(\lambda_s) = \frac{P_{\text{ESR}}(\lambda_s)}{A_{\text{slit}} \cdot \int \alpha_\lambda \cdot T_\lambda \cdot \phi_\lambda \cdot S(\lambda, \lambda_s) \, d\lambda}
\]

- Aperture area
- ESR Absorptance
- Slit diffraction
- Prism transmission
- Instrument function

ESR detected power:

Long-term measurements of SSI

NOAA Climate Data Record Project
TSI and SSI Requirements Workshop
SIM Measurement Equation Details

Absolute measured spectrum

\[ \mathcal{E}_\lambda(\lambda_s) = \frac{P_{ESR}(\lambda_s)}{A_{\text{slit}} \int \alpha \tau \Phi \lambda \text{S}(\lambda, \lambda_s) d\lambda} \quad (W m^{-2} nm^{-1}) \]

Photodiode Power

\[ P_d = \frac{I_d(\lambda_s)}{R_d(\lambda_s)} \quad \text{(Watts)} \]

SIM has variable spectral resolution
\[ E_\lambda(\lambda_s) = \frac{P_{ESR}(\lambda_s)}{A_{slit} \cdot \int \alpha_\lambda \cdot T_\lambda \cdot \phi_\lambda \cdot S(\lambda, \lambda_s) \, d\lambda} \]

**ESR Power detection follows TIM**

\[ \tilde{P}_{ESR} = \frac{1}{64000} \frac{V_{ref}^2}{R_{eff}} \left\{ \frac{1+G}{\tilde{G}} \cdot \frac{\tilde{Z}_H}{\tilde{Z}_R} \right\} \tilde{p} \cdot \tilde{D} \]

\[ \tilde{p} = \exp(i \cdot \omega_{1J}) \]

\[ E_{Sun}(\lambda) = \frac{E_\lambda(\lambda_s)}{f_{1AU} \cdot f_{pnt}(\lambda) \cdot f_{degr}(\lambda)} \]

**Applied correction factors**
**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, 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.*
# SIM Calibration Error Budget Allocation

<table>
<thead>
<tr>
<th>Correction</th>
<th>Origin</th>
<th>Value [PPM]</th>
<th>1σ [PPM]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance to Sun, Earth &amp; S/C</td>
<td>Analysis</td>
<td>33,537</td>
<td>0.1</td>
</tr>
<tr>
<td>Doppler Velocity</td>
<td>Analysis</td>
<td>43</td>
<td>1</td>
</tr>
<tr>
<td>Pointing</td>
<td>Analysis</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>Shutter Waveform</td>
<td>Component</td>
<td>100</td>
<td>1</td>
</tr>
<tr>
<td>Slit Area</td>
<td>Component</td>
<td>1,000,000</td>
<td>360</td>
</tr>
<tr>
<td>Diffraction</td>
<td>Component</td>
<td>3,000-22,000</td>
<td>500</td>
</tr>
<tr>
<td>Prism Transmittance</td>
<td>Component</td>
<td>230,000-450,000</td>
<td>1,000</td>
</tr>
<tr>
<td>ESR Efficiency</td>
<td>Component</td>
<td>1,000,000</td>
<td>1,000</td>
</tr>
<tr>
<td>Standard Volt + DAC</td>
<td>Component</td>
<td>1,000,000</td>
<td>50</td>
</tr>
<tr>
<td>Pulse Width Linearity</td>
<td>Component</td>
<td>0</td>
<td>50</td>
</tr>
<tr>
<td>Standard Ohm + Leads</td>
<td>Component</td>
<td>1,000,000</td>
<td>50</td>
</tr>
<tr>
<td>Instrument Function Area</td>
<td>Instrument</td>
<td>1,000,000</td>
<td>1,000</td>
</tr>
<tr>
<td>Wavelength (Δλ/λ = 150 ppm)</td>
<td>Instrument</td>
<td>1,000,000</td>
<td>750</td>
</tr>
<tr>
<td>Non-Equivalence, ZH/ZR-1</td>
<td>Instrument</td>
<td>2,000</td>
<td>100</td>
</tr>
<tr>
<td>Servo Gain</td>
<td>Instrument</td>
<td>2,000</td>
<td>100</td>
</tr>
<tr>
<td>Dark Signal</td>
<td>Instrument</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>Noise</td>
<td>Instrument</td>
<td>-</td>
<td>100</td>
</tr>
<tr>
<td>Total RSS</td>
<td></td>
<td>2000</td>
<td>0.2%</td>
</tr>
</tbody>
</table>
ESR Performance Meets Requirements for Solar Spectral Power

- Long-term measurements of SSI

**Graph Details:**
- **X-axis:** Prism incidence angle (deg.)
- **Y-axis:** ESR noise floor (0.01 Hz)
- **Graph Title:** ESR noise floor at 0.01 Hz
- **Logarithmic scale:** Logarithmic scale is used for both axes, indicating a wide range of values.

**Legend:**
- **UV Photodiode Range:** Wavelengths from 200 to 300 nm
- **Vis Photodiode Range:** Wavelengths from 350 to 500 nm
- **IR PD:** Wavelengths from 1000 to 2400 nm

**Note:** The graph shows the performance of ESR in meeting requirements for solar spectral power measurements, highlighting the noise floor at 0.01 Hz across different incidence angles and wavelengths.
**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**

**TSIS SIM ESR Prototype**

- Channel A aperture
- Channel B aperture
- Channel C aperture

**Housing Ti flexure**
- Cu block Ti flexure
- ESR detector

**Thermistor**
- NiP Black on CVD diamond substrate

**ESR detector**
- In/Pb solder w/0.001” SS wire leads

**In/Pb solder**
- 100 kΩ Integral thin film resistor on diamond

**10 kΩ Thermistors**
- 10 mm

**1.5 mm**

**Illuminated Face**

**Back Face**

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**NOAA Climate Data Record Project**

**TSI and SSI Requirements Workshop**

**Long-term measurements of SSI**

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**ESR Absolute Power Calibration**

**SORCE Witness ESR Results**

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

ESR = \((0.9834 \pm 0.0021) \times \text{SIRCUS} + (-0.005 \pm 0.06)\)

\(r^2 = 0.99998\)

\(\lambda = 457.9 \text{ nm}\)
**TSIS SIM Flight ESR Detector**

Long-term measurements of SSI
Long-term measurements of SSI
Long-term measurements of SSI
Entrance Slit Area

Slit_32.txt

From the Rectangle Fit:

\[ X_w = 6.4992052 +/- 4.8458688e-05 \text{ mm}, \quad 7.4560946 \text{ ppm} \]

\[ Y_w = 0.29548950 +/- 5.9737257e-05 \text{ mm}, \quad 202.16372 \text{ ppm} \]

\[ \text{Area} = 1.9204469 +/- 0.00038918850 \text{ mm}^2, \quad 202.65517 \text{ ppm} \]

From the Polygon Fit:

\[ X_{w1} = 6.4992214 +/- 0.00014328210 \text{ mm}, \quad 22.046041 \text{ ppm} \]

\[ X_{w2} = 6.4991890 +/- 0.0001965122 \text{ mm}, \quad 18.410177 \text{ ppm} \]

\[ Y_{w1} = 0.29620263 +/- 6.3523079e-05 \text{ mm}, \quad 214.45819 \text{ ppm} \]

\[ Y_{w2} = 0.29477526 +/- 8.4713185e-05 \text{ mm}, \quad 287.38227 \text{ ppm} \]

\[ dX_w = 3.2310793e-05 +/- 0.00023814754 \text{ mm}, \quad 737.05259 \% \]

\[ dY_w = 0.0014273674 +/- 0.00013324065 \text{ mm}, \quad 9.3347129 \% \]

\[ \text{Area} = 1.9204433 +/- 0.00022322385 \text{ mm}^2, \quad 116.23559 \text{ ppm} \]

\[ \text{Difference Between Rectangle & Polygon Area} = 1.8979249 \text{ ppm} \]
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

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

We will utilize NIST traveling SIRCUS (Spectral Irradiance and Radiance Responsivity Calibrations using Uniform Sources) to generate laser light across the SIM spectrum of 200-2400 nm.
SIM Prism Assembly

Pre-aligned SIM prism carrier

Fery prism drive assembly

Long-term measurements of SSI
Full Spatial Transmission Mapping

Prism #4, 700nm

Prism #6, 700nm

Prism #8, 700nm

Prism #9, 700nm

Prism #10, 700nm

Prism #11, 700nm

Long-term measurements of SSI
Transmission measurements at ESR optical geometry

- **two-surface Fresnel "p"**
- **two-surface Fresnel "s"**

Diagram showing:
- **p-polarization**
- **s-polarization**

Wavelength (nm)

Transmission

- Measured
- Theory
This facility will allow for irradiance calibration of the SIM ESR and the full SIM build over the operation wavelength range of the SIM instrument.

Main parts of SIMRF:
- STOVE tank
- Manipulator for SIM and ESR subassembly
- Steering mirror vacuum housing
- Cryogenic radiometer (NIST)
- SIRCUS lasers (NIST)
Long-term measurements of SSI
SIMRF L1 Cryo Assembly
4X PI LINEAR ACTUATORS  
(M-235.2DG, BALL SCREW W/ DC MOTOR)  
1-21 mm RANGE  
PUSH/PULL FORCE CAPACITY:  
120 NEWTONS (27 LBS)

NEWPORT LINEAR STAGE  
(MTM250 PE1 GEAR MOTOR WITH 2mm PITCH LEADSCREW)  
250 mm RANGE  
1 μm RESOLUTION  
Normal load capacity: 1000 NEWTONS (224 LBS)

AZIMUTH BEARING ASSEMBLY (existing)  
ELEVATION  
±0.5° REQMNT  
±1° GOAL

AZIMUTH  
±0.5° REQMNT  
±1° GOAL
ESR ASSEMBLY

ESR TO CRADLE BRACKET

ESR EXIT SLITS ARE LOCATED IN THE SAME POSITION (RELATIVE TO INCOMING BEAM) AS SIM ENTRANCE SLITS

SIM Manipulator with ESR

Long-term measurements of SSI
INCOMING BEAM IS HORIZONTAL
Prototype ESR in SIMRF
Entrance Slit Diffraction

Measured Diffraction from SIM Slit

- Diffraction from Long Edge
- Diffraction from Short Edge

Signal [arb]

Arm Angle [Deg]

Image of Diffracted Light

Long edge

Short edge

Long-term measurements of SSI
SIM Optical Configuration

Non-Sequential Ray-Trace Layout

SIM Layout – Dispersion Plane

Entrance Slit
UV Diode
VIS Diode
IR Diode
ESR

400 mm
Diffraction Loss vs. Pointing Error

- ESR at 2400 nm
- IR at 1655 nm
- VIS at 950 nm
- UV at 315 nm

Long-term measurements of SSI
Change in Diffraction vs. Pointing

- ESR at 2400 nm
- IR at 1655 nm
- VIS at 950 nm
- UV at 315 nm

Change in Diffraction Loss [ppm]

Off-Pointing Angle [Arc-Mins]
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.
TSIS SIM will incorporate true 20 bit A/D precision with signal integration.
Spectral Variability and SIM Measurement Capabilities

Long-term measurements of SSI
- **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
**Long Term Stability Requirement Met Through On-orbit Degradation Correction**

**Time and wavelength dependent optical transmission degradation**

\[ T(\lambda, t - t_0) = T(\lambda, t_0) e^{-\tau(\lambda, t - t_0)} \]

\[ \tau(\lambda, t) = \kappa(\lambda) \cdot c(t) \]

*Independently evaluated by periodic ESR measurements between separate channels*

- A to B comparison to obtain \( \kappa(\lambda) \)
- \( \kappa(\lambda) \) applied to B to provide \( \tau_B(\lambda, t) \) at each B exp.
- C used to verify calibration of A

---

**5 year solar equivalent exposure (110 - 160 nm)**

\[ \kappa(\lambda) = \frac{\tau(\lambda, t - t_0)}{c(t - t_0)} \]

**Channel A (Daily)**

**Channel B (Bi-weekly)**

**Channel C (every 225 days)**

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**NOAA Climate Data Record Project**

**TSI and SSI Requirements Workshop**

**Long-term measurements of SSI**
• The degradation correction is going to be determined using the Channel A to Channel B ratio data
  – Channel B spectra will be taken once every two weeks

• We will use the Channel A to Channel C comparison as check on the degradation correction
  – Channel C spectra will be taken about once every year
    • 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 of less than 0.01%/year in this A to C ratio data
    • This puts a limit on the spectra to spectra repeatability
Minimum Detectable Trend vs. Wavelength

Channel A to Channel C Degradation Uncertainty

Long Term Stability Limit
Long Term Stability Limit with Margin
1-Sigma Minimum Detectable Trend, 5 nm window

Included Uncertainties (1σ):
Prism incidence angle: 1 asec
Pointing Range: 2 amin
Pointing Knowledge: 1 amin
IR Long-term Stability
A to C validation: 2000 nm

2000 nm A to C Ratio over 5 years

Ratio Trend at 2000 nm

- 0.01%/Year
- Fit Trend
- 1-Sigma Trend Uncertainty
- A/C Ratio Data
UV Long-term Stability
A to C validation: 280 nm

280 nm A to C Ratio over 5 years

Ratio Trend at 280 nm

- 0.05%/Year
- Fit Trend
- 1-Sigma Trend Uncertainty
- A/C Ratio Data

Long-term measurements of SSI
Summary

- Spectral Solar Irradiance (SSI) is important in understanding solar variability and its impact on Earth climate
- TSIS SIM meets the measurement requirements of SSI Solar Cycle variability, including:
  - High absolute irradiance accuracy (0.2% 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 required capabilities over SORCE SIM
  - 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