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

Odele Coddington, Erik Richard, Dave Harber, and Peter Pilewskie

Laboratory for Atmospheric and Space Physics
University of Colorado, Boulder, Colorado
Motivation & Outline

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

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

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

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

SSI observational composites → V1 UV composite [Deland and Cebula, 2008]; V2 in development
Full spectrum ‘SOLID’ composite [Haberreiter et al., 2017]
TSIS SIM designed for long-term spectral irradiance measurements

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

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

- Improve uncertainty quantification in prism degradation correction to meet long-term stability requirement
  - Ultra-clean optical environment to mitigate contamination
  - Addition of 3rd channel to reduce degradation uncertainties

- Improve noise characteristics of ESR and photodiode detectors to meet measurement precision requirement
  - Improved ESR thermal & electrical design (sensitivity)
  - Larger dynamic range integrating ADC’s (21 bits)

- Improve absolute accuracy (pre-launch) verification
  - SI-traceable Unit and Instrument level pre-launch spectral irradiance calibration (LASP SRF-NIST SIRCUS-L1 Cryo Rad)
Féry prism spectrometer. Modular design.

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

Measurement Equation (Units: Wm\(^{-2}\)nm\(^{-1}\))
# TSIS SIM Correction Factors

*Instrument uncertainties determined at the component level --&gt; characterization of error budget*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Origin</th>
<th>Value (ppm)</th>
<th>Type</th>
<th>Unc. (ppm) k=1</th>
<th>Status (532 nm)</th>
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<tbody>
<tr>
<td>Distance to Sun, Earth &amp; S/C</td>
<td>Analysis</td>
<td>33,537</td>
<td></td>
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<tr>
<td>Doppler Velocity</td>
<td>Analysis</td>
<td>43</td>
<td></td>
<td>1</td>
<td></td>
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<tr>
<td>Pointing</td>
<td>Analysis</td>
<td>0</td>
<td></td>
<td>100</td>
<td></td>
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<tr>
<td>Shutter Waveform</td>
<td>Component</td>
<td>100</td>
<td>B</td>
<td>10</td>
<td></td>
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<tr>
<td>Slit Area</td>
<td>Component</td>
<td>1,000,000</td>
<td>A</td>
<td>300</td>
<td>165</td>
</tr>
<tr>
<td>Diffraction</td>
<td>Component</td>
<td>5,000-62,000</td>
<td>B</td>
<td>500</td>
<td>380</td>
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<tr>
<td>Prism Transmittance</td>
<td>Component</td>
<td>230,000-450,000</td>
<td>A</td>
<td>1,000</td>
<td>830</td>
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<tr>
<td>ESR Efficiency</td>
<td>Component</td>
<td>1,000,000</td>
<td>A</td>
<td>1,000</td>
<td>940</td>
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<tr>
<td>Standard Volt + DAC</td>
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<td>A</td>
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<tr>
<td>Pulse Width Linearity</td>
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<tr>
<td>Standard Ohm + Leads</td>
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<td>50</td>
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<tr>
<td>Instrument Function Area</td>
<td>Instrument</td>
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<td>A</td>
<td>1,000</td>
<td>870</td>
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<tr>
<td>Wavelength</td>
<td>Instrument</td>
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<td>B</td>
<td>750</td>
<td>530</td>
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<tr>
<td>Non-Equivalence, Zₐ/Zₐ⁻¹</td>
<td>Instrument</td>
<td>2,000</td>
<td>B</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Servo Gain</td>
<td>Instrument</td>
<td>2,000</td>
<td>A</td>
<td>100</td>
<td></td>
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<tr>
<td>Dark Signal</td>
<td>Instrument</td>
<td>0</td>
<td>B</td>
<td>100</td>
<td></td>
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<tr>
<td>Scattered Light</td>
<td>Instrument</td>
<td>0</td>
<td>B</td>
<td>200</td>
<td></td>
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<tr>
<td>Noise</td>
<td>Instrument</td>
<td>-</td>
<td>A</td>
<td>100</td>
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</table>

**Combined Rel. Std. Unc.**

<table>
<thead>
<tr>
<th>Value</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>1668</td>
</tr>
</tbody>
</table>
TSIS SIM Correction Factors

- Total Correction
- Prism Transmission
- Diffraction
- ESR Calibration

Correction [%]

Wavelength [nm]

500 1000 1500 2000

Coddington 7
The LASP SRF uses an *L-1 Standards & Technologies* Absolute Cryogenic Radiometer with calibrated aperture to provide *irradiance mode* calibration.
The LASP SRF utilizes NIST SIRCUS laser sources coupled to L-1 cryogenic radiometer

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

✓ Past absolute uncertainty of spectral irradiance measurements is ~2% and recent developments during the TSIS SIM project have achieved factor of 10 improvement – 0.2% (Richard et al., 2011; Harber et al., 2013).
Absolute Irradiance Scale (LASP-SRF)

Cryogenic Radiometer Uncertainty Budget

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>% Effect</th>
<th>% Unc. (k=1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>W</td>
<td>100</td>
<td>0.015</td>
</tr>
<tr>
<td>Cavity Reflectance</td>
<td>-</td>
<td>0.01</td>
<td>0.004</td>
</tr>
<tr>
<td>Cavity Non-Equiv.</td>
<td>-</td>
<td>0</td>
<td>0.01</td>
</tr>
<tr>
<td>Slit Area: Measured</td>
<td>m²</td>
<td>100</td>
<td>0.05</td>
</tr>
<tr>
<td>Slit Area: Contraction</td>
<td></td>
<td>0.04</td>
<td>0.01</td>
</tr>
<tr>
<td>Slit Area: Cosine effect</td>
<td></td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>Slit Diffraction Loss</td>
<td></td>
<td>0.13</td>
<td>0.02</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>0.07</strong></td>
</tr>
</tbody>
</table>

\[ I_0 = \frac{DN(\lambda_0)}{AD(\lambda_0)C(\lambda_0)G(\lambda_0, p)} \]

\[ I_0 = \frac{\left( \int DN(c)dc \right)}{AD(\lambda_0)T(\lambda_0, p)G(\lambda_0, p) W(c)} \]

LASP SRF End-to-End Uncertainty Budget

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>% Effect</th>
<th>% Unc. (k=1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cryo Measurement</td>
<td>W/m²</td>
<td>100</td>
<td>0.07</td>
</tr>
<tr>
<td>Turning Mirror Repeatability</td>
<td>-</td>
<td>0</td>
<td>0.004</td>
</tr>
<tr>
<td>Laser: Stability</td>
<td>-</td>
<td>0</td>
<td>0.060</td>
</tr>
<tr>
<td>Laser: Pattern Uniformity</td>
<td>-</td>
<td>0</td>
<td>0.023</td>
</tr>
<tr>
<td>Path Length Correction</td>
<td>-</td>
<td>0</td>
<td>0.0002</td>
</tr>
<tr>
<td>CSIM Spectral Integration</td>
<td>W/m²</td>
<td>100</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>0.14</strong></td>
</tr>
</tbody>
</table>
Full Spectrum Irradiance Validation

**TSIS SIM**

- Channel A Calibrated, Mean Offset = $-0.01 \pm 0.12\%$
- Channel B Calibrated, Mean Offset = $0.02 \pm 0.21\%$
- Channel C Calibrated, Mean Offset = $-0.01 \pm 0.18\%$

![Graph showing the difference from Cryo in different wavelength ranges for various channels with error bars.](image-url)
**TSIS SIM First Light Comparison**

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

*Integrated SSI contribution outside 205-2390 nm*

- **SIM Spectral range covers ~ 96% of TSI**
  - TSIS SIM (3-5 Mar. 2018)
  - SORCE SIM (28 Feb. 2018)

**TSIS & SORCE SSI overlap began March 2018 and will continue for 1 year (SORCE EOM scheduled 2019)**
First Light Spectrum (200 - 300 nm)

4 March 2018

4 March 2018
TSIS is lower in the near-IR by 2-6% (between 1000 and 2400 nm). TSIS is higher in the VIS by ~0.5 %.
Differences from TSIS can reach +/- 5% in the UV.

First Light: TSIS – SORCE SSI Differences

SORCE SSI
SOLSTICE SSI
< 310 nm
SIM
> 310 nm
First Light: Brightness Temperature

Brightness Temperature [K°]

wavelength [nm]

ΔTB=200K

SOLAR-ISS 2018
SORCE SIM (uncorr.)
SIRS WHI
ATLAS-3
TSIS
Solar irradiance variability models estimate time-dependent variability against a static, baseline, “Quiet Sun” (i.e. low solar activity) reference spectrum.

The NRLSSI2 reference spectrum is developed from the LASP WHI spectrum and the ATLAS-3 composite.
Adjustments to the NRLSSI2 reference spectrum were made to within the magnitudes of the individual datasets (reported as 2-3% at wavelengths > 300 nm). 

TSIS is lower in the near-IR by up to 4% (between 1500 and 2000 nm). 

TSIS is higher in the VIS by ~1-2 %. 

Comparison at wavelengths < 300 nm are dominated by noise (slight wavelength shifts?) in the NRLSSI2 reference as a result of the adjustment process.
**Solar Exposure Degradation**

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

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

*Next Channel C exposure planned for April 2019*
After SORCE End-of-mission, there will be a gap in full-spectrum SSI measurements between 100-200 nm, necessitating the use of models, like NRLSSI2, to provide spectral & temporal variability.
New and Future UV Datasets

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

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

GOES-17 launched March 2018

Compact SOLSTICE (CSOL) 2U CubeSat
115-310 nm
Calibration Underflight June 2018
To be mounted on INSPIRESat-3 for launch in 2021
CSIM First Light – TSIS SIM Comparison

CSIM First Light UV Scans

- CSIM CHA
- CSIM CHB
- TSIS

CSIM A/B Data Preliminary
Summary

- **TSIS-1 is performing as expected thus far.**

- **Repeatability**: TSIS SIM is measuring smaller changes in SSI than previous sensors.

- **Accuracy**: Pre-launch measurement uncertainties validated in LASP SRF to 0.2% absolute accuracy

- **Stability**: 2nd “C” channel measurement period in April 2019 (for degradation monitoring & correction)

- **In development**: Time-dependent on-orbit measurement uncertainties and a TSIS SIM ‘reference’ spectrum.

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