Measured solar spectral irradiance variability using the SORCE SIM

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Discussion Topics

• Review of the SIM instrument
  – Detectors and spectral ranges, resolution, sampling
  – Instrument configuration

• The SIM measurement equation

• Sources of noise
  – ADC noise limited performance on photodiodes
  – Noise spectrum of the ESR

• Sources of irreversible time dependent degradation
  – Prism degradation – the dominant source of instrument sensitivity loss
  – Effects of spacecraft safe-hold events
Instrument Overview

- **Instrument Type:** Féry Prism Spectrometer
- **Wavelength Range:** 200-2400 nm
- **Wavelength Resolution:** 0.24-34 nm
- **Detector:** ESR, n-p silicon, InGaAs
- **Absolute Accuracy:** 2-8%
- **Relative Accuracy:** ~0.5-0.02% (210-2400 nm)
- **Long-term Accuracy:** 0.3-0.02%/yr (210-2400 nm)
- **Field of View:** 1.5x2.5° total
- **Pointing Accuracy/Knowledge:** 0.016°/0.008°
- **Mass:** 21.9 kg
- **Dimensions:** 88 x 40 x 19 cm
- **Orbit Average Power:** 17.5 W
- **Orbit Average Data Rate:** 1.5 kbits/s
- **Redundancy:** 2 Redundant Channels

\[
\lambda = 2423 \\
\int E(\lambda) \, d\lambda \approx 1324.49 \text{ Wm}^{-2} \\
\lambda = 201 \\
\approx 97.3\% \text{ of TSI} \\
\Leftrightarrow 36.32 \text{ Wm}^{-2} \text{ missing from TSI}
\]


Corrections based on measured telemetry

- No assumptions are made about magnitude, slope, or time dependent behavior of SSI.
- Method of degradation correction is similar to the method used to correct TSI instruments but done as a function of wavelength.
- Degradation Corrections:
  - Exposure-related prism transmission loss accounts for the majority of sensitivity loss in SIM
    - Correct by comparing two spectrometers at different exposure rates
    - These spectrometers are in the same, physical, chemical, and thermal environments, so instrument changes are common mode.
  - Non-exposure related effects from space and spacecraft environment must be handled independently from prism transmission.
    - Correct ESR gain changes through routine gain measurement experiments
    - Correct photodiode detectors by comparing with the ESR’s
    - Identify time periods when the instrument is affected by spacecraft disturbances
Instrument Configuration

SIM A: Cross section in dispersion direction (SIM B mirror image)

1/2° Solar Input Beam

- Stability of the ESR anchors the corrections for SIM
  - Energetic photons do not make it to the ESR
  - Input flux is very small (<60 μW)
  - Critical power replacement resistors and 7.1 V reference are radiation hard
  - Weekly ESR gain measurements test and correct the ‘softer’ ESR electronics

- Only one optical element to degrade through transmission loss

- Transmission loss probably arises from exposure of the prism to energetic solar photons:
  - Directly induce compositional changes in the first few monolayers of the glass
  - Transmission losses due to polymerization of trace amounts of organic materials on the surface
Fundamental SIM Measurement Equation

\[ E(\lambda) = \frac{\text{measuredDetectorCounts}(\lambda)}{\text{entranceApertureArea} \times \text{detectorResponseFunction}(\lambda) \times \text{spectralBandwidth}(\lambda) \times \text{OpticalTransmission}(\lambda) \, d\lambda} \quad \text{(units of Wm}^{-2}\text{nm}^{-1}) \]

**ESR Power (phase sensitive detection)**

\[ E_{\text{ESR}}(\lambda_s, t) = \frac{1}{A_{\text{slit}}(T)} \int \alpha(\lambda) \, Tr_0(\lambda) \, \Phi(\lambda) \, S(\lambda_s, \lambda) \, d\lambda \times \frac{1}{1 - a_{\text{ESR}} \exp(-\kappa(\lambda)C(t)) + (a_{\text{ESR}}) \exp\left(-\frac{\kappa(\lambda)C(t)}{2}\right)} \]

**Profile Integral**

\[ E_{\text{Diode}}(\lambda_s, t) = \frac{V_{\text{max}}}{M} \left\{ \frac{D - D_0}{R_f} \right\} \int A_{\text{slit}} \int R_s(\lambda, t, T) \, Tr_0(\lambda) \, \Phi(\lambda) \, S(\lambda_s, \lambda) \, d\lambda \times \frac{1}{1 - a_{\text{diode}} \exp(-\kappa(\lambda)C(t)) + (a_{\text{diode}}) \exp\left(-\frac{\kappa(\lambda)C(t)}{2}\right)} \]

**ORBIT Correction**

\[ \frac{1}{f_{\text{au}}} \times \frac{1}{f_{\text{doppler}}} \]

**Detector photocurrent**

**Exposure related degradation**

**Non-exposure related degradation**
## Sources of Uncertainty in the SIM Time Series

<table>
<thead>
<tr>
<th>Rank</th>
<th>Cause</th>
<th>Effect</th>
<th>Mitigation/magnitude of effect</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Short-term effects – do not accumulate with time</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Detector Noise</td>
<td>Ultimate limit of comparison of two spectra</td>
<td>ESR: $10^{-3}$ to $10^{-5}$ Diodes; $3 \times 10^{-3}$ to $5 \times 10^{-5}$</td>
</tr>
<tr>
<td>2</td>
<td>Spacecraft pointing</td>
<td>Local perturbation in prism transmission/wavelength shift</td>
<td>Can produce spurious noise on the order of 1%, problem fixed through data masking</td>
</tr>
<tr>
<td>3</td>
<td>Detector Temperature</td>
<td>Spurious structure to photodiode data (700-900 nm range)</td>
<td>Adds about 500 ppm of noise at these wavelengths, refinements needed in processing.</td>
</tr>
<tr>
<td>4</td>
<td>Prism Temperature</td>
<td>Wavelength shift</td>
<td>Corrected to ~$150$ ppm in data processing</td>
</tr>
<tr>
<td>5</td>
<td>Scattered light</td>
<td>Increases apparent irradiance – decreases contrast in ‘lines’</td>
<td>&lt;$100$ ppm in ESR, VIS, IR detectors, &lt;0.5% in UV photodiode, not corrected</td>
</tr>
<tr>
<td></td>
<td><strong>Long-term effects – accumulate with time</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Prism Transmission</td>
<td>Long-term reduction in instrument response.</td>
<td>Residual uncertainty 0.3-0.01%/yr</td>
</tr>
<tr>
<td>2</td>
<td>Optical alignment changes</td>
<td>Produces ‘jumps’ in the data at well-defined times</td>
<td>Problem significant after 2009/01/01 uncertainty ~0.1% in certain wavelength bands</td>
</tr>
<tr>
<td>3</td>
<td>Photodiode Radiant sensitivity</td>
<td>Reduction in photodiode sensitivity (750-950 nm range)</td>
<td>Comparisons to ESR; Comparable to diode noise ~$10^{-4}$</td>
</tr>
<tr>
<td>4</td>
<td>ESR servo gain degradation</td>
<td>Reduction in responsivity of the ESR detector</td>
<td>7 ppm/year, uncertainty ~1 ppm/year</td>
</tr>
</tbody>
</table>
Detector Noise
Short Term effects: ESR Detector Noise

- Noise spectrum invariant with time
- Other effects ($\lambda$-shift, roll effects) can reduce the effective precision of the measurement
  - Typical noise level ~ 4 nW, 50 sec half cycle, 2 cycles
Short Term effects: Photodiode Noise

- Photodiode noise determined by noise on the ADC - not photon noise.
  - Output of photodiode detectors multiplex and read-out by the same ADC, therefore noise level is common to all photodiode detectors.

- Noise levels have not changed over the course of the mission, independent of where in the orbit the spectrum is taken (i.e. no SAA effects)

- Distribution of noise independent of whether shutter is opened or closed.
  - Determined from daily darks and 2005/2006 fixed wavelength experiments
Noise Equivalent Irradiance

Contours of signal-to-noise ratio are relative to the ESR 50 sec half-cycle, 200 sec integration.
Prism Degradation
Working assumption for prism/ESR degradation correction

- **Degradation is proportional to exposure**
  - SIM B has only ~1/4 of the exposure of SIM A
  - A function $F(t)$ can be found that produces the same trends in A&B channels
    - This is reasonable since the two instruments are in the same physical enclosure and their environment cannot evolve independently
Lambert's Law: \[ I(\lambda) = E(\lambda) e^{-\tau} \]

For a single wavelength, \( \lambda \). At two times 0 and 1.

\[
\ln(I_{A0}) = \ln(E_0) - \tau_{A0}, \quad \ln(I_{A1}) = \ln(E_1) - \tau_{A1}
\]
\[
\ln(I_{B0}) = \ln(E_0) - \tau_{B0}, \quad \ln(I_{B1}) = \ln(E_1) - \tau_{B1}
\]

Combine and recase equations for SIM A & B in terms of measured quantities:

For SIM A: \[
\ln \left( \frac{I_{A1}}{I_{A0}} \right) = \ln \left( \frac{E_1}{E_0} \right) - F(t) \cdot \Delta X_{A0\rightarrow A1}
\]

For SIM B: \[
\ln \left( \frac{I_{B1}}{I_{B0}} \right) = \ln \left( \frac{E_1}{E_0} \right) - F(t) \cdot \Delta X_{B0\rightarrow B1}
\]

\[ F(t) = \text{Time dependent degradation factor} \]
\[ \Delta X_{A0\rightarrow A1} \text{ or } \Delta X_{B0\rightarrow B1} = \text{Measured exposure time between times } t=0 \text{ and } t=1 \]
Determination of the Degradation Function

\[
F = \frac{\ln \left( \frac{I_{B1}}{I_{B0}} \right) - \ln \left( \frac{I_{A1}}{I_{A0}} \right)}{\Delta X_{A_{0\rightarrow1}} - \Delta X_{B_{0\rightarrow1}}}
\]

Degradation accumulates with time and must be determined for each wavelength.

\[
\tau_A(\lambda, t_1 - t_0) = \int_{t_0}^{t_1} F(\lambda, t') \frac{\partial X_{A_{0\rightarrow1}}}{\partial t'} dt + \text{Const.}
\]

(analogous for SIM B)

Decompose \( \tau(\lambda, t_1 - t_0) \) into two components:

- \( C(t_1 - t_0) \) a time dependent part
- \( \kappa(\lambda) \) a wavelength dependent part

Then:

\[
\tau_{A_{orb}}(\lambda, t_1 - t_0) = \kappa(\lambda)C_{A_{orb}}(t_1 - t_0)
\]

The degradation correction is:

\[
E_{A_{orb}}(\lambda, t) = \frac{I_{A_{orb}}(\lambda, t)}{\exp(-\kappa(\lambda)C_{A_{orb}}(t_1 - t_0))}
\]
Time Series of Degradation Corrected Irradiance

- Perturb the value of $\kappa(\lambda)$, apply to both SIM A & B
- Time series for the two instruments will diverge because the rates of exposure are different
  - Provides a method to estimate the uncertainty in $\kappa(\lambda)$

\[
\frac{\Delta \tau}{\tau} = \frac{\Delta \kappa}{\kappa} \quad \frac{\Delta \kappa}{\kappa} \leq 0.02 \quad (\pm 2\sigma)
\]

\[
\frac{\Delta E_{\text{degradation}}}{E} = \Delta \tau = \kappa(\lambda) \left( C_{t_1} - C_{t_0} \right) \frac{\Delta \kappa}{\kappa}
\]
Contributions of Uncertainty to trend

- Time range 2004/06/1-2007/11/15, 1262 days, 3.45 years
- $\Delta N_{\text{esr}} = 4nW$
Transfer ESR correction onto adjacent photodiodes

\[
\frac{E_{\text{corrected}}}{E_{\text{uncorrected}}} = \left(1 - a_d\right) \exp(-\tau(\lambda, t)) + a_d \exp\left(-\frac{\tau(\lambda, t)}{2}\right)
\]

- No pristine area on the surface of the prism and different light paths through the prism encounter different amounts of absorbing material.
- \(a_d\) initially estimated from ray traces and then adjusted to match the trends seen in the ESR.
Effects of OBC Anomalies and Wavelength Stability
SIM A: Cross Dispersion Direction

Date

\[ \gamma = (1 + \alpha) \gamma_z + \frac{1}{2} \tan^{-1}\left(\frac{(C - C_z) \times p \times (1 + \beta)}{F_{\text{REF}}}\right) \]

\[ n_{\text{vis}1} = \frac{1}{\sin(2\theta_p)} \sqrt{\sin^2(\gamma) + 2 \cos(2\theta_p) \sin(\gamma) \sin(\gamma - \phi) + \sin^2(\gamma - \phi)} \]
Status of SIM after October 2010

- 4 different safe-hold events since September 26, 2010 caused observatory temperatures to drop below -15°C producing small be noticeable changes in the responsivity of SIM.
  - The cause of these anomalies has been corrected in flight software

- Because of decreased battery capacity, power cycling on every orbit started on 2011/05/04
  - Power cycling has no instrument safety issues and has not disrupted normal data acquisition
  - Detectors have 3-5 degree temperature swings
  - Prism temperature drifts continuously (~1.5°C) but does not effect data processing
  - ~1 year of data may be needed to detect second order effects
Effects of SORCE Anomalies

- OBC events cause a change in the orientation of the steering mirror relative to prism face, wavelength correction performed but it re-maps the CCD pixels onto the wavelength scale.

Spacecraft Events

- 05/18/2007
- 01/09/2009
- 10/19/2009
- 10/14/2009
- 09/26/2010
- 12/26/2010
- 01/28/2011
- 05/13/2011
- 09/06/2011
Optical alignment changes

- Wavelength drive exhibits remarkable precision over very long time periods
  - Wavelength registration within the limits set by hardware
  - Cardinal wavelength step = 38 subpixel steps, precision ~ 1/38 of a step

±1 CCD subpixel = 0.7 arc-sec/subpixel
Current SIM Data Composite

- OBC anomalies after 2007 disrupt the continuity of the A-to-B data
- Spectra from the two channels are valid in a piecewise sense
- Connecting data sets after OBC events is a ‘compositing’ activity and induces discontinuous uncertainty beyond AB comparisons
- Alternate/improved methods are understudy to correct and effectively concatenate the pieces.
• No systematic slope through the data, suggests no common-mode degradation
Conclusions

• Long-term degradation corrections in SIM are based solely on measured instrument quantities.
  – Correction is based on the comparison of two identical (mirror image) spectrometers that have been exposed at different rates.
  – Corrections for photodiode detectors in the same channel are made by comparison with the spectrally flat ESR detector after correcting for the different optical paths through the prism.
  – Safe hold events decrease the precision after 2009, further work is underway to correct the influence of these events.
Additional Uncertainty Analyses
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Short Term effects: Scattered Light

- Scattered light contribution dominated by polish on prism (near-field scattering)
- Reflections from prism ⇒ cavity ⇒ detector (far-field scattering) are baffled in front of prism & in front of detectors.
- Scattered light cannot be detected above noise level of the instrument. No corrections made in data processing.
Short Term effects: Scattered Light

- At the same resolution feature depths match (though absolute scales differ) indicating little discernible scattered light in either instrument.
- Reflects fidelity in determination of the instrument profile integral.
Short Term effects: Temperature

- Index of refraction a function of temperature and effects wavelength reaching the detectors – if not corrected induces wavelength shift
  - Temperature of the prism(s) monitored and corrected continuously in data processing
- Radiant sensitivity is weakly temperature dependent – induces temperature structure in irradiance in the 900-1000 nm range
  - Processing includes a temperature correction, imprecision due to gradients between temperature sensor and the photodiode.
Short Term effects: Temperature

- Prism Temperature variation of ~1.2 °C
- \( P-p \) \( \lambda \) shift ~0.04 nm
- less than 1/4 of cardinal prism step.
- Corrected in data processing

- Residual structure in irradiance related to inaccurate corrections for diode temperature
- Adds uncertainty of <0.1% to determining long-term trend in the 900-1000 bands.
Short Term effects: Spacecraft Pointing

- Roll maneuvers contaminate only 2.8% of the viable science data
- Effects of rolls tend to preferentially effect data towards the end of scans but can effect any portion of the scan.
- Not all ‘spikes’ in the data are identifiable as caused by roll maneuvers and vice versa
  - ‘De-spike’ more practical than filtering: no correction made in data processing
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Long Term effects: ESR Gain

- Gain change discernable, but small
- Change in SIM B comparable to SIM A
  - \[ G_{\text{open}} = (68.541 \pm 0.018) + (-7.78 \pm 0.86) \times 10^{-5} \quad r^2 = 0.16238 \]
- Corrections made in data processing
Long Term effects: Photodiode Radiant Sensitivity changes

- High Energy Particle Spectrum
  - High energy particles (particularly protons) penetrate deep into the instrument case

- The majority of high energy particles will be protons
  - Shielding ineffective against proton penetration
Photodiode Radiant Sensitivity changes

Photon absorption is a necessary condition to produce a photoelectron.

The photoelectric effect occurs over a very broad depth scale:

Degradation processes at the skin will behave differently than the bulk processes.

Radiation damage in the base of the diode decreases $L_b$ (minority carrier diffusion length) and effectively moves $\alpha_{\text{max}}$ to shorter wavelengths (larger $\alpha$).

$L_{\text{skin}}$ dominates the diode's performance at the shorter wavelengths.

Radiation testing suggests p-n diode incurs greater damage than n-p:

- $\sim 100x >$ for electrons, $\sim 3x >$ for protons


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SIM Measurement Equation and Error Budget

\[ E(\lambda_s) = \frac{P_{ESR}(\lambda_s)}{A_{slit} \int \alpha_{\lambda} T_{\lambda} \Phi_{\lambda} S(\lambda, \lambda_s) d\lambda} \quad \text{or} \quad E(\lambda_s) = \frac{P_{detector}(\lambda_s)}{A_{slit} \int R_{\lambda} T_{\lambda} \Phi_{\lambda} S(\lambda, \lambda_s) d\lambda} \]

<table>
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<tr>
<th>Term (units)</th>
<th>Symbol</th>
<th>Value/Range</th>
<th>Uncertainty</th>
<th>Derived from:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength (nm)</td>
<td>(\lambda)</td>
<td>265-2423</td>
<td>0.2 ± (\lambda \times (150 \times 10^{-6}))</td>
<td>(\lambda) standards, solar spectrum</td>
</tr>
<tr>
<td>Power (watts) of the ESR</td>
<td>(P)</td>
<td>1×10^{-7} - 5×10^{-5}</td>
<td>~2×10^{-9} WHZ^{1/2}</td>
<td>Detector testing</td>
</tr>
<tr>
<td>Entrance slit area (mm²)</td>
<td>(A_{slit})</td>
<td>2.1</td>
<td>5×10^{-5}</td>
<td>Slit diffraction</td>
</tr>
<tr>
<td>ESR optical efficiency (%)</td>
<td>(\alpha_{\lambda})</td>
<td>100</td>
<td>+0 to -2 (200-1000 nm) +0 to -10 (1000-2700 nm)</td>
<td>SIRCUS, flight spare ESR (measured in power mode)</td>
</tr>
<tr>
<td>Photodiode radiant sensitivity (amps/watt)</td>
<td>(R_{\lambda})</td>
<td>0.08 -1.0</td>
<td>2-4% (wavelength dependent)</td>
<td>Comparisons with ESR</td>
</tr>
<tr>
<td>Prism transmission (%)</td>
<td>(T_{\lambda})</td>
<td>0.55-0.77</td>
<td>±0.1% 200-700 nm ≥ ±1% 700-2700 nm</td>
<td>Laboratory measurements (see Harder et al, 2005a)</td>
</tr>
<tr>
<td>Diffraction loss (%)</td>
<td>(\Phi_{\lambda})</td>
<td>0.3-2.2</td>
<td>~0.01</td>
<td>Diffraction theory</td>
</tr>
<tr>
<td>Instrument function area (nm)</td>
<td>(S)</td>
<td>0.58-34.5</td>
<td>~0.4%</td>
<td>Ray tracing, laser scans</td>
</tr>
</tbody>
</table>

Time series of solar spectral variability from SORCE

Integrated SIM 200-2423 nm: 1324.49 W m$^{-2}$
TSI (T1M): 1260.81 W m$^{-2}$

Precision estimate on integrated SIM:
$1\sigma$ = $\sim$0.2 W m$^{-2}$ ($\sim$130 ppm)

Decreasing trend with decreasing solar activity

Increasing trend with decreasing solar activity

TSI-like • further refinements in diode degradation needed

Increasing trend with decreasing solar activity • neutral by $\sim$2000 nm