Intercomparing Solar Spectral Irradiance From SORCE SIM

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Abstract

We compare solar spectral irradiance (SSI) measurements obtained from the Spectral Irradiance Monitor (SIM) on board the Solar Radiation and Climate Experiment (SORCE), corrected for instrument degradation using three different methods; SIM Version 25, Multiple Same-Irradiance-Level and SIM constrained Version 2 (SIMc V2), to quantify their differences and gain understanding about the relative performance of each method. Furthermore, we compare the three data sets to independent SSI observations that include the SORCE SIM successor Total and Spectral Solar Irradiance Sensor SIM and solar irradiance models. While we find agreement between the SSI for the three correction methods for wavelengths in the visible, differences persist for shorter and longer wavelengths, on time scales on the order of the 11-year solar cycle. The comparisons to independent SSI observations reveal remaining instrument trends in some of the corrected SORCE SIM data.

1. Introduction

Observing changes in the Sun’s irradiance is important to quantify its effect on our climate. While observations of total solar irradiance (TSI) inform us about the total energy received by Earth, measurements of solar spectral irradiance (SSI) inform us how this energy is spectrally distributed. Hence, measuring SSI, combined with the wavelength-dependent optical properties of Earth’s atmosphere, ocean, and land masses, allows us to infer where solar energy is absorbed on Earth (Ermolli et al., 2013; Gray et al., 2010; Haigh, 1994; Haigh et al., 2010). This provides clues on how the atmosphere and climate respond to changes in solar irradiance. Changes in TSI and SSI follow an 11-year solar cycle with the Sun transitioning between quiescent and active states that are manifested by the absence or presence of faculae and sunspots. Due to the Sun’s rotational period of ~27 days, there is a secondary 27-day solar cycle dominated by sunspots rotating in and out of the visible solar disk. On time scales on the order of the 11-year solar cycle, TSI varies by about 0.1% (Kopp, 2016). SSI variability is wavelength dependent with greatest variability in the ultraviolet (UV: <400 nm). Near 200 nm, solar cycle variability may be as high as 6%, while in the visible (VIS: 400–700 nm) and near infrared (NIR: >700 nm) it is less than 0.1% (Gray et al., 2010). To detect these small changes on decadal time scales, instruments require high long-term stability, which in turn requires accurate correction of unavoidable instrument degradation. The main source of this instrument degradation is related to hydrocarbons that originate from outgassing of the materials used to build the instruments. These hydrocarbons contaminate optical surfaces and can become polymerized by unfiltered solar UV and X-ray radiation. The resulting layer can grow throughout the mission as outgassing progresses, decreasing the transmittance through optical elements such as lenses, filters, or prisms. Correcting for this degradation process currently poses the largest uncertainties in measured solar variability on decadal and longer time scales and typically relies on assumptions that are challenging to validate. An extensive overview of degradation in solar instruments is given by BenMoussa et al. (2013).

In this study, we present a comparison of three degradation-correction methods for instrument degradation in the Spectral Irradiance Monitor (SIM) (Harder et al., 2005) on board the Solar Radiation and Climate Experiment (SORCE) (Rottman, 2005). The corrected SSI data sets are compared to each other and to independent SSI observations from the AURA Ozone Monitoring Instrument (OMI) (Levelt et al., 2006), SORCE Solar Stellar Irradiance Comparison Experiment (SOLSTICE) (McClimont et al., 2005), and Total and Spectral Solar Irradiance Sensor (TSIS) SIM (Carlisle et al., 2015; Pilewskie et al., 2018). Additionally, we compare the integrated SSI of SORCE SIM to TSI measurements from the SORCE Total Irradiance Monitor (TIM) (Kopp, 2014). Finally, we compare to the Naval Research Laboratory solar variability...
model for SSI (NRLSSI2) (Coddington et al., 2015) and Spectral And Total Irradiance REconstruction for the Satellite era (SATIRE-S) (Yeo et al., 2014) solar irradiance models.

2. Degradation Corrections of SORCE SIM

The SIM on board SORCE makes daily observations of SSI from 200 to 2,400 nm (Harder et al., 2005). The instrument utilizes a Féry prism that disperses the unfiltered, incoming sunlight and focuses it onto three photodiodes as well as an electrical substitution radiometer (ESR). The ESR, which makes a direct measurement of solar irradiance is primarily used to calibrate the photodiodes. The direct exposure of the prism to unfiltered solar radiation causes an ongoing reduction in prism transmission that is strongest in the UV (Harder et al., 2010; Mauceri et al., 2018). To correct for this degradation, SIM uses two identical instrument channels, with a separate prism in each channel, that are operated in an exposure duty cycle. While the primary Channel A is exposed daily, Channel B is exposed about 20% of the time of Channel A. A periscope that was intended to monitor in-flight changes in prism transmission (Harder et al., 2005) was found to introduce optical aberrations that rendered it ineffective. Currently, there are three SORCE SIM SSI data sets available, each employing a different method for degradation tracking and correction. In this study we compare SSI from all three methods in order to quantify their differences and gain understanding about the relative performance of each method.

2.1. SIM Version 25

The first correction we discuss is for the official SIM data product, SIM Version 25 (SIM V25), that is archived at the Goddard Earth Sciences Data and Information Services Center and provided at the SORCE web site. It uses the disagreement in coincident measurements of SSI from both SIM channels to derive a prism degradation that brings both channels into agreement. For the employed methodology, SIM V25 implicitly assumes that both channels of SORCE SIM are subjected to identical physical, chemical, and thermal environments such that their degradations can be described by the same underlying function (Béland et al., 2013). This function describes an exponentially decaying prism transmission that depends on accumulated exposure time ($t_A$), calendar time ($t_{cal}$), wavelength ($\lambda$), and sensor position ($i$). The equation for the prism degradation of Channel A, $\varepsilon_A(\lambda, t_A, t_{cal}, i)$, is given by

$$
\varepsilon_A(\lambda, t_A, t_{cal}, i) = \left[ (1-a(i, \lambda)) \exp(-\kappa(\lambda) t_A F(t_{cal}, \lambda)) + a(i, \lambda) \exp\left( -\frac{\kappa(\lambda) t_A F(t_{cal}, \lambda)}{2} \right) \right]^{-1} \quad (1)
$$

where $\kappa(\lambda)$ accounts for the wavelength-dependent attenuation of the prism degradation; $F(t_{cal}, \lambda)$ is the calendar time dependency of the prism degradation; and $t_A$ is the accumulated exposure time of Channel A. Channel B degradation, $\varepsilon_B$, is identical to equation (1) except the Channel B accumulated exposure time, $t_B$, replaces $t_A$. As a result of the nonuniform exposure of the prism surface, SIM V25 further assumes that the contamination on the prism is not uniform. Taking this into account, equation (1) contains the parameter $a(i, \lambda)$, which is the fraction of solar radiation that passes through the contaminated surface, when it enters the prism but exits through an “unobscured” part of the prism surface (Béland et al., 2014). The remaining fraction of the radiation enters and exits through the contaminated prism surface. If all solar radiation would pass through the contaminated prism surface twice, $a(i, \lambda)$ would be 0. Therefore, $a(i, \lambda)$ depends on the angle of the prism as well as the position of the individual detectors.

To derive all model parameters shown in equation (1), multiple fits are performed iteratively to bring the corrected, simultaneous irradiance measurements of Channels A and B into agreement. First, $\kappa(\lambda)$ is derived. To do this, $F(t_{cal}, \lambda)$ is set to 1 and $a(i, \lambda)$ is determined from ray tracing simulations. Then, $\kappa(\lambda)$ is determined by minimizing the difference in uncorrected irradiance measured by the corresponding photodiodes in Channel A, $A_i$, and Channel B, $B_i$. Only measurements between 2004 and 2007 are considered. In contrast to later observations, these measurements were not disturbed by “safe hold” events that interrupted the nominal instrument operation. If the instrument degradation could be described by an exponential function of wavelength and accumulated exposure time, the correction process would be complete. However, there are remaining systematic differences between the Channels A and B measurements. Therefore, SIM V25 fits a second parameter, $F(t_{cal}, \lambda)$, with a third-order polynomial as a function of calendar time for irradiance at every wavelength. This further minimizes the remaining residual between Channels A and B. The
previously derived \( \kappa(\lambda) \) and \( a(i, \lambda) \) stays fixed. Then, parameter \( a(i, \lambda) \) is adjusted by minimizing the slope of the difference between the corrected irradiance from both channels, at each wavelength from 2004 to 2007. The adjusted parameter \( a(i, \lambda) \) for the UV diode varies between 0.05 and 0.15 and for the VIS diode, between 0.16 and 0.17. Finally, the photodiode degradation is determined from comparisons between corrected ESR and photodiode irradiance measurements. After the multiple fits and corrections are performed, the uncertainties are derived from the remaining difference between the corrected measurements from Channels A and B (Béland et al., 2013).

SIM V25 is available from 240 to 2,400 nm with daily SSI from May 2003 to present. The sampling resolution varies from about 0.1 nm in the UV to about 5 nm in the NIR. SIM V25 can be found at this site (http://lasp.colorado.edu/lisird/). The latest iteration from Version 24 to Version 25 updated the temperature correction of the diodes, improved the wavelength alignment, and revised how the calendar time component and solar exposure component of the degradation are combined in the processing code (Laboratory for Atmospheric and Space Physics, 2019).

### 2.2. MuSIL

The Multiple Same-Irradiance-Level (MuSIL) method (Woods et al., 2018) identifies non–solar cycle trending and is applied to the Level 3 SORCE SIM V25 data. Assuming that there is no significant long-term solar variability trend with periods longer than the 11-year solar cycle, the MuSIL trends represent uncorrected instrument trends in the previously corrected SSI observations. These trends represent residual degradation or recovery trends in addition to those previously corrected by the instrument teams. The key assumption of the MuSIL method is that SSI is the same for identical levels of solar activity, as represented by a normalized mean of multiple solar proxies, called a super proxy (Woods et al., 2018). The super proxy is derived in equal fractions from the sunspot number (SSN), which describes the number of sunspots on the visible solar disk; Magnesium II index (Mg II) core-to- wing ratio at 280 nm (Viereck et al., 2001); Lyman-alpha (Ly-\( \alpha \)) irradiance at 121 nm (Woods et al., 2000); and the F10.7 radio flux (Tapping, 2013). All solar proxies are normalized such that their respective minimum and maximum values in the period from 1980 to 2017, fall between 0 and 100. The super proxy is then calculated by taking the average of the four normalized solar proxies. A piecewise linear fit of the SSI selected at times when the super proxy is at the same level provides an additional instrument degradation correction that once applied to the selected SSI points, makes its long-term trend flat (Woods et al., 2018).

The SORCE SIM MuSIL-corrected SSI can be found at this site (http://lasp.colorado.edu/lisird/). It has a wavelength range from 240 to 1,600 nm at the SIM sampling resolution and contains daily SSI from May 2003 to present. Note that MuSIL requires to extrapolate its correction for the current solar cycle minimum. Thus, trends in the SSI after 2018 have to be interpreted with caution.

### 2.3. SIMc Version 2

SIM constrained Version 2 (SIMc V2) corrects the uncorrected Level 1 irradiance measurements of SORCE SIM by matching the relative change in integrated SSI to an independent measure of TSI by the SORCE TIM instrument (Mauceri et al., 2018). This can be done independently for Channels A and B and makes no assumption of the degradation following the same functional form in both channels or being dependent on accumulated exposure or calendar time. However, the correction method assumes that the SORCE SIM instrument degradation can be described as a smooth function in time and wavelength that is not forced to follow an exponential or any other predefined functional form. Furthermore, SIMc V2 does not differentiate in its correction between the degradation of the prism, the photo diodes or the ESRs. The correction for the uncorrected irradiance in Channel A is given by

\[
\varepsilon_A(\lambda, t_{\text{cal}}) = \frac{\Delta A_u(\lambda, t_{\text{cal}})}{\Delta TSI^{S-F}(t_{\text{cal}})} \frac{\Delta TSI^{S-T}(t_{\text{cal}})}{\int_{205\text{nm}}^{2300\text{nm}} \Delta A_u(\lambda, t_{\text{cal}}) d\lambda} \tag{2}
\]

with \( \Delta A_u(\lambda, t_{\text{cal}}) \) being the change in irradiance to a reference date \( t_0 \) and \( \Delta TSI^{S-F}(t_{\text{cal}}) \) describing the difference in the change of integrated SSI and TSI to the same reference date. \( \Delta A_u(\lambda, t_{\text{cal}}) \) and \( \Delta TSI^{S-F}(t_{\text{cal}}) \) are calculated by
with \( TSI_{\text{cal}}(t_0) \) representing the integrated, uncorrected SSI measured by SORCE SIM at the end of 2004. \( TS_{\text{cal}}(t_0) \) is the same integrated, uncorrected SSI but for a given day in the mission that we wish to correct. \( TSI^T(t_\text{cal}) \) and \( TSI^T(t_\text{cal}) \) are the corrected and calibrated TSI by SORCE TIM for the reference date and the date we wish to correct our SORCE SIM measurements, respectively. The attribution to the individual wavelengths is performed proportional to their relative change to the reference day. As shown in Mauceri et al. (2018), comparing TSI variability to integrated SSI variability from 205 to 2,300 nm is a valid option since the integrated SSI over this wavelength band captures most of the total solar variability. The uncertainty for the SIMc V2 trending results is time and wavelength dependent. The time average is ~0.1% per year from 205 to 300 nm, 0.03% per year from 300 to 400 nm and 0.01% per year for wavelengths ranging from 400 to 2,375 nm. In comparison to Version 1, Version 2 of SIMc has a larger wavelength range from 205 to 2,375 nm and interpolates measurements in time for wavelengths between 1,550 and 2,375 nm to fill gaps in the observational record. Furthermore, Version 2 extends from September 2004 to August 2019. SORCE SIM observations before September 2004 have large uncertainties in their wavelength scale and were omitted from the data set (Mauceri et al., 2018). Finally, Version 2 is absolutely adjusted to match TSIS SIM, while Version 1 is adjusted to match the solar irradiance reference spectra whole heliosphere interval (SIRS WHI) reference spectrum (Woods et al., 2009). The adjustment of Version 2 is derived from a period of coinciding SSI observations from both instruments between April 2018 and April 2019. SIMc V2 can be found at this site (http://lasp.colorado.edu/lisird/).

3. Comparisons

To quantify differences between the three correction approaches, we compare their resulting corrected spectral irradiances. Furthermore, we compare to observations from other instruments and to solar irradiance models. For ease of comparison, a summary of the three correction approaches is provided in Table 1.

3.1. SSI

We first compare the degradation-corrected SSI derived from SIM V25, MuSIL, and SIMc V2 to each other and then to measurements from TSIS SIM, SORCE SOLSTICE, and AURA OMI. TSIS SIM is the successor to SORCE SIM and started operations in February 2018. It measures daily SSI from 200–2,400 nm and utilizes three instrument channels for degradation tracking. Each instrument channel employs a Féry prism to disperse the incoming solar radiation onto three photodiodes and an ESR. The spectral resolution of TSIS SIM is wavelength dependent and ranges from 1 nm in the UV to 35 nm in NIR. The three instrument channels are operated at varying duty cycles with the primary channel being exposed daily, the secondary channel 10% of the primary channel, and the tertiary channel just twice a year. Degradation correction is performed by bringing the observed SSI from the three instrument channels into agreement with piecewise linear fits. The correction method is different to SIM V25 and does not prescribe an exponential degradation model. For its absolute calibration TSIS SIM is adjusted to match a National Institute of Standards and Technology-traceable radiometric reference standard. We make use of the latest available data, Version 3, which can be found online (http://lasp.colorado.edu/lisird/). SOLSTICE (McClintock et al., 2005) and OMI AURA (Levett et al., 2006) acquire SSI from 115 to 320 and 264 to 504 nm, respectively. OMI, operating since mid-2004, is a backscatter spectrometer used primarily for deriving trace gas concentrations in Earth’s atmosphere. To calibrate and monitor solar absorption features, OMI performs daily SSI measurements. For degradation tracking, three diffusers are employed that are operated at different duty cycles. We make use of OMI’s SSI Version/Date: 20180328 that is described in Marchenko and Deland (2014), Marchenko, DeLand, et al. (2016) and Marchenko, Woods, et al. (2019) and can be found at this site (https://sbuv2.gsfc.nasa.gov/solar/omi/). The data differ from that published in 2016, in that it adopted a time-dependent exponential degradation model that forces consistent irradiance levels at solar minima (Marchenko & DeLand, 2018). The estimated stability for OMI is 0.2% per year (Marchenko et al., 2016). SOLSTICE, on board SORCE,
Table 1

Comparison of Three Methods to Correct for Instrument Degradation in SORCE SIM Observations

| Method                                      | SIM V2                  | MuSIL                  | SIMc V2                |
|---------------------------------------------|-------------------------|------------------------|------------------------|
| Wavelength range resolution                 | 240–2,400 nm 0.1 nm (UV) to 5 nm (NIR) | 240–1,600 nm 0.1 nm (UV) to 5 nm (NIR) | 205–2,375 nm 0.5 nm (UV) to 30 nm (NIR) |
| Time range resolution                       | 2003.4 to present daily | 2003.4 to present daily | 2004.7 to present daily |
| Assumptions                                 | Degradation is caused by direct solar radiation of contaminants on the prism that lead to a reduction of the prism transmittance depending on accumulated solar exposure, calendar time, sensor position, and wavelength. | The mean of four normalized solar proxies (SSN, Mg II, Ly-a, and F10.7) are smoothed over 27 days and averaged to make the “super proxy” to be the measure of solar cycle activity. | Differences in integrated SSI from SORCE SIM and TSI by SORCE TIM are attributed to degradation in SIM. |
|                                          |                         |                        |                        |
| Prism surface is not evenly illuminated and thus not evenly degraded | The 27-day smoothed SSI selected at the same level of solar activity have the same SSI values. | Degradation is a smooth function of time and wavelength. | Contribution to solar cycle variability of TSI from wavelengths below 205 nm and above 2,375 nm is small. |
| Functional form of prism degradation follows an exponential trend | The trends of the selected SSI points are described by a piecewise linear fit. | Degradation is large compared to 11-year solar cycle variability at a given wavelength. | No assumptions regarding the cause of the instrument degradation. |
| Degradation in Channel A and Channel B follows the same functional form | Deviations from a flat trend for the selected SSI points represent additional degradation/recovery for the instrument. | No assumptions regarding the cause of the instrument degradation. | |
| ESR has no degradation                      |                         |                        |                        |
| Diodes degrade as a function of mission time and are corrected with ESR-diode cross calibrations | No assumptions regarding the cause of the instrument degradation. | No assumptions regarding the cause of the instrument degradation. | |
| Degradation correction method               | Differences between simultaneous SSI measurements from Channel A and Channel B are minimized by fitting an exponential as a function of wavelength, exposure time, calendar time, and sensor position to the degradation and correcting for it. | The piecewise linear fit of SSI observations selected at the same solar activity level, indicated by the super proxy, poses remaining instrument artifacts and are adjusted to be flat. MuSIL trending analysis is done at each wavelength independently. | Changes in the long-term trend of integrated SSI are adjusted to match changes in the long-term trend of TSI. |
| Absolute calibration                        | Preflight calibration is adjusted with a smooth wavelength-dependent offset to minimize differences to the ATLAS-3 spectrum. | Inherits calibration from SIM V2 | Adjusted to match the first year of overlapping observations with TSIS SIM. |

Note: “Correction Method” and “Assumptions” are not complete lists but summarize their respective key points from section 2.

performs SSI measurements in the UV at 1-nm spectral resolution every 6 hr (McClintock et al., 2005). Degradation tracking of SOLSTICE uses in-flight calibrations to stars and redundant SOLSTICE channels. Thus, SOLSTICE degradation tracking is independent to SORCE SIM. The estimated stability for SOLSTICE is 0.5% per year as well (Snow et al., 2005). We make use of the latest available data, Version 16, which can be found at this site (http://lasp.colorado.edu/lisird/).

To compare the degradation-corrected SSI derived from SIM V25, MuSIL, and SIMc V2, we bin the SSI into five wavelength bands, 240–300, 300–400, 400–700, 700–1,000, and 1,000–1,600 nm, similar to that done by Harder et al. (2009). A comparison from May 2003 to October 2019 relative to 2009 is shown in Figure 1. For the shortest wavelength band, we find large differences between all three data sets with SIM V25 having the steepest decline in irradiance (~0.5% per year) for the declining phase of Solar Cycle (SC) 23 followed by MuSIL (~0.2% per year) and SIMc V2 (~0.1% per year). For the rising phase of SC 24 we find the steepest incline for MuSIL (0.09% per year). SIM V25 and SIMc V2 show close agreement for this phase with their slopes being about half that of MuSIL (0.05% per year and 0.04% per year, respectively). For the wavelength band from 300–400 nm we find closer agreement between MuSIL and SIMc V2 (1σ:0.07%) than either with SIM V25 (1σ:0.18%). Again, SIM V25 reproduces the steepest decline in SC 23 (~0.15% per year). From 400–700 nm we find close agreement between the corrected SSI from all three methods (1σ:<0.04%). This can be
attributed in part to less optical degradation at these wavelengths (less than: 5% in the VIS) than at shorter wavelengths (more than 20% at 214 nm) (Mauceri et al., 2018). For 700–1,000 and 1,000–1,600 nm SIMc V2 and MuSIL reproduce each other closely, while SIM V25 reproduces an upward and downward trend for the two wavelength bands after 2015, respectively. The discrepancies at these longer wavelengths are unexpected since degradation in the NIR is small (less than 1%) compared to shorter wavelengths. Note that trends before May 2004, most visible in MuSIL at 300–400 nm, are likely caused by problems with the wavelength alignment of SORCE SIM for this period.

A comparison for the same wavelength bands to TSIS SIM is shown in Figure 2 starting in 2018. The SSI is shown relative to the first 81 days of observations from TSIS SIM. Upper uncertainty bounds in the trending of TSIS SIM are shown with gray bars for wavelengths shorter than 1,000 nm. For the 1,000–1,600 nm wavelength band TSIS SIM is found to not degrade and the error bars show the 3σ instrument precision. For the 240–300 nm range SIM V25 exhibits a systematic downward trend of −0.3% per year, not present in TSIS SIM (0.02% per year), or SIMc V2 (0.02% per year) that exceeding TSIS SIM uncertainties. MuSIL shows a similar downward trend than SIM V25 until January 2019. Afterward, MuSIL shows a steep upward trend that

![Figure 1](https://example.com/figure1.png)

Figure 1. Comparison of SIMc V2, MuSIL, and SIM V25 for five integrated wavelength bands from May 2003 to October 2019. Shown is the relative difference from the mean in 1 January 2009 ± 15 days in (%). (the scale of the y axis differs for each subplot).
might be a result of the MuSIL technique needing to extrapolate during solar cycle minimum. For 300–400 nm SIM V25 trends upward with 0.12% per year followed by MuSIL with 0.07% per year. TSIS SIM and SIMc show a trend that is closer to zero with −0.04% and 0.01% per year, respectively. Differences between SIM V25 and MuSIL with respect to TSIS SIM stay mostly within the TSIS SIM uncertainties for wavelengths longer than 400 nm until early 2019. After 2019 the differences exceed TSIS SIM uncertainties. Differences between SIMc V2 and TSIS SIM stay within the TSIS SIM uncertainties for the five shown wavelength bands.

A second comparison of the trending of the three SORCE SIM data sets to TSIS SIM is shown in Figure 3. Here we compare the linear fit from April 2018 to April 2019 for SSI at every wavelength separately. Since this period covers the current solar cycle minimum, we expect all fits to be close to zero. The linear fits of TSIS SIM and SIMc V2 are close to 0 across the spectrum with the exception of wavelengths shorter than 215 nm. MuSIL is mostly flat for wavelengths longer than 350 nm. Shorter wavelengths are marked by rapid changes in their slope for neighboring wavelengths, exceeding 1% per year for some wavelengths. The same holds true for SIM V25 in this wavelength range. For wavelengths ranging from 300 to 400 and 800 to 950 nm SIM V25 exhibits an upward trend, that exceeds TSIS SIM uncertainties, with a maximum of 0.5% per year near 300 nm. For 600–770 nm SIM V25 follows a downward trend of −0.1% per year.

**Figure 2.** Comparison of SIMc V2, MuSIL, SIM V25, and TSIS SIM for four wavelength bands from January 2018 to September 2019. Shown is the relative difference to the first 81 days of TSIS SIM observations (February 2018 to April 2018) in (%). (the scale of the y axis differs for each subplot).
On an absolute scale SORCE SIM V25 and MuSIL agree closely (see Figure 4) with each other and show significant differences to TSIS SIM. SIMc V2 is absolutely adjusted to TSIS SIM and therefore nearly identical.

To show how SIMc V2 differs on an absolute scale to SIMc V1, we also compare to SIMc V1. For wavelengths shorter than 305 nm SIM V25 and MuSIL are higher than TSIS SIM which amount to ~0.6 W m$^{-2}$. For 305–360 nm SIM V25 and MuSIL are lower than TSIS SIM by about −0.7 W m$^{-2}$. For 850–1,600 nm both data sets are 10 W m$^{-2}$ higher than TSIS SIM. Compared to TSIS SIM, SIMc V1 is 8 W m$^{-2}$ higher for the integrated SSI from 1,000 to 2,375 nm and −0.6 W m$^{-2}$ lower for 205–305 nm. Since SIMc V1 is calibrated with the SIRS WHI reference spectrum, the comparison indirectly compares SIRS WHI to TSIS SIM.

Comparing the three SORCE SIM data sets to SORCE SOLSTICE and AURA OMI, SIM V25 shows again the steepest downward slope for the declining phase of SC 23 for the 265–300 nm range (see Figure 5). For SC 24, MuSIL’s solar cycle variability is about twice that of any of the other SSI data sets. For the declining phase of SC 23, variability in SORCE SOLSTICE is similar to MuSIL. SIMc V2 solar cycle variability (0.7% for SC 24) shows close agreement with SORCE SOLSTICE (0.7% for SC 24) and is almost twice that of AURA OMI (0.4% for SC 24). For the 300–500 nm wavelength band AURA OMI shows significantly less solar cycle variability, compared to the other three data sets, all based on SORCE SIM observations.

### 3.2. TSI

The three integrated SSI data sets are compared to TSI from SORCE TIM (Kopp & Lawrence, 2005). TIM uses four ESRs that are operated in pairs. For a TSI measurement, one ESR is exposed to solar irradiance...
while the others are kept shuttered. The exposed ESR is coupled with a shuttered ESR and held in thermal equilibrium by electronic heaters. The difference in electrical power required to keep both ESRs in thermal equilibrium, together with the known entrance slit area of the TIM, is a direct measurement of TSI (Kopp et al., 2005; Kopp & Lawrence, 2005). The long-term stability is 10 ppm per year (Kopp, 2014). Although agreement between integrated SSI and SORCE TIM TSI is insufficient for validation because spectral anomalies of varying sign may compensate across the spectrum, disagreement may indicate residual uncorrected instrument trends in the data sets. None of the three data sets measure the full solar spectrum as is done by SORCE TIM. However, the integrated SSI between 240 and 1,600 nm, approximately 89% of the TSI, captures most of the solar cycle variability. To estimate the error due to the omission of variability from the unmeasured bands outside of 240–1,600 nm, we use the SATIRE-S solar model. For the last three solar cycles the solar cycle variability from 115–240 nm and 1.6 to 170 μm had a combined variability of 0.03 W m\(^{-2}\) or 20 ppm of TSI, in phase with solar activity on the 11-year solar cycle, that is, smaller than the long-term stability of TIM. It has to be noted that SIMc V2 is constrained by TSI but over a larger wavelength range (205 to 2,375 nm) (Mauceri et al., 2018).

As shown in Figure 6, there is a downward trend in MuSIL (−17 ± 1 ppm per year) and SIM V25 (−5 ±4 ppm per year) relative to TIM. SIMc V2 has an upward trend of +3 ± 1 ppm per year. The small difference between SIMc V2 TSI and SORCE TIM is expected as SORCE TIM is used directly for the SIMc V2 correction.

### 3.3. Solar Models

The three corrected SSI data sets are compared to two solar irradiance models, NRLSSI2 and SATIRE-S. NRLSSI2 (Coddington et al., 2015) estimates daily solar irradiance from 1882 to present day. The model is an updated version of empirical models established in a series of papers (Lean, 2000; Lean et al., 2005; Lean & Woods, 2010). The models derive solar irradiance from fitting the Mg II core-to-wing ratio (proxy for “faculae brightening”) and photometric sunspot index (proxy for “sunspot darkening”) to measurements of solar irradiance on solar rotation time scales (~27 days). SATIRE-S is a semiempirical model that directly relates magnetic activity from full-disk magnetograms to solar irradiance (Fligge et al., 2000; Krivova et al., 2003, 2006; Yeo et al., 2014). SATIRE-S reproduces SSI from 115 nm to 160 μm back to 1974. In contrast to NRLSSI2, SATIRE-S employs a radiative transfer model of the solar atmosphere composed of the quiet Sun,

![Figure 5. Comparison of SIM V25, SIMc V2, MuSIL, AURA OMI, and SORCE SOLSTICE for two wavelength bands from may 2003 to October 2019. Shown is the relative difference from the mean in 1 January 2009 ± 15 days in (%). (the scale of the y axis differs for each subplot).](image-url)
facula, and sunspots. Thus, the two models rely on different observations and different methodologies to derive SSI and can be considered independent to each other.

Regardless of the underlying methodology, there is still an ongoing debate in how far solar irradiance models reproduce true solar variability, particularly over single to multiple solar cycles. Multiple studies have shown disagreement between models and observations as well as disagreement between the models themselves (Lean & DeLand, 2012; Marchenko et al., 2016; Yeo et al., 2015). Nevertheless, we compare SIM V25, SIMc V2, and MuSIL to NRLSSI2 and SATIRE-S over five wavelength bands (see Figure 7).

For the 240- to 300-nm wavelength band the differences between SIM V25 and both solar models ($\sigma > 0.40\%$) and MuSIL and the models ($\sigma > 0.22\%$) is $\sim 4$ and 2 times that of SIMc V2 and the models ($\sigma > 0.09\%$). Compared to MuSIL, the solar models and SIMc V2 exhibit lesser variability by at least a factor of 2. Compared to SIM V25 the slope in the declining phase of SC 23 is less in either solar model by a factor of 4. For SC 24, both models agree with SIM V25 until 2016 ($\sigma < 0.17\%$ between 2009 and 2016), when they start to diverge. From 2017 to 2018 SIM V25 is on average 0.4% higher than both models. For the integrated SSI from 300–400 nm we find closer agreement between SIM V25 and the models between 2009 and 2016 ($\sigma < 0.09\%$). However, we note again a steeper downward trend in SIM V25 in the declining phase of SC 23. SIMc V2 agrees with the models over the whole period ($\sigma = 0.06\%$). MuSIL is in agreement with the two models at these wavelengths ($\sigma < 0.1\%$) but indicates a downward trend from 2015 to 2019 ($\sim 0.14\%$ per year), not present in the two models. For 400–700 nm we find close agreement between all SSI data sets ($\sigma < 0.04\%$). From 700 to 1,000 nm the solar models and corrected SORCE SIM observations overlap until 2012 when they start to diverge. Compared to the models, SIM V25 exhibits a systematic upward trend after 2012. For the longest wavelengths from 1,000–1,600 nm we note out-of-phase solar cycle variability for SIM V25 until 2015, not present in NRLSSI2 or SATIRE-S. After 2015, SIM V25 exhibits a downward trend relative to all other data sets.

Figure 6. Comparison of integrated SSI between 240 and 1,600 nm of SIMc V2, MuSIL, SIM V25, and TSI measured by SORCE TIM. (top) the points show daily and the lines the 360-day moving average in percent relative to 2009. (bottom) differences between SIMc V2, MuSIL, and SIM V25 with respect to TIM TSI, normalized to 2009 in percent. The three lines show a linear fit of these differences for the period from 2004.7 to 2019. *TIM TSI is measured over the full solar spectrum. We account for that by removing 156 W m$^{-2}$ before calculating its relative change in percent.
4. Discussion

During the descending phase of SC 23, SIM V25 reports the steepest downward trend in the two UV bands (240–300 and 300–400 nm), followed by MuSIL and SIMc V2. Our comparison to SSI observed by AURA OMI and SORCE SOLSTICE, and SSI modeled with the NRLSSI2 and SATIRE-S indicates that the steep downward slope in SC 23 exhibited by SIM V25 and, to a lesser extent, by MuSIL for the 240- to 300-nm wavelength band, is most likely residuals from uncorrected instrument degradation. Several other studies came to similar conclusion for data processing predecessors to SIM V25 (Ball et al., 2011; Ball et al., 2016; DeLand & Cebula, 2012; Ermolli et al., 2013; Gray et al., 2010; Haigh et al., 2010; Yeo et al., 2015).

To further analyze the downward trend in SC 23 together with the uncertainties of the individual data sets, we show the relative irradiance change between 2005 and 2009 for all five wavelength bands in Figure 8. For comparison, the discussed solar irradiance models as well as observations from SORCE SOLSTICE and SORCE TIM are also shown. For SIM V25, we rely on the stability estimates provided by Woods et al. (2018) of 0.03% per year.

At wavelength shorter than 400 nm, SIMc V2, MuSIL, and SIM V25 disagree outside their 2σ uncertainties. For wavelength longer than 400 nm the uncertainties of all three SSI data sets overlap.
4.1. SIM V25

The driving assumptions for the correction performed in SIM V25 are that the degradation of the prism follows an exponential, with dependencies on exposure time, calendar times, wavelength, and sensor position. Furthermore, it is assumed that both channels follow the same form of degradation, differing only by their respective exposure times. Multiple, unplanned events over the course of the SORCE mission draw into question the validity of exponential prism degradation, and even the assumption of identical functional forms of degradation in both channels. For example, a series of safe-hold events that caused temperatures to drop to as low as $-40 \, ^\circ\text{C}$ may have affected the alignment of the steering mirror for the charge-couple device (CCD); atypical solar pointing and, therefore, atypical exposure of the prism was caused by problems related to a reaction wheel; and degradation of the batteries forced the instrument to be powered only when the solar panels are exposed to sunlight, leading to temperature cycling during every orbit (Harder et al., 2012). All these events might impact the assumption that degradation in Channels A and B is similar and can be described by the same exponential rate proportional to exposure time.

While all components of equation (1) are based on physical processes, none of the three parameters, $\kappa(\lambda)$, $H(t_{\text{cal}}, \lambda)$, or $a(i, \lambda)$ are derived independently. Instead, they are derived fits and adjustments from the uncorrected SSI observations of Channels A and B. The multiple fits do not separate the degradation in purely wavelength- and time-dependent components as originally intended. This runs the risk that good agreement between Channels A and B can be established without revealing the true functional form of the degradation. Thus, the parameter fits are underconstrained, in part because degradation was not strictly separated into a wavelength and exposure time component. Therefore, the agreement between both channels should not be used to derive uncertainties.

We suggest that the larger out-of-phase solar variability in the NIR for SIM V25 in SC 23 may be an artifact of the assumed exponential prism degradation that leads to the steep downward slope in SC 23 in the UV. An indication that SIM V25 contains artifacts at these longer wavelengths, where prism degradation is assumed to be small, can be found in a rapid downward trend after 2015 (see 700 to 1,600 nm in Figure 1) and in comparison to TSIS SIM (see 700 to 1,600 nm in Figure 2). Furthermore, the comparison to TSIS SIM revealed systematic uncorrected instrument degradation for 240–300 nm where SORCE SIM degradation is highest, which exceed TSIS SIM uncertainties. The mechanisms contributing to the degradation of the prism are poorly understood and, therefore, challenging to model. It might depend on many processes, such as the molecular transport, diffusion, dissociation, or ionization of the involved hydrocarbons (Hollenshead & Klebanoff, 2006) that are not captured in the SIM V25 model.

Finally, the comparison on an absolute scale of SIM V25 and MuSIL to TSIS SIM revealed differences in their calibration of more than 5% for part of the UV and NIR, which far exceed the TSIS SIM accuracy estimates. After launch, the calibration of SORCE SIM was adjusted with a smooth, wavelength-dependent function to match the ATLAS-3 spectrum (Harder et al., 2010; Thuillier et al., 2004). The largest adjustment of +8% was performed for wavelengths longward of 1,500 nm. The comparison of SIM V25, MuSIL, and SIMc V1 to TSIS SIM indicates that the ATLAS-3 spectrum overestimates SSI in the NIR. This finding is in agreement with...
Bolsée et al. (2014), Meftah et al. (2017), and Pereira et al. (2018). The differences in the UV between SORCE SIM and TSIS SIM warrant further investigation and are a likely result of the challenging nature of calibrating both instruments at these wavelengths.

4.2. MuSIL

MuSIL makes use of what appears to be undercorrected SSI for SC 23 in the UV, thereby overcorrecting during SC 24 because of this bias. We hypothesize that this leads to the large solar cycle variability in SC 24, exhibited by MuSIL for the 240- to 300-nm wavelength band. To test our hypothesis, we applied the MuSIL technique to uncorrected SORCE SIM observations. These observations have an even steeper downward trend in SC 23. As expected, the MuSIL-corrected solar irradiance showed an even steeper downward trend in SC 23 followed by larger solar cycle variability for SC 24, than MuSIL applied to the degradation-corrected SORCE SIM SSI.

In the NIR (1,000–1,600 nm) MuSIL shows out-of-phase solar cycle variability (see Figure 8). Similar to the large solar cycle variability in SC 24 in the UV, this can be attributed to the large upward trend of SIM V25 between 2004 and 2008 in the NIR, which might be an artifact of the applied degradation correction. Our findings indicate that the MuSIL technique is successful in mitigating these artifacts but does not completely remove them. Therefore, the resulting correction by MuSIL adjusts the original SSI to follow in phase with the original SSI solar cycle variability that, as a result, can overestimate or underestimate true solar cycle variability. One consequence is that remaining instrument artifacts may be obscured by physically plausible 11-year solar cycle variability. The rapid changes in MuSIL during the current solar cycle minimum are a consequence of MuSIL being required to extrapolate its correction at these times. An updated version of MuSIL is currently under development that is expected to resolve this issue.

MuSIL does not differentiate between the effects of different solar proxies; instead, it relies on their mean. Thus, solar irradiance in the UV, mostly governed by active regions, is partially corrected with the SSN. Similarly, a correction in the NIR, mostly governed by the presence of sunspots, is partially corrected by Mg II and Ly-α. The MuSIL super proxy consists of three proxies of faculae brightening (Mg II, Ly-α, and F10.7) and one proxy of sunspot darkening (SSN). Therefore, there is an imbalance in the relative contribution between active regions and sunspots in the determination of the super proxy. This suggests that the super proxy is more informative of the UV than the NIR and raises the question, How well does the mean of four solar proxies describe the 11-year solar cycle variability in the UV, VIS, and NIR? Furthermore, there are significant differences between the normalized solar proxies. For example, normalized SSN and Lyα disagree at times by more than 30%. This leads to another question: How does the choice of solar proxies influence the correction? These questions were explored as part of the original development of the MuSIL technique, with Woods et al. (2018) concluding that the MuSIL trending results have about 10% uncertainty relative to the amount of solar variability at each wavelength. The derived uncertainties in the MuSIL-corrected SSI is calculated by comparing SSI variability of two consecutive solar cycles. Similar to SIM V25, this approach might systematically underestimate uncertainties, since the MuSIL technique forces SSI to agree for the same phase in the 11-year solar cycle.

4.3. SIMc V2

SIMc V2 makes no assumption of the functional form of the prism or sensor degradation or the physical processes involved. It agrees with TSIS SIM within TSIS SIM uncertainties, the NRLSSI2 solar model (1σ: < 0.08 %), and the SATIRE-S solar model (1σ: < 0.14 %) over the whole wavelength range. Its uncertainty is derived by correcting artificially degraded NRLSSI2 SSI and comparing it to the original model output. While this method is not perfect, it derives realistic uncertainties based on representative errors and their propagation during all steps of the degradation correction. Furthermore, SIMc V2 is based on few assumptions and few equations that facilitate easy reproducibility. One concern with the SIMc V2 approach is that the TSI variability could force its solar cycle variability magnitude onto most SSI wavelengths in the same way. This is of particular concern for wavelengths in the UV and might be an important contributor to the rather large uncertainties of SIMc V2. Furthermore, the SIMc V2 approach relies on a stable measure of SORCE TIM TSI so residual instrument degradation in SORCE TIM would directly affect SIMc V2.

The agreement between SIMc V2 and TSIS SIM is encouraging but a longer overlap will be necessary for a true validation. SIMc V2 was absolutely adjusted to TSIS SIM from comparisons over their overlapping
period in 2018–2019, thereby extending the TSIS SIM improved calibration back to the beginning of the SORCE mission in 2004.

5. Conclusion

In this study we compared three independent degradation correction methods applied to SORCE SIM observations that ideally should resemble each other. However, differences between the three data sets persist, especially at shorter wavelengths where most of the degradation occurs. Closer agreement is found for wavelengths longer than 400 nm where SORCE SIM observations benefit from a good signal-to-noise ratio and the degradation of the prism is small compared to that in the UV. Unfortunately, Earth’s climate is most sensitive to solar irradiance variability at shorter wavelengths (Ermolli et al., 2013; Gray et al., 2010; Haigh, 1994; Haigh, 2007). Therefore, resolving these discrepancies is important for Sun-climate studies.

SIM V25 appears to underestimate instrument degradation for wavelengths shorter than 400 nm, and MuSIL suffers from these remaining instrument trends in SIM V25. Wavelengths longer than 700 nm contain artifacts from the degradation correction in SIM V25 that have been successfully removed by the MuSIL method. Using the overlapping period of SORCE SIM and TSIS SIM to validate the individual SORCE SIM corrections is possible only to a limited extent. The comparison is restricted by a duration shorter than 2 years during which there was little solar activity. However, we found trends in SIM V25 relative to TSIS SIM that exceed TSIS SIM stability estimates.

For most applications we recommend the use of SIMc V2 over SIM V25 because the SIM V25 SSI variability in the UV and NIR exhibits behavior that is inconsistent with the other correction methods, independent observations of SSI, and solar irradiance models. Similarly, we caution the use of MuSIL-SIM before May 2004 and after January 2018 due to end-range deviations for the MuSIL technique and for wavelengths shorter than 300 nm related to larger deviations, partially due to SIM V25 worse precision at the shorter wavelengths. While not presented here, the MuSIL-SOLSTICE results are much improved over that of the shorter SIM-SIM for below 310 nm (Woods et al., 2018). Continued solar irradiance observations will be needed to determine the extent to which SIMc V2 recovers true solar cycle variability. To date, the agreement with TSIS SIM is encouraging. For each of the three SORCE SIM data sets examined here, their absolute irradiance values result from adjusting them to other solar spectra: ATLAS-3 for SIM V25/MuSIL, and TSIS SIM for SIMc V2. Therefore, they are best used to investigate relative changes in SSI rather than absolute irradiance values. Finally, all data sets are similar in their short-term variability since the three independent degradation corrections are applied to trends longer than solar rotational time scales.

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