Session 4

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Ultraviolet Solar Spectral Irradiance Variation on Solar Cycle Timescales

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Abstract. Ultraviolet (UV) Solar spectral Irradiance (SSI) has been measured from orbit on a regular basis since the beginning of the space age. These observations span four Solar Cycles, and they are crucial for our understanding of the Sun-Earth connection and space weather. SSI at these wavelengths are the main drivers for the upper atmosphere including the production and destruction of ozone in the stratosphere. The instruments that measure UV SSI not only require good preflight calibration, but also need a robust method to maintain that calibration on orbit. We will give an overview of the catalog of current and former UV SSI measurements along with the calibration philosophy of each instrument and an estimation of the uncertainties in the published irradiances.

Keywords. Sun: UV radiation, Sun: activity, instrumentation: spectrographs

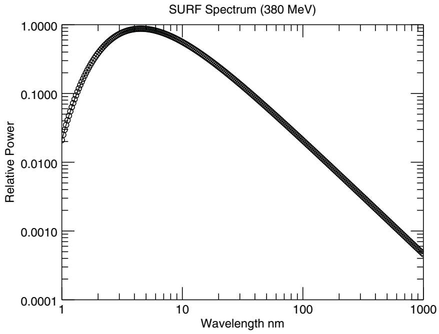
1. Introduction

Solar spectral irradiance (SSI) variability is the primary driver for the atmosphere. In particular, the ultraviolet (UV) wavelength range controls the production and destruction of ozone as well as heating, dynamics, and ionization in the upper atmosphere. Since these wavelengths are absorbed before they reach the ground, observations need to be carried out from space. Data records that are consistent on solar cycle timescales (i.e. decades-long) typically require merging data from several instruments. In order to create a useful composite, the calibration of each instrument, along with its uncertainty, must be well understood.

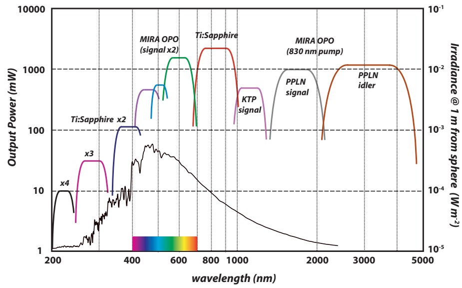
This manuscript will give an overview of the ground calibration used for SSI instruments before launch, as well as a discussion of how this calibration is maintained on-orbit. Some examples of SSI cross-calibration and comparison of time series will be shown in Section 4.

2. Ground Calibration

The first step in creating a physically meaningful UV SSI data record is calibration before launch. In order to tie the measurements to Système Internationale (SI) standards, the calibration must also be tied to a SI standard. For wavelengths less than 300 nm, we use the Synchrotron Ultraviolet Radiation Facility (SURF III, Arp *et al.* 2000) for end-to-end instrument calibration. The spectrum of the SURF beam is shown in Figure 1. We can transport our instruments to the SURF facility in Gaithersburg, MD and directly observe the beam in vacuum at controlled temperature and viewing geometry. An example of such a calibration is described in McClintock, Snow, & Woods (2005). Although the



(a) Synchrotron Ultraviolet Radiation Facility (SURF III) spectrum.



(b) Spectral coverage of the Spectral Irradiance and Radiance Responsivity Calibrations using Uniform Sources (SIRCUS) laser system.

Figure 1. Two approaches to ground calibration: using a SI-traceable source (left) or using a stable source and comparing to a SI-traceable radiometer (right).

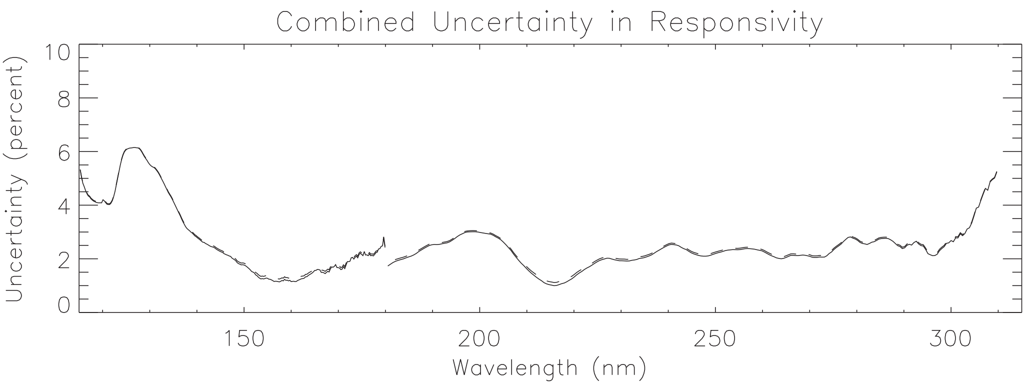


Figure 2. Preflight absolute uncertainty of SORCE SOLSTICE. Solid line shows uncertainty for solar observations, dashed is for stellar. Based on Fig. 10 from McClintock, Snow, & Woods (2005).

uncertainty in the SURF beam itself is less than 1%, it is a point source and a smooth continuum, not an extended source with a rich spectrum such as the Sun. After taking account of geometric correction factors, uncertainties in the wavelength scale, and several other instrument corrections, the absolute uncertainty for a UV instrument is generally several percent. Figure 2 shows the final uncertainty for the SOLar-STellar Irradiance Comparison Experiment (SOLSTICE II, McClintock, Rottman, & Woods 2005) on the SOlar Radiation and Climate Experiment (SORCE, Rottman 2005).

While the SURF beam is brighter than the Sun for wavelengths in the Extreme UV (EUV), the photon flux falls off rapidly at longer wavelengths. For wavelengths between 200 and 5000 nm, we use the Spectral Irradiance and Radiance Responsivity Calibrations using Uniform Sources (SIRCUS, Brown *et al.* 2006) system of lasers. The wavelength coverage of the SIRCUS system is shown in the right hand panel of Figure 1. Unlike the SURF beam, the SIRCUS sources are not an SI standard; but they do provide a stable light source at a chosen wavelength. By alternating the lasers between an instrument and a SI-traceable radiometer, we can achieve accuracies of $\sim 0.2\%$ from the near-UV to the near-infrared Richard *et al.* (2011).

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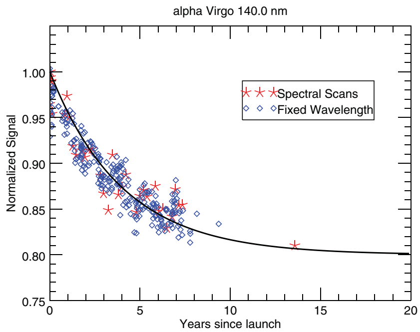
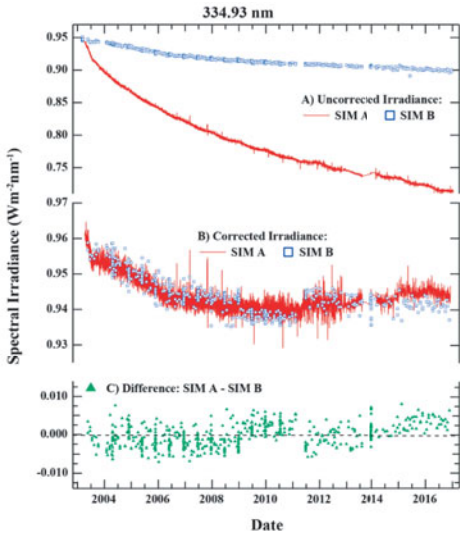


(a) Observations of α Virgo at 140 nm. The change in irradiance is due to instrument degradation.



(b) Two-channels

Figure 3. Two approaches to on-orbit degradation corrections. (left) Stellar measurements from SORCE SOLSTICE. (right) Two independent channels from SORCE SIM.

3. On-Orbit Calibration

After launch, instruments in the harsh environment of space that are exposed to solar radiation will inevitably degrade over time. Different instrument designs will use different methods to maintain their calibration. The following list gives an overview of the range of techniques used by current missions.

- External irradiance reference (stars, moon) UARS/SOLSTICE, SORCE/SOLSTICE
- Internal irradiance reference (lamps) UARS/SUSIM, ISS/SOLSPEC
- Multiple channels SORCE/SIM, TSIS/SIM
- Underflight cross-calibration SDO/EVE, TIMED/SEE, SORCE/SOLSTICE
- Proxy model GOES/EXIS, NOAA/SBUV, GOME, AURA/OMI, ISS/SOLSPEC

The uncertainty over time for these methods are not always simple to quantify and, more importantly, are not always published. The SOLSTICE technique of using an ensemble of stars as an irradiance reference is fairly straightforward. Observations of a set of stable stars is monitored and the time series of stellar irradiance is fit with an exponential function (Snow *et al.* 2005). The left panel of Figure 3 shows an example at one wavelength of this technique. Statistical uncertainty in the fit is a lower bound to the uncertainty in the degradation correction.

Estimating the uncertainty for multiple independent channels as shown in Figure 3 (right panel) is also fairly straightforward. Irradiances plotted as a function of exposure time can then be fit with a function and uncertainties in the fit can be used to estimate the uncertainty in the degradation function.

Using internal lamps to track degradation adds another layer of complication because the lamps themselves can degrade and must be duty cycled. Both the internal and external irradiance reference methods may have to correct for differing illumination of the optics between the Sun and the reference source.

Cross-calibration using simultaneous observations from a rocket-launched copy of the instrument and the instrument in orbit has both advantages and disadvantages. The underflight instrument can be calibrated on the ground both before and after the launch.

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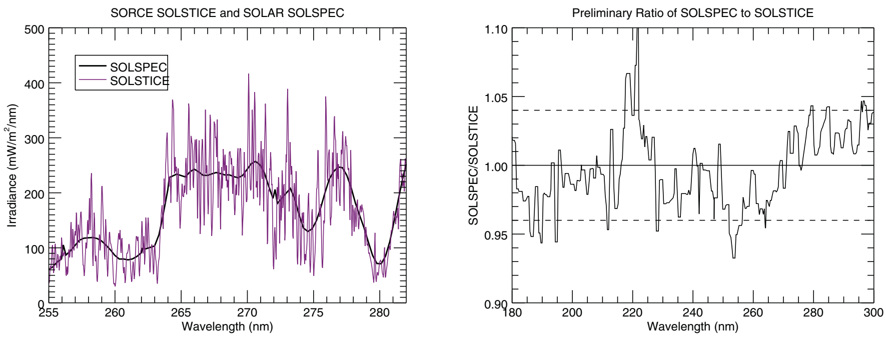

(a) SSI Spectra (b) SSI Ratio

Figure 4. Comparison of SOLAR SOLSPEC and SORCE SOLSTICE in April 2008. The expected uncertainty in the ratio (shown as dashed lines) is the rms of each instrument's preflight calibration uncertainty and the uncertainty of SOLSTICE's degradation correction five years after launch.

If the two instruments are indeed identical copies, the correction is a simple ratio. It is often the case that the rocket version of the instrument is not identical. In either case, the uncertainty in the degradation correction is the uncertainty of the ratio of two spectra, which in general is about $\sqrt{2}$ times the calibration uncertainty. One significant advantage is that the time dependence of the uncertainty is a function of how often rockets can be launched.

Finally, using an irradiance model to correct the SSI measurements is sometimes a necessary design choice. If the uncertainty in the model is significantly smaller than the variation of the SSI at the measured wavelength, then the instrument is making a statistically significant measurement of the Sun's variation. of solar variability

4. Results

4.1. *Cross-calibration*

Much like an underflight of a rocket instrument, two SSI observations can be used to validate the calibration of both measurements. Figure 4 shows an example of a comparison of SORCE SOLSTICE to the first light spectrum from SOLAR SOLSPEC (Meftah *et al.* 2018). The expected uncertainty in this ratio is $\pm 4\%$. The calibration uncertainty for SOLSTICE is about 2% in this wavelength range (Figure 2), and the uncertainty in the degradation correction after five years is about 1.5% (Figure 3). These are statistically independent sources of uncertainty, so they are added in quadrature for a combined standard uncertainty of about 2.5% ($k = 1$). The calibration uncertainty of SOLSPEC described in Meftah *et al.* (2018) is a strong function of wavelength. It varies from 2% up to 19% in the UV. An average SOLSPEC uncertainty of 3% would yield an average uncertainty of 4% in the ratio. Dashed lines at $\pm 4\%$ are shown in Figure 4. The ratio between SOLSTICE and SOLSPEC falls well within this uncertainty envelope.

4.2. *SSI intercomparison*

In addition to comparing the absolute calibration between instruments, it is also essential to validate the solar cycle timescale trends between independent observations. Comparisons between measurements and models are also critical to validate the long-term behavior of models. There is a significant disagreement between SSI observations from SORCE and SSI models during the decline of solar cycle 23 as shown in the left

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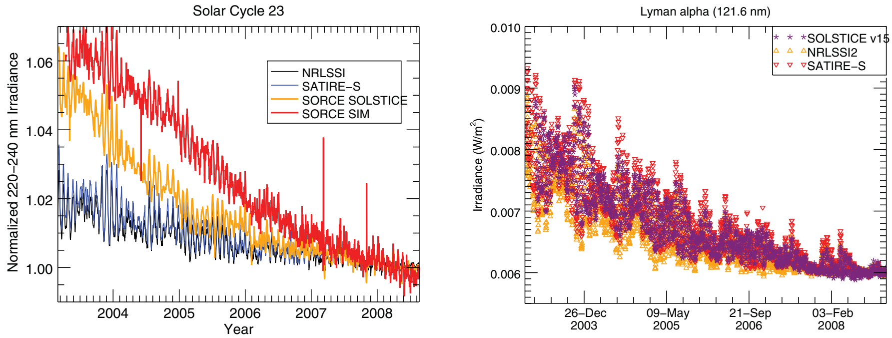
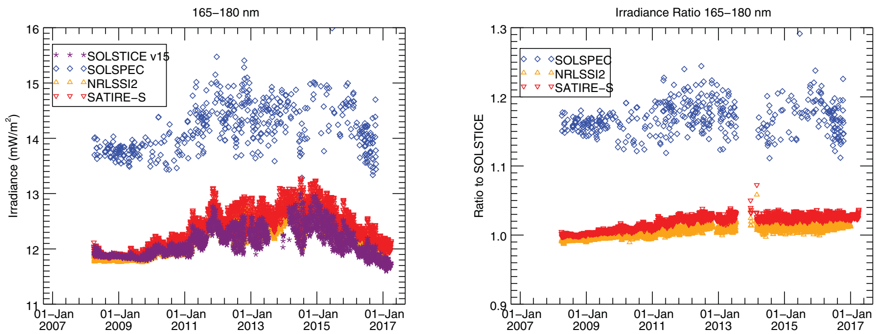


(a) Cycle 23 MUV (b) Cycle 23 Lyman alpha

Figure 5. Comparison of SSI time series during Solar Cycle 23. (left) Updated version of Fig. 8 from Ermolli *et al.* (2013) showing large discrepancy between SORCE MUV and irradiance models. (right) Time series from SORCE SOLSTICE and two models at Lyman alpha (121 nm) showing good agreement.



(a) SSI Time Series 165-180 nm (b) SSI Ratio to SOLSTICE 165-180 nm

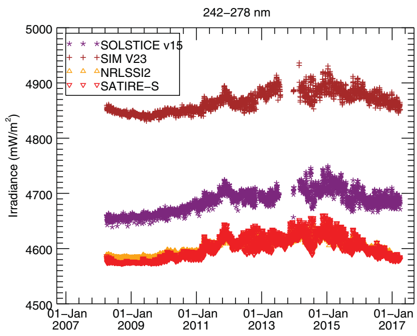
Figure 6. Comparison of SOLAR SOLSPEC, SORCE SOLSTICE, NRLSSI2, and SATIRE-S integrated from 165 to 180 nm during solar cycle 24. Trends between datasets are less than 0.3% per year.

panel of Figure 5 (c.f. Ermolli *et al.* 2013) for the middle ultraviolet (180-300 nm). Agreement is good for the far ultraviolet (115-180 nm) as shown in the right hand panel of Figure 5.

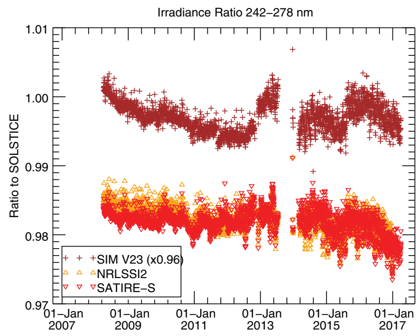
However, during solar cycle 24, there is much better agreement between measurements and models at all wavelengths. Figures 6 and 7 show time series on the left, and the ratio to the SOLSTICE SSI on the right. There are calibration offsets for SOLSPEC and SIM relative to SOLSTICE, but in each selected wavelength range, the trends agree to within the uncertainty of the SOLSTICE degradation correction. Similarly, both SSI models, NRLSSI2 (Coddington *et al.* 2016) and SATIRE-S (Yeo *et al.* 2014), also agree with the SOLSTICE SSI trends to within the SOLSTICE uncertainty.

5. Summary

Absolute calibration of orbiting SSI instruments can use a variety of techniques to achieve 1% or better accuracy above 200 nm. Calibration techniques below 200 nm are less accurate, but can yield uncertainties of 2-3% using SI-traceable sources. There are



(a) SSI Time Series 242-278 nm



(b) SSI Ratio to SOLSTICE 242-278 nm

Figure 7. Comparison of SORCE SOLSTICE, SORCE SIM, NRLSSI2, and SATIRE-S integrated from 242-278 nm. There is a 4% calibration difference between SIM and SOLSTICE, but there is no statistically significant trend during SC 24.

a wide variety of techniques to maintain this calibration over solar cycle timescales, and we have shown a few examples from the SORCE mission.

Validation of these methods can come from intercomparison of independent simultaneous observations. Comparisons between measurements and models can help to confirm model results. Instrument teams can also use comparisons to models to help assess their uncertainty estimates. Measurements and models show good agreement during solar cycle 24 throughout the UV, but discrepancies during the decline of solar cycle 23 still exist and are still an active area of research.

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