



## Solar Irradiance Reference Spectra (SIRS) for the 2008 Whole Heliosphere Interval (WHI)

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[1] The IHY2007 Whole Heliosphere Interval (WHI) for solar Carrington Rotation 2068 (20 March to 16 April 2008) has been very successful in obtaining a wide variety of solar, heliospheric, and planetary observations during times of solar cycle minimum conditions. One of these efforts is the generation of solar irradiance reference spectra (SIRS) from 0.1 nm to 2400 nm using a combination of satellite and sounding rocket observations. These reference spectra include daily satellite observations from TIMED Solar Extreme ultraviolet Experiment (SEE) and Solar Radiation and Climate Experiment (SORCE) instruments. The extreme ultraviolet range is also improved with higher spectral resolution observations using the prototype SDO Extreme ultraviolet Variability Experiment (EVE) aboard a sounding rocket launched on 14 April 2008. The SIRS result is an important accomplishment in that it is the first data set to have simultaneous measurements over the full spectral coverage up to 2400 nm during solar cycle minimum conditions. **Citation:** Woods, T. N., P. C. Chamberlin, J. W. Harder, R. A. Hock, M. Snow, F. G. Eparvier, J. Fontenla, W. E. McClintock, and E. C. Richard (2009), Solar Irradiance Reference Spectra (SIRS) for the 2008 Whole Heliosphere Interval (WHI), *Geophys. Res. Lett.*, *36*, L01101, doi:10.1029/2008GL036373.

### 1. Introduction

[2] Reference spectra of the solar irradiance are important products for studying the solar influences on Earth's climate system and the atmospheres of Earth and other planets. For example, solar reference spectra are used as input in general circulation models of Earth's coupled atmosphere-ocean system to study long-term variations, ranging from changes due to the 11-year solar cycle to changes occurring over centuries that can be affecting global climate change [e.g., Rind *et al.*, 2003]. Solar reference spectra are also useful for establishing and validating models of the solar irradiance. These models are essential for times when no solar observations are available, which includes times between current space-based observations and for reconstructing the solar irradiance at times prior to the space era such as the Maunder Minimum period during the late 17th century. The solar minimum spectrum is of special interest because it establishes the baseline from which solar variability is compared, and

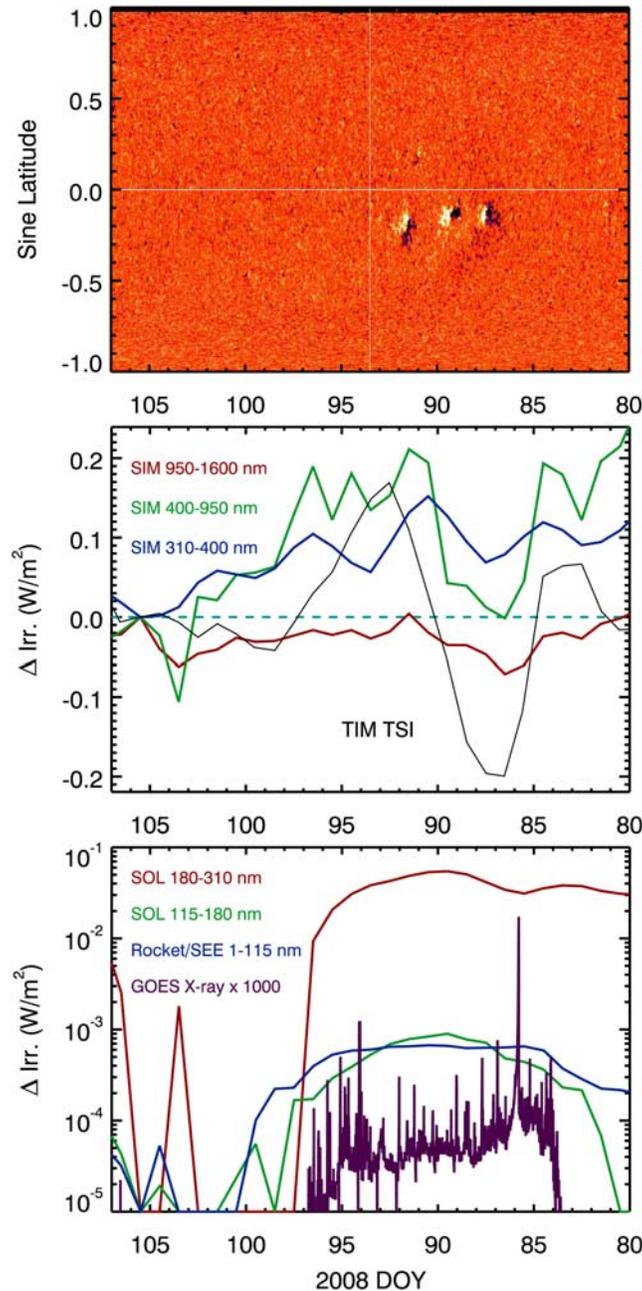
comparisons between different solar minima can provide indications of long-term (decadal) trends in the solar irradiance.

[3] A recent effort to establish solar reference spectra was completed by Thuillier *et al.* [2004a, 2004b] using data during the declining phase of solar cycle 22. While these recent reference spectra are an improvement over prior efforts (more details are given by Thuillier *et al.* [2004a, 2004b]), they are limited by not having simultaneous observations over the full spectral range (extreme ultraviolet to near infrared) and are not representative of true solar cycle minimum conditions. These issues are overcome with the new reference spectrum presented here with improved calibrations, simultaneous observations from 0.1 nm to 2400 nm, higher 0.1-nm resolution, and being during solar cycle minimum conditions. This broad spectral range can be subdivided into the X-ray ultraviolet (XUV: 0–30 nm), extreme ultraviolet (EUV: 30–120 nm), far ultraviolet (FUV: 120–200 nm), middle ultraviolet (MUV: 200–300 nm), near ultraviolet (NUV: 300–400 nm), visible (VIS: 400–800 nm), and near infrared (NIR: 800–2400 nm).

[4] The Whole Heliosphere Interval (WHI) for March–April 2008 was an excellent opportunity to coordinate observations and compare results for solar cycle minimum conditions. While it will not be certain for another six months to a year if the actual solar cycle minimum irradiance values have been obtained for the transition between solar cycles 23 and 24, it is clear that minimum-like conditions have dominated the irradiance time series since November 2007 as evidenced by weak solar rotational variability. The WHI campaign focused on the solar Carrington Rotation 2068 (20 March to 16 April 2008) and included a Quiet Sun campaign for 10–16 April 2008; during this timeframe solar activity indicators show the Sun did indeed have minimum-like conditions. During this period, the average international (Zurich) sunspot number (SSN) was 2, and the average Pen-ticton 10.7 cm radio flux (F10.7) was 69 ( $\times 10^{-22}$  W/m<sup>2</sup>/Hz). Our “minimum” spectrum for the WHI Solar Irradiance Reference Spectra (SIRS) is for this Quiet Sun campaign period and is appropriate for solar cycle minimum studies of the Sun and its influences on Earth and other planets.

[5] Prior to this quiet Sun period, there were three small active regions on the solar disk between 24 March and 4 April as illustrated in Figure 1. The total solar irradiance (TSI), infrared (IR), and visible bands clearly show sunspot blocking effect (darkening) near day of year (DOY) 87 due to the three active regions being near solar disk center. The period from 25 March (DOY 085) to 29 March (DOY 089) is used to generate a “sunspot active” spectrum for the WHI SIRS. During this sunspot period, the average SSN was 33, and the average F10.7 was 84. The TSI, IR, and visible

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**Figure 1.** Time series of solar irradiance measurements during Carrington rotation 2068 (20 March 2008 to 16 April 2008). (top) The SOHO MDI magnetic field synoptic image. Note that time is backwards (goes right to left) for synoptic images. (middle) and (bottom) The irradiance time series in broad bands.

radiation then show enhanced (brighter) irradiance from 30 March (DOY 090) through 4 April (DOY 095), and this period is used to generate a “faculae active” spectrum. During this faculae period, the average SSN was 16, and the average F10.7 was 77. In contrast to the TSI and visible variability, the ultraviolet bands are brighter throughout both of these periods, and the X-rays indicate several flare events while those active regions were observable on the solar disk. These two active spectra indicate a small amount of irradiance variability relative to the minimum spectrum and are appropriate for solar rotation variation studies during the WHI campaign. However, it should be noted that these active spectra are not at all appropriate for solar cycle maximum

studies because the observed variability is just a fraction of variability expected for solar maximum conditions.

## 2. Solar Irradiance Data Sets

[6] For the first time, there are several concurrent space-based programs with solar irradiance measurements to allow complete spectral coverage during solar cycle minimum conditions. The primary data sets used are from NASA’s Solar Radiation and Climate Experiment (SORCE: launch in January 2003), Solar EUV Experiment (SEE) aboard the Thermosphere, Ionosphere, Mesosphere, Energetics, and Dynamics (TIMED: launch in December 2001) satellite, and the

underflight SEE calibration rocket payload that also included the prototype EUV Variability Experiment (EVE) developed for the future Solar Dynamics Observatory (SDO) mission. Along with using these observations, which are the most accurate to date, another goal for the WHI SIRS is to provide higher spectral resolution. The full spectral range from 0.1 to 2400 nm is reported in 0.1-nm intervals on 0.05-nm centers, but this higher spectral resolution is realized only shortward of 310 nm.

[7] The TIMED SEE [Woods *et al.*, 2005a] and prototype EVE calibration rocket experiment [Woods *et al.*, 2006; Chamberlin *et al.*, 2007] provide the irradiance shortward of 116 nm for SIRS. The calibration rocket was flown on 14 April 2008 to provide underflight calibration for TIMED SEE and to coincide with the WHI Quiet Sun campaign. The Multiple EUV Grating Spectrograph (MEGS) as part of the prototype EVE instrument aboard the calibration rocket payload provides the higher spectral resolution and more accurate irradiances from 6 to 106 nm (P. C. Chamberlin *et al.*, New, higher resolution solar extreme ultraviolet (EUV) irradiance results for solar cycle minimum conditions on April 14, 2008, submitted to *Geophysical Research Letters*, 2008). The TIMED SEE observations fill in the spectral gaps (0–6 nm and 106–116 nm), and the variability ratio between March (active) and April (minimum) from TIMED SEE are applied to the rocket result (minimum) to obtain the active spectrum at the higher spectral resolution. The XUV Photometer System (XPS) measurements [Woods *et al.*, 2005a, 2005b] are broadband measurements (7–10 nm), but analysis of the XPS data with high resolution spectral models [Woods *et al.*, 2008] supply 0.1-nm resolution spectra for the 0.1 to 6 nm range for SIRS. The SEE results in the 106 to 116 nm range were adjusted for SIRS to be consistent with the carbon continuum extrapolation from the EVE rocket experiment and the hydrogen Lyman- $\alpha$  blue wing continuum extrapolation from SORCE.

[8] The SORCE observations provide the irradiance long ward of 116 nm for SIRS. The SORCE Solar Stellar Irradiance Comparison Experiment (SOLSTICE) [McClintock *et al.*, 2005a, 2005b; Snow *et al.*, 2005] provides the solar irradiance with 0.1-nm resolution between 116 and 310 nm. These SOLSTICE results include the FUV channel results up to 180 nm and the MUV channel results long ward of 180 nm. The SORCE Spectral Irradiance Monitor (SIM) [Harder *et al.*, 2005a, 2005b] provides the solar irradiance from 310 to 2400 nm with varying resolution from about 1 nm at 310 nm to about 30 nm in the near infrared. The SIM spectra have internal boundaries at 950 nm and 1600 nm from using different detectors.

[9] Other solar irradiance observations are also available to help provide validation but are not used directly in the new reference spectra. These other measurements include two X-ray bands from the GOES X-Ray Sensor (XRS) [e.g., Garcia, 1994], two EUV broadband measurements from the SOHO Solar EUV Monitor (SEM) [e.g., Judge *et al.*, 1998], and 1-nm resolution spectra in the 200 to 400 nm range from NOAA Solar Backscatter UltraViolet (SBUV) instrument [e.g., DeLand *et al.*, 2004].

### 3. Results

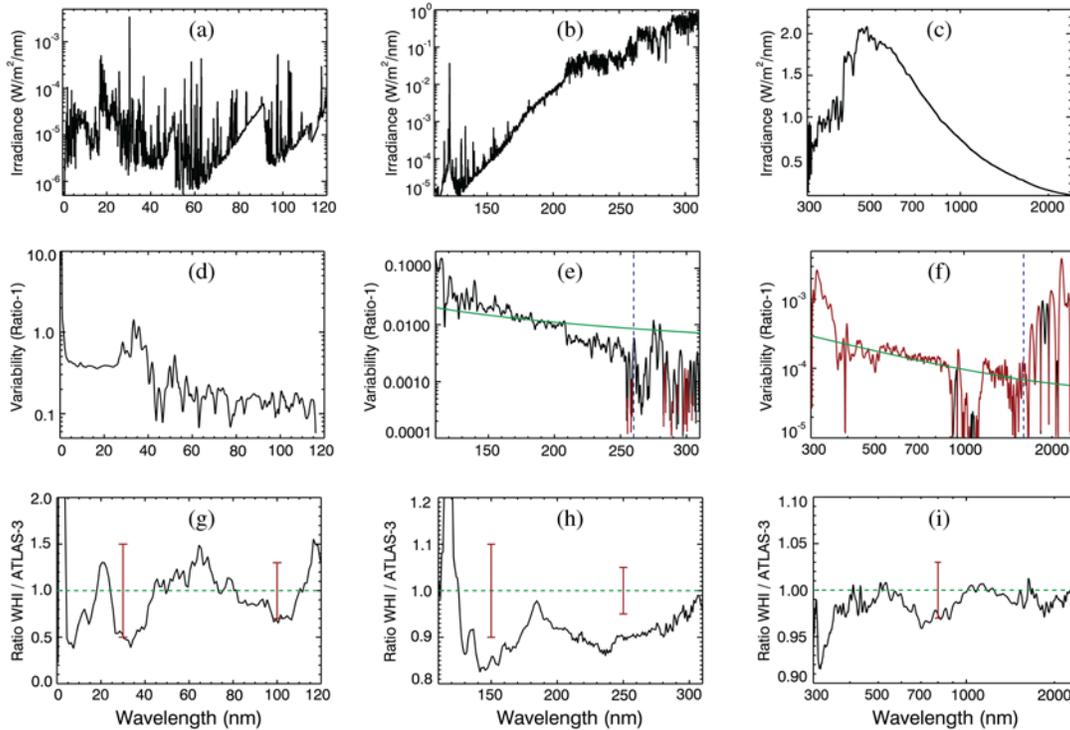
[10] There are three spectra generated for the WHI SIRS. The solar cycle minimum spectrum is the irradiance averaged

over 10–16 April 2008 (DOY 101–107). The two active spectra are the irradiances averaged over 25–29 March (DOY 085–089) and 29 March and 4 April (DOY 090–095). These two active spectra are very similar in the ultraviolet (UV) but are different in the visible and IR; namely the first period shows sunspot darkening (thus the “sunspot” spectrum), and the second period shows faculae brightening (thus the “faculae” spectrum). The exception for the averaging is for the 6 to 106 nm EUV range that consists of the rocket EVE measurement on 14 April 2008 for the minimum spectrum. Figures 2a–2c show the minimum spectrum separated out in the EUV-XUV range (TIMED SEE/rocket EVE), FUV-MUV range (SORCE SOLSTICE), and NUV-Visible-NIR range (SORCE SIM).

[11] These reference spectra are normalized to the total solar irradiance (TSI) values from SORCE Total Irradiance Monitor (TIM). These TSI results for the sunspot, faculae, and minimum spectra periods are 1360.70 W/m<sup>2</sup>, 1360.94 W/m<sup>2</sup>, and 1360.84 W/m<sup>2</sup>, respectively. These TSI values are lower by about 0.3% than other concurrent TSI measurements by the Active Cavity Radiometer Irradiance Monitor (ACRIM) and the Variability of Irradiance and Gravity Oscillations (VIRGO) instruments. The TIM results were chosen for the normalization due to its improved accuracy of 0.04% [Kopp *et al.*, 2005]. The spectral irradiance long ward of 2400 nm is estimated to be 51 W/m<sup>2</sup> with an uncertainty of about 0.5 W/m<sup>2</sup> [Thuillier *et al.*, 2004a, 2004b], so TSI values are first adjusted to 0–2400 nm by subtracting 51 W/m<sup>2</sup> from the TSI. These reference spectra are normalized to the adjusted TIM TSI by dividing the sunspot, faculae, and minimum spectra by 1.00921, 1.00925, and 1.00909 respectively. These differences of about 1% are well within the accuracy of the spectral irradiance measurements from SORCE and TIMED. With the TIM TSI accuracy of about 0.04%, the normalization to TSI can provide improved accuracy for the reference spectra.

[12] The amount of solar variability between the active and minimum spectra, as shown in Figures 2e–2f, is small relative to the full variability (maximum to minimum) over a solar cycle. The UV variability relative to the quiet Sun is very similar for both active spectra, so the UV variability shown in Figures 2d and 2e is the ratio of the two active spectra averaged together to the minimum spectrum. The visible and IR irradiances are, however, very different between the two active spectra. To maximize the variability during this period, the visible and IR variability shown in Figure 2f is the ratio of the sunspot active spectrum to the faculae active spectrum. The active spectrum includes the effects of the three small active regions, being mainly sunspot blocking (darkening) for the visible and NIR and faculae/plage brightening for most ultraviolet wavelengths, even reaching a factor of 2 or more for the shorter EUV wavelengths.

[13] The solar variability is very dependent on wavelength, being related to the height within the solar atmosphere from which the radiation is emitted. The visible and IR emissions are dominated by the sunspot blocking in the photosphere (red lines indicate negative changes in irradiance). The NIR variation is about –0.01% and increases to more than –0.04% in the NUV. It should be noted that the variability results between 900 and 1000 nm and long ward of 1600 nm (blue dashed line in Figure 2f) are not considered



**Figure 2.** (a)–(c) Solar Irradiance Reference Spectra (SIRS), (de)–(f) its variability, and (g)–(i) comparison to ATLAS-3 reference spectrum [Thuillier *et al.*, 2004a, 2004b]. The results shortward of 116 nm are from the rocket EVE and TIMED SEE. The results between 116 and 310 nm are from SOLARcycle SOLSTICE, and results from 310 to 2400 nm are from SOLARcycle SIM. The variability shown in red are negative variations associated with sunspot blocking (darkening). The green solid lines are the derivatives of 5700 K Planck function with a change of temperature of 5 K (lower chromosphere) and  $-0.2$  K (photosphere) in Figures 2e and 2f, respectively. Most of the variability to the right of the dashed lines in Figures 2e and 2f are not statistically significant. The red error bars in Figures 2g–2i are the comparison uncertainties that include both WHI SIRS and ATLAS-3 uncertainties.

significant due to poorer SIM measurement precision at those wavelengths.

[14] As expected, the variability from the chromosphere, transition region, and corona shows only positive increases in irradiance with the presence of the active regions. The middle ultraviolet range shows about 1% variations for the lower chromospheric emissions such as the Mg II emissions near 280 nm and the continuum below the Al ionization edge of 208 nm. At even shorter wavelengths, the transition region and corona emissions vary even more, from a few percent to about a factor of 2. The X-ray (XUV) region shows variations up to a factor of 10 or more. The variability in the XUV range between 1 and 27 nm is based on broadband XPS measurements and is not expected to fully reflect the true solar variability of individual emission lines [Woods *et al.*, 2008]. The SOLSTICE measurement precision is about 0.1%, so the variability results long ward of 260 nm (blue dashed line in Figure 2e) are not considered statistically significant except for the more variable chromospheric emissions near 280 nm.

[15] The measured irradiance variations correspond to different brightness temperatures. For example, the UV and IR variations are different than the visible because of opacity changes in those emissions coming from different layers of the solar atmosphere. But we did not expect to find that this brightness temperature change appears very similar over most of the visible range. In particular, the spectral variations in Figure 2f are similar to the spectral variations estimated by

changing the Planck continuum temperature by  $-0.2$  K in the photosphere (green line in Figure 2f). While it is well known that the sunspots are cooler in the photosphere, it is interesting (somewhat surprising) that the irradiance variability appears similar to the variability related to a small “global” cooling of the photosphere when sunspots are present. We do not intend to imply a global solar cooling. Instead, this result reflects that the combination of two Planck continuum spectra with different temperatures (quiet Sun and sunspot in this case) can have a well defined spectral shape (green line) if the variability is due to temperature changes of the Planck continuum. It is well known that the chromosphere is warmer near sunspots while the photosphere is cooler, and this effect is seen for the UV wavelengths that show brighter irradiances. For example, the lower chromospheric continuum in the MUV between 160 nm and 208 nm and the Mg emissions near 280 nm are consistent with a warming of the lower chromosphere by +5 K (green line in Figure 2e). More detailed analysis and modeling are needed to understand better these spectral variations and possible implications on the solar atmosphere.

[16] These new measurements used in the WHI SIRS have, in general, improved accuracy for the irradiance over previous solar reference spectra. The comparison of the new minimum spectrum to the ATLAS-3 reference spectrum [Thuillier *et al.*, 2004a, 2004b] is shown in Figures 2g–2i. For the ATLAS-3 measurement on November 11, 1994, the SSN was 20, and the F10.7 was 77.5. Because the ATLAS-3

data were not obtained during solar cycle minimum conditions, it is expected that the ratio of WHI SIRS to ATLAS-3 will be slightly less than one for most wavelengths. This is generally the result of this comparison, but the differences are also strongly influenced by calibration offsets between the different data sets. The uncertainty for the previous reference spectrum is 30–50% in the EUV range, and the SIRS accuracy in the EUV range is significantly improved to 10–15% (Chamberlin et al., submitted manuscript, 2008). Similarly, the accuracies for the FUV-MUV ranges have also improved from 3–10% to 2–5% [McClintock et al., 2005b]. The ATLAS-3 SOLSPEC and SORCE SIM accuracies are similar at about 1–3%. These accuracies do include uncertainties for the corrections made to each data set for long-term degradation of the instruments. The additional uncertainties range from 0.5% for SIM, to 1–2% for SOLSTICE, and up to 10% in the EUV range. For TIMED SEE, the long-term degradation is derived from weekly calibrations with redundant channels and five underflight rocket calibrations made between 2002 and 2008 [Woods et al., 2005a]. Bright, early-type stars are used daily to track degradation for SORCE SOLSTICE [Snow et al., 2005], and weekly calibrations with a redundant channel are used to track degradation for SORCE SIM [Harder et al., 2005b]. In addition, these instruments have some spectral overlap and thus provide limited validation for each other.

[17] While a more detailed validation is needed, wavelength-by-wavelength, the preliminary comparison between WHI SIRS and the ATLAS-3 reference spectrum shows good agreement considering that the ATLAS-3 period was not during solar minimum and that differences are mostly within their combined uncertainties. The largest irradiance differences outside instrument uncertainties are in the FUV-MUV ranges but are understood as the offsets between the UARS and SORCE instrument calibrations [McClintock et al., 2005b].

#### 4. Summary

[18] The WHI campaign during March and April 2008 has led to the development of Solar Irradiance Reference Spectra (SIRS) that include a spectrum representative of solar cycle minimum condition and two active spectra representative of the three active regions present on the solar disk in late March 2008, representative of solar rotation activity. The SIRS result is an important accomplishment because it is the first data set to have simultaneous measurements over the full spectral coverage up to 2400 nm, higher spectral resolution of 0.1-nm shortward of 310 nm, and during solar cycle minimum conditions. Comparison to the ATLAS-3 reference spectrum shows reasonably good agreement, and the WHI SIRS results are considered an improvement with its better accuracy and higher spectral resolution.

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