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duced during the on-ground characterization, since under ambient conditions it is very difficult to perfectly thermally stabilize and remove (through normalization) the etalon introduced by water layers at the detector level.

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Use of Solar Reference Spectra for Satellite Instruments

by Matthew DeLand, SSAI

The extraterrestrial solar irradiance (i.e., measured outside Earth's atmosphere) has numerous benefits as a calibration source for remote sensing satellite instruments. For example:

- It is available for an extended period of time during every orbit.
- Its intensity is high across a wide spectral range.
- It is, for much of the spectrum, extremely stable compared to any onboard calibration source. And, in regions where it is not stable, the variations are often highly correlated.
- Many spectral features are available for use in wavelength calibration.

Each of these benefits also brings some challenge in terms of instrument design and data analysis:

- The constant presence of solar illumination requires instrument designers to limit exposure of optical surfaces to minimize degradation, particularly at UV wavelengths.
- Solar irradiance can be stronger than terrestrial radiance at a given wavelength by factors ranging from 10^2 to 10^4, which must be considered when designing the optical system and instrument electronics.
- Solar irradiance does have natural variability at UV wavelengths (particularly below 300 nm), with time scales ranging from minutes to years.
- The solar spectrum incorporates millions of emission and absorption features, so that the exact irradiance spectrum produced by any instrument will depend on its characteristics and design.

In order to use the Sun as a calibration source, it is necessary to first have a reference spectrum to understand what the instrument is expected to see. This article will briefly describe some published reference solar spectra, and issues that users should be aware of when selecting a dataset for their own use.

Overview

It is important for users to realize that no single instrument measures solar irradiance at high resolution simultaneously over all spectral regions of interest (X-ray, UV, visible, IR). Thus, any reference solar spectrum is typically a composite of measurements from multiple instruments, taken at different times, and often with varying spectral resolution. In addition, the final reference spectrum may incorporate radiometric adjustments based on comparisons with lower resolution measurements. Differences in spectral resolution and sampling are particularly important in the UV, where many deep Fraunhofer lines occur. The next section presents basic information about some reference solar spectra published during the last decade. Table 1 summarizes specific parameters for each spectrum.

Reference Solar Spectra

ATLAS. The solar reference spectra created by Thuillier et al. (2004) take advantage of the ATLAS missions conducted in the early 1990s, when three solar irradiance instruments (along with other remote sensing instruments) were flown together on the NASA Space Shuttle. The UARS satellite (carrying two additional solar instruments) was also operating during this period, so that up to five datasets were available for some spectral regions. Thuillier et al. selected reference dates during the ATLAS-1 and ATLAS-3 missions (29 March 1992 and 11 November 1994, respectively) to construct spectra corresponding to moderately high and moderately low levels of solar activity. Each spectrum covers the spectral range 0.5-2,400 nm, using rocket data for the EUV region below 120 nm. They created average irradiance values for UV spectral regions where multiple data sets were present. They also used the high resolution model spectrum of Kurucz (1995) to insert spectral features into lower-resolution measurements in the visible and IR regions.

KNMI. Dobber et al. (2008) created a high resolution solar reference spectrum covering 250–550 nm to support on-orbit calibration of the OMI instrument on the EOS Aura satellite. Very high resolution data from AFGL balloon measurements (Hall and Anderson, 1991) and KPNO ground-based measurements (Kurucz et al., 1984) were convolved to a slightly lower resolution, and then adjusted radiometrically through

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Table 1. Summary of Solar Reference Spectra

Name WvL Sampling	Sources	Resolution	Time	Calibration	Accuracy
ATLAS 0.5–2400 nm 0.5–120 nm: 1 nm 120–400 nm: 0.05 nm 400–2400 nm: 0.2–0.6 nm	0.5-120 nm: Rocket 120-200 nm: UARS SOLSTICE, UARS SUSIM 200-400 nm: UARS SOLSTICE, UARS SUSIM, ATLAS SUSIM, SSBUV, SOLSPEC 400-870 nm: SOLSPEC 870-2400 nm: SOSP	0.5-120 nm: 1.0 nm 120-400 nm: 0.25 nm (smoothed) 400–2,400 nm: 0.5 nm (degraded model)	0.5-120 nm: 1991 rocket 120–2400 nm: 29 Mar 1992 for ATLAS-1, 11 Nov 1994 for ATLAS-3	Satellite data + normalization of integrated TSI	0.5–120 nm: 30–40% 120–2,400 nm: 2–4%
KNMI 250–550 nm 0.01 nm	200–310 nm: AFGL balloon 300–550 nm: KPNO	0.025 nm (convolved)	Multiple dates	Adjusted based on comparison with low resolution data (UARS SUSIM)	< 5% for 300–550 nm
WHI 0.1–2400 nm 0.01 nm	0.1-6 nm: TIMED XPS 6–106 nm: MEGS EVE (rocket) 106-116 nm: TIMED SEE 116–310 nm: SORCE SOLSTICE 310–2400 nm: SORCE SIM	0.1–310 nm: 0.1 nm 310–2400 nm: 1–30 nm	Quiet: 10–16 Apr 2008 Active: 25–29 Mar 2008, 29 Mar – 4 Apr 2008	Satellite data + normalization of integrated TSI to SORCE TIM	0.1-116 nm: 10–15% 116–2,400 nm: 2–4%
SAO 2010 200–1000 nm 0.01 nm	200–300 nm: AFGL 300–1,000 nm: KPNO	0.04 nm (convolved)	Multiple dates	Adjusted based on comparison with low resolution data (ATLAS-1)	< 5% for 300–1,000 nm

comparisons with UARS SUSIM data (Floyd et al., 2003) and balloon data (Gurlit et al., 2005). It should be noted that any terrestrial measurements of absolute solar irradiance must also account for absorption effects due to the Earth's atmosphere.

WHI. During the most recent solar minimum between Cycles 23 and 24, a focused program called the Whole Heliosphere Interval (WHI) collected approximately simultaneous solar measurements at minimum activity conditions from X-ray to IR wavelengths. Woods et al. (2009) used rocket measurements to supplement operational satellite measurements over a wide spectral range (0.1–2,400 nm) and produce three reference spectra representing active and quiet conditions during March-April 2008. The primary data sources are EVE rocket data in the X-ray and EUV regions, SORCE SOLSTICE data in the FUV and MUV, and SORCE SIM data from the NUV to the IR. The only radiometric adjustment came from comparison of the integrated reference spectrum to SORCE TIM total solar irradiance data.

SAO 2010. Chance and Kurucz (2010) have also produced a solar reference spectrum using the AFGL balloon data and the KPNO ground-based data, in this case covering the spectral range 200–1000 nm. They used a revised analysis of the KPNO data, and normalized those data to the Thuillier et al. (2004) ATLAS-1 spectrum longward of 300 nm.

Effects of Resolution and Sampling

Differences in spectral resolution, either from the original measurements or from later re-convolution, and in dataset sampling should be considered when selecting a solar reference spectrum. To illustrate this point, Figure 1 shows irradiance data between 300–320 nm from each of the reference spectra described here. While the KNMI and SAO 2010 spectra are both based on KPNO data and sampled at 0.01 nm, the slightly broader bandpass used for SAO 2010 is evident in Figure 1(b). The WHI spectrum shown in Figure 1(d) is reported at 0.1 nm sampling over its entire range, but the change in resolution between SOLSTICE and SIM data at 310 nm is clear.

Conclusion

Numerous solar irradiance reference spectra, created by combining multiple data sets, are currently available. These spectra can differ in spectral resolution and sampling by a factor of 10. The quoted accuracy of each spectrum is typically 2–4% at UV and visible wavelengths, but differences between spectra can show larger variations locally. Choosing a specific reference spectrum for regular use should be guided by user requirements.

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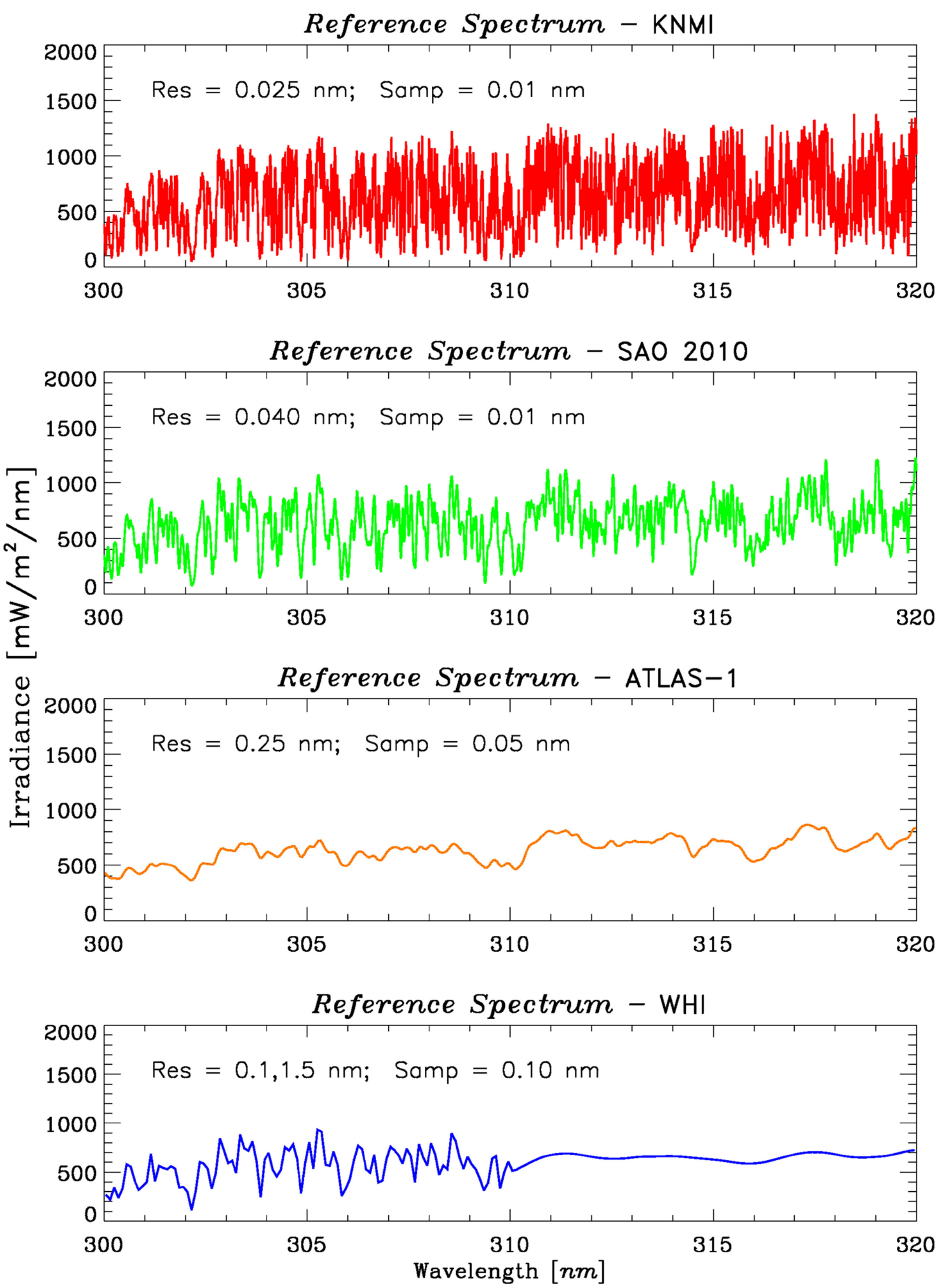

Figure 1. Sample data at 300–320 nm from different solar reference spectra. (a) = KNMI, (b) = SAO 2010, (c) = ATLAS-1, (d) = WHI. Res = resolution, Samp = sampling.

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