Solar Energy 169 (2018) 434–440

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Revised composite extraterrestrial spectrum based on recent solar irradiance observations

Christian A. Gueymard[1]

Solar Consulting Services, Colebrook, NH, USA

ARTICLE INFO

Keywords:
Extraterrestrial spectrum
Solar spectral irradiance
Solar physics
ASTM

ABSTRACT

A revision of a previous composite spectrum (Gueymard, 2004) is undertaken here, with a focus on the 200–4000 nm waveband, where most of the sun's energy is concentrated. The methodology is based on 31 sources of spectral data covering various parts of the spectrum. The data sources include observations from surface observatories, aircraft, high-altitude balloons, satellites, as well as modeled estimates of the solar flux. All existing spectra are downscaled to a single, relatively low spectral resolution to allow their direct comparison. Three successive filtering steps make it possible to eliminate outliers at each of the 2165 wavelengths under scrutiny here. The mean irradiance at each wavelength is then obtained by averaging the values of the surviving data points. The 2004 spectrum is used below 200 nm and above 4000 nm to create a complete spectrum from 0.5 nm to near-infinity. In a final step, the irradiance values are properly scaled so as to integrate to the revised solar constant value of 1361.1 W m^{-2}. Compared to the earlier 2004 spectrum, this new composite differs mostly in the UV and visible parts of the spectrum. Based on the present findings, a revision of the outdated ASTM E490 standard extraterrestrial spectrum is recommended.

1. Introduction

Knowledge of the solar spectrum and its variations is required in a wide variety of disciplines, including astronomy, astrophysics, atmospheric physics, climatology, biology, human health, materials degradation, radiometry, and terrestrial or space solar energy applications. In particular, applications in atmospheric sciences and remote sensing typically require the determination of irradiance at many vertical levels of the atmosphere, where the solar spectrum is attenuated in various wavebands due to strong absorbers that are active either in the ultraviolet (UV), such as oxygen or ozone, or in the infrared (IR), such as water vapor or carbon dioxide. At the earth's surface, the solar spectrum is almost completely attenuated below ≈300 nm and above ≈4000 nm. These limits change somewhat with altitude, to the point where upper stratospheric applications require the complete solar spectrum at all wavelengths, just like space applications. In any case, all calculations of the solar irradiance transmitted by the atmosphere of a planet belonging to the solar system must start with some knowledge of the solar spectrum at the top of that atmosphere. For terrestrial applications, this solar spectral irradiance (SSI) is usually referred to as top-of-atmosphere (TOA) spectrum, or extraterrestrial spectrum (ETS). The latter acronym is used here. Spaceborne remote sensing applications rely on the selection of an ETS having as little bias as possible over the atmospheric windows sensed by the radiometer. Significant uncertainties can occur in the remote-sensed products if the ETS is biased, which makes the selection of the proper ETS critical (Trishchenko, 2006).

Atmospheric transmission codes, such as MODTRAN (Berk et al., 1999b), libRadtran (Emde et al., 2016), or SMARTS (Gueymard, 1995, 2001), typically provide various user-selectable ETS options to ultimately simulate the solar irradiance incident at the surface or at various altitudes throughout the atmosphere, potentially using various nominal spectral resolutions. The ETS spectral resolution conditions that of the simulated irradiance. For solar applications, some standard reference terrestrial spectra have been promulgated based on SMARTS predictions, using 2002 wavelengths between 280 and 4000 nm (ASTM, 2003, 2014; IEC, 2016). This type of application is the focus in what follows, with however an extended spectral range from 200 to 4000 nm. In case a higher spectral resolution is required for more demanding applications, it is customary to modulate a low-bias/low-resolution ETS with a high-bias/high-resolution one through appropriate scaling (Bernhard et al., 2004, 2007; Kiedron et al., 2007; Michalsky and Kiedron, 2008).

Over the years, many ET spectra, covering at least large parts of the complete solar spectrum, have been proposed in the literature. A partial list, covering the period 1940–2004, was compiled by this author (Gueymard, 2006). This list included the associated value of the solar

---

E-mail address: Chris@SolarConsultingServices.com.

[1] ISES Member.

https://doi.org/10.1016/j.solener.2018.04.067
Received 13 March 2018; Received in revised form 24 April 2018; Accepted 30 April 2018

Table 1
Sources of spectral data for the new ETS. The left part is for sources that were previously used to develop the synthetic spectrum in G04 (Gueymard, 2004). The right part is for additional sources, not considered in the latter's construction. Wavelength limits are expressed in nm.

Sources (old)	Lower limit	Upper limit	Sources (new)	Lower limit	Upper limit
Arvesen et al. (1969)	300	2495	Bernhard et al. (2006)	275	630
ASTM (2000)	119	Inf.	Bolsée et al. (2014)	16	2902
Burlov-Vasiljev et al. (1995, 1998)	310	1070	Dobber(2008)	202	600
Colina et al. (1996)	119	410	Gueymard (2004)	0	Inf.
Kitt Peak (Kurucz et al., 1984)	296	1300	Gurlit et al. (2005)	316	652
Lockwood et al. (1992)	329	850	KNMI (Dobber et al., 2008)	250	520
MODTRAN-cebchkur (Berk et al., 1999a)	0	Inf.	Meftah et al. (2017a, 2017b)	199	3000
MODTRAN-chkur (Berk et al., 1999a)	0	Inf.	Menang et al. (2013)	1000	2500
MODTRAN-newkur (Berk et al., 1999a)	0	Inf.	Neckel (2003)	330	1099
MODTRAN-oldkur (Berk et al., 1999a)	0	Inf.	Pfeilsticker (2006)	317	653
MODTRAN-thkur (Berk et al., 1999a)	0	Inf.	PMOD (Egli et al., 2012; Gröbner, 2016; Gröbner et al., 2017)	200	1190
Neckel and Labs (1984)	330	1250	SAO (Chance and Kurucz, 2010)	200	1001
SOLSPEC-ATLAS1 (Thuillier et al., 2003)	0	2398	SORCE-SIM[a] (Harder et al., 2010); http://lasp.colorado.edu/lisird/data/sorce_ssi_l3/)	240	2412
Thuillier et al. (2003)	200	2400	SOLSTICE-ATLAS1 (Woods et al., 1996)	119	410
UARS-ATLAS2 (Brueckner et al., 1993)	115	420	SUSIM-ATLAS2 (Andrews and VanHoosier, 1996) (http://wwwsolar.nrl.navy.mil/susim_atlas_data.html)	119	410
			WHI (Woods et al., 2009)	0	2400

[a] Average 2003–2015.

constant (i.e., the summation of the spectral irradiance over all wavelengths), whose determination varied between a minimum of 1322 W m^{-2} and a maximum of 1429.5 W m^{-2} during that period. Just like the solar constant, all ETS determinations refer to the average sun-earth distance (1 ua)[2], and are thus directly comparable. Not all spectra are obtained for the exact same intensity of solar activity, however, which causes variance between measurements undertaken over many decades.

In 2000, the American Society for Testing and Materials (now known as ASTM International) promulgated Standard E490-00 (ASTM, 2000), which defines a reference spectrum between 119.5 nm and 1000 µm. E490 was reapproved in 2014. The solar constant associated with it is 1366.1 W m^{-2}. In contrast, ISO Standard 21348 (ISO, 2007), reapproved in 2015, promulgates a similar solar constant (1366 W m^{-2}) but does not specify a particular ET spectrum. Rather, it defines the method (experimental or otherwise) that should be followed to define a reference solar spectrum. Hence, it is not a normative standard but a process-based standard. Overall, five different types of solar irradiance products are specifically defined in it. The development below corresponds to "Type 2", i.e., the process of preparing a reference spectrum product that is derived from multiple measured or modeled data sets.

In a previous contribution (Gueymard, 2004), hereafter G04, this author prepared a "Type 2" reference spectrum covering the range 0.5–1000 µm, with a corresponding SC of 1366.1 W m^{-2}. The latter confirmed the ASTM value—as expected, since based on similar datasets. The G04 study, however, underlined the discrepancy between the SC value just mentioned and total solar irradiance measurements made with a new type of radiometer. Based on a 42-year time series of recalibrated irradiance data, a revised SC of 1361.1 W m^{-2} was recently proposed (Gueymard, 2018), thus confirming other recent determinations that were close to 1361 W m^{-2} (Gueymard, 2012; Kopp and Lean, 2011). (This SC value has an estimated standard uncertainty of 0.5 W m^{-2} (or 0.037%), which is far less than the uncertainty of current spectral measurements in space.) In addition, new spectral irradiance measurements have been conducted during the last two decades, using various observational platforms. In an effort to improve accuracy, all this justifies a revision of the ETS that was proposed in (ASTM, 2000) and G04.

2. Solar spectrum revision: new sources of data

Many ETS distributions have been proposed in the literature, based on models (Berk et al., 1999a) or various types of observations and instruments. The observational platforms include terrestrial observatories (Bolsée et al., 2014; Burlov-Vasiljev et al., 1995, 1998; Chance and Kurucz, 2010; Kurucz et al., 1984; Menang et al., 2013; Neckel, 2003), aircraft (Arvesen et al., 1969), stratospheric balloons (Gurlit et al., 2005; Pfeilsticker, 2006), and satellites. In the latter category, the data sources include reference spectra from various instruments: SOLSTICE (ATLAS-1 mission and SIRS-WHI reference spectrum; Woods et al., 1996, 2009), SUSIM (ATLAS-2 mission; Andrews and VanHoosier, 1996), SOLSPEC (Meftah et al., 2017a, 2017b; Thuillier et al., 2003), and SORCE-SIM (Harder et al., 2010). In the latter case, a single spectrum has been derived here by simply calculating an average from the 2003–2015 time series available at http://lasp.colorado.edu/lisird/data/sorce_ssi_l3/. This averaging is intended to smooth out temporal variations due to solar activity. Additionally, composite or convolved spectra are also used (ASTM, 2000; Bernhard et al., 2006; Dobber et al., 2008; Gröbner et al., 2017; Gueymard, 2004). All sources of data used here consist of a single spectrum, as developed by each author; in parallel, the SORCE-SIM average spectrum is specific to this study.

All synthetic spectra that are based, at least partially, on actual measurements rely on a variety of data sources that must be appropriately selected to complement each other. For instance, the current ASTM standard spectrum is based on six data sources between 119.5 nm and 1000 µm. In the case of the G04 synthetic spectrum, 23 sources of ETS data were used in its construction. Eight of them have not been considered for the present study, due to their lower relevance (older and low-resolution data, or arguable surface-based extrapolations). In contrast, 16 new sources have been added, based on a review of the recent literature. Including the G04 synthetic spectrum, a new total of 31 different data sources is reached—most of them typically with a

---

[2] The abbreviation to be used for the *astronomical unit* is somewhat confusing: ISO stipulates "ua" whereas the International Astronomical Union (IAU) favors "au", and ASTM reports it as "AU". The ISO nomenclature is used here.