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Version 2 of the TSIS-1 Hybrid Solar Reference Spectrum and Extension to the Full Spectrum

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Key Points:

- Version 2 of the Total and Spectral Solar Irradiance Sensor-1 (TSIS-1) Hybrid Solar Reference Spectrum (HSRS) is an incremental update from the original release in 2021
- The HSRS Extension builds upon the TSIS-1 HSRS with independent observations and theoretical knowledge where no observations exist
- The HSRS Extension has at least 0.1 nm spectral resolution, spans 0.115–200 μm, and integrates to the total solar irradiance

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Abstract This work describes two achievements to a key data set. First, we present version 2 of the Total and Spectral Solar Irradiance Sensor-1 Hybrid Solar Reference Spectrum (TSIS-1 HSRS), which has recently been recognized as a new solar irradiance reference standard (https://calvalportal.ceos.org/). Second, we present a new "full spectrum extension" of the TSIS-1 HSRS. The TSIS-1 HSRS observational composite solar irradiance reference spectrum spans 0.202–2.730 μm and encompasses more than 97% of the energy in the total solar irradiance (TSI). Version 2 is an incremental update that corrects the radiometric baseline between 0.202 and 0.210 μm and updates the solar lines at wavelengths longward of 0.743 μm to those listed in the most recent database. The full spectrum extension builds off version 2 of the TSIS-1 HSRS and supports applications that require a solar spectrum encompassing nearly 100% of the energy in the TSI. It spans 0.115–200 μm and was developed by incorporating additional observations and theoretical knowledge where no direct observations currently exist.

Plain Language Summary The Sun's irradiance spectrum is used in many applications such as constraining the solar forcing in climate models. Recently, the TSIS-1 Hybrid Solar Reference Spectrum (HSRS), a spectrum developed by adjusting high spectral resolution solar line data to the irradiance scale of the more accurate, but lower spectral resolution, Total and Spectral Solar Irradiance Sensor-1 (TSIS-1) Spectral Irradiance Monitor (SIM) and Compact SIM observations, was formally recognized as a new standard. In this work, we provide an incremental update to that reference spectrum. Furthermore, we extend it to the "full spectrum," beyond the wavelength range of direct observations of the Sun's irradiance spectrum. The HSRS Extension differs by less than 0.1% in its integral quantity to observations of the total solar irradiance. Above the range of the SIM observations, the solar line data are normalized to the irradiance scale of a theoretical spectrum and then adjusted in magnitude to match the SIM observations at their long wavelength cut-off. Below the range of the SIM observations, Solar Stellar Irradiance Comparison Experiment observations from the Solar Radiation and Climate Experiment mission are incorporated.

1. Introduction

The Total and Spectral Solar Irradiance Sensor-1 Hybrid Solar Reference Spectrum (TSIS-1 HSRS) (Coddington et al., 2021) provided a new solar irradiance reference spectrum that is representative of solar minimum conditions between solar cycles 24 and 25 for atmospheric science and climate applications. The TSIS-1 HSRS has high radiometric accuracy (0.3%–1.3%), broad spectral coverage (0.202–2.730 μm) and high spectral resolution (0.01 nm or better). Since its release to the Earth science community in 2021, the TSIS-1 HSRS has been formally recognized as a new solar reference standard by the Committee for Earth Observation Sensors (CEOS) Calibration and Validation Working Group (CVWG) (https://calvalportal.ceos.org/). Independent studies have shown, for example, its value for converting measured satellite radiances to reflectance and vice versa to ensure consistent satellite data inter-comparisons (Bhatt et al., 2021), for converting surface reflectances into top-of-atmosphere radiances for the vicarious calibration of satellite sensors (Bruegge et al., 2022), for enabling the traceability of global column aerosol optical depth retrievals to the International System of Units (Kouremeti et al., 2022), and for on-orbit absolute radiometric calibration using sunlight reflected from the moon (Stone, 2022).

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The integrated energy encompassed by the TSIS-1 HSRS, spanning 0.202–2.730 μm, exceeds 97% of the energy in the total solar irradiance (TSI). Given the demonstrated importance of the TSIS-1 HSRS to the Earth science community we develop version 2 of the spectrum, which is an incremental update to the original release. Between 0.21 and 2.7 μm and at lower spectral resolution, the predominant difference is that Version 2 of the TSIS-1 HSRS is scaled at all wavelengths (reduced) by 0.999061, a change that falls within the uncertainties. However, certain climate applications also require a solar spectrum that spans "all wavelengths" and integrates to TSI. This motivates the second goal of this work, in which we produce an extension to the TSIS-1 HSRS, called the "HSRS Extension," that meets these criteria. When producing our full spectrum extension, our selected wavelength boundaries were chosen to meet the combined needs of operational solar irradiance variability models from 0.115 to 100 μm (Coddington et al., 2016) and the MODerate resolution atmospheric TRANsmission (MODTRAN) radiative transfer software package from 0.2 to 200 μm (Berk et al., 2014). There is energy in the solar spectrum at wavelengths beyond these boundaries, however, their contribution to the total integrated energy is small. For example, below 0.115 μm, the solar spectrum contributes ~0.003 W/m^2, or less than 0.0002%, to the TSI (Woods et al., 2009). Similarly, at wavelengths longward of 100 μm, the solar spectrum contributes less than 0.0001% to the TSI. Thus, when developing the HSRS Extension for the climate applications targeted in this work, we can safely ignore the portion of the solar spectrum beyond our selected wavelength boundaries because those irradiance contributions are much smaller than the uncertainty (~0.015%) of the direct TSI observations themselves (https://lasp.colorado.edu/lisird/data/tsis_tsi_24hr/).

The paper is organized as following. In Section 2, we describe version 2 of the TSIS-1 HSRS. In Section 3, we describe the methodology and data sets used to produce the HSRS Extension. In Section 4, we present our results, associated uncertainties, and compare integrated values to TSI. Conclusions follow in Section 5.

2. Version 2 of the TSIS-1 HSRS

Version 2 of the TSIS-1 HSRS is an incremental update from the originally released data. Version 2 updates correct the radiometric baseline between 0.202 and 0.210 μm and replaces the solar lines at wavelengths longward of 0.743 μm to match a database version update.

The TSIS-1 HSRS is developed by adjusting high spectral resolution datasets to match a lower resolution, but higher accuracy, spectrum with a wavelength-dependent scaling factor. The high accuracy spectrum is an average of the TSIS-1 Spectral Irradiance Monitor (SIM) (Richard et al., 2020) observations from 0.202 to 2.365 μm during 1–7 December 2019 extended in wavelength to 2.73 μm with observations from the Compact SIM (CSIM) technology demonstration instrument (Richard et al., 2019). The scaling factor was the ratio of the high-accuracy spectrum and the high-resolution datasets, after first convolving both datasets to the same spectral resolution and interpolating to a common sampling grid.

During reprocessing, an error was discovered where the instrument line shape used to convolve the high-resolution solar line data to match the resolution of the TSIS-1 SIM was incorrectly applied for wavelengths <0.210 μm. Figure 1 (top) shows the resulting correction to the radiometric baseline reaches 1% at 0.202 μm and becomes vanishingly small by 0.210 μm. Additionally, we took advantage of the reprocessing effort to update the Solar Pseudo-Transmittance Spectrum (SPTS) solar lines to their latest 2020 release (described in Toon, 2014 and available from https://mark4sun.jpl.nasa.gov/toon/solar/solar_spectrum.html). SPTS solar line data are used in the TSIS-1 HSRS at wavelengths longward of 0.743 μm. Figure 1 (bottom) shows a subset of the tens of thousands of individual lines that were solely affected by this update, predominantly in the 1.1–1.3 μm range.

An additional difference, not shown in Figure 1, results from a <0.1% reduction in irradiance at all wavelengths in order to scale to TSI. This adjustment is discussed further in Section 4.2 and falls within the uncertainties of the TSIS-1 HSRS.

As was done in the original release, we also produce four variants of version 2 of the TSIS-1 HSRS that standardize the reference spectrum to fixed, lower spectral resolutions (1.0, 0.1, 0.025, and 0.005 nm) using Gaussian convolution filters (not shown).

3. The HSRS Extension

The TSIS-1 HSRS comprises the bulk of the energy in the TSI. Here, we describe how we extend the TSIS-1 HSRS in wavelength using additional solar irradiance and solar line data sources as well as theoretical knowledge

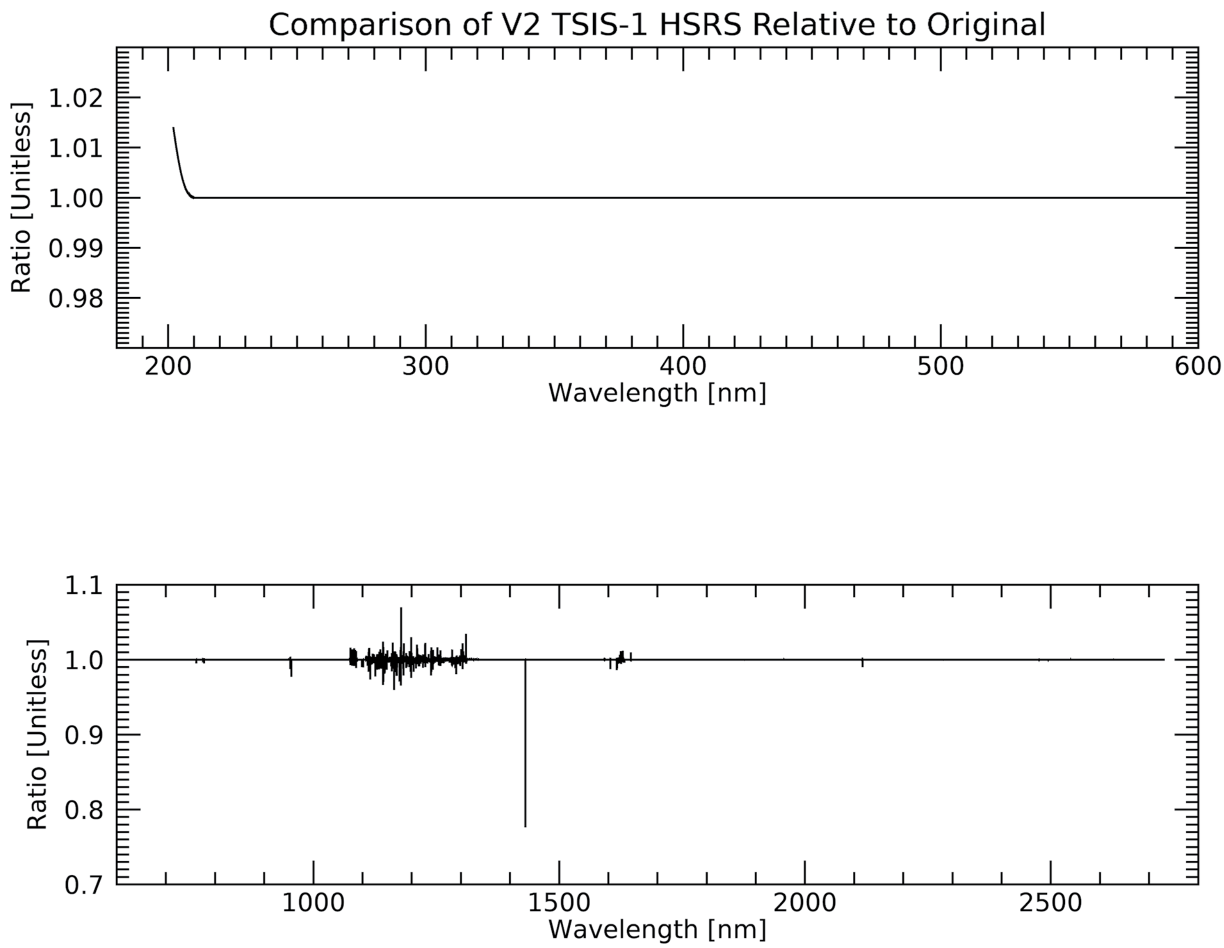

Figure 1. Ratio of the TSIS-1 HSRS (Version 2) to the original illustrates the ~8-nm wavelength region impacted by the re-processing of the radiometric baseline (top) and the near-infrared region impacted from an updated solar line database (bottom).

where no observations exist. We accomplish the HSRS Extension in parts: "section A" of the infrared (IR) extension from 2.73 to 16.5 μm, "Section B" of the IR extension from 16.5 to 200 μm, and the ultraviolet (UV) extension from 0.115 to 0.202 μm.

From here forward, references made to the TSIS-1 HSRS imply version 2 unless otherwise stated.

3.1. Section A of the Infrared Extension From 2.73 to 16.5 μm

Due to a lack of solar spectral irradiance (SSI) observations at wavelengths longward of ~2.8 μm, it is necessary to invoke theoretical knowledge to extend the TSIS-1 HSRS into the longwave infrared. For these purposes, we use the computed solar spectrum of Kurucz (1995). This spectrum, which also has heritage in the solar input spectra available with the MODTRAN software package, spans 0.15–200 μm and contains 58 million solar lines. After reducing to coarser resolution it was reported (Kurucz, 1995) to match a model of the solar photosphere that had been evaluated, between 0.2 and 1.1 μm, against irradiance observations (Kurucz, 1992).

To increase the utility of the HSRS Extension in high-resolution applications, we replace the combination of predicted and observed solar lines in Kurucz (1995) with version 2020 of the SPTS solar line database (Toon, 2014). SPTS is an empirically-generated data set that contains the transmittance from solar absorption lines observed between 600 and 26316 cm^{-1} (0.38–16.6 μm) and sampled every 0.01 cm^{-1}. At wavelengths longward of ~2.8 μm, measured spectra from the Atmospheric Trace Molecule Spectroscopy Experiment (ATMOS) instrument during space shuttle missions (Farmer & Norton, 1989), supplemented with Mark IV (MkIV) balloon interferometer data (Toon, 1991) are the predominant observation source in the SPTS database (Toon

10.1029/2022EA002637

et al., 2015). Validation of these solar lines (Toon et al., 2015) was performed with Atmospheric Chemistry Experiment satellite observations (Hase et al., 2010) and MkIV balloon spectra. An iterative process, involving the HITRAN database (Rothman et al., 2005), identifies and removes telluric line contributions from molecules in Earth's atmosphere.

The spectral ratio method is used to scale the SPTS solar lines to the Kurucz (1995) irradiance scale. As described in Coddington et al. (2021) for a single-step convolution, the resolution of both data sets is first reduced using a Gaussian filter kernel of 0.1 μm full-width at half-maximum. Then, the ratio of the convolved data sets, after interpolation to a common sampling grid, is the smooth, wavelength-dependent, scaling factor that is used to adjust the SPTS solar lines to the Kurucz (1995) irradiance scale. The scaling factor has units of SSI ($W/m^2/\mu m$) and its shape approximates the solar continuum theorized by Kurucz (1995) when devoid of absorption and emission features. It adjusts broad features while leaving the fine spectral features undisturbed.

In a final step, a scalar adjustment factor is derived that merges Section A irradiances seamlessly with the TSIS-1 HSRS at 2.73 μm. The scaling factor, equal to 0.9939 or a reduction of ∼0.6%, is applied to all wavelengths. The integrated energy contained in Section A is 35.5 W/m^2, equivalent to 2.6% of the TSI.

3.2. Section B of the Infrared Extension From 16.5 to 200 μm

The computed spectrum of Kurucz (1995) alone specifies the HSRS Extension at wavelengths longward of 16.5 μm. A scalar factor of 0.9941 reduces the irradiance at all wavelengths by ∼0.6% in order to seamlessly merge Section B to Section A at 16.5 μm. The integrated energy contained in Section B is 0.2 W/m^2, equal to ∼0.01% of TSI.

3.3. The Ultraviolet Extension From 0.115 to 0.202 μm

Grating spectrometer observations of the Sun's ultraviolet (UV) irradiance from 2003 to 2020 by the Solar Stellar Irradiance Comparison Experiment (SOLSTICE) instrument (McClintock et al., 2005) on the Solar Radiation and Climate Experiment (SORCE) satellite mission (Rottman, 2005) specify the HSRS Extension below 0.202 μm. The primary SOLSTICE data product is a 1-nm-binned and daily-averaged spectrum, computed from many individual spectra of 0.1 nm spectral resolution and 0.025 nm sampling. In this work, we use version 18 SOLSTICE data (Snow et al., 2022) at its native, 0.1 nm, spectral resolution.

Specifically, the UV extension is the median of daily SORCE SOLSTICE irradiance observations taken from 23 March to 19 April 2009, which is a time period of minimum solar activity between solar cycles 23 and 24 that coincides with the superposition of the 11-year solar cycle and the ∼100-year Gleissberg solar activity cycle (Feynman & Ruzmaikin, 2014; Wang & Lean, 2021). The SOLSTICE data is appended, without scaling, to the TSIS-1 HSRS below 0.202 μm. The motivation for using SOLSTICE observations from the 2009 solar minimum, while the TSIS-1 HSRS represents observations from the following 2019 solar minimum, is given in Section 4.1. The integrated energy contained in the UV extension is 0.1 W/m^2, less than 0.01% of TSI.

4. Results

In this section, we present the full-spectrum extension of the Hybrid Solar Reference Spectrum (HSRS Extension), its associated uncertainties, and compare the integral of the HSRS Extension to the TSI.

Figure 2 shows the HSRS Extension at 0.1 to ∼0.001 nm spectral resolution and spanning 0.115–200 μm. Also shown is a 1-nm binned version. The data is shown on a log-log scale and spans 9 orders of magnitude in irradiance and 3 orders of magnitude in wavelength. The uncertainties, discussed next, have different interpretations depending on region of the spectrum. The detailed specifics of the HSRS Extension, including version 2 of the TSIS-1 HSRS and its variants at fixed spectral resolution, are given in Table 1.

4.1. Uncertainties

Below 0.202 μm, the total uncertainty is the root-sum square of the uncertainties in the published SORCE SOLSTICE data product, that account for instrument and pre-launch calibration uncertainty, and a stability

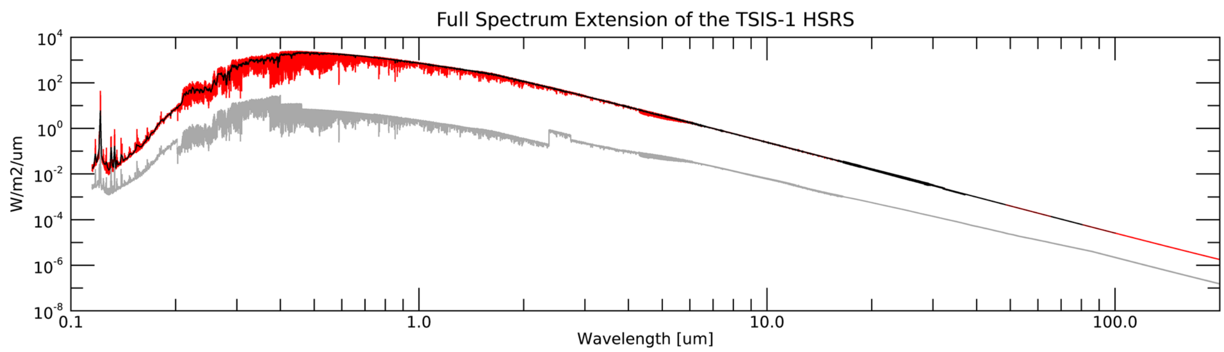

Figure 2. The Hybrid Solar Reference Spectrum (HSRS) Extension (red) and its associated uncertainties (gray) on a log-log scale. A variant of the HSRS Extension, integrated into 1-nm bins, is also shown (black).

uncertainty that reflects the accumulation in uncertainty from correcting for instrument degradation (Snow et al., 2022). Over the ~6-years of SOLSTICE operations from launch through 2009, these latter uncertainties are 1.2% for wavelengths smaller than 0.18 μm (0.2%/year) and 1.8% (0.3%/year) for wavelengths larger than 0.18 μm. Because the UV irradiance observed by SORCE SOLSTICE in the 2009 solar cycle minimum was

Table 1
Summary of the Hybrid Solar Reference Spectrum Extension and Version 2 of the TSIS-1 HSRS

File name	Low resolution data sets and wavelength coverage (μm)	High resolution datasets and wavelength coverage (μm)	Spectral resolution	Sampling resolution	Uncertainty (%)
HSRS Extension	SORCE SOLSTICE: 0.115–0.202	SORCE SOLSTICE: 0.115–0.202	Varies; equal to that of the high resolution datasets	0.001 nm	0.115 ≤ 0.202 μm ~ 2%–15%
	TSIS-1 SIM: 0.2–2.365	AFGL: 0.202–0.3065			0.202 ≤ 0.4 μm = 1.3
	CSIM: 2.365–2.73	QASUMEFTS: 0.3055–0.3736			0.4 ≤ 0.46 μm = 0.5
	Kurucz (1995) (reduced in magnitude by ~0.6%): 2.73–200	KPNO: 0.3735–0.745			0.46 ≤ 2.365 μm = 0.3
		SPTS: 0.743–16.5			2.365 ≤ 2.73 μm = 1.3
		Kurucz (1995) 16.5–200			2.73 ≤ 100 μm = 1%–8%
					100–200 μm = 8%
HSRS Extension "binned"	As above	As above	N/A; integrated into 1-nm bins	1 nm	As above

Listed below are the TSIS-1 HSRS (v2) and variants convolved to differing, fixed, spectral resolution (see text).

File name	Low resolution data sets and wavelength coverage (nm)	High resolution datasets and wavelength coverage (nm)	Spectral resolution (nm)	Sampling resolution	Uncertainty (%)
TSIS-1 HSRS (v2)	TSIS-1 SIM: 202–2365	AFGL: 202–306.5	Varies; equal to that of the high resolution datasets	0.001 nm	≤400 nm = 1.3
	CSIM: 2365–2730	QASUMEFTS: 305.5–373.6			400–460 nm = 0.5
		KPNO: 373.5–745			460–2365 nm = 0.3
		SPTS: 743–2730			>2365 nm = 1.3
TSIS-1 HSRS "p005 nm"	As above	As above	0.025 nm (below 374 nm)	0.001 nm	As above
			0.005 nm (above 374 nm)		
TSIS-1 HSRS "p025 nm"	As above	As above	0.025 nm	0.005 nm	As above
TSIS-1 HSRS "p1nm"	As above	As above	0.1 nm	0.025 nm	As above
TSIS-1 HSRS "1 nm"	As above	As above	1 nm	0.1 nm	As above

Note. Column 2 details the spectral range of the low-resolution data sets. Column 3 is as column 2 but for the high-resolution datasets. Columns 4 and 5 are the spectral and sampling resolutions, and column 6 is the total uncertainty. The spectral resolution of variants of the TSIS-1 HSRS (v2), at fixed spectral resolution, is defined by the full-width half-maximum value of the Gaussian convolution kernel.

identical, within instrument uncertainty, to that observed during the 2019 solar cycle minimum (not shown), we chose the irradiances from the 2009 period, with smaller total uncertainty, for developing the HSRS Extension.

From 0.202 to 2.73 μm, the approach to estimating the uncertainties for version 2 of the TSIS-1 HSRS is unchanged from that of the original release (Coddington et al., 2021). Specifically, the uncertainty is the root-sum-square of the TSIS-1 SIM and CSIM measurement uncertainties, including those incurred from instrument degradation corrections, and the uncertainty in the methodology to scale the solar lines to the high-accuracy spectrum. Because the methodology uncertainty is assessed at the coarser spectral resolution of the SIM instruments and over broad portions of the spectrum, the total uncertainties for version 2 are unchanged from the original release and equal to 0.3% over most of the spectrum, increasing to 1.3% below 0.4 μm and longward of 2.365 μm. The integrated energy in this part of the spectrum, 1327 W/m^2, is also unchanged from the original release.

At wavelengths longward of 2.73 μm, due to the lack of observations, we can only estimate an uncertainty from our available resources. Here, we assign the uncertainty as equal to the magnitude of the difference between the Kurucz (1995) irradiance level and that given by a different model of the Sun's irradiance (Fontenla et al., 2011), after smoothing with a 2-μm Gaussian convolution kernel to remove any high-frequency signatures attributed to discrepancies at individual lines. The magnitude of this difference is approximately 1% at 2.7 μm and reaches 8% by 100 μm. At all wavelengths, therefore, the difference between two independent approaches to predicting the Sun's infrared spectrum exceeds the ~0.6% scaling we needed to apply to adjust sections A and B of the HSRS Extension to match the TSIS-1 HSRS at 2.73 μm. At wavelengths longer than 100 μm, where Fontenla et al. (2011) data is not reported, we simply assign the same percentage uncertainty as at 100 μm.

4.2. Scaling to TSI

Observations of the TSI from the TSIS-1 Total Irradiance Monitor (TIM) instrument (https://lasp.colorado.edu/lisird/data/tsis_tsi_24hr/), averaged over the Dec 1-7, 2019 time period, are equal to 1361.52 ± 0.2 W/m^2. TSIS-1 TIM observations support the TSI value from the SORCE TIM observations (Kopp & Lean, 2011). The HSRS Extension, produced with the datasets as described in Section 3 and the uncertainties as described in Section 4.1, integrates to 1362.8 ± 5.8 W/m^2 and agrees with the TSIS-1 TIM observations to within uncertainties. However, because the primary motivation for developing the HSRS Extension is for applications used in climate studies where a spectrum integrating to TSI is desired, we reduce the spectral irradiance at all wavelengths by less than 0.1% by multiplying with a scaling factor of 0.999061. This overall adjustment falls within the uncertainties at all wavelengths.

5. Conclusions

Version 2 of the TSIS-1 Hybrid Solar Reference Spectrum (TSIS-1 HSRS) is an incremental update to a solar minimum irradiance reference spectrum, spanning 0.202–2.73 μm, that has been formally recognized as an important new constraint for science analyses in a broad array of fields. It has high accuracy (0.3%–1.3%) and high spectral resolution (0.01–~0.001 nm). The high spectral resolution comes from normalizing solar line data to the absolute irradiance scale of the TSIS-1 SIM and CSIM instruments. Version 2 fixes an error in the radiometric baseline between 0.202 and 0.210 μm and updates the solar lines at wavelengths longward of 0.743 μm to the most recent database. Primary impacts of the solar line updates are in the 1.1–1.3 μm range.

The full-spectrum extension (HSRS Extension), spanning 0.115–200 μm, builds upon the foundations of the TSIS-1 HSRS using SORCE SOLSTICE observations at 0.1 nm spectral resolution below 0.202 μm and high spectral resolution solar line data normalized to a predicted spectrum, followed by <1% adjustment to match the TSIS-1 HSRS, at wavelengths longward of 2.73 μm. Where available, the observed and predicted solar lines of the theoretical spectrum at wavelengths longer than 2.73 μm are replaced by those from an observation-based, empirical, solar linelist. Between 0.202 and 2.730 μm, the HSRS Extension is equivalent to the TSIS-1 HSRS (version 2). We provide the TSIS-1 HSRS and the HSRS Extension datasets in separate files due to their large volume and in recognition that not all applications will require the wavelength coverage given by the full-spectrum extension.

Notably, the integral of the HSRS Extension (1362.8 ± 5.8 W/m^2) agrees with space-based TSI observations to within uncertainties. *A* < 0.1% adjustment, applied by multiplying the irradiance at all wavelengths with a scaling factor of 0.999061, ensures the integral of the HSRS extension is identically equal to TSI observed by the TSIS-1

TIM instrument. We attribute our ability to achieve this result to the observations of the SSI by the TSIS-1 SIM and CSIM instruments, between 0.2 and ~2.8 μm, that constrain the absolute magnitude of the solar spectrum to higher SSI accuracy than predecessor instruments over a spectral range that exceeds 97% of the energy in TSI.

Data Availability Statement

Version 2 of the TSIS-1 HSRS is published at https://doi.org/10.25980/ta3f-7h90 and the HSRS Extension is published at https://doi.org/10.25980/249q-fs39. The creation of these data sets utilized the following sources: The original TSIS-1 HSRS published at https://doi.org/10.25980/34v1-xk83, the Kurucz (1995) theoretical model published at http://kurucz.harvard.edu/sun/irradiance/irradiancebins.dat, and the 2020 version of the JPL Solar Pseudo-Transmittance Spectrum (SPTS) published at https://mark4sun.jpl.nasa.gov/toon/solar/solar_spectrum.html. The TSIS-1 mission TSI and SSI data products are available from LASP at https://lasp.colorado.edu/home/tsis/data/ and also archived at the Goddard Earth Sciences Data and Information Services Center (GES-DISC) at https://disc.gsfc.nasa.gov/datasets?project=TSIS.

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