



Can measurements of the near-infrared solar spectral irradiance be reconciled? A new ground-based assessment between 4000-10000 cm⁻¹

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Elsey, J., Coleman, M. D., Gardiner, T. and Shine, K. P. (2017) Can measurements of the near-infrared solar spectral irradiance be reconciled? A new ground-based assessment between 4000-10000 cm⁻¹. *Geophysical Research Letters*, 44 (19). pp. 10071-10080. ISSN 0094-8276 doi: <https://doi.org/10.1002/2017GL073902> Available at <http://centaur.reading.ac.uk/72842/>

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Published version at: <http://dx.doi.org/10.1002/2017GL073902>

To link to this article DOI: <http://dx.doi.org/10.1002/2017GL073902>

Publisher: American Geophysical Union

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RESEARCH LETTER

10.1002/2017GL073902

Key Points:

- In light of continuing disagreement in observations of near-infrared solar spectral irradiance (SSI), we present a new SSI with full uncertainty evaluation
- This SSI shows good agreement with the commonly-used ATLAS3 SSI at shorter wavelengths but is ~7% lower at longer wavelengths
- This discrepancy is significant since the near-infrared contains several strong water vapor bands, which influence the atmospheric energy budget

Supporting Information:

- Supporting Information S1
- Data Set S1

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Citation:

Elsey, J., Coleman, M. D., Gardiner, T., & Shine, K. P. (2017). Can measurements of the near-infrared solar spectral irradiance be reconciled? A new ground-based assessment between 4,000 and 10,000 cm^{-1} . *Geophysical Research Letters*, 44, 10,071–10,080. <https://doi.org/10.1002/2017GL073902>

Received 8 MAY 2017

Accepted 17 SEP 2017

Accepted article online 22 SEP 2017

Published online 13 OCT 2017

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Can Measurements of the Near-Infrared Solar Spectral Irradiance be Reconciled? A New Ground-Based Assessment Between 4,000 and 10,000 cm^{-1}

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Abstract The near-infrared solar spectral irradiance (SSI) is of vital importance for understanding the Earth's radiation budget, and in Earth observation applications. Differences between previously published solar spectra (including the commonly used ATLAS3 spectrum) reach up to 10% at the low wavenumber end of the 4,000–10,000 cm^{-1} (2.5–1 μm) spectral region. The implications for the atmospheric sciences are significant, since this spectral region contains 25% of the incoming total solar irradiance. This work details an updated analysis of the CAVIAR SSI, featuring additional analysis techniques and an updated uncertainty budget using a Monte Carlo method. We report good consistency with ATLAS3 in the 7,000–10,000 cm^{-1} region where there is confidence in these results due to agreement with other spectra, but ~7% lower in the 4,000–7,000 cm^{-1} region, in general agreement with several other analyses.

Plain Language Summary The total energy arriving to Earth from the Sun is well known, but how much of this is visible; ultraviolet or infrared light is also important. This paper presents measurements of the Sun's infrared energy that reaches Earth. This infrared energy heats up the atmosphere as it is absorbed by the surface and by gases such as carbon dioxide and water vapor. Knowing how much of this infrared energy reaches us is important for weather prediction and for simulations of climate change (which depends on the amount of energy arriving at and leaving the atmosphere). Previous measurements of the Sun's infrared energy from both the ground and from satellites show significant disagreement. Our measurements help resolve this disagreement, and will enable more accurate representation of the Sun's infrared energy in weather and climate predictions.

1. Introduction

The top of atmosphere incoming solar spectral irradiance (SSI) is identified by the Global Climate Observing System as an “essential climate variable” (Bojinski et al., 2014). It is the primary driver of meteorological processes, through absorption and scattering of radiation (Stephens et al., 2012). It is therefore essential to ensure that this quantity is well constrained.

Observations of SSI have been performed over the last 50 years (e.g., the pioneering airborne study of Arvesen et al., 1969). Many recent SSI measurements (primarily from space-based instruments) have focused on ultraviolet wavelengths, since these are difficult to measure on Earth due to absorption by oxygen and ozone in the stratosphere and mesosphere (e.g., Fligge et al., 2001), and the large variation in the UV over the 11 year solar cycle (Fröhlich & Lean, 2004). There has been a comparative dearth in measurements of spectral region between 4,000 and 10,000 cm^{-1} (2.5–1 μm , henceforth referred to as the near infrared (NIR)), due to the difficulty in maintaining the stability or sensitivity of space-borne spectroradiometers. About 25% of the Sun's energy reaches Earth in this spectral region, which makes it important for quantifying the global energy budget, particularly since it is home to several strong water vapor, CO_2 , and other absorption bands. Many meteorological models use the semiempirical spectrum from Kurucz and Bell (1995), for example, Walters et al. (2014). Such solar models derive directly the line structure and envelope and tie these to observations. The Kurucz and Bell spectrum shows a similar absolute level to the ATLAS3 (ATmospheric Laboratory for Applications and Science) spectrum from Thuillier et al. (2003). This is an issue, however, as recent measurements report a NIR SSI which is up to 8% lower than ATLAS3 (see section 2 for details).

This controversy has primarily manifested itself in the solar physics literature, but it is of significant importance for the understanding of atmospheric processes, as SSI is a vital input into radiative transfer schemes used in climate and weather models, and in passive remote sensing systems such as MODIS (MODerate

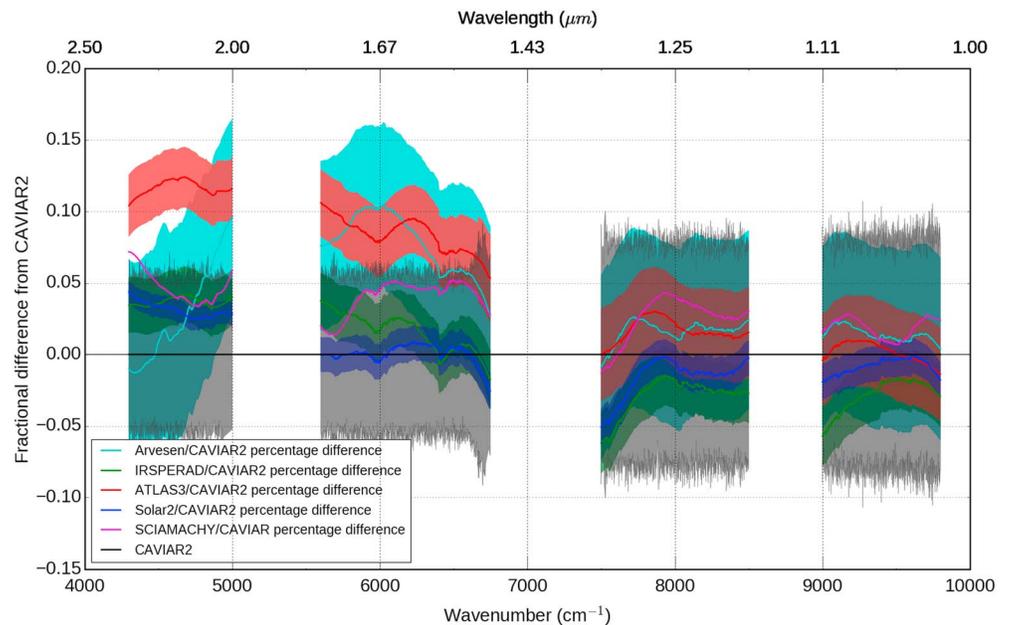


Figure 1. Fractional deviation of various solar spectra from the CAVIAR2 spectrum derived in this work. The shaded regions show the reported $k = 2$ uncertainties associated with each spectrum. The gaps show regions in which water vapor absorption is too strong to retrieve the spectrum from the ground. These spectra have been smoothed over 15 cm^{-1} , to remove the effect of solar lines which are present in the original CAVIAR2 high-resolution measurements.

Imaging Spectroradiometer, Platnick & Fontenla, 2008; Thome et al., 2001). For example, Menang and Shine (2013) found that using different NIR SSI from recent observations leads to $\sim 8\%$ differences in atmospheric absorption and heating rates. It is therefore important to measure the SSI as accurately as possible from a number of independent sources. This work presents an update to the CAVIAR (Continuum Absorption in the Visible and Infrared and its Atmospheric Relevance) SSI (Menang et al., 2013), in an attempt to reconcile these differences, referred to here as CAVIAR2. This analysis features an updated calibration and uncertainty budget and uses an additional method of deriving SSI to cross-check our results.

2. Current State of Measurements

Most modern measurements of SSI are either performed at ground sites or used airborne or space-based instrumentation. The first such campaign was the pioneering study by Arvesen et al. (1969), using an aircraft-based spectrometer measuring across the spectrum from the ultraviolet to the near IR. Typically however, these efforts have focused on the visible and ultraviolet parts of the spectrum. A major step forward in measuring the NIR SSI from space was the ATLAS3 spectrum from Thuillier et al. (2003), which presented SSI out to $2.4 \mu\text{m}$. This was developed using measurements from the SOLSPEC (SOLAR SPECTROMETER) instrument and was used as to constrain the SSI derived from semiempirical models of the photosphere (e.g., Fontenla et al., 2006). Figure 1 shows the fractional deviations of some recent spectra (including ATLAS3) from the result presented in section 5 of this work and the associated coverage factor $k = 2$ (95% confidence) uncertainty limits of each. There is consistency between CAVIAR2, ATLAS3 and the other spectra shown between $7,000$ and $10,000 \text{ cm}^{-1}$ ($1.4\text{--}1 \mu\text{m}$), but this is not the case between $4,000$ and $7,000 \text{ cm}^{-1}$ ($2.5\text{--}1.4 \mu\text{m}$). This emphasizes the lack of consensus between ATLAS3 and alternative sources, where deviations vary between 5 and 10% over large portions of the spectrum and exceed the quoted $k = 2$ measurement uncertainties. There is, however, better agreement between several of the other spectra, the impact of which will be discussed later.

Aside from ATLAS3, of particular interest here are the spectra obtained from Thuillier et al. (2014), henceforth referred to as Solar2, and that from Bolsée et al. (2014). The Solar2 spectrum was obtained using SOLSPEC (an updated version of the instrument used for ATLAS3). This spectrum was taken using measurements made immediately after the instrument was launched into space, and therefore closest in time to its absolute

calibration (performed using a 3,000 K blackbody). This spectrum was ~8% lower than ATLAS3 between 2.5 and 1.6 μm . A reanalysis of this data (Solar2rev) was presented in Thuillier et al. (2015) and was in better agreement with ATLAS3; Thuillier et al. (2015) state that they believe ATLAS3 to be more reliable than either spectrum. This adjustment of Solar2 was justified by readings of the low-power tungsten ribbon lamp used to assess calibration drift in-flight; the signal obtained using this lamp reached an “equilibrium” state 2 years after launch, closely matching the signal observed during preflight calibration. The authors note that they “have no clear explanation” for the drift and note that “it is most likely due to some temperature effect and/or the outgassing of the instrument” (see BenMoussa et al., 2013 for details on how this may occur).

The justification used by Thuillier et al. (2015) to favor ATLAS3 over Solar2 has caused controversy (Bolsée et al., 2016; Weber, 2015). This represents an issue with the reliance on space-based measurements of SSI, since the calibration and optical setup of these instruments is more difficult to reliably assess compared to those on the ground. Space-based measurements do in principle provide the best form of SSI measurement, as use of neither a radiative transfer model (RTM) nor measurements with varying solar zenith angle (SZA) are required; achieving this in practice, however, is extremely difficult. This is illustrated by the disagreements in the processing of the SOLSPEC data. Also, as shown in Harder et al. (2010), SIM (Spectral Irradiance Monitor) measurements (used, e.g., in Coddington et al., 2015) are 8% lower than ATLAS3 at wavelengths higher than 1.5 μm ; the SIM spectrum is adjusted in this region to agree with ATLAS3. This adjustment is justified by the authors’ statement that the uncertainty in SIM is higher than that in ATLAS3. Hence, the data from SIM are not independent from ATLAS3 (and is therefore not shown in Figure 1). SSI data from the SCIAMACHY (Scanning Imaging Absorption Spectrometer for Atmospheric Cartography/Chemistry) satellite instrument (Weber, 2015) are also lower than ATLAS3 at 1.6 μm , with a spectral shape broadly consistent with Solar2. Weber (2015) shows that the SCIAMACHY spectra are all consistent with one another in this region, contrary to the claims of Thuillier et al. (2015).

There is agreement between the airborne spectrum of Arvesen et al. (1969) and ATLAS3 at ~1.6 μm , with better agreement with CAVIAR2 toward 2.5 μm . The degree of this agreement changes strongly with wavenumber, however, and at 2.4 μm there is no agreement between ATLAS3 and Arvesen et al. even within the $k = 2$ uncertainties. The Arvesen et al. analysis uses the Langley method, but the variation with solar zenith angle was derived from measurements made on different days and at markedly different locations. Thus, the effect of varying water vapor may have large implications for their derived SSI, particularly in the band regions of strong absorption. The Arvesen et al. measurements also predict a total solar irradiance (TSI) of 1,390 W m^{-2} , above the 1,360 W m^{-2} from contemporary sources (Kopp & Lean, 2011). Accounting for this difference would bring their values closer toward agreement with CAVIAR2 between 2.5 and 1.4 μm , assuming that this adjustment was applied evenly across the spectrum. It is important to emphasize here that within the uncertainties, there is consistency between Arvesen et al. and CAVIAR2 in the entire 4,000–10,000 cm^{-1} range.

Bolsée et al. (2014) presented an additional set of measurements from a ground-based spectrometer at the Izaña meteorological station in Tenerife, Spain, henceforth referred to as IRSPERAD (InfraRed SPectroRADiometer). This spectrum (see Figure 1) was found to be in modest agreement at 1.6 μm with the lower (Solar2) values of the solar irradiance reported in Thuillier et al. (2014). At lower wavenumbers, these also agreed with the similar ground-based measurements of Menang et al. (2013), using an absolutely calibrated high-resolution spectrometer.

There are several drawbacks with the use of ground-based instruments, principally stemming from the fact that any observing system must look through the atmosphere, which leads to attenuation of the solar signal by absorption and scattering. However, these can be mitigated through the careful use of various techniques such as the Langley method, or the use of a radiative transfer code, provided they are applied in relatively transparent regions between major atmospheric absorption bands. Thuillier et al. (2015) suggests that the use of ground-based methods could lead to incorrect SSI values because of “residual atmosphere absorption and aerosol scattering that consequently can make ground measurements necessarily lower than the space measurements.” We demonstrate here that this is not the case. Aerosol scattering is the most important source of extinction in the microwindows in between individual spectral lines in this region, typically contributing up to 90% of the overall optical depth in the center of the 1.6 μm window. However, the absolute value is small (on the order of 0.03 optical depths) and therefore has minimal effect on SSI retrievals. In our

case, any changes in aerosol optical depth are automatically accounted for in the Langley method if the atmospheric state is constant throughout a day of measurements, or incorporated into the uncertainty budget from the Monte Carlo method (see section 4 for more details).

Scattering by water vapor and other gases also affects the observed radiation. This Rayleigh scattering can be calculated easily in the NIR. Bucholtz (1995) shows that for a midlatitude summer atmosphere (comparable to the conditions in this work), the Rayleigh scattering optical depth is 8.67×10^{-3} at $1 \mu\text{m}$, reducing to 1.315×10^{-3} at $1.6 \mu\text{m}$. This is less than 5% of the overall optical depth in the center of this window and does not significantly vary over the course of a day; any impact on the derived SSI will be minimal.

Similarly, absorption due to water vapor in the atmospheric windows has minimal effect on SSI. Menang et al. (2013) demonstrated that even for a 20% systematic change in absolute humidity over the course of a day, the effect on the derived SSI in the windows is less than 1%.

It is important to emphasize that if the optical depth contributions from any of these effects are constant throughout a day, then they will be removed by the Langley method (see section 3.1). Variability can be detected via changes in the observed direct current voltage and filtered out or can be included within the statistical uncertainty estimates. The estimates presented in the last paragraph apply to the sea-level Camborne field site used here and in Menang et al. (2013); the high-altitude field site used by Bolsée et al. (2014) is less affected. We also note that the optical depth from aerosol and Rayleigh scattering is strongly wavenumber dependent and is largest at the higher wavenumbers ($7,000\text{--}10,000 \text{ cm}^{-1}$) where we show that the various spectra agree well (Figure 1).

An additional advantage of ground-based measurements is the high spectral resolution that can be achieved. For example, Gardiner et al. (2012) presents a calibration method suitable for measurements of the Sun at the 0.03 cm^{-1} resolution presented in this work. By contrast, SOLSPEC has a resolution of 4 cm^{-1} at $1 \mu\text{m}$. The optical alignment of a ground-based setup can be constantly monitored and adjusted, in a way which is generally difficult on a satellite. There is also more scope for assessing the calibration drift of a ground-based instrument.

The lack of agreement in the near-IR SSI among the various data sets (both space and ground based) is clearly a serious issue. Accepting that there are advantages and disadvantages of all observing systems, there is nevertheless a requirement that they should agree within their respective uncertainties, and that agreement between independent measurements gives the most confidence in any result. This is clearly not the case at present.

3. Analysis Methods

Section 5 will focus on two methods of deriving SSI from a ground-based setup; the Langley method and the radiative closure method. These methods have their own distinct advantages and disadvantages, and together provide a quasi-independent assessment of SSI even when using the same observations. To increase the confidence in these methods, it is ideal to use measurements from as many days as possible and to constrain the atmospheric state to minimize the effect of changes throughout a day, particularly in the case of the Langley method.

The irradiance reaching the surface from the Sun is described by the Beer-Bouguer-Lambert law

$$I(\nu) = I_0(\nu) \exp(-m(\theta)\tau(\nu)) \quad (1)$$

where ν is spectral wavenumber, I is the irradiance measured at the surface, I_0 is SSI, τ is the atmospheric optical depth (including absorption and scattering), and m is the airmass factor as a function of SZA θ .

3.1. Langley Method

The Langley method is a commonly used method of measuring both τ (calibrating Sun photometers, for example) and SSI (e.g., Arvesen et al., 1969; Bolsée et al., 2014; Menang et al., 2013). The method is based on equation (1). The second-order effects of atmospheric refraction and the Earth's curvature are neglected here. The technique is not suitable for measuring in spectral regions where there is strong absorption.

From equation (1), by taking the natural logarithm of both sides, we obtain;

$$\ln(I(v)) = \ln(I_0(v)) - \tau(v)m(\theta) \quad (2)$$

Assuming constant SSI and τ , equation (2) describes a linear relationship between the logarithm of the observed intensity and the airmass factor allowing an estimate of τ from the gradient of the slope, and $\ln(I_0)$ from the intercept. Since data points are taken at discrete intervals throughout a day, an ordinary least squares fit is performed to the data. Assuming τ is constant throughout the day, the derived SSI is independent of τ . It is desirable to take measurements over a wide range of airmass factors, and as the technique relies on the assumption of constant τ , it is preferable to have at least 1 day of mostly clear skies. There should also be supplementary atmospheric measurements to monitor any variations in τ .

3.2. Radiative Closure Method

The radiative closure method also exploits equation (1). In this case, we calculate SSI from the measured irradiance and independent estimates of τ . Here τ is calculated using the Reference Forward Model (RFM) (Dudhia, 2017), using line parameters from the HITRAN2012 spectroscopic database (Rothman et al., 2013), continuum absorption (Shine et al., 2016) from MT_CKD 2.5 (Mlawer et al., 2012), and atmospheric profiles from coincident radiosonde ascents (see section 4.3). It is necessary to focus on atmospheric windows between strong absorption bands. In contrast to the Langley method; one can derive the SSI with a single observation provided there are clear skies. However, the reliance on an RTM (and knowledge of the atmospheric state) introduces additional uncertainty into the final value. For high-resolution measurements, any error in the strength or position of spectral lines in the RTM could result in incorrect SSI, necessitating filtering (see section 4.4). The Langley-derived values are preferred to those from the closure method, since the lack of reliance on a model means that there is less uncertainty. However, the closure-derived spectra provide an important consistency check.

4. Experimental Methods

We use measurements taken during a field campaign between August and September 2008 at Camborne, UK (50.219°N, 5.327°E). These used an absolutely calibrated Sun pointing Fourier transform spectrometer (FTS) at 0.03 cm⁻¹ resolution over the region 2,000–10,000 cm⁻¹ (5–1.6 μm). The precampaign calibration phase took place at the National Physical Laboratory (NPL), UK (see Gardiner et al., 2012). Our analysis focuses primarily on measurements of 22 August and 18 September 2008; these days had clear-sky conditions over sufficient SZA for use of the Langley technique.

4.1. Calibration

The spectrometer calibration is discussed by Gardiner et al. (2012). To produce a reliable SSI, measurements must be radiometrically calibrated against an irradiance source of comparable magnitude. Our spectrometer was calibrated against the ultrahigh temperature blackbody (UHTBB), based at NPL which is capable of reaching temperatures around 3,000 K, and is directly traceable to the International System of Units (BIPM, 2006). While this system is not directly comparable to the effective temperature of the Sun's surface, the attenuation experienced in the UHTBB system is minimal, whereas the solar signal travels through the atmosphere. The integrated intensity measured by the spectrometer during solar measurements is therefore comparable to that of the UHTBB, giving similar behavior and minimizing potential detector response issues.

The UHTBB is not transportable; as such, a transfer source was used in the field to assess calibration drift. The spectra from Menang et al. (2013) include a correction from this transfer source; however, as a result of further analysis of the stability of this source, this correction was not applied in this work.

In addition, the instrument relies on an external optical setup which is exposed to the elements (Gardiner et al., 2012). This results in a loss of mirror reflectivity over time, which must be corrected for, but this was not done in Menang et al. (2013). Measurements of mirror reflectivity were taken before and after the measurement campaign, with the reflectivity values after the campaign taken as representative of the mirror reflectivity during the campaign. Hence, the reflectivity adjustment is likely an overestimate, which could

potentially result in an overestimate of the derived SSI. The potential for this overestimate is accounted for in the uncertainty budget.

4.2. Spectrometer Measurement Uncertainty

The uncertainty in the FTS setup comes primarily from four sources. The first arise from the calibration procedure (including the calibration checks from the transfer source). The second are from the solar source and atmospheric path itself (particularly the nonuniformity of the solar disc, and the effect of subvisible cirrus). The third are uncertainties arising from the external optics, and the fourth is the uncertainty from the spectrometer itself, including optical alignment. The combined ($k = 1$) measurement uncertainty varies with wavenumber, between around 3.3% in the region where the tracker optics had been directly measured before and after the campaign with a reference reflectometer and up to a maximum of 5.9% outside of this region. Gardiner et al. (2012) present a detailed assessment of the measurement uncertainties.

4.3. Atmospheric State Analyses

Data were obtained from Vaisala RS92-SGP radiosonde (Vaisala, 2013) launches from Camborne, analyses from the UK Met Office, and Microtops Sun photometer measurements (Solar Light Company, 2001). These include estimates of aerosol optical depth (AOD), temperature, pressure, and water vapor profiles of the atmosphere. All other relevant gases are considered to be well mixed. These are necessary for quantification of the SSI from the closure method, since in conjunction with an RTM, they provide values of the atmospheric optical depth. More information is presented in the supporting information Figure S1. The AOD values for the relevant spectral region are calculated from the Sun photometer measurements using the Ångström exponent method (Schuster et al., 2006).

4.4. Filtering of Observed Spectra

To focus on the higher quality data, several filtering methods were used to remove regions of strong absorption, not only in the bands but also in areas of strong absorption within windows, such as individual water vapor lines. These filters also mitigate or remove the effect of subvisible clouds and other time-varying extinction sources. This filtering follows the procedure of Menang et al. (2013) and is not discussed further here.

5. Results and Discussions

The results presented here have been normalized to 1 astronomical unit. The Langley-derived spectrum from 18 September 2008 is our best estimate of the SSI (as discussed in Menang et al., 2013) and is referred to as CAVIAR2.

The uncertainty in CAVIAR2 is obtained using a Monte Carlo uncertainty evaluation method (see supporting information Figures S2 and S3). The Langley method uses multiple measurements, which each have a random component which varies from measurement to measurement, and a systematic component which is in principle the same for all the measurements across a day (see Gardiner et al., 2012). The use of a Monte Carlo method allows the different effects of the random and systematic components on the Langley results to be rigorously assessed. This distinction is not considered in the treatment of Menang et al. (2013), which leads to a less rigorous assessment of the overall uncertainty as the random effect (which will mostly average out across a day provided there are enough samples) is treated as the same for all spectra. The spectra presented in the figures use the resolution of the Monte Carlo simulations (1 cm^{-1}); a spectrum at full resolution (0.03 cm^{-1}) is available in the supporting information, with fractional uncertainties interpolated from the Monte Carlo derived uncertainty (which varies smoothly with wavenumber). The lower spectral resolution does not affect the envelope of the spectrum.

The uncertainty in the closure method is obtained using the measurement uncertainty from Gardiner et al. (2012), with an additional uncertainty due to the use of the RTM (see Text S1 in the supporting information). Figure 2 shows the mean of the closure-method spectra from 2 days' worth of measurements, alongside CAVIAR2 from 18 September 2008, and their associated $k = 2$ uncertainties. There is a high level of consistency between the spectra derived using these two quasi-independent methods. Given the fact that the measurements are taken on differing days with differing meteorological conditions, the agreement between these spectra indicates that neither the methodology nor the atmospheric state bias the results.

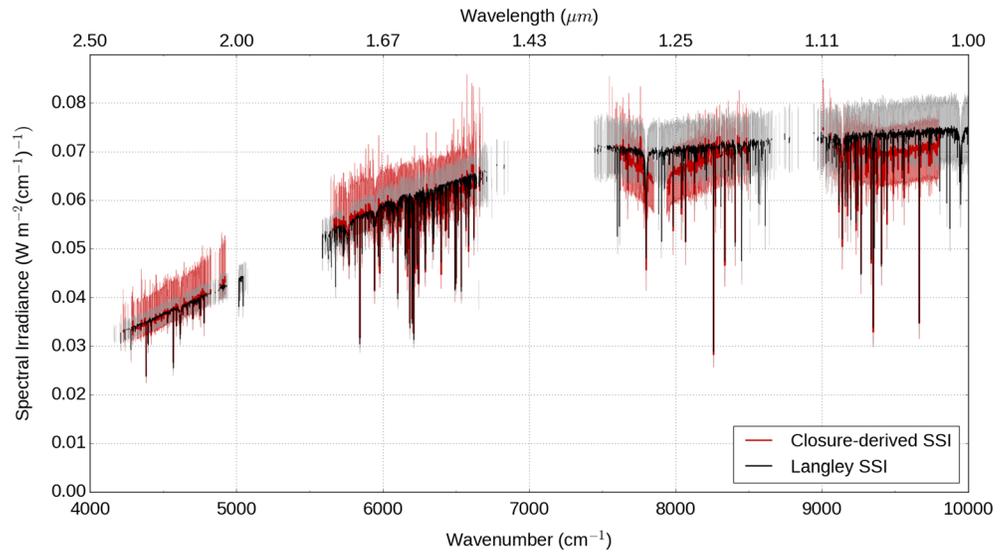


Figure 2. Derived CAVIAR spectra using both the Langley method and the mean of radiative closure method over 2 days of measurements, and their associated $k = 2$ uncertainties. The gray shaded region indicates the uncertainty in the Langley-derived values, and the red that in the closure-derived values. The feature at 8000 cm^{-1} in the closure-derived spectra is an oxygen continuum band not modeled in the RFM.

Figure 3 shows CAVIAR2 alongside ATLAS3 and Solar2. Our measurements in the $7,000\text{--}10,000 \text{ cm}^{-1}$ region are consistent with both ATLAS3 and Solar2. Our confidence in the space-based instruments is good in this region, and the uncertainties in CAVIAR2 are relatively large. The quoted values lie very close to one another even without considering the larger uncertainties. This is in contrast with Menang et al. (2013), in which there was an underestimation of the SSI in this region relative to ATLAS3, due to the missing mirror reflectivity correction (see Figure S4 in the supporting information). The level of consistency between ATLAS3 and CAVIAR2 in this region is indication that any differences are not a systematic effect across the spectrum. There is also

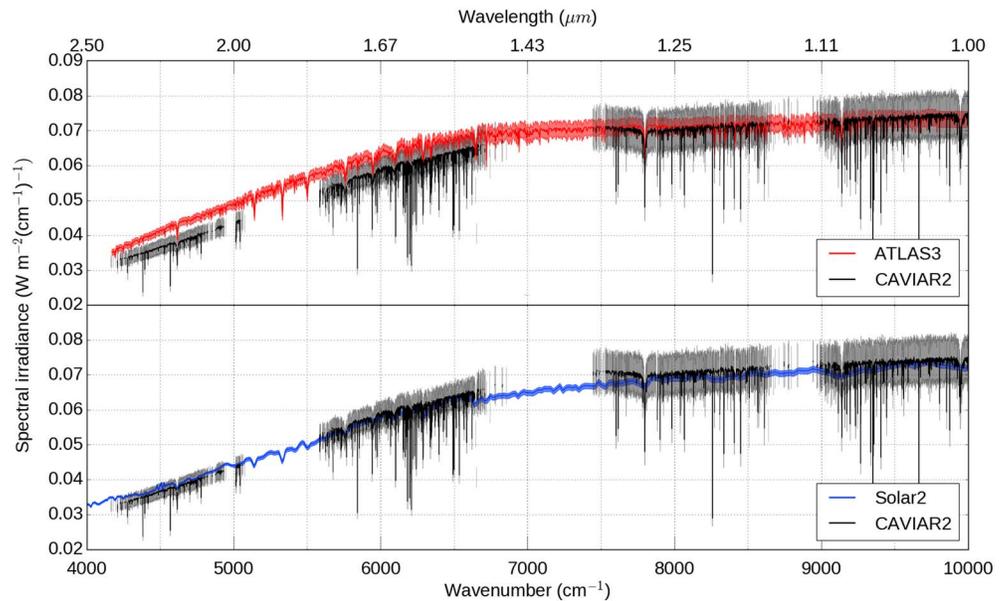


Figure 3. Derived spectra from this work and the ATLAS3/Solar2 spectra, with associated $k = 2$ uncertainties.

broad consistency between the fine structure of the two spectra; however, the higher spectral resolution of CAVIAR2 means that a direct comparison is not possible.

Given the 1–3% uncertainty quoted in Thuillier et al. (2003), there is poor agreement between the spectrum derived in this work and ATLAS3 between 4,000 and 7,000 cm^{-1} . There is good agreement between this work, IRSPERAD and Solar2 in this region (as shown in Figure 1). This weight of data provides a clear indication that the NIR SSI is well represented by these spectra, since there is agreement not only between several independent ground-based spectra but also from the initial SOLSPEC measurements used to derive Solar2. There is also some consistency between this and the unexplained 8% difference between the NIR SSI from SIM relative to ATLAS3 (see section 2). Relative to the other spectra (e.g., in Figure 1), CAVIAR2 appears to show larger values in the region starting at $\sim 6,700 \text{ cm}^{-1}$ and ending at $\sim 7,700 \text{ cm}^{-1}$. This is likely to due to a combination of the mirror reflectivity correction (which is an extrapolation beyond $6,600 \text{ cm}^{-1}$), and the stronger water vapor absorption since these data are on the edges of the windows where any effects due to changing water vapor start to become more significant (Menang et al., 2013). Nevertheless, the uncertainty budget accounts for these effects and consistency within these uncertainties is maintained for all the spectra (the increased uncertainty brings it into consistency with ATLAS3 in this narrow region).

6. Conclusions

The uncertainty in near-infrared observations of the SSI is an important issue in atmospheric and solar sciences. We have presented an improved reanalysis of the high-resolution CAVIAR SSI from Menang et al. (2013), with updated uncertainty estimates and calibration, incorporating additional analysis methods and data. This reanalysis shows excellent agreement with various spectra in the 7,000–10,000 cm^{-1} (1.4–1 μm) region (Figure 1). In the 4,000–7,000 cm^{-1} (2.5–1.4 μm) region we show good agreement with Bolsée et al. (2014) and Solar2 (Thuillier et al., 2014), but significant ($\sim 7\%$) differences from the ATLAS3 spectrum of Thuillier et al. (2003) and the revised Solar2rev spectrum from Thuillier et al. (2015). We demonstrate that our results are fundamentally consistent with the spectrum of Arvesen et al. (1969) within the $k = 2$ uncertainties, which has varying levels of agreement with our work and ATLAS3 across the 4,000–7,000 cm^{-1} region. We believe that our data set is a significant evidence in favour of the lower SSI in this spectral region due to our more robust calibration, agreement with the various solar spectra in the high-frequency end of the NIR (in contrast with Menang et al., 2013), our rigorous uncertainty budget, and the agreement between various sets of measurements at different sites with different calibration and methodology.

We question the arguments expressed in Thuillier et al. (2015) regarding the uncertainty of the ground-based methods. We find no evidence that residual atmosphere absorption could lead to a significant bias in our derived SSI. In addition, the optical depth due to aerosols and Rayleigh scattering is highest toward 1 μm , where there is much better agreement between the spectra. Their argument also does not resolve the reason for differences between the various space-based measurements. Given the range of NIR measurements and our detailed assessment of the uncertainty in our measurements, we question whether ATLAS3 should be regarded as a reference spectrum at wavelengths greater 1.3 μm .

The measurements presented in this work are taken close to solar minimum. However, in the near-IR the variation due to solar cycles contributes on the order of 0.25% at 1.6 μm (Coddington et al., 2015; Lean & DeLand, 2012), well below the 7% difference between this work and ATLAS3. The 27 day solar variability also has little effect, since there were only five sunspots observed on 22 August and none on 18 September (SIDC, 2008).

These results have significant implications on our understanding of the total solar irradiance. Using the stated values of ATLAS3 and CAVIAR2 and integrating over the region 4,000–10,000 cm^{-1} (interpolating the absolute level in the band regions, with lines from Kurucz & Bell, 1995), we find that as a central estimate CAVIAR2 is $\sim 16 \text{ W m}^{-2}$ (4.5%) lower than ATLAS3. This is less than the 8% of Menang et al. (2013), primarily because of the better consistency beyond 8,000 cm^{-1} . As pointed out in Weber (2015), a reduction in SSI in the NIR can be accounted for not only by uncertainties elsewhere in the spectrum but also by uncertainties in TSI measurements. While there must fundamentally be consistency between measurements of TSI and SSI, constraining the SSI in this narrow region to the TSI would require reduced uncertainty in both the TSI and SSI. Given the robust nature of our uncertainty budget, and the lack of overlap in the $k = 2$ uncertainties of the CAVIAR and ATLAS3 spectra, this indicates that the ATLAS3 uncertainty budget may require re-assessment. Indeed,

Thuillier et al. (2003) note that their calculated variance (based on their uncertainty estimate) is smaller than the observed variance from their measurements and likely implies some unknown source of uncertainty.

We do not believe that there is fundamental inconsistency between the TSI from current spectral observations and CAVIAR2 within the uncertainties. Accounting for the ($k = 1$) uncertainties in Solar2 (Thuillier et al., 2009) from the far UV out to $1 \mu\text{m}$ leads to a 6 W m^{-2} uncertainty in this spectral region. Applying the same analysis in the near-IR using the ATLAS3 uncertainty from 7,000 to 10,000 cm^{-1} and the CAVIAR2 uncertainty between 4,000 and 7,000 cm^{-1} (i.e., using the lowest uncertainty limits for measurements which we believe are accurate in the respective spectral regions) gives a further 8 W m^{-2} . Thus, without even accounting for any uncertainty in TSI measurements (believed to be $\sim 0.5 \text{ W m}^{-2}$ (Kopp & Lean, 2011)), accounting for the $k = 2$ uncertainties, or any uncertainties in wavelengths longer than $2.5 \mu\text{m}$ (which contributes 50 W m^{-2} to the TSI), the differences in the TSI budget are almost reconciled.

It is clear that more measurements of the SSI are required, from as wide a range of sources as possible. It is expected that the TSIS-1 mission will launch in late 2017 (Science.nasa.gov, 2017, NASA webpage, <https://science.nasa.gov/missions/tsis-1>), which includes a version of SIM with a new calibration method. This involves the use of both a tunable laser and a cryogenic radiometer, which should provide greater accuracy in both the irradiance scale and the spectrometer response. In addition, further ground-based and airborne measurements are also required. These should involve the use of a high-intensity calibration source, and a robust calibration transfer. One such possibility is the use of radiatively calibrated lasers at specifically chosen frequencies, such that the spectral response of the spectrometer can be measured quickly and efficiently in the field. For a system set up as in the one in Gardiner et al. (2012), it would be also useful to track the reflectance change in the tracker optics over time, rather than once before and once at the end of the campaign. In addition, while it is not strictly necessary (since the Langley method filters out the nontime-varying components of the atmosphere and is affected minimally by nontime-varying components in the microwindows), an ideal system would be set up at high altitude, to minimize the effect of atmospheric aerosols and gaseous absorption. Such measurements would be useful not least as a cross check to the space-based measurements but also for long-term monitoring of the SSI across solar cycles. Any such measurement campaigns should particularly focus on a rigorous uncertainty budget, in accordance with the Guide to the Expression of Uncertainty in Measurement (Joint Committee For Guides In Metrology, 2008).

Acknowledgments

CAVIAR (NE/D012082/1) was funded by the Natural Environment Research Council (NERC) and Engineering and Physical Sciences Research Council. Jonathan Elsey would like to thank the NERC SCENARIO Doctoral Training Partnership for funding his PhD research (studentship number 1503015), and NPL for providing additional financial support. We thank Kaah Menang for his prior work and helpful discussions and Liam Tallis for his work in performing the initial measurements. We thank the reviewers for their comments, which have significantly improved the manuscript. Spectra (at the full instrument resolution) and the corresponding $k = 1$ fractional uncertainties are available as supporting information to this paper.

References

- Arvesen, J. C., Griffin, R. N. J., & Pearson, B. D. J. (1969). Determination of extraterrestrial solar spectral irradiance from a research aircraft. *Applied Optics*, 8(1), 2215–2232. <https://doi.org/10.1364/AO.8.002215>
- BenMoussa, A., Gissot, S., Schühle, U., Del Zanna, G., Auchère, F., Mekaoui, S., ... Woods, T. N. (2013). On-orbit degradation of solar instruments. *Solar Physics*, 288(1), 389–434. <https://doi.org/10.1007/s11207-013-0290-z>
- BIPM (2006). Le système international d'unités (SI) (8th ed., pp. 94–180 for English version).
- Bojinski, S., Verstraete, M., Peterson, T. C., Richter, C., Simmons, A., & Zemp, M. (2014). The concept of essential climate variables in support of climate research, applications, and policy. *Bulletin of the American Meteorological Society*, 95(9), 1431–1443. <https://doi.org/10.1175/BAMS-D-13-00047.1>
- Bolsée, D., Pereira, N., Cuevas, E., García, R., & Redondas, A. (2016). Comments to the article by Thuillier et al. "The Infrared Solar Spectrum Measured by the SOLSPEC Spectrometer Onboard the International Space Station" on the interpretation of ground-based measurements at the Izaña Site. *Solar Physics*, 291(8), 2473–2477. <https://doi.org/10.1007/s11207-016-0914-1>
- Bolsée, D., Pereira, N., Decuyper, W., Gillotay, D., Yu, H., Sperfeld, P., ... Weber, M. (2014). Accurate determination of the TOA solar spectral NIR irradiance using a primary standard source and the Bouguer-Langley technique. *Solar Physics*, 289(7), 2433–2457. <https://doi.org/10.1007/s11207-014-0474-1>
- Bucholtz, A. (1995). Rayleigh-scattering calculations for the terrestrial atmosphere. *Applied Optics*, 34(15), 2765–2773. <https://doi.org/10.1364/AO.34.002765>
- Coddington, O., Lean, J. L., Pilewskie, P., Snow, M., & Lindholm, D. (2015). A solar irradiance climate data record. *Bulletin of the American Meteorological Society*. <https://doi.org/10.1175/BAMS-D-14-00265.1>
- Dudhia, A. (2017). The Reference Forward Model (RFM). *Journal of Quantitative Spectroscopy and Radiation Transfer*, 186, 243–253. <https://doi.org/10.1016/j.jqsrt.2016.06.018>
- Fligge, M., Solanki, S. K., Pap, J. M., Fröhlich, C., & Wehrli, C. (2001). Variations of solar spectral irradiance from near UV to the infrared—Measurements and results. *Journal of Atmospheric and Solar - Terrestrial Physics*, 63(14), 1479–1487. [https://doi.org/10.1016/S1364-6826\(01\)00020-7](https://doi.org/10.1016/S1364-6826(01)00020-7)
- Fontenla, J. M., Avrett, E., Thuillier, G., & Harder, J. (2006). Semiempirical models of the solar atmosphere. I. The quiet and active sun photosphere at moderate resolution. *The Astrophysical Journal*, 639(1), 441–458. <https://doi.org/10.1086/499345>
- Fröhlich, C., & Lean, J. (2004). Solar radiative output and its variability: Evidence and mechanisms. *Astronomy and Astrophysics Review*, 12(4), 273–320. <https://doi.org/10.1007/s00159-004-0024-1>
- Gardiner, T. D., Coleman, M., Browning, H., Tallis, L., Ptashnik, I. V., & Shine, K. P. (2012). Absolute high spectral resolution measurements of surface solar radiation for detection of water vapour continuum absorption. *Philosophical Transactions of the Royal Society A - Mathematical Physical and Engineering Sciences*, 370, 2590–2610. <https://doi.org/10.1098/rsta.2011.0221>

- Harder, J. W., Thuillier, G., Richard, E. C., Brown, S. W., Lykke, K. R., Snow, M., ... Pilewskie, P. (2010). The SORCE SIM solar spectrum: Comparison with recent observations. *Solar Physics*, 263(1), 3–24. <https://doi.org/10.1007/s11207-010-9555-y>
- Joint Committee For Guides In Metrology (2008). Evaluation of measurement data—Guide to the expression of uncertainty in measurement, Int. Organ. Stand. Geneva ISBN, 50(September), 134. <https://doi.org/10.1373/clinchem.2003.030528>.
- Kopp, G., & Lean, J. L. (2011). A new, lower value of total solar irradiance: Evidence and climate significance. *Geophysical Research Letters*, 38, L01706. <https://doi.org/10.1029/2010GL045777>.
- Kurucz, R. L., & Bell, B. (1995). 1995 atomic line data, Kurucz CD-ROM No. 23. Cambridge, Mass: Smithsonian Astrophysical Observatory.
- Lean, J. L., & DeLand, M. T. (2012). How does the Sun's spectrum vary? *Journal of Climate*, 25, 2555–2560. <https://doi.org/10.1175/JCLI-D-11-00571.1>
- Menang, K. P., & Shine, K. P. (2013). The effect of chosen extraterrestrial solar spectrum on clear-sky atmospheric absorption and heating rates in the near infrared, Radiation Processes Atmosphere Ocean: Proceedings of the International Radiation Symposium (eds Cahalan RF, Fischer J) Date 6-10 August 2012 AIP Conf. Proc. 1531, pp. 520–523. <https://doi.org/10.1063/1.4804821>.
- Menang, K. P., Coleman, M. D., Gardiner, T. D., Ptashnik, I. V., & Shine, K. P. (2013). A high-resolution near-infrared extraterrestrial solar spectrum derived from ground-based Fourier transform spectrometer measurements. *Journal of Geophysical Research: Atmospheres*, 118, 5319–5331. <https://doi.org/10.1002/jgrd.50425>
- Mlawer, E. J., Payne, V. H., Moncet, J.-L., Delamere, J. S., Alvarado, M. J., & Tobin, D. C. (2012). Development and recent evaluation of the MT_CKD model of continuum absorption. *Philosophical Transactions of the Royal Society A-Mathematical Physical and Engineering Sciences*, 370, 2520–2556. <https://doi.org/10.1098/rsta.2011.0295>
- Platnick, S., & Fontenla, J. M. (2008). Model calculations of solar spectral irradiance in the 3.7- μm band for earth remote sensing applications. *Journal of Applied Meteorology and Climatology*, 47(1), 124–134. <https://doi.org/10.1175/2007JAMC1571.1>
- Rothman, L. S., Gordon, I. E., Babikov, Y., Barbe, A., Benner, D. C., Bernath, P. F., ... Wagner, G. (2013). The HITRAN2012 molecular spectroscopic database. *Journal of Quantitative Spectroscopy and Radiation Transfer*, 130, 4–50. <https://doi.org/10.1016/j.jqsrt.2013.07.002>
- Schuster, G. L., Dubovik, O., & Holben, B. N. (2006). Angstrom exponent and bimodal aerosol size distributions. *Journal of Geophysical Research*, 111, D07207. <https://doi.org/10.1029/2005JD006328>.
- Shine, K. P., Campargue, A., Mondelain, D., McPheat, R. A., Ptashnik, I. V., & Weidmann, D. (2016). The water vapour continuum in near-infrared windows—Current understanding and prospects for its inclusion in spectroscopic databases. *Journal of Molecular Spectroscopy*, 327, 193–208. <https://doi.org/10.1016/j.jms.2016.04.011>
- SIDC (2008). SILSO, World Data Center - Sunspot Number and Long-term Solar Observations, Royal Observatory of Belgium, Monthly Report on the International Sunspot Number, on-line Sunspot Number catalogue. Retrieved from: <http://www.sidc.be/SILSO/>
- Solar Light Company (2001). Microtops II ozone monitor and Sun photometer manual. Retrieved from: <http://solarlight.com/wp-content/uploads/2014/05/MTPMAN-RevC.pdf>, Accessed 1 January 2017.
- Stephens, G. L., Li, J., Wild, M., Clayson, C. A., Loeb, N., Kato, S., ... Andrews, T. (2012). An update on Earth's energy balance in light of the latest global observations. *Nature Geoscience*, 5(10), 691–696. <https://doi.org/10.1038/ngeo1580>
- Thome, K., Biggar, S. F., & Slater, P. N. (2001). *Effects of assumed solar spectral irradiance on intercomparisons of earth-observing sensors*. Presented at the Proceedings of SPIE 4540, Sensors, System Next-Generation Satellites (Vol. 4540, pp. 260–269). Toulouse, France: International Symposium on Remote Sensing. <https://doi.org/10.1117/12.450668>
- Thuillier, G., Bolsée, D., Schmidtke, G., Foujols, T., Nikutowski, B., Shapiro, A. I., ... Schmutz, W. (2014). The solar irradiance spectrum at solar activity minimum between solar cycles 23 and 24. *Solar Physics*, 289(6), 1931–1958. <https://doi.org/10.1007/s11207-013-0461-y>
- Thuillier, G., Foujols, T., Bolsée, D., Gillotay, D., Hersé, M., Peetermans, W., ... Hartmann, J. (2009). SOLAR/SOLSPEC: Scientific objectives, instrument performance and its absolute calibration using a blackbody as primary standard source. *Solar Physics*, 257(1), 185–213. <https://doi.org/10.1007/s11207-009-9361-6>
- Thuillier, G., Harder, J. W., Shapiro, A., Woods, T. N., Perrin, J. M., Snow, M., ... Schmutz, W. (2015). The infrared solar spectrum measured by the SOLSPEC spectrometer onboard the International Space Station. *Solar Physics*, 290(6), 1581–1600. <https://doi.org/10.1007/s11207-015-0704-1>
- Thuillier, G., Hersé, M., Simon, P. C., Labs, D., Mandel, H., & Gillotay, D. (2003). Observation of the solar spectral irradiance from 200 nm to 870 nm during the ATLAS 1 and ATLAS 2 missions by the SOLSPEC spectrometer. *Metrologia*, 35(4), 689–695. <https://doi.org/10.1088/0026-1394/35/4/79>
- Vaisala (2013). Vaisala RS92-SGP datasheet. Retrieved from: <http://www.vaisala.com/VaisalaDocuments/BrochuresandDatashets/RS92SGP-Datasheet-B210358EN-F-LOW.pdf>, Accessed 1 January 2017.
- Walters, D. N., Williams, K. D., Boutle, I. A., Bushell, A. C., Edwards, J. M., Field, P. R., ... Vidale, P. L. (2014). The Met Office Unified Model Global Atmosphere 4.0 and JULES Global Land 4.0 configurations. *Geoscientific Model Development*, 7(1), 361–386. <https://doi.org/10.5194/gmd-7-361-2014>
- Weber, M. (2015). Comment on the article by Thuillier et al. "The Infrared Solar Spectrum Measured by the SOLSPEC Spectrometer onboard the International Space Station". *Solar Physics*, 290(6), 1601–1605. <https://doi.org/10.1007/s11207-015-0707-y>