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Comment on the Article by Thuillier *et al.* "The Infrared Solar Spectrum Measured by the SOLSPEC Spectrometer onboard the International Space Station"

Invited Review

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Abstract Thuillier *et al.* (*Solar Phys.*, 2015, DOI:10.1007/s11207-015-0704-1) discuss the apparent discrepancy between the ATLAS-3 composite solar spectral irradiances (SSI) covering the ultraviolet/visible/near-infrared (NIR) spectral region with more recent SSI measurements in the NIR. Recent measurements from IRSPERAD, CAVIAR, SCIAMACHY, SOLSPEC/ISS (the SOLAR2 spectrum from 2008), and unadjusted SIM show that above about 1600 nm, SSI is lower by about 8 % with respect to ATLAS-3. A new correction is presented in Thuillier *et al.* (2015) that leads to SOLSPEC/ISS (SOLAR2rev) which is in better agreement with ATLAS-3. SOLSPEC/ISS SSI underwent a +10 % change from 2008 to 2010, leading to better agreement with ATLAS-3, but it remains unclear which year provided the proper radiometric level, 2008 (SOLAR2) or 2010 (SOLAR2rev) as no link to pre-launch calibration is established. Before interpreting the NIR SSI observations using our current physical understanding (constraints by the total solar irradiance and solar models), the cause for the discrepancy between the early ATLAS-3 and all recent measurements (without a-posteriori adjustments) needs to be understood considering instrument and calibration performance alone.

Keywords Infrared spectrum · Instrumentation · Solar irradiance

1. Introduction

Thuillier *et al.* (2015), from here on referred to as T15, discuss the apparent discrepancy of several recent SSI NIR observations to the ATLAS-3 composite solar spectrum widely considered a standard reference for solar spectral irradiances (SSI); (Thuillier *et al.*, 2004) covering the UV/Vis/NIR spectral region. They also propose a new correction that brings SOLSPEC/ISS (the SOLAR2 spectrum; Thuillier *et al.*, 2014) in better agreement with ATLAS-3.

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In this comment we discuss the following points: 1) the new near-infrared calibration of SOLSPEC/ISS (SOLAR2rev), 2) adjustments of the error budget of ground measurements, 3) constraints from the total solar irradiance (TSI), and 4) interpretation of the SCIAMACHY data.

2. New Calibration of SOLSPEC/ISS

The SOLSPEC/ISS spectrum (called SOLAR2 in T15 and Thuillier *et al.*, 2014) stems from the beginning of the mission in early 2008, where solar measurements near 1600 nm and the tungsten ribbon lamp showed lower signals than in 2010. A revised SOLSPEC/ISS spectrum (called SOLAR2rev) was presented in T15. This uses a polynomial fitted to the ratio of the mean raw Sun spectrum from 2010 over 2008 (bottom panel of Figure 2 in T15) to correct the SOLAR2 spectrum from 2008. T15 justified this correction because this ratio agrees with the signal change of the tungsten ribbon lamp (W3) over the same time period (Figure 2c in T15). Despite the better average agreement of SOLAR2rev2 with ATLAS-3, the SOLAR2rev2/ATLAS-3 ratio still changes from 1.03 to about 0.97 (a change of −6 %) from 1000 nm to 1600 nm (Figure 5 in T15), a similar percentage change as observed in the ratios of IRSPERAD (Bolsée *et al.*, 2014), CAVIAR (Menang *et al.*, 2013), SCIAMACHY (Noël *et al.*, 2007; Pagaran *et al.*, 2011), and SIM (Harder *et al.*, 2010, without the corrections applied to adjust the NIR to ATLAS-3 as reported in Harder *et al.*, 2010) over ATLAS-3.

It is unclear which responsivity condition (2008 or 2010) more closely matched the prelaunch conditions when the instrument was radiometrically calibrated, but is important to decide whether the SOLSPEC/ISS spectra from 2010 may be more accurate than those from the early period. The tungsten lamp signal levels before launch agree to within 2 – 3 % with lamp measurements onboard the ISS in early 2008 (see p. 162 in Bolsée, 2012), suggesting that the instrument response shortly after launch was more consistent with that on the ground during the calibration campaigns.

3. Uncertainties in Ground-Based Measurements

The authors of T15 criticise the uncertainty budget for the IRSPERAD ground measurements as provided by Bolsée *et al.* (2014) as too optimistic. As explained in Bolsée *et al.* (2014) an atmospheric correction using the Boguer–Langley approach was made under highly ideal conditions (stable and low AOD, no cirrus clouds). The cloudiness in percentage as indicated in Tables 1 and 2 applies to the global sky view and not to the field of view of the SSI measurement, and cloud cover is biased towards the horizon. Only data where the Langley plots provide a linear fit of R^2 exceeding 0.99 were used in Bolsée *et al.* (2014), which means that conditions were very stable. The revised uncertainty budget as suggested by T15 with ≈ 2 % uncertainties due to atmospheric effects (including subvisible cirrus) still cannot explain the systematic difference of 8 % in the NIR. The remarkable agreement between the ground observations from two different sites (UK and Tenerife) with very different meteorological conditions indicate their high quality (Menang *et al.*, 2013; Bolsée *et al.*, 2014).

4. TSI or Solar Constant Constraint

I am very critical of using the TSI constraint as an argument to evaluate SSI in a limited spectral region, particularly outside the visible and near-UV spectral regions, as the latter dominate TSI. A 1 % change across the near UV and visible would suffice to account for about 10 $\mathrm{W\,m^{-2}}$ about half of the 19 $\mathrm{W\,m^{-2}}$ deficit cited for SOLAR2 with respect to ATLAS-3. Adding the uncertainty of current TSI measurements of about 6 $\mathrm{W\,m^{-2}}$ (0.5 %) closely fills the gap. The TSI is a useful diagnostics, but one has to be cautious of using it to justify SSI corrections.

5. Interpretation of SCIAMACHY SSI Comparisons

The discussion on the SCIAMACHY SSI data needs some clarification. The SCIAMACHY spectrometer was radiometrically calibrated on an absolute scale on ground (Skupin *et al.*, 2005; Lichtenberg *et al.*, 2006; Pagaran, Weber, and Burrows, 2009; Pagaran *et al.*, 2011). Skupin *et al.* (2005) compared V5 data and Pagaran *et al.* (2011) V6 data with other solar data. The first fully consolidated Level 1 datasets (irradiances and Earth radiances) were provided with V7, which is the data version of the 2002 spectrum termed SCIAMACHY2002 spectrum in T15 and also shown in Thuillier *et al.* (2014) and Bolsée *et al.* (2014).

In addition to the ESA/DLR calibration (Lichtenberg *et al.*, 2006), additional corrections are applied by us mainly to correct for degradation. Skupin *et al.* (2005) proposed the on-board white-light source (WLS, a quartz-tungsten-halogen lamp) for a relative correction from pre-launch condition. A brief description of the WLS correction can be found in the Appendix of Pagaran *et al.* (2011). The lamp temperature increased from pre-launch to post-launch condition as a result of a lack of convection for cooling. This temperature change is an additional fitting parameter in the WLS ratio fitting (Pagaran *et al.*, 2011). This correction mainly affects the two spectral windows near 1.9 μm and 2.4 μm, which suffer from throughput losses that are due to icing on the detector, and the UV channels. The spectral region between 1000 and 1700 nm is unaffected. Since the WLS suffers from optical throughput changes with time, this WLS correction across the entire wavelength range from the UV to NIR is only appropriate for measurements made in space shortly after launch in 2002. Both Pagaran *et al.* (2011) and Skupin *et al.* (2005) later used SCIAMACHY data from 2004 and from an older data version. The SCIAMACHY2002 spectrum is based upon V7 data, in addition includes our WLS correction, and is from August 2002 (first month of regular measurements).

Results from SCIAMACHY SSI comparisons with other data were discussed in three articles (Skupin *et al.*, 2005; Noël *et al.*, 2007; Pagaran *et al.*, 2011). Skupin *et al.* (2005) clearly stated that the SCIAMACHY data were still very preliminary at that time. Nevertheless, Figure 2 of Skupin *et al.* (2005) shows a drop in the SCIAMACHY-ATLAS-3 difference from +5 % at 1000 nm to −4 % at 1600 nm, which is very consistent with the relative change observed in the SCIAMACHY2002 difference to ATLAS-3. The main difference between the old SCIAMACHY data and more recent SCIAMACHY data version is the absolute scale. In later data versions the radiometric calibration based upon the NASA sphere was replaced with the spectralon calibration (Lichtenberg *et al.*, 2006), thus changing among others the absolute scale in the SCIAMACHY SSI in V6 and upwards. First results from the new calibration (V6) were presented in Noël *et al.* (2007). Figure 9 of Noël *et al.* (2007) and Figure 7 of Pagaran *et al.* (2011) show comparisons of SCIAMACHY V6

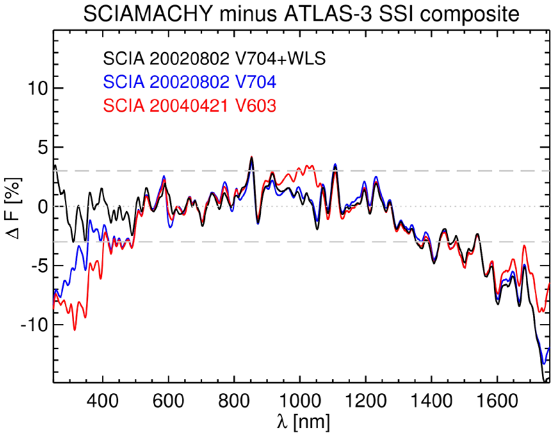

Figure 1 Various SCIAMACHY SSI data versions compared with the ATLAS-3 composite. All SSI have been smoothed using twice a 10 nm wide boxcar. Black: SCIAMACHY SSI V7 (V7.04) with additional WLS lamp corrections, called SCIAMACHY2002 in T15. Blue: the same data, but without the WLS correction. Red: SCIAMACHY SSI V6 (V6.03) without WLS correction as used in Pagaran *et al.* (2011). Between 1590 and 1770 nm, In and Ga composition was modified in the InGaAs detector layer, leading to a reduced performance in that spectral range (Lichtenberg *et al.*, 2006).

with ATLAS-3, and the results are very consistent with the results for SCIAMACHY2002, showing a ≈ 8 % drop in the SSI/ATLAS-3 ratio between 1000 and 1600 nm.

Despite the different data versions and radiometric scale of SCIAMACHY SSI, all reported SCIAMACHY data show the relative change of about -8 % from 1000 to 1600 nm with respect to ATLAS-3 (see also Figure 1), in agreement with ground observations, SOLAR2, and unadjusted SIM. An inconsistency between different SCIAMACHY datasets as concluded by T15 does not exist.

6. Conclusion

Several recent NIR SSI data show a systematic negative difference of about 8 % with respect to the ATLAS-3 composite above 1600 nm. This NIR SSI drop challenges our current understanding of the H^--opacity near 1600 nm with an expected brightness peak near 1600 nm (Thuillier *et al.*, 2015). But before we can decide whether we have to revise our physical understanding (and modelling) or not, we need to ensure that a consensus on the NIR SSI observations is reached. A thorough and critical review and assessment of all existing NIR SSI observations including the early shuttle experiments (*e.g.* ATLAS-1, -3, and Eureca; Thuillier *et al.*, 2003) is required. Such a review will be also very helpful in preparing future SSI satellite missions, which may be needed at the end to finally resolve the NIR issue.

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