SCIAMACHY V8 Solar Spectral Irradiance Validation

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1 Introduction

SCIAMACHY (Scanning Imaging Absorption Spectrometer for Atmospheric Chartography) aboard the ESA Envisat satellite platform provided atmospheric trace gas measurements on a global scale for nearly a decade from August 2002 to April 2012 (Burrows et al., 1995; Bovensmann et al., 2011, and references therein). The trace gas retrievals are based upon Sun-normalized radiances, which are limb or nadir radiances divided by the solar irradiance. SCIAMACHY observes, therefore, the Sun directly once a day. Like other UV satellite sounders, the SCIAMACHY spectrometer suffers from optical degradation due to polymerisation of optical surfaces from the harsh UV radiation in space (e.g. Bramstedt et al., 2009; DeLand et al., 2012; Krijger et al., 2014). In data version 8 of SCIAMACHY a physical model of the scanner unit was applied to provide a degradation correction (Bramstedt et al., 2009; Krijger et al., 2014). It only corrects for degradation changes since the first measurements in space just after launch but does not account for changes between the pre-flight and post-launch environment.

In this document, the SCIAMACHY solar spectral irradiance (SSI) in its data version 8 is validated. In Section 2 the SCIAMACHY instrument and solar measurements are described based on Pagaran et al. (2009). Section 3 shows the comparison of different SCIAMACHY data versions represented by one begin of the mission spectrum and the total time series from August 2002 to April 2012. Finally, the SCIAMACHY SSI is compared to several other established solar reference spectra in Section 4.

2 Solar Spectral Irradiance

2.1 Instrument

SCIAMACHY is a UV, vis, near-IR and SWIR double monochromator for trace gas observations in our terrestrial atmosphere (Burrows et al., 1995; Bovensmann et al., 1999). It covers the wavelength region from 212 nm to 2386 nm (2.4 μm) in eight spectral channels with some gaps in the near-IR where atmospheric water vapour saturates (1.8–1.9 μm and 2.0–2.2 μm). The spectral resolution is moderately high (with respect to most spaceborne sensors) varying from 0.2 nm (Channel 1: 212–334 nm) to 1.5 nm (Channel 6: 971–1773 nm). Incoming light is pre-dispersed by a prism and further dispersed by holographic diffraction gratings in each of the eight channels. For the UV - visible channels 1-5 (up to 1 μm) EG&G Reticon diode arrays with 1024 detector pixels are used, in the remaining three near-IR channels InGaAs detectors with 1024 detector pixels each (Manufacturer EPITAXX, now owned by JDS Uniphase). For optimum detector performance, a mixture of 53% Indium and 47% Gallium has been epitaxially grown on the InP substrate. For longer wavelengths (detector pixels 794–1024 in Channel 6 and all pixels in Channels 7–8) a mixture with a higher Indium content was selected, however, this mixture has a reduced performance with regard to dark current noise and number of usable detector pixels (Lichtenberg et al., 2006). The detectors are cooled with a passive radiative cooler, Channels 1–6 down to about 200 K to 224 K, lower temperatures ($\sim$150 K) are provided for Channel 7 and 8 detectors. Ice contamination on the near-IR detectors in space strongly reduced the optical throughput. After repeated decontamination periods, where the detector was heated, the throughput had improved but residual ice contaminations remained. Dead or bad pixels, mostly in the near-IR channels are excluded (Gloudemans et al., 2005).

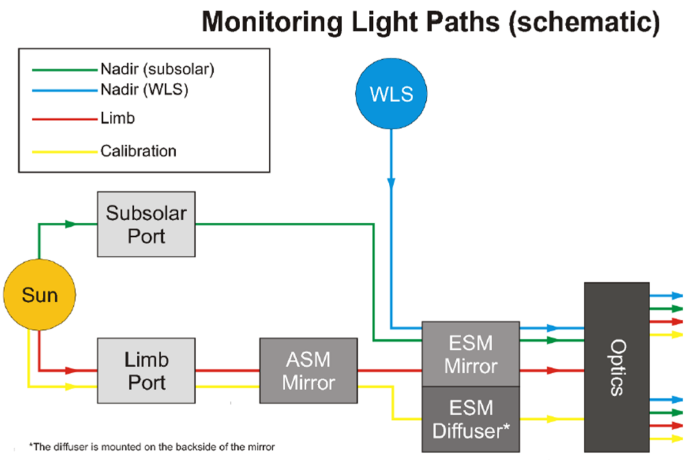

Figure 1: SCIAMACHY has three light paths used for scientific measurements. The Figure shows a schematic view of SCIAMACHY monitoring light paths for each of them: For calibration measurements the limb port together with ASM mirror and ESM diffuser is used. Scientific limb measurements use for monitoring the limb port with ASM mirror and ESM mirror. Monitoring for nadir measurements could be done via subsolar port and ESM mirror or with the internal white light source (WLS). In-flight monitoring and wavelength calibration are done using the WLS and the spectral line source (SLS, not shown), respectively. (modified Fig. 5-6 of Gottwald et al., 2006).

2.2 Solar Measurements

The primary purpose of direct solar measurements is to Sun-normalize the backscattered light from the terrestrial atmosphere, which to first order does not require absolute radiometric calibration. Different atmospheric viewing geometries are available for SCIAMACHY including nadir viewing, limb, and solar (lunar) occultation (Bovensmann et al., 1999). For each viewing geometry different combinations of scan mirrors (elevation and azimuth scan mirrors) and diffusers (mounted on the back of each scan mirror) are used to observe the Sun (see Fig. 1). Only one solar light path was absolutely radiometrically calibrated before launch and provides solar spectral irradiance in physical units from the full solar disc. This path involves the Azimuth Scan Module (ASM) and the diffuser mounted on the back of the Elevation Scan Module (ESM diffuser). The diffuser scatters solar light into a diffuse beam to illuminate the entrance slits evenly. The obtained solar spectra have to be corrected for the characteristics of the diffuser by applying its BSDF (Bi-directional Scattering Distribution Function). Absolute radiometric calibration has been carried out pre-flight using a combination of spectralon/NASA sphere and FEL lamps. ESM diffuser solar measurements are carried out in most cases once a day. A measurement sequence lasts about 30 s from which a mean solar spectrum is derived. A mean ESM diffuser solar spectrum recorded with SCIAMACHY is shown in Figure 2. About 94% of the TSI (total solar irradiance, solar constant) is covered by SCIAMACHY. Wavelengths are calibrated using atomic lines from a Pt/Ne/Cr/Ar lamp that are regularly measured in-flight (Bovensmann et al., 1999).

Daily solar observations with SCIAMACHY aboard Envisat started in August 2002. Continuous observations were interrupted for short periods for ice decontamination of the near-IR detectors (detector warming) and during Envisat platform or SCIAMACHY instrument anomalies, and for other maintenance activities. During night time of each orbit, dark current measurements are performed and used to correct the detector signal (Lichtenberg et al., 2006). Other important calibrations are the

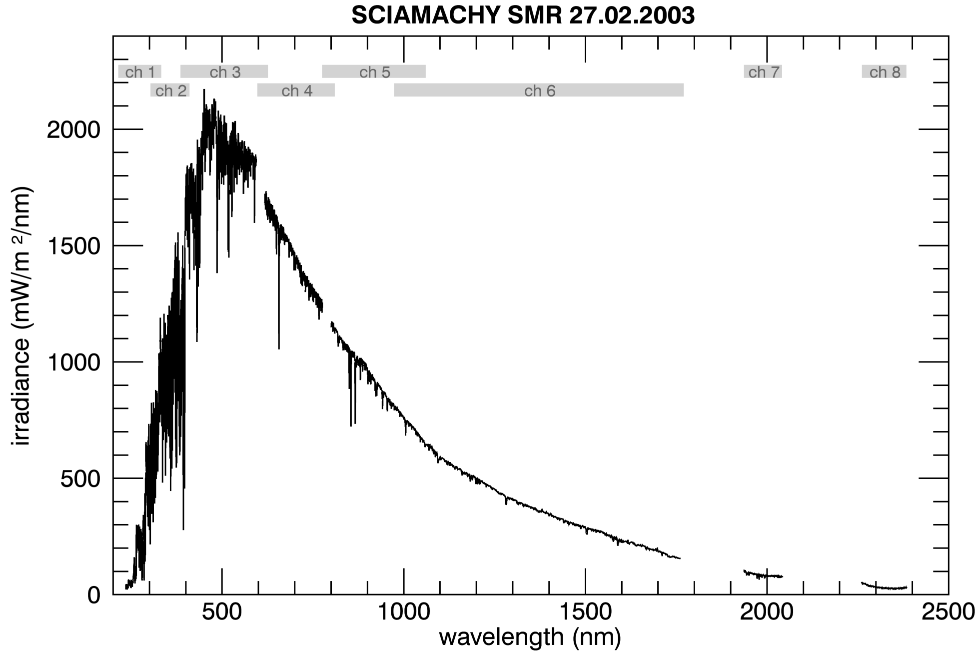

Figure 2: SCIAMACHY solar mean reference spectrum (SMR) data version 8 for 27 February 2003, provided for Sun-Earth distance of 1 AU; SCIAMACHY spectral channels are indicated

memory effect (residual signal from the previous detector readout, UV–vis channels only), straylight, pixel-to-pixel gain, and nonlinearity effect of the near-IR detectors. Most of these calibration parameters were determined pre-flight on ground (Lichtenberg et al., 2006). Not all calibrations on-ground were done in thermal vacuum (Lichtenberg et al., 2006). The change into space vacuum may have changed the calibration parameters.

3 Comparison of different Data Product Versions

3.1 Version History

Version 7

Data product version 7, released in 2012, shows the "classic" radiometric calibration. In version 7 of the SCIAMACHY level-1 spectral data no direct corrections of optical degradation have been foreseen. In order to improve aerosol and reflectance retrievals which utilise broadband spectral features, an m-factor approach for radiances and irradiances was introduced (Bramstedt et al., 2009). For the various optical paths as shown in Fig. 1 ratios with respect to initial spectral solar data from August 2002 (begin of SCIAMACHY measurements) were determined which are called m-factors. The m-factors are available as time series and can be optionally used for correcting level-1 spectral data in version 7. This approach does not distinguish between degradation and natural variability in solar radiation, so that this correction, in fact, destroys any trend information in SCIAMACHY SSI. Nevertheless, it proved to be useful for atmospheric applications.

Version 8

A more sophisticated approach has been introduced for version 8 data: a physical model of the scanner unit. Time series of solar data for the different optical paths are fitted to an optical throughput model that uses the thickness and optical properties of the contamination layer on mirrors as a fit parameter (Krijger et al., 2014). The refractive properties of the contaminated mirrors are thus taken into account. As the various optical paths are realised using different scan angles of both ASM and ESM mirrors, the scan angle dependence of the optical degradation is properly modelled. The radiometric Key Data from the on-ground calibration campaigns are revised for all wavelengths and adopted for the use with the scanner model.

Both the m-factor and mirror model approach only reflect changes with respect to the initial post-launch condition. Calibration changes from pre-flight conditions are not accounted for. The mirror model also assumes that the Sun is constant so that all changes seen in solar time series are attributed to instrumental changes.

Upcoming Version 9

For the future data product version 9 (expected 2017) the following revisions are applied. The physical model is revised and a new fitting scheme for contamination thicknesses and degradation of the Optical Bench Module (OBM) is applied. Limitations in the ESM diffuser calibration lead to seasonal variations in ESM diffuser solar reference spectra (see time series in Fig. 6). To adjust this a model describing the individual solar measurements was constructed (Snel, 2015). Another issue is the drop of the constant Sun assumption. The solar activity dependence is included in the model mentioned above by using the MgII index and the 10.7 cm radio flux. This dependency is needed to separate instrumental effects and solar spectrum effects.

For changes from on-ground to in-flight conditions a correction scheme is implemented that uses onboard measurements from the internal white light source (WLS) (mentioned before in Skupin, 2005; Pagaran et al., 2011).

Finally, the reference date for the degradation correction was changed to 27 February 2003. This is still early in the mission so that no severe degradation took place. In February 2003 a change in detector temperature was performed to adjust the detector temperatures to those used during on-ground calibration. Furthermore, the sub-solar calibration measurements failed in 2002 and this February date was the first date with a full set of calibration measurements.

3.2 Solar Mean Reference Spectrum

Figure 2 shows a SCIAMACHY solar spectrum in its version 8. In addition, detector pixels with reduced data quality (i. e. in the channel overlaps and bad or dead pixels in the IR) are removed and the spectrum is scaled to a mean Sun-Earth distance of one astronomical unit (AU). For validation the SCIAMACHY SSI is compared with the ATLAS-3 composite (Thuillier et al., 2004) that is widely used as a standard solar reference and therefore for validation of solar spectral irradiance data sets. Due to different spectral resolutions, both spectra are convolved with a 10 nm Gaussian and the ratio SCIAMACHY to ATLAS-3 composite is displayed in Fig. 3. The same SCIAMACHY spectrum is also shown in the previous data version 7 and the upcoming version 9. The SCIAMACHY spectral channels each with its own grating as dispersing element and detector are indicated. Some gaps occur due to the exclusion of overlap regions (channel boundary), where reduced accuracy in the wavelength calibration and associated calibration coefficients as well as polarisation issues leads to larger errors.

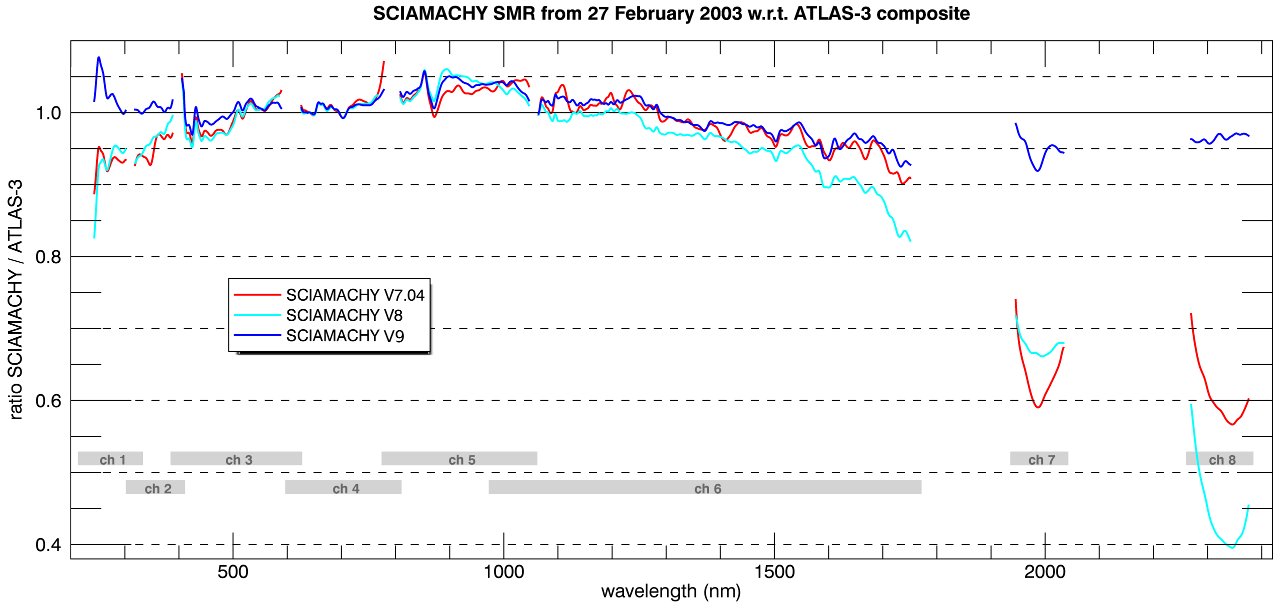

Figure 3: SCIAMACHY SSI of 27 February 2003 in different data versions in comparison with the ATLAS-3 composite. All spectra are convolved with a 10 nm Gaussian before generating the ratio.

The comparison results of version 8 are quite similar to version 7. Below 400 nm SCIAMACHY is lower by about -3% increasing to -8% near 250 nm. The dip in the differences near 350 nm seen with V7 (about -8%) is not evident in the V8 data. In Channel 5 the ratio shows a peak in the differences near 850 nm of about +6% and a decrease afterwards. These features seem to originate in the ATLAS-3 composite and might be explained by the merging of SOLSPEC and SOSP data at about 870 nm. Furthermore, the infrared part of the SOLSPEC spectrum is the least accurate due to weak signal (Thuillier et al., 1998). Higher values between 900-1050 nm arise in SCIAMACHY data. The reason is currently unknown and in progress. At the end of Channel 6 (1600-1750 nm - Channel 6+) an additional drop in the differences to ATLAS-3 is observed. The cause for this is unknown and may point at some other instrumental issue with SCIAMACHY.

However, for most parts of the spectrum between 400 nm to 1500 nm (excluding the channel boundaries) there is excellent agreement between SCIAMACHY and ATLAS-3 well within a few percent. Above 1200 nm SCIAMACHY gets lower with increasing wavelengths to about -10% near 1600 nm. Here the differences are larger in V8 (about -10%) compared to -6% for V7. A similar bias has been observed in the comparison of the ATLAS-3 composite with groundbased NIR measurements (Bolsée et al., 2014) and SOLAR aboard the ISS (Thuillier et al., 2014; Bolsée et al., 2014).

The biases seen in the differences between SCIAMACHY and ATLAS-3 may point at some calibration changes between the on-ground calibration to post-launch condition. The change into space vacuum may have changed the calibration parameters. The WLS correction, implemented in the next data product version, provids a clue at these changes.

More clear improvement regarding the single spectrum can be seen in version 9. The WLS-corrected SCIAMACHY Sun reference spectrum shows a clear improvement over the prior spectrum in Channel 1-3, 6+, 7 and 8 in relation to the ATLAS-3 composite Sun spectrum. The agreement in the UV channels is much improved and for most parts of the spectrum between 250 nm and 1500 nm the bias is within 3%. The higher values in Channel 1 result not only from the WLS correction but also from a change in the BSDF of the diffuser with data version 9 in contrast with V8. Like already mentioned in Skupin (2005), the correction improves the radiometric offset at the channel boundaries and the influence of temperature changes (Channel 6+). In particular for the NIR Channel 7 and 8 a significant improvement is seen. They suffer from strong icing on the detectors (e.g. Gloudemans et al., 2005) thus leading to substantial throughput losses. The optical throughput in the NIR was improved by several later decontamination phases when detectors were heated. Using the WLS correction the NIR channels can be re-calibrated and for first time reasonable results in Channel 7 and 8 are provided.

3.3 Time Series

The major improvement in the version 8 solar irradiances become apparent when viewing the time series. An overview for version 8 Channels 1 to 6 (212-1773 nm) is given in Figure 4. The different spectral channels are clearly visible. The white lines indicate days when data is rejected or not available. Figures 5 and 6 show time series for both the previous version 7 and current version 8, respectively. Some example wavelengths are selected from SCIAMACHY Channel 1 to 6. The time series are normalised to the reference date (27 February 2003) and shifted vertically. The marked “bad orbits” are due to decontamination periods, platform anomalies or peculiar spectra. These data are not used in the time series (white or blue lines).

The time series of Version 7 clearly show the influence of instrument degradation. With the new approach of a physical model of the scanner unit, implemented in the version 8 calibration, a correction of this effect is possible. The spectra are corrected for a mean Earth-Sun distance of 1 AU. However, there is still some seasonal variation evident in the ESM diffuser solar spectra (see Fig. 6). This might be due to limitations in the ESM diffuser calibration and is one issue to be covered in future version 9.

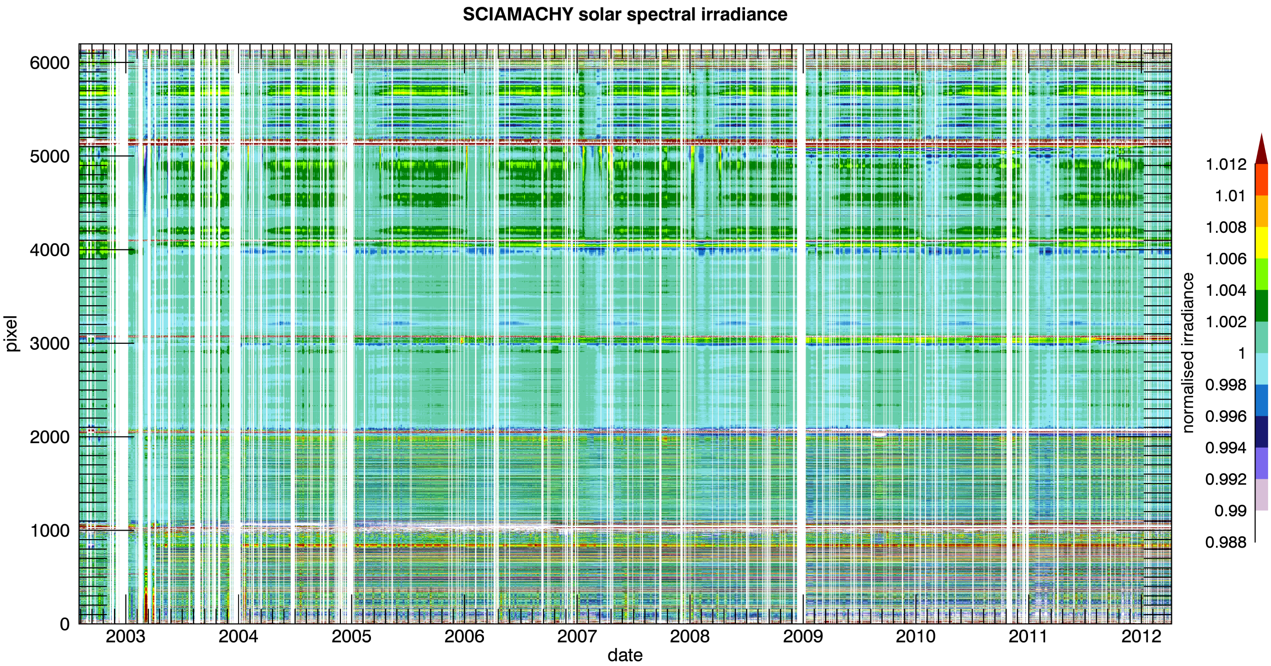

Figure 4: SCIAMACHY SSI time series of Version 8; normalised to solar spectrum of 27.02.2003 shown in Fig. 3

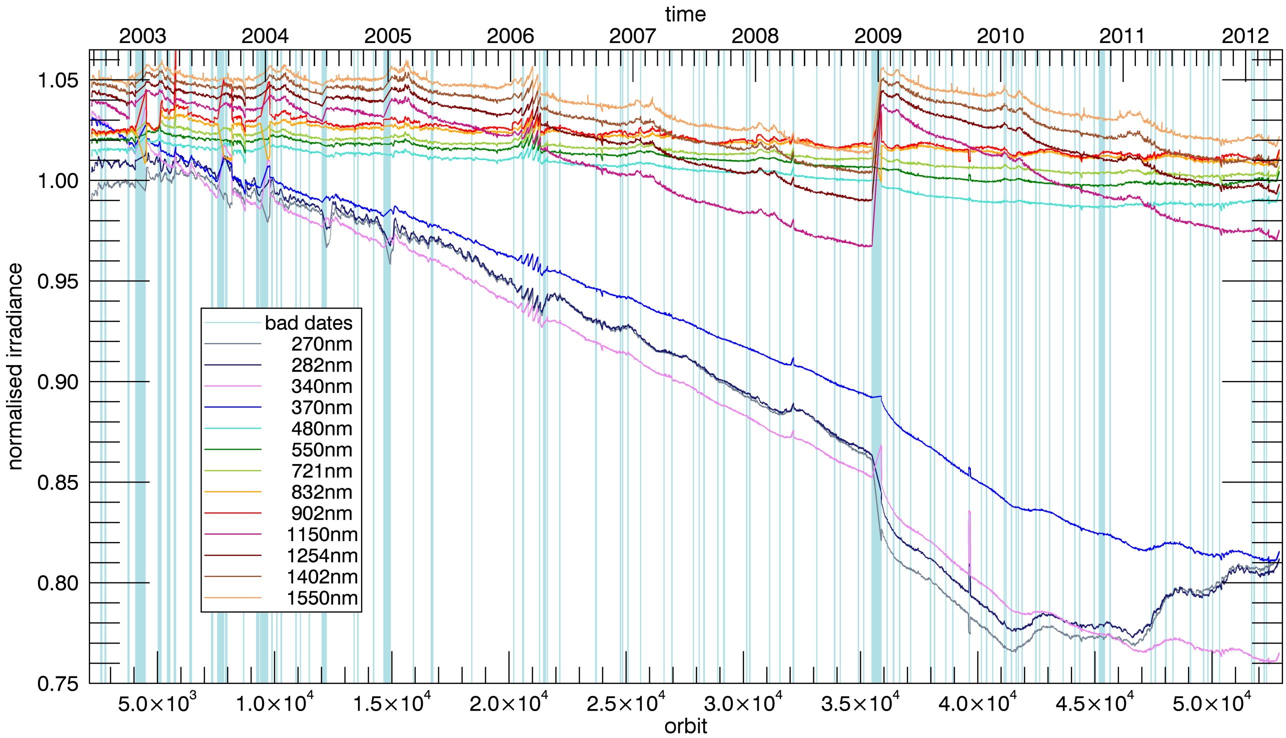

Figure 5: SCIAMACHY SSI time series of Version 7; normalised to solar spectrum of 27.02.2003 shown in Fig. 3

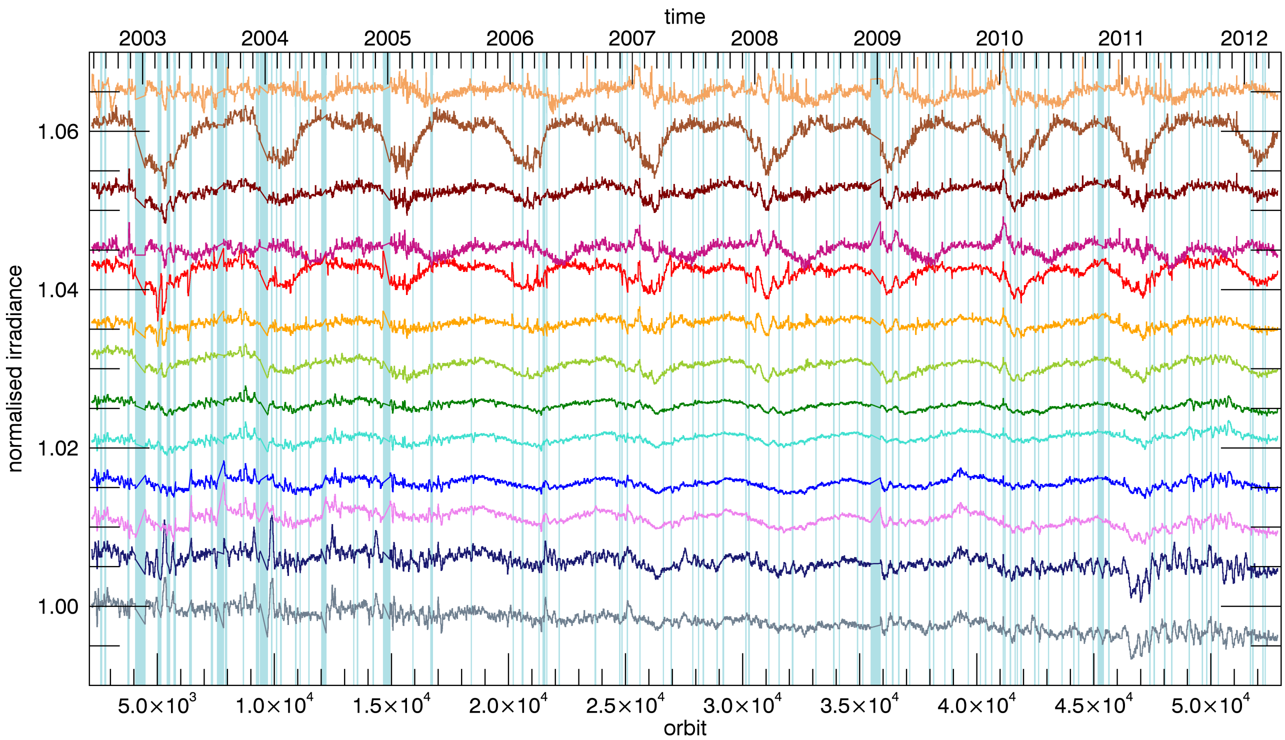

Figure 6: SCIAMACHY SSI time series of Version 8, normalised to solar spectrum of 27.02.2003 shown in Fig. 1 and 3. The colors indicate the same wavelengths like in Fig. 5.

4 Comparison with other Solar Reference Spectra

In this section, the re-calibrated SCIAMACHY V8 solar reference spectrum is compared with several other publicly available solar spectra, which are briefly described in Table 0.1. Figure 7 shows all spectra on a logarithmic scale. For the comparison the ratios of the SCIAMACHY spectrum from 27 February 2003 and each solar reference spectrum, described in Table 0.1, are displayed in Figure 8 for the full wavelength range of SCIAMACHY. Due to different spectral resolutions all spetra are convoluted with a 10 nm Gaussian. Solar observations are done at different times and at different stages of the 11-year solar cycle.

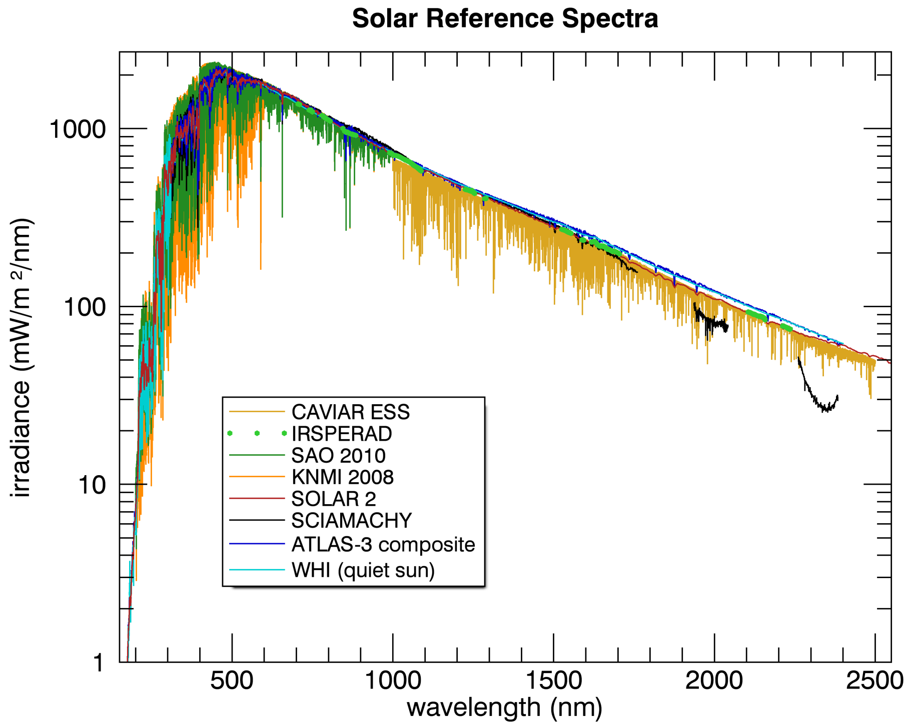

Figure 7: Solar reference spectra in comparison to the SCIAMACHY solar reference spectrum (27.02.2003)

For the comparison, the ATLAS-3 composite is shown again. From 500 nm to 1250 nm (excluding the channel boundaries and the feature from 900-1050 nm, see Section 3.2) there is an excellent agreement between SCIAMACHY and ATLAS-3 well within a few percent. Below 500 nm SCIAMACHY is lower than ATLAS-3 about -3% to -8% near 250 nm. Above 1300 nm SCIAMACHY gets also lower with increasing wavelengths, reaching a deficit of 10% near 1600 nm. In SCIAMACHY Channel 7 and 8 significant throughput losses due to ice layers on the detectors become evident. The comparison of SCIAMACHY and the WHI reference spectrum (Woods et al., 2009) shows in the NIR the expected similar behaviour like ATLAS-3 due to the application of an SIM-to-ATLAS-3 correction in the NIR (1350-2400 nm, Harder et al., 2010). It shows in general a good agreement with SCIAMACHY within $\pm$5% up to 1500 nm. Between 600 and 850 nm WHI is lower than SCIAMACHY by about 3-5% decreasing with increasing wavelength and lower than the other reference spectra except for the IRSPERAD values.

The KNMI solar reference spectrum (Dobber et al., 2008) shows an excellent agreement with

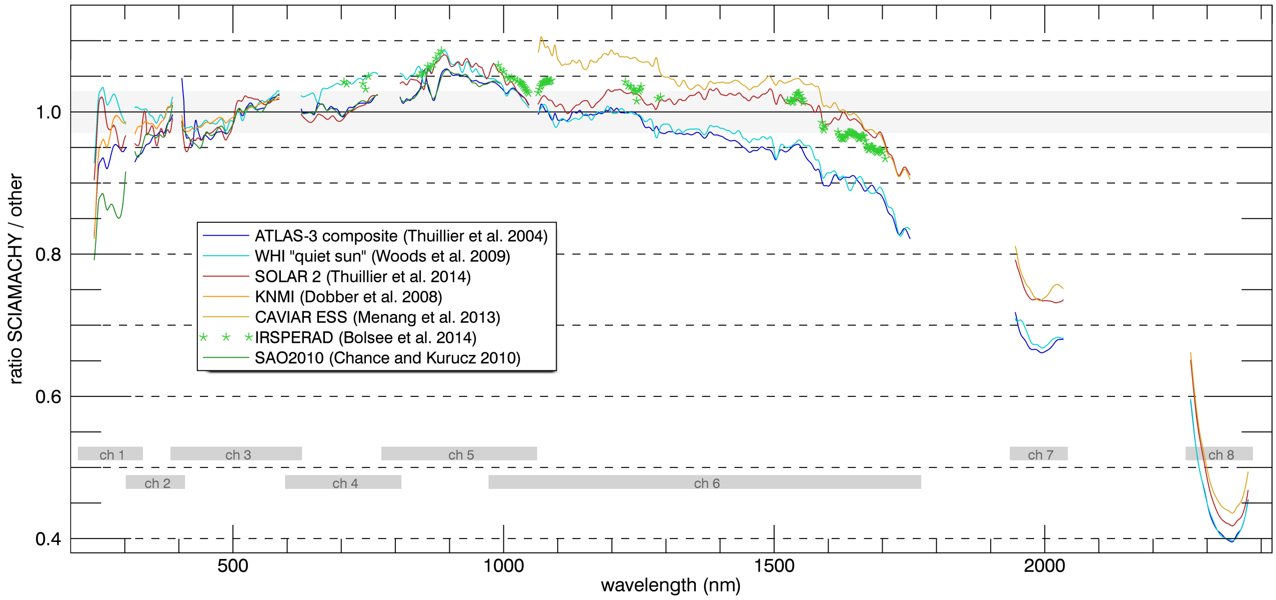

Figure 8: Ratio of SCIAMACHY to solar reference spectra shown in Figure 7, convolved to resolution of 10 nm.

SCIAMACHY well within ±3% above 280 nm and indicates only in the UV some larger deviations with respect to SCIAMACHY. The SAO 2010 (Chance and Kurucz, 2010) behaves in the same manner than the ATLAS-3 composite for wavelengths >400 nm. This is expected since it is matched in intensity to the ATLAS-1 spectrum which equals the ATLAS-3 above 400 nm. The SAO 2010 and KNMI spectra are based on the same measurements but differ in calibration. Especially the UV data based on the AFGL balloon measurements (Hall and Anderson, 1991) were not recalibrated for SAO 2010. This could be one reason for the largest deviations with respect to SCIAMACHY in the UV spectral region by up to -15%. It might be also partly explained by different solar activity levels. While KNMI and SAO 2010 are based on measurements obtained at multiple dates, report SCIAMACHY on medium and ATLAS-3 on moderately low solar activity. In contrast, the WHI spectrum displayed in Fig. 8 originates in the “Quiet Sun” campaign where solar activity indicators refer to minimum conditions.

The SOLAR 2 spectrum (Thuillier et al., 2014) behaves in a similar way than the WHI reference spectrum for 250-400 nm (Channel 1-2) in comparison to SCIAMACHY but with slightly higher values. The selected days to create the SOLAR 2 spectrum (UV to IR data) are 5/8 April and 2/4/5 May 2008 which is also close to solar minimum and the dates of the WHI (“Quiet Sun”) reference spectrum. In the vis/NIR up to 1050 nm the spectral differences are in the same order of magnitude than the comparison with the other reference spectra considered in this paper. SOLAR 2 agrees very well with SCIAMACHY over the full wavelength range but especially between 500-1600 nm. There is a clear difference between SOLAR 2 and ATLAS-3 (together with WHI/SIM) in relation to SCIAMACHY in the NIR (above 1100 nm). This trend can also be seen in solar spectra obtained from ground-based measurements, like IRSPERAD and the CAVIAR ESS. These discrepancies are also discussed in e.g. Bolsée et al. (2014) and can not be explained by the uncertainties of the spectra (see Table 0.1). Higher deviations with respect to the CAVIAR ESS were already reported in Menang et al. (2013). They found that the absolute levels of the CAVIAR ESS and the ATLAS composite are significantly different. The absolute level of the CAVIAR ESS is about 7-8% lower than the ATLAS-3 composite in the spectral range 1.5-2.5 μm and can increase to up to more than 10% in other spectral regions.

5 Conclusions & Outlook

This document reports on the validation of SCIAMACHY solar spectral irradiances (SSI) version 8 in the wavelength region from 0.24 μm to 2.4 μm and over the full mission from August 2002 to April 2012. A recent implementation of a physical model of the scanner unit is used for SCIAMACHY's radiometric calibration. One SCIAMACHY solar spectrum from the beginning of the space mission (before optical degradation sets in) was compared with several other established solar reference spectra. For validation especially the ATLAS-3 composite (Thuillier et al., 2004), which is widely considered as a reference solar SSI in the optical spectral range, was used. It should be noted that the spectra have different spectral resolution. The following conclusions can be drawn from the comparisons:

- SCIAMACHY SSI in both version 7 and version 8 agree to within 4% with present solar reference spectra in most parts of the visible and NIR from about 350 to 1400 nm. Largest deviations appear in the UV spectral region, with differences increasing towards lower wavelengths, mainly due to the weak signal in this spectral region.
- SCIAMACHY V8 improves in the overlap regions between Channels 3 and 4 (near 600 nm) and between 4 and 5 (near 800 nm), but also produces features (900-1050 nm, $>$ 1500 nm).
- In the NIR (>1200 nm) a deficit of up to 10% can be seen with respect to ATLAS-3. A similar deficit has been observed between ground-based NIR measurements (Bolsée et al., 2014) as well as SOLAR aboard the ISS (Thuillier et al., 2014) with respect to ATLAS-3. A bias correction of the same magnitude has been applied to SIM (Solar Irradiance Monitor)/SORCE to bring SIM in better agreement with ATLAS-3 (Harder et al., 2010; Bolsée et al., 2014).
- Correction of optical degradation due to hard radiation in space. However, both m-factors (V7) (Bramstedt et al., 2009) and optical throughput model (V8) (Krijger et al., 2014) do not account for natural solar variability (solar cycle, 27-day solar rotation), which is ok for trace gas and cloud/aerosol atmospheric retrievals but not for trend studies of SSI. Both approaches do not correct for calibration changes between preflight and the beginning of the space mission nor account for icing of the NIR detectors.

In the future version 9 (expected 2017), the current physical model of the scanner unit will be improved and the solar activity is considered by using various solar proxies. Furthermore SCIAMACHY's internal white light source (WLS) is used to correct for on-ground to in-flight changes. This brings the UV spectral range in better agreement with the ATLAS-3 composite and corrects for the strong throughput losses due to detector icing in the near-IR (NIR). This leads to first reasonable results for the SCIAMACHY Channels 7 and 8. Even with the WLS correction, a deficit with respect to ATLAS-3 and SORCE/SIM SSI measurements is observed in the NIR spectral region (4-8%). In contrast, SCIAMACHY exceeds ISS SOLAR and two ground-based measurements in the NIR.

The recent calibration of SCIAMACHY SSI V9 and its validation using several other established solar reference spectra is described in a publication submitted to Solar Physics (Hilbig et al., The New SCIAMACHY Reference Solar Spectral Irradiance and its Validation, Sol. Phys., in review, 2017).

Name Reference	Wavelength range Spectral Sampling	Sources	Spectral Resolution	Time	Calibration	Accuracy
SCIAMACHY	235 - 2384 nm 0.1 - 0.8 nm	Envisat SCIAMACHY	0.2 - 1.5 nm	27 Feb 2003	- physical model of scanner unit	
ATLAS-3 Thuillier et al. (2004)	0.5 - 2400 nm 0.5-120 nm: 1 nm 120-400 nm: 0.05 nm 400-2400 nm: 0.2-0.6 nm	0.5-120 nm: Rocket 120-200 nm: UARS SOLSTICE, UARS SUSIM 200-400 nm: UARS SOLSTICE, UARS SUSIM, ATLAS SUSIM, SSBUV, SOLSPEC 400-870 nm: ATLAS 1-2-3 SOLSPEC 870-2400 nm: EURECA SOSP	0.5-120 nm: 1.0 nm 120-400 nm: 0.25 nm (smoothed) 400-2400 nm: 0.5 nm (degraded model)	0.5-120 nm: 3 Nov 1994 rocket 120-870 nm: 11 Nov 1994 for ATLAS-3 (29 Mar 1992 for ATLAS-1) (15 Apr 1993 for ATLAS-2) 870-2400 nm: 1992-93 EURECA	- composite for selected date, up to 5 data sets in some spectral regions - vis: mean of ATLAS 1-2-3 SOLSPEC - vis/NIR: high-resolution structures from modelled Kurucz (1995) data - normalization of integrated TSI	0.5-120 nm: 30-40 % Lyα-200 nm: <3.5 % 200-400 nm: 2-4 % 400-870 nm: 3 % >870 nm: 2-3 %
WHI Woods et al. (2009)	0.1 - 2400 nm 0.1 nm	0.1-6 nm: TIMED SEE XPS 6-105 nm: Rocket 105-116 nm: TIMED SEE EGS 116-310 nm: SORCE SOLSTICE 310-2400 nm: SORCE SIM	0.1-105 nm: 0.1 nm 105-116 nm: 0.1 nm 116-310 nm: 0.1 nm 310-2400 nm: 1-30 nm	3 periods in 2008: “quiet Sun”: Apr 10-16 “sunspot active”: Mar 25-29 “faculae active”: Mar 30-Apr 4	(- SIM: normalization to ATLAS-3 for NIR) - normalized to the SORCE/TIM TSI	0.1-116 nm: 10-15 % 116-2400 nm: 2-4 %
SOLAR 2 Thuillier et al. (2014)	16 - 2900 nm 16.5-177 nm: 1 nm 177-340 nm: 0.4 nm 340-775 nm: 1 nm 775-2900 nm: 4 nm	ISS SOLAR: 16-150 nm: SolACES 170-2900 nm: SOLSPEC	16-150 nm: 0.3-0.6 nm 170-2900 nm: 0.6-9.5 nm (variable with wavelength)	16-150 nm: 21 Aug 2009 170-2900 nm: early 2008 (5/8 Apr and 2/4/5 May)	- SORCE/SOLSTICE data for 149.5-170 nm of 5 Apr 2008 and linear transition btw. the data sets	16-150 nm: 10-20 % 170-2900 nm: <3.5 %
CAVIAR ESS Menang et al. (2013)	1000 - 2500 nm (4000-10000 cm^{-1}) 0.0015-0.0095 nm (0.015 cm^{-1})	Ground-based Fourier transform spectrometer measurements at the UK Met Office Observation station in Camborne	0.03 cm^{-1}	(22 Aug 2008 and) 18 Sep 2008	- Langley technique - gaps filled with ACE and KPNO FTS measurements and modelled ESS	3.4-6.0 % (22 Aug) 3.3-5.9 % (18 Sep)
IRSPERAD Bolsée et al. (2014)	705 - 2236 nm (600-2300 nm)	Ground-based measurements at Izaña Atmospheric Observatory (IZO)	10 nm	Jun - Oct 2011	- TOA SSI values are extrapolated using the Bouguer-Langley technique	0.4-2.5 % (variable with wavelength, see reference)
KNMI Dobber et al. (2008)	250 - 550 nm 0.01 nm	200-310 nm: AFGL balloon 300-550 nm: KPNO ground-based data	0.025 nm	Multiple dates	- Adjusted based on comparison with low resolution data (UARS SUSIM, balloon data)	300-550 nm: $\sim$2 %
SAO 2010 Chance and Kurucz (2010)	200 - 1000 nm 0.01 nm	200-305 nm: AFGL balloon 300-1000 nm: KPNO ground-based data (FTR-measurements)	0.04 nm (convolved)	Multiple dates	- Adjusted based on comparison with low resolution data (ATLAS-1) (only KPNO)	305-1000 nm: <5 %

Table 0.1: Solar Reference Spectra (Revision and extension of DeLand, 2014)

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