

# **CALIBRATION OF SCIAMACHY IN-FLIGHT MEASURED IRRADIANCES AND RADIANCES – FIRST RESULTS OF LEVEL 1 VALIDATION (CASIMIR, ENVISAT AOID 406)**

**J. Skupin, S. Noël, M. W. Wuttke, H. Bovensmann and J. P. Burrows**

*Institute of Environmental Physics, University of Bremen, Otto-Hahn-Allee 1, D-28359 Bremen, Germany  
Email of J. Skupin: jochen.skupin@iup.physik.uni-bremen.de*

## **ABSTRACT**

SCIAMACHY is part of the payload of ESA's new Environmental Satellite ENVISAT which was launched into a sun-synchronous polar orbit on 2002-02-28. As a prerequisite for high quality data products an in-flight radiometric and spectral calibration and validation of SCIAMACHY (ir)radiance measurements has to be performed. This paper covers part of the validation efforts during the first nine months of SCIAMACHY in orbit with special emphasis on the application of the internal light sources for radiometric and spectral calibration. Presented is the comparison of the solar irradiance spectrum contained in SCIAMACHY level 1b data products with a solar spectrum derived by R. L. Kurucz, solar irradiances measured by the UARS instruments SOLSTICE and SUSIM, and with the SCIAMACHY solar irradiance derived with independent implemented calibration routines.

## **1. INTRODUCTION**

SCIAMACHY is designed to retrieve the amount and distribution of various trace gases and aerosol as well as cloud cover and cloud top height. Therefore the absorption, reflection and scattering characteristics of the atmosphere have to be determined by measuring the extraterrestrial solar irradiance as well as Earthshine radiances observed in different viewing geometries [3]. A special feature of SCIAMACHY is the combined limb-nadir measurement mode which enables the tropospheric column of trace gases to be determined. As a prerequisite for high quality data products an in-flight radiometric and spectral calibration and validation of SCIAMACHY (ir)radiance measurements has to be performed.

The optical part of the instrument consists mainly of two components: The optical bench (OBM) and a scanner mechanism used to perform measurements in different viewing geometries. The incoming light is distributed into 8 channels covering the wavelength ranges given in Tab. 1. The wavelength range of channel 1 starts with 214 nm but only wavelengths above 240 nm are used for retrieval, because the spectral region below 240 nm is outside the full performance range of the instrument. OBM and scanner mechanism were calibrated extensively on-ground using internal and external light sources. For the in-flight calibration two internal light sources are available: A PtCrNe-hollow-cathode lamp as spectral light source (SLS) for the wavelength calibration and a quartz-tungsten-halogen lamp as white light source (WLS) for the radiometric calibration. In addition solar and lunar irradiance measurements are used for in-flight calibration.

SCIAMACHY is the first spaceborne instrument covering a wavelength range of 214 to 2380 nm thus including ultraviolet, visible and near infrared spectral regions (see Fig. 1). The data products to be validated include:

- solar/lunar irradiances
- earthshine radiances (limb and nadir geometry)
- solar/lunar occultation radiances
- fractional polarization

Tab. 1. Wavelength range, spectral resolution and detector material of the eight SCIAMACHY channels

Channel	Wavelength range in nm	Spectral resolution in nm	Detector material
1	240(214) – 314	0.24	Si
2	309 – 405	0.26	Si
3	394 – 620	0.44	Si
4	604 – 805	0.48	Si
5	785 – 1050	0.54	Si
6	1000 – 1750	1.48	InGaAs
7	1940 – 2040	0.22	InGaAs
8	2265 – 2380	0.26	InGaAs

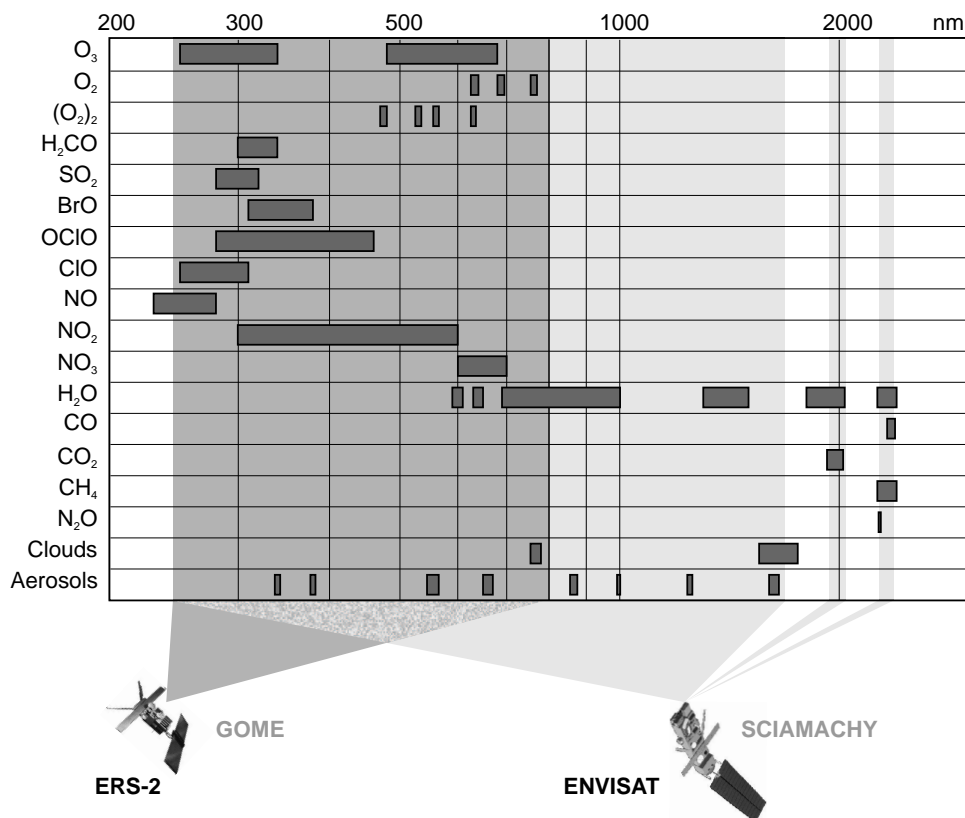


Fig. 1. Products to be retrieved from different SCIAMACHY wavelength ranges.

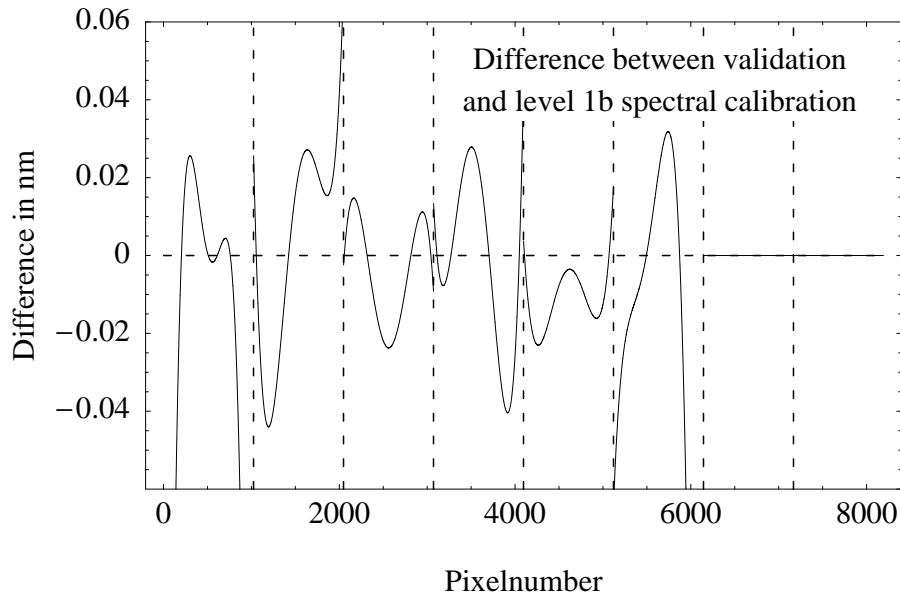


Fig. 2. Difference between the validation result of an in-flight spectral calibration with independent implemented routines and the spectral calibration contained in the level 1b product (channel boundaries marked by vertical dashed lines).

As there is no other spaceborne instrument covering the spectral range of SCIAMACHY a validation approach has to be applied which includes the comparison of SCIAMACHY measurements with different independent data sources. The work planned in the project 'Calibration of SCIAMACHY In-flight Measured Irradiances and Radiances' (CASIMIR, ENVISAT AOID 406) covers the validation of SCIAMACHY with satellite based instruments (e.g. GOME, OSIRIS, SAGE III, SBUV/2, SOLSTICE, SUSIM), solar spectra from high-altitude ground stations (e.g. the McMath FTS at Kitt Peak Observatory), modeled solar spectra (e.g. by [4]), and radiative transfer models (e.g. MODTRAN, SCIATRAN).

This paper places its emphasis on the validation of the solar spectrum measured by SCIAMACHY with a scanner setup using a diffuser plate and a mirror that is tracking the azimuthal motion of the sun (state 62, sun over ESM diffuser). This spectrum is spectral and radiometric calibrated by the 0 to 1 processor and contained as sun mean reference (SMR) in the global annotation data set (GADS) of the level 1b data product and will be referenced as  $SMR_{L1b}$  in the following.

Recently two verification orbits were distributed containing a solar spectrum using in-flight derived parameters for e.g. etalon and spectral calibration. Only the SMR from these verification orbits

1. SCI\_NL\_\_1PNPDK20020823\_085459\_000060882008\_00451\_02509\_0899.N1
2. SCI\_NL\_\_1PNPDK20020823\_103445\_000061272008\_00452\_02510\_0900.N1

is validated since the SMR from older level 1b data has to be regarded as out-dated.

The sources used for validation presented in this paper are a Kurucz solar spectrum from MODTRAN 3.7 convoluted with the SCIAMACHY slit function and solar UV spectra measured by the UARS instruments SOLSTICE and SUSIM. In addition the level 1b SMR ( $SMR_{L1b}$ ) is compared with results from an independent implementation of calibration routines to validate also the 0 to 1 processor. These routines follow roughly the algorithms given in the ATBD [8] and use mainly SCIAMACHY level 0 data. This independent calibrated sun mean reference will be called  $SMR_{Val}$  below.

## 2. INDEPENDENT IMPLEMENTATION OF CALIBRATION ROUTINES

### 2.1. Spectral calibration

The on ground spectral calibration was performed with internal and external calibration sources. From this measurements polynomial fits were derived which are used as the precise basis of the spectral calibration of the level 1 data

(SPECTRAL\_BASE in level 1b products). For channels 1 to 6 spectral line source (SLS) measurements were used. The polynomial fits for channels 7 and 8 are based on trace gas absorption spectra [1]. Previous level 1b data products contained a spectral calibration that was valid only for the lower 200 pixels of channel 8. This has been replaced in the actual products by a calibration valid for the whole channel 8 [7].

The on-ground spectral calibration has to be verified, monitored and updated in-flight. On an operational level this is done with the internal line source (SLS) of SCIAMACHY and optionally by the analysis of Fraunhofer lines. Up to now only internal SLS spectra have been analyzed, the use of Fraunhofer lines is still open.

As part of the validation an independent analysis of the internal SLS spectrum was performed. 106 out of the 108 spectral lines defined in the keydata could be fitted. In comparison the operational 0 to 1 processor fits only 48 lines. The possible cause are more restrictive rules regarding the quality of the lines (to much noise or dead/bad pixels . . .), i.e. more lines are rejected by the 0 to 1 processor than by the independent implemented spectral calibration algorithm.

The 106 fitted line positions agree with the positions predicted in the keydata within  $\pm 0.5$  pixel which is as good as it can be because the predicted positions are given as integers i.e. without a fractional part. In addition to earlier works also the blocking shift due to a partial blocking of the SLS light path [1] was taken into account for the calculation of the polynomial fits. Using the SLS an in-flight spectral calibration can only be derived for channels 1 to 6. Channels 7 and 8 contain too few SLS lines to allow a reasonable polynomial fit. Therefore for these channels still the on-ground calibration is used in both level 1b data and the independent implemented spectral calibration algorithm.

Fig. 2 shows the difference between the in-flight spectral calibration derived as a validation approach from SLS measurements and the spectral calibration contained in the level 1b product. The difference is in the range of  $\pm 0.04$  nm for channels 2 to 5 but larger in channels 1 and 6. For the impact of the deviations in channel 1 see also section 3.1. Both spectral calibrations use the on-ground data for channels 7 and 8 so the difference is 0.

## 2.2. Radiometric calibration

A simple approach using the internal WLS has been applied for a first verification of the radiometric calibration of the sun mean reference ( $SMR_{L1b}$ ) contained in the level 1b data product:

It was shown in [2] that the in-flight spectral calibration of SCIAMACHY is stable with variations  $< 0.02$  nm over the lifetime of the instrument with even weaker orbital dependence. Also the difference between on-ground and in-flight spectral calibration is  $< 0.1$  nm. This means that the variation of the spectral calibration is mainly on sub-pixel scale. For this first analysis it is therefore assumed that the in-flight spectral calibration is constant and equals the on-ground one.

With this assumption pixel dependent effects (like pixel-to-pixel-gain) and wavelength dependent effects (like etalon) do not have to be distinguished and a simple in-flight radiometric calibration using the internal white light source (WLS) can be applied. Presuming small changes between on-ground and in-flight performance of the instrument only first order (i.e. linear) changes have to be taken into account. These are given by the ratio between dark signal corrected on-ground and in-flight WLS measurements. Due to the unpolarized WLS light these measurements do not show changes of the polarization sensitivity of the instrument. Therefore this approach can be applied only to unpolarized (ir)radiance like the sun. The effects corrected this way cover pixel-to-pixel gain (PPG), etalon, temperature dependent quantum efficiency of the detectors, throughput change of OBM components. An ice layer buildup is observed on the detectors of channels 7 and 8 causing a loss of radiative sensitivity. The ice layer can be removed by decontaminating the instrument but slowly regrows until the next decontamination. The described approach automatically corrects also the transmission loss due to the ice buildup as long as the used WLS measurement is temporally close to the measurement of the solar irradiance.

The above is only valid assuming the same WLS performance on-ground and in-flight. Since the WLS does change in orbit its spectrum has to be corrected for the following in-flight effects [see also: 6]:

**In-flight WLS Temperature is increased** by 85 K compared to the on-ground temperature of 2950 K. This can be explained by the missing convective heat transfer under zero-gravity conditions which results in a weaker cooling of the filament by the gas filling of the light bulb than on-ground.

**Over-all increase of the WLS output** of 3 % is observed. This may be due to increased throughput of the WLS light-path or a changed emissivity of the WLS (under investigation).

**UV degradation of the WLS** is observed in timeseries of in-flight WLS measurements.

Tab. 2. Statistical results for the difference between the SCIAMACHY solar irradiance  $SMR_{Val}$  and the Kurucz spectrum from MODTRAN 3.7 convoluted with the instrument's slit function

Channel	1	2	3	4	5	6	7	8
Mean difference in %	-0.27±5.8	0.75±9.1	0.66±2.1	2.4±1.4	2.3±1.2	-2.0±1.7	-4.6±5.5	-0.18±11.

### 2.3. Calibration of the SMR

Based on the in-flight instrument characterization described in the previous two sections the spectral and radiometric calibrated validation result  $SMR_{Val}$  for the solar irradiance measured by SCIAMACHY is derived by performing the following steps:

**Memory effect** is corrected for the SI detector readouts of channels 1 to 5.

**Modeled dark signal** as given in the level 1b product of verification orbit 2509 is subtracted.

**On-ground to in-flight instrument changes** derived from the ratio of dark signal corrected on-ground and in-flight white light source (WLS) measurements are corrected.

**Spectral calibration** derived in-flight from SLS measurements with an independent implemented spectral calibration algorithm is applied.

**Doppler shift correction** is applied to the spectral calibration.

**Internal straylight** is subtracted.

**Absolute radiometric calibration** from the on-ground calibration given in the instrument keydata is applied to convert the detector readouts from binary units to irradiance.

**Removal of dead/bad pixels** given by the in-flight derived dead/bad pixel mask proposed by Q. Kleipool (SRON).

In addition an overall offset of about 8 % is observed in the absolute radiometric calibrated spectra. Possible causes may be changes of optical components since the on-ground calibration, unidentified offsets of the scanner mechanism or inadequate interpretation of on-ground calibration results. This topic is under investigation. In contrast to the SCIAMACHY sun mean reference  $SMR_{Lib}$  from the level 1b data product the validation result  $SMR_{Val}$  is already corrected for this offset even if its source is still unknown. <sup>1</sup>

## 3. VALIDATION WITH INDEPENDENT DATA SOURCES

### 3.1. Kurucz solar spectrum

In Figs. 3 and 4 the solar irradiance spectrum  $SMR_{Val}$  measured by SCIAMACHY and radiometric calibrated with independent routines is compared with the SCIAMACHY  $SMR_{Lib}$  as given in the level 1b data product and a Kurucz spectrum. Zoomed plots for the UV wavelength range of 240 to 310 nm (SCIAMACHY channel 1) are shown in Figs. 5 and 6. The plotted differences are given in % and calculated by:

$$\text{difference} = 100 \cdot \left( \frac{\text{irradiance}_{\text{SCIAMACHY}}}{\text{irradiance}_{\text{Validation source}}} - 1 \right) \quad (1)$$

The Kurucz spectrum is based on the file `newkur.dat` taken from the atmospheric modeling program MODTRAN 3.7, which is a merged spectrum made from Kurucz's theoretical model and data taken from empirical results [5]. To compare it with SCIAMACHY measurements the Kurucz spectrum is convoluted with the instrument's slit function. Statistical

<sup>1</sup>During the ENVISAT calibration review in September 2002 presentations of J. Frerick and R. de Beek showed SMRs which were in good agreement with the Kurucz spectrum, i.e. without an 8 % offset. Unfortunately the Kurucz spectrum used in this presentations had been wrong due to a typo for which I (J. Skupin) am responsible. I deeply apologize for this mistake and any trouble it may have caused.

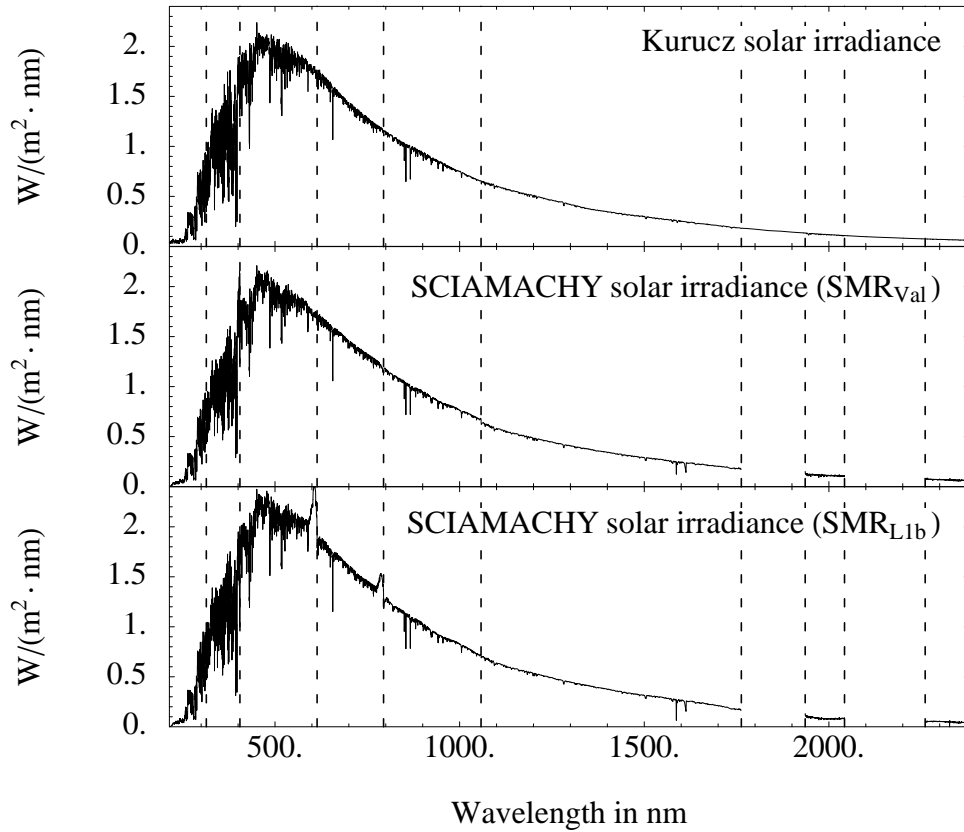


Fig. 3. Comparison of solar irradiances measured by SCIAMACHY ( $SMR_{L1b}$ ,  $SMR_{Val}$ ) with a Kurucz spectrum from MODTRAN 3.7 convoluted with the instrument's slit function (channel boundaries marked by vertical dashed lines).

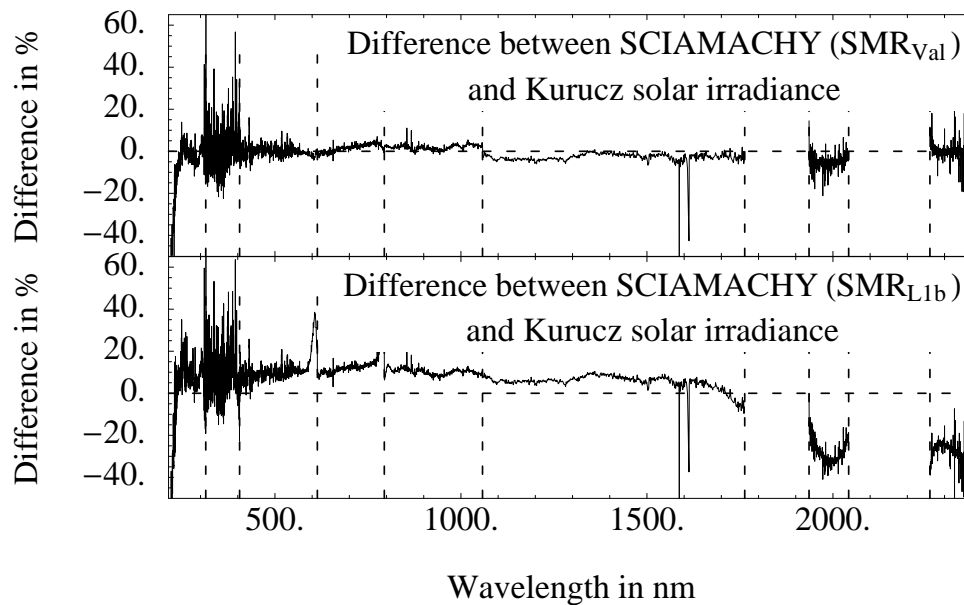


Fig. 4. Difference between solar irradiances measured by SCIAMACHY ( $SMR_{L1b}$ ,  $SMR_{Val}$ ) and a Kurucz spectrum from MODTRAN 3.7 convoluted with the instrument's slit function (channel boundaries marked by vertical dashed lines).

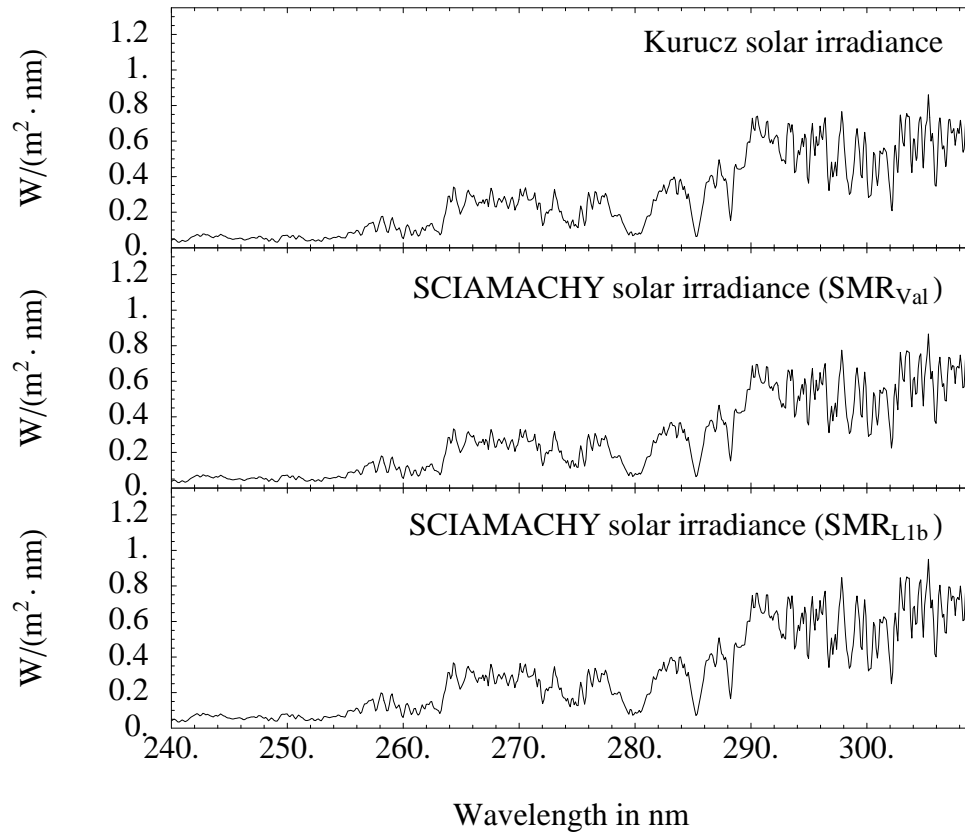


Fig. 5. Comparison of the solar irradiance measured by SCIAMACHY (SMR<sub>L1b</sub>, SMR<sub>Val</sub>) with a Kurucz spectrum from MODTRAN 3.7 convoluted with the instrument's slit function in the UV range of 240 to 310 nm (SCIAMACHY channel 1).

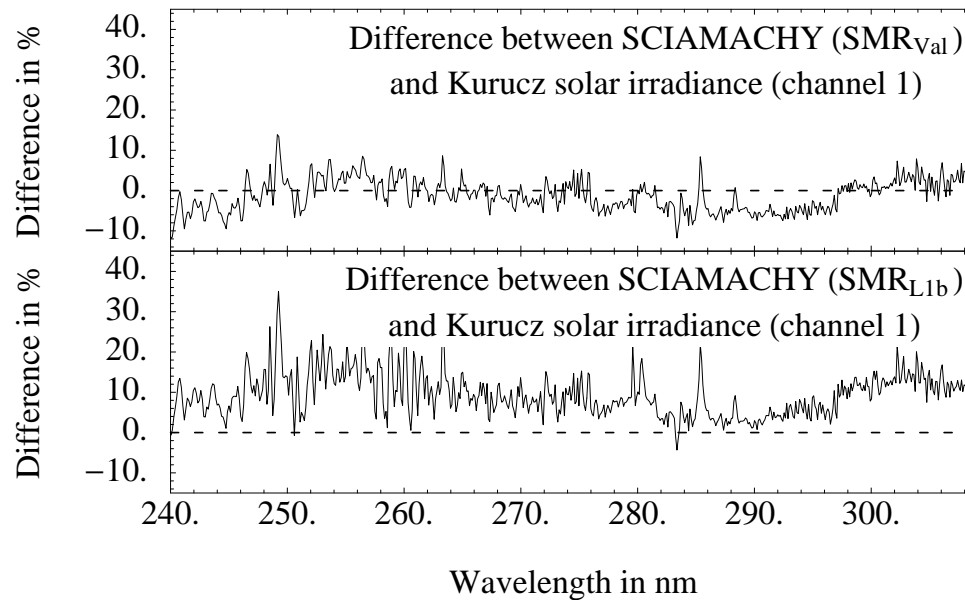


Fig. 6. Difference between solar irradiances measured by SCIAMACHY (SMR<sub>L1b</sub>, SMR<sub>Val</sub>) and a Kurucz spectrum from MODTRAN 3.7 convoluted with the instrument's slit function in the UV range of 240 to 310 nm (SCIAMACHY channel 1).

results for the difference between the SCIAMACHY solar irradiance  $SMR_{val}$  and the Kurucz spectrum for the 600 center pixels of each channel are given in Tab. 2. This analysis shows that the design goal of a mean radiometric accuracy  $< 5\%$  can be met.

Some of the deviations between the SCIAMACHY solar irradiance and the Kurucz spectrum can already be explained: At the channel boundaries (marked by vertical dashed lines in the plots) the radiometric sensitivity of SCIAMACHY decreases which leads to a reduced signal-to-noise level and thus to larger errors. The InGaAs detectors (channels 6 to 8) have changed since the on-ground calibration, i.e. new dead/bad pixel masks and the in-flight pixel-to-pixel gain are still under investigation and not yet optimized. The strong variance in the UV (channels 1 and 2 from 200 to 400 nm) might be related to the strong Fraunhofer structures in this area. Small errors in the spectral calibration lead to relatively large differences in the irradiance. This is supported by the good agreement between SCIAMACHY and the UARS instruments where binned data with lower spectral resolution is used as shown in the next section.

In Figs. 3 and 4 the transmission loss due to ice in channels 7 and 8 is clearly visible in the level 1b  $SMR_{L1b}$  in contrast to the  $SMR_{val}$  due to the different calibration approaches. The level 1b  $SMR_{L1b}$  also shows stronger errors at the boundaries between channels 3 to 4 and 4 to 5 than the  $SMR_{val}$ . A possible reason might be that on-ground to in-flight changes of the instrument performance are not yet fully considered by the 0 to 1 processor. Neither etalon, pixel-to-pixel gain nor M-factors have been updated for these channels yet. In addition Fig. 6 shows stronger residual Fraunhofer structures for the level 1b  $SMR_{L1b}$  than for the solar irradiance  $SMR_{val}$ . This may indicate that the level 1b spectral calibration for channel 1 derived by the 0 to 1 processor still needs some optimization.

### **3.2. UARS instruments SOLSTICE and SUSIM**

A comparison of the SCIAMACHY solar irradiance  $SMR_{L1b}$  with the UARS instruments SOLSTICE and SUSIM for the UV wavelength range of 240 to 400 nm is shown in Figs. 7 and 8. The SCIAMACHY solar irradiance has been binned to 1 nm intervals to match the wavelength grid of SOLSTICE and SUSIM data distributed by the Goddard Space Flight Center. The difference between SCIAMACHY and these UARS instruments (upper both plots in Fig. 8) is in the same range as the difference between SOLSTICE and SUSIM (lower plot in Fig. 8). Thus SCIAMACHY agrees perfectly within the accuracy limits of SOLSTICE and SUSIM. Comparable results (despite the not yet corrected offset of  $\approx 8\%$ ) can be derived for the level 1b  $SMR_{L1b}$ .

## **4. CONCLUSION**

SCIAMACHY was successfully launched and put into operation. An in-flight calibration has been performed by characterizing the change of instrument performance since the on-ground calibration using the internal light sources. Based on this work a spectral and radiometric calibrated solar irradiance  $SMR_{val}$  measured by SCIAMACHY has been calculated. The comparison with a solar spectrum derived by Kurucz [5] shows that the design goal of a mean radiometric accuracy  $< 5\%$  can already be met in all channels despite of an overall offset of  $\approx 8\%$  of the whole instrument which is still under investigation. When binned to the wavelength grid of the solar irradiance of the UARS instruments SOLSTICE and SUSIM the SCIAMACHY measurement is in perfect agreement considering the accuracy of these instruments.

The comparison with the sun mean reference  $SMR_{L1b}$  contained in the level 1b data product shows an overall good agreement with the solar irradiance  $SMR_{val}$  derived with independent calibration routines. Some deviations like the spectral calibration in channel 1, stronger errors at the channel boundaries and the to be corrected influence of the ice grow in channels 7 and 8 still have to be improved in  $SMR_{L1b}$ . Also the 8% offset is not yet corrected which may have an impact on sun normalized radiances.

## **5. ACKNOWLEDGMENTS**

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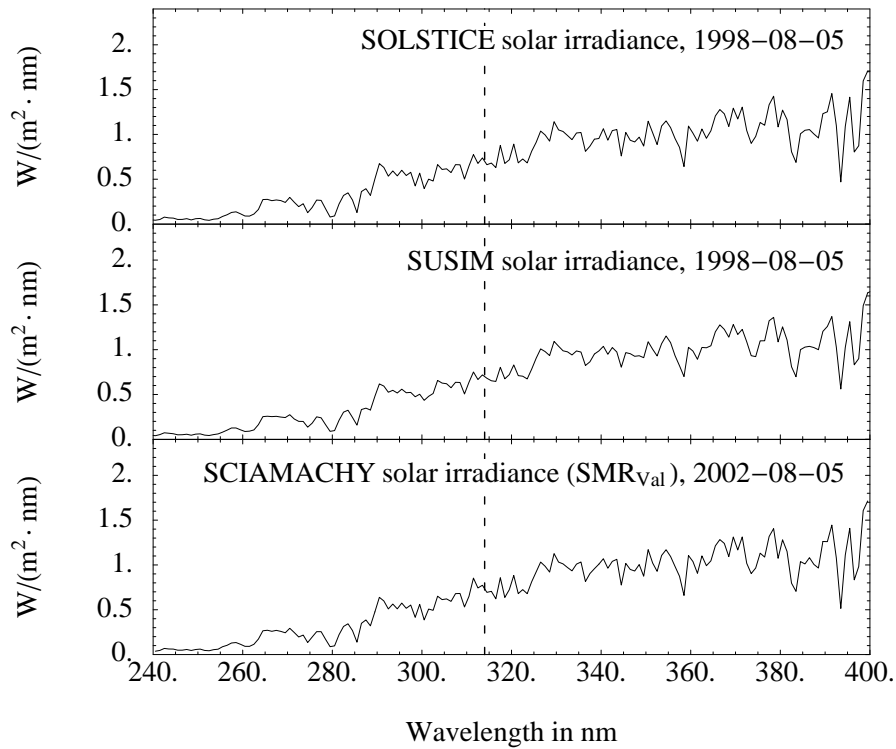


Fig. 7. Comparison of the solar irradiance measured by SCIAMACHY (SMR<sub>Val</sub>) binned to 1 nm intervals with measurements of the UARS instruments SOLSTICE and SUSIM (channel boundaries marked by vertical dashed lines).

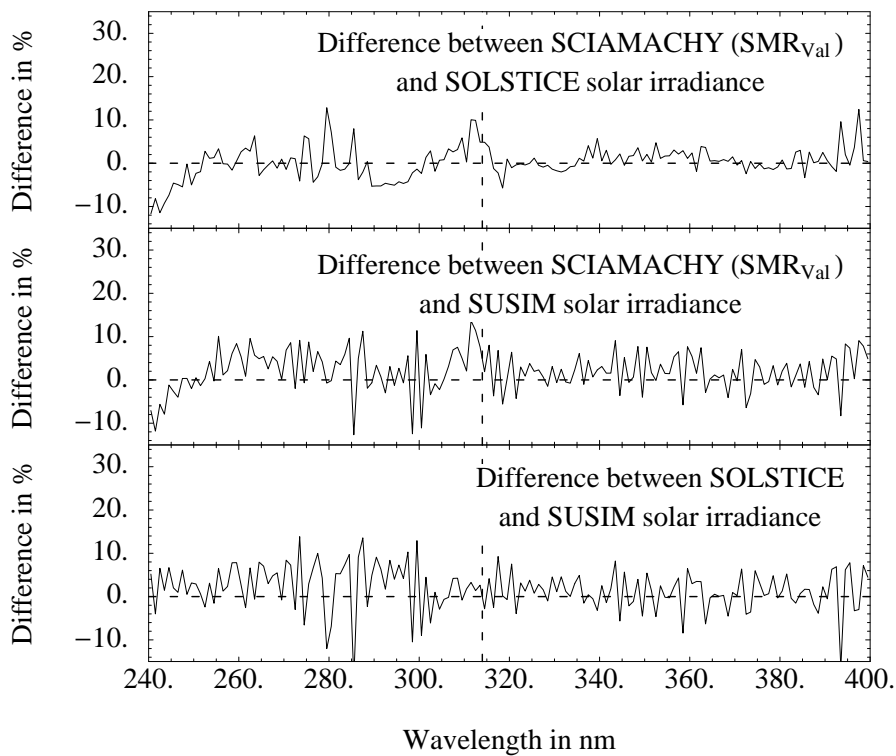


Fig. 8. Difference between the solar irradiance measured by SCIAMACHY (SMR<sub>Val</sub>) binned to 1 nm intervals and measurements of the UARS instruments SOLSTICE and SUSIM (channel boundaries marked by vertical dashed lines).

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