SCIAMACHY SOLAR IRRADIANCE VALIDATION USING RADIOMETRIC CALIBRATION OF BALLOONBORNE DOAS AND FTIR INSTRUMENTS

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ABSTRACT

Solar occultation measurements of balloonborne LPMA and DOAS spectrometers are used for SCIAMACHY validation. The SCIAMACHY level-1 product solar irradiance is validated by extrapolation of measured spectra at different solar zenith angles. To achieve this, a radiometric calibration is performed before and after each balloon flight. To correct for atmospheric effects, the Langley-plot method will be used to calculate the TOA (top of atmosphere) incoming solar irradiation. It is a standard procedure that has been applied for a number of satellite sensors like SeaWiFS [1], SBUV [2] (Nimbus 7) and many ground – based sensors [3-5]. As the campaign work will start in 2002, this paper concentrates on general theoretical and technical aspects of the solar irradiance validation.

1. SCIAMACHY ON ENVISAT

The sensor to be validated by the procedures described here is SCIAMACHY on ENVISAT-1, a spaceborne atmospheric chemistry instrument. SCIAMACHY is a passive optical remote sensing instrument that measures the absorption, reflection and scattering characteristics of the atmosphere between 240 and 2380 nm wavelength. Measurements are made using scattered sunlight in nadir and limb geometry, transmitted solar and lunar radiation in occultation geometry, and solar and lunar irradiance. For each orbit solar occultation measurements, including measurements of the solar irradiance, will be performed during sunrise. All measurements will be converted to provide information about the amounts and distributions of selected atmospheric constituents (O_3, BrO, OCLO, SO_2, NO, NO_2, H_2O, CO, CO_2, CH_4, N_2O among others), as well as information about aerosol, pressure, temperature, radiation field, cloud cover, cloud top height and surface reflectance. ENVISAT-1 is scheduled to be launched to a sun-synchronous orbit in October 2001. Global coverage will be obtained each time after 3 days equaling 42 orbits.

2. PRODUCT: SOLAR IRRADIANCE

The solar irradiance is a level 1 product of SCIAMACHY. It is an input quantity for retrieval algorithms like FURM (FULL Retrieval Method) which was already used for the retrieval of GOME O_3 profiles. Solar irradiance data also play a major role in the development of the data retrieval in limb-geometry and as an input parameter for chemical models (i.e. Ring). Solar irradiance measurements are useful for long-term instrument performance monitoring and their validation will help to maintain the calibration of SCIAMACHY during its lifetime. Instrument aging is known to be a large source of uncertainty. Experience with the GOME sensor [6] shows that the calibration may vary significantly after launch as a result of degradation in orbit. Further interest arises from the field of solar physics. The influence of the solar UV-light on the upper atmosphere and on earth´s climate has already been subject of dedicated satellite measurements. Spectrally resolved UV-irradiance with emphasis on the 27-day solar rotation and the 11-year solar cycle has been monitored by the satellite instruments SOLSTICE [7] (calibrated against stellar targets) and SUSIM [8]. Calibration concepts of these instruments had to take into account the strong degradation in orbit. In the case of SUSIM an independent backup instrument carried by Space-Shuttle was included, which could be repeatedly calibrated pre- and post-flight. The solar irradiance validation of SCIAMACHY described here also relies on repeated calibrations of the balloonborne spectrometers used.

3. GENERAL CONCEPT

The LPMA (Limb Profile Monitor of the Atmosphere, an IR Fourier-transform spectrometer) and DOAS [9] (Differential Optical Absorption Spectrometer, a UV / visible grating spectrometer) are used together as a combined balloon payload. During regular flights of the payload scheduled for the validation of SCIAMACHY level-2 products within the framwork of the ESABC (Envistat Stratospheric Aircraft & Balloon Campaign), additional solar irradiance measurements will be made. Both the LPMA and the DOAS instrument use solar occultation for the determination of trace-gas profiles. The combined wavelength range of the instruments (320 – 2400 nm) covers most of the SCIAMACHY spectral range at a comparable resolution, and thus offers the unique opportunity for a validation of the level-1 product solar irradiance. SCIAMACHY channels 2 and 3 are covered by DOAS, while channels 5, 7, 8 and possibly 4 and 6 are accessible by the LPMA depending on its configuration.

Prerequisite for the validation is a radiometric calibration of the LPMA and DOAS instruments. The possibility to recalibrate the two instruments in the field prior and after each flight of the balloon is an advantage over satellite measurements that can increase overall accuracy. Radiation from a QTH (quarz tungsten halogen) calibration source will then be coupled into the optical inlet port of the LPMA / DOAS payload. The irradiance of the QTH lamp depends upon the distance between lamp and target, the orientation of the lamp, and the directional nature of the lamp´s output. A custom-designed field calibration unit containing the QTH source and an optomechanical arrangement to assure defined optical coupling will be used. As this will have to be done in the field prior to each balloon launch, evacuation of the calibration unit will be difficult to achive. Thus, atmospheric absorptions (mainly water vapor) on the path between QTH source and balloon instruments have to be considered as an error source. These lines will be visible in the recorded spectra and correction should be possible by a procedure described below. From the known spectral input to the instruments I_{cal}, and the instruments response I_2, the spectral response function I_{ins} of the balloon spectrometer can then be calculated as the ratio $I_{ins} = I_2/I_{cal}$. The desired solar spectrum I_{sun} for the given solar zenith angle (SZA) can be calculated by dividing the solar spectrum seen by the instrument I_{meas} by the instrument´s response function I_{ins} as $I_{sun} = I_{meas}/I_{ins}$. From these spectra, recorded as a function of SZA, the extraterrestrial solar irradiance is extrapolated.

Ballon lauches will be scheduled as to enable occultation measurements during sunrise or sunset from the float position at an altitude of 30-35 Km. Measurements can then be made at different solar zenith angles ranging from 83 to 95 degrees in a relatively short time interval. Airmass factor is a function of the SZA. As a result of the stratospheric observational position the airmass-factor is relatively small and the effects of the planetary boundary layer reported in [3] will be eliminated. Extrapolation of the spectra measured at different SZA to zero-airmass then yields the desired extraterrestrial solar irradiance using the Langley-plot method. It is important, that while the solar disk is monitored under different zenith angles, the atmosphere can be considered constant. The SZA should be the only variable parameter during the measurement. From the solar irradiance data acquired in stratospheric float and the instruments transmission function acquired using the calibration source, the solar spectrum can be calculated and plotted as a function of the airmass-factor. The zero-intercept (zero airmass) is the solar irradiation above the atmosphere.

The SCIAMACHY solar irradiance validation will be performed as an additional measurement using the two-instrument balloon-payload already included in the validation programme. There is no need for instrument modification or additional balloon launches.

3.1 Calibration Sources and Procedures

The balloon-instruments LPMA and DOAS used as transfer devices have to be radiometrically calibrated. This can be done using a light source of adequate and precisely known radiation. QTH sources similar to the lamps used in imaging systems like slide projectors can be used for this purpose. Selected lamps of high quality and temporal stability are individually calibrated by a (small) number of institutions like the NIST (National Institute of Standards and Technology) in the USA or the PTB (Physikalisch-Technische Bundesanstalt) in Germany. Both institutions realise the spectral radiation scale using a gold point blackbody and the Planck radiation law. Details of the procedure and the transfer standards involved can be found in [10]. As a spectral irradiance standard, NIST issues a 1000-watts QTH lamp which is used by a number of commercial vendors to produce secondary standards. All these lamps emit radiation in the spectral range between 240 and 2400 nm. Thus, a single source can be used to cover the entire range of interest in the calibration described here.

From a theoretical point of view, the spectral radiation for a given lamp could be calculated with formalism derived from the Planck blackbody radiation, if a number of lamp parameters were known precisely. The complete radiance then depends on one single parameter, the filament temperature as an analogy to the blackbody temperature. From that point of view, the spectral radiance for a given electrical power input could quite easily be calculated. However, the practical error budget of the QTH lamp´s radiation contains uncertainty from parameters like composition of filament, composition of glass envelope and difficulties to measure the precise color temperature. These data are hard to acquire by measurements, and are not available from the makers of the lamps. A mathematical model for QTH sources is under development, but for the work described here, a set of NIST (or NIST-traceable) QTH sources will be used. This is the most practical and safe way to transfer a certified calibration to the instruments.

For the radiometric calibration of a spectrometer aiming at solar irradiance measurements, one desires the calibration source (QTH lamp) to be as similar as possible to the source to be analysed (sun) in three aspects. These aspects are 1) similar irradiance, 2) similar spectral distribution (color temperature), and 3) similar imaging properties (geometry of rays, e.g. focused, divergent or collimated).

3.2 Irradiance

A similar irradiance (radiometric flux per unit area) of calibration source (QTH) and unknown source (sun) is preferable in order to stay well within the dynamic range of the optical sensors of the instrument to be radiometrically calibrated. If the intensites of the two sources to be compared differ by several orders of magnitude, dynamic limitations and nonlinearities of the sensors can introduce additional uncertainty. Total solar irradiance is in the order of 0.1 watts per cm^2 for small zenith angles and clear sky conditions. This power per area can be obtained from a 1000-watts lamp at an operating distance of approximately 28 cm (inverse square law), assuming uniform light distribution.

3.3 Spectrum (Color Temperature)

A similar color temperature (spectral distribution of the total irradiance) of the two sources is desired for very similar reasons: to assure sensor linearity by using similar intensities of calibration source and unknown source in each part of the spectrum. Unfortunately, this demand can only be fulfilled in part. As an approximation, the sun can be considered as a blackbody with a color temperature of 5800 K, with the UV radiation deviating somewhat from the Planck blackbody. An artifical calibration source of similar color temperature cannot be realised. The emission of a QTH lamp is also similar to a blackbody, but color temperature is typical around 3000 K, and in comparison to the sun significantly less UV-radiation is produced. As a result of the relatively low UV-power of the QTH lamp, uncertainty of the radiometric calibration below 350 nm is expected to be slightly larger than in the visible. Blackbody radiation at several color temperatures is shown in fig. 1 [11]. The extraterrestrial solar irradiance compared to a blackbody at 5800 K can be seen in fig. 2 [11].

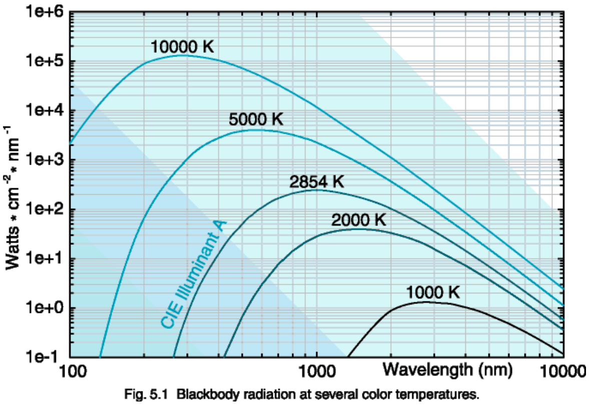

Fig. 1. Blackbody Radiation [11]

3.4 Geometry

The sunlight reaching the instrument´s optical aperture can be considered a parallel, collimated beam as a result of the large distance between source and target. This is not true for a calibration source illuminating the entrance aperture of a spectrometer from a distance of typically 0.2 to 5 meters. Of the two instruments to be radiometrically calibrated in this work (LPMA and DOAS), especially the Fourier-transform meter LPMA relies on a collimated beam as a consequence of its interferometric working principle. From the imaging point of view, of course a collimating system, composed of a mirror or a lens, might be used. These components however will introduce spectral transmission (lens) or reflection (mirror) functions that will modulate the lamp´s spectral output. While one solution to the problem might be to have the lightsource (lamp and collimator) calibrated as a whole, in this work it is intended to use the bare lamp without any collimating system.

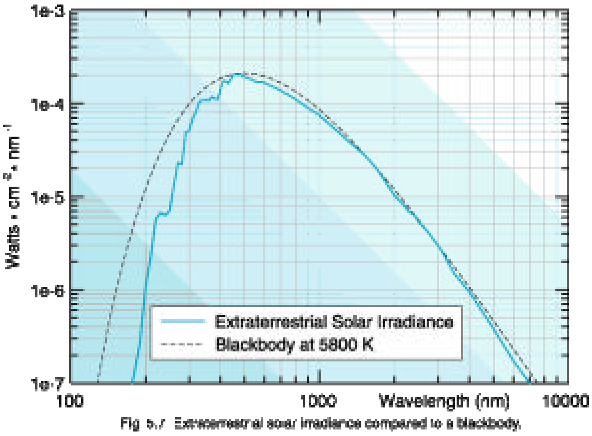

Fig. 2. Extraterrestrial Solar Irradiance [11]

The experience gained during the radiometric calibration of SCIAMACHY in limb-mode using different geometries with the same light source is used here: In order to get an illumination independently of the distance between the source (1000 watts QTH) and the target (SCIAMACHY), a sperical mirror was used to produce a collimated beam. In practice the distance between source and target turned out to be an important parameter because filament imaging in the beam depended strongly on this distance [12]. Also, the reflectance properties of the spherical mirror may depend on the angle of incidence of the rays emitted by the lamp. This increases the risk that the spectral composition of the parallel beam may not be uniform throughout its cross-section. Finally, the beam may become partly polarised as a result of the reflection on the mirror´s surface.

If the bare lamp is used without any collimating system, a divergent beam will reach the entrance aperture of the LPMA / DOAS System. When the 60-mm aperture of the LPMA is illuminated by the bare lamp from a distance of one meter, the path difference between a ray on the optical axis reaching the center of the aperture, and a peripheral ray reaching the edge of the aperture is 450 micrometer. Instead of being planar like with a collimated beam, the divergent beam will produce a slightly sperical interferogram inside the FTIR spectrometer. Depending on instrumental parameters, this will cause some reduction of the spectral resolution. The DOAS uses an aperture of 10 mm

spectro-
diameter followed by light-fibres, and path difference will be around 130 micrometers for the same condition. Lab experiments to clarify the imaging aspects will be made with LPMA and DOAS in order to optimise the final design of the calibration source.

4. ERROR BUDGET

The accuracy of the SCIAMACHY level-1 product solar irradiance is specified with 3-5 % [14], but the value is not given as a function of wavelength. For the 1990 NIST Scales of Spectral Radiance and Spectral Irradiance, Planck´s radiation law is used with a gold point blackbody as a reference standard. Calibration uncertainty of NIST lamps [10] (two standard deviation estimate) is specified with 1.8% at 240 nm, 0.9 % at 655 nm, 1.4% at 1600 nm and 4.4% at 2400 nm. The use of a secondary standard (NIST-traceable) adds another 1% of uncertainty. However, the use of more than a single lamp seems highly recommendable to improve the statistical significance. Sometimes even NIST-lamps fail to comply to their specification as found in a comparison study [4]. For the transfer of the radiometric calibration from the QTH source to the balloon instruments, as an estimation a total additional error of 2% can be expected [4] for the VIS and NIR part of the spectrum. These estimated 2% include uncertainties from optomechanical positioning (0.5 %), effects of lamp current uncertainty (0.1 %), atmospheric absorptions during calibration (0.8%) and spectrometer output uncertainty (0.5%).

As the pre- and postflight calibrations will be made in the field at ambient pressure, atmospheric absorbers (mainly water vapor) on the lightpath between calibration source and LPMA/DOAS optical inlet will increase uncertainty in some spectral regions. A calculated blackbody emission for these spectral regions can be used as a fit function to correct for the atmospheric absorbers. This approach is similar to the interpolation method recommended by NIST for wavelengths between the calibration points of the QTH-sources.

The precision limits (repeatability) of the balloon spectrometers used as transfer devices are another source of uncertainty, as some parameters of their optical detectors depend on temperature, which can only be kept constant with a limited accuracy during the balloon flight. For the LPMA, output has known to vary by several percents as a function of temperature fluctuations [private communication LPMA] depending on the configuration used. Error studies using the original balloon-instruments in the lab are currently under preparation and will be finalised well before the launch of ENVISAT.

Extrapolation of the stratospheric solar irradiance measured under various solar zenith angles to the top of atmosphere irradiance with the Langley-plot also the measurements under clean-air conditions at small airmass factors (high altitude) or small solar zenith angles (transmission uncertainty reduced). The high altitude of the ballon measurements provide small airmass, and stratospheric variability also can be considered small. In order to reach the overall target accuracy of 3%, the error produced by extrapolation of the solar irradiance measured under different SZAs should be no greater than 1%. In ground-based high-altitude applications of the method, total errors in the radiometric calibration using Langley-plot between 0.6 to 1.6% depending on spectral region [3] were reported. Measurement precision of the standard Dobson spectrophotometer is known to an uncertainty of 0.5% using Langley-plot method [13] over 25 years.

5. LABORATORY BACK-UP

The use of a single calibration source involves the risk of a change of the lamp´s radiation over time as a result of aging or degradation. Also, even the quite costly lamps issued by NIST have been found sometimes to contain outliers [4] and to not always comply with their specification. With a single lamp, there is a hardly any chance to detect these errors. For this reason, a set of three lamps will be purchased for intercomparison in the lab. This method of working with a "family" of calibration sources of the same type has proven to produce the best precisions (0.5%) over extended periods of time [13]. The sources can be compared to each other using a BRUKER 120 HR FTIR spectrometer available at the IUP lab as a transfer device.

6. TECHNICAL ADVANCES

QTH sources exhibit excellent stability in the laboratory. In order to maintain this stability in field campaigns where warm-up times and ambient temperature cannot always be kept constant, an active feedback and stabilisation scheme for the calibration unit has been developed. In addition to the constant-current drive normally used for QTH-lamps, a constant power drive using realtime power calculation for electronic feedback has been installed. Further, the lamp´s color temperature can be actively monitored using optical bandpass filters and feedback to correct the lamp´s operating parameters. This will compensate the negative effects of lamp degradation, ambient temperature fluctuations or necessary lamp changes and maintain a constant color temperature of the radiation.

7. SUMMARY

The balloonborne spectrometers DOAS and LPMA already forming part of the ESABC will be additionally used to validate the SCIAMACHY level-1 product solar irradiance. To assure valid measurements, these spectrometers will be radiometrically calibrated before and after each flight using stabilised QTH calibration lamps. Solar occultation measurements made can produce errors. In general it is preferable to make at the float altitude at different solar zenith angles can be extrapolated to calculate the extraterrestrial solar irradiance using the Langley-plot method. Almost the entire spectral range of SCIAMACHY will be covered. ENVISAT with SCIAMACHY is scheduled for launch in october 2001, the validation campaigns with stratospheric balloons are planned for 2002 and 2003.

8. REFERENCES

1. Biggar S. F., Slater P.N, Thome K. J., Holmes A. W., Barnes R. A., *Preflight solar-radiation-based calibration of SeaWiFS*. Proceedings of SPIE 1993 Vol. 1939, 233-242

2. Bhartia P. K, S. Taylor S, McPeters R. D., Wellemeyer C, *Application of the Langley plot method to the calibration of the solar backscattered ultraviolet instrument on the Nimbus 7 satellite*, J. Geophys. Res, 100, 2997-3004, 1995

3. Schmidt B., Spyak P. R., Biggar S. F., Wehrli C., Sekler J., Ingold T., Matzler C., Kampfer N., *Evaluation of the applicability of solar and lamp radiometric calibrations of a precision sun photometer operating between 300 and 1025 nm*, Applied Optics, Vol. 37, 3923-3941, 1998.

4. Michalsky J.J., Berndt J.L., Kiedron P. W., Harrison L. C., *Calibration of ARM spectral shortwave radiometers*, University at Albany, available online: http://uvb.asrc.cestm.albany.edu/rssdocs/spec_cal.pdf

5. Pietras, C. *Sun photometer calibration*, available online: http://simbios.gsfc.nasa.gov/Sunphotometers/

6. Eisinger M., Burrows J. P., Richter A., *Studies on the precision of GOME irradiance and radiance products and GOME measurements of OCLO and BrO over Antarctica*, GOME calibration and valiadation handbook

7. SOLSTICE homepage:
http://lasp.colorado.edu/solstice

8. SUSIM homepage:
http://wwwsolar.nrl..navy.mil/susim.html

9. Ferlemann F., Bauer N., Fitzenberger R., Harder H., Osterkamp H., Perner D., Platt U., Schneider M., Vradelis P., Pfeilsticker K., *Differential optical absorption spectroscopy instrument for stratospheric trace-gas studies*, Appl. Opt.Vol 39, No 15, 2377-2386, 2000.

10. NIST website:
http://www.physics.nist.gov/Divisions/Div844/facilities/fascal/fascal.htm

11. Ryer A., *Light measurement handbook* , International Light, Inc ISBN 0-9658356-9-3, 1997.

12. *SCIAMACHY PFM calibration results review*, data package Vol. 3, TN-SCIA-1000TP/190

13. Komhyr W. D., Grass R. D., Leonard R. K., *Dobson spectrometer 83: A standard for total ozone measurements, 1962-1987*, J. of. Geophys. Res., Vol. 94, No D7, 9847-9861, 1989.

14. *SCIAMACHY Instruments Requirements Document (SIRD)*

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