RETHINKING SATELLITE BASED SOLAR IRRADIANCE MODELLING

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ABSTRACT

Accurate solar irradiance data are not only of particular importance for the assessment of the radiative forcing of the climate system, but also absolutely necessary for an efficient planning and operation of solar energy systems. Within the European project Heliosat-3 a new type of solar irradiance scheme is developed. This new type will be based on radiative transfer models (RTM) using the information of atmospheric parameters retrieved from the MSG satellite (clouds, ozone, water vapour) and the ERS-2/ENVISAT satellites (aerosols).

This paper focuses on the description of the clear sky module of the new scheme, especially on the integrated use of a radiative transfer model. The linkage of the clear sky module with the cloud module is also briefly described in order to point out the benefits of the integrated RTM use for the all sky situations. The integrated use of a RTM within the new SOlar Irradiance Scheme SOLIS is applied by introducing a new fitting function called the modified Lambert-Beer (MLB) relation. Consequently, the modified Lambert-Beer relation and its role for an integrated RTM use are discussed. Comparison of the calculated clear sky irradiances with ground based measurements and the current clear sky module demonstrates the advantages and benefits of SOLIS. For example, spectral resolved data as well as the possibility to use enhanced information of atmospheric parameters. Since SOLIS provides spectral resolved irradiance data, it can be used for different applications. Beside improved information for the planning of solar energy systems, the calculation of photosynthetic active radiation, UV-index and Illuminance is possible.

1 INTRODUCTION

An accurate estimation of the downward solar irradiance is not only of particular importance for assessing the radiative forcing of the climate system, but also absolutely necessary for an efficient planning and operation of solar energy systems and the estimation of the energy load. Solar resource assessment from geostationary satellites constitutes a powerful alternative to meteorological ground network for both climatological and operational data (Perez et al., 1998a). For an optimal and sufficient usage of solar energy and for the integration into the electricity grid, accurate solar irradiance data in a high spatial and temporal resolution are necessary. Solar irradiance schemes provide these data using weather satellites such as METEOSAT and MSG. Currently, most of the operational calculation schemes for solar irradiance are semi-empirical and based on statistical methods. They use cloud information from the current METEOSAT or GOES satellite and climatologies of atmospheric parameters, e.g. turbidity (characterising the combined effect of aerosols and water vapour), see Perez et al. (2001) and references therein. The Heliosat method (Cano et al., 1986) and (Beyer et al., 2003) is certainly one of the most known. It converts METEOSAT satellite data into irradiance with a better accuracy than interpolated ground measurements could provide (Perez et al., 2001) and (Perez et al., 1998b). It is applied routinely in real time at the University of Oldenburg since 1995. It has permitted to establish the server Satel-Light, which delivers valuable information on daylight in buildings to architects and other stakeholders (Fontoynont et al., 1997). It has also been used within the SoDa project [1] (Wald et al., 2002) for the calculation of the solar irradiance. Furthermore there

[1] Integration and exploitation of networked Solar radiation Databases for environment monitoring project.

exists derivates of Heliosat, e.g Heliosat-2 (Lefèvre et al., 2002) which is optimised as an operational processing chain for climatological data. With the launch of the Meteosat Second Generation (MSG) satellite the possibilities for monitoring the earth atmosphere, have improved enormously. The MSG satellite will not only provide higher spatial (1km) and temporal (15 minutes) resolution, but also offers with its 11 channels from 0.6 to 13 $microm$ the potential for the retrieval of atmospheric parameters such as additional cloud parameters, ozone, water vapour column, and with restrictions aerosols. These capabilites plus the synergy with other sensors, such as those aboard ERS-2 and ENVISAT (GOME and SCIAMACHY), permit to attain a refinement in the solar irradiance modelling. These refinements necessitate a rethinking in satellite based solar irradiance modelling, going ahead with a drastic revision of the current Heliosat processing scheme. The current Heliosat scheme can not exploit the enhanced information about the atmosphere provided by the improved satellite capabilities. Thus, it was necessary to develop a new scheme, which will be able to exhaust the enhanced capabilities of MSG (SEVIRI) and ENVISAT (SCIAMACHY). The accuracy of the calculated irradiance is expected to increase significantly with a scheme that can exhaust the capabilities of the new satellites. The new calculation scheme has to be fast, accurate and should provide - in contrast to Heliosat and Heliosat-2 - spectral resolved solar irradiance data.
As a consequence of the things mentioned above the new scheme is based on the integrated use of a radiative transfer model (RTM), whereas the information of the atmospheric parameters retrieved from the MSG satellite (clouds, ozone, water vapour) and from the GOME/ATSR-2 instruments aboard the ERS-2 satellites (aerosols, ozone) will be used as input to the RTM based scheme. The direct integration of a RTM into the calculation schemes - instead of using pre-calculated look-up tables - is only possible if the necessary computing time can be kept small. For this purpose a functional treatment of the diurnal solar irradiance variation is applied. This allows an appropriate operational use of a RTM within the calculation scheme.
This paper focuses on the description of the new clear sky module, especially on the integrated use of the radiative transfer model (section 2) . The linkage of the clear sky module with the cloud module is briefly described in order to point out the benefits of the integrated RTM use for all sky situations as well.

2 SOLIS - THE NEW SCHEME

2.1 Overview

In order to benefit from these enhanced capabilities a new calculation scheme based on radiative transfer models (RTM) is developed. The information about the atmospheric parameters retrieved from the MSG satellite (clouds, ozone, water vapour) and from the GOME/ATSR-2 instruments (aerosols, ozone) will be used as input to the RTM based scheme.[2] The integrated usage of the RTM within the scheme is related to the clear-sky scheme using the well established *n-k* relation of the Heliosat method (Cano et al., 1986) and (Beyer et al., 1996) or the Cloud Optical Depth (COD) option to consider cloud effects. It is important to note that the integrated use of the RTM within the clear sky module is linked with an enormous improvement for all sky situations as well. The benefits and needs of the described clear sky module can only be understood if it is seen in the context of its main purpose – the operational satellite based solar irradiance modelling with a large geographical coverage. Keeping this in mind, it is also necessary to describe briefly the treatment of the clouds and the basics of the linkage between the clear sky module -described in detail in this paper- and the cloud modules, which are partly still under development.
Using n-k relation:
The Heliosat method was originally proposed by Cano et al. (1986) and later modified by Beyer et al. (1996) and Hammer (2000). The basic idea of the Heliosat method is a two step approach. In a first step a relative normalised cloud reflectivity – the cloud index – is derived from METEOSAT images. The derived cloud index is correlated to the clear sky index k, which relates the actual ground irradiance G to the irradiance of the cloud free case $G_{clearsky}$. Consequently, in addition to the cloud index derived from the satellite signal a clear sky model, providing $G_{clearsky}$, is necessary for the estimation of the actual ground irradiance.
The *n-k* relation is powerful, validated and leads to small Root Mean Square Deviation (RMSD) between measured and calculated solar irradiance for almost homogenous cloud situations (RRMSD of 13-15 % for hourly values (Hammer, 2000)). With MSG data it can be expected that the treatment of clouds using the current n-k will be improved only due to the higher spatial and temporal resolution. Nevertheless, an improvement of the *n-k* relation

[2] In the near future the information from GOME/ATSR-2 will be replaced by SCIAMACHY/AATSR on ENVISAT.

using physically retrieved cloud parameters is in preparation.
Using COD based code:
Within this option the information of the cloud optical depth (COD) is used to consider the cloud effect. The COD will be retrieved operationally from MSG with software from the German Aerospace Center (DLR), based on the Apollo (Kriebel and Gesell, 1989) and (Saunders and Kriebel, 1988) or Nakajima (Nakajima and King, 1990) method. The RTM model SBDART (Ricchiazzi et al., 1998) has been used to find a parameterisation in order to relate the all sky irradiance to the clear sky irradiance. Within this parameterisation also the effective radii, derivable with the Nakajima and King (1990) based scheme can be used. The derived parametrisation needs some fine-tuning and has to be tested with MSG data.
Independently which way is chosen for the treatment of clouds, the basis for the calculation of the all sky radiation is the clear sky module. More over, the clear sky situations are the most energy efficient. This exhausts the importance of an accurate and powerful clear sky module, which is described in detail in the next section.

2.2 Basic considerations

MSG will scan the atmosphere with a very high spatial and temporal resolution. Thus, the computing time necessary to calculate the solar irradiance for each pixel has to be very small to make an operational usage of the solar irradiance scheme possible.
One possibility to manage the computing time problem, with respect to RTM applications, is the use of look-up tables to consider the effect of atmospheric parameter on the solar irradiance. Instead of doing this a new, more powerful and flexible method, the integrated use of RTM within the scheme based on a modified Lambert-Beer relation, will be applied.
The integration of a RTM into the calculation schemes, instead of using pre-calculated look-up tables, is only possible if the necessary computing time can be decreased enormously. For this purpose, a ingenious functional treatment of the diurnal solar irradiance variation had to be applied. Thus making an appropriate explicit operational use of a RTM within the calculation schemes possible.
Starting point of the integrated use is the assumption that daily values of the atmospheric clear sky parameters in a spatial resolution of 100x100 km or 50x50 km are sufficient. This assumption is reasonable for solar energy applications in consideration of accuracy and operational practicality. It is not linked with significant restrictions of the model. This has been discussed in detail in Müller et al. (2003)
Since daily values of the atmospheric parameters (O_3, H_2O, aerosols) within a region of 100x100 km (50x50 km) are assumed to be sufficient, the diurnal variation of the solar irradiance is dependent only on the Solar Zenith Angle (SZA, θ_z). The RTM calculates the diurnal variation of the solar irradiance for each region using the daily atmospheric parameters as input. The cloud effect and hence the temporal disturbance of the diurnal clear sky irradiance of each pixel is considered by using the *n-k* relation or the COD option, see section 2.1. As a consequence, not every pixel has to be processed with the RTM. With the modified Lambert-Beer function, the diurnal variation of the clear-sky irradiance can be matched very well. Therefore, the number of RTM calculations necessary to define the diurnal variation of the clear sky irradiance can be reduced enormously. Only 2 RTM calculations are necessary to define the complete diurnal variation of the clear sky irradiance for a given atmospheric state. These 2 RTM calculation are enough to calculate the solar irradiance for the whole region (100x100 or 50x50 km), independent whether a pixel is cloudy or not.
Figures 1 illustrates the new scheme and the integrated use of the RTM within the clear sky scheme. The used modified Lambert-Beer (MLB) function is discussed in the next section.

2.3 The Modified Lambert-Beer function

For monochromatic radiation and atmospheric applications the Lambert-Beer relation is given by

$$I = I_0 * exp(\frac{-\tau_0}{cos(\theta_z)}) * cos(\theta_z) \quad (1)$$

where τ is the optical depth, θ_z is the solar zenith angle, I is the direct radiation at ground and I_0 is the extraterrestrial irradiance. For direct monochromatic irradiance the SZA dependent diurnal variation of the irradiance described by this formula matches the results of explicit RTM results very well, once the optical depth is calculated at a SZA of 0 degree.
A good match for wavelength bands and global or diffuse irradiance is only possible if an additional correction

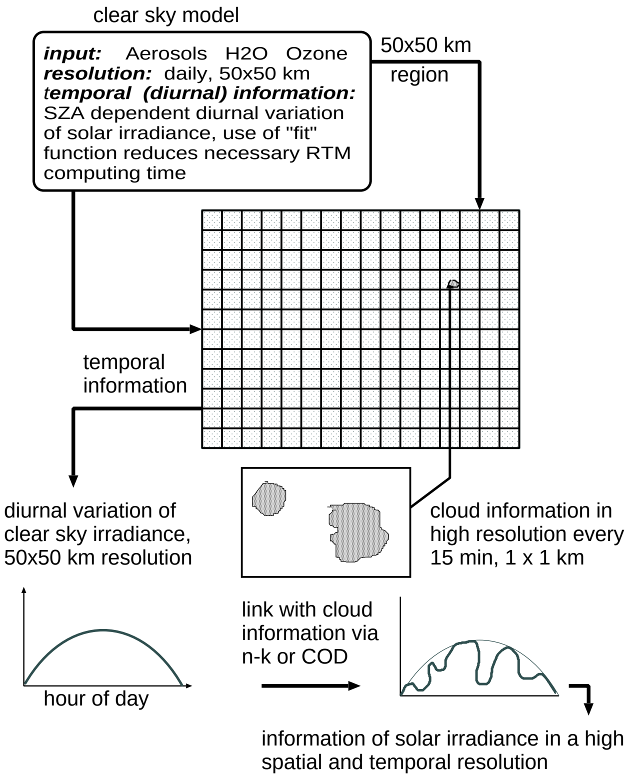

Figure 1: Diagram of the spatial and temporal linkage between clear-sky and cloud information.

parameter a is used. Hence a correction of the optical depth, or equivalent to this, of the parameter $\frac{\tau_0}{cos(\theta_z)}$ is necessary.

$$I = I_{0,enh} * exp(\frac{-\tau_0}{cos^a(\theta_z)}) * cos(\theta_z) \tag{2}$$

In a first step the effective optical depth is calsulated at a SZA of zero, via.

$$\tau_0 = -ln(I/I_0) \tag{3}$$

In a second step the correction parameter a is calculated at a SZA of 60 degree.
Using the so-called Modified Lambert-Beer (MLB) function, the calculated direct radiation and global irradiance can be reproduced very well (see e.g. Fig. 2).
It is important to notice that the fitting parameter a has different values for direct and gloabl irradiancec At low visibilities (high optical depth, high aerosol load) I_o has to be enhanced for global and diffuse radiation. Therefore, a general equation has been developed which is applied to I_0 to get $I_{0,enh}$.

$$I_{0,enh} = (1 + I_0 \cdot \frac{I_{diffuse}}{I_{direct} \cdot I_{global}}) \cdot I_0 \tag{4}$$

The function was tested for many different atmospheric states, e.g four different aerosol types, five different visibilities (5, 10, 23, 50, 100), different water vapour amounts, different standard atmospheres, and surface models. There are no reasons to assume that there exist an atmospheric state for that the fit does not work very well. The differences between fitted and explicitely calculated irradiances are very small. The differences are usually less than 8 W/m^2 for high SZA and less than 5 W/m^2 for SZA below 70 degrees.

2.4 Radiative Transfer Model

The radiative transfer model (RTM) used within the clear-sky module is the model libRadtran. libRadtran is a collection of C and Fortran functions and programs for calculation of solar and thermal radiation in the Earth's atmosphere (A. Kylling and B. Mayer, http:// www.libradtran.org). It has (also) been validated by comparison with other models (Koepke et al., 1998), and radiation measurements (Mayer et al., 1997).
libRadtran offers the possibility of using the correlated-k approach of Kato et al. (1999). The correlated-k method is developed to compute the spectral transmittance (hence the spectral fluxes) based on grouping of gaseous absorption coefficients. The main idea is to benefit from the fact that the same value of the absorption coefficient k

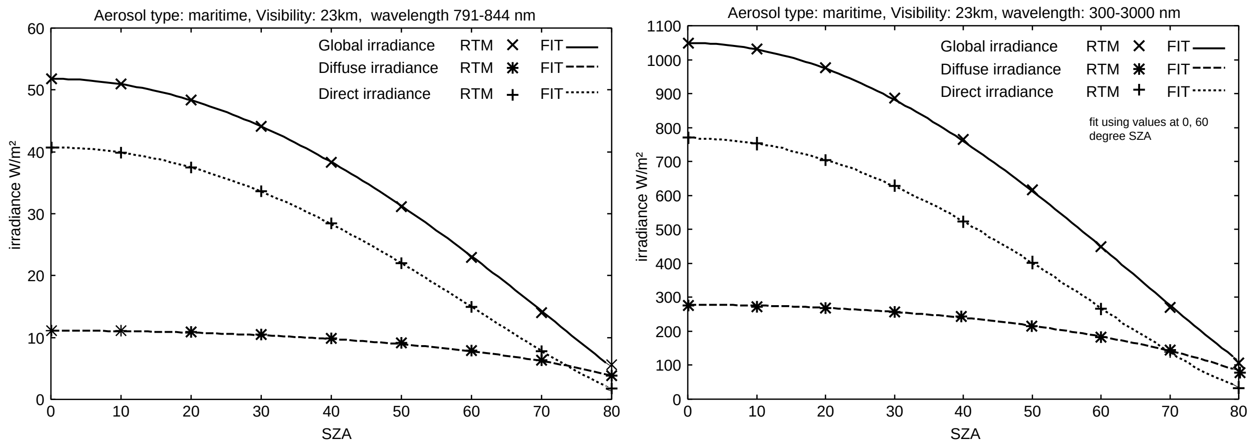

Figure 2: Comparison between RTM calculations and fit using the modified Lambert-Beer relation. Example for fit within a small wavelength band (left hand) and for a wide wavlength region (right hand)

is encountered many times over a given spectral interval. Thus, the computing time can be decreased by eliminating the redundancy, grouping the values of k, and performing the transmittance calculation only once for a given value of k. Using the correlated-k option, the spectral resolved data can be calculated operationally in MSG pixel resolution, a new feature, so far not implemented in the Heliosat or Heliosat-2 method.

In addition, libRadtran is very flexible with respect to the atmospheric input, e.g. different possibilities for the input of the aerosol information can be chosen by the user.

Since the correlated-k option of libRadtran is used within SOLIS, the described procedure for the calculation of the global, direct, and diffuse irradiance is performed not only for the broadband wavelength region but for each wavelength band of the SOLIS clear sky model. The SOLIS wavelength bands are in accordance with correlated-k (Kato et al., 1999) wavelength bands. The spectral output is provided between 306.8 and 3001.9 nm, which is sufficient for solar energy applications. Also additional wavelength bands below 306.8 nm or above 3001.9 nm can be used. The MLB relation works very well for the spectral resolved data, see figure 2 as an example.

3 Comparison of measurements and model, Freiburg, August 2000

Cloud-free situations were selected according to the cloud-index derived with the Heliosat method from METEOSAT images. A situation was assumed to be cloud-free if the cloud index n of the respective pixel was within the interval from -0.03 to 0.03 and the spatial variation of the cloud index was less than 0.02. The possibility still exists that some situations with little cloud cover are included, which especially effects the direct irradiance, leading to an increasing statistical uncertainty.

The ground measurements have originally a temporal resolution of 10 seconds. They are averaged to 30 minutes means in accordance to the temporal resolution of the satellite. The point in time, when the pixel above the measurements station is scanned from the satellite lies in the middle of the 30 minutes averaging window.

The input values for ozone and water vapor were 275 DU and 15mm respectively. This values are based on retrievals from the German Aerospace Center, using state of the art retrieval techniques.

The turbidity map (Wald et al., 2002) provides a turbidity of 4 for the respective months. That corresponds to a visibility of 34 km and an aerosol optical depth (AOD) of 0.23 respectively. The conversion of turbidity to visibility has been performed with the radiative transfer model MODTRAN (Abreu and Anderson, 1996).

GADS/OPAC (Hess et al., 1998) and (Koepke et al., 1997) provides an AOD of 0.18-0.25 for relative humidities between 50 and 80 % and urban as an aerosol type. The range of the AOD is in consistency with the visibility derived from the Linke turbidity climatology. The average relative humidity for the clear sky days was approximately 50 %, leading to an AOD of 0.18.

In figure 3 and 4 the comparison between SOLIS calculated and measured direct and global irradiance is diagrammed. It has to be noted that whether urban or rural aerosols are used, no significant differences in the calculated direct solar irradiance occur. Hence just the results for the urban aerosols are diagrammed. In the case of global irradiance the chosen aerosol type has a significant effect on the global irradiance. In both figures, the results of the Heliosat clear sky model, described in Beyer et al. (2003), are also diagrammed.

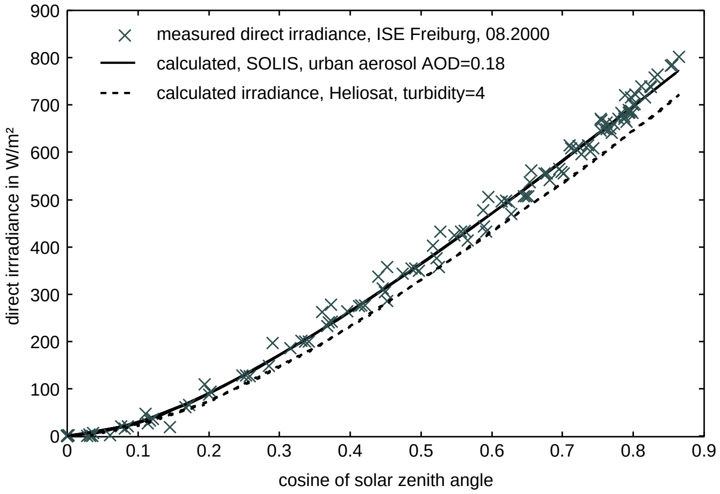

Figure 3: Comparison between SOLIS and measurements using the GADS/OPAC information for the aerosols. The calculated Heliosat clear sky irradiance is also diagrammed. The differences betwen the models are mainly due to the different atmospheric input information.

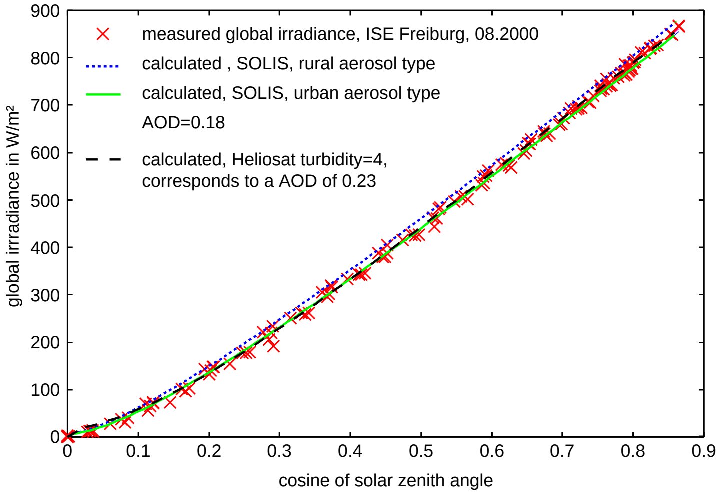

Figure 4: Comparison between SOLIS and measurements using the GADS/OPAC information for the aerosols.The calculated Heliosat clear sky irradiance is also diagrammed.

Using the aerosol information provided by the OPAC/GADS climatology (AOD of 0.18, urban aerosol type) as input, the calculated global and direct irradiance matches the measurements very well, as shown in figure 3 and figure 4. The relative root mean square error is 1.9 % for global and 4.2 % for direct irradiance with a relative bias of 0.6 and 0.5 % respectively. Also the SZA dependency is reproduced very well by the SOLIS model.
In contrast to the results of the SOLIS calculations the Heliosat model results in a good match for the global irradiance, but to a significant underestimation of the direct irradiance for the given turbidity of 4. Since the turbidity defines the attenuation of the direct irradiance this indicates that the choosen turbidity is too low. Yet decreasing the turbidity to values around 3 leads to a better match between the measurements and the Heliosat modelled direct irradiance on the one hand, but it leads to an overestimation of the global irradiance on the other hand. The reason is the redundant information of the turbitiy in comparison with a separated treatment of aerosol type, aerosol optical depth, and water vapour.
Consequently, a consistent match between measurements and calculated direct and global irradiance is only possible using information about the aerosol optical depth, the aerosol type and the water content ”separately”. Using the Heliosat clear sky model or any other model that is just based on turbidity, the effect of different aerosol types on the global irradiance can not be considered, because the information about the atmospheric state is redundant. This effect is even significant for the measurement site, but is higher for sites with higher aerosol load, or for sites characterised by special types of aerosols events, like desert storms or biomass burning. That is a drawback of Heliosat-1 and 2 , but demonstrates the advantages of the SOLIS model. Moreover, reliable information of the spectral distribution of the irradiance cannot be derived by using only turbidity, without any additional information

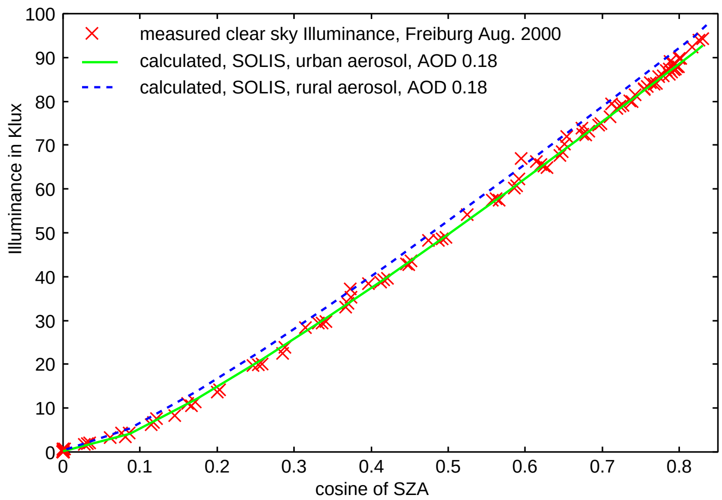

Figure 5: Mesaured and modelled illuminance, clear sky situations, Freiburg August 2000

about the atmospheric state. Additionally, changes in stratospheric aerosols, e.g an increase of the load after a volcanic eruption, can not be treated with the current Heliosat method without a re-fitting of the empirical equation. Using SOLIS, just the enhanced aerosol load has to be changed in the input file and the effect is considered.
In a comparison with measurments at Mannheim it was possible to verificate that urban aerosols with a AOD of 0.18 is a reliable input for Freiburg. The station Mannheim is nearby the station Freiburg and is characterised by a similar micro-climate - cities within the rhine valley climate. The bias between SOLIS results and measurments was below 1 per mill.

Spectral resolved irradiance data Using the same atmospheric input (urban aerosol, AOD=0.18), the measured and calculated illuminance has been compared for August 2000, Freiburg. The illuminance is a measurement of a quantity of light as perceived by the human eye. In order to calculate the illuminance the spectral resolved irradiance output of SOLIS is weighted with the light-sensitivity of the human eye. The so derived value is than multiplied with 0.683 in order to convert W/m^2 to Klux. The measurments and the calculation matches very well, demonstrating that the spectral output of the model is reliable, see figure 5. In addition the model results for rural aerosols are also diagrammed.

4 Summary

The concept and design of SOLIS have been presented and discussed. Within section 3 it has been demonstrated that SOLIS is able to reproduce very accurately (hourly) values of direct and global clear sky irradiance. However, the model depends on very accurate input. For the direct clear sky irradiance aerosol optical depth is by far the most important parameter, while for global irradiance the aerosol type has a significant effect. Reliable information of the type increase the accuracy of the calculated clear sky irradiance. In order to benefit from the enhanced information about the atmospheric state a model like SOLIS is necessary.

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