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THE USE OF MSG DATA WITHIN A NEW TYPE OF SOLAR IRRADIANCE CALCULATION SCHEME

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ABSTRACT

A successful integration of solar energy into the existing energy structure highly depends on a detailed knowledge of the solar resource. The recently started European project HELIOSAT-3 will supply high-quality solar radiation data and taking advantage of the enhanced capabilities of the new Meteosat Second Generation (MSG) satellites. The expected quality represents a substantial improvement with respect to the available methods and will better match the needs of the solar energy community. These goals will be achieved by an improvement of the current semi-empirical Heliosat calculation schemes (see section 2) as well as by the development and establishment of a new type of calculation scheme. 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 vapor) and the GOME/ATSR-2 satellites (aerosols). Within this paper, the new type of the solar irradiance calculation scheme, including the functional treatment of the diurnal variation of the solar irradiance, is described.

1 INTRODUCTION

Remote Sensing from satellites is a central issue in monitoring and forecasting the state of the earths atmosphere. Geostationary satellites such as METEOSAT provide cloud information in a high spatial and temporal resolution. Such satellites are therefore not only useful for weather forecasting, but also for the estimation of solar irradiance since the knowledge of the radiance reflected by clouds is the basis for the calculation of the transmitted irradiance. Additionally a detailed knowledge about atmospheric parameters involved in scattering and absorption of the sunlight are necessary for an accurate calculation of the solar irradiance. An accurate estimation of the downward solar irradiance is 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.

Currently, most of the operational calculation schemes for solar irradiance are semi-empirical, based on statistical methods. They use cloud information from the current METEOSAT satellite and climatologies of atmospheric parameters e.g. turbidity (aerosols and water vapor). The Meteosat Second Generation satellite (MSG, to be launched in 2002) will provide not only a higher spatial and temporal resolution, but also the potential for the retrieval of atmospheric parameters such as additional cloud parameters, ozone, water vapor column and with restrictions aerosols.

Using the enhanced capabilities of the new MSG satellite, solar irradiance data with a high accuracy, a high spatial and temporal resolution and a large geographical coverage will be provided, within the EU funded project HELIOSAT-3.

These goals will be achieved by an improvement of the current semi-empirical Heliosat calculation scheme (see section 2) as well as by the development and establishment of a new type of calculation scheme (see section

3). This new type will be based on radiative transfer models (RTM) using the information of the atmospheric parameters retrieved from the MSG satellite (clouds, O_3, water vapor) and the GOME/ATSR-2 satellites (aerosols, O_3).
In order to enable a better understanding of the new scheme the current scheme is described in the next section. Afterwards the new solar irradiance calculation scheme, including the functional treatment of the diurnal variation of the solar irradiance, is described. The improvements linked with the adaption of the new calculation scheme are discussed taking into account benefits and limitations of the new method.

2 The current HELIOSAT scheme

The basic idea of the Heliosat method is to deal with atmospheric and cloud extinction separately. In a first step a cloud index is derived from METEOSAT imagery. This step uses the fact that the planetary albedo measured by the satellite is proportional to the amount of cloudiness. The derived cloud index is then correlated to the cloud transmission, described with the clear sky index k, which relates the actual ground irradiance G to the irradiance of the cloud free case $G_{clearsky}$. As a consequence a clear sky model, providing $G_{clearsky}$, is necessary for the estimation of the actual ground iradianace

2.1 Cloud Transmission

Clouds have the largest effect on atmospheric radiative transfer. The cloud amount is derived from METEOSAT imagery. First the METEOSAT images have to be normalized with respect to the solar zenith angle. Therefore the relative reflectance ρ is introduced:

$$\rho = \frac{C - C_0}{G_{ext}}. \tag{1}$$

Here C is the measured value of the satellite pixel and C_0 is the instrument offset. Since G_{ext} is used, ρ is a measure of the planetary albedo. Originally C_0 was considered as a constant. Beyer et. al (1996) split this offset into an instrument offset C_{off} and atmospheric offset C_{atm} which is due to backscatter of the atmosphere. C_{atm} was derived by an analysis of ocean pixels:

$$C_{atm} = \left(1 + \cos^2 \Psi\right) \cdot \frac{f(\theta_z)}{cos^{0.78}\phi}, \tag{2}$$

where Ψ is the angle between sun and satellite as seen from the ground, ϕ the zenith angle of the satellite and θ_z the solar zenith angle (SZA). The function $f(\theta_z)$ is defined as:

$$f(\theta_z) = -0.55 - 25.2 \cdot \cos\theta_z - 38.3 \cdot \cos^2\theta_z + 17.7 \cdot \cos^3\theta_z. \tag{3}$$

The cloud index is a measure of the cloud cover, it varies between 0 for cloud-free and 1 for full cloud cover. It is calculated using the reflectivity ρ from equation 1:

$$n = \frac{\rho - \rho_{min}}{\rho_{max} - \rho_{min}}. \tag{4}$$

To calculate n, the maximum ρ_{max} and minimum ρ_{min} values of ρ are needed. ρ_{min} corresponds to the ground albedo. Maps of the ground albedo are computed on a monthly basis by statistical analysis of the dark pixels. The maximum reflectivity ρ_{max} has to be computed once per satellite since there are differences in the sensor properties in the different METEOSAT satellites (Hammer et. al, 2001)
Cloud transmission can be described as seen from the ground by the clear-sky index k which compares the actual ground irradiance G with the irradiance of the cloud free case $G_{clearsky}$:

$$k = \frac{G}{G_{clearsky}}. \tag{5}$$

The cloud index is then empirically correlated to the clear sky index k. This relationship is basically $k = 1 - n$ with minor modifications for $n \to 0$ and $n \to 1$:

$$\begin{array}{rl} n \leq -0.2 & k = 1.2 \\ -0.2 < n \leq 0.8 & k = 1 - n \\ 0.8 < n \leq 1.1 & k = 2.067 - 3.667 \cdot n + 1.667 \cdot n^2 \\ 1.1 < n & k = 0.05 \end{array} \tag{6}$$

The ground irradiance G is then obtained from

$$G = k \cdot (G_{direct,clearsky} \cdot \cos\theta_z + G_{diffus,clearsky}) \tag{7}$$

	spatial resolution (sub sat. point)	temporal resolution	spectral channels
MSG	1km	15 min	12
METEOSAT	2.5km	30 min	3

Table 1: Improvements in METEOSAT resolution

2.2 The current Clear-Sky Model

The HELIOSAT-Method was originally proposed by Cano et. al (1986) and later modified by Beyer et. al (1996) and Hammer (2000). For the calculation of the clear sky irradiance it uses the direct irradiance model of Page (1996) and diffuse irradiance model of Dumortier (1995). Both use the Linke turbidity factor to describe the atmospheric extinction. The direct irradiance is:

$$G_{direct,clearsky} = G_0 \cdot \epsilon \cdot e^{-0.8662 \cdot T_L(2) \cdot \delta_R(m) \cdot m} \tag{8}$$

where G_0 is the extraterrestrial irradiance, ϵ the eccentricity correction, $T_L(2)$ the Linke-Turbidity factor for airmass 2, $\delta_R(m)$ the Rayleigh optical thickness and m the airmass. For the air mass the following relation developed by Kasten and Young (1989) is used:

$$m = \frac{1 - z/10000}{cos\theta_z + 0.50572(96.07995^\circ - \theta_z)^{-1.6364}} \tag{9}$$

using z as the height in meters and the SZA θ_z in degrees. The Rayleigh optical thickness $\delta_R(m)$ is the optical thickness of a dry and clean atmosphere, an atmosphere without aerosols and water vapor, where only Rayleigh scattering occurs.

The Linke-Turbidity is defined as the number of Rayleigh atmospheres necessary to represent the real optical thickness $\delta(m)$:

$$T_L(m) = \frac{\delta(m)}{\delta_R(m)} \tag{10}$$

Since this turbidity still has a daily variation, it is normalized to the turbidity for the airmass 2:

$$T_L(2) = \frac{T_L(m) \cdot \delta_R(m)}{\delta_R(2)}. \tag{11}$$

The diffuse irradiance is an empirical fit by Dumortier (1995)

$$G_{diffus} = G_0 \cdot \epsilon \cdot cos\theta_z^2 \cdot (0.0065 + (-0.045 + 0.0646 \cdot T_L(2)) \cdot cos\theta_z \quad + (0.014 - 0.0327 \cdot T_L(2)) \tag{12}$$

The turbidity information can not be derived from the Meteosat spectral channels. Therefore a climatological model must be used. To account for the annual variation of the turbidity a relation of Bourges (1992) is used:

$$T_L = T_0 + u \cos\left(\frac{2\pi}{365J}\right) + v \sin\left(\frac{2\pi}{365J}\right), \tag{13}$$

T_0, u and v are site specific fit parameters, J is the day of the year. A map with the parameters for Europe has been set up during the EU-funded Satel-Light project (www.satellight.com).

3 THE NEW SCHEME

With the launch of the Meteosat Second Generation (MSG) satellite the possibilities for monitoring the earth atmosphere, especially for cloud description, will be enormously improved. The MSG weather satellite will provide not only a higher spatial and temporal resolution but will also scan the earth atmosphere using more spectral channels than the current satellite. The improved spectral information is linked with the potential for the retrieval of atmospheric parameters such as ozone, water vapor and with restrictions aerosols as well as an improved description of clouds.

With this more detailed knowledge about atmospheric parameters we will establish a new calculation scheme based on a radiative transfer model (RTM) that uses the retrieved atmospheric parameters as input. This new scheme will be based on the integrated use of a radiative transfer model, whereas the information of the atmospheric parameters retrieved from the MSG satellite (clouds, ozone, water vapor) and from the GOME/ATSR-2 satellites (aerosols, ozone) will be used as input to the RTM based scheme.[1]

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

However an operational usage of a RTM for the treatment of heterogenous clouds (whether directly or via the usage of pre-calculated look-up tables) is not possible. The limitations of 3-D cloud modeling do not enable realistic RTM calculations of 3-D cloud problems in an operational manner, but just case studies, since the necessary 3-D cloud input information can (yet) not be provided operationally. Hence with respect to the use of a RTM the problem is the non-availability of realistic specification of heterogenous clouds from measurements. MSG will not provide sufficient information about 3-D cloud characteristics. No other satellite or measurement setup provides this information for the needed temporal resolution and spatial coverage.
Beside these problems an explicit or integrated use of RTM is not practicable since the needed calculation time of 3d-RTM models is to large for operational adaption. Even homogenous clouds can not treated explicitly in an operational manner with a RTM (MSG pixel resolution). The usage of look-up tables for homogenous clouds has no advantages compared to the usage of the described *n*-*k* relation.
As a consequence of the things mentioned above, the integrated usage of the RTM within the scheme is related to the clear-sky scheme using the well established *n*-*k* relation (see formula 6) to consider cloud effects. The *n*-*k* relation is powerful and validated and leads to small Root Mean Square Deviation (RMSD) between measured and calculated solar irradiance for almost homogenous cloud situations. Nevertheless the *n*-*k* relation can and will be improved with respect to the following tasks.

- Within the HELIOSAT-3 project it has been shown that the cloud height in correlation with the geometry has an effect on the *n*-*k* relation. In contrast to the current scheme such effects will be considered in the new scheme.
- Heterogenous cloud effects will be investigated in order to correct the *n*-*k* relation in a statistical manner e.g. improve the calculated relation between diffuse and direct irradiance, e.g. using cloud height and a variability index to correct the *n*-*k* relation. This work could be based on previous studies of Skartveit et al. (1998), adapting a similar approach to the new scheme.

The ramaining part of this paper deals with the integrated use of the RTM within the scheme and hence focuses on the clear-sky module of the scheme.

3.1 The new clear-sky module

MSG will scan the earth atmosphere in a very high spatial resolution (see table 1, e.g approximately 2.5 million pixels have to be processed every 15 min. for Europe). 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 more flexible method, the integrated use of RTM within the scheme based on a modified Lambert-Beer relation, will be applied within the HELIOSAT-3 project.
The integration of RTM into the calculation schemes, instead of using just pre-calculated look-up tables, is only possible if the necessary computing time can be decreased enormously. For this purpose a tricky functional treatment of the diurnal solar irradiance variation has to be applied. Thus making an appropriate operational use of a RTM within the calculation schemes possible.
The basis (or starting point) of the integrated use is the assumption that daily values of the atmospheric parameters in a spatial resolution of 100x100 km or 50x50 km are sufficient. This assumption is appropriate and is not linked with restrictions of the model because of the reasons listed below.

- This resolution is most reasonable for solar energy applications in consideration of accuracy and operational practicality.
- Restrictions in the art of retrieval limits the available input of the atmospheric clear sky parameters with respect to the temporal and spatial resolution. E.g. the retrieval of Aerosols from satellite is handicapped by the small Aerosol reflectance and the perturbation of the weak signal by clouds and surface reflection. For that reasons retrieval of daily Aerosol values in 100x100 km resolution with a ´´global´´ coverage in an appropriate accuracy is a task for the far future.
- The temporal daily fluctuations of solar irradinace are in general dominated by the fluctuations of clouds. The cloud information is used in its high temporal and spatial resolution (MSG pixel resolution).

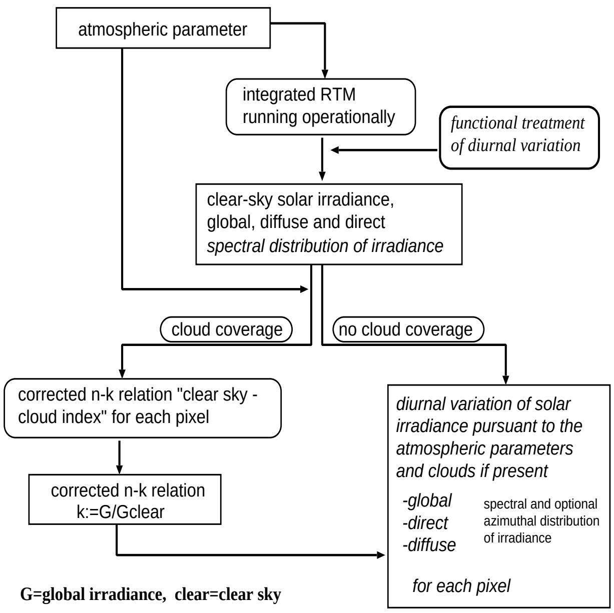

Figure 1: Overview of the new calculation scheme

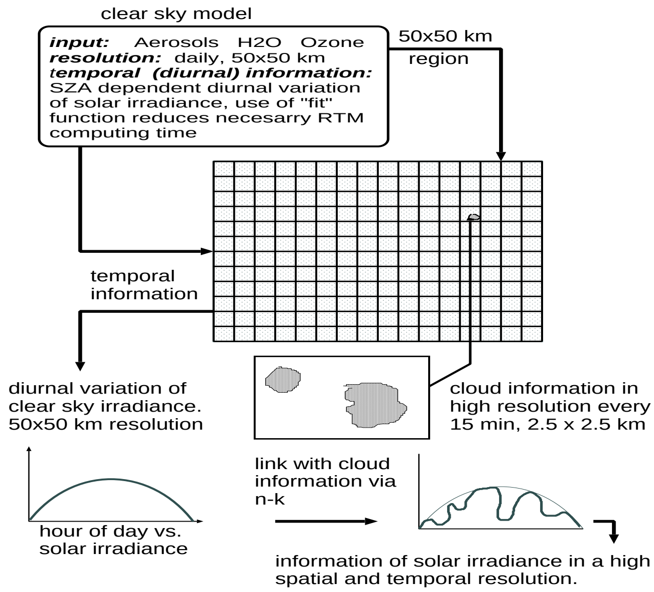

Figure 2: Diamgramm of the spatial and temporal linkage between clear-sky and cloud information.

- The usage of the modified Lambert-Beer function, described later on, should enable the correction of derivations from the daily values of the atmospheric clear sky parameters on the irradiance in an easy and fast manner (see also the conclusions).

Since daily values of the atmospheric parameters (O_3,H_2O,aerosols) within a region of 100x100km (50x50km) can be assumed to be sufficient, the diurnal variation of the solar irradiance is just dependent on the Solar Zenith Angle(SZA) θ_z. The RTM calculates the diurnal variation of the solar irradiance for each region using the averaged atmospheric parameters as input. The cloud effect and hence the temporal disturbtion of the diurnal clear sky irradiance of each pixel is considered using the *n-k* relation. As a consequence not every pixel has to be processed with the radiative transfer model. With the modified Lambert-Beer function, described in detail later on, the diurnal variation of the clear sky irradiance can be matched very well. As a consequence the RTM calculations necessary to define the diurnal variation of the clear sky irradiance can be reduced enormously. Using the modified Lambert-Beer function only 2 RTM calculations are necessary to define the complete diurnal variation of the clear sky irradiance for a given atmospheric state. As a conseuence, independent if a pixel is cloudy or not, 2 RTM calculation are enough to calculate the solar irradiance for the whole (e.g. 100x100 km) region, where it has to be remembered that the effect of clouds is considered by using the *n-k* relation (see equation 6). Figure 1 and 2 illustrates the new scheme and the integrated use of the RTM within the clear sky module.

3.2 The fitting function

The Lambert-Beer relation is given by

$$I = I_0 * exp(\tau) \tag{14}$$

where τ is the optical depth
Considering path prolongation and projection to the earth surface leads to.

$$I = I_0 * exp(\frac{\tau}{cos(\theta_z)}) * cos(\theta_z) \tag{15}$$

This formula describes the behavior of the direct monochromatic radiation in the atmosphere, hence an effective optical depth τ can be estimated for all SZA (θ_z).

$$\tau = ln(I/I_0) \tag{16}$$

Using equation (16) for θ_z=0 leads to τ_0. If we are dealing with **monochromatic radiation** then τ is constant, hence τ equals τ_0 for all SZA.

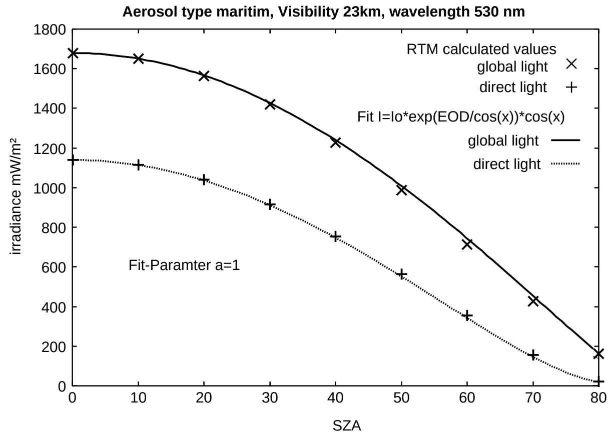

Figure 3: Illustration: For monochromatic radiation the Lambert-Beer relation is still a relative good approximation if the effective optical depth (EOD) is used. In order to yield a better match a correction of formula 15 (the Lambert-Beer relation) is necessary

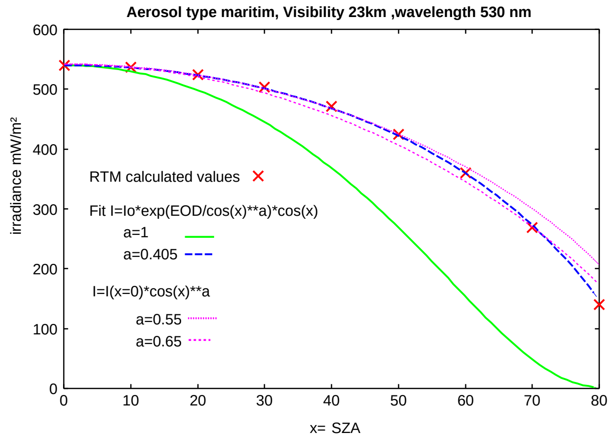

Figure 4: Since the modified Lambert-Beer relation does not describe the behavior of diffuse radiation, a correction of the Lambert-Beer relation is absolutely necessary. Fitting with a simple cosine relation lead to a much poorer agreement.

If we are dealing with **wavelength bands** τ is not constant, but changes smoothly with increasing SZA . τ_0 is just the effective optical depth at θ_z=0, The reason for that is the non-linear nature of the exponential function. Hence a correction of the optical depth, or equivalent to this, of the parameter $\frac{\tau}{cos(\theta_z)}$ is necessary.

$$I = I_0 * exp(\frac{\tau}{cos^a(\theta_z)}) * cos(\theta_z) \tag{17}$$

Using this function the calculated direct radiation can be reproduced very well (see Fig. 5). The fitting parameter a is calculated based on two RTM calculations.

3.2.1 Global irradiance

As explained above a correction of formula 15 is necessary for direct radiation if the formula is applied to wavelength bands, hence it is necessary for global radiation too. But in addition to the wavelength band effect the Lambert-Beer law is no longer ´´valid´´ for monochromatic radiation due to the effect of scattered photons that are ´´coming back´´. This effect is mainly described (considered) by the usage of the effective optical depth τ_0. As a consequence, using the effective optical depth the Lambert-Beer is still a (relative) good approximation for ´´monochromatic´´ global radiation (e.g. see Fig. 3) . But due to e.g. the atmospheric vertical inhomogeneity the change in the amount of photons coming back due to changes in SZA is not described by $1/cos(\theta_z)$ in detail. Hence a correction of formula 15 is necessary even for monochromatic incoming radiation, in order to yield a better match between RTM calculated and function values. Since the Lambert-Beer relation, using the effective optical depth τ_0, is still a (relative) good approximation if the incoming radiation is monochromatic, it is not so surprising that for wavelength bands the function

$$I_{global} = I_0 * exp(\frac{(\tau)}{cos^b(\theta_z)}) * cos(\theta_z) \tag{18}$$

is (similar to the direct radiation case) also a good fitting function for global radiation (see Fig. 5).

3.2.2 Diffuse irradiance

The Lambert-Beer realtion describes the attenuation of the incoming radiation. The incoming diffuse radiation at the top of the atmosphere is negligible. The source of the diffuse radiation is the attenuation of the direct radiation due to scattering processes. Hence the Lambert-Beer law is related to the irradiance of diffuse radiation but does not describe the irradiance of diffuse radiation, since diffuse radiation can not be described in terms of attenuation of incoming radiation (e.g. see Fig. 4). However fitting with the modified Lambert-Beer relation works very well (see Fig. reffig:comp1).

Since the scaling with cos(x) is not appropriate for diffuse radiation it is skipped and equation (19) is used for fitting.

$$I_{diffuse} = I_0 * exp(\frac{(\tau)}{cos(\theta_z)^c}) \tag{19}$$

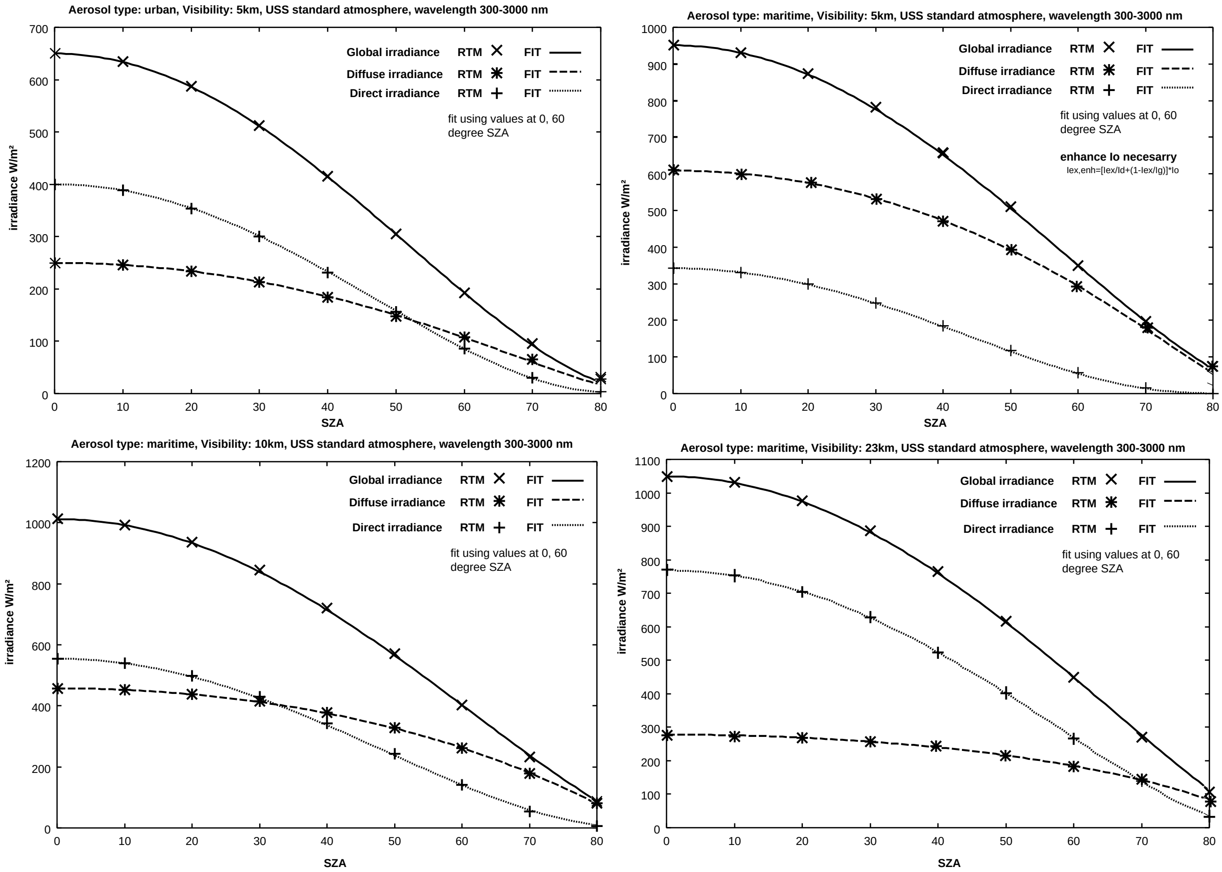

Figure 5: Comparison between RTM calculations and fit using the modified Lambert-Beer relation, for different atmospheric states

3.2.3 General remarks

The usage of the modified Lamber-Beer function is physically motivated, but it is actually a fitting function. This is especially obvious for the case of diffuse radiation In principle it is possible to fit the RTM calculations with any appropriate function for example a modified polynomial of third degree $(a \cdot cos^3(x) + b \cdot cos^2(x) + c)$ (see Fig. 7). Hence the big advantage of the modified Lambert-Beer function is not the feasibility to fit the RTM calculations, but that it is possible to yield a very good match between fitted and calculated values by using only 2 SZA calculations. This is possible since the change of the irradiance with SZA is related to the Lamber-Beer law, hence using the modified Lambert-Beer relation ´´the degrees of freedom can be reduced´´. More over the parameter can calculated without the need for a numerical fit.
The function was tested for many different atmospheric states, e.g four different aerosol types, four different visibilities (5, 10, 23, 50), different water amounts, different standard atmospheres. Additionally it was tested that the fit also works if another RTM model (instead of libradtran) is used for the RTM calculations. There are no reasons to assume that there exist a atmospheric state for that the fit does not work very well. Hence it can be assumed that the fit works very well for all atmospheric states.
For our purpose the sense of a appropriate fitting function is to save calculation time without losing ´´significant´´ accuracy. The question if a fitting function is usable for that purpose depends on the difference between the fitted values and the RTM calculated values (which are very small, less than 8W/m^2 below a SZA of 85 Deg.).
At low visibilities (high optical depth, high aerosol load) I_o has to be enhanced for global and diffuse radiation (formula $I_{oe} = (1 + Io * I_{diffuse}/(I_{direct} * I_{global})) * Io$ is used).

4 Conclusions

- Modified Lambert-Beer relation enables the integrated use of RTM within the Clear-Sky-Scheme. The integrated use of RTM is linked with high flexibility relating to the input of the atmospheric state, changes in theory and the desirable output parameters.

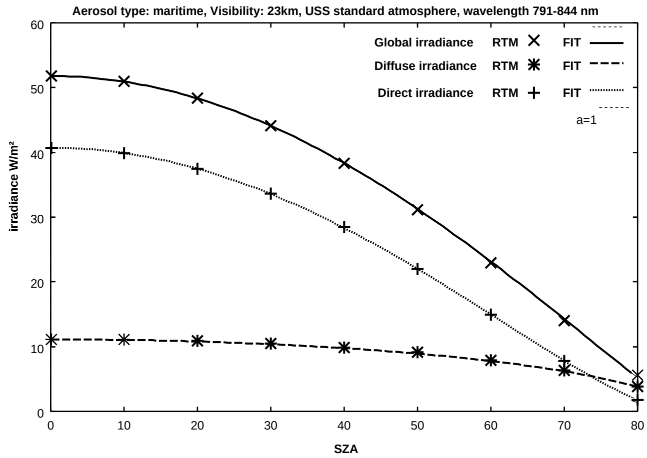

Figure 6: Comparison between RTM calculations and fit using the modified Lambert-Beer relation. Example for fit within a small wavelength band

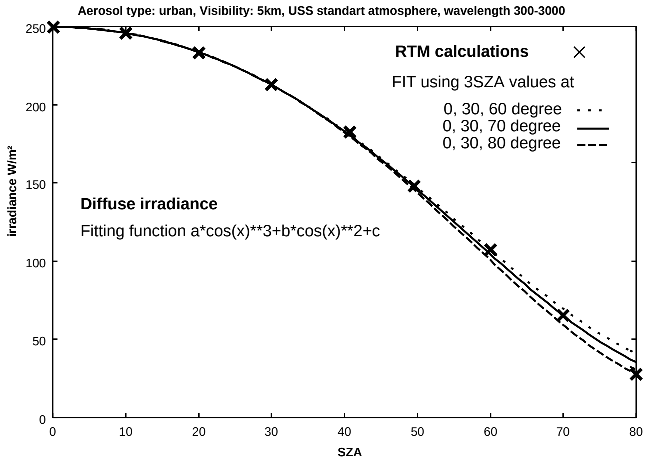

Figure 7: Comparison of the fit using a polynomial of third degree and the RTM calculations

- Spectral information is automatically provided, using the correlated-k option provided within the RTM libRadtran package (http://www.libradtran.org/). Optionally information about the azimuthal distribution of the diffuse radiation possible.
- Consistent calculations of global, direct and diffuse radiation for clear sky cases within one single scheme considering different aerosol types and not only turbidity are possible. Hence a improved estimation of the relation between diffuse and direct radiation is possible, especially for clear sky situations.
- It seems that deviations of the atmospheric state from the average (O_3, H_2O, aerosols) can easily be corrected with the modified Lambert-Beer law. A correction of the effective optical depth τ_0, whereas the a,b,c parameter remain unchanged, leads to a good match between RTM calculated and function values for H20. For aerosols similar tests have to be performed.
- Clear and easy linkage with cloudy sky scheme, whereas the treatment of the heterogenous cloud effects is not restricted. The improvement of the correction of heterogenous cloud effects is aimed for.

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