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DERIVATION OF DAYLIGHT AND SOLAR IRRADIANCE DATA FROM SATELLITE OBSERVATIONS

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1. INTRODUCTION

The estimation of the downward surface shortwave irradiance from satellite observations has been subject to numerous investigations in the past. Different methods from simple transmittance-reflectance correlations to the extensive use of radiative transfer calculations have been applied leading to generally satisfying results with an accuracy almost independent of the chosen method.

In the framework of the European Community research project SATELLIGHT an attempt is made to use satellite methods to derive daylight and solar irradiance data with a continuous spatial coverage for Western and Central Europe from Meteosat images. For potential end users these data will be placed in a data base in the Internet (Fontoynont et al., 1998).

In daylighting applications, knowledge of the luminance distribution of the sky is of primary concern. Thus, beyond the retrieval of surface global irradiance, the separation of diffuse and direct components as well as a better representation of these quantities for low sun elevations had to be derived in the scope of this project.

We present improvements and additions to an existing method for the derivation of the global irradiance. This includes new correction schemes for the influence of atmospheric extinction processes. These have been partly developed by simulating the satellite signal for a cloudless atmosphere using the radiative transfer code MODTRAN. In addition, the derivation of the diffuse irradiance is briefly outlined.

2. METHOD

The Heliosat method as proposed by Cano et al. (1986) is an estimation technique to infer the shortwave surface irradiance from satellite images. For this purpose a measure of cloud cover is derived from METEOSAT visible counts C. The method is basically driven by the strong complementarity between the planetary albedo recorded by the satellite's radiometer and the surface shortwave radiant flux. The planetary albedo increases with increasing atmospheric turbidity and cloud cover.

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2.1. *Normalization of radiometer counts*

For a correct estimation of the change in the albedo the influence of the incoming radiation on the total radiation reflected by an image element has to be considered. Therefore a normalization with respect to the zenith angle of the sun is applied:

$$\rho = \frac{C - C_0}{I}, \tag{1}$$

where C_0 represents an offset in the registration and I the incoming radiation. Originally, I was assumed to be the surface global irradiance under a clear sky I_{clear} (Bourges, 1979). Instead, here the extraterrestrial global irradiance I_{ext} is used. In this case ρ is a measure for the planetary albedo.

2.1.1. *Registration offset*

Within the original Heliosat method the registration offset C_0 is assumed to be constant. Beyer et al. (1996) have attempted to describe the dependency of C_0 upon the sun's position for METEOSAT 4 data by

$$C_0 = C_{off} + C_{atm}. \tag{2}$$

$$C_{off} = 4.3,$$

$$C_{atm} = 4.5 \cdot (1 + \cos^2(\psi)) \frac{\cos^{0.15}(\theta)}{\cos^{0.8}(\phi)},$$

where θ is the sun zenith angle, ϕ is the satellite zenith angle and ψ is the angle between the sun and the satellite as measured from the ground. C_{off} and C_{atm} are the instrument offset and the contribution by backscattering effects, respectively.

The atmospheric backscatter term was derived by Beyer et al. (1996) from cloudfree ocean pixels in Central Europe for sun elevations exceeding 15 degrees.

To extend the validity of the backscatter term to the total European area and to lower sun elevations time series of METEOSAT 5 counts for 26 different ocean locations over Europe have been investigated. The time series include the days 0–60 and 120–180 of the year 1996. To restrict the analysis to cloudfree cases, the 10% lowest counts for each zenith angle interval have been selected for each site.

From these data and an instrument offset of C_{off}=5 (Moulin et al., 1996) the registration offset is

$$C_0 = C_{off} + C_{atm} \tag{3}$$

$$C_{off} = 5,$$

$$C_{atm} = (1+\cos^2\psi)\cdot\frac{f(\theta)}{\cos^{0.78}\phi}.$$

$$f(\theta) = -0.55 + 25.2\cos\theta - 38.3\cos^2\theta + 17.7\cos^3\theta.$$

The third order polynom $f(\theta)$ accounts for the low solar elevations.

2.2. *Cloud index*

As a measure of cloud cover a cloud index is derived for each pixel:

$$n = \frac{\rho - \rho_g}{\rho_c - \rho_g}, \tag{4}$$

where ρ_g and ρ_c refer to the planetary albedo in the cloudfree and total cloudy case, respectively.

2.3. *Atmospheric transmission*

In solar energy applications the atmospheric transmittance is commonly expressed in terms of either the clearness index or the clearsky index.

The clearness index k is defined as the ratio of surface global horizontal irradiance to the extraterrestrial horizontal irradiance:

$$k = \frac{I_g}{I_{ext}}. \tag{5}$$

The clearsky index k^* is defined as the ratio of surface global horizontal irradiance to the global horizontal irradiance under clear sky conditions:

$$k^* = \frac{I_g}{I_{clear}}, \tag{6}$$

where I_{clear} has to be inferred from a clearsky irradiance model.

2.3.1. *Clearsky global irradiance model*

In the scope of the SATELLIGHT project a clearsky model is used which includes the sun elevation, the altitude of the site z and the Linke turbidity T_L as parameters. The surface global irradiance under cloudless skies is modeled as a sum of direct and diffuse irradiance:

$$I_{clear} = I_{dir}\cos\theta + I_{diff}. \tag{7}$$

The direct component is given by Page (1996) as

$$I_{dir} = I_0\epsilon\exp(-0.8662 T_L(2)\rho_R(m)m), \tag{8}$$

where I_0 and ϵ are the solar constant and the eccentricity correction factor, respectively.

The Linke turbidity T_L is a measure for the optical thickness of the atmosphere with respect to the Rayleigh optical thickness of dry and clean air:

$$T_L(m) = \rho(m)/\rho_R(m). \tag{9}$$

The relative airmass m is given by Kasten and Young (1989):

$$m = \frac{1 - z/10000}{\cos\theta + 0.50572(96.07995° - \theta)^{-1.6364}}, \tag{10}$$

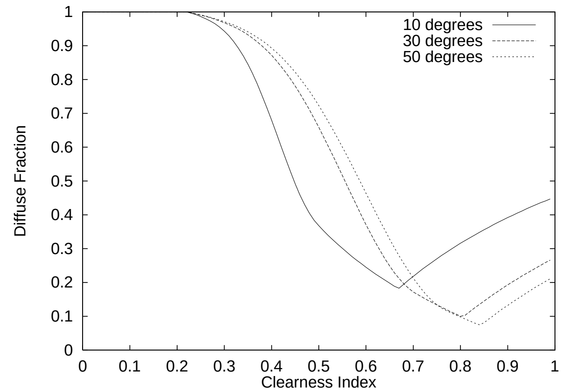

Figure 1: Diffuse fraction of global horizontal irradiance with respect to sun elevation and clearness index (Skartveit and Olseth, 1987).

with z in meter and θ in degrees. The Rayleigh optical thickness $\rho_R(m)$ is taken from Kasten (1996):

$$\rho_R(m)^{-1} = 6.6296 + 1.7513m - 0.1202m^2 + 0.0065m^3 - 0.00013m^4. \tag{11}$$

For the diffuse component of clearsky global irradiance a parameterization of Dumortier (1994) is used. It has been derived empirically from 5 min averaged global and diffuse horizontal irradiance data measured in Vaulx-en-Velin (1992-1994):

$$I_{diff} = I_0\epsilon(0.0065 + (-0.045 + 0.0646T_L(2))\cos\theta - (-0.014 + 0.0327T_L(2))\cos\theta^2). \tag{12}$$

2.4. *Relation of cloud index and clearsky index*

In the original Heliosat method a linear relationship between clearness index and cloud index is assumed ($k = a_1 \cdot n + b_1$). Beyer et al. (1996) have shown that a closer relationship holds for the clearsky index ($k^* = a_2 \cdot n + b_2$). The coefficients a_i and b_i result from a linear regression with ground data. For German data the generic relationship ($k^* = 1 - n$) led to satisfying results. Analyses for additional European sites have shown that this relationship can be applied for the European region. However, the use of the clearsky model makes information on the atmospheric turbidity a critical issue. Fontoynont et al. (1998) present a nonlinear relationship between cloud index and clearsky index which accounts for the overcast case.

2.5. *Global irradiance from satellite counts*

The global irradiance at the ground is determined by the atmospheric transmittance and the clearsky irradiance. While the clearsky irradiance is modeled with a site specific turbidity, the atmospheric transmittance is derived from the satellite images. It is represented by the clearsky index, which is closely related to the cloud index. The cloud index is derived from the normalized satellite counts.

2.6. *Diffuse fraction model*

In the cloudless case the diffuse irradiance can be derived from eqn. 12. Skartveit and Olseth (1987) suggested an allsky model for the diffuse fraction of hourly global radiation, assuming that the diffuse fraction depends on the clearness index and the solar elevation h. For a clearness index below a certain threshold the hourly radiation is expected to be completely diffuse. With increasing clearness index the diffuse fraction decreases. For high clearness index values it increases again due to cloud reflection effects. The position of the minimum of diffuse fraction depends on the solar elevation (fig. 1). An improved version of this model also accounts for the hour-to-hour variability of the clearness index (Skartveit et al., 1998).

3. COMPARISON WITH RADIATIVE TRANSFER CALCULATIONS

In this section the empirical findings for the atmospheric backscattering and the clear sky diffuse irradiance are supported by radiative transfer calculations. These calculations have been performed using the computer code MODTRAN (Kneizys et al. 1996).

3.1. *Atmospheric backscattering*

For the MODTRAN simulation of the radiance reflected by the ocean surface towards the satellite position the wavelength band was set to the range from 0.4 to 1.1μm. The simulation was carried out for the day 132. Variation of the sun's position and of the satellite's position was achieved by choosing the time period 1200-1900 UCT and a 3×3 pixel array located in an area given by 40-60° N and 0-20° E, respectively. As additional input for MODTRAN the US-Standard-atmosphere with maritime aerosols and 23 km visibility and the default ocean albedo was used.

Fig. 2 shows a comparison of the MODTRAN radiances with the counts C_0 calculated from eqn. 3. The calibration functions for METEOSAT 4 and METEOSAT 5 as given by Kriebel and Amann (1993, 1996) are plotted. These functions are assumed to be linear, which is only valid for high radiances (Moulin et al. 1996). The use of the offset value C_0 introduced in eqn. 3 results in a good approximation of the instrument offset C_{off}=5.

3.2. *Clearsky diffuse irradiance*

Radiative transfer calculations have been performed by Beyer et. al (1997) to express the clearsky diffuse irradiance as a function of Linke turbidity and solar zenith angle only. For MODTRAN calculations the turbidity has to be expressed in terms of visibility, this relationship has been derived from direct irradiance values calculated by MODTRAN for different visibilities (US Standard Atmosphere). With the resulting relation VIS=53/(T_L-2.5) the diffuse irradiance was expressed as:

$$I_{diff} = I_0\epsilon(a + bT_L + cT_L^2 + (d + eT_L + fT_L^2)\cos\theta + (g + hT_L + iT_L^2)\cos\theta^2) \quad (13)$$

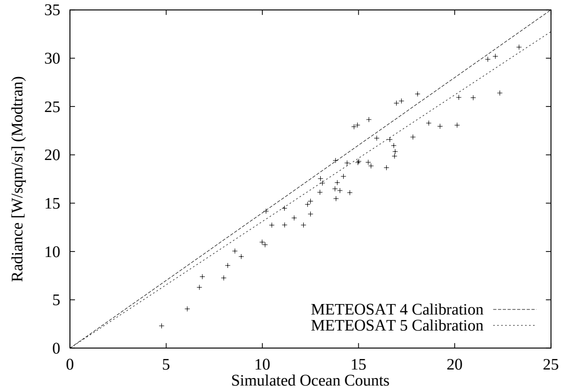

Figure 2: MODTRAN radiances compared to parameterization of ocean counts, eqn. 3.

$a = 0.017991$	$d = -0.112593$	$g = -0.019104$
$b = -0.003967$	$e = 0.101826$	$h = -0.022103$
$c = 0.000203$	$f = -0.006220$	$i = 0.003107$

This model gives similar results as the model of Dumortier (eqn. 12) for low solar elevations but differs distinctly for high elevations. Both models were tested with data for 7 locations. While the model of Dumortier shows an underprediction for high diffuse irradiances, eqn. 13 leads to an overprediction, especially for locations with high atmospheric turbidity.

4. RESULTS

For ground truth time series of 30-min-averaged irradiance data for several European sites have been considered. The stability of the relations for different solar elevations was of special interest.

Although the rmse lies around 30% for global irradiance and is even higher for diffuse irradiance, the statistical characterizations of the sites which are important for applications are reproduced (distribution of clearsky index, percentage of time a given irradiance threshold is exceeded). As an example Freiburg data are given in fig. 3.

5. CONCLUSION

The Heliosat method, an operational satellite-based method for the derivation of surface solar irradiance, has been enhanced towards the needs of daylighting applications.

For the normalization of counts a generalisation of the atmospheric backscatter term from Beyer et al. (1996) has been derived from a database of 26 ocean counts spread over Europe with special emphasis on low solar elevations.

The normalized radiometer counts are directly converted into the clearsky index. Using a clearsky irradiance model and a diffuse fraction model the global and diffuse irradiances are calculated.

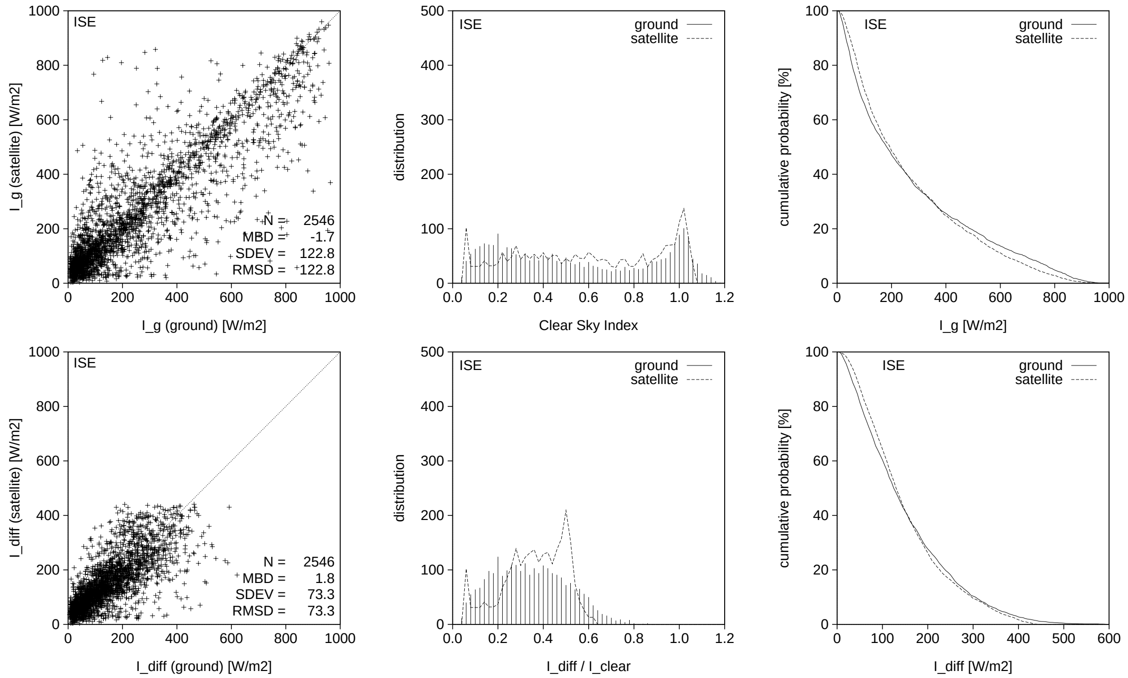

Figure 3: Ground measured and satellite derived data for Freiburg, Germany, April 1993–March 1994. Top: Global horizontal irradiance. Bottom: Diffuse horizontal irradiance. Left column: Comparison of 30-min-averaged irradiances. Center column: Frequencies of occurrence of clearsky index values. Right column: Percentage of time a certain threshold of irradiance is exceeded.

It could be shown that the statistical characterizations are well reproduced by the data. This feature is essential for the use of irradiance data in daylighting applications.

6. REFERENCES

H. G. Beyer, C. Costanzo, D. Heinemann, 1996: *Modifications of the Heliosat procedure for irradiance estimates from satellite data.* Solar Energy **56**, 207–212.

H. G. Beyer, A. Hammer, D. Heinemann, A. Westerhellweg, 1997: *Estimation of diffuse radiation from Meteosat data.* 7^{th} International Conference on Solar Energy at High Latitudes, Espoo-Otaniemi.

B. Bourges, 1979: *Courbes de fréquences cumulées de l'irradiances solaire globale horaire recue par une surface plane.* Technical Report, Centre d'Energétique de l'Ecole Nationale Supérieure des Mines de Paris.

D. Cano, J. M. Monget, M. Albuisson, H. Guillard, N. Regas, L. Wald, 1986: *A method for the determination of the global solar radiation from meteorological satellite data.* Solar Energy **37**, 31–39.

D. Dumortier 1995: *Modelling global and diffuse horizontal irradiances under cloudless skies with different turbidities.* Daylight II, JOU2-CT92-0144, Final Report Vol. 2.

M. Fontoynont et al. 1998: *Satellight: A WWW server which provides high quality daylight and solar radiation data for Western and Central Europe.* 9^{th} Conference on Satellite Meteorology and Oceanography, Paris.

F. Kasten 1996: *The Linke turbidity factor based on improved values of the integral Rayleigh optical thickness.* Solar Energy **56**, 239–244.

F. Kasten and A. T. Young 1989: *Revised optical air mass tables and approximation formula.* Applied Optics **28**, 4735–4738.

F. X. Kneizys et al. 1996: *The Modtran 2/3 Report and LOWTRAN 7 Model.* Phillips Laboratory, Geophysics Directorate, Hanscom AFB.

K. T. Kriebel and V. Amann, 1993: *Vicarious Calibration of the Meteosat Visible Channel.* Journal of Atmospheric and Oceanic Technology **10**, 225–232.

K. T. Kriebel, H. Mannstein, V. Amann, 1996 : *Absolute Calibration for the Meteosat-5 Visible Channels.* 1996 Meteorological Satellite Data Users' Conference, Vienna.

C. Moulin, C. E. Lambert, J. Poitou, F. Dulac, 1996: *Long term 1983-1994 calibration of the Meteosat solar VIS channel using desert and ocean targets.* International Journal of Remote Sensing **17(6)**, 1183–1200.

J. Page 1996: *Algorithms for the Satellight programme.* Technical report.

A. Skartveit, J. A. Olseth 1987: *A Model for the Diffuse Fraction of Hourly Global Radiation.* Solar Energy **38**, 271–274.

A. Skartveit, J. A. Olseth, M. E. Tuft 1998: *The Potential for Improvement of Hourly Diffuse Fraction Models.* Submitted to Solar Energy.