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Research Article

A New GIS-based Solar Radiation Model and Its Application to Photovoltaic Assessments

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Abstract
The solar radiation model *r.sun* is a flexible and efficient tool for the estimation of solar radiation for clear-sky and overcast atmospheric conditions. In contrast to other models, *r.sun* considers all relevant input parameters as spatially distributed entities to enable computations for large areas with complex terrain. Conceptually the model is based on equations published in the European Solar Radiation Atlas (ESRA). The *r.sun* model was applied to estimate the solar potential for photovoltaic systems in Central and Eastern Europe. The overcast radiation was computed from clear-sky values and a clear-sky index. The raster map of the clear-sky index was computed using a multivariate interpolation method to account for terrain effects, with interpolation parameters optimized using a cross-validation technique. The incorporation of terrain data improved the radiation estimates in terms of the model's predictive error and the spatial pattern of the model outputs. Comparing the results of *r.sun* with the ESRA database demonstrates that integration of the solar radiation model and the spatial interpolation tools in a GIS can be especially helpful for data at higher resolutions and in regions with a lack of ground measurements.

1 Introduction

Solar radiation, incident to the earth's surface, is a result of complex interactions of energy between the atmosphere and surface. At a global scale, the latitudinal gradients

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of radiation are caused by the geometry of the earth and its rotation and revolution about the sun. At regional and local scales, terrain (relief) is the major factor modifying the distribution of radiation. Variability in elevation, surface inclination (slope) and orientation (aspect) and shadows cast by terrain features create strong local gradients. The spatial and temporal heterogeneity of incoming solar energy determines the dynamics of many landscape processes (e.g. air and soil temperature and moisture, snowmelt, photosynthesis and evapotranspiration) with direct impacts on human society. Accurate and spatially distributed solar radiation data are desired for various applications (environmental sciences, building design, remote sensing, photovoltaics, land management, etc.).

Throughout Europe there are several hundred ground meteorological stations where solar radiation is directly or indirectly measured. To derive spatial databases from these measurements different interpolation techniques are used. These include spline functions, weighted average procedures or kriging (e.g. Hutchinson et al. 1984, Hulme et al. 1995, Zelenka et al. 1992). In mountainous regions, the use of additional information gained from satellite images may improve the quality of solar radiation interpolation using a co-kriging approach (D'Agostino and Zelenka 1992, Beyer et al. 1997). Spatially continuous irradiance values also can be derived directly from meteorological geostationary satellites (e.g. Meteosat). Processing of satellite data provides less accurate values (compared to ground measurements) but the advantage is data coverage over vast territories at temporal resolutions of 0.5–12 hours (Noia et al. 1993a, b).

At present, spatially distributed solar radiation data for Europe at a continental level can be found in the European Solar Radiation Atlas (ESRA) (Scharmer and Greif 2000, Page et al. 2001), and in the Meteonorm (Remund et al. 1999) and Satellight databases (Hammer et al. 1998). However, these data do not possess sufficient accuracy or the spatial detail needed for regional studies. For example, solar radiation in mountainous regions is significantly influenced by local terrain features. To account for spatial variations of solar radiation in these areas, solar radiation models integrated within geographical information systems (GIS) can be helpful. Such models provide rapid, cost-efficient and accurate estimates of radiation over large regions, while considering slope inclination, aspect and shadowing effects. Coupling radiation models with GIS and image processing systems improves their ability to use different environmental data and to cooperate with other models.

Significant progress has been made towards developing solar radiation models in the last two decades (Dubayah and Rich 1995). One of the first GIS-based solar radiation models was *SolarFlux* (Dubayah and Rich 1995, Hetrick et al. 1993), developed for the Arc/Info GIS. A series of solar radiation algorithms was also implemented in the Genasys GIS, using AML script (Kumar et al. 1997). Another approach for computing all three components of radiation was realised in a standalone model *Solei* under MS Windows that was linked to the GIS software IDRISI by means of data format (Mészároš 1998, Miklánek 1993). All of the above three models use rather simple empirical formulas. Some of their parameters are spatially averaged (lumped) and therefore not suitable for calculations over large areas. More advanced methods for ecological and biological applications are implemented in *Solar Analyst*, developed as an ArcView GIS extension (Fu and Rich 2000). In the pre-processing phase, the model generates an upward-looking hemispherical viewshed based on a digital terrain model. Generating a sunmap for every raster cell makes calculation of solar radiation considerably faster. The model is suitable for fine scale studies. It is not flexible enough for calculations of atmospheric transmissivity and the diffuse proportion as it allows setting the available parameters only for the nearest weather stations or just typical values. This makes its use for larger areas rather limited. The *SRAD* model (Wilson and Gallant 2000, McKenney et al. 1999) was designed to model a complex set of short-wave and long-wave interactions of solar energy with the earth's surface and atmosphere. Although based on a simplified representation of the underlying physics, the main solar radiation factors are considered and the model is able to characterize the spatial variability of the landscape processes. However, it is designed for the modelling of topo- and mesoscale processes and the calculation of solar radiation over large territories is also limited.

As a result of progress and discussions in the ESRA project (Scharmer and Greif 2000), it was decided to develop a new model, denoted as *r.sun*. It is based on previous work by Hofierka (1997) and is implemented in the GRASS GIS environment (Neteler and Mitasova 2002). Its functionality eliminates the limitations of the previously discussed models. The first part of this paper presents the capabilities, structure and performance of the model. The second part briefly describes an application of the model in building a solar radiation database for Central and Eastern Europe that is being used for the estimation of the potential electricity yield of photovoltaic systems.

2 Interactions of Solar Radiation with Landscape

According to widely accepted terminology (Page 1986) two terms for solar (i.e. shortwave) radiation are adopted in this paper. The term *irradiance* denotes the solar power (instantaneous energy) falling on a unit area per unit time [W m^{-2}]. The term *irradiation* denotes the amount of solar energy falling on a unit area over a stated time interval [Wh m^{-2}]. The same symbols are used for irradiance and irradiation and these two terms can be differentiated by context or by the attached units.

The interaction of solar radiation with the earth's atmosphere and surface is determined by three groups of factors:

1. The Earth's geometry, revolution and rotation (declination, latitude, solar hour angle);
2. Terrain (elevation, surface inclination and orientation, shadows);
3. Atmospheric attenuation (scattering, absorption) by:
   - 3.1. Gases (air molecules, ozone, CO_2 and O_2);
   - 3.2. Solid and liquid particles (aerosols, including non-condensed water);
   - 3.3. Clouds (condensed water).

The first group of factors determines the available extraterrestrial radiation based on solar position above the horizon and can be precisely calculated using astronomical formulas. The radiation input to the earth's surface is then modified by terrain, namely slope inclination and aspect, as well as shadowing effects of neighbouring terrain features. The second group of factors also can be modelled at a high level of accuracy. Elevation above sea level determines the attenuation of radiation by thickness of the atmosphere. As described above, the intensity of extra-terrestrial solar radiation traversing the earth's atmosphere is attenuated by various atmospheric constituents, namely gases, liquid and solid particles and clouds (third group of factors). The path length through the atmosphere is also critical. Because of its dynamic nature and complex interactions the atmospheric attenuation can be modelled with only a certain level of accuracy.

The attenuation by gas constituents (factor 3.1) describes clear and dry (Rayleigh) atmosphere and is given by the relative optical air mass and optical thickness (m and $\delta_R(m)$ respectively, see below). These parameters can be determined with a good level of precision.

The attenuation by solid and liquid particles (factor 3.2) is described by the Linke turbidity index (T_{LK}). It indicates the optical density of hazy and humid atmosphere in relation to a clean and dry atmosphere. Due to the dynamic nature of the turbidity factor, its calculation and subsequent averaging leads to a certain degree of generalisation. There are clear seasonal changes in the turbidity with the lowest values in winter and highest values in summer. The values of the turbidity factor always differ from place to place in a similar degree of magnitude and these differences are also correlated with the terrain elevation. They increase with the degree of industrialisation and urbanisation. The values of the Linke turbidity for different landscapes or world regions can be found in the literature (e.g. Scharmer and Greif 2000, Page 1986, Kitler and Mikler 1986) or at http://www.soda-is.com/ (Wald 2000).

Maximum insolation is obtained when the sky is absolutely clean and dry, relatively less radiation is received when aerosols are also present. Clouds (factor 3.3) are the strongest attenuates. Theoretical analysis of the attenuation of solar radiation passing through clouds requires a great deal of information regarding instantaneous thickness, position and number of layers of clouds, as well as their optical properties (Louche et al. 1986). Therefore, simple empirical techniques are used to estimate the attenuation of cloud cover.

The radiation selectively attenuated by the atmosphere that is not reflected or scattered and reaches the surface directly is known as *direct* (beam) radiation. The scattered radiation that reaches the ground is called *diffuse* radiation. The small part of radiation that is reflected from the ground onto an inclined receiver is described as *reflected* radiation. These three components of radiation together create *global* radiation.

Considering all three factors of atmospheric attenuation (3.1–3.3) in a calculation scheme results in *real-sky* (overcast) radiation values. Omitting the cloud attenuation (factor 3.3) results in *clear-sky* (cloudless) radiation values. In many applications, a study of global radiation under clear skies is important (e.g. for estimation of global radiation from satellite images).

3 Implementation of the Solar Radiation Model

The equations of the *r.sun* model follow the latest research conducted for the European Solar Radiation Atlas (ESRA) project (Scharmer and Greif 2000, Rigollier et al. 2000). While the calculation of the beam component is quite straightforward, the main difference between the various models available in the literature is in treatment of the diffuse component (Perez et al. 1987). This component depends on climate and regional terrain conditions and is often the largest source of estimation error. The equations implemented in *r.sun* reflect European climate conditions. The ground reflected radiation contributes to inclined surfaces by only a few percent and in some computations it is ignored altogether.

The *r.sun* model is implemented in the GRASS GIS open source environment using the C programming language and is freely available (http://grass.itc.it/). The model works in two modes. In *mode* 1 for the instant time [second], it calculates raster maps of selected components (beam, diffuse and reflected) of solar irradiance [W m^{-2}] and solar incident angle [degrees]. In *mode* 2, the raster maps of daily sum of solar irradiation [Wh m^{-2}] and duration of the beam irradiation [minutes] are computed from the integration of irradiance values that are calculated for a selected time step from sunrise to sunset. Using a command script, these two modes can be used separately or in combination to provide estimates for any desired time steps or intervals. Besides clear-sky irradiances/irradiations, the model can calculate overcast values once the clear-sky index is defined. The model accounts for a sky obstruction by local terrain features using an optional shadowing parameter. Considering shadowing effects in mountainous areas can result in a dramatic decrease of radiation values especially at low sun altitudes.

The model requires only a few mandatory input parameters – elevation above sea level, slope and aspect of the terrain or surface, day number (for mode 2), and a local solar time (for mode 1). The other input parameters are either internally computed (solar declination) or the values can be overridden by explicitly defined settings to fit specific user needs: Linke atmospheric turbidity, ground albedo, beam and diffuse components of clear-sky index, time step used for calculation of all-day irradiation from sunrise to sunset and sampling density at which the visibility of a raster cell is evaluated. Spatially distributed parameters can be set as raster maps. Geographical latitude for each cell can be computed internally using the PROJ4 library. The model automatically distinguishes modes 1 and 2 based on the parameter settings. Details of the command (synopsis, description, notes) can be found at http://grass.itc.it/gdp/html_grass5/html/r.sun.html (see also Neteler and Mitasova 2002).

3.1 Computing clear-sky radiation

3.1.1 Beam radiation

Outside the atmosphere, at the mean solar distance, the beam irradiance, also known as the solar constant (I_0), is 1,367 W m^{-2} (Page 1986). The earth's orbit is lightly eccentric and the sun-earth distance varies slightly across the year. Therefore, a correction factor ε, to allow for the varying solar distance, is applied for calculation of the extraterrestrial irradiance G_0 normal to the solar beam [W m^{-2}]:

$$G_0 = I_0 \varepsilon \tag{1}$$

where:

$$\varepsilon = 1 + 0.03344 \cos(j' - 0.048869) \tag{2}$$

the day angle j' is represented in radians as follows:

$$j' = 2\pi j/365.25 \tag{3}$$

and j is the day number which varies from 1 on January 1st to 365 (366) on December 31st. The beam irradiance normal to the solar beam B_{0c} [W m^{-2}], is attenuated by the cloudless atmosphere, and calculated as follows:

$$B_{0c} = G_0 \exp\{-0.8662 T_{LK} m \delta_R(m)\} \tag{4}$$

The term $-0.8662T_{LK}$ is the air mass 2 Linke atmospheric turbidity factor [dimensionless] corrected by Kasten (1996). The parameter m in equation (4) is the relative optical air mass [–] calculated using the formula (Kasten and Young 1989):

$$m = (p/p_0)/(\sin h_0^{\text{ref}} + 0.50572(h_0^{\text{ref}} + 6.07995)^{-1.6364}) \tag{5}$$

where h_0^{ref} is the solar altitude h_0 (an angle between the sun and a horizon) in degrees corrected by the atmospheric refraction component Δh_0^{ref}:

$$\Delta h_0^{\text{ref}} = 0.061359(0.1594 + 1.123h_0 + 0.065656h_0^2)/(1 + 28.9344h_0 + 277.3971h_0^2)$$

$$h_0^{\text{ref}} = h_0 + \Delta h_0^{\text{ref}} \tag{6}$$

The p/p_0 component in equation (5) is a correction for a given elevation z [m]:

$$p/p_0 = \exp(-z/8434.5) \tag{7}$$

The parameter $\delta_R(m)$ in equation (4) is the Rayleigh optical thickness at air mass m and is calculated according to the improved formula by Kasten (1996) as follows:

for $m \leq 20$:

$$\delta_R(m) = 1/(6.6296 + 1.7513m - 0.1202m^2 + 0.0065m^3 - 0.00013m^4) \tag{8}$$

for $m > 20$

$$\delta_R(m) = 1/(10.4 + 0.718m) \tag{9}$$

The beam irradiance on a horizontal surface B_{hc} [W m^{-2}] is then calculated as:

$$B_{hc} = B_{0c} \sin h_0 \tag{10}$$

where h_0 is the solar altitude angle given by equation (13).

The beam irradiance on an inclined surface B_{ic} [W m^{-2}] is calculated as:

$$B_{ic} = B_{0c} \sin \delta_{\exp} \tag{11}$$

or

$$B_{ic} = B_{hc} \sin \delta_{\exp}/\sin h_0 \tag{12}$$

where $\delta_{\exp}$ is the solar incidence angle measured between the sun and an inclined surface (equation 17).

The position of the sun with respect to a horizontal surface is given by the two coordinates – the solar altitude h_0 (an angle between the sun path and a horizontal surface) and the solar azimuth A_0 (horizontal angle between the sun and meridian – measured from East), and is calculated as follows (Krcho 1990, Jenčo 1992):

$$\sin h_0 = C_{31} \cos T + C_{33} \tag{13}$$

$$\cos A_0 = (C_{11} \cos T + C_{13})/((C_{22} \sin T)^2 + (C_{11} \cos T + C_{13})^2)^{1/2}$$

where:

$$\begin{aligned} &C_{11} = \sin\varphi \cos\delta,\ C_{13} -\cos\varphi \sin\delta \\ &C_{22} = \cos\delta,\ C_{31} = \cos\varphi \cos\delta,\ C_{33} = \sin\varphi \sin\delta \end{aligned} \tag{14}$$

The sun declination δ [rad] is computed according to Gruter (1984):

$$\delta = \arcsin(0.3978 \sin(j' - 1.4 + 0.0355 \sin(j' - 0.0489))) \tag{15}$$

where the calculation of the day angle j' [radians] is explained in equation (3). The hour angle T [rad] is calculated from the local solar time t expressed in decimal hours on the 24 hour clock as:

$$T = 0.261799(t - 12) \quad (16)$$

The position of the sun with respect to an inclined surface (the solar incidence angle) is defined by the angle δ_{exp} (Krcho 1990, Jenčo 1992). If an inclined surface is defined by the inclination angle γ_N and the azimuth (aspect) A_N (an angle between the projection of the normal on the horizontal surface and East) then:

$$\sin \delta_{exp} = C'_{31} \cos(T - \lambda') + C'_{33} \quad (17)$$

where:

$$C'_{31} = \cos \varphi' \cos \delta, \; C'_{33} = \sin \varphi' \sin \delta \quad (18)$$

and:

$$\sin \varphi' = -\cos \varphi \sin \gamma_N \cos A_N + \sin \varphi \cos \gamma_N \quad (19)$$

$$\mathrm{tg}\, \lambda' = -(\sin \gamma_N \sin A_N)/(\sin \varphi \sin \gamma_N \cos A_N + \cos \varphi \cos \gamma_N).$$

The hour angle of the time of sunrise/sunset over a horizontal surface $T_h^{r,s}$ can be calculated then as:

$$\cos T_h^{r,s} = -C_{33}/C_{31} \quad (20)$$

The hour angle of the time of sunrise/sunset over an inclined surface $T_i^{r,s}$ can be calculated by analogy:

$$\cos(T_i^{r,s} - \lambda') = -C'_{33}/C'_{31} \quad (21)$$

3.1.2 *Diffuse radiation*

As the cloudless sky becomes more turbid, the diffuse irradiance increases while the beam irradiance decreases. The estimation of the diffuse component on a horizontal surface D_{hc} [W m^{-2}] is made as a product of the normal extraterrestrial irradiance G_0, a diffuse transmission function Tn dependent only on the Linke turbidity factor T_{LK}, and a diffuse solar altitude function F_d dependent only on the solar altitude h_0 (Scharmer and Greif 2000):

$$D_{hc} = G_0 Tn(T_{LK}) F_d(h_0) \quad (22)$$

The estimate of the transmission function $Tn(T_{LK})$ gives a theoretical diffuse irradiance on a horizontal surface with the sun vertically overhead for the air mass 2 Linke turbidity factor. The following second order polynomial expression is used:

$$Tn(T_{LK}) = -0.015843 + 0.030543 T_{LK} + 0.0003797 T_{LK}^2 \quad (23)$$

The solar altitude function is evaluated using the expression:

$$F_d(h_0) = A_1 + A_2 \sin h_0 + A_3 \sin^2 h_0 \quad (24)$$

where the values of the coefficients A_1, A_2 and A_3 depend only on the Linke turbidity T_{LK} defined in the following expressions:

$$A'_1 = 0.26463 - 0.061581 T_{LK} + 0.0031408 T_{LK}^2 \quad (25)$$

$$A_1 = 0.0022/Tn(T_{LK}) \quad \text{if } A'_1\, Tn(T_{LK}) < 0.0022$$

$$A_1 = A'_1 \quad \text{if } A'_1\, Tn(T_{LK}) \geq 0.0022$$

$$A_2 = 2.04020 + 0.018945T_{LK} - 0.011161T_{LK}^2$$

$$A_3 = -1.3025 + 0.039231T_{LK} + 0.0085079T_{LK}^2$$

The model for estimating the clear-sky diffuse irradiance on an inclined surface D_{ic} [W m^{-2}] distinguishes between sunlit, potentially sunlit and shadowed surfaces. The equations are as follows (Muneer 1990):

(a) for sunlit surfaces and non-overcast sky (h_0 in radians):

if $h_0 \geq 0.1$ (i.e. 5.7°)

$$D_{ic} = D_{hc}\{F(\gamma_N)(1 - K_b) + K_b \sin \delta_{exp}/\sin h_0\} \quad (26)$$

if $h_0 < 0.1$

$$D_{ic} = D_{hc}\{F(\gamma_N)(1 - K_b) + K_b \sin \gamma_N \cos A_{LN}/(0.1 - 0.008h_0)\} \quad (27)$$

where

$$\begin{aligned} A_{LN}^* &= A_0 - A_N \\ A_{LN} &= A_{LN}^* && \text{if } -\pi \leq A_{LN}^* \leq \pi \\ A_{LN} &= A_{LN}^* - 2\pi && \text{if } A_{LN}^* > \pi \\ A_{LN} &= A_{LN}^* + 2\pi && \text{if } A_{LN}^* < -\pi \end{aligned} \quad (28)$$

(b) for surfaces in shadow ($\delta_{exp} < 0$ and $h_0 \geq 0$):

$$D_{ic} = D_{hc}F(\gamma_N) \quad (29)$$

where $F(\gamma_N)$ is a function accounting for the diffuse sky irradiance that may be calculated by the following equation (γ_N in radians):

$$F(\gamma_N) = r_i(\gamma_N) + (\sin \gamma_N - \gamma_N \cos \gamma_N - \pi \sin^2(\gamma_N/2))N \quad (30)$$

$r_i(\gamma_N)$ is a fraction of the sky dome viewed by an inclined surface [dimensionless]:

$$r_i(\gamma_N) = (1 + \cos \gamma_N)/2 \quad (31)$$

and the value of N for surfaces in shadow is 0.25227. For sunlit surfaces under clear sky the term N is calculated as:

$$N = 0.00263 - 0.712K_b - 0.6883K_b^2 \quad (32)$$

The K_b is a measure of the amount of beam irradiance available (proportion between beam irradiance and extraterrestrial solar irradiance on a horizontal surface):

$$K_b = B_{hc}/G_{0h} \quad (33)$$

where G_{0h} [W m^{-2}] is calculated as:

$$G_{0h} = G_0 \sin h_0 \quad (34)$$

3.1.3 Ground reflected radiation

The estimation of the clear-sky ground reflected irradiance for inclined surfaces (R_i) relies on an isotropic assumption. The ground reflected clear-sky irradiance received on an inclined surface [W m^{-2}] is proportional to the global horizontal irradiance G_{hc}, to the mean ground albedo ρ_g and a fraction of the ground viewed by an inclined surface $r_g(\gamma_N)$ (Muneer 1997):

$$R_i = \rho_g G_{hc} r_g(\gamma_N) \tag{35}$$

where:

$$r_g(\gamma_N) = (1 - \cos \gamma_N)/2 \tag{36}$$

and global irradiance on a horizontal surface G_{hc} [W m^{-2}] is given as a sum of its beam and diffuse component:

$$G_{hc} = B_{hc} + D_{hc} \tag{37}$$

In Scharmer and Greif (2000, p. 141) typical albedo values for a variety of ground surfaces are listed. In general the values of 0.2 or 0.15 are mostly used.

3.2 Computing radiation under overcast conditions

Overcast irradiance/irradiation are calculated from clear-sky raster maps by the application of a factor parameterizing the attenuation of cloud cover. Examples of explicit calculations of this parameter can be found in Becker (2001) and Kitler and Mikler (1986). However, the cloudiness observation by a meteorological service routine is usually prone to subjective errors and does not describe sufficiently the physical nature and dynamic spatio-temporal pattern of different types of cloud cover. Therefore, a simpler parameter has to be used. The solutions for horizontal and inclined surfaces are slightly different.

For the assessment of global irradiance/irradiation on a *horizontal surface* under overcast conditions G_h the clear-sky values G_{hc} are multiplied by a clear-sky index k_c (Beyer et al. 1996, Hammer et al. 1998, Rigollier et al. 2001):

$$G_h = G_{hc} k_c \tag{38}$$

The index k_c represents the atmospheric transmission expressed as a ratio between horizontal global radiation under overcast and clear-sky conditions. For a set of ground meteorological stations the clear-sky index can be calculated from measured global radiation G_{hs} and computed values of clear-sky global radiation G_{hc}:

$$k_c = G_{hs}/G_{hc} \tag{39}$$

As an alternative the k_c can be derived also from other climatologic data (e.g. cloudiness, cf. Kasten and Czeplak 1980). The raster maps of k_c must then be derived by spatial interpolation. The k_c can be calculated directly as a raster map from short-wave surface irradiance measured by satellites. This method is based on the complementarity between the planetary albedo recorded by the radiometer and the surface radiant flux (Cano et al. 1986, Beyer et al. 1996, Hammer et al. 1998).

To compute the overcast global irradiance/irradiation for *inclined surfaces* G_i, the beam, diffuse and reflected components are computed analogically to the equations (12), (26), (27), (29) and (35), substituting B_{hc} for B_h and D_{hc} for D_h. To compute D_h and B_h, the clear-sky index k_c has to be treated separately as follows:

$$\begin{aligned} D_h &= D_{hc} k_c^d \\ B_h &= B_{hc} k_c^b \end{aligned} \tag{40}$$

The ratio of diffuse to global radiation D_h/G_h for clear and overcast skies changes according to the cloudiness. In Europe the D_h/G_h values typically fall into the interval 0.3–1.0 (Kasten and Czeplak 1980). The underlying physical processes are quite complicated and computationally represented only by empirical equations (cf. Scharmer and Greif 2000, Kasten and Czeplak 1980, Hrvol' 1991). However, for many meteorological stations, besides the global horizontal radiation G_{hs}, the diffuse component D_{hs} is either measured or calculated from cloudiness, sunshine or other climatologic data. The raster map of D_{hs}/G_{hs} can be derived from the point values by spatial interpolation. Consecutively, the raster maps of diffuse and beam components of the clear sky index can be computed:

$$D_h = G_h D_{hs}/G_{hs} \tag{41}$$

$$\begin{aligned} B_h &= G_h - D_h \\ k_c^d &= D_h/D_{hc} \\ k_c^b &= B_h/B_{hc} \end{aligned} \tag{42}$$

where subscript s is meant to distinguish data measured at meteorological stations B_{hs} and D_{hs} from the estimated values B_h, and D_h.

4 Solar Radiation Database for Assessment of Photovoltaic Systems in Central and Eastern Europe

Solar energy is one of the environmentally sustainable resources for producing electricity using photovoltaic (PV) systems. However, there are barriers to the widespread use of PV systems. One significant problem is their initial capital costs. Therefore, their design and location has to be planned and calculated.

Within a project entitled "Environment and Solar Energy Resource" run by the European Commission Joint Research Centre in Ispra, a map-based inventory of the suitability of areas for the installation of PV systems was realized (Šúri et al. 2002). The study area covers 10 European Union Candidate Countries (Bulgaria, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Slovakia, and Slovenia). Part of this work was dedicated to building a solar database using the *r.sun* model and the interpolation techniques *s.surf.rst* and *s.vol.rst*. The database consists of raster maps representing twelve monthly averages and one annual average of daily sums of global irradiation for horizontal surfaces, as well as those inclined at angles of 15, 25, and 40 degrees. Besides these data, raster maps of clear-sky irradiation, the Linke turbidity, and the ratio D_h/G_h were computed on the basis of the following three steps:

1. Computation of clear-sky global irradiation on a horizontal surface;
2. Calculation and spatial interpolation of the clear-sky index and computation of raster maps of global irradiation on a horizontal surface;
3. Computation of the diffuse and beam components of overcast global irradiation and raster maps of global irradiation on inclined surfaces.

4.1 Clear-sky global irradiation on a horizontal surface

All raster maps (2145 × 1410 cells) with a cell resolution of 1 km^2 were integrated in a single GIS database. The elevation was derived from the USGS GTOPO30 digital elevation model (http://edcdaac.usgs.gov/gtopo30/gtopo30.html) with a primary resolution of 30 arc seconds (approx. 1 km^2). The latitude raster map was interpolated from points using the regularized spline with tension *s.surf.rst* (Mitasova and Mitas 1993). The monthly averages of the Linke turbidity factor T_{LK} for 317 sites over the study area were extracted from the SoDa database (Wald 2000). The accuracy of the data from this source is reported to RMSE = 0.7 T_{LK} units. To eliminate the effect of elevation, the T_{LK} values were normalised to the elevation at sea level before interpolation (WMO 1981):

$$T_{LKn} = T_{LK} + 0.00035\,z \qquad (43)$$

where z is the elevation of the raster cell. The T_{LKn} sites were interpolated using *s.surf.rst* to derive 12 monthly raster maps. T_{LK} values were obtained from equation (43) using T_{LKn} and elevation.

The annual average of daily sums of clear-sky global irradiation for a horizontal surface is presented in Plate 8a. The time step for the integration of irradiance values was set to 0.25 hour while day numbers and declination values for each month were set according to the ESRA (Scharmer and Greif 2000, p. 108). The most critical issue in this stage is the Linke turbidity factor as its estimation is still prone to large uncertainty.

4.2 Global irradiation on a horizontal surface

The global irradiation for overcast conditions was calculated using the clear-sky index k_c. For the study area, the climatologic database for 182 meteorological stations was available (source ESRA), comprising geographical position and monthly means of daily sums of global G_{hs}, beam B_{hs} and diffuse D_{hs} irradiation on a horizontal surface. The clear-sky irradiation values G_{hc}, B_{hc} and D_{hc}, computed in the previous step, were added to this database and for each meteorological station, the k_c was calculated (equation 39).

Although the available meteorological stations do not cover the study area evenly and in mountainous regions they are rather rare, it can be seen that the clear-sky and D_h/G_h indices are correlated with GTOPO30 elevation, especially in summer and winter (Figure 1). Therefore, to create the raster maps of k_c, accounting for changes in vertical dimension, it was decided to apply a multivariate spatial interpolation procedure using regularized spline with tension that was implemented in the GRASS GIS as the *s.vol.rst* command (Neteler and Mitasova 2002). As the interpolation results are very sensitive to the setting of input parameters (tension, smoothing and vertical scaling; cf. Hofierka et al. 2002), a crossvalidation procedure was applied separately for each of the twelve monthly data sets (Plate 8b). The raster maps of overcast global irradiation on a horizontal surface G_h were then calculated using equation (38) (Plate 8c). The spatial pattern of radiation in individual months is quite dynamic as can be seen from Plate 9.

4.3 Global irradiation on inclined surfaces

To compute global irradiation on inclined surfaces G_i at real (overcast) atmospheric conditions, the ratio D_{hs}/G_{hs} was calculated using the meteorological data. The monthly averages of raster maps were interpolated using *s.vol.rst* with the same procedure as for the clear-sky index (Plate 10). The raster maps of diffuse and beam components of global irradiation for overcast conditions as well as both components of the clear-sky index were computed (equations 41 and 42). Finally, the monthly averages of daily sums of global irradiation input to southwards-oriented PV modules were computed for three

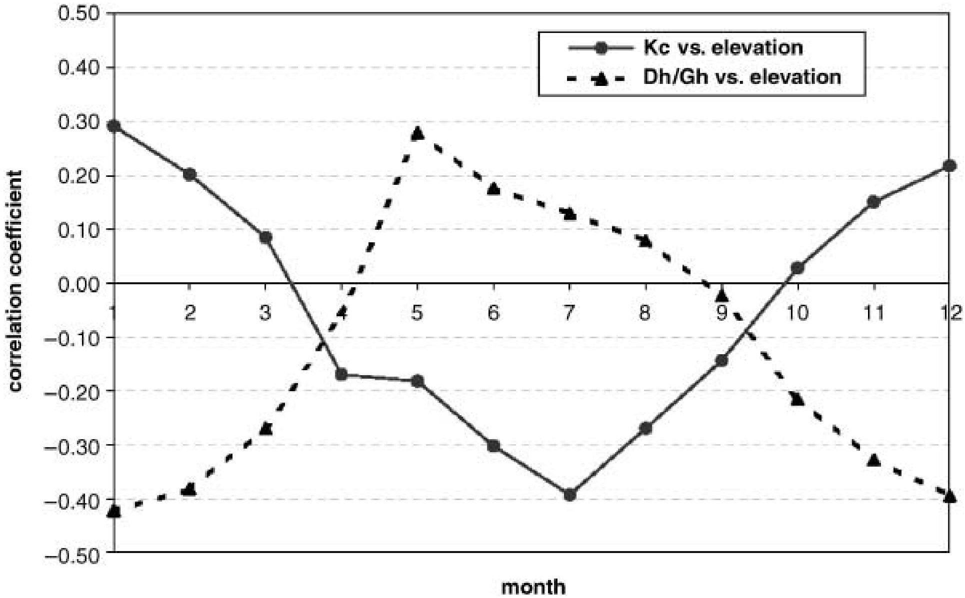

Figure 1 Seasonal correlations between monthly averages of clear-sky index k_c and elevation, and ratio of diffuse to global irradiation D_h/G_h and elevation

inclination angles –15, 25, and 40 degrees (Plate 11). The ground albedo was considered as a constant 0.15.

4.4 Comparison of ESRA and r.sun *results*

The ESRA database (Scharmer and Greif 2000) consists of primary irradiation data measured or calculated for a set of European meteorological stations (182 of them in our study area). The raster maps of monthly averages of daily sums of global radiation for a horizontal surface were created from the primary data by kriging (cf. Beyer et al. 1997). The co-kriging method supported by satellite data did not prove to give higher accuracy due to the low resolution of the satellite data and their unsatisfactory correlation with ground measurements, particularly in winter months.

The calculation of relative root square error (RMSE) for comparing the primary radiation data with ESRA and *r.sun* raster maps respectively is presented in Figure 2. The average RMSE is almost the same, the *r.sun* approach shows better performance for the period from October to April. The important advantage of our approach is linking the terrain features with changes in radiation fields and considering the shadowing effects (Plate 12). The multivariate regularized spline with tension could provide k_c raster maps that better fit the regional particularities of radiation climate in the mountainous areas on condition that a more dense pattern of ground measurements would be available. The influence of terrain shadowing is more visible when higher resolution data (namely digital terrain models) are used. As can be seen on Plate 12, the raster cell resolution of 1 km^2 is still too rough to reveal the real shadowing patterns in mountainous landscape.

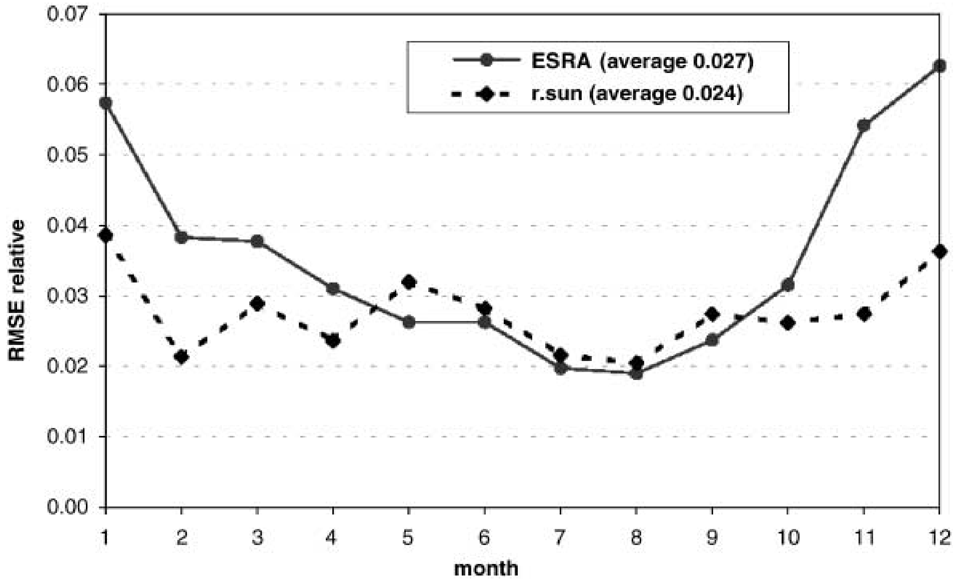

Figure 2 Prediction relative root mean squared error (RMSE) in monthly averages of daily sums of global irradiation on a horizontal surface G_h by ESRA and *r.sun*

5 Conclusions

The *r.sun* is a complex and flexible solar radiation model, fully integrated within the open source environment of the GRASS GIS. It calculates all three components of solar irradiance/irradiation (beam, diffuse and reflected) for clear-skies as well as overcast conditions. The implemented equations follow the latest European research in solar radiation modelling. Integration in the GRASS GIS enables the use of interpolation tools that are necessary for data preparation. The *r.sun* is especially appropriate for modelling large areas with complex terrain because all the spatially variable input parameters can be defined as raster maps. The model can be used easily for long-term calculations at different map scales – from continental to local. Two operational modes take into account the temporal variability of solar radiation within a selected time interval.

At present the digital terrain models are available at different resolutions, including very detailed ones. This enables the simulation of the dynamics of radiation fields influenced by terrain (including shadowing) at a high level of accuracy. The other needed parameters are much less reliable. The clear-sky values are very sensitive to the Linke turbidity factor that is still estimated with a high level of uncertainty. The lower reliability of Linke turbidity is partly resolved by a clear-sky index that links clear-sky values with real (overcast) ones. The application of multivariate interpolation by regularized spline with tension requires preliminary testing of settings using cross-validation analysis to minimize errors of prediction. The adequate density of points and their representative distribution can strongly enhance the resulting spatial patterns. However the actual availability of ground measured radiation data cannot meet these requirements satisfactorily, particularly in regions with complex terrain.

The presented results indicate that the application of the GIS-based model and the multivariate interpolation tools with higher resolution elevation data and a denser network of ground measurements could substantially improve our knowledge of the dynamics and spatial patterns of solar radiation fields, particularly in complex terrain. The open source code should facilitate additional model modifications and improvements in the future, taking advantage of research developments in solar radiation modelling and/or to better fit user-specific needs.

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