ESTIMATION AND MAPPING OF THE SPATIAL DISTRIBUTION OF TOTAL SOLAR IRRADIANCE AT HETEROGENEOUS SURFACES

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Abstract
In this study, the spatial distribution of total solar irradiance at the surface was estimated taking into account the effect of topography on the surface orientation. The direct irradiance on surfaces normal to the solar beam, as well as the diffuse irradiance on horizontal surfaces were simulated using SBDART (Santa Barbara DISORT Atmospheric Radiative Transfer) model and following a spatial model was developed to calculate the solar irradiance reaching any arbitrary oriented surface using a DEM (Digital Elevation Model). Finally, the spatial distribution of daily irradiation was calculated using this spatial model. The SBDART vegetation standard surface type was used for surface albedo parameterisation, AVHRR (Advance Very High Resolution Radiometer) data were used for cloud cover estimation, while typical atmospheric trace gases concentrations and MODIS (Moderate Resolution Imaging Spectrometer) derived precipitable water were used in SBDART simulations. The application area was the central and eastern Crete and the simulations were performed for May 20, 2003. A sensitivity analysis was carried out based on the spatial model results. The methodology developed in this study is considered capable of supporting local and regional level climatological, agrometeorological and forestry studies, as well as of providing professionals and decision makers with accurate estimations for spatial-temporal irradiance distribution and energy budget related parameters such as daily irradiation.

Keywords: Solar Irradiance, Atmospheric Radiative Transfer, Inclined Surface, Digital Elevation Model

1. Introduction
The main driving force of the earth system is radiation forcing. The spectral composition of the radiation impacts life on earth through photosynthesis. A detailed and quantitative knowledge of the earth radiation field is crucial for understanding and predicting the evolution of the components of the earth system. When solar radiation enters the atmosphere, a part of the incident energy is removed by scattering and a part by absorption. The scattered radiation is called diffuse radiation. The radiation arriving on the ground directly in line from the solar disk is called direct radiation. Direct radiation is the most important component of the total radiation arriving at the surface, because it contributes the most to the energy balance and also to the other components depend on it.

Atmospheric radiative transfer models have provided an accurate and expedient way to compute radiation levels at low and moderate spectral resolution (Pierluissi and Peng, 1985; Kneizys et al., 1988; Bernstein et al., 1996). It is extremely difficult to constrain models with accurate estimates of cloud optical depth and microphysics, however the cloud cover and the main cloud parameters (cloud height, cloud path, cloud effective radius) can be estimated using moderate spatial resolution satellite data (King et al., 1997). Ricchiazzi et al. (1998) developed the SBDART (Santa Barbara DISORT Atmospheric Radiative Transfer) model, a software tool that computes plane-parallel radiative transfer in clear and cloudy conditions within the earth’s atmosphere and at the surface. This model is a marriage of a sophisticated discrete ordinate radiative transfer module, low resolution atmospheric transmission models and Mie scattering results for light scattering by water droplets and ice crystals. Even under clear skies, the uncertainty of atmospheric state, particularly aerosol turbidity and atmospheric water vapor distribution, produces significant variation in the shortwave simulations. Atmospheric water vapor is the predominant absorber of the incoming solar radiation. Calculation of the vertical profile of the water vapor depends on the existence of radiosondes in the area under consideration. Due to this dependency, the spatial resolution of the water vapor profiles is low, a fact which results in considerable difficulties for the calculation of the incoming solar radiation. An alternative way for defining water vapor in the atmosphere is using the Precipitable Water (PW) defined as the total amount of water vapor in the zenith direction between the surface of the earth and the top of the atmosphere (Cartalis and Chrysoulakis, 1997; Chrysoulakis and Cartalis, 2000). PW can be estimated from radiosonde measurements, as well as from satellite observations.

Solar radiation data are measured at a limited number of climatic ground stations. At present, low
resolution data for Europe are commercially available (Scharmer and Greif, 2002; Remund et al., 1999). Geographic Information Systems (GIS) have been employed in several radiation models that calculate solar irradiance on a land surface (Kumar et al., 1997, McKenny et al., 1999). However, professional and decision makers need spatially continuous solar radiation data at high spatial and temporal resolutions. Empirical relations have been developed in several studies in order to take into account the effects of surface slope and orientation the total irradiance, but most of the results are in graphical or tabular form. To consider the spatial dynamics of radiation fields determined by local topography, solar radiation models based on Digital Elevation Models (DEMs) have to be used. The digital format of a DEM is capable of deriving additional information for various applications, so that elevation modeling has become an important part of the international research and development programs related to geospatial data. However, DEMs of usable details are still not available for much of the Earth, and when they are available they frequently lack sufficient accuracy (Toutin Th., 2001).

In this study, the spatial distribution of total solar irradiance at any arbitrary oriented surface was estimated for the area of central and east Crete, Greece. The direct irradiance on surfaces normal to the solar beam, as well as the diffuse irradiance on horizontal surfaces were simulated using SBDART model. Satellite data were used for SBDART parameterization. Following a spatial model was developed to calculate the solar irradiance reaching any inclined surface using a DEM. Finally, the spatial distribution of daily irradiation was computed.

2. Data and methodology

The data used in this study were a DEM, derived from 20 m contour lines by interpolation, for the central and east Crete, surface observations from Heraklion station (35.33 N, 25.18 E) of National Meteorological Service, AVHRR (Advance Very High Resolution Radiometer) images from FORTH (Foundation for Research and Technology – Hellas) satellite ground receiving station (35.31 N, 25.07 E) and MODIS (Moderate Resolution Imaging Spectroradiometer) data from NASA (Earth Observing System Data Gateway) for May 20, 2003.

In order to determine the position of the sun with respect to an inclined and arbitrary oriented surface, it is necessary to prescribe the slope of the surface with respect to the horizontal position and its orientation to the local meridian. The total solar irradiance arriving at an inclined surface is given by the formula (Iqbal, 1983):

$$I_{Total}(x, y, z, \theta, t) = I_{Direct}(x, y, z, t) \cos \theta + I_{Diffuse}(x, y, z, \theta, t)$$  \hspace{1cm} (1)

where, x, y, z are the coordinates of the central point of the surface; \( \beta \) is the surface slope, measured from horizontal position, in degrees; \( \theta \) is the angle of incidence, that is the angle between normal to the surface and the sun-earth vector, in degrees; \( t \) is the time of observation; \( I_{Total} \) is the total solar irradiance at the inclined surface (W/m²); \( I_{Direct} \) is the direct irradiance at a surface normal to the sun-earth vector (W/m²); \( I_{Diffuse} \) is the diffuse irradiance at the inclined surface (W/m²).

For a surface oriented in any direction with respect to the local meridian (Figure 1), the trigonometric relation for the incidence angle \( \theta \) has been given in past studies (Kondratyev, 1969; Coffari, 1977; Iqbal, 1983):

$$\cos \theta = \cos \beta \cos z_s + \sin \beta \sin z_s \cos(a - a_s)$$  \hspace{1cm} (2)
where, $\theta$ is the angle of incidence; $\beta$ is the slope of the surface; $a$ is the surface azimuth angle, that is the deviation of the normal to the surface with respect to the local meridian, measured from North, in degrees; $z_s$ is the solar zenith angle, that is the angle between the local zenith and the sun-earth vector, in degrees; $a_s$ is the solar azimuth angle, that is the deviation of the projection of the sun-earth vector on the horizontal plane with respect to the local meridian, measured from North, in degrees.

The total solar irradiance on a horizontal surface can be computed by using SBDART model. SBDART can be also used for inclined surfaces if their slope and azimuth angles are known. However, for application on a real extended and heterogeneous surface, a DEM should be used to describe topographic characteristics. It is therefore obvious that, the combined use of radiative transfer models, such as SBDART, with spatial tools such as GIS, is necessary when the calculation of the spatial distribution of total solar irradiance is needed. In this way, both atmospheric and topographic effects to solar radiation reaching the ground are taken into account. Moreover, GIS computations should be applied for the estimation of total solar irradiance at the surface at different time steps during the course of the day (when incidence angle is continuously changing), as well as for the computation and mapping of daily irradiation.

In this study, the time and the coordinates of each surface determine the solar zenith ($z_s$) and azimuth angles ($a_s$) for each SBDART simulation. The vegetation type was selected, as the most appropriate type for the study area, since simulations were performed for May 20, 2003. The study area was cloud free, as it can be seen in Figure 2, where AVHRR channel 4 (10.3 – 11.3 µm) is used for cloud detection (the black tones in Figure 2, correspond to clouds, because of the low temperatures of cloud tops). Atmospheric horizontal visibility observations were available from Heraklion meteorological station. Moreover, typical trace gases concentrations (360 ppm for CO$_2$, 1.74 ppm for CH$_4$ and 0.32 ppm for N$_2$O) were used in SBDART simulations, whereas for the calculation of PW spatial distribution over the study area, the MODIS Atmospheric Profile data (MYD07_L2) were used. MYD07_L2 data consist of several parameters: they are total-ozone burden, atmospheric stability, temperature and moisture profiles and atmospheric water vapor. All of these parameters are produced at 5×5 km pixel resolution.

![Figure 2. NOAA/AVHRR Channel 4 for May 20, 2003 at 12.05 UTC (a) and 14.50 UTC (b).](image)

Elevation values for each pixel of the DEM were interpolated with SBDART calculations for direct and diffuse irradiance. For each pixel $(x,y)$ at a given elevation $(z)$ the $I_{\text{Direct}}$ and $I_{\text{Diffuse}}$ components were calculated. As a result, the spatial distributions of $I_{\text{Direct}}(x,y,z,t)$ and $I_{\text{Diffuse}}(x,y,z,t)$ were estimated. At this step, $I_{\text{Diffuse}}(x,y,z,t)$ values were calculated for horizontal surfaces and $I_{\text{Direct}}(x,y,z,t)$ values were calculated for surfaces normal to the solar beam. For the estimation of the actual diffuse solar irradiance at each pixel, $I_{\text{Diffuse}}(x,y,z,t)$ values should be multiplied by the sky view factor of the surface. Therefore:

$$I_{\text{Diffuse}}(x,y,z,\beta,t) = (1 - \frac{\beta}{180}) I_{\text{Diffuse}}(x,y,z,t) \quad (3)$$

where $\beta$ is the slope of the surface, measured from horizontal position, in degrees.

For the estimation of the actual direct solar irradiance at each pixel, $I_{\text{Direct}}(x,y,z,t)$ values should be multiplied by $\cos \theta$, where $\theta$ is is the angle of incidence. Thus $I_{\text{Direct}}(x,y,z,\theta,t) = I_{\text{Direct}}(x,y,z,t)\cos \theta$. The cosine of $\theta$ was calculated from surface slope ($\beta$) and azimuth ($a$) angles, solar zenith ($z_s$) and azimuth ($a_s$) angles values using equation (2). For each surface corresponded to a pixel of the DEM raster, $z$ and $a$ values were provided by SBDART, whereas $\beta$ and $a_s$ values were calculated from the DEM. The DEM used in this study is shown in Figure 3. It has been produced by interpolation of 20 m contours and producing a raster image with 200 m pixel size. Slope and aspect images for the study area were produced using this DEM. The slope image illustrates changes in elevation over a certain distance. Slope is most often expressed as a percentage, but can also be calculated in degrees. For a pixel at a given location, the elevations around it were used to
calculate the slope. In practice, 3x3 pixel window was used to calculate the slope at each pixel. The aspect image illustrates the prevailing direction that the slope faces at each pixel. Aspect is expressed in degrees from north, clockwise, from 0 to 360. Due north is 0 degrees. A value of 90 degrees is due east, 180 degrees is due south and 270 degrees is due west. The value of 361 degrees is used to identify flat surfaces. As with slope calculations, aspect uses a 3x3 window around each pixel to calculate the prevailing direction it faces.

Figure 3. DEM for Central and East Crete (high elevations correspond to bright tones).

In practice, for the estimation of $I_{\text{Total}}(x,y,z,\theta,t)$, a GIS-based model was developed. Inputs for this spatial model at a given time step are the DEM and several ASCII files containing: a) the value of the solar zenith angle, b) the value of the solar azimuth angle, c) the values of the direct solar irradiance on surface normal to the solar beam for the lower tropospheric levels (0 to 5 Km), d) the diffuse solar irradiance on an horizontal surface for the lower tropospheric levels. All these ASCII are SBDART outputs at this time step. The model calculates the slope and aspect values for each pixel and following the cos$\theta$ spatial distribution using the solar zenith and azimuth angles. It also interpolates the elevation values from DEM with SBDART outputs for $I_{\text{Direct}}$ and $I_{\text{Diffuse}}$ to produce $I_{\text{Direct}}(x,y,z)$ and $I_{\text{Diffuse}}(x,y,z)$ spatial distributions. The output of the spatial model is the total solar irradiance at the surface $I_{\text{Total}}(x,y,z,\theta,t)$. Moreover, if the time period between the sunshine and sunset was divided into N time steps (assuming that the solar position is constant for each time step), N spatial model runs should be performed in order to estimate the spatial-temporal distribution of the surface irradiance for the study area.

A very useful parameter for engineers and decision makers may be produced by integrating the aforementioned spatial-temporal irradiance distribution over a given time period to estimate the solar energy that each area receives and finally, if the land cover is known, the energy that each area absorbs during this time period. Therefore, the total solar energy per unit area arriving at each surface during the course of a day (daily irradiation) can be computed by the integration of the irradiance values calculated at a selected time step and summarized between the sunshine and sunset:

$$E = \int_{t_1}^{t_2} I_{\text{Total}}(x,y,z,\theta,t)dt$$

where, $E$ is the total daily irradiation (KWh/m$^2$); $t$ is the time; $t_1$ is the sunrise time; $t_2$ is the sunset time; $I_{\text{Total}}(x,y,z,\theta,t)$ is the total solar irradiance at the surface at the time $t$ (W/m$^2$).

The daily irradiation was estimated in this study as follows: The time period from 03:30 to 17:30 UTC was divided to 27 time steps of 30 min ($N = 27$). The spatial model was run once for each time step to calculate the average irradiance and the daily irradiation was calculated by the sum of $I_{\text{Total}}(x,y,z,\theta,t)$ values:

$$E = \frac{KWh}{m^2} = 0.5 \sum_{i=1}^{27} I_{\text{Total}}(x,y,z,\theta,t)$$

3. Results and discussion

SBDART atmospheric simulation model was used to estimate the spatial distribution of direct and diffuse solar irradiance at the surface. Following, a spatial model was developed to deal with the solar – surface geometry, as well as with the topography effects on surface irradiance. For the calculation of PW spatial distribution over the study area MODIS data were used. The resulted PW spatial distribution is shown in Figure 4. PW values were found within the range of values from 1.20 to 2.45 g/cm$^2$ as it was expected according to Chrysoulakis and Cartalis (2002).
Figure 4. PW spatial distribution as derived from MODIS measurements.

Figure 5. Spatial distribution of total solar irradiance at the surface for May 20, 2003.

The spatial distribution of total solar irradiance at the surface for May 20, 2003 is presented in Figure 5. A time step of 30 minutes was used. The spatial model was run using SBDART outputs for each time step to produce irradiance spatial distribution during the course of the day. Irradiance reached its maximum values around the local noon as it was expected, however the strong topography effect is evident in all cases. For example, at 11:00 UTC when the irradiance values for the most of the study area are greater than 750 W/m², there are a lot of pixels with irradiance values less than 200 W/m². It is therefore observed in Figure 5 that the sinusoidal change of surface irradiance with time is substantially modified by the topography in most surfaces of the study area. The location of the high mountains (Idi or Psiloritis Mountains, Dikti Mountains and Mountains of Sitia), as well as their effect to the local irradiance field is clearly depicted in all maps in Figure 5. For example, the northwest areas of these mountains can be easily detected in maps of 07:00 UTC and 07:30 UTC as low irradiance islands (bluish tones). These areas are obscured during the morning, but they receive larger amounts of solar radiation in the afternoon. The opposite phenomenon can be observed for the northeast mountainous areas (maps of 13:00 UTC and 13:30 UTC). These areas are also depicted as low irradiance islands, they receive larger amounts of solar radiation during the morning time, but they are obscured during the afternoon and therefore they receive only the diffuse part of solar irradiance (around 100 W/m²). The location of extended horizontal areas is also evident in Figure 5. In these areas, the spatial distribution of total solar irradiance is characterized by a spatial-temporal homogeneity. For example, at the Messara Valley (the most extended valley in the study area, located at southwest parallel to the south coast as
can be seen in Figure 3) the irradiance field is almost unchanged around the local noon (maps from 08:30 UTC to 11:30 UTC). In general, for pixels correspond to horizontal surfaces the sinusoidal change of irradiance during the day is observed, as for example for the area of Lassitthi Plateau (area A in Figure 3).

Since MODIS derived PW values and in-situ observed atmospheric visibility values have been used in SBDART simulations, the error in SBDART predictions of total surface irradiance is less than 20 W/m², as it has been analyzed by Ricchiazzi et al. (1998). Therefore, it can be stated that for what concerns horizontal surfaces, the irradiance estimation error in this study is around ± 20 W/m². For inclined surfaces the respective error depends on the uncertainty the spatial model introduces. The accuracy of the spatial model depends on the accuracy of the DEM used, because the error introduced when the solar irradiance is estimated for inclined surfaces is depended on the accuracy in estimation of the surface slope and azimuth parameters. In any case, the results of this study are not valid for urban surfaces for two reasons: a) the standard vegetation type is not appropriate for urban surface type parametrization and b) either the planimetric (200 m) or the elevation (20 m) accuracy of the DEM used in this study does not allow to take into account the spatial heterogeneity of the urban surface. Due to the lack of field measurements of solar radiation, a sensitivity analysis of the spatial model is necessary to understand how the uncertainties in estimation of surface slope and azimuth angles affect the surface irradiance estimation.

Figure 6. Sensitivity analysis of the developed spatial model, based on SBDART simulations.

Figure 6 shows the dependence of solar irradiance of both surface slope and azimuth angle for five different time steps. The uncertainty in estimation of surface slope mainly affects the resulted irradiance at steep surfaces. This effect is stronger for the morning and for the afternoon cases. For surfaces with gentle slopes, the uncertainty in estimation of β lightly affects the resulted irradiance. Therefore, at the local noon (10:00UTC), for gentle surfaces an error of 10% in surface slope, results in less than 2.5% error in estimated irradiance value, whereas for steep surfaces it results in less than 5% error, for any combination of solar and surface azimuth angles. Moreover, 20% uncertainty in β, results in less than 3% and less than 12% errors in estimated I_{TOTAL} value, respectively. For the late morning case (08:00 UTC), as well as for the early
afternoon case (12:00 UTC) the uncertainties in surface slope may cause higher errors in irradiance values. Thus, for gentle surfaces 10% uncertainty in $\beta$, results in around 3% error in estimated irradiance, whereas for steep surfaces the resulted error is around 6%, for any combination of solar and surface azimuth angles. Moreover, 20% uncertainty in estimation of $\beta$, results in around 5% and 11% errors in $I_{TOTAL}$ estimation, respectively. For the early morning case (06:00 UTC), as well as for the late afternoon case (14:00 UTC) the uncertainties in estimation of surface slope may cause high errors in irradiance as well. Thus, for gentle surfaces 10% uncertainty in $\beta$, results in around 5% error in estimated irradiance, whereas for steep surfaces the resulted error is around 5%, for any combination of solar and surface azimuth angles. Moreover, 20% uncertainty in $\beta$, results in around 11% and 9% errors in $I_{TOTAL}$, respectively. In the case when the solar azimuth angle is equal to the surface azimuth angle ($\alpha=\alpha_s$), the surface irradiance reaches its maximum values, for all surface slope angles, as it can be clearly seen from the solid corves. Moreover, for all $\alpha=\alpha_s$ cases, the surface irradiance reaches its maximum values when the surface slope angle is equal to the solar zenith angle ($\beta=\beta_s$) as it can be seen in Figure 6. This result is easily explained, because in this case, the cosine of the angle of incidence is maximized. So, for $\alpha=\alpha_s$, $\cos(\alpha-\alpha_s)=1$ and therefore equation (2) becomes:

$$
\cos \theta = \cos \beta \cos \beta_s + \sin \beta \sin \beta_s = \cos^2 \beta + \sin^2 \beta = 1
$$

Equation (6) practically means that the normal to the inclined surface is parallel to the sun earth vector and therefore all the amount of solar direct radiation reaches the surface. The latter is not valid for all combinations of solar and surface azimuth angles, because as the difference $\alpha-\alpha_s$ increases (or decreases), especially around the local noon, $I_{TOTAL}$ reaches its maximum values for surfaces with slopes smaller than the solar zenith angle. Especially for $\alpha-\alpha_s > 60^\circ$, $I_{TOTAL}$ is maximum for small surface slopes. This effect is clearly depicted in Figure 7 (10:00UTC) for $\alpha-\alpha_s$ around 90°. In this case the difference in resulted $I_{TOTAL}$ values between gentle and steep surfaces is maximum. For example $I_{TOTAL} = 950 \ W/m^2$ for $\beta=5^\circ$ while $I_{TOTAL} = 725 \ W/m^2$ for $\beta=45^\circ$. Therefore, the difference between the value of solar irradiance at a near horizontal surface and its value at a steep surface is 225 W/m² (about 25%). This difference lies around 18%, 11% and 9% for $\alpha-\alpha_s$ around 60°, 30° and 0°, respectively. The latter explains why horizontal surfaces receive the highest amounts of solar energy during the course of the day.

![Figure 7. Daily irradiation (KWh/m²) for May 20, 2003](image)

Figure 7 shows the spatial distribution of the daily irradiation (KWh/m²) for May 20, 2003. It can be observed that the horizontal surfaces without obscures receive the highest amounts of solar energy during the course of the day. The higher the surface elevation, the higher the amount of solar radiation it receives. For example, the area of the Lassithi Plateau receives 6.5 – 7 KWh/m², which is of the highest irradiation amounts over the study area. It is well known that the higher the received solar energy, the higher the photosynthetic activity at a given area. Therefore, for the Lassithi Plateau, taking into account that the local economy is based on agriculture, it is evident the importance of the location of this area in relation to the solar irradiance it receives.

4. Conclusions

Low spatial resolution databases have been developed, but they do not pose sufficient accuracy and spatial detail needed for local studies, especially when complex terrain is considered. In this study, the spatial distribution of total solar irradiance at the surface was estimated within ± 20 W/m² using SBDART radiative
transfer model simulations for the area of Central and East Crete. MODIS data were used to derive atmospheric precipitable water values, while in-situ observations for atmospheric horizontal visibility were used as inputs in SBDART. Land cover was parametrized using the standard vegetation type. A DEM derived from interpolation of 20 m contour lines were used to take into account the effect of topography on irradiance estimation. Slope and aspect values were calculated for each arbitrary oriented surface and finally the angle of incidence was calculated using the surface slope and aspect values, as well as the solar zenith and azimuth angles. A spatial model was developed to compute the total solar irradiance value at each arbitrary oriented surface. Inputs of this model were the DEM, the resulted slope and aspect distributions as well as the SBDART simulation outputs. Surface irradiance values were calculated during the course of the day and finally, the spatial distribution of the daily irradiation was estimated.

A model sensitivity analysis was performed to estimate the error in surface irradiance estimation caused by uncertainties in surface slope and aspect. Both the SBDART accuracy and DEM planimetric and elevation accuracy DEM (± 200 m and ± 20 m, respectively) were considered quite satisfactory for large area surface irradiance spatial distribution estimation. Although the developed spatial model is independent of the spatial resolution of the DEM, it underestimates the surface irradiance, because the reflected from the terrain component has not been taken into account. This component is more important in mountainous areas. For this reason, further research aiming at anisotropic reflectance correction is required to account for multi-scale topographic influences, solar and viewing geometry, as well as for shadowing effects of neighboring terrain features.

References