Solar Irradiation Forecast Model Using Time Series Analysis and Sky Images

Jorge Casa Nova [1], José Boaventura Cunha [1,2], and P. B. de Moura Oliveira[1,2]

1 Universidade de Trás-os-Montes e Alto Douro, 5000-911 Vila Real, Portugal, jfgcasanova@yahoo.pt

2 CETAV/Universidade de Trás-os-Montes e Alto Douro, 5000-911 Vila Real, Portugal, {jboavent; oliveira}@utad.pt

Abstract

Prediction of short-range solar irradiance at the earth surface is of great importance in order to improve the efficiency of solar energy conversion processes. Examples are the management of photovoltaic systems and the environmental control of greenhouses and solar driers, which are dependent of the incident solar radiation. For greenhouse climate control, this model can be used to estimate the heat energy that is expected to be free available from the Sun, and so to better compute the heating and ventilation needs from an optimal point of view, i.e. regarding the minimization of the energy consumption. This paper presents a model to forecast the solar irradiation at earth surface with the aim of predicting available solar renewable energy fluxes for time scales from a minute range up to one day.

Key words: Image Processing, Modeling, Neural Network, Solar Irradiation.

1 Introduction

Prediction of global solar radiation at earth surface is a complex problem. Deterministic models, based on solar geometric equations, could be employed to estimate the solar radiation behavior for cloudless conditions (Page, J. K., 1986). However, it must also be taken in account the processes that occur when the solar radiation interacts with the atmosphere due to water vapor, aerosols, etc.. Among the factors that attenuate solar radiation, size and distribution of the cloud cover are the most relevant. Due to the strong impact of the clouds on surface irradiance, it will be necessary to predict the temporal development of the cloud situation in order to compute the irradiance forecasts (Page, J. K., 1986; Hammer, A., *et. al*, 1999).

The cloud attenuation process is highly stochastic in nature, which makes its prediction a complex task. Several works were conduced to forecast solar irradiance using satellite data and time series analysis techniques (Hammer, A., *et. al*, 1999; Beyer, H.G., C. Costanzo, D. Heinemann, 1996; Saunders, R., Matricardi, M., Brunel B., 1999; Olseth, J. A., Skartveit, A. ,1997; Coelho, J. P. et. al, 2001, 2002). Generally speaking, the methods described in the literature are based on the estimation of cloud index images from satellite images at different wavelengths. To predict the future cloud index images, from a sequence of subsequent images, different approaches are applied: motion vector field approach, linear and non-linear models to describe the development of the cloud structure.

However, some limitations were reported when used satellite images (Saunders et al., 1999; Olseth, J. A. and Skartveit, A., 1997; Tobiska, W.K., 2002), such as: the long time interval between images acquired by orbiting satellites, low accuracy for high latitudes when geostationary satellites are used, the high costs and the low spatial resolution.

Here, soft computing methods are applied to ground-based sky images in order to infer about the motion of cloud structures and to predict solar radiation. Sky images are acquired using low-cost image cameras, being the image processing made with a neural network. This network detects the spatial distribution of clouds and by using sets of consecutive past images it is predicted the clouds future positions.

By combining this information with irradiation models based on times series prediction techniques (Coelho, J. P, et. al, 2001 and 2002), it is provided a low-cost irradiation forecast model with adequate accuracy for greenhouse climate control and other solar based management applications.

The proposed models are evaluated using solar radiation data and images acquired at the University Campus located in Vila Real, north of Portugal. Their performances will be analyzed for *RMSE*-Root Mean Squared Errors, Mean Bias Error and estimated versus measured irradiance graphs over different prediction horizons.

2 Matherials and Methods

The developed algorithms to foresee the solar irradiation at the ground surface use two techniques, as illustrated in figure 1.

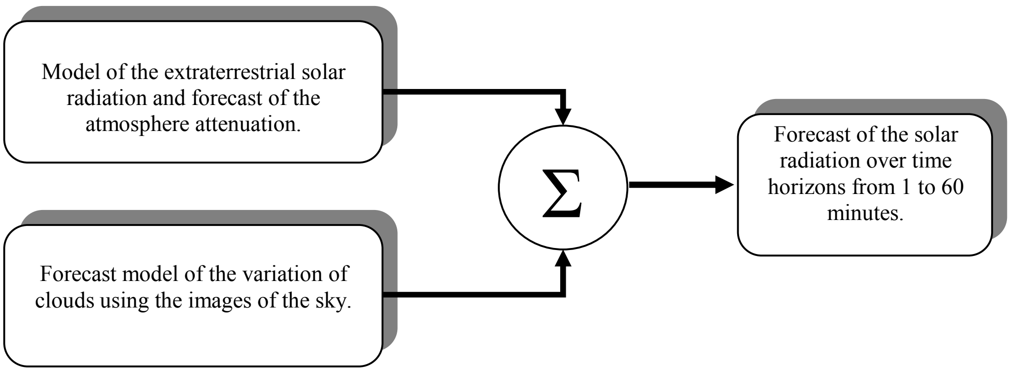


Fig.1 Solar irradiation forecast system

One method is based on the forecast of the atmosphere attenuation, computed with a model derived by processing the radiation measured in the ground and the one that arrives at the top of the atmosphere, which is calculated using the equations of solar geometry (Page, J. K., 1986). The other model perform the forecast of cloud evolution base on the processing of cloud/sky acquired images using a sample time of 1 minute.

The method based on the processing of the images of clouds, uses an algorithm that identifies the areas of the sky where clouds exist and an algorithm to survey about the direction of their displacements (William T. Freeman et. al, 1998). Figure 2 shows the block diagram of the implemented solar irradiation prediction system. Next is described each of the blocks, hardware and software algorithms, used to perform the predictions.

2.1 Measurement of the solar Radiation

The solar radiation is measured using a photodiode BF3 sensor, Delta-T devices, which provides diffuse and direct solar irradiation signal outputs. This sensor is connected to a data acquisition card, PCL 814, National Instruments, installed in a personal computer. The measurements are acquired using a sampling time of 6s and the average of these samples are stored with a time interval of 1min.

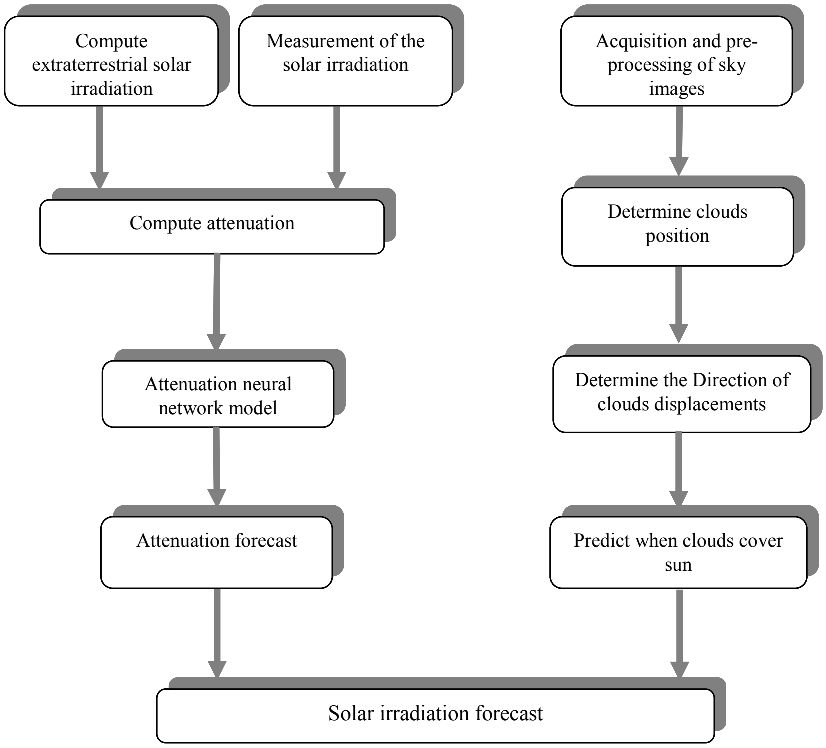


Fig.2 Diagram of blocks of the forecast system

2.2 Acquisition of the Images of sky

The cloud/sky images are acquired, every minute, using a spherical mirror (to reflect the image of the sky), a CCD device - web camera - pointed and focused to the mirror image, which is linked to a personal computer as showed in figure 3.

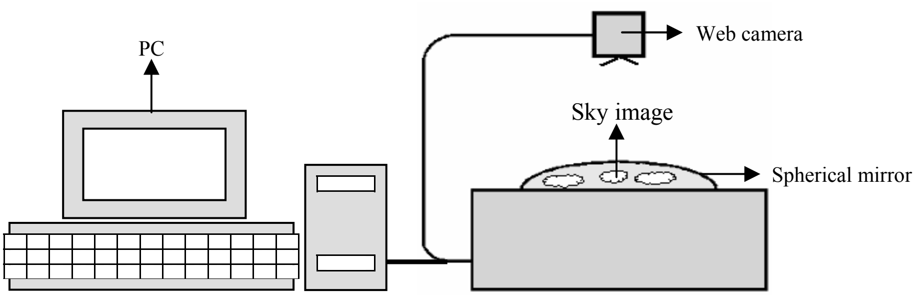
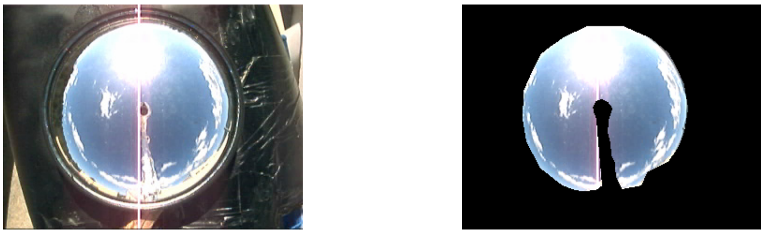


Fig.3 Image acquisition system

Based on these sky images it is first done a pre-processing to eliminate undesired information, figure 4. In this way all the image pixels outside the mirror bounds and from the web camera support image are converted to black.



a) b)

Fig.4 Image collected with the acquisition system (a) and pre-processed image (b).

This image acquisition system has the drawback of generating white spots in the images. This can be observed in the top region of the above images, which corresponds to the mirror regions where the Sun is reflected directly to the CCD device. Moreover, due to the saturation of the CCD image sensor a pink colour line is also generated.

2.3 Cloud cover

Generally, cloud sky cover is estimated by human observers who evaluate in a subjective form the hidden sky percentage. With the proposed system it is also computed the sky cloud cover. This is done using the cloud/sky in RGB format and processing each pixel and categorizing it as belonging or not to a cloud. To develop this technique it was first identified by a human operator the image regions corresponding to cloud cover and clear sky for various weather conditions.

These pixel samples are stored in a matrix, where each pixel value is in RGB format. Afterwards, the matrix is normalized, by dividing all its elements by 255. Other matrix is generated on the basis of the regions defined by an operator, with 0 (zeros) and 1 (ones), corresponding to pixels of clear sky regions and of clouds, respectively. These two matrices are used to train a neural network model that will be used to detect automatically cloud cover regions from other sky images. The implemented neural network has two layers. The first layer of inputs has three neurons and an output layer with one neuron. Figure 5 shows a real sequence of cloud/sky images acquired between the time instants 12:43 and 12:48 of March 13, 2004, and the respective processed images. Due to the limitations of the acquisition system, the white spot generated by the direct incidence of the Sun in the mirror is considered by the neural network as belonging to a cloud. The percentage of cloud cover is computed as the rate between the number of white pixels and the total number of pixels stored in the sky image.

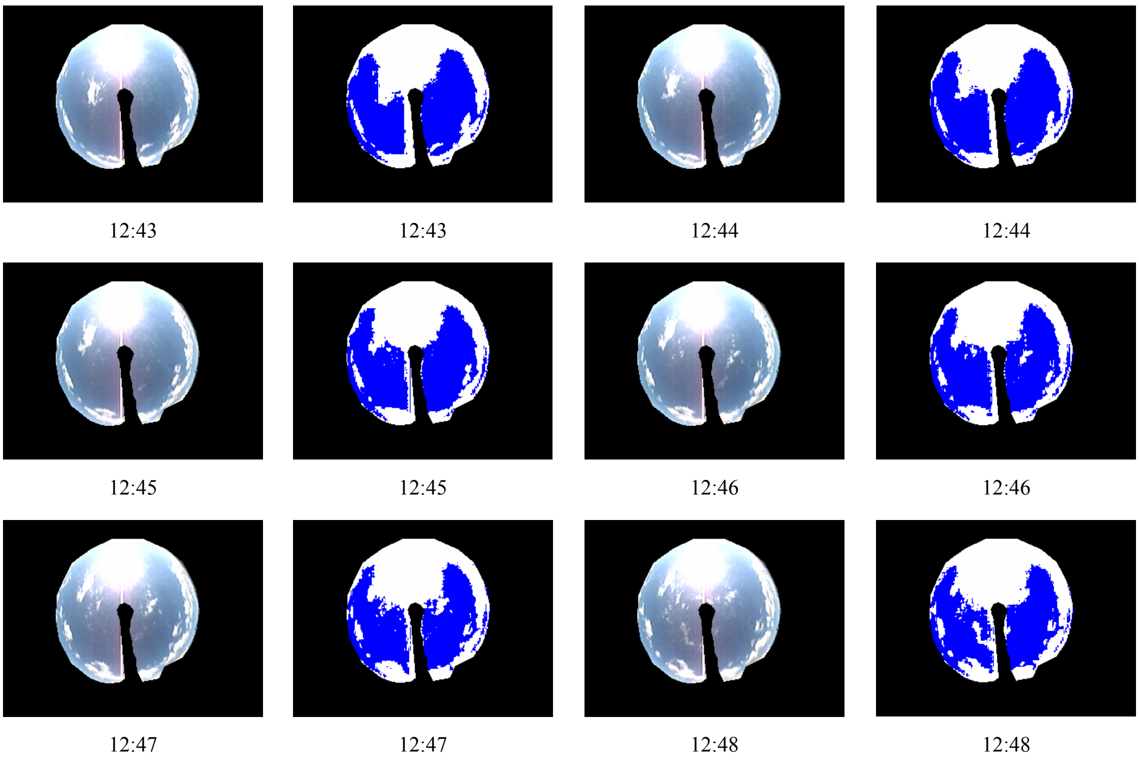


Fig.5 Clouds/sky images and pre-processed images by neural network at the specified times of March 13, 2004.

2.4 Movement of Clouds

After identifying the regions of the sky images with clouds, it is performed the estimation of the clouds movements, velocities and directions, between two consecutive acquired images. This knowledge is used to foresee the future behaviour of the clouds movements and so to predict solar irradiation attenuation by the atmosphere. The direction of cloud movements is computed using the fast algorithm of Freeman that can be described in four steps (William T. Freeman et. al, 1998):

1. Generate and store the difference between the current and the previous processed cloud/sky images, with zeros and ones elements.

2. For all pixels where the value of the difference is not null, it will be computed all the possible consistent movements tacking in account that:

   a. If the pixel difference is negative then its movement is tacking place in the direction of the pixel neighbour with higher intensity.

   b. If the pixel difference is positive then its movement is tacking place in direction of the pixel neighbour with lesser intensity.

3. Movements are considered in four possible directions: horizontal line, vertical line and two diagonal lines.

4. On the basis of the previous four estimates, which give four vectors, a sum resulting vector is computed and applied to each image pixel.

2.5 Equations of Solar Geometry

The radiation that arrives at the top of the atmosphere is not constant. It depends on factors, such as latitude and time (year, month, day and hour). The equations of solar geometry allow determining the solar radiation that arrives at the top atmosphere at a given time. The value of the solar radiation that reaches the terrestrial surface on a horizontal plan, $Rad_{ground,hour}$, is first determined on the basis of the laws of solar geometry without taken in account the attenuation of the atmosphere, by using equations 1 to 4.

$$I_{of} = I_o(1+0.03344)\times\cos(J'-2.80^{\circ})\ \mathrm{W.m}^2 \tag{1}$$

$$Rad_{ground,hor} = I_{oj}\times\cos(\upsilon)\ \mathrm{W.m}^2 \tag{2}$$

$$\upsilon = \cos^{-1}(\sin\gamma) \tag{3}$$

$$\gamma = \sin^{-1}(\sin\phi.\sin\delta + \cos w.\cos\phi.\cos\delta) \tag{4}$$

where: $J' = 360^{\circ}J/365.25$ represents the day of the year as an angle, J is the number of the year measured from day 31 of December, $I_o = 1367\ \mathrm{Wm}^{-2}$, is the solar constant, υ is the angle of incidence for horizontal surfaces, γ is the solar height, or either, the angle enters the center of the solar record and the horizontal plan, ø is the latitude of the place, δ is the solar declination and w denotes the hour as an angle.

2.6 Forecast of the Attenuation

Due to the atmosphere composition, presence of aerosols, water vapour, etc., the atmosphere attenuates the extraterrestrial solar radiation that reaches the top of the atmosphere, being the radiation level at the ground surface smaller. To foresee the incident solar radiation on a horizontal surface at ground, it is first computed the attenuation generated by the atmosphere layer over the previous past time horizon. This is done by using the ratio between the measured solar irradiation and the estimated solar irradiation, using eq.2, at the ground surface.

Afterwards, a neural network with two layers is trained to model the attenuation process. The inputs of the neural network are the data of the 20 atmosphere attenuations computed at the previous past sampling times and the outputs are the next 10 predicted values. The attenuation values vary in the range of 0 to

100%, corresponding to inputs ranging from 0 to 1 in the neural network. To perform the training of the neural network it was used a dataset for several days of the year with different weather conditions. However, it will be also implemented and tested a recursive model estimation based on the training using the data of the previous days, in order to conclude about the model performance for both cases.

2.7 Experimental results

To illustrate the performance of the implemented algorithms, it is showed in the next figures the predicted attenuations for different future time horizons, computed for a cloudy day, 22 of February of 2004, using the method of the forecast of the attenuation and the equations of solar geometry.

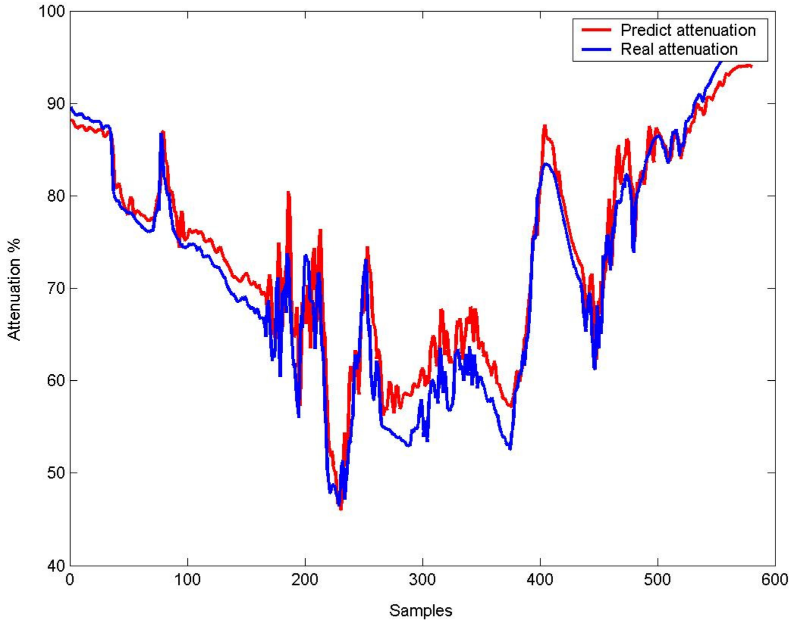


Fig.7 Forecast of the attenuation for a time horizon of 1 minute, February 22, 2004

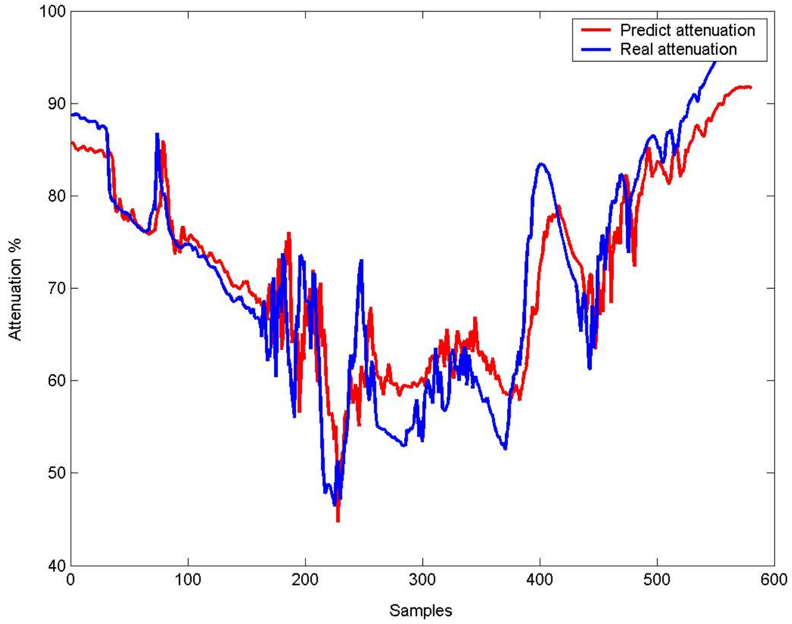


Fig.8 Forecast of the attenuation for a time horizon of 5 minutes, February 22, 2004

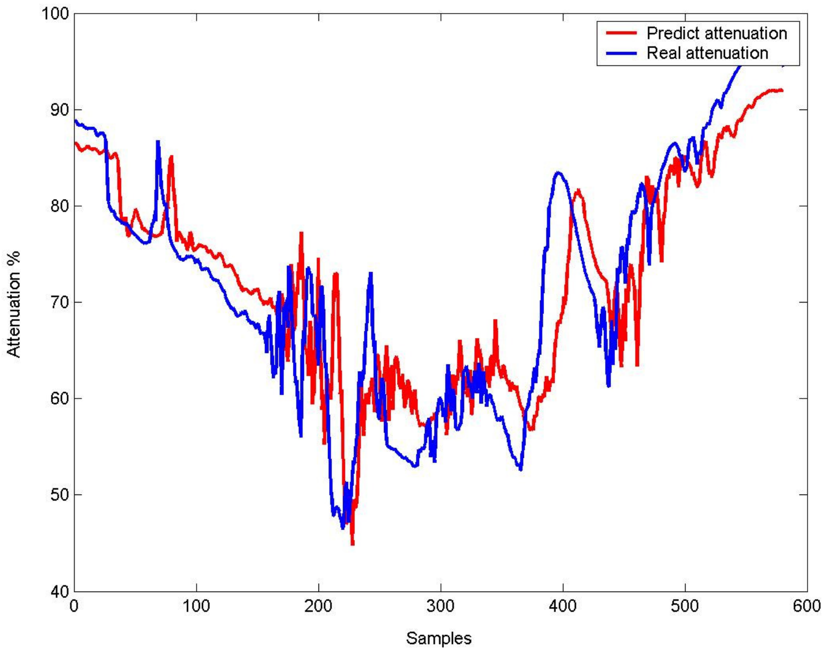


Fig.9 Forecast of the attenuation for a time horizon of 10 minutes, February 22, 2004

3 Conclusions

At the present this work is being conduced to combine the attenuation forecast models with the forecasts of clouds evolution in the sky. By combining these two techniques it is expected to achieve more accurate predictions of the atmosphere attenuation process and so, more reliable predictions of the solar irradiation that reaches the ground over a horizontal plane.

4 Acknowledgements

This work was developed with the support of the *Comissão de Coordenação e Desenvolvimento Regional do Algarve* (CCDR Algarve) through the project Number 04-02 TELEAGRISOL, INOVAlgarve Program.

5 References

Beyer, H.G., C. Costanzo, D. Heinemann, Modifications of the Heliosat procedure for irradiance estimates from satellite images, Solar Energy, 56, 207-212 (1996)

Hammer, A., Heinemann, D., Lorenz E. and Luckehe B., (1999). Short-Term Forecasting of Solar Radiation based on Image Analysis of Meteosat Data, Proc. EUMETSAT Meteorological Satellite Data Users Conference, pp:331-337

J. P. Coelho, J. Boaventura Cunha, P. B. de Moura Oliveira, (2001). "Solar Radiation Prediction Using Classical and Evolutionary Techniques". Computacion aplicada a la Industria de Processos, pp.278-281.

J. P. Coelho, J. Boaventura Cunha, P.B. de Moura Oliveira, (2002). "Solar Radiation Prediction Methods Applied to Improve Greenhouse Climate Control", Proceedings of the World Congress of Computers in Agriculture and Natural Resources, ASAE, 13-15 Março, 2002, Iguaçu Falls, Brazil, pp:154-160.

Olseth, J. A., Skartveit, A. (1997). High latitude global and diffuse radiation estimated from heliosat-versions 7, 8, 9 and 10. Satellight Programme JOR3-CT950041, pp:1-34

Page, J. K. (1986). Prediction of Solar Radiation on Inclined Surfaces. Solar Energy R&D in the European Community, Series F: Solar radiation Data, 459pp.

Saunders, R., Matricardi, M., Brunel B., (1999). An improved fast radiative transfer model for assimilation of satellite radiance observations, RTTOV5. ECMWF Research Dep. Tech Memo, 282.

Tobiska, W.K., Forecast E10.7 for Improved Low Earth Orbit Satellite Operations, J. Spacecraft. Rock., Journal of Spavecraft and Rockets vol. 40, N.º 3, May-June 2003.

William T. Freeman , David B. Anderson , Paul A. Beardsley , Chris N. Dodge , Michal Roth , Craig D. Weissman , William S. Yerazunis , Hiroshi Kage , Kazuo Kyuma , Yasunari Miyake , Ken-ichi Tanaka, Computer Vision for Interactive Computer Graphics, IEEE Computer Graphics and Applications, v.18 n.3, p.42-53, May 1998