# VALIDATION OF DNI ESTIMATIONS IN BRAZIL USING BRAZIL-SR MODEL

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## ABSTRACT

This work describes the methodology to estimate the direct normal component (DNI) of surface solar irradiation using the radiative transfer model BRASIL-SR. The model validation was performed by using two reference sites in Brazil: at Caicó (06°28'01"S – 037°05'05"W, 175.8 m), and Florianópolis (27°34'18"S – 048°31'42"W, 10 m). Satellite data were collected by INPE-CPTEC for GOES-8. The validation results shown correlation factors among measured and estimated values around 0.9 and relative root mean square error (rRMSE) around 0.20.

## 1. INTRODUCTION

The international concerns on the increasing demands for energy in developing countries and the necessity to conciliate development and environment protection, led to the creation of the Solar and Wind Energy Resource Assessment (SWERA) project. SWERA – Solar and Wind Energy Resource Assessment is a project financed by United Nations Environment Programme (UNEP), with co-financing by GEF in the area of renewable energies, more specifically, solar and wind energy. The project is assembling high quality information on solar and wind energy resources and ancillary data into consistent GIS (Geographic Information System) analysis tools. The project is aimed at the public and private sectors involved in the development of the energy market and it shall enable policy makers to assess the technical, economic, and environmental potential for large-scale investments in renewable and sustainable technologies.

The Brazilian Institute for Space Research (INPE) is coordinating the SWERA activities in Brazil which is now in its final stage. The Solar Energy Laboratory of University of Santa Catarina (LABSOLAR), the Brazilian Center of Wind Energy (CBEE) and Brazilian Centre for Research in Electricity (CEPEL) are partners involved with SWERA activities in Brazil and they are working together to develop several products and tools.

The INPE and LABSOLAR/UFSC are working together to produce solar energy resources maps for Brazil and for South America using the radiative transfer model BRASIL-SR (Martins, 2001; Colle and Pereira, 1998). The solar irradiation maps are being calculated from satellite images of geo-stationary satellites (GOES-8 and GOES-12). In addition to global solar irradiation maps, maps of direct and diffused components were also generated as well as irradiation values for tilted surfaces.

This work describes how direct normal solar irradiation (DNI) modeling was implemented in model BRASIL-SR. In this work we also report the validation step where DNI estimates were compared with ground truth data measured in Caicó (Northeast region of Brazil) and in Florianópolis (a BSRN site located in South of Brazil).

## 2. BASIC DESCRIPTION OF SOLAR RADIATION SITES

The DNI estimates were compared to ground truth data acquired in two reference sites:

- Caicó (06°28'01"S – 037°05'05"W / 176m)
- Florianópolis (27°34'18"S – 048°31'42"W / 10m)

The two sites were chosen because they provide high quality radiation data and represent different climatic/environmental regions and different ground cover. The measure data is qualified according to BSRN criteria and are available at each minute interval.

The ground site at Caicó is in this small city located in the semi-arid region of the Brazilian northeast (annual precipitation under 700 mm), over a relatively flatland area with a sparse brushwood type vegetation known as "caatinga" (average albedo 13.3%). It is characterized by a large insolation of about 120 days/year, and high annual mean temperature (22°C to 33°C), which allows it to be a good place for model adjustments for bias errors under cloudless skies. The site became operational in November 2002 collecting data for global and direct solar radiation. Caicó site is operated in partnership with University of Rio Grande do Norte (UFRN).

The site at Florianópolis is located in a medium size city (under 400,000 inhabitants) situated on an island in the Brazilian South region. Rains is fairly well distributed along the year. The summer is hot and the winter is mild with some few cold days. This radiometric station was installed in 1991 as part of the Baseline Solar Radiation Network (BSRN) and provides data of global, direct, and diffuse radiation. The BSRN site is operated by the Solar Energy Laboratory of the University of Santa Catarina (LABSOLAR/UFSC).

## 3. SATELLITE DATA

Effective cloud cover index (CCI), an input data for model BRASIL-SR, was obtained from GOES-8 images collected by INPE-CPTEC, which also provides for its quality assessment, sectoring, and storing. The GOES-8 satellite was launched in April 1994 and was located at longitude 75°W, latitude 0° and altitude of 36,000 km. The main purposes of GOES-8 are weather monitoring and forecasting and it has a scanner camera that supplies images from a small sector to the full extent of the Earth's disk in five different channels. Visible images (channel 1, 0.52–0.72μm) and infrared images (channel 4, 10.2–11.2μm) from the measurement sites are as well as ground data are available in the SWERA Latin America web page: http://www.cptec.inpe.br/swera.

## 4. RADIATIVE TRANSFER MODEL BRASIL-SR

The INPE (Brazilian Institute for Space Research) and LABSOLAR/UFSC (Solar Energy Laboratory) are working together to develop a radiative transfer model BRASIL-SR in order to map the surface solar irradiation in Brazil and South America. The model BRASIL-SR is a physical model that combines satellite and climatological data with the "two-stream" approach to solve the radiative transfer equation for atmosphere. (Martins, 2001).

The model assumes that the global solar irradiation at ground and at top of the atmosphere is linearly correlated. (Martins, 2001; Pereira et al., 2000; Stuhlmann et al., 1990). Global horizontal solar irradiance incident on the surface is provided by equation (1).

$$GHI = G_0\{(\tau_{clear} - \tau_{cloud})(1 - C_{eff}) + \tau_{cloud}\} \quad (1)$$

where GHI is the global horizontal irradiance at surface, $G_0$ is the solar irradiation at the top of the atmosphere. The "two-stream" approach is used to obtain two independent components that are used as boundary condition for the model: the clear sky transmittance, $\boldsymbol{\tau_{clear}}$, and the overcast sky transmittance, $\boldsymbol{\tau_{cloud}}$. The first component is a function of the surface albedo, the solar zenith angle and the optical thickness of the atmospheric constituents. The component $\boldsymbol{\tau_{cloud}}$ is a function of the solar zenith angle, the cloud optical thickness, and height of cloud top. Both components may be estimated from climactic data (temperature, relative humidity, surface albedo and cloud properties) and parameterizations of well-known physical processes that occur in the atmosphere.

The dimensionless effective cloud cover index, $C_{eff}$, describes both effects: the cloud coverage and the spatial variation of cloud optical depth. It is determined from satellite images by using the following equation:

$$C_{eff} = \frac{\rho - \rho_{clear}}{\rho_{cloud} - \rho_{clear}} \quad (2)$$

where $\rho$ is the visible reflectance measured by satellite, $\rho_{cloud}$ and $\rho_{clear}$ stand for overcast and cloudless reflectance measured by the satellite, respectively. The $\rho_{cloud}$ and $\rho_{clear}$ are obtained monthly from statistical analysis of visible (channel 1 - 0.52-0.75μm) and the thermal infrared (channel 4 - 10.2-11.2μm) images of GOES-8 satellite. By using this scheme, the degradation of the satellite sensors with time has no influence on the model estimations.

### 4.1 DNI estimates

The methodology developed to estimate direct normal irradiance (DNI) assumes that cloud cover contribution to the direct transmittance can be added to the clear sky direct transmittance ($\tau_{atm-dir}$) due to all other atmospheric constituents (aerosols and gases). Therefore, the direct solar estimate is calculated from the following equation:

$$DNI = G_0 . \tau_{atm-dir} . \tau_{cloud-dir} \qquad (3)$$

where $\tau_{cloud-dir}$ represents the cloud transmittance for direct component of solar irradiation. The $\tau_{clear-dir}$ is obtained using the "Two-Stream" technique for clear sky condition and $\tau_{cloud-dir}$ is estimated from cloud cover index, $C_{eff}$, using the approach presented by Stuhlmann et al. (1990):

$$\tau_{cloud-dir} = \frac{(1-\tau_c)}{(\beta - \tau_c)} \qquad (4)$$

$$\text{where} \begin{cases} \tau_c = (C_{eff} + 0{,}05) & \text{if } C_{eff} < 0.95 \\ \tau_c = 1.0 & \text{if } C_{eff} \geq 0.95 \end{cases}$$

## 4. MODEL RESULTS AND VALIDATION

This work presents the validation results for summer season – from November/2002 until February/2003. The ground sites were chosen due to high quality radiation data and geographical location. The geographical location is an important factor to be considered in order to evaluate the model's performance for different climate and environments. Table 1 shows the prime information for the two ground sites. These ground sites represent different climatic environments in the tropics: the coastal semi-arid region and a sub-tropical industrialized area. The climatological and geographical data presented in Table 1 was used to feed model BRASIL-SR.

Table 2 presents the deviations values for daily DNI estimates. The following criteria were adopted to calculate de rMBE and rRMSE for daily estimates: a) discard hourly estimates with solar zenith angle larger than 80°; b) discard days with less than 3 estimates fulfilling the first criteria.

The Figure 2 shows the "estimated values" versus "measured values" for daily DNI in Florianópolis and Caicó. It can be noted a good correlation between estimated and measured values. The correlation factors calculated using all data were 0.92 and 0.88 for Florianópolis and Caicó, respectively. The lowest correlation factor and larger rRMSE deviation value were obtained for February in Caicó (0.70). The calculation procedure to obtain cloud cover index from satellite images is the most feasible reason for this lower correlation. Caicó has a great number of clear sky days per year and cloud types are mainly fair weather Cumulus, which are hard to detect in satellite images with the spatial resolution adopted in this task. Besides that, shadows of the broken clouds can mask clear sky radiance, $\rho_{clear}$, used to get effective cloud cover index from satellite images. However, the reason of these low correlation factor obtained in February for Caicó must be better investigated in the future.

The validation procedure is being prepared for one year period to allow a more comprehensive analysis in order to find out the sources of errors and weak points of the parameterization adopted. Simultaneously, a cross-comparison task is being prepared in order to evaluate the BRASIL-SR performance with other three radiative models: NREL model, SUNY-ALBANY model and HELIOSAT model.

TABLE 1: GEOGRAPHICAL AND CLIMATOLOGICAL INFORMATION FOR THE VALIDATION SITES.

| Site | Latitude Longitude | Altitude (m) | Month | Temp. (°C) | RH (%) | Surface Albedo | Other information |
|---|---|---|---|---|---|---|---|
| Caicó | 6°28'01''S 37°05'05''W | 175,85 | Nov | 27,98 | 60,5 | 0,134 | Installed to provided ground data to the SWERA Project |
| | | | Dec | 28,25 | 64,6 | 0,136 | |
| | | | Jan | 28,06 | 74,6 | 0,138 | |
| | | | Feb | 28,22 | 82,9 | 0,145 | |
| Florianópolis | 27°34'18''S 48°31'42''W | 12 | Nov | 21,53 | 86,2 | 0,164 | BSRN site |
| | | | Dec | 23,52 | 87,2 | 0,168 | |
| | | | Jan | 22,99 | 88,6 | 0,167 | |
| | | | Feb | 24,16 | 89,6 | 0,173 | |

TABLE 2: DEVIATIONS OF DNI ESTIMATES PROVIDED BY MODEL BRASIL-SR FOR THE TWO VALIDATION SITES.

| Month | Ground Sites | | | |
|---|---|---|---|---|
| | Florianópolis | | Caicó | |
| | rMBE | rRMSE | rMBE | rRMSE |
| November 2002 | 0,12 | 0,21 | - | - |
| December2002 | 0,15 | 0,25 | -0,07 | 0,18 |
| January 2003 | 0,19 | 0,30 | -0,02 | 0,08 |
| February 2003 | 0,11 | 0,17 | -0,001 | 0,35 |

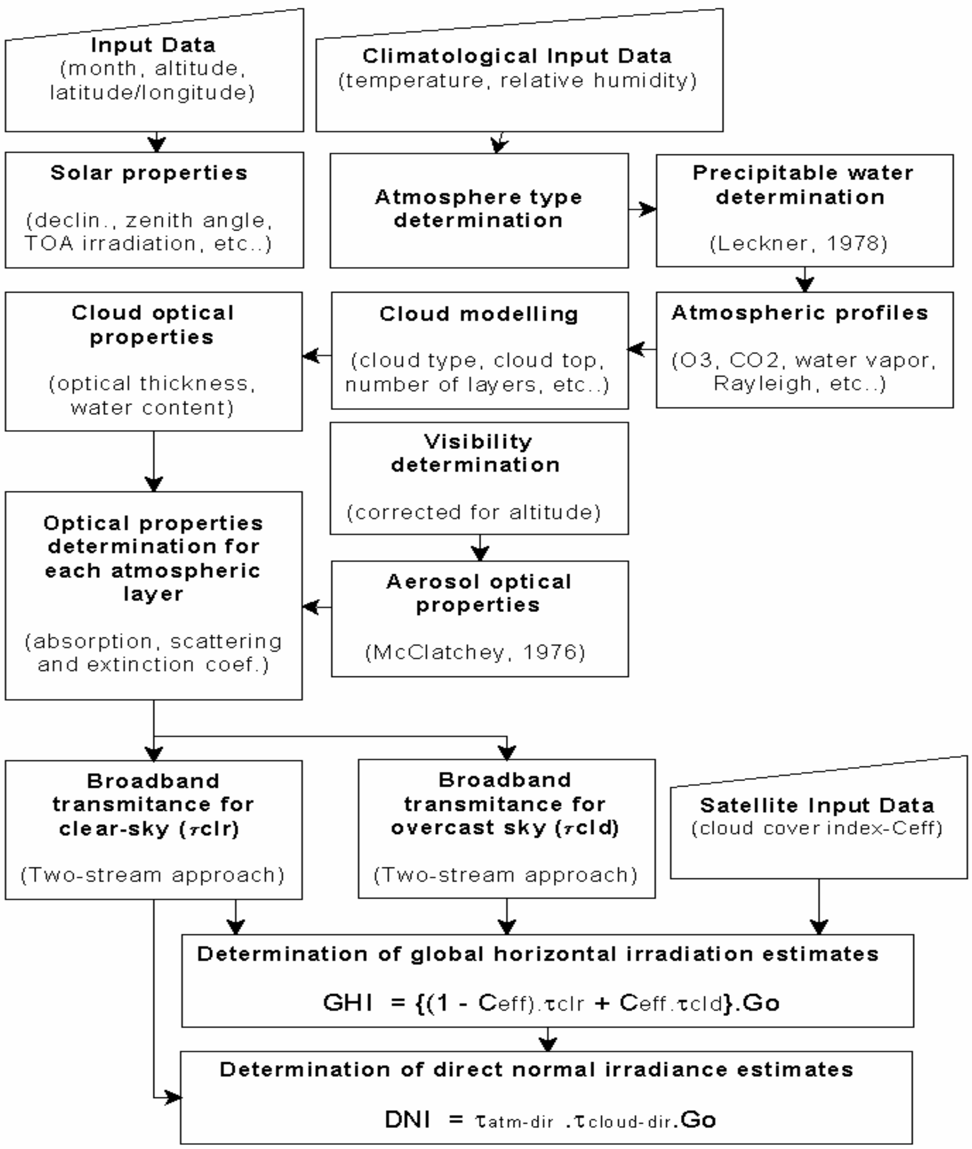
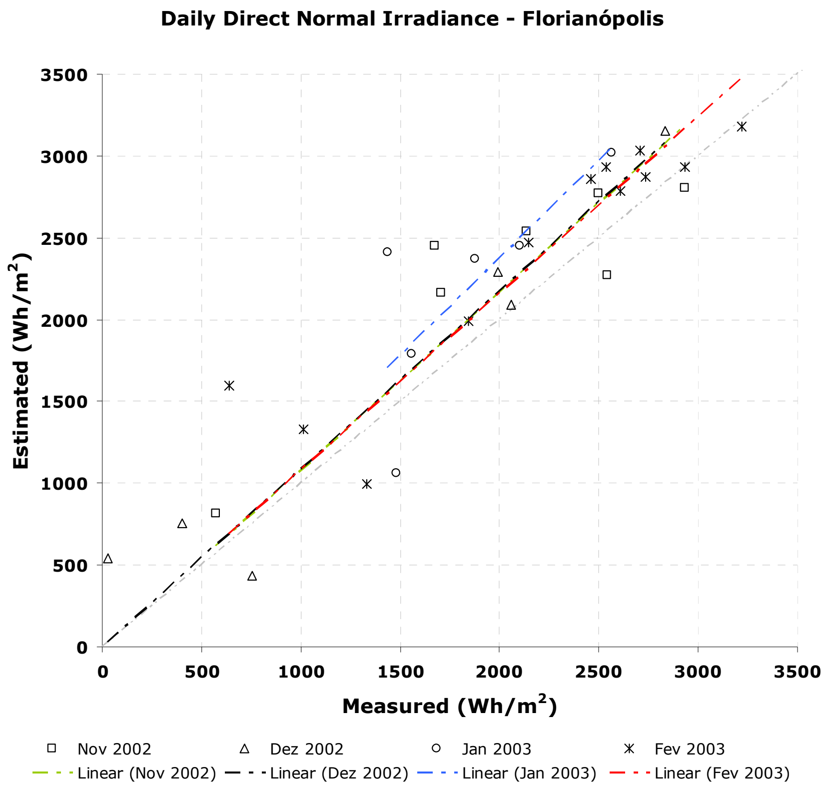
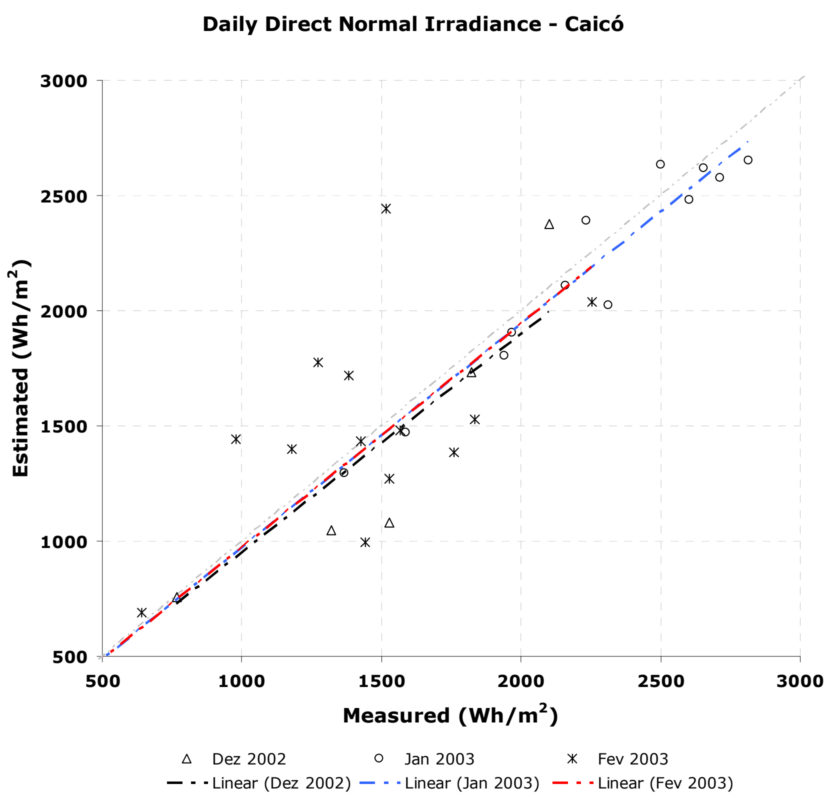



Fig. 1: Schematic diagram of radiative transfer model BRASIL-SR.




(A)




(B)

Fig.2. Estimated versus Measured values for daily DNI in: (A) Florianópolis and (B) Caicó.

## 4. CONCLUSIONS

This works presented a DNI parameterization implemented in model BRASIL-SR and its first validation results. The comparison among estimated DNI values and ground truth data was done for two sites located in very different climate and environment in Brazil: Caicó in the Northeast semi-arid region and Florianópolis in the South industrialized region. The estimates provided by the model have presented a good agreement with measured values for both sites and correlation factors around 0.9 were obtained. The larger rRMSE was obtained in February/2003 for Caicó. Probably, this large deviation is related to errors in determination of effective cloud cover index from satellite image as consequence of climatic features observed in Caicó: long periods of clear sky condition, and presence of broken clouds (fair weather cumulus) hard to detect in spatial resolution of satellite images available for this work. A more detailed analysis of weak points of the DNI parameterization and sources of errors will be possible after finish the validation task for one-year period and the comparison with other branded radiative transfer models.

## 5. ACKNOWLEDGMENTS

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