Recent Advances in Solar Resource Assessment in Uruguay

Rodrigo Alonso Suárez, Pablo Toscano, Ricardo Siri, Pablo Musé, and Gonzalo Abal

***Abstract*—In the last few years, considerable effort has been invested by the Uruguayan government to increase the amount of renewable energies in its energy matrix. Research and development aiming at introducing solar energy at large scale has been initiated only recently. A ground measurement network for solar irradiation deployed by Facultad de Ingeniería, Universidad de la República, started to operate in 2009, and new measurement sites have been continuously added since then. A first characterization of the solar resource was made in 2009, based only on ground data. More recently, in 2011, a pre-existing statistical satellite-based model proposed by Justus, Paris and Tarpley (JPT) has been implemented and adjusted to the Uruguayan territory. An improved version of the model has then been proposed and implemented. These models are built by integrating data from ground measurement networks with satellite data captured by GOES-East satellites.**

In this paper we describe the current state of the solar measurement network administrated by Facultad de Ingeniería, as well as other networks of ground stations deployed over the country. We also discuss two satellite-based irradiation models that have been and are being used for solar resource assessment in Uruguay. Performance evaluation and comparison of both models is presented. In particular, we show that a simple modification of the JPT model, that explicitly introduces brightness dependence in the model parameters, significantly improves theestimation accuracy, and allows to achieve uncertainties as low as 13.7% and 6.8% at hourly and daily time basis, respectively.

***Index Terms*—Solar energy, solar measurements, instrumentation, remote sensing, satellite-based models.**

I. Introduction

URUGUAY is a country with no conventional energy resources such as coal, oil, natural gas or fissible materials. Renewable energies are an attractive alternative to reduce the dependence on international oil and gas prices and availability. The national government has set ambitious goals concerning the gradual insertion of renewable energies in the national primary energy mix. It is expected that, by the year 2015, more than 50% of the country's primary energy supply comes from renewable sources (basically wind, biomass, solar thermal and hydroelectric power). A reliable resource assessment is a basic first step for a successful introduction of renewable energies and, in particular, solar energy applications. A long-term characterization of the available solar energy at ground level requires decades of careful measurements. In Uruguay, a systematic measurement program for ground solar irradiation at several points has been initiated only recently. A first characterization of the solar resource was made in 2009 using historical ground data. This resulted in the Solar Map (MSU, version 1.0) [1], built using the Angström-Prescott methodology [2], [3] to correlate sunshine duration with ground solar irradiation on a monthly average basis. Since then, a systematic research effort is under way with the aim at improving our knowledge on the solar resource.

In a small country such as Uruguay, the spatial resolution with which the solar resource is known is an important concern. The spatial and temporal resolution which can be obtained from methodologies based on correlating irradiation measurements at a few sparse points with other sparse indirect measurements (such as sunshine duration, in Angström-Prescott methodology), is very limited. The MSU, using suitable interpolation schemes, provided monthly averages of daily irradiation with a spatial resolution of the order of 100 km. However, interpolation techniques used in this context, tend to reduce accuracy even over relatively small distances, due to the inhomogeneous spatial distribution of clouds and its high temporal variability. It has been established that even simple satellite-based irradiation models can provide better accuracy for hourly irradiance than interpolation over distances as short as 30 km [4]. This means that, from an end-user perspective, it is preferable to rely on satellite-based hourly estimates than using ground data from stations located more than 30 km away of the target point.

In this work we describe the current state of the solar measurement network administrated by Facultad de Ingeniería (FING) at Universidad de la República, and briefly mention other existing complementary measurement networks in the country, such as the one run by UTE, the local public electrical utility company. We discuss the satellite-based irradiation models that have been implemented in Uruguay and include an updated performance analysis for them. This article is organized as follows. In Section II we describe the measurement stations and satellite images that were used for solar resource modeling. The satellite-based solar radiation models implemented for the Uruguayan territory are described in Section III. Performance evaluation and comparison are presented in Section IV. Finally, in Section V we discuss future work and summarize our conclusions.

II. New data for solar irradiance estimation

After the first Solar Map was concluded [1], it became clear that solar irradiance data series with acceptable quality were very scarce in the country. Details on the few available

R. Alonso Suárez, R. Siri and G. Abal are with the Department of Physics, Facultad de Ingeniería, Universidad de la República, Uruguay.

P. Toscano and P. Musé are with the Department of Electrical Engineering, Facultad de Ingeniería, Universidad de la República, Uruguay.

historical radiation series can be found in the MSU's Technical Report at http://www.fing.edu.uy/if/solar. A measurement program was initiated by FING (with partial support from government agencies) in 2009 and at present there are several automatic and semi-automatic stations distributed over the national territory that measure global solar irradiance on a horizontal plane at 1 minute intervals. There is also a base station, located at FING at Montevideo, in which all the radiometers are calibrated against a Kipp & Zonen CMP22 secondary standard and more sophisticated measurements, such as ultraviolet spectral band and diffuse irradiance, are maintained.

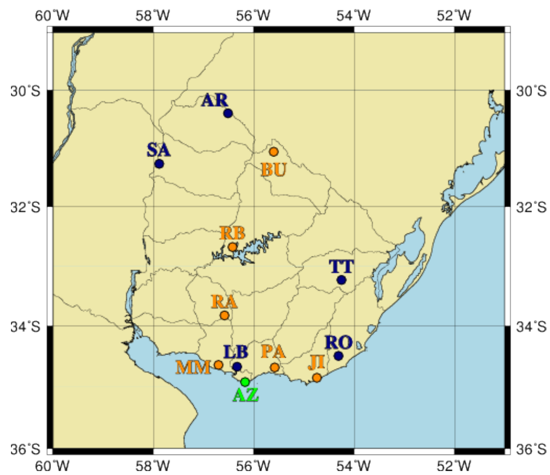


Figure 1. Spatial distribution of measurements' stations. Blue: FING/UdelaR's global solar measurement network. Orange: Some sites of UTE's global solar measurement network. Green: FING/UdelaR station.

A. Ground-based measurement network

At the present time, FING's ground-based network for global solar irradiance measurement consists of six measurement points, distributed as shown in Fig. 1. These measurements were deployed between January 2010 and December 2011. Each of them is equipped with First Class or Secondary Standard Kipp & Zonen pyranometers models CMP6 or CMP11, which measure global irradiance with less than 5% (2% for CMP11) uncertainity for daily totals under ideal conditions (i.e. clean dome). These sensors produce an output voltage of a few mV at 1000 W/m^2 solar irradiance, so the signal requires reliable amplification at the data-logger. The stations are equipped with different types of data-loggers. Three of them (AR, SA and TT) use data-loggers developed at the Department of Electrical Engineering, FING, with PV solar panels as their only energy source and remote communication capabilities across the GPRS network. They are designed to operate autonomously and the control and data retrieval can be done remotely, for further details see [10]. Stations LB and RO are equipped with ultra-low consumption data-loggers from Kipp & Zonen (LOGBOX), which store data on a SD memory card and have no remote communication capability. Their power requirements for several months are met by a small conventional battery (6V, 10Ah) which is replaced periodically. The reference measurement station at FING (AZ) is equipped with a DataQ data-logger connected to the electrical grid with UPS backup, to prevent power failure. These measurement points are listed in Table I and located as dark blue dots in the map shown in Fig. 1.

Table I
STATIONS FROM FING'S MEASUREMENT NETWORK

Location	Latitude	Longitude	Code	Installation date
Canelones	-34.67	-56.33	LB	12/2009
Treinta y Tres	-33.23	-54.25	TT	05/2010
Salto	-31.27	-57.88	SA	06/2010
Rocha	-34.49	-54.31	RO	06/2011
Artigas	-30.40	-56.51	AR	12/2011
Montevideo	-34.92	-56.17	AZ	04/2011

The reference station (AZ), located on FING's rooftop, is shown in Fig. 1 with a green dot. The calibration facility in this station can accommodate up to eight pyranometers. According to the manufacturer, the pyranometers must be re-calibrated at most every 24 months to ensure data integrity to within specifications. For a long-term climatological characterization of the solar resource, at least ten years of reliable, controlled-quality measurements are required. Thus, a calibration program is continuously under way for our sensors. We also calibrate radiometers for other institutions with which we collaborate, such as UTE or DNM (the National Meteorological Service). In this reference station, other measurements are routinely maintained. The diffuse component of solar irradiance on a horizontal plane is measured, with a Delta T SPN1 sensor with no moving parts. We have checked this measurement against diffuse measurements from a conventional shadow band and they agree to less than 4%. This composite sensor uses an array of detectors and a unique shadowing pattern, so that at any time, at least one sensor is in sunlight and at least one is in shadow. Simple electronic circuitry then processes these signals to output global and diffuse irradiance in separate channels. This instrument is equipped with an internal heater to ensure thermal stability in winter. Global irradiance on a tilted plane (with a slope of 35°) facing North is also recorded, using a Kipp&Zonen CMP6 pyranometer. Recently, an ultraviolet radiometer UV-AE, also from Kipp & Zonen, was installed. This instrument measures solar irradiance in the UV-A (315 to 400 nm) and global solar UV index at one sample per minute. All of these measurements are available for research purposes.

A complementary measurement network is maintained by UTE, the public electrical utility. They measure since 2010, at 10 minute intervals, wind speed and direction at several heights, ambient air temperature and global solar irradiance on horizontal plane, among other variables. These measurements are taken in more than ten locations over the country. Some of these locations (with more than 1 year data) are indicated in Fig. 1 by orange dots. Solar irradiance is measured with Licor SZ200 sensors, equipped with silicon cells. Collaboration between both institutions assures that the sensors are regularly calibrated and quality checks are routinely run on the solar radiation data.

In sum, solar radiation is being routinely measured at almost 20 sites in Uruguay. This represents an important measurement density, given the relatively small size of the country and its quasi-uniform topography (gentle hills and slopes). If these efforts are sustained over time for at least one decade, an adequate solar resource characterization will result.

B. GOES-East satellite data bank

Satellite-based solar radiation estimates can be considered as indirect measurements and can provide a spatial resolution of about 2 km on an hourly, daily and monthly basis. A model (physical [5] or statistical [6]) is required to translate the brightness readings of the orbiting radiometer into solar irradiance at ground level. We have implemented two statistical models for the Uruguayan territory. The first model, implemented in 2011 [7], is based on the Justus, Paris and Tarpley (JPT) model [8]. Recently, this model was substantially improved in 2012 by introducing a brightness dependence on the coefficients [9]. This models are described in the next section. In order to adjust and evaluate the performance of a statistical satellite-based irradiation model, both reliable ground measurements and simultaneous satellite images are required. To use the model, i.e. to obtain estimations of ground level solar irradiance for a given position and period of time, only satellite observations are required.

A satellite data bank of GOES-East satellite images was constructed and is currently being used to operate these models. At present, Uruguay still does not have a facility for downloading images directly from any satellite. Thus, we have built up a GOES-East local database by downloading the images from NOAA's CLASS website (http://www.class.noaa.gov). To the best of our knowledge, this is the only satellite data bank available in the country, so we shall briefly describe it.

GOES-East satellite is the series of GOES satellites located at 75 °W longitude in geostationary orbit. At that location, several different satellites (GOES 8, GOES 12 and currently GOES 13) have operated for different time periods. Our database contains images from these different satellites in five spectral bands (one visible, four infrared) for the period 01/01/2000 to date (more than 12 years) with a frequency of approximately two images per hour. Our images are restricted to daylight periods and to a geographical window that includes the Uruguayan territory and is approximately the same as that shown in Fig. 1. The composition of this data bank, which includes of the order of 10^5 data files, is summarized in Table II. Each image is an array of geo-referenced dimensionless brightness counts B_t. Since the GOES radiometer is prone to small orientation movements, latitude and longitude values for each pixel are recorded for every image separately. The spatial resolution of the visible channel in the target region is approximately 2 km between pixels.

Table II
SATELLITE DATABASE COMPOSITION

Satellite	Start	End	Images
GOES 8	01/01/2000	31/03/2003	24750
GOES 12	01/04/2003	14/04/2010	51900
GOES 13	14/04/2010	30/04/2012	15300
Total	01/01/2000	30/04/2012	91950

The results and analysis reported in this work are based exclusively on GOES 13 images for the time period from 05/2010 to 04/2012, for which simultaneous measurements and satellite images are available. No correction factor was applied and we used directly the brightness counts, without conversion to radiance.

III. SATELLITE-BASED MODELS IMPLEMENTED IN URUGUAY

The training phase of the statistical model under consideration consists in adjusting a set of parameters for a target region using ground measurements data. The data used for model training was obtained from the three FING/UdelaR stations, and includes more than one year of irradiance measurements. The universality of these parameters in space-time is not granted and shall not be applied outside a tested region for reliable estimates. In that sense, coefficients are regularly updated, and the updated model is evaluated by comparing the estimates with independent ground measurements distributed over the territory. These testing measurements, which were of course not considered for the training phase, are provided by the stations operated by UTE (shown in orange dots in Fig. 1).

Two statistical models for solar irradiation were locally adjusted for the Uruguayan territory. The first model, implemented in 2011 [7], was the one proposed by Justus, Paris and Tarpley [8]. In the sequel we refer to this model as Tarpley's model or simply JPT model. Then, it was replaced in 2012 for a modified version, which significantly improves the estimates by explicitly introducing brightness dependency in the regression parameters [9]. Both models and their implementation are discussed in this section.

A. Tarpley's original model

A statistical solar irradiation model was proposed by Tarpley in 1979, as part of the Great Plains experiment [11]. This model had a tendency to overestimate irradiation for cloudy hours, while underestimating it for clear sky conditions. An improved version, to which we refer to as the JTP model, was later proposed by Justus, Paris and Tarpley [8] to reduce the significant biases observed in the previous model.

JPT model proposes the following parametrization for the hourly solar irradiation at ground level in horizontal plane, denoted by I:

$$\begin{aligned} I \;=\; & I_{sc}\,(r_0/r)^2\cos\theta_z\,(a+b\cos\theta_z+\ldots \\ & c\cos^2\theta_z)+d\left(B_m^2-B_0^2\right) \end{aligned} \qquad (1)$$

When I is measured in kJ/m^2, the value of the hourly integral of the Solar Constant I_{sc} is 4921kJ/m^2. The factor $(r_0/r)^2$ accounts for the variation of the Sun-Earth distance (assumed constant within a day) and depends on the Julian day number [12]. The solar zenith angle, θ_z, is the angle formed by the Sun-observer direction with the local vertical. It depends on location, day number and local time [13].

The terms with coefficients a, b and c in Eq. (1) represent the clear-sky part of the model, while the last term introduces the cloudiness information obtained directly from the satellite counts in the visible channel. B_m is the hourly mean brightness in a small neighborhood of a given location and B_0 is the clear-sky brightness for the same time and location. The presence of clouds enhances reflection so $B_m > B_0$ and d must be negative.

The computation of B_m and B_0 hourly values must be carried out for every site and every hourly interval. For instance, the B_m hourly value for the hour 10, is calculated using all the images in the time interval 10:30 to 11:29. B_0 hourly value is obtained from a parametrization that is trained for each site using the B_m hourly values set for the same site. Once the parametrization is adjusted, it can be used to obtain values of the clear-sky brightness for every hour.

The effect of the space-time variability of clouds within the hour is reduced by averaging the brightness counts over a spatial neighborhood for every location of interest. We are currently using neighborhoods of $10' \times 10'$ latitude-longitude cells, which correspond to a ground area of about 16 km × 19 km. For each cell, centered at the latitude and longitude (ϕ, ψ) of the given site, the mean brightness B_m is calculated as the simple average of all pixels in the cell using all the available images within the hour.

Clear-sky brightness hourly values, B_0 are estimated locally, according to the following time-dependent parametrization outlined in [11]:

$$\begin{aligned} B_0(\phi,\psi) \;&=\; A(\phi,\psi) + B(\phi,\psi)\cos\theta_z + \\ &\quad C(\phi,\psi)\sin\theta_z\cos\gamma + \\ &\quad D(\phi,\psi)\sin\theta_z\cos^2\gamma \end{aligned} \tag{2}$$

Parameters A, B, C and D should be calculated for every site (position (ϕ, ψ)) using only B_m data which correspond to clear-sky hours. This is done by an iterative filtering procedure in which cloudy data is discarded using the residuals obtained between the current parametrization trained and B_m data for every iteration step [7], [9].

Once the hourly values for B_m, B_0 and $\cos\theta_z$ are computed for every training site, ground data from these stations is used to adjust the model parameters a, b, c and d. The most recent update of JPT parameters was done in May 2012 using data from 05/2010 to 04/2012 from LB, SA and TT stations, and resulted in the coefficients listed in Table III. Brightness counts must be normalized with a factor of 2^8 to agree with the value reported for d.

Table III
JPT MODEL COEFFICIENTS ADJUSTED TO THE URUGUAYAN TERRITORY (LAST UPDATE: MAY 2012)

JPT coefficients	a	b	c	d (kJ/m^2)
Last update	0.2915	0.8369	-0.3770	-0.7464

The JPT model was used till september 2011 when it was replaced by the Brightness-Dependent Tarpley's model, which provides more precise estimates. To differentiate it from the original JPT model, we refer to this other model as BD-JPT because of its Brightness-Dependent conception.

B. Brightness-dependent Tarpley's model

It was observed from the hourly and daily estimates scatterplots that the JPT model still tends to underestimate irradiation in clear-hour conditions while over-estimates in cloudy conditions [7]. In order to avoid this systematic bias in each condition, we decided to introduce a brightness dependence in the determination of Tarpley's parameters. The idea is to perform the estimation using two different sets of parameters $\{a_1, b_1, c_1, d_1\}$ and $\{a_2, b_2, c_2, d_2\}$, and selecting the set depending on whether the hour is classified as clear-sky or cloudy.

The classification of an hour as cloudy or clear-sky is done by a simple fixed threshold, B_m^{thr}, calculated by the mean value of the B_m dataset of the ensemble of training sites. The rationale behind this choice is discussed in [9]. This seemingly minor modification significantly reduces the variance of the estimator, while preserving the attractive simplicity of JPT model. The BD-JPT model is then given by

$$I = \begin{cases} I_{sc}\,(r_0/r)^2\cos\theta_z(a_1 + b_1\cos\theta_z + \dots \\ \quad + c_1\cos^2\theta_z) + d_1\left(B_m^2 - B_0^2\right) & B_m \le B_m^{thr} \\ I_{sc}\,(r_0/r)^2\cos\theta_z(a_2 + b_2\cos\theta_z + \dots \\ \quad + c_2\cos^2\theta_z) + d_2\left(B_m^2 - B_0^2\right) & B_m > B_m^{thr} \end{cases} \tag{3}$$

The most recent update of the BD-JPT model was also performed on May 2012, using the same data and time period that was used for the determination of JPT model parameters, reported in Table III. The two sets of coefficients obtained for the BD-JPT model are listed in Table IV.

Table IV
BD-JPT MODEL COEFFICIENTS ADJUSTED TO THE URUGUAYAN TERRITORY (LAST UPDATE: MAY 2012).

BD-JPT coefficients	a	b	c	d kJ/m^2)
clear-sky hours	0.3621	0.8999	-0.5049	-2.4467
cloudy hours	-0.0092	1.1746	-0.4674	-0.5884

IV. PERFORMANCE EVALUATION OF IMPLEMENTED MODELS

We start this section with a brief review of previous implementations of JPT model. Then, in the second part of this section, we present a performance analysis of our implementations of JPT and BD-JPT.

A. Previous implementations of JPT model

Performance evaluation of solar irradiation models is usually reported in terms of the Root Mean Square error and the Mean Bias Error, hereafter RMS and MBE respectively. We recall their definitions for the sake of completeness,

$$RMS = \sqrt{\frac{\sum_{k=1}^{k=N}(\hat{x}_k - x_k)^2}{N}} \qquad MBE = \frac{\sum_{k=1}^{k=N}(\hat{x}_k - x_k)}{N}, \tag{4}$$

where x_k denotes a measured value, $\hat{x}_k$ its estimate, and N is the sample size. It is also common to report their relative counterparts, rRMS and rMBE, where the absolute quantities are normalized by the mean value of the measurements.

In the original proposal of JPT model [8], Tarpley and collaborators made an estimation of the model's performance on an hourly basis for the period August–December 1980. Using 7200 ground-based data they report an rRMS of 16.2% of the observed mean. On a daily basis, against a set of 282 pyranometer measurements from a single site at Atlanta, Georgia, they report a rRMS of 12.6%.

In the region, JPT model has been tested in the past in Argentina and Brazil. In [17] a daily comparison from Tarpley's model with ground data from several stations in Argentina, using the coefficients adjusted by Tarpley, is reported. Using 5322 daily measurements from 13 stations for the 1982-1983 period a rRMS of 19.6% was found. Then, in the the southern part of Brazil a similar study was conducted [18], comparing 4404 site-days from 9 stations for the 1982-1983 period with Tarpley's model estimates for each site, and reporting a rRMS of 20.3%. An example of an implementation of JPT model in which coefficients were locally estimated can be found in [19]. The estimation was performed using images from the GOES 8 satellite and data from 5 pyranometric stations in Argentina. A comparison between daily irradiation estimates and ground measurements for 715 site-days yield to a rRMS error of 17.3%. Table V summarizes a comprehensive review of the performance of JPT model in the bibliography.

B. Performance discussion of implemented models

Performance evaluation is reported in terms of the rRMS and rMBE indices obtained from the comparison between both models' estimates and ground measurements. Since the same ground data is used to assess both models' performance, comparison between them in such conditions is meaningful. Evaluation is done based on records from the sites which have more than one year of collected data from UTE's measurement network. The spatial distribution of these measurement stations was shown in orange in Fig. 1.

Evaluation is carried out for each site independently. The results obtained at hourly and daily basis are presented in Tables VI and VII, respectively. These tables report the percentage values for rRMS and rMBE, jointly with the mean value which was used to calculate the relative indicators, and the amount of valid hours used for the uncertainty estimation. It shall be noticed that due to satellite's image or ground data loss or corruption, some hours were discarded. If one hour is missing in a given day, this whole day is discarded, that is, hour interpolation was not applied to obtain daily estimates for evaluation purposes. To inform an overall performance index for the whole target territory, a weighted average of the site's performance is compute using the amount of valid data of each site as weighting law.

Over a total of 35532 valid hours, an overall rRMS of 17.9% for JPT model and of 13.7% for BD-JPT model were obtained. On a daily basis, using a total of 1694 valid days, a rRMS of 12.0% and 6.8% were obtained for JPT and BD-JPT models respectively. Results for JPT model are comparable to the better past results informed for this model presented in Table V. Mean bias errors remain at low levels for both models for the overall performance as well as for every evaluation site.

Table VI
PERFORMANCE COMPARISON BETWEEN JPT AND THE BD-JPT MODELS ON AN HOURLY BASIS. $\bar{I}$ DENOTES THE MEAN OF THE MEASURED DATA.

			JPT model		BD-JPT model	
Site	Hours	$\bar{I}$	rRMS	rMBE	rRMS	rMBE
BU	6565	1.51	18.9	3.4	14.5	3.1
JI	6967	1.54	16.5	-0.9	13.0	-1.1
MM	3857	1.46	18.4	1.9	14.1	2.4
PA	6409	1.47	20.6	3.2	15.6	2.2
RA	4355	1.53	17.2	-1.2	13.4	-1.0
RB	7379	1.52	16.2	-0.4	12.0	0.1
overal	**35532**	**–**	**17.9**	**1.0**	**13.7**	**0.9**

Table VII
PERFORMANCE COMPARISON BETWEEN JPT AND THE BD-JPT MODELS ON A DAILY BASIS. $\bar{H}$ IS THE MEAN OF THE MEASURED DATA.

			JPT model		BD-JPT model	
Site	Days	$\bar{H}$	rRMS	rMBE	rRMS	rMBE
BU	249	14.0	15.6	4.8	9.6	4.1
JI	388	19.4	9.9	-0.6	5.6	-1.1
MM	200	18.4	12.1	2.9	7.2	2.8
PA	233	13.5	16.1	5.4	8.5	3.3
RA	209	18.6	11.1	0.7	5.6	-0.1
RB	415	19.1	10.1	0.2	5.8	0.5
overal	**1694**	**–**	**12.0**	**1.8**	**6.8**	**1.2**

On the other hand, these results show the improvement in root mean square error that is achieved when introducing explicit brightness dependence in the model.

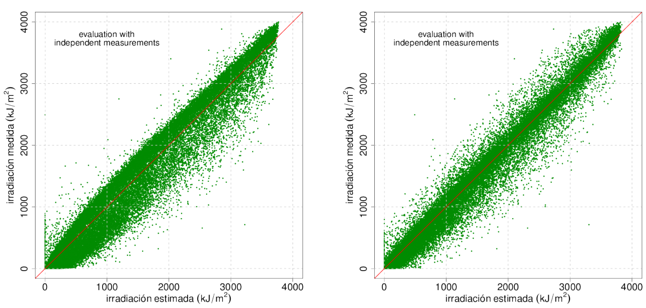
The significant improvement in the rRMS of about 4% on an hourly basis and about 5% on a daily basis relies on the discrimination between clear-sky hours and cloudy hours. Figures 2 and 3 shown the scatter plots between ground data and model estimates for the ensemble of the evaluation sites, at hourly and daily time scales, for both JPT and BD-JPT models. In Fig. 2(a) the accumulation of dots above the red diagonal line are the clear-sky hours, while the noisy pattern distributed below it corresponds to cloudy hours. This show that JPT model systematically bias the estimate to under-estimate in clear-sky conditions and to over-estimate on cloudy conditions. The introduction of the discrimination into clear-sky / cloudy hours succeeds in displacing the noisy pattern around the diagonal red line while reducing the error of the estimates in each situation (clear-sky or cloudy). This effect is clearly seen in Fig. 2(b), where the bias in each condition becomes unnoticeable in the BD-JPT scatter plot. Daily totals are computed by the integration of hourly values within a given day. A similar effect is observed in the daily scatter-plots, for instance, low irradiation days are over-estimated and high irradiation days are under-estimated by JPT model. As a consequence of the brightness discrimination the daily scatter plot for BD-JPT model, shown at Fig. 3(b), does not present a systematic bias along the irradiation values except for values below 5 MJ/m^2 where a small tendency to over-estimate is present.

V. CONCLUSION

A systematic research line aimed at developing local expertise and knowledge of Uruguayan solar resource was launched in 2009, and some advances related to solar resource assessment were presented. In this paper we describe the

Table V
REPORTED JPT MODEL'S PERFORMANCE FROM RELATED WORKS.

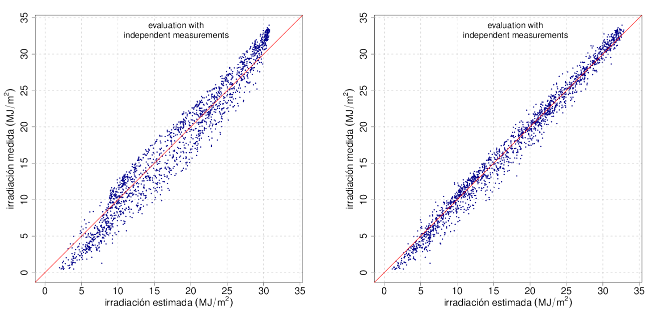
time basis	**data points**	**time period**	**observed mean** (MJ/m^2)	**absolute RMS error** (MJ/m^2)	**relative RMS error** (%)	**Sites**	**Ref.**
hourly	7200	08-12/1980	–	–	16.2	–	[8]
daily	1021	08-12/1980	14.6	1.6	11.0	–	[8]
daily	282	1982	15.1	1.9	12.6	1	[8]
daily	765	1982	15.7	2.1	13.6	5	[14]
daily	195	01-05/1983	–	2.8	–	2	[15]
daily	1240	03-09/1983	–	3.0	–	7	[16]
daily	5322	1982-1983	16.3	3.2	19.6	13	[17]
daily	4404	1982-1983	15.8	3.2	20.3	9	[18]
daily	715	2000-2002	–	–	17.3	5	[19]
monthly	18	1982-1983	14.8	0.8	5.4	1	[8]
monthly	30	2000-2002	–	–	8.9	5	[19]



(a) JPT model.

(b) BD-JPT model.

Figure 2. Scatter plots for hourly ground data vs. hourly estimates for each model. A red diagonal line which corresponds with the perfect agreement situation was draw to guide the eye.



(a) JPT model.

(b) BD-JPT model.

Figure 3. Scatter plots for daily ground data vs. daily estimates for each model. A red diagonal line which corresponds with the perfect agreement situation was draw to guide the eye.

measurements that are being collected and the corresponding instrumentation. Based on the measurement network we implemented two satellite-based models to estimate global solar irradiation, that can be used to estimate hourly irradiation for every point in the target territory with a spatial resolution of 2 km. A comparison between both models and a uncertainty estimation are presented.

The development of a measurement network by FING/UdelaR was an initiative that started in 2008, and the first site began to operate in 2009 based on a locally designed data-logger. This network was expanded up to 5 points distributed in the country, and is continuously recording global solar controlled quality data. Currently this network consists of Kipp&Zonen CMP6 and CM11 measurement instruments, and two different kinds of data-loggers (ADQ-VX national data-logger and Kipp&Zonen Logbox data-logger). The ADQ-VX data-logger provides remote access and configuration, and data is automatically stored and sent to a server via GPRS. Data availability for ADQ-VX data-logger is about 92%. For the Logbox datalogger, a commercial fully-tested equipment, data availability is 100%.

The implementation of satellite-based models adjusted specifically to the Uruguayan territory is quite recent. A local satellite data-bank was constructed for that purpose, and is currently composed of more than 90.000 images. The first model implemented was a pre-existing one and was adjusted during the year 2011. An improved model, that we refer to as BD-JPT, was developed during the last months of 2011 and 2012. An evaluation of this improved model yielded to an uncertainty estimation of 13.7% and 6.8% on hourly and daily bases respectively. This mean than the uncertainty of the estimate is comparable at daily basis to the measure of a field sensor, with the strong advantage that the satellite-based model is capable to produce daily irradiation estimates with a spatial resolution of 2 km.

The generation of a second version of a Uruguayan Solar Map built on a satellite-based tool is the next step in the research line. Future work includes the implementation of a physical satellite-based model, research on spectral knowledge of solar radiation, and studies aimed at achieving differentiation between direct and diffuse radiation components in a national approach.

ACKNOWLEDGMENT

The research line and measurement equipment was partially supported by CSIC, ANII, PEDECIBA and DNE, Uruguay. The authors would like to thank DNM and INIA, Uruguay, for allowing to install measurement equipments in their facilities, and UTE, Uruguay, in particular D. Larrosa, E. Cornalino and M. Draper Vanrell for kindly providing us with ground data.

REFERENCES

[1] G. Abal and M. D'Angelo and J. Cataldo and A. Gutierrez, *Mapa Solar del Uruguay*, Anales de la IV Conferencia Latinoamericana de Energía Solar (IV ISES-CLA), 1–12, 2010. See also the Technical Report available at http://www.fing.edu.uy/if/solar (in spanish).

[2] A. Angström, *Solar and terrestrial radiation. Report to the international commission for solar research on actinometric investigations of solar and atmospheric radiation*, Q. J. Royal Meteorological Society 50, 121–126, 1924.

[3] A. J. Prescott, *Evaporation from a water surface in relation to solar radiation*, Trans. R. Soc. Sci. S. Austr 64, 114–118, 2940.

[4] R. Perez and R. Seals and A. Zelenka, *Comparing satellite remote sensing and ground network measurements for the production of site/time specific irradiance data*, Solar Energy 60, 89–96, 1997.

[5] M. Noia and C.F. Ratto and R. Festa, *Solar irradiance estimation from geostationary satellite data: 2. Physical Models*, Solar Energy 51, 457–465, 1993.

[6] M. Noia and C. Ratto and R. Festa, *Solar irradiance estimation from geostationary satellite data: 1. Statistical Models*, Solar Energy 51, 449–456, 1993.

[7] R. Alonso Suárez and G. Abal and R. Siri and P. Musé, *Global solar irradiation assessment in Uruguay using Tarpley's model and GOES satellite images*, Annals of the Solar World Congress (SWC 2011), resource assessment 162–173, 2011.

[8] C. Justus and M. Paris and J. Tarpley, *Satellite-measured insolation in the United States, Mexico, and South America*, Remote Sensing of Environment 20, 57–83, 1986.

[9] R. Alonso Suárez and G. Abal and R. Siri and P. Musé, *Brightness-dependent Tarpley model for solar irradiation from GOES satellite images*, accepted to Solar Energy (2012).

[10] P. Toscano and J. Cataldo, *Solar irradiation measurement in Uruguay*, Annals of the Solar World Congress (SWC 2011), resource assessment 332–338, 2011.

[11] J. Tarpley, *Estimating incident solar radiation at the surface from geostationary satellite data*, Journal of Applied Meteorology 18, 1979.

[12] J.A. Duffie and W.A. Beckman, *Solar Engineering of Thermal Processes*, Wiley and Sons, third edition, 2006.

[13] M. Iqbal, *An introduction to Solar Radiation*, Academic Press, 1983.

[14] C. Espoz and A. Brizuela, *Application of remote sensing and agrometeorological methods for crop assesment in the Pampa Húmeda*, technical report, FAO, 1983.

[15] C.J. Riordan, *A preliminary comparison of insolation measurements, forecasts and estimates from satellite imagery*, technical report, SERI, 1984.

[16] G.H. Sullivan and V. French and S.K. LeDuc and J.L. Sevaug and W.W. Wilson, technical report, AgRISTARS, 1984.

[17] L.A. Frulla and D.A. Gagliardini and H. Grossi Gallegos and R. Lopardo, *Incident solar radiation on argentina from the geostationary satellite GOES: comparison with ground measurements*, Solar Energy 41, 61–69, 1988.

[18] L.A. Frulla and H. Grossi Gallegos and D.A. Gagliardini and G. Atienza, *Analysis of satellite-measured insolation in Brazil*, Solar & wind technology 7, 1990.

[19] R. Righini and D. Barrera, *Empleo del modelo de Tarpley para la estimación de la radiación solar global mediante imágenes satelitales GOES en Argentina*, Avances en Energías Renovables y Medio Ambiente 12, 9–15, 2008.

Rodrigo Alonso Suárez, received the Electrical Engineer degree from the Universidad de la República, Uruguay, in 2010. Since 2007 he has been with the Physics and the Electrical Engineering Departments, Facultad de Ingeniería, Universidad de la República. He is currently pursuing the PhD degree in Electrical Engineering, on satellite-based modeling of ground solar radiation.

Pablo Toscano, received the Electrical Engineer degree from the Universidad de la República, Uruguay, in 2011. He is a Teaching Assistant of electric power systems in the Department of Electrical Engineering, Facultad de Ingeniería, Universidad de la República, since 2009.

Gonzalo Abal, holds a PhD in Physics from Universidad de la República Uruguay, since 2001. He is Associate Professor of Physics at the Department of Physics, Facultad de Ingeniería, Universidad de la República. He was head of the Department for the 2008–2012 period. He is an honorary researcher from PEDECIBA (Basic sciences development program) and Researcher, level II, of the SNI (National System of Researchers). He has published more than 23 specialized papers and a book in several areas of theoretical physics, including statistical physics, nuclear physics and quantum information processing. Currently his research interest is focused on solar energy applications and, more specially, in developing new solar resource assessment techniques.

Ricardo Siri, received the Electrical Engineer degree from Universidad de la República, Uruguay, in 1980. He is an Associate Professor at the Department of Physics, Facultad de Ingeniería, Universidad de la República. He worked on several areas of theoretical physics, field theory, statistical physics, and quantum information. Currently, his research interest is focused on solar energy.

Pablo Musé, received the Electrical Engineer degree from Universidad de la República, Uruguay, in 1999, the Diplôme d'Etudes Approfondies degree in Mathematics, Vision and Learning, and the Ph.D. degree in Applied Mathematics both from Ecole Normale Supérieure de Cachan, France, in 2001 and 2004, respectively. From 2005 to 2006 he was with Cognitech, Inc., Pasadena, CA, where he worked on computer vision and image processing applications. In 2006 and 2007 he was a Postdoctoral Scholar with the Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena. He is currently an Associate Professor of signal processing with the Department of Electrical Engineering, Facultad de Ingeniería, Universidad de la República.