SOLAR IRRADIATION MEASUREMENT IN URUGUAY

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1. Introduction

In 2009 the Faculty of Engineering (FIng) of the University of the Republic of Uruguay has signed an agreement with the National Energy Board for the investigation of the solar resource in Uruguay. It was decided on this basis the implementation of a network based on autonomous measuring stations, consisting of data loggers and pyranometer sensors.

It was considered from the beginning as a design target, the development of a self-powered measuring station, so independence from the mains is guaranteed.

2. Measuring station localization

To establish the locations of the stations, similar work from other countries has been studied, to have some idea of the density of measuring points required. Since there was not enough reliable long term series of irradiation in Uruguay, we began developing a solar resource map based on the Angstrom-Prescott correlation, which establishes a linear relationship between the average sunshine hours and normalized average irradiation. Since there are several long-term series of sunshine hours in the country, it was decided to establish the correlation at a few points with pyranometer equipped measuring stations and then extrapolate to points where only sunshine hours measure are available. The Angstrom-Prescott correlation considers two parameters (*a* and *b*) for the linear relationship, which have a geographic variation, and therefore it is required to know the measuring point density necessary to take these variations into account.

Studying the solar resource surveys conducted in Argentina, the variation of the parameters *a* and *b* in regions near the border with Uruguay and similar geography was analyzed. As a result of this analysis it was established that a network of three points distributed in the Uruguayan territory, turns out to be sufficient to consider the variability of the parameters a and b of the Angstrom-Prescott correlation.

It was decided to install the measuring stations at the meteorological stations of the National Institute for Agricultural Research (INIA) because of their geographical distribution, and in particular, there were sunshine hours records available at the same points. The coordinates of each measurement station are shown in Table 1.

Tab. 1: Coordinates of measurement points.

Measurement station	Coordinates
INIA - Las Brujas	34°40'19" S, 56°20'24" W
INIA - Salto	31°16'22" S, 57°53'27" W
INIA - Treinta y Tres	33°16'31" S, 54°10'20" W

The location of measurement points is shown in Fig. 1.

Fig. 1: Location of measurement points.

3. Brief description of the measurement system

The measuring station consists of a *ADQ-VX* datalogger with remote communication using the GPRS network and text messages (SMS). It is designed to operate completely autonomously, it is not necessary even an operator to collect data. The control and data download can be done remotely. The sensor is a pyranometer Kipp & Zonen CMP6, which produces an output voltage at full irradiance of the order of mV. To adapt the output of the pyranometer to datalogger's analog input range, an amplifier was implemented (with a gain of nearly 130), this leaves the dynamic range of the voltage measured by the datalogger in the order of V, making better use of the input range (0-5V).
Both the datalogger and the amplifier are fed through a set of battery and 12Wp PV panel, controlled by a solar charge regulator. The battery is sealed type, 12V, 40Ah.

The measuring stations were to be installed in meteorological stations controlled by operators, so, although the installation was designed to be completely autonomous, a datalogger "reset" switch was installed, accessible from the outside (there is already a reset switch but inside the datalogger, making its operation unfeasible by untrained operators). The switch is located next to the battery in the bottom of the station, protected from direct rain water through the exterior cover, but still is implemented with a rugged moisture-proof design.

The datalogger, battery, solar charge regulator and reset switch are protected from the elements by a two piece metal cover, designed to ensure adequate ventilation and to avoid excessive heat inside the battery, that shortens its life expectancy. The complete station layout before placing the cover, is shown in Fig. 2. Figure 3 shows the final assembly of the station.

Fig. 2: Measuring station before placing exterior cover.

Fig. 3: Final assembly of the measuring station.

3.1. ADQ-VX datalogger

The *ADQ-VX* datalogger is the result of a final degree project developed by electrical engineering students at FIng, in 2008. This project was funded by the Institute of Fluid Mechanics and Environmental Engineering (IMFIA) of FIng, given the interest of this institute for having a data recording technology available to avoid time losses resulting from sending out equipment for repair (up to several months). It aims to have a local know-how for maintenance.

As a result of this project, a prototype of the *ADQ-VX* was built, with the following characteristics:

- Supply voltage between *6V and 18V*.
- *Stand-by* consumption: 32 *mA* @ 12*V*. Continuous logging consumption: 110 *mA* @ 12*V*.
- GSM/GPRS modem.
- 5 analog inputs (12 bits, 0-5*V*).
- 8 digital inputs (0-5*V)*.
- 4 digital outputs (0-3.3*V)*.
- i2c bus .
- 1 AC/DC 60*V* 300*mA* relay output.
- 5*V* output for sensor powering.
- 2 RS-232 ports.
- 1 USB host port.
- Surge, short circuit and over current protection.

The datalogger consists of two separate circuit boards, one of them is the datalogger itself (ADC, computer-on-module, modem) and the other board implements surge, over current and short circuit protection. Measured signals and power supply pass through the protection circuit board, serving as a barrier to shocks that could damage the measurement system.

All application control is made by the Gumstix embedded computer Verdex (400 *MHz*, 64*MB* RAM, 16*MB* FLASH). Communications are implemented via a GSM / GPRS Telit GM862 (850/900/1800/1900*MHz*).

The *ADQ-VX* enables continuous measurements at a configurable sampling rate, storing them on a flash drive, and sending the data generated to an external FTP server for remote download. Datalogger also includes local configuration through a serial connection and remotely using the SSH protocol.

3.2. Kipp & Zonen pyranometer CMP6

This pyranometer is a classified as a "First Class Standard" (ISO 9060 / WMO). It has a spectral range from 285 to 2800 *nm* and a sensitivity 5 to 20$\mu V/W\ m^{-2}$, which causes its output must be amplified to be measured by the *ADQ-VX*. The directional error (up to 80 ° @ 1000 $W\ m^{-2}$) is less than 20 $W\ m^{-2}$.

4. Construction of measuring stations and field installation

The *ADQ-VX* dataloggers were assembled and programmed locally, based on the design documented in the prototype construction. Electronic components and circuits boards were imported from USA. The final assembly was done in Uruguay. Finally, software was installed as in the initial prototype.

Parallel to datalogger construction, other tasks required for assembly of the network: pyranometer importation and metal stand building.

The installation of the three measuring stations was carried out gradually, starting with the nearest to have it as a test installation during the first months.

The field deployment of the stations was performed in the sequence indicated in Table 2.

Tab. 2: Dates of measurement station installation.

Measurement station	Initial operation date
INIA - Las Brujas	29/12/09
INIA - Treinta y Tres	28/05/10
INIA - Salto	02/06/10

5. Network operation

The first months of operation of the first measuring station at INIA-Las Brujas were useful to detect some faults that had the datalogger software, because it was not a fully tested commercially produced equipment. Working with a datalogger that was taking its first field test implied a risk of data loss, a situation that occurred in some periods of time.

Since the datalogger has remote communication, this gives the advantage of having real-time control of the operation. If something unforeseen happens, a quick response can be performed, preventing a massive data loss. This is an advantage compared to other dataloggers, simpler, but without communication features.

The data series had several "holes" as a result of these periods of failure, which were gradually decreasing. Table 3 summarizes the performance of the three stations from the time of installation to date (August 2011).

Tab. 3: Availability of data at the three measurement stations.

Measurement station	Days since installation	Days with available data	Data availability
INIA - Las Brujas	549	467	85.06%
INIA - Treinta y Tres	439	397	90.43%
INIA - Salto	434	382	88.02%

From what is observed in the above table is noticed that, despite the failure periods, over 85% of data availability was achieved in the first year of operation, which is good considering that prototype datalogger were used.

6. Measured data

Daily, the datalogger connects to the internet through the GPRS modem and uploads the data generated the previous day to an FTP server from which data is downloaded and processed.

The raw data is a plain text file which generates a line for each measure (at a rate of one per minute, as configured). From the raw data, hourly irradiation averages are generated for each measurement station.

By mid 2010 was launched the first version of the Solar Map of Uruguay (MSU), based on sunshine hour records and some existing irradiation series. The data collected by the network that is described in this article were not used because the records were too short at that moment. In future versions of MSU, it is desirable to have longer measurements to use as input for these improvements in the survey of the resource.

Table 4 shows a comparison between the monthly average irradiation in different measuring stations and the correspondent estimation of MSU. This comparison is done for illustrative purposes only, as values of monthly average irradiation of MSU are compared to specific measures, which do not yet have statistical values.

It is clearly shown that INIA-Las Brujas and INIA-Treinta y Tres measurements are far above the estimate of MSU, while INIA-Salto is in reasonable agreement within the precision level of MSU and measurement.

It is suspected that a series of data for southern Uruguay that was used in developing the first version of MSU, is responsible for the underestimation of the irradiation in the south, probably due to an uncalibrated pyranometer.

Tab. 4: MSU-measured irradiation monthly averages comparison.

Average monthly irradiation values (MJ m^{-2}) measured and estimated by MSU																		
Measuring station	**Year**	**2010**										**2011**						
	Month	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
INIA - Las Brujas	MSU	15.8	11.9	8.6	6.8	7.9	9.7	13.3	17.3	21.6	22.7	23.0	20.2	15.8	11.9	8.6	6.8	7.9
	Measured	19,0	13,5	8,7	n/a	n/a	n/a	13,9	21,0	25,4	28,4	n/a	n/a	19,7	14,4	10,3	7,4	8,9
	Diff. (%)	**20.3**	**13.4**	**1.1**	**n/a**	**n/a**	**n/a**	**4.5**	**21.4**	**17.6**	**25.1**	**n/a**	**n/a**	**24.7**	**21.0**	**19.8**	**8.8**	**12.7**
INIA - Treinta y Tres	MSU	15.8	12.6	9.0	7.6	8.3	10.4	13.7	17.6	21.6	23.0	23.0	20.2	15.8	12.6	9.0	7.6	8.3
	Measured	n/a	n/a	n/a	8,1	n/a	n/a	14,3	21,9	24,4	27,4	24,7	22,8	20,0	13,9	10,2	8,4	8,1
	Diff. (%)	**n/a**	**n/a**	**n/a**	**6.6**	**n/a**	**n/a**	**4.4**	**24.4**	**12.0**	**19.1**	**7.4**	**12.9**	**26.6**	**10.3**	**13.3**	**10.5**	**-2.4**
INIA - Salto	MSU	18.0	13.7	10.4	7.9	9.7	12.6	15.8	18.4	23.8	24.8	24.8	22.0	18.0	13.7	10.4	7.9	9.7
	Measured	n/a	n/a	n/a	7,6	9,7	n/a	n/a	n/a	26,9	27,7	25,1	21,4	20,4	15,3	11,3	7,8	9,9
	Diff. (%)	**n/a**	**n/a**	**n/a**	**-3.8**	**0.0**	**n/a**	**n/a**	**n/a**	**13.0**	**11.7**	**1.2**	**-2.7**	**13.3**	**11.7**	**8.7**	**-1.3**	**2.1**

7. Network expansion

From late 2010 began the expansion of the network to more points, including two inside the country and the third in the FIng building in Montevideo. The choice of new locations was made taking into account the positions of existing stations: a new measuring point at the Atlantic coast in the southeast of the country (Rocha city, in June 2011) since it is convenient to measure in this type of sea environment because it is different from the rest of the country and the most populated areas are located along the coast.

The other measuring station is not yet installed and would be located in the north of the country (Cities of Artigas or Rivera) to cover the northeastern area of Uruguay. Figure 4 shows the complete network once the new points are installed.

Fig. 4: Location of measurement points (original and new ones).

The two new measuring points inside the country are implemented with CMP6 pyranometers (to maintain uniformity of the network and keep pyranometers interchangeable between different points) and

Kipp & Zonen *Logbox* dataloggers which are aimed at a very low power consumption, but with the counterpart of not having communication module.

Finally, we implemented in late 2010 on the roof of FIng building, a tower where a Delta-T SPN1 pyranometer (to measure global and diffuse irradiance) has been installed.

This equipment was installed permanently at this tower in order to have a long term reliable series to test correlations between global and diffuse more accurately. For measurements of diffuse component it is also available a Kipp & Zonen shadow ring of acquired in 2009 along with CMP6 pyranometers.

There are also installed in the tower two Davis 6450 photo-voltaic pyranometers, one horizontal and the other tilted, in order to have a correlation between these two measures.

The FIng measuring point is equipped with a DataQ DI-710 16 channel datalogger. Figure 5 shows the tower installed at FIng roof, at that time were installed two new CMP6 pyranometers to be tested prior to installation inside the country, besides the two Davis 6450 and the Delta-T SPN1 in the central part.

Fig. 5: Measurement tower at FIng (Montevideo).

8. Future prospect

The first objective to meet is the installation of the sixth measuring point. Besides the six fixed points of measurement, it is planned to have a measuring point in the form of a rapid deployment kit, so measurement can be made at a given place for short periods of time. These measures allow comparison with already installed pyranometer of which little is known about the validity of their measures, but if are checked and validated, will serve as important data because in some cases extensive measurement records are available.

Along with expanding the measurement network, there is a second objective essential to maintain reliable long-term measures: calibration of the pyranometer.

Currently (August 2011) is close to meeting the first two years of using the first CMP6 acquired in 2009, which is taken as a reasonable time range for calibration thereof. In this sense, it is intended to implement locally the pyranometer calibration against a reference standard pyranometer Kipp&Zonen CMP22, following the procedure of ISO 9847: Solar Energy - Calibration of field pyranometers by comparison to a reference pyranometer. The reference pyranometer will be transferred to a regional center to be calibrated periodically against a standard of greater stability. This calibration will be developed in the recently installed tower at FIng, and done with natural sunlight .

9. Conclusions

The installation of this solar irradiation measurement network is the first attempt at a nationwide network with reliable measurements and calibrated equipment. During the construction of this network, the first version of the MSU was launched, carried out based on a few national data series and some border points. In the development stage of the map, investigators had to discard several series because there was not enough information about the maintenance of the equipment used and calibration of them.

In this sense, the aim is to have a network designed so that in the medium term, reliable series of irradiation will be available at various points of Uruguay.

The choice of the *ADQ-VX* datalogger for the first three measurement stations was a challenge that involved the risk of operational problems and data loss, but also had the secondary goal of generating knowledge and independence by creating local know-how, an objective that has been achieved. Despite using a prototype datalogger, good rates of availability of data were achieved and gradually converged towards an improved design.

Nowadays, a local pyranometer calibration program is in design stage, which once developed will mean significant progress, taking into account that in prior attempts, pyranometers have never been calibrated. This lead to earlier solar irradiation measurement efforts often to failure in the weakest point of measurement: calibration of the pyranometer.