Everyone has the right to prosper from their energy

Validation White Paper

July 2014

Summary: This white paper provides an overview of the solar resource assessment (SRA) methodology of Sunmetrix, a web-based service powered by Turquoise Technology Solutions Inc. Global Horizontal Irradiance (GHI) validation results are provided for four ground stations in the US.

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1 Introduction

Earth observation data from meteorological satellites provide essential information for solar resource assessment (SRA). SRA is the statistical characterization of solar radiation at a specific location on Earth and it is a key part of feasibility studies for solar thermal and solar photovoltaic projects. Cloud climatology and the Clear Sky model are the two main building blocks of any satellite-based resource assessment method. This paper provides an overview of our SRA method as well as preliminary results of validation studies performed for various ground stations. Validation is a continuous process in our company, and new results will be available as our models evolve and wider geographical areas are covered.

2 Terminology and Units

Irradiance: Power received per area. It is measured in watts per square meter (W/m^2)

Irradiation/Insolation: Energy received per area. It is measured in joules per square meter (J/m^2) or watt-hour per square meter (Wh/m^2).

Direct Normal Irradiance (DNI): Irradiance produced by the direct solar radiation on a surface perpendicular to the sun's rays. DNI is particularly relevant for solar thermal and concentrating solar applications.

Diffuse Horizontal Irradiance (DHI): Irradiance produced by the diffuse solar radiation on a horizontal surface on Earth. Diffuse radiation is the portion of solar radiation that reaches the Earth after being scattered by various atmospheric molecules and aerosol particles.

Global Horizontal Irradiance (GHI): Irradiance produced by solar radiation on a horizontal surface on the earth. GHI is particularly relevant for photovoltaic applications.

Please note that GHI is <u>not</u> equal to the sum of DNI and DHI (solar zenith angle has to be taken into account when conversions are made between these three components of solar radiation).

3 Overview of our Methodology

The Clear Sky model and cloud climatology are the two main building blocks of any satellite-based resource assessment method. By integrating cloud data, derived from meteorological satellite images, into the Clear Sky model, our proprietary database and software can estimate the solar radiation levels at the surface of the Earth.

3.1 Clear Sky Model

The amount of solar radiation reaching the top of the atmosphere, the solar flux, is relatively stable around 1367 watts/m^2. Although the 11-year solar cycle and the relative distance of Earth from the Sun throughout the year slightly change the solar flux, it is still possible to build a deterministic model, also called the Clear Sky model, to estimate the solar radiation at the surface of the Earth. This model takes into account various atmospheric phenomena, such as aerosols, which affect the level of radiation reaching the surface of the Earth.

These phenomena are factored in by incorporating solar geometry, altitude and turbidity data into the Clear Sky model. Since the solar radiation estimates based on the Clear Sky model assume that there is no cloud cover, they provide the upper bound of radiation estimates.

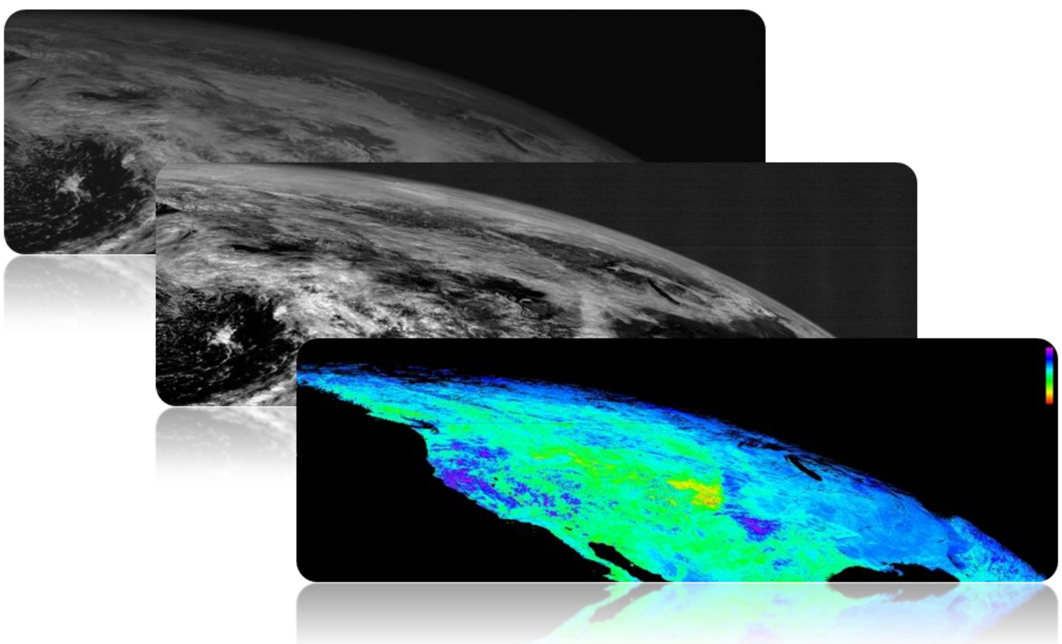

Figure 1: Steps of our methodology

3.2 Cloud Climatology

Determining the long-term characteristics of cloud cover ("climatology") is also an essential part of solar radiation modeling. Clouds have a significant impact on the amount of solar radiation reaching the surface of the Earth. By absorbing the incoming radiation and reflecting some of the energy back into space, they play a complex role in shaping our climate. Generally speaking, about 20% of the incoming radiation is absorbed by gases and clouds, and another 20% is reflected back to space. Thus, determining the cloud cover over a project site is an integral part of solar resource assessment.

The statistical analysis of the cloud cover enables us to build a "cloud index", an indicator numerically representing the degree of cloud cover. Each satellite image has a unique time stamp and each pixel has a specific cloud index value. For each time stamp, we first compute the Clear Sky values and then account for the cloud cover using the cloud index. This basic algorithm has to be repeated for each satellite image covering the desired time period. For example, in order to obtain an hourly time series data set covering a single year, close to 30,000 individual images have to be processed.

The steps of this process can be observed in Figure 1. The top panel is a raw satellite image for North America taken on February 10th, 2007 at 9pm GMT. The middle panel shows the corresponding cloud index and the bottom panel shows the global horizontal irradiance values estimated for this particular point in time.

4 Validation Results

At Turquoise, we take pride in our quality assurance. Our data products are rigorously tested and validated against ground station data from Canada and the U.S. Continuous quality improvement is a priority of our R&D activities. Working with our university partners, we perform objective quality assurance and we continuously invest in future improvements of our technology.

As part of a quality assurance process, it is imperative to validate the satellite-based estimates by comparing them to the on-site solar radiation data measured at ground stations. Typically, validation results are reported using statistical methods to assess the performance of the model. In order to determine the overall quality of ground measurements, two main metrics are commonly used. To determine the overall bias, the mean bias difference (MBD) is used. To determine the dispersion from measured values, correlation coefficient and R^2 values are calculated.

4.1 Graphical Representation of the Validation Results

Figure 2 illustrates the comparison of satellite-derived data and on-site measurements for a validation campaign completed for Goodwin Creek (Mississippi) [34.2547° N, 89.8729° W]. The red line in the scatter plot represents the ideal model with perfect correlation. The data covers the period from December 2012 to July 2014. The data set includes 4451 daytime hours during which both satellite data and ground measurements were available.

The average hourly GHI value of our estimates is 386.58 Wh/m^2. In comparison, the average hourly measured GHI is 390.80 for the same period. Thus, the MBD is just above 1%.

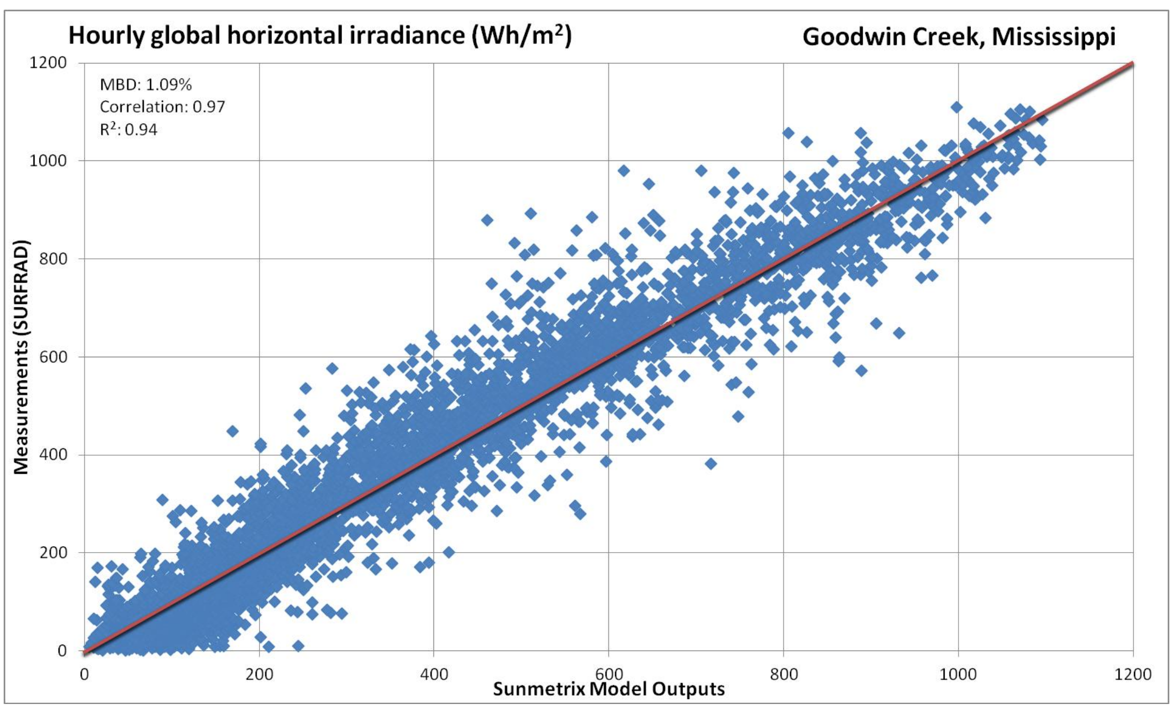

Figure 2: Goodwin Creek validation results

4.2 Tabular Representation of the Validation Results

Validation results for daytime global horizontal irradiance values are shown in the table below, including R^2 and correlation values for four ground stations in the US.

Please note that extreme values in the time series are included in the values reported in the table. Some performance statistics reported in the SRA community exclude the extreme values, thereby reducing the error terms further. As this decreases the transparency of the validation results, we decided to report our results without any adjustments.

Ground Station	Correlation of estimates vs. ground station	R^2	Hourly GHI in watt-hours/m^2 (Sunmetrix estimate)	Hourly GHI in watt-hours/m^2 (ground station)	Estimates vs. ground station (% difference) MBD	Number of data points
Bondville, IL [40.05192° N, 88.37309° W]	0.93	0.86	331.19	355.91	6.95%	5543
Desert Rock, NV [36.62373° N, 116.01947° W]	0.95	0.90	483.25	528.49	8.56%	5266
Goodwin Creek, MS [34.2547° N, 89.8729° W]	0.97	0.94	386.58	390.80	1.09%	4451
Penn State, PA [40.72012° N, 77.93085° W]	0.95	0.91	325.52	329.90	1.33%	7952

5 Conclusion

Satellite-based solar resource assessment is a viable method rapidly maturing with numerous applications around the world. The unique vantage point of satellites enables us to assess the solar resource potential of very large geographical areas with a resolution of 1-2 kilometres. Archived satellite imagery makes it possible to construct hourly time series data going back more than ten years. Our near real-time algorithms enable processing the latest satellite images to provide up-to-date results. All of these capabilities render satellite-based SRA an excellent tool for designing and monitoring solar energy systems.

Our validation campaigns are an integral part of our product development and we will make more validation results available in the future. Finally, using on-site observations together with our data sets ("measure-correlate-predict") can further increase the overall accuracy of the results presented in this document. Thus, satellite-based SRA can also be used to increase the power of your on-site measurements by extending their temporal coverage.