Best Practices of Uncertainty Estimation for the National Solar Radiation Database (NSRDB 1998–2015)

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Aron Habte and Manajit Sengupta
National Renewable Energy Laboratory

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BEST PRACTICES TO UNCERTAINTY ESTIMATION FOR THE NATIONAL SOLAR RADIATION DATABASE (NSRDB 1998–2015)

Aron Habte and Manajit Sengupta
National Renewable Energy Laboratory, Golden, CO, 80401, USA

ABSTRACT:

It is essential to apply a traceable and standard approach to determining the uncertainty of solar resource data. Solar resource data are used for all phases of solar energy conversion projects, from the conceptual phase to routine solar power plant operation, and to determine performance guarantees of solar energy conversion systems. These guarantees are based on the available solar resource data derived from measurement stations or modeled data sets, such as the National Solar Radiation Database (NSRDB). Therefore, quantifying the uncertainty of these data sets provides confidence to the financiers, developers, and site operators of solar energy conversion systems, and ultimately it reduces deployment costs. In this study, we implemented the *Guide to the Expression of Uncertainty in Measurement* [1] to quantify the overall uncertainty of the NSRDB data. First, we start by quantifying measurement uncertainty, then we determine each uncertainty statistic of the NSRDB data, and finally we combine them using the root sum squared method. The statistics were derived by comparing the NSRDB data to the seven measurement stations from the National Oceanic and Atmospheric Administration's Surface Radiation Budget Network (SURFRAD), National Renewable Energy Laboratory's (NREL's) Solar Radiation Research Laboratory (SRRL), and the Atmospheric Radiation Measurement (ARM) program's Southern Great Plains (SGP) Central Facility, in Billings, Oklahoma. The evaluation was conducted for hourly values, daily totals, monthly mean daily totals, and annual mean monthly mean daily totals. Varying time averages assist to capture the temporal uncertainty of the specific modeled solar resource data required for each phase of a solar energy project; some phases require a higher temporal resolution than others. Overall, by including the uncertainty of measurements of solar radiation made at ground stations, bias, and root mean square error (RMSE), the NSRDB data demonstrated expanded hourly and annual uncertainties of 17%–29% and 5%–8%, respectively.

Keywords: uncertainty, pyranometer, NSRDB, GUM

1 INTRODUCTION

Recognizing the importance of solar resource to industry and other stakeholders, the National Solar Radiation Database (NSRDB) has been updated over the years to meet the demand and be useful for the deployment of current technologies. Recently, the National Renewable Energy Laboratory (NREL) released a version of the NSRDB (1998–2015) that contains gridded solar irradiance—global horizontal irradiance (GHI), direct normal irradiance (DNI), and diffuse horizontal irradiance at a 4-km by 4-km spatial resolution and half-hourly temporal resolution covering 18 years. Details of the data set are available at https://nsrdb.nrel.gov. Additional details about the NSRDB are also described in [2], [3]. Understanding the impacts of the atmospheric constituents on the solar resource and quantifying the uncertainty are essential to accurately designing utility-scale solar energy conversion systems. This study attempts to provide a comprehensive uncertainty estimate that demonstrates the performance characteristics of the NSRDB (1998–2015) when including all sources of uncertainty at various time-averaged periods, a protocol that is not often used in model evaluations. Further, to have a good uncertainty analysis representing the spatial coverage of the model, it is advisable to obtain enough ground measurement locations that encompass various climatic regions; however, it is challenging to obtain long-term, high-quality ground measurements of solar radiation in various regions because ground measurement stations are expensive to commission and operate. For this study, nine good quality stations were chosen representing seven U.S. climatic regions (Figure 1).

2 METHOD

Determining the accuracy and uncertainty of satellite-derived data sets is based on a wide range of approaches and data analysis techniques. Some of these techniques use mean bias error (MBE) and root mean square error (RMSE) as statistical measures; however, to perform comprehensive uncertainty estimation, all known sources of uncertainties must be included [4], [5], [6], and one of these sources of uncertainty is the ground-based measurement uncertainty.

2.1 MEASUREMENT UNCERTAINTY

Many studies have reported that the uncertainty of the ground measurements from pyranometers could range from 3%–5% [7], [8], [9]. In this report, we considered the conservative value of 5% uncertainty for the ground-based measurement data (Figure 2).

Determining the uncertainty of the solar radiation measurement using pyranometers and/or pyrheliometers includes sources of uncertainties, such as the specifications of the instrument, calibration procedure, measurement conditions and maintenance, and environmental conditions. In this paper, we follow the steps required to quantify a traceable uncertainty estimate using a *Guide to the Expression of Uncertainty in Measurement* (GUM) method.

2.2 NSRDB UNCERTAINTY STATISTICS

Statistical measures were used to investigate the performance of the NSRDB relative to ground-based measurements. These included:

MBE in units of irradiance (W/m^2) and percentage of reading (%) were calculated using the following equations:

$$MBE(W/m^2) = \frac{1}{n}\sum_{i=1}^{n}(x_i - x_{true})$$

$$MBE(\%) = \frac{\left(\frac{1}{n}\sum_{i=1}^{n} (x_i - x_{true})\right)}{\left(\frac{1}{n}\sum_{i=1}^{n} (x_{true})\right)} * 100$$

where n represents the total number of measurements at each time average, x_i represents values from the NSRDB (1998–2015) satellite-derived data, and x_{true} represents the concurrent ground-measured data for both GHI and DNI at a given site, which were evaluated separately. Similarly, RMSE values were computed using the ground measurements (x_{true}):

$$RMSE(W/m^2) = \sqrt{\left(\frac{1}{n}\sum_{i=1}^{n} (x_i - x_{true})^2\right)}$$

$$RMSE(\%) = \sqrt{\frac{\left(\frac{1}{n}\sum_{i=1}^{n} (x_i - x_{true})^2\right)}{\left(\frac{1}{n}\sum_{i=1}^{n} (x_{true})^2\right)}} * 100$$

These statistics provided insight into the performance of the modeled data set relative to the ground-based measurements [10], [3]. For instance, RMSE is useful in determining the error distribution [11]. MBE describes the direction (+/-) of the error or difference bias.

To understand and quantify the overall uncertainty of the modeled data set, the approach outlined in the GUM was used. The method applies RMSE, MBE, and the ground-based measurement uncertainties as sources of estimated combined uncertainty. This approach provides uncertainty estimation on a 95% confidence interval (U_{95}%) representing two standard deviations (coverage factor of $k = 1.96$) and assuming a Gaussian or normal distribution of the data. Details of this methodology are described in [7], [12], [13]:

$$U_{95}\% = k * \pm\sqrt{\left(\frac{U_{meas}}{k}\right)^2 + \left(\frac{MBE}{k}\right)^2 + \left(\frac{RMSE}{k}\right)^2}$$

where U_{meas} is the estimated uncertainty of the surface measurement (ground truth), and MBE and RMSE are derived from the model validation analyses.

3 RESULTS AND DISCUSSION

Figure 2 shows that the hourly data set demonstrated a higher uncertainty estimation of the NSRDB. As the time average changed from hourly to annually, the uncertainty decreased and approached the measurement uncertainty. The estimated uncertainty ranged from approximately 30% on an hourly basis to 5% annually. However, these ranges differ from one location to another because of multiple reasons, such as climatic and microclimate differences among regions and differences in instrumentation, maintenance, and operation of measurements of solar radiation made at ground stations.

The surface measurement uncertainty was left unchanged at 5% throughout the averaging period because the inherent uncertainties of the radiometers should remain the same throughout the averaging. The 5% uncertainty was derived using the method outlined in the GUM, which applies both the statistical and nonstatistical sources of uncertainty [7], [12]. Evaluating the random component of the ground measurement requires a statistic, such as standard deviation; however, the inherent nature of changing weather during the ground-based measurements cannot be considered a source of uncertainty to determine the standard deviation because it is not about the instrument that measures the changes. In future studies, statistical sources of uncertainties of measurements could be included by analyzing the time response and stability of the radiometer that measures the solar resource and the data acquisition system. We believe that these sources will not have a significant effect in reducing the estimated uncertainty of the ground-based data as the averaging time increases, but this needs further investigation.

Figure 3 illustrates the relative GHI and DNI biases and RMSE. The results show that the hourly-averaged satellite-derived data have a bias of approximately ±5% for GHI and less than +10% for DNI; however, RMSE is higher for the hourly averages: the GHI of the NSRDB demonstrated on average up to 20% RMSE when compared to the ground-based GHI measurements and up to 30% RMSE on average when compared to the ground-based DNI measurements.

On the other hand, the RMSE in the NSRDB (1998–2015) decreased significantly with the increase in the time average. This is partly because as averaging time increased, there is a cancellation of the random error. Further, the reason for the high RMSE in the hourly data set is that the NSRDB pixel represents a 4-km by 4-km area, whereas a ground-based station represents only a small area above the measuring station. The subpixel variability in clouds appears to contribute to the higher differences.

4 SUMMARY and CONCLUSION

A full characterization of uncertainty estimation provides the basis to assess the predicted output of planned solar conversion systems and is thus a key factor when determining the bankability of the project. The integrity of modeled data can be improved by applying a comprehensive description of the model uncertainty. As reported in the paper, this can be achieved using the

GUM method. Proper uncertainty estimation provides confidence in the data; however, it is important to determine the uncertainty using a standard methodology that others can also use and will obtain identical results.

Acknowledgements

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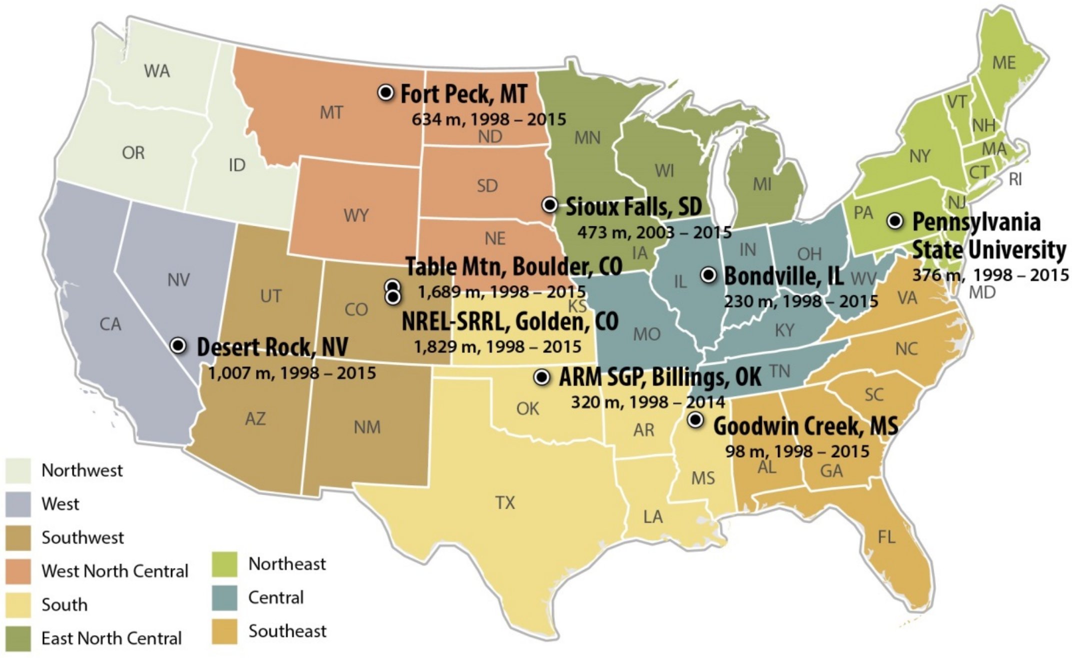

Figure 1: SURFRAD network, NREL's SRRL, and the ARM's SGP locations overlaid on the United States climatic regions

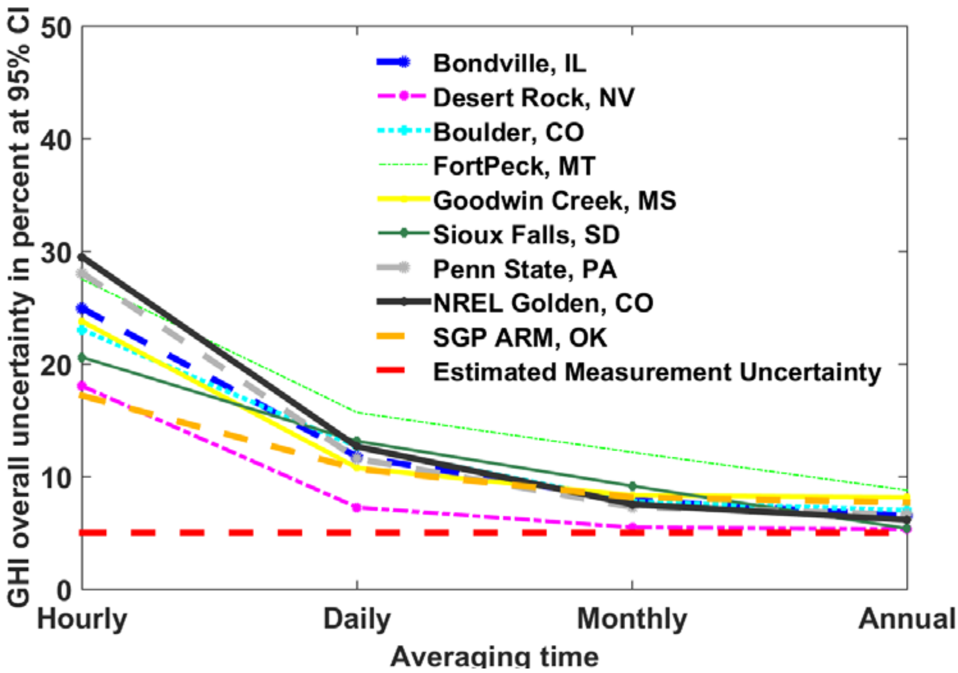

Figure 2: NSRDB uncertainty under various time averages

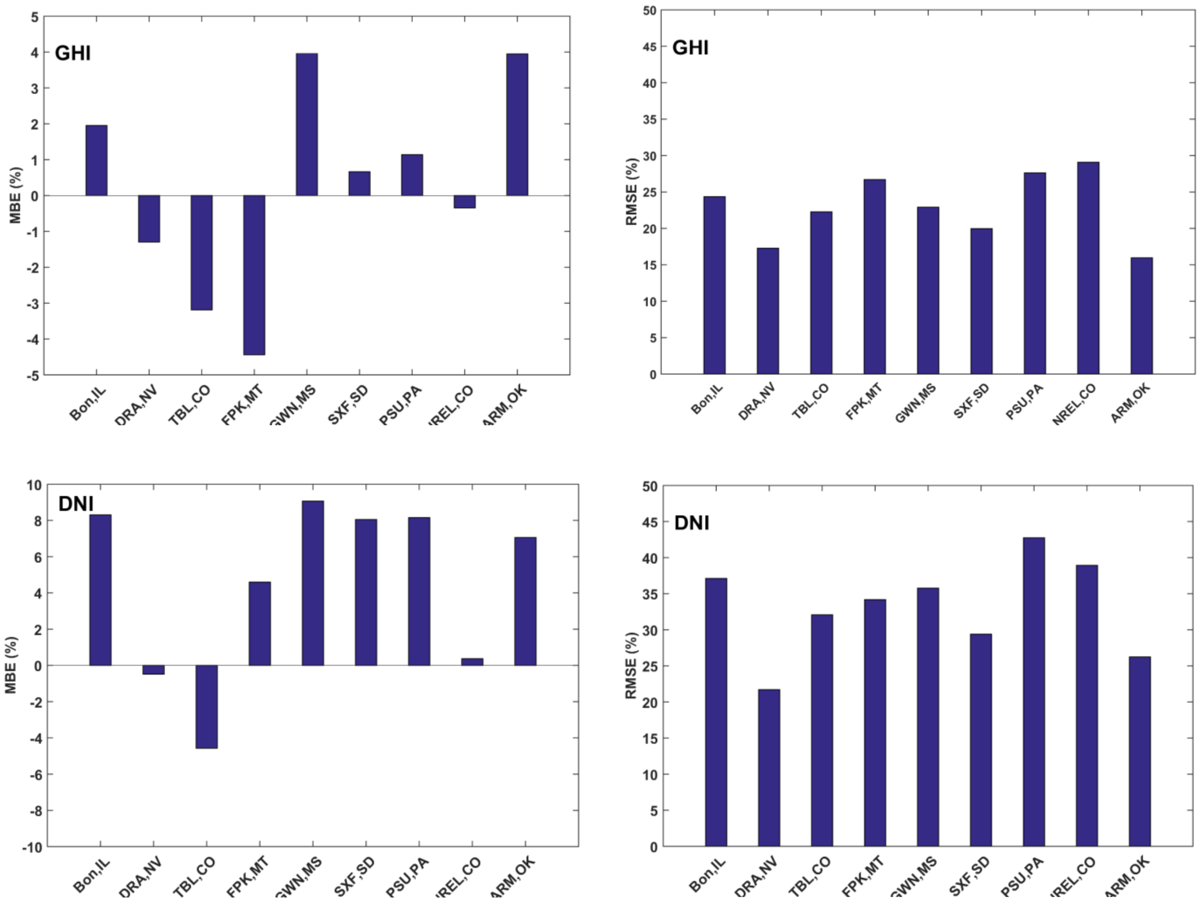

Figure 3: MBE percentage (left) and RMSE percentage (right) comparison results for both GHI (top) and DNI (bottom) between the NSRDB and ground-measured data for nine locations. Data obtained from the hourly data.