NREL
Transforming ENERGY

Toward Integrating Data Quality Assessments and Radiometer Uncertainty for Determining the Expanded Uncertainty of Three-Component Solar Radiation Measurements

Presenter: Aron Habte

Stephen Wilcox,[1] Tom Stoffel,[1] Aron Habte,[2] and Manajit Sengupta[2]

[1] Solar Resource Solutions, LLC, Louisville, CO 80401 USA

[2] National Renewable Energy Laboratory, Golden CO 80204 USA

Photo from iStock-627281636

IEEE PVSC 50, June 13, 2023

Solar Resource Solutions, LLC

Introduction

- ***How accurate are data from this station?***

- **The challenge:** Estimate the uncertainty of archived, high-resolution, surface measurements of solar resources collected in accordance with accepted best practices in the absence of an independent field reference radiometer.

Image Credit: NREL

Estimating Uncertainty of Solar Resources

The issues:

- Historically, the uncertainty of a data set has frequently been solely represented by either the manufacturer's stated instrument uncertainty or the uncertainty assigned by the calibration process.
- This approach, while providing some basis for data set uncertainty, fails to acknowledge many additional sources of error during field operations that are difficult to account for prior to the measurement.

Approach

Integrate the results from *radiometer measurement uncertainty estimates* and automated *data quality assessments* consistent with the *Guide to the Expression of Uncertainty in Measurements* (GUM).[1]

Pre-Measurement

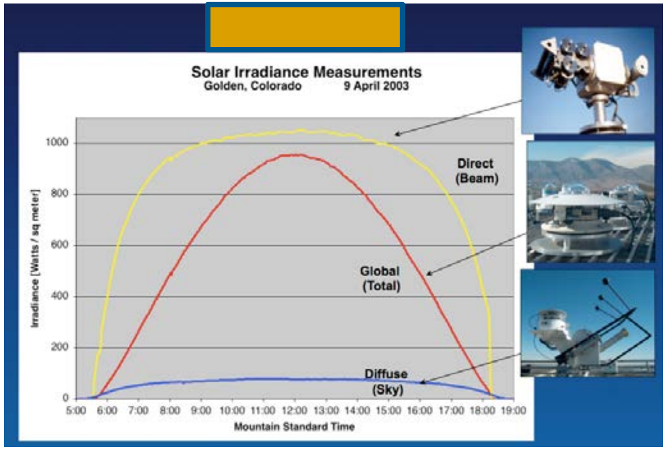
Radiometer Measurement Uncertainties (U_R)

Pyranometers ± x.x%
Pyrheliometers ± x.x%

NREL Radiometer Measurement Uncertainty Tool:

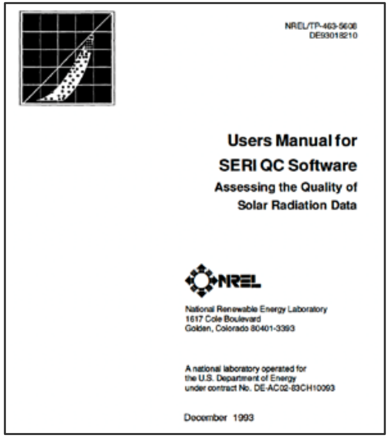
https://midcdmz.nrel.gov/radiometer_uncert.xlsx

Measurement



Post-Measurement

Data Quality Assessment



https://www.nrel.gov/docs/legosti/old/5608.pdf

[1] International Organization for Standardization (ISO). 2008. ISO/IEC Guide 98-3:2008(E): Uncertainty of measurement—Part 3: Guide to the expression of uncertainty in measurement (GUM: 1995). Geneva, Switzerland.

Project Goal

- Produce an *Integrated Solar Resource Uncertainty Software Package* providing a method to assign expanded uncertainty estimates to three-component measured solar radiation data.

- The system will merge static uncertainty information about radiometer measurement performance with the dynamic operational uncertainty information extracted from the data quality assessment.

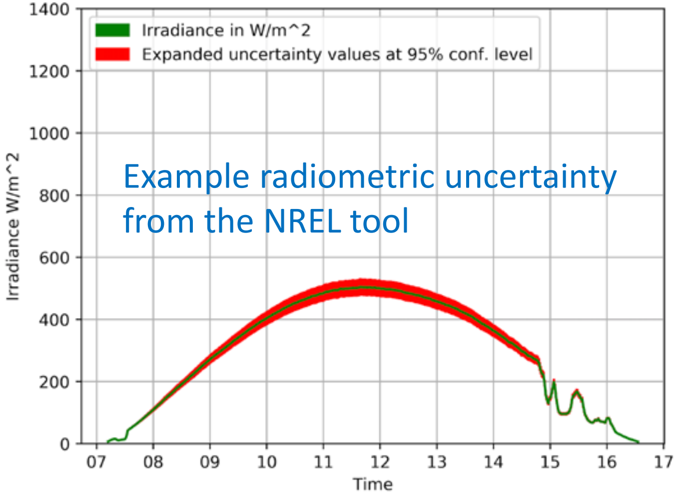
Step 1. Determine Radiometer Uncertainties

NREL Radiometer Uncertainty Tool

Some Sources of Measurement Uncertainty

- Calibration
- Spectral Response
- Zenith Angle
- Data logger uncertainty
- Temperature dependence
- Non-linearity
- Aging

From the tool, the expanded measurement uncertainties for each instrument are provided as input to the operational uncertainty process as U_RGHI, U_RDNI, and U_RDHI.



Example radiometric uncertainty from the NREL tool

https://midcdmz.nrel.gov/radiometer_uncert.xlsx
https://github.com/NREL/SolarResourceTools/tree/master/Solar%20Resource%20Uncertainty%20(SOLARUN)%20Application

Deriving the Expanded Uncertainties

Measurement uncertainty of the three radiometers per GUM:

$$U_{RADS} = 2 \cdot \sqrt{\left(\frac{UrGHI}{2}\right)^2 + \left(\frac{UrDNI}{2}\right)^2 + \left(\frac{UrDHI}{2}\right)^2}$$

where the expanded uncertainties of each radiometer are determined by the NREL tool based on the make, model, and application:

UrGHI = Pyranometer (unshaded)
UrDNI = Pyrheliometer
UrDHI = Pyranometer (shaded)

Step 2. Perform Data Quality Assessment by *SERI QC*

A well-established automated method based on the fraction of normal incidence extraterrestrial irradiance (ETRN)*

Variable	Definition
K_t	Global / [ETRN * cos (Z)]
K_n	Direct / ETRN
K_d	Diffuse / [ETRN * cos(Z)]
Z	Solar zenith angle

$$K_t = K_n + K_d$$

* https://www.nrel.gov/docs/legosti/old/5608.pdf

SERI QC performs the initial evaluation of the incoming data for uncertainty analysis, and its flags provide filtering for suitable data (only *three-component data* that pass routine checks).

Step 3. Determine Operational Uncertainty (U_O)

Rearrange the K-space identity to compute the residual (ideally zero):

$$U_O = (\frac{Kt}{Kn+Kd} - 1) \cdot 100$$

In addition to the radiometer uncertainties, U_O includes errors introduced during field measurement operations:

1. Maintenance frequency—cleaning optics, checking alignments
2. Calibrations—sensor degradation
3. Supporting equipment failure—solar trackers
4. Weather impacts—dust, dew, ice, or snow on optics.

Step 4. Derive the Expanded Uncertainties

We can refine the previous U_{RADS} equation by examining the denominator in the U_O equation: $U_O = (\frac{Kt}{Kn+Kd} - 1) \cdot 100$

The contribution of Kn and Kd in the denominator commonly differ by an order of magnitude; thus, instead, we can rewrite the U_{RADS} expression with uncertainty contributions *proportional to irradiance*:

$$U_{RADS} = 2 \cdot \sqrt{\left(\frac{UrGHI}{2}\right)^2 + \left(\frac{UrDNI \cdot Kn\_frac + UrDHI \cdot Kd\_frac}{\sqrt{3}}\right)^2}$$

where:

Kn_frac = Kn / (Kn + Kd)
Kd_frac = Kd / (Kn + Kd)

Note: Kn_frac + Kd_frac = 1

Step 5. Application of the Method

The U_O determined from the measured data consists of two mutually exclusive uncertainty sources:

1. Radiometer uncertainties (those from manufacturing and calibration)
2. Additional field operational uncertainties attributable to the measurement environment:

$$U_O = U_{RADS} + U_O\text{Field}$$

The goal is to isolate the field operational uncertainties so they can be applied to each measurement.

Application of the Method

The two measures of uncertainty can be separated to form U_OField by subtracting the U_{RADS} from the U_O (but limited to positive numbers):

$$U_O Field = MAX\ [U_O - U_{RADS},\ 0]$$

$U_O Field$ then represents the measurement uncertainty (if any) beyond that of the radiometers' measurement performance.

A zero $U_O Field$ indicates that operations are within the bounds of the radiometer measurement uncertainties.

Application of the Method

With the field uncertainty isolated, it can be merged with the individual radiometer uncertainties according to the GUM protocols to derive an uncertainty for a particular measurement of GHI, DNI, or DHI:

- $U_{95}GHI = 2 \cdot \sqrt{\left(\frac{UrGHI}{2}\right)^2 + \left(\frac{UoField}{2}\right)^2}$
- $U_{95}DNI = 2 \cdot \sqrt{\left(\frac{UrDNI}{2}\right)^2 + \left(\frac{UoField}{2}\right)^2}$
- $U_{95}DHI = 2 \cdot \sqrt{\left(\frac{UrDHI}{2}\right)^2 + \left(\frac{UoField}{2}\right)^2}$

With this method, the expanded uncertainty of the data will never be less than that of the radiometer, but it can be greater if additional field operational uncertainty has been identified.

Limitations

The system is designed to accurately evaluate data acquired using best practices[1] for solar measurements. *It is not intended to evaluate data from neglected or substandard stations.*

- Requires three-component data (GHI, DNI, DHI)
- Cannot evaluate at very low irradiance (DNI < 25 W/m^2)
- Filters out data with blatant errors (high SERI QC flags)
- Will not evaluate data at high zenith angles (near sunrise/sunset).

The process works well for the high irradiance data of greatest interest to solar power applications.

[1] Sengupta, et al. 2021. *Best Practices Handbook for the Collection and Use of Solar Resource Data for Solar Energy Applications: Third Edition*. Golden, CO: National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy21osti/77635.pdf.

Algorithm Evaluation

Data from three well-maintained stations were assembled for analysis:

- National Renewable Energy Laboratory’s Solar Radiation Research Laboratory
- The NOAA SURFRAD network’s Fort Peck and Penn State stations

One-minute data for all of 2021 were acquired for each station.

Algorithm Evaluation

Radiometer uncertainties (U_R) for each station are estimated using the NREL Uncertainty Tool:

NREL

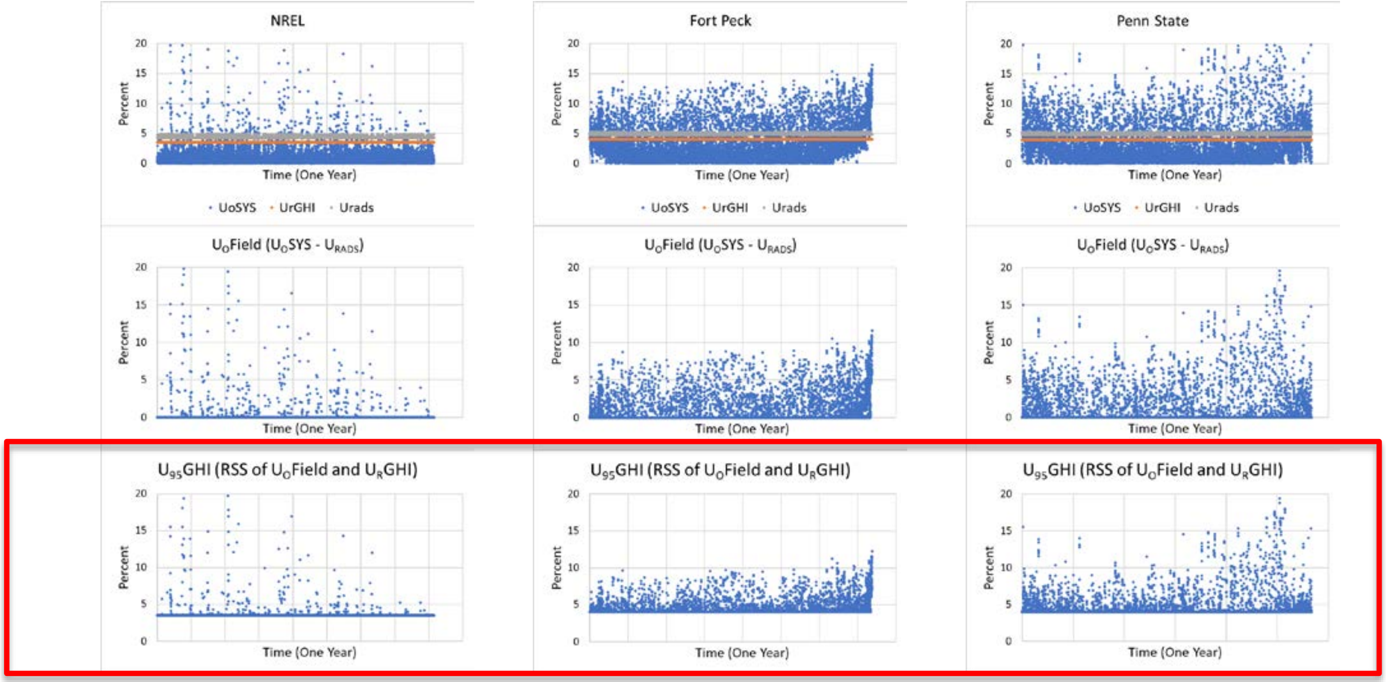
Parameter	Instrument	Value (%)
U_RGHI	Kipp & Zonen CMP22	±3.5
U_RDNI	Kipp & Zonen CHP1	±2.3
U_RDHI	Kipp & Zonen CMP22	±3.5

SURFRAD

Parameter	Instrument	Value (%)
U_RGHI	Spectrolab SR-75	±4
U_RDNI	Eppley NIP	±2.5
U_RDHI	Eppley 8-48	±3.5

Algorithm Evaluation

The plots show each constituent parameter in the uncertainty process for the 1-minute data. The bottom plots show the final $U_{95}GHI$ values.



Algorithm Evaluation

Summary statistics for each constituent parameter in the uncertainty process and the final $U_{95}GHI$ values.

NREL

Parameter	Value (%)
U_OSYS	±1.04
U_OField	±0.12
$U_{95}GHI$	±3.58
U_{RADS}	±4.39
$U_{95}GHI$ exceeds U_RGHI	2.3

Fort Peck

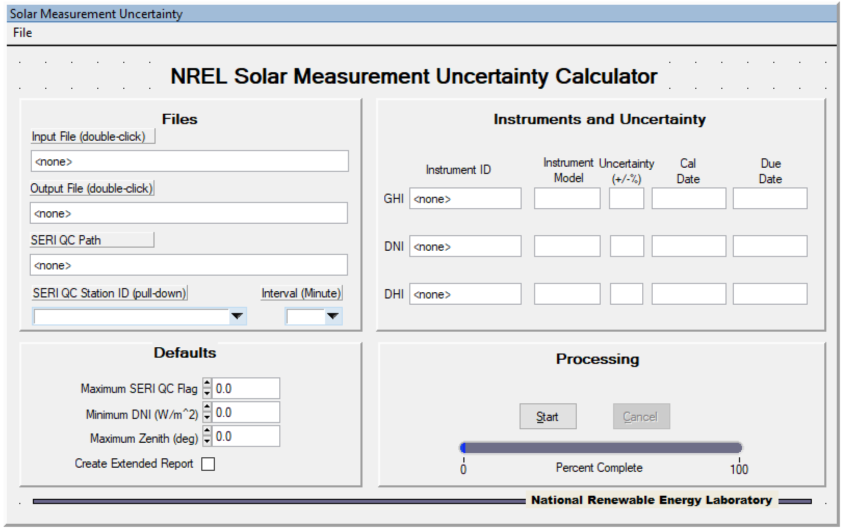
Parameter	Value (%)
U_OSYS	±2.96
U_OField	±0.58
$U_{95}GHI$	±4.24
U_{RADS}	±4.92
$U_{95}GHI$ exceeds U_RGHI	20.4

Penn State

Parameter	Value (%)
U_OSYS	±3.16
U_OField	±0.76
$U_{95}GHI$	±4.38
U_{RADS}	±4.93
$U_{95}GHI$ exceeds U_RGHI	21.3

Software Development

- NREL is developing a stand-alone application to ingest solar measurement data and provide a record-by-record uncertainty evaluation in an output file.
- Work will continue through Fiscal Year 2024.



Conclusions

- A new algorithm has been developed to assess the uncertainty of three-component solar irradiance measurements consistent with GUM.
- The method estimates operational Uncertainties based on *SERI QC*, an existing data quality assessment tool.
- It uses static radiometer measurement uncertainties and an operational uncertainty derived from field data to determine the overall uncertainty of data used for PV.
- The method has been evaluated using 1-minute solar irradiance measurements collected during 2021 according to accepted best practices from three stations.
- After further testing, the resulting software package will be based on the new algorithm and made publicly available.

Thank you

www.nrel.gov

NREL/PR-5D00-86545

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes..

Photo from iStock-627281636

NREL
Transforming ENERGY