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Methodology and calculator for high precision regression fits of pyranometer angular responsivities and the associated uncertainties

Matthew Boyd [1]

National Institute of Standards and Technology (NIST), Gaithersburg, MD, USA

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Abstract

An easy to implement method for accurately utilizing pyranometer incidence angle dependent calibration factors, or responsivities (μV/W/m^2), along with the associated uncertainties has been developed. This method uses algorithms for creating single polynomial functions dependent on the incidence angle to characterize both the pyranometer responsivity and the upper prediction interval of the associated standard uncertainties. Single polynomial functions are easier to implement in spreadsheet software and programming environments than the simpler to formulate piecewise polynomials and splines. The polynomials are of high degree, extrapolated to 0° and 90°, and solved using robust techniques to avoid oscillations and overshoots, which can occur when using other interpolation methods. A free software tool was created that calculates the functions using the algorithms presented in this paper, and it was tested on the calibrated responsivities and uncertainties of 40 pyranometers representing six (6) different models. All of the obtained fits closely represent the data with R^2 values greater than 0.98.
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Keywords: Pyranometer; Responsivity; Incidence angle; Uncertainty

1. Introduction

The default method of converting pyranometer signals to engineering units, as suggested by pyranometer manufacturers and prevalent in the solar resource community, is to divide the pyranometer output signal in micro-volts (μV) by a constant responsivity in μV/W/m^2 to obtain the shortwave irradiance in W/m^2. This approach does not account for the large incidence angle (angle from the surface normal) dependency of the responsivity, nor to a lesser extent the effect of net infrared radiation (*net* IR = IR_{in}–IR_{out}). Responsivities can vary 5% from the middle of a 0° to 70° incidence angle range and cause equally large differences in the measured irradiance. These differences, or errors, can have large impacts on a range of applications, one being solar photovoltaics (PV) where power output is proportional to the irradiance. It has been suggested that a 1% increase in a PV project's yield results in a 10% increase in the project's profitability (Granata and Howard, 2011), so even small improvements in the irradiance measurements can have a large impact on PV's viability and bankability.

Methods to correct for the incidence angle and net-IR response of pyranometers have been published (Myers et al., 2002; Reda et al., 2008), but adoption has been slow due to the more extensive calibration procedure needed to obtain incidence angle dependent responsivities, as well as the added complexity of applying the calibrated responsivities and uncertainties. The National Renewable Energy

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Nomenclature

AM	morning
BORCAL	Broadband Outdoor Radiometer Calibration
c_i	polynomial coefficient of the *i*th degree
G	total irradiance, W/m^2
G_{bn}	beam (direct) normal radiation, W/m^2
G_d	diffuse horizontal irradiance, W/m^2
GUM	*Guide to the Expression of Uncertainty in Measurement*
IR	infrared radiation, W/m^2
N_{df}	number of degrees of freedom
NIST	National Institute of Standards and Technology
NREL	National Renewable Energy Laboratory
PM	afternoon
PV	photovoltaic
R	shortwave responsivity, μV/W/m^2
R^2	coefficient of determination
R_{net}	net-IR responsivity, μV/W/m^2
RSS	root-sum-square
SER	standard error of regression
U_{95}	expanded uncertainty at a 95% confidence level
u_c	combined standard uncertainty
V	voltage, μV
W_{net}	net infrared radiation, W/m^2
x_i	*i*th measured or reference data value
y_i	*i*th modeled or measured data value

Greek symbols

θ	incidence angle, °

Subscripts

bn	beam normal
c	combined
d	diffuse
df	degrees of freedom
i	data point index or polynomial degree
net	input minus output

Laboratory (NREL) offers the only known calibration service that provides the incidence angle dependent responsivities, termed the Broadband Outdoor Radiometer Calibration (BORCAL) (Reda et al., 2008), but as customary with calibration services they do not provide an assessment of how the results may be employed.

The responsivity as a function of incidence angle can be modeled using piecewise polynomial regression, like those used by Reda et al. (2008), but the complex regression functions needed for the fit are not easily transferrable to other software and do not include extrapolations beyond the measured range, most importantly to a 0° incidence angle. Single polynomial regression functions are much simpler to implement, but direct solutions using least squares methods like that derived by Reda (1998) can result in overshoots and oscillations between measured data points; they also do not include extrapolations outside the measured range. Lester (2006) presents functions based on the cosine of the incidence angle for modeling the responsivity, but the simple four-term functions do not closely follow the complex responsivity curve or include extrapolations outside the measured range. Furthermore, the stepwise regressions needed to create these individualized functions rely on data measured over a significant time period which is not feasible for most calibrations.

This paper presents an algorithm for creating single polynomial regression fits of pyranometer responsivities as a function of incidence angle that include extrapolations outside the measured range to 0° and 90°. This paper is not aiming to understand or model the perceived angular response, nor evaluate the validity of the calibration data or calibration service. These calculated functions are interpolations of the calibrated responsivities for easier implementation, not pyranometer calibration curves. They should only be used for similar conditions as those during the calibration, namely for times when the majority of the irradiance is beam (direct) irradiance and thus coming largely from the same incidence angle. The regression functions can be made for either a full range of azimuth (compass direction) angles (i.e., 90° incidence angle in the morning to near 0° at solar noon to 90° incidence angle in the afternoon) or irrespective of azimuth (i.e., 0° to 90°). A second algorithm is also presented for creating single, simple polynomial regression functions of the uncertainty of the responsivity as a function of incidence angle. These two algorithms are employed in a freely distributable software tool that allows easy implementation of the functions for data measured in a BORCAL or similar procedure. This software is then used to test calibration data from six (6) different models of pyranometers.

2. Responsivity regression

2.1. Measurements

Calibration procedures for indirectly measuring the incidence angle dependent pyranometer responsivities include those by Myers et al. (2002), Reda (2008), and ASTM G167 – 05 (2010). These methods can capture the incidence angle response of the pyranometer during the calibration period and correct for the net-IR response by using the following functional relationship: