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DERIVING A LATITUDE-OPTIMIZED PYRANOMETER CALIBRATION FACTOR

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ABSTRACT

Work in recent years has produced improvements in determining the solar resource by better characterizing the responsivity of pyranometers. The calibration process can characterize a common responsivity dependency on the solar zenith angle, which can then be used to compensate for sensor variations during instrument deployment. However, daily compensation throughout the range of zenith angles might not be necessary for applications requiring only annual irradiance. This paper describes a method of identifying a measurement bias due to latitude of deployment and optimizing an instrument's clear-sky responsivity for annual solar radiation measurements based on the relationship between solar zenith angles and the latitude.

1. SOLAR ZENITH ANGLE AND LATITUDE

Many pyranometers have a well-known dependency of responsivity (RS) on the incident angle of the sun to the pyranometer detector (solar zenith angle) (1). This effect is demonstrated in Fig. 1, a plot of calibrated radiometer (Eppley model PSP) responsivity as a function of zenith angle. The differing responsivity curves for morning and afternoon data likely are caused by imperfect leveling of the instrument sensor or other variations in the sensor surface.

As a tool for automated application of responsivities to massive amounts of measurement data, a responsivity function was developed (2). This function, which fits a cosine curve to multiple data points throughout the zenith angle range of calibration data, can be programmed to return an estimated instrument responsivity for any zenith angle from morning or afternoon. Fig. 2 shows a plot of the responsivity function for the calibration data in Fig. 1.

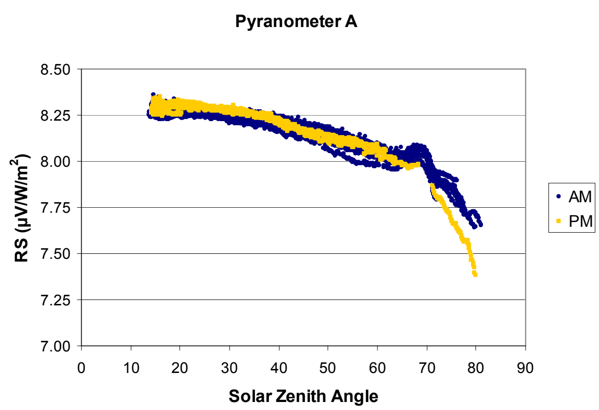

Fig 1: Example responsivity calibration data for test instrument.

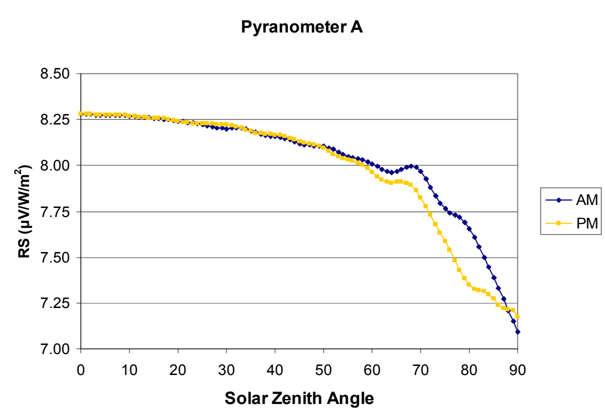

Fig. 2: Responsivity function derived from Pyranometer A calibration data.

As is typical of our calibration process, the full range of zenith angles was not available during the calibration event. As a result, note that the function was interpolated and extrapolated to provide responsivities from zero to 90 degrees.

Ideally, all voltage readings from an instrument would have the appropriate zenith angle responsivity applied, which in itself is not a straightforward process because knowledge of the sky radiance distribution is required (3). However, in practice many data loggers are programmed with a single calibration factor ($C_f \propto 1/RS$), either for the sake of simplicity or because the measurement application does not require critical time-series measurements (for example, monthly or annual means). It is for annual summary applications that a latitude-optimized pyranometer calibration factor can increase the accuracy of measurements.

One can easily visualize the effect of latitude on an instrument's sensitivity. The minimum daily solar zenith angles (highest solar elevation angles) incurred at any given site are determined by latitude and season: The range of the daily minimum zenith angle throughout the year is ±23.5 degrees from the site latitude. Hence, an instrument's clear sky responsivity at lower zenith angles would not be encountered at higher latitudes, and a single-number sensitivity that excludes instrument effects at lower zenith angles would be appropriate for high latitude sites.

2. LATITUDE-OPTIMIZED RESPONSIVITY

Our discussion of a latitude bias in pyranometer measurements focuses on four areas: 1) Deriving a latitude-optimized instrument responsivity, 2) describing an alternate method more suitable for bulk processing, 3) measurement uncertainty, and 4) applying the latitude-optimized responsivity.

2.1 Deriving a Latitude-Optimized Responsivity

Because the instruments are calibrated under clear sky conditions, the zenith angle effect seen in Fig. 1 is limited to the direct beam component of the global solar radiation. Therefore, the weighted contribution of a responsivity at any given zenith angle is a function of the cosine of the zenith angle. A latitude-optimized instrument responsivity can be determined from a composite of weighted responsivities for all zenith angles sampled at a small time interval for each day throughout the year:

(1) $$RS_{opt} = \frac{\sum RS(z) \bullet \cos(z)}{\sum \cos(z)}$$

Where:

RS(z) = responsivity function for a given zenith angle

cos(z) = cosine of the given zenith angle

Fig. 3 shows the optimized instrument responsivity for the data in Fig. 2, derived in this manner for latitudes zero through 90. The scale has been set to that of Fig. 2, and the variation in responsivity throughout the range of latitudes for this instrument is about 4%.

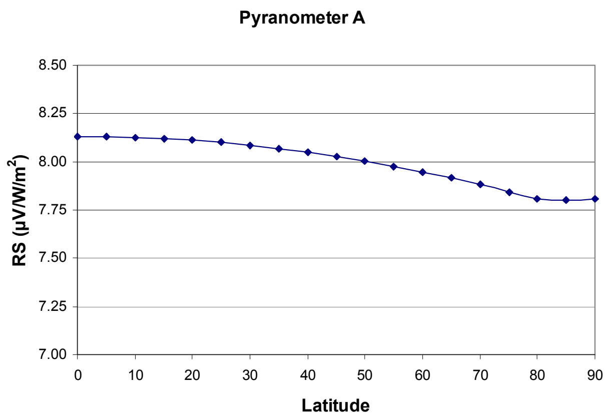

Fig. 3: Latitude optimized responsivities for instrument data in Figs. 1 and 2.

2.2 A Simplified Derivation

In practice, calculating the optimized responsivity using equation (1) requires tens or hundreds of thousands of calculations over an entire year at the desired latitude; for example, for each sunup minute of the year. When a latitude profile (as in Fig. 3) is desired for each of multiple instruments, the process is simplified by initially calculating the annual solar zenith angle frequency distribution for all latitudes (or a reasonable interval of latitudes). The frequency of a given zenith angle bin at a given latitude over the year may be calculated for all sunup periods as:

(2) $$F_z = \frac{N_z}{N_{tot}}$$

Where:

F_z = frequency of the given zenith angle

N_z = occurrences of the given zenith angle

N_{tot} = occurrences of all zenith angles

The solar zenith angle frequency distribution calculated using a one-minute time interval for latitudes 0-90 (at five-degree intervals) is shown in Fig. 4.

Using the frequency distribution, the process is thus reduced to a few dozen calculations at each desired latitude:

(3) $$RS_{opt} = \frac{\sum_{z=0}^{90} RS(z) \bullet \cos(z) \bullet F(z)}{\sum_{z=0}^{90} \cos(z) \bullet F(z)}$$

Where:

z	= zenith angle
$RS(z)$	= responsivity function for a given zenith angle
$cos(z)$	= cosine of the zenith angle
$F(z)$	= proportion (frequency) of the annual distribution for the given zenith angle

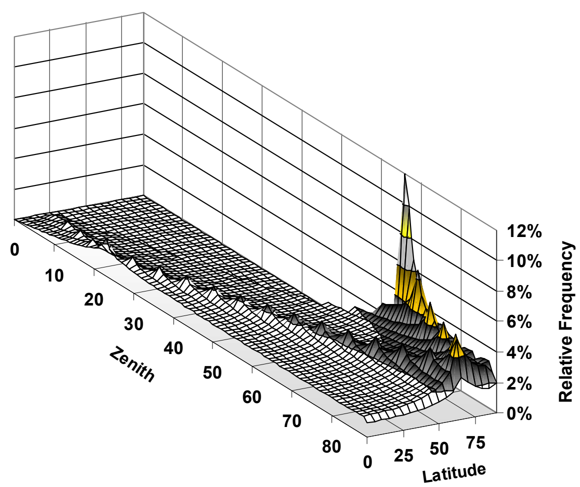

Fig. 4: Annual solar zenith angle distribution by latitude.

2.3. Uncertainty

The responsivity function (Fig. 2) is assigned a single uncertainty based on the maximum variability of data around the selected fit points and includes uncertainty from other sources such as calibration reference instruments and the data acquisition system. Because parts of the responsivity function are based on extrapolated data, function uncertainty is defined only for the zenith angle range that encompasses measured data. The method of deriving a latitude-optimized responsivity described here will likely include responsivities at zenith angles with undefined uncertainty. *Therefore, under such conditions, this method yields a responsivity with an undefined uncertainty.*

In practice, however, it might be possible to make a useful estimate of the measurement error despite using extrapolated function data. For mid- to high-latitude locations, the optimization method places the greatest weight on responsivities from zenith angles that fall in the range of measured data and, conversely, minimizes influence from portions of the function with an undefined uncertainty. Thus, we derive an estimate of the error using the root sum square of the responsivity function uncertainty and the range of responsivities (variability) used to form the latitude-specific responsivity:

(4)
$$+e = \sqrt{\left[100 \bullet \left(\frac{RS_{\max} - RS_{opt}}{RS_{opt}}\right)\right]^2 + [U_{fctn}]^2}$$

$$-e = \sqrt{\left[100 \bullet \left(\frac{RS_{opt} - RS_{\min}}{RS_{opt}}\right)\right]^2 + [U_{fctn}]^2}$$

Where:

$\pm e$	= positive and negative estimated error (percent of reading)
RS_{opt}	= latitude-optimized responsivity
RS_{max}	= maximum responsivity used for RS_{opt}
RS_{min}	= minimum responsivity used for RS_{opt}
U_{fctn}	= uncertainty of the responsivity function (percent)

Table 1 shows the estimated error by latitude for Pyranometer A shown in Fig. 1. Since the range of included zenith angles decreases as latitude increases, this method provides a correspondingly smaller estimate of measurement error.

While the numbers in Table 1 may seem unusually large, they are necessarily so because of the zenith angle biases. These error estimates assume no knowledge of the zenith angle for a given measurement and are typical of single number responsivities for an instrument similar to that in Fig. 1. However, with annual summations or averages, much of the zenith angle biases cancel throughout the year. Under ideal but admittedly unrealistic conditions (perpetually clear skies), the measurement error in annual statistics may be reduced to the uncertainty of the responsivity function. Nonetheless, the latitude-optimized responsivity described here reduces any bias introduced by the latitude of deployment.

TABLE 1: LATITUDE-OPTIMIZED RESPONSIVITIES WITH ERROR ESTIMATES

Latitude	RS	+Error (%)	–Error (%)
0	8.13	2.49	12.17
5	8.13	2.50	12.16
10	8.13	2.53	12.12
15	8.12	2.59	12.06
20	8.11	2.67	11.97
25	8.10	2.78	11.85
30	8.09	2.86	11.69
35	8.07	2.94	11.51
40	8.05	3.05	11.30
45	8.03	3.07	11.07
50	8.00	3.23	10.79
55	7.98	3.45	10.47
60	7.95	3.37	10.16
65	7.92	3.48	9.85
70	7.88	3.49	9.44
75	7.84	3.66	8.96
80	7.81	3.37	8.61
85	7.80	3.03	8.49
90	7.81	2.94	8.58

2.4 Applicability of the Derived Responsivity

The zenith angle dependency of an instrument has a profound effect on the shape of its latitude-optimized responsivity across the range of all latitudes. An instrument with an insignificant dependency would also show a relatively flat latitude-optimized curve. However, it is possible for an instrument with a significant dependency to produce a fairly flat latitude-optimized curve. Fig. 5 shows the responsivity function for such an instrument (an Eppley model 8-48), and Fig. 6 shows its relatively flat latitude-optimized curve (for comparison, the scale in Figs. 5 and 6 have been ranged similar to that of Figs. 2 and 3). For this instrument, the range of responsivities across all latitudes varies less than 1%.

Under isotropic sky conditions (such as encountered with overcast skies), the cosine influence of the direct normal radiation is removed, and the sensor receives uniform radiation from all points in the sky dome. Under such conditions, the instrument's responsivity to *all* solar zenith and azimuth angles is significant, regardless of the latitude. Hence, any responsivity determined with clear sky conditions may not be correct for isotropic skies, nor may a latitude-optimized responsivity derived from that data. For isotropic sky conditions, our calibration process derives a single composite responsivity by weighting the instrument's sensitivity to all zenith angles. (We have found that this isotropic responsivity is typically quite close to the latitude-optimized responsivity for the equator.) Therefore in practical use, the instrument's responsivity lies somewhere between its latitude-optimized responsivity and its isotropic responsivity, depending on the annual spatial and temporal distribution of clouds (or more accurately, of sky radiance). Hence, the user must have knowledge about measurement site climatology to best determine the applicability of instrument calibration results.

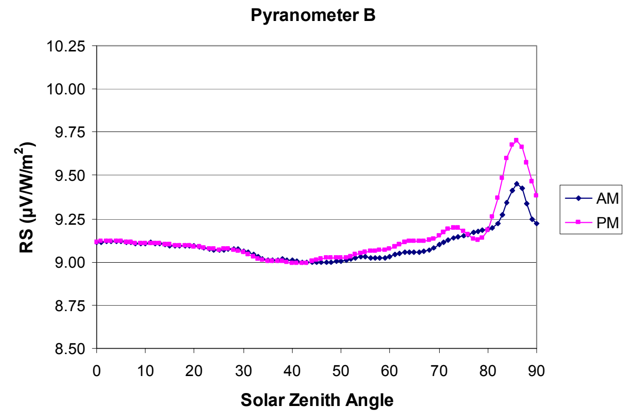

Fig. 5: Derived responsivity function for instrument with relatively flat latitude-optimized response (see Fig. 6).

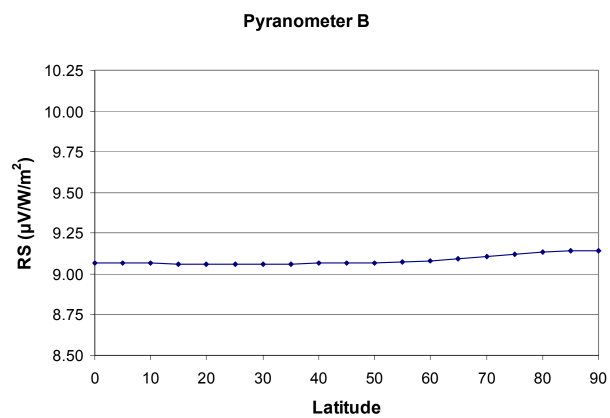

Fig. 6: Latitude-optimized responsivities for Pyranometer B (Fig. 5).

3. CONCLUSIONS

We have identified and demonstrated a potential measurement bias attributable to the latitude of deployment for a pyranometer. Using a weighting algorithm, a latitude-optimized responsivity was derived to help remove or minimize the bias for annual data sets. Because of seasonal variations in the distribution of zenith angles, this method is optimized for annual or multi-annual data sets and is not recommended for other time scales.

The calibration process described here is most applicable for clear-sky conditions. However, this method offers a better understanding of an instrument's measurement characteristics. This information, combined with the knowledge of a measurement site's climate, will contribute to an understanding that will help site operators choose the best instrument and the appropriate responsivity to most accurately determine the solar radiation resource at the site.

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