Evaluating calibrations of normal incident pyrheliometers

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ABSTRACT

When an Eppley Normal Incident Pyrheliometer is calibrated against an Eppley Hickey Frieden Absolute Cavity Radiometer, the instrument systematically deviates from the absolute cavity readings. The reason for this deviation is not understood. Comparisons are made between one pyrheliometer and an absolute cavity radiometer on selected clear days over a period of 8 months in Eugene, Oregon. The ratios of the readings from the two instruments are correlated against wind speed, pressure, temperature, relative humidity, beam intensity, and zenith angle to determine if any of these parameters statistically influence the calibration process. Wind speed, pressure, beam intensity, and air mass are shown to be statistically significant factors in determining the responsivity of the normal incident pyrheliometer. The results of these tests are evaluated and discussed. Use of air mass instead of zenith angle is proposed for calibration reports.

Key words: Beam irradiance, NIP, pyrheliometer, HF, absolute cavity radiometer, calibration

1. INTRODUCTION

As new solar energy systems are being designed and tested, the accuracy of the solar irradiance data is becoming more important. Models used to estimate and model system performance can only be as good as the input data used to develop the models. Characterizing system performance and optimizing system design are also limited by the accurate measurement of the incident energy. Therefore it is important to have quality irradiance data and, as much as feasible, develop models to remove any systematic errors in the measured data.

Eppley Normal Incident Pyrheliometers (NIPs) have proven to be reliable instruments in the field and have maintained their calibration over decades of use in the field [1]. Typical NIP calibration uncertainty found by the National Renewable Energy Laboratory (NREL) during their Broadband Outdoor Radiometer Calibration (BORCAL) runs is between ±1 and 2%. NREL uses a Hickey Frieden Absolute Cavity Radiometer (HF) for these calibrations and the HF radiometer's calibration is maintained against the international standard and is calibrated periodically in Davos, Switzerland during the international pyrheliometer comparisons. An HF radiometer is self-calibrating and uses electrical measurements to improve the accuracy of the measurement. The absolute accuracy of an HF radiometer is better than 0.5%.

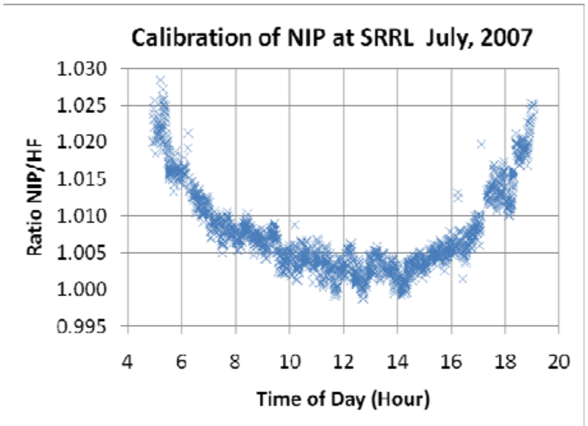

Fig. 1: Calibration data of Eppley NIP 18948E6 as compared with the beam data from Eppley Absolute Cavity Radiometer HF 31104. Plot uses original calibration value. NIP values are about 0.3% too high at a 45° zenith angle.

When NIPs are calibrated against absolute cavity radiometers, the resulting responsivities vary systematically over the day (Fig. 1). This plot is from an NREL BORCAL run for the NIP that is being studied and is typical of NIP responsivities. Some instruments may exhibit more or less asymmetry in their plots, but this "smile" in the responsivity data is fairly universal. The exact cause for this shape in responsivity is unknown and is being investigated in this study. This article looks at possible correlations between meteorological and physical parameters in an attempt to better isolate the possible causes for this systematic deviation in the NIP responsivity.

This article is organized as follows. First a description is given of how the data for this study was obtained. This is followed by an analysis of the data and a discussion of the findings. A summary of the results is then given along with suggestions for further work.

2. CALIBRATION DATA

As part of the Oregon Best's effort to equip university faculty and other researchers in Oregon with high quality instruments for solar energy research and to build the Support Network for Research and Innovation in Solar Energy (SuNRISE), funds were made available for the purchase of an Eppley Absolute Cavity Radiometer (AHF). The equipment obtained for SuNRISE is shared by researchers across the state and is available for use by the solar industry.

An AHF consists of a balanced cavity receiver pair attached to a wire-wound and -plated thermopile. The blackened cavity receivers are fitted with heater windings which allow for absolute operation using the electrical substitution method, which relates radiant power to electrical power. The forward cavity views the direct beam irradiance through a precision aperture. The precision aperture area has a 5° field of view. The rear receiver views an ambient temperature blackbody [2]. The control box for the AHF was modified to use NREL's software program, a different relay board, and a 1 ohm resistor in place of the 10 ohm resistor usually used.

The AHF, used in this study, has its calibration traceable to the international standard through a pyrheliometer inter-comparison conducted at NREL against its reference AHF. The NREL AHF is used in the international pyrheliometer inter-comparison that sets the international calibration standard and therefore instruments calibrated at NREL have their calibration traceable to the international standard.

The AHF and associated electronics are connected to a National Instruments GPIB ExpressCard that is plugged into a laptop computer to record and format the reference beam data. The AHF is calibrated before and after each 12-minute run and data are collected every 20 seconds. This is the method used at the pyrheliometer inter-comparison and it was used to check the calibration of the AHF.

Eppley Labs lists the NIP characteristics as follows:

- Sensitivity: approx. 8 $\mu V/Wm^{-2}$.
- Impedance: approx. 200 Ohms.
- Temperature Dependence: ±1% over ambient temperature range -20 to +40°C.
- Linearity: ±0.5% from 0 to 1400 Wm^{-2}.
- Response time: 1 second (1/e signal).
- Aperture 5.7°

The response time for the AHF is on the order of 2 seconds and is similar to that of the NIP. The absolute accuracy of the AHF is better than 0.5%.

The NIP and meteorological data are connected to a Campbell CR10x data logger that records the average data over one-minute intervals. Besides the beam data from the NIP, global, diffuse, temperature, wind speed, relative humidity, and atmospheric pressure are measured.

The AHF and NIP were compared on five clear day periods October, 8, 2009, December, 4, 2009, March 18, 19, 2010, April 23, 2010, and May, 13, 2010. Comparisons will also be made this summer to produce a more comprehensive data set that is representative of all seasons. Utilizing data from a variety of conditions helps reduce the chance that seasonal patterns influence the comparisons. In addition, a wider variety of meteorological conditions will be represented in the comparisons.

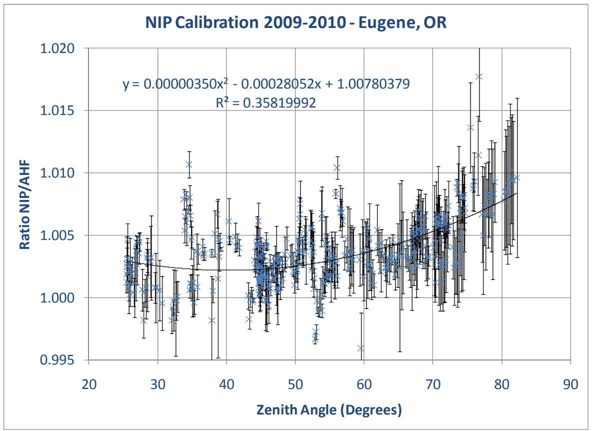

Fig. 2: Plot of NIP/AHF ratio against zenith angle. R^2 is about 0.358, meaning that the ratio correlates with zenith angle. The equation for the fit is given in the figure.

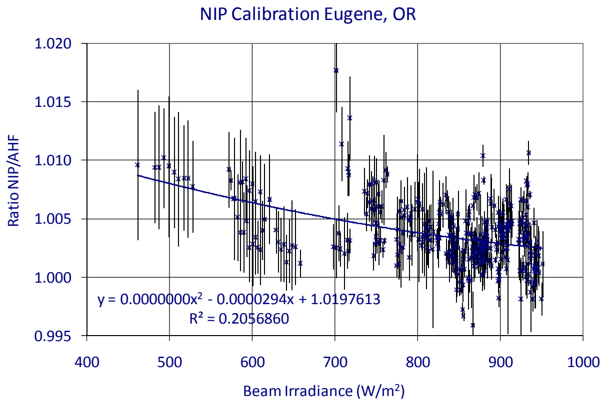

Fig. 3: Plot of NIP/AHF ratio against beam irradiance. R^2 is about 0.206, meaning that the ratio correlates with beam irradiance intensity.

3. CORRELATING AHF DATA WITH NIP AND METEOROLOGICAL DATA

Because the AHF is measured once every twenty seconds and the NIP values are integrated over one minute, it is necessary to average the AHF data to compare it with the NIP values. Four AHF readings, the beginning reading, the 20 second reading, the 40 second reading, and the end reading are averaged. Since clear periods with stable readings were used in this study the averaging process should introduce little uncertainty into the comparison. The data analysis program classifies some of the AHF measurements as unstable when the readings vary beyond set limits. All four measurements used for the average had to be stable for the value to be used in these comparisons. Periods with nearby clouds were also eliminated from the comparison data set.

For each averaged reading, the standard deviation of the reading was also collected and this variation is used to put "error bars" on the values. The standard deviations were plotted against incident radiation and three data points were eliminated because their standard deviation was significantly greater than the rest of the data points for the given level of irradiance. Data with larger deviations in the morning and evening hours caused by more rapid changes in the beam irradiance were not eliminated because the deviations were not caused by changing atmospheric conditions but by changes in the air mass making the beam irradiance change more rapidly. Therefore in plots that will be shown, larger "error" bars in the morning and evening hours do not necessarily indicate that the data are less reliable but that there was a larger change in irradiance during the minute interval.

3.1 Comparison of AHF and NIP Data

The figures, discussed in this section, show plots the ratio of the NIP values divided by corresponding AHF measurements against various meteorological variables and the zenith angle. As seen in Fig. 1, the NIP/AHF ratio varies with time of day in a symmetric manner and hence will vary as a function of zenith angle. Fig. 2 shows the correlation of the ratio as a function of zenith angle. There is a fairly good correlation between the zenith angle and the NIP/AHF ratio.

The intensity of the direct beam irradiance also changes with time of day. Fig. 3 shows the correlation between the NIP/AHF ratio and the intensity of solar radiation. The linearity of the NIP is quoted as better than 0.5%. The Eppley linearity tests were performed indoors in a controlled environment. The changes seen are larger than what one would expect from any non-linearity in the response. The zenith angle and beam intensity are not independent variables and since the fit with zenith angle is better than that to intensity, the variation will be assumed to be mostly from zenith angle.

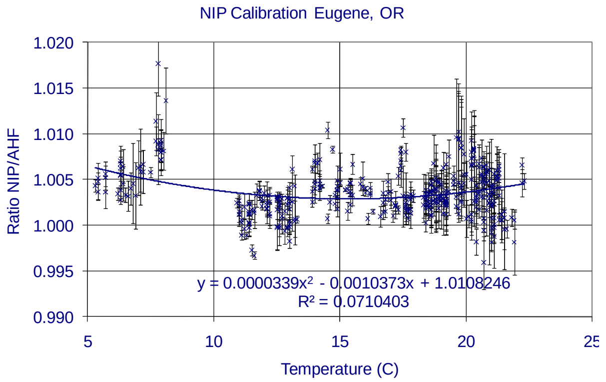

Fig. 4: Plot of NIP/AHF ratio against temperature. R^2 is about 0.071, meaning that the ratio does not correlate well with temperature. Note the limited range of temperature readings. Some temperature dependence is expected in the summer when temperatures reach the 30 to 40 °C range.

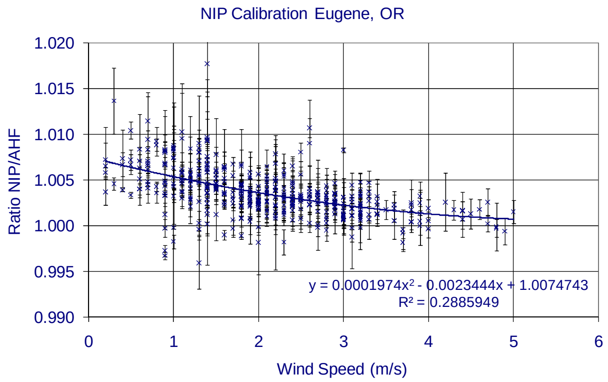

Fig. 5: Plot of NIP/AHF ratio against wind speed. R^2 is about 0.289, meaning that the ratio correlates well with wind speed.

When an Eppley NIP is purchased, it comes with a plot of responsivity verses the temperature. The responsivity of all thermopile instruments will vary somewhat with ambient temperature. In an earlier paper [3], utilizing a different NIP, a temperature dependence of the responsivity was measured and the results were consistent with those found at Eppley Labs. However, no clear temperature dependence was found in the data with the NIP under study [Fig. 4]. The temperature range in the current was limited and a dependence on temperature may become apparent with runs at higher temperatures.

Among the meteorological parameters that might have an effect on the NIP calibrations is wind speed. However, there is no clear evidence in the literature showing wind speed correlates with the NIP responsivity. With the NIP under study, there is a clear correlation of the NIP responsivity with wind speed and this is shown in Fig. 5. The output of the NIP decreases with respect to the AHF measurements as the wind speed increases. It is unclear what mechanism would cause this trend.

Another possible correlation is with relative humidity (Fig. 6). There does not seem to be much of a correlation with relative humidity.

Atmospheric pressure is another meteorological parameter that is measured. Fig. 7 plots the NIP/AHF ratio against air pressure. There is a good correlation, but the amount of data at higher pressures is limited.

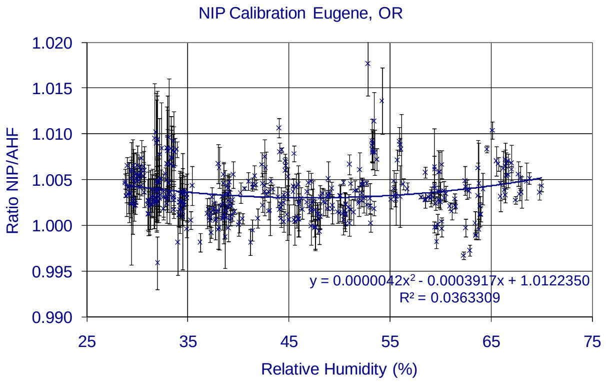

Fig. 6: Plot of NIP/AHF ratio against relative humidity. R^2 is about 0.036, meaning that the ratio does not correlate well with relative humidity. Note limited range of relative humidity. It is uncertain if higher humidity will affect the comparison.

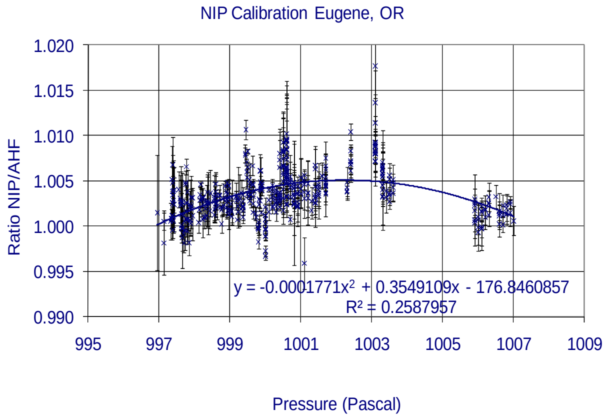

Fig. 7: Plot of NIP/AHF ratio against atmospheric pressure. R^2 is 0.259, indicating that the ratio does correlate well with atmospheric pressure.

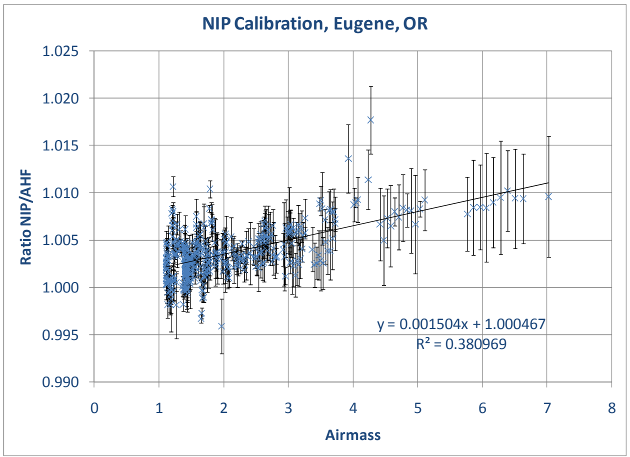

Fig. 8: Plot of NIP/AHF ratio against air mass. R^2 is 0.38, showing a strong correlation between the ratio and air mass.

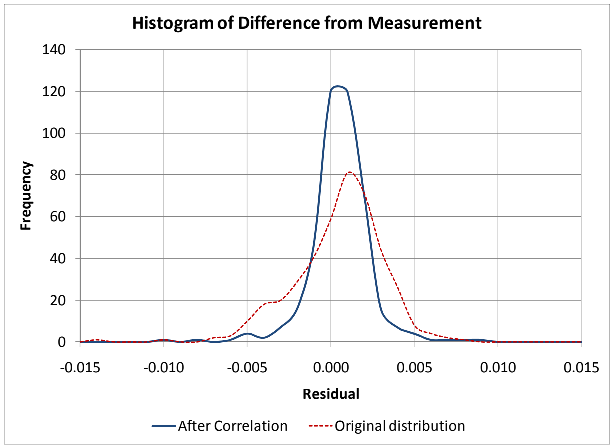

Fig. 9: Solid line is the frequency distribution of the residuals from correlation. The dotted line is the frequency distribution of the NIP/AHF ratio values from the average ratio value.

The correlation with air mass was also examined since the NIP/AHF ratio correlates with zenith angle and pressure (Fig. 8). It turns out that the correlation with air mass produces the largest R^2 (0.381) of all the correlations.

4. REGRESSION ANALYSIS

Now that we have a rough idea of how the NIP/AHF ratio varies with the different parameters, the relationship is studied using a multivariate regression. As expected, the regressions using temperature and relative humidity are not statistically significant. The regressions between irradiance, zenith angle and air mass are all similar and the best result is obtained using air mass.

Table 1: Correlation Results

Parameter	Coefficient	Standard Error of Coefficient
Intercept	-86.0597	15.5614
Air mass	0.00117	0.00009
Barometric Pressure	0.1736625	0.0310675
Barometric Pressure Squared	-0.0000866	0.0000155
Wind Speed	-0.000596	0.0001207

The ratio of the NIP to AHF measurements was correlated against the air mass, barometric pressure, and wind speed. Attempts to correlate the ratio against ambient temperature did not produce statistically significant results. The results of the regression analysis are shown in Table 1. The standard error for the analysis was 0.00179. Note that the air mass parameter is the most significant parameter (and least uncertain).

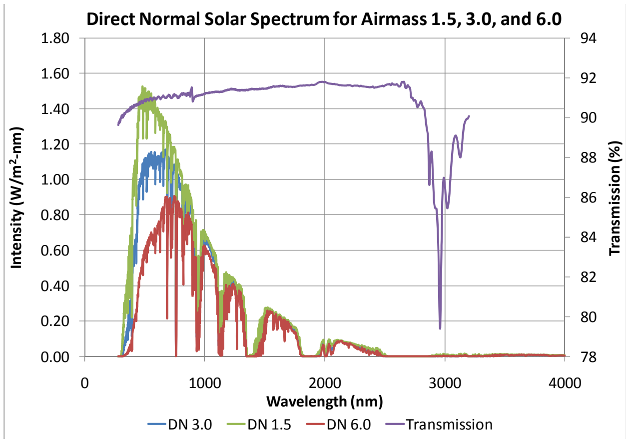

Fig. 10: Plot of the solar spectrum for three different air masses. Also included is the transmission of a NIP window. The scale on the right is percent transmission.

The correlated results reduced the spread of the ratio by about 1/3. This is shown in Fig. 9, which plots the histogram of the residuals. For comparison, a histogram of the difference of the NIP/AHF ratio to the average ratio is also plotted.

5. EFFECT OF AIR MASS

There is a significant dependence of the NIP/AHF ratio on air mass. Air mass affects the solar spectrum and the more atmosphere the beam irradiance encounters, the greater the change in spectrum. For example, on clear days, the atmosphere preferentially scatters blue light. The more atmosphere traversed, the more blue light will be scattered (Fig. 10). The Smarts2 model [4] was used,

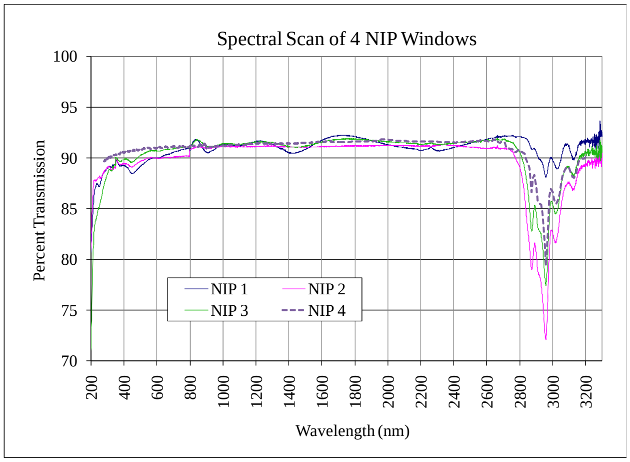

Fig. 11: Spectral scan of 4 NIP windows. Three of the scans were performed using a Cary 5e spectrophotometer by Patrick Disterhoft at CIRES at U. Colorado and NIP 4 was obtained using a Perkin Elmer Lambda 1050 spectrophotometer.

with Shettle and Fenn rural aerosols, to generate the solar spectra in Fig. 10.

Two NIP components can be affected by the spectral change. The transmission of the NIP window is dependent on the spectral wavelength, and the absorption of light by the detector. For NIPs, Eppley uses a 1-mm thick window of Infrasil II quartz. While the transmission of light is fairly constant over a wide range of wavelengths, it does vary. To estimate the spectral affect on the NIP/AHF ratio, the transmission of several NIP windows were measured (Figs. 10, 11). Note that the AHF was run without a window.

The spectral transmission of four NIP windows is shown in Fig. 11. Some of these windows have been exposed in the field for more than 10 years. While these windows were cleaned before measurement, it is possible that contaminants or scratches on the window could affect the measurements. Transmission measurements varied depending upon the precise location of the spectrophotometer beam on the window. In general, the transmission varies from around 89% at a wavelength of 300 nm to 91% at 2700 nm.

As air mass increases, the distribution of the wavelength changes since short wave irradiance is preferentially scattered by the air molecules (Rayleigh scattering). At a wavelength of 500 nm, the beam irradiance is reduced by over 50% when the air mass goes from 1.5 to 6. At a wavelength of 1000 nm, the beam irradiance is reduced by only 10% when the air mass goes from 1.5 to 6. Because the transmission of light through the NIP window changes with wavelength and the spectral distribution changes with air mass, the percentage of beam irradiance transmitted through the NIP window will change with air mass. Initial efforts were made to estimate the magnitude of the change in responsivity with the shift in spectral distribution.

The total beam irradiance transmitted through the window can be estimated by multiplying the modeled solar spectrum by the percent transmission of each wavelength. The percent of beam irradiance transmitted is calculated by dividing the transmitted irradiance by the sum of the spectral beam irradiance. This percentage changes with air mass. This process was run on all four tested windows and the average transmission through the NIP window increased, when air mass was increased from 1.5 to 6, from 0.1% to 0.3% depending on the transmission curve used in the analysis. This value will vary depending on the aerosol mix used to estimate the spectrum.

6. DISCUSSION

Billions of dollars are now being invested in solar energy systems being deployed around the world and there is a demand for higher quality irradiance measurements for data that are being used to evaluate the performance of these systems and to identify techniques that improve the system performance. Direct beam measurements are especially important for concentrating systems but are also used to obtain better measurements of total irradiance. Absolute cavity radiometers have an absolute accuracy of better than 0.5% but are expensive and require supervised handling to get the best results. Pyrheliometers are more rugged but have an absolute accuracy in the range of 1 to 2%. It would be useful if systematic errors in these pyrheliometers could be indentified so that more accurate estimates of the solar resource can be made and any skewing of the analysis by systematic errors can be eliminated.

Quantifying systematic errors is not easy because there are many factors that can affect the calibration of Eppley NIPs. These range from tracking alignment errors, to pyrheliometer detector temperature response, to transfer errors relating the reference instrument calibration to the international standard. Identifying and associating systematic errors to specific Eppley NIPs has been difficult and while each NIP performs in a similar manner each year when calibrated under similar circumstances, associating any systematic variation with other parameters has been difficult. In this study, one NIP was studied during various times of year to perform the calibrations under a variety of conditions. For this NIP, the wind speed, barometric pressure, and air mass were found to systematically affect the responsivity of the instrument when compared with the AHF reference instrument. Temperature and relative humidity did not appear to systematically affect the calibration of this instrument. The NIP was calibrated over a limited temperature range and it is expected that there will be systematic temperature effects over a wider range of environmental conditions.

The spectral transmission of the NIP window was found to affect the responsivity of the NIP. The responsivity of the NIP increased by 0.1 to 0.3% as the air mass increases from 1.5 to 6. This spectral transmission of the NIP window accounts for between 15 and 50% of the air mass effect seen in the calibration data. The causes for other responsivity increases with air mass are unknown, but one cause might be a small spectral dependence in the absorption of the NIP detector. In addition, a small non-linearity of the NIP response may also play a role, although this is difficult to separate from spectral and air mass affects.

In this study an increase in the wind speed was found to reduce the NIP/AHF ratio. Wind speed is measured about 15 meters from the NIP, but at the same height as the NIP. While wind speed has been considered as potentially affecting the NIP responsivity, a consistent effect across a number of NIPs has not been documented.

The change in responsivity of the NIP with the change in atmospheric pressure may be associated with the change of atmospheric air mass and, hence, be a spectral affect. More data are needed to ascertain if pressure systematically affects the responsivity of the NIP.

In many calibration reports, the responsivity of the NIP has been plotted against zenith angle. It is recommended that instead the responsivity be plotted against air mass. In this study, the plot would be more linear, and air mass can be tied to spectral characteristics, while the correspondence of zenith angle with spectral effects is more nebulous. It is also recommended that spectral measurements be conducted during calibration events to more precisely determine the spectral affects on calibrations.

7. SUMMARY AND FUTURE DIRECTIONS

Some systematic affects on the NIP calibration have been identified in this limited study. The systematic errors found are small and may have sources in the measurement procedures. Care also should be taken when using the findings in this article because the results come from one NIP using one absolute cavity radiometer. The regression results do give clues that may prove useful in studying NIPs at other locations but the regression results should not be applied to other NIPs. The NIP in this study did not exhibit a change in responsivity with temperature and therefore might not be typical of other NIPs. Of course test runs over different temperature ranges may be needed to see the temperature dependence of this NIP.

The variation of responsivity with air mass does suggest a physical explanation for the change in responsivity. Therefore, air mass might be the more appropriate variable to correlate with responsivity rather than zenith angle which is used in the BORCAL reports and other calibration studies in plots of zenith angle with responsivity changes.

More comparisons during summer months will help increase the variety of meteorological conditions under which the NIP is calibrated. In addition, spectral measurements should be carried out when the calibrations are done. These spectral measurements could be useful in proving or disproving the hypothesis that spectral changes affect the responsivity of the NIP in a systematic manner.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

1. Laura Riihimaki, L.S. Lohmann, R. Meyer, R. Perez, F. Vignola, Long-Term Variability of Global and Beam Irradiance in the Pacific Northwest Proc. of the 36th ASES Annual Conference, Cleveland, OH, (2007).
2. http://www.eppleylab.com/
3. F. Vignola and I. Reda, Responsivity of an Eppley NIP as a Function of Time and Temperature, Proceedings of the 1998 Annual Conference American Solar Energy Society, 517-522, 14 Jun 1998
4. Gueymard C.A. Advanced Solar Irradiance Model and Procedure for Spectral Solar Heat Gain Calculation (RP-1143). ASHRAE Trans., in press (2007).