Establishing a Consistent Calibration Record for Eppley PSPs

Laura Riihimaki
Frank Vignola
Department of Physics
1274 – University of Oregon
Eugene, OR 97403-1274
lriihim1@uoregon.edu
fev@uoregon.edu

ABSTRACT

A process is described that is used to establish a consistent calibration record for Eppley Precision Spectral Pyranometers (PSPs) employed in the University of Oregon (UO) Solar Radiation Monitoring Network. Several calibration methodologies are discussed and compared, and the relationship between different calibration results are given. The long-term decrease in reponsivity of PSPs under study is determined. Clear day solar noon irradiance values are used to check the consistency of the calibration procedures. The rate of decrease in responsivity of the PSPs was found to be between 0.4% to 1% per year.

1. INTRODUCTION

This article documents the rationale for and methodology used in establishing a consistent set of calibration numbers for Eppley PSPs employed by the UO Solar Radiation Monitoring Network from 1977 to 2007.

Long-term records of solar radiation are important to assess the variability and capacity of the solar resource over long time periods. Also, long-term solar radiation records are sought to evaluate changes in the earth's energy budget caused by anthropogenic impacts on the climate. Quality control is important when assessing the uncertainty and reliability of these long-term trends and the correctness of conclusions drawn from analysis of these data.

The responsivity of a pyranometer is the number of volts (often microvolts) created by 1 watt/m^2 of solar radiation and this number is used to calculate the incident solar energy from the voltage produced by the pyranometer. The responsivity of a pyranometer is determined by calibration against a standard.

The phenomenon of degradation of responsivity in pyranometers is well known [1, 2] and the periodic calibration of pyranometers is necessary to ensure a high-quality dataset. However, as knowledge of the characteristics of pyranometer response has increased over the years, some methods used to calibrate pyranometers have been modified to incorporate that new knowledge. These changes have caused shifts in the calibration record of 2 to 3%. Thus to fully and correctly utilize a long-term dataset, it is necessary to establish a consistent and documented calibration record.

It is difficult to determine the absolute calibration of a pyranometer since the calibrations have an uncertainty of 2 to 3% and the instrument response varies based on environmental conditions and the solar zenith angle. Calibration results depend on the methodology and reference instruments used as well as the environmental conditions on the day of calibration. The difference between sequential instrument calibrations is often much greater than the actual change in the instrument responsivity over time. Thus it is better to look at a long series of calibrations to establish how the responsivity is changing rather than changing the responsivity after each calibration.

One of the few studies of long-term calibration degradation [1] reported that the sensitivity of Eppley Precision Spectral Pyranometers (PSPs) changed by 1.9% per year as a result of exposure to sunlight. A more recent study [2] shows that degradation is more clearly correlated with irradiance and temperature exposure than with the length of time a pyranometer is out in the field. This study also showed that the responsivity decline matches predictions using a model commonly used to predict the aging of paint.

Because of this significant degradation, PSPs should be frequently calibrated to ensure accurate readings. Thus, as described in this article, once the rate of degradation has been determined for a PSP, the responsivity should be adjusted annually to reflect the changes in instrument sensitivity. Keeping good calibration records enables a check and refinements to this rate.

This article is organized as follows. First, the UO Solar Radiation Monitoring Laboratory (UO SRML) data are discussed. The discussion also covers the effects of infrared (IR) radiative losses inherent in PSPs. Then, the calibration methodologies used at the factory and national labs are described, included the effect of IR radiative losses on the responsivity values. The rationale for and the methodology employed in calibrations for the UO SRML network data are presented followed by a description of the adjustments made to develop a consistent calibration history. Clear noon values are used to corroborate the responsivities determined for the pyranometers. The summary contains the conclusions drawn and makes recommendations for calibration procedures.

2. DESCRIPTION OF THE DATA

The UO SRML has been monitoring global and direct normal solar radiation since 1979 for three stations. Global and beam irradiance monitoring commenced in Eugene in December 1977. During this period Eppley PSP pyranometers were used. These PSPs have been calibrated at the Eppley factory, at NOAA calibration centers and at the National Renewable Energy Laboratory (NREL).

In addition, the instruments were calibrated at our reference site in Eugene, Oregon using the shade and unshade method, against reference pyranometers that were calibrated by NOAA or NREL, and more recently from reference global values obtained by adding direct horizontal values from reference Eppley Normal Incident Pyrheliometers (NIPs) and high quality diffuse measurements. All these calibration methods produced slightly different results, but were usually within 2-3% of each other. Typically the absolute accuracy of any PSP calibration has an uncertainty in the ±3% range.

The PSP thermopile produces a voltage proportional to the energy flow from the sensing disk to the body of the instrument, the cold junction. At night the energy flow reverses as the sensing disk sees the cold sky (though interacting with the pyranometer's domes) and a negative voltage results. Even during the day, there is some heat flow (IR radiation) from the sensor disk to the sky. This reduces the energy flow thorough the thermopile and hence reduces the voltage produced. This radiation to the sky is called the IR radiative loss and this complicates the calibration of pyranometers.

As part of its data processing, the UO SRML subtracts these night time IR radiative losses from daytime values to partially correct for some of the thermal offset. This methodology added about 5 to 10 W/m^2 back to the daytime values, depending on the location and climate conditions. Fig. 1 shows recent work [3] that indicates PSP pyranometers radiate between 1 and 7 W/m^2 during the day and between 1 and 3 W/m^2 during the night in Eugene, Oregon. Fig. 2 shows that between 6 and 16 W/m^2 is radiated during the day in Golden, Colorado. The nighttime IR radiation is between 30 and 50% of the daytime IR radiation.

3. PSP CALIBRATIONS

Pyranometers used in the UO SRML Network have been

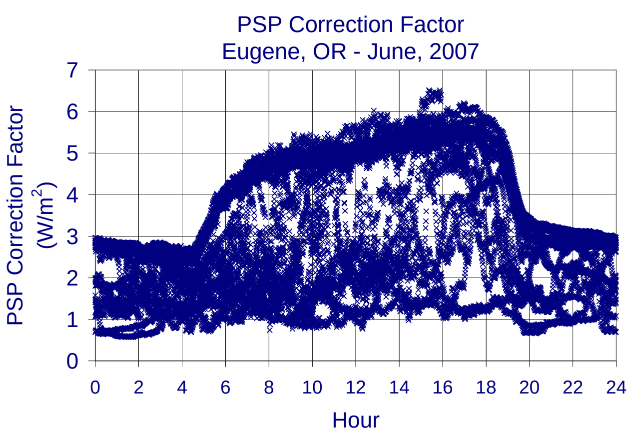

Fig. 1: Calculated PSP Correction Factor using pyrgeometer data. This is a model attempt to calculate the IR radiation from a PSP [1]. 1-minute data.

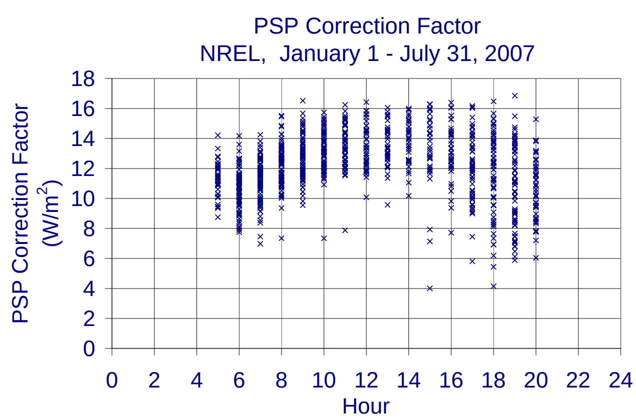

Fig. 2: Calculated PSP Correction Factor using pyrgeometer data at NREL's solar lab. Data courtesy of Ibrahim Reda of NREL.

calibrated at the factory, national labs and in the field. Calibration methodologies differ at these facilities, and procedures have been modified and standardized over the past 30 years. In order to achieve a uniform calibration record, the various methods of calibration have been examined. An attempt has been made to adjust the responsivities obtained by the various calibration methods to the current NREL standard for responsivity defined at an incident angle of 45º. An additional adjustment was made to match measurement techniques and sky conditions at the Eugene, Oregon reference station. The adjustment to the Eugene station is necessary because of the difference in IR radiation between the NREL site and Eugene. The methods used to adjust the different calibration methodologies to the new standards are discussed and evaluated with long-term calibration data and clear day measurements.

3.1 Eppley Lab calibrations

Eppley PSPs are calibrated indoors under a dome with a solar lamp. A reference pyranometer is used to help validate the calibrations. The sky dome provides for a fairly uniform "sky" condition and the temperature of the artificial sky dome is at approximately the same temperature as the table and the atmosphere in the calibration chamber. This methodology eliminates IR radiation losses from the calibration. In addition, the controlled conditions eliminate such factors as wind speed and ambient temperature that can affect the calibration results.

3.2 Shade and unshade method

The shade and unshade method consists of measuring the voltage signal from the pyranometer when it is unshaded and then measuring the output of the pyranometer when it is shaded. The difference between the two readings is the contribution of the direct horizontal irradiance to the global measurement. The direct normal irradiance is measured with a NIP or an absolute cavity radiometer. Projecting the direct normal irradiance onto the horizontal surface gives the direct horizontal irradiance. By comparing the measured direct horizontal irradiance from the shade and unshade method with the direct horizontal irradiance obtained from the direct normal irradiance one can determine the calibration of the pyranometer.

If one assumes that the IR radiation during the shaded and unshaded period is the same, then calibration results are unaffected by the IR radiation.

3.3 Calibration with beam and diffuse irradiance

One of the most often-used calibration methods is to calculate global irradiance values from measured direct normal and diffuse irradiance. The direct normal irradiance is measured by an Absolute Cavity Radiometer (ACR) or a pyrheliometer and projected onto a horizontal surface by multiplying by the cosine of the solar zenith angle. The diffuse irradiance is then obtained by shading a pyranometer with an occulting disk. The sum of the horizontal beam irradiance and the diffuse irradiance is compared to the measured global irradiance.

If an Eppley PSP is used for the diffuse measurement, the diffuse measurement is impacted by IR radiative losses described in section 2. B&W type pyranometers measure the temperature difference between the black and white surfaces to obtain the incident radiation. Because the black and white surfaces are in the same thermal environment, IR radiative losses are greatly reduced. Therefore, the global radiation values obtained by using an Absolute Cavity Radiometer and a B&W type pyranometer are the most accurate global irradiance values obtainable.

When calibrating a PSP with an IR offset using the calculated reference global values obtained without the IR offset, a small systematic error is introduced because the instrument is calibrated under different IR conditions than is likely to be experienced in the field.

3.4 Side-by-side calibrations

One of the easiest methods of calibration and one that is often used in the field is the side-by-side calibration. The responsivity of the pyranometer under study is checked against the output of the reference pyranometer. A side-by-side calibration of Eppley PSPs results in a calibration that is minimally affected by environmental conditions, like IR radiative losses, because both pyranometers respond similarly to the environmental conditions.

Of course, this method is only as accurate as the calibration number of the reference instrument. Any errors in the calibration of the reference pyranometer will be transferred to the other instrument. Side-by-side calibrations lose validity if the pyranometers are not the same type because different types of pyranometers exhibit different systematic errors.

3.5 Comparisons with NREL's BORCAL calibrations

There have been at least three variations of outdoor calibration methods used at NREL that involve an Absolute Cavity Radiometer and high quality diffuse measurements. These calibrations are part of NREL's Broadband Outdoor Radiometer Calibration (BORCAL) program. Initially a reference Eppley PSP was utilized for the diffuse measurements and the responsivity assigned to the pyranometer being was obtained by averaging values obtained when the zenith angle was between 45° and 55°.

Starting in 2000, the BORCALs used an Eppley B&W for

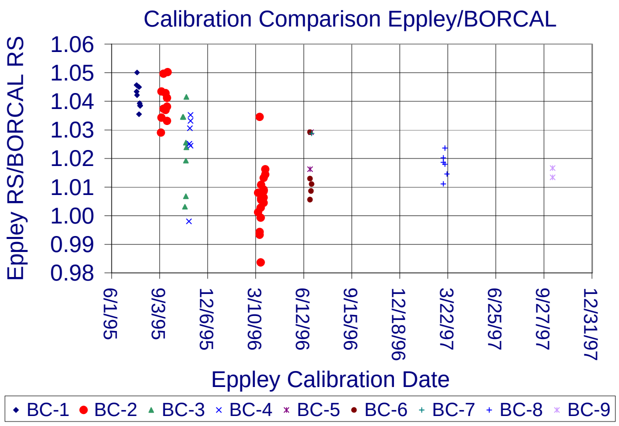

Fig. 3: Comparison of Eppley and NREL calibrations. The large red circles are data from one NREL BORCAL run on June 8, 1996. The two distinct calibration run at Eppley give two distinct distributions.

the diffuse measurements. These calibrations produced calibration numbers at both 45º and between 45º and 55º along with a composite number obtained from measurements over many angles.

The latest change in BORCAL reports comes from listing only the responsivity at 45º and an "average" responsivity. The responsivities from older BORCAL reports can be converted to the 45º standard using the responsivities given at different zenith angle ranges.

The switch between using a PSP to a B&W instrument as the diffuse reference, however, introduces a change in the calibration results. Using the Eppley PSP for the reference diffuse values yielded diffuse values that are about 15 W/m^2 too low, at Golden, because of the IR radiative losses[4]. Therefore, NREL BORCAL responsivity values reported before 2000 are up to 2.5-3% too high compared to values obtained by current techniques.

4. CHOOSING THE REFERENCE CALIBRATION

First, to make calibration methods consistent, a "reference" method was determined to which responsivities from other calibration methods were adjusted. Though the recent calibrations from NREL use one of the best methods available, these calibrations give responsivity values 2-3% lower than those found in Eugene against a reference global irradiance found by summing measured diffuse and direct normal irradiance. This difference is likely due primarily to the difference in thermal offset response to sky temperature. The different altitudes and sky conditions in Eugene versus those at the Colorado NREL site lead to different sky temperatures on clear days, and this affects the IR radiative losses.

The UO SRML uses a data processing procedure that subtracts the negative nighttime values from the values during the day and this corrects for 1/3 to 1/2 of the IR radiative losses. No correction for radiative losses is done in the BORCAL program and this adds to difference between the responsivities derived at NREL and at the UO SRML.

The responsivities from NREL have to be increased by approximately 2.5% to yield consistent results in Eugene. This is reasonable because the IR radiation is much less of a factor in Eugene than in Golden. This difference is accentuated because the UO SRML data subtracts the nighttime irradiance from the daytime values. Therefore the responsivities determined at NREL prior to 2000, are fairly consistent with the Eugene values. This may be because the influence of the IR radiation is canceled in the older NREL calibrations using the PSP diffuse measurements.

It was decided to adjust all other calibration methods to calibrations done at Eugene against a reference global irradiance calculated by summing direct normal measurements projected onto a horizontal surface from a NIP and a shaded black and white pyranometer at a zenith angle of 45º.

5. ADJUSTING RESPONSIVITIES FROM OTHER CALIBRATION METHODS

In order to derive a consistent calibration history, responsivities determined using different calibration methods are adjusted to the standard method used by the UO SRML. To make these adjustments, it is necessary to compare instruments calibrated under different methodologies.

5.1 Comparisons between NREL and Eppley

To check the consistency of Eppley calibrations with those of NREL, 69 instrument calibration records with pairs of responsivities found by Eppley and NREL BORCAL calibration events were provided by NREL. Ratios between the responsivities from the two calibration methods were calculated (Fig. 3). These NREL calibrations were done prior to 2000, so the responsivities are consistent with the UO SRML reference method. The results showed surprising variation. The distribution of ratios is bimodal. While the mean of the ratios is 1.023, one group is centered around 1.01 and another centered around 1.035.

In order to examine this further, the responsivity ratios are plotted by date of calibration at Eppley Labs and marked with different symbols for the different BORCALs at NREL (Fig. 3). Of particular interest are the two groups of pyranometers that were calibrated at NREL on June 8, 1996. All of these points were calibrated at the same time at NREL, so the sky conditions and methods should be identical. However, the two groups were calibrated at Eppley Labs at different times, one group in September of 1995 and the other group in March of 1996. Fig. 3 shows about a 3% offset between the two groups, though each group has a spread of only 2%. The small spread indicates that the 3% gap between the two groups is unlikely to result from the calibration process at NREL, although that can't be totally ruled out.

Thus the methodologies are different enough to make it difficult to compare the calibration methods directly. It does appear, however, that the responsivities measured at Eppley Labs are generally 2.3±1.6% higher than those determined at NREL prior to 2000. Since the NREL calibration numbers prior to 2000 are consistent with the Eugene calibration numbers, the Eppley factory responsivities were decreased by 2.3%.

5.2 Comparison of Eppley and NOAA

There was no similar dataset available to compare calibrations done at NOAA and those done at NREL. However, there was a study done by the UO SRML comparing the responsivities done at NOAA with those done at Eppley. This study showed that Eppley responsivities were, on average, 1% higher than the responsivities determined by NOAA based on a sample of sixty-seven calibration record pairs [5]. This is excellent agreement for laboratory and outdoor calibrations.

The NOAA calibrations used the shade and unshade method. This should produce results similar to the calibration results used by NREL before 2000 because the IR radiative losses are similar in both the shade and unshade situations. The direct horizontal reference values came from an Eppley Normal Incident Pyrheliometer (NIP) calibrated against an ACR. For a consistency check, a reference pyranometer was also used in the calibrations. The reference pyranometer was calibrated using the ACR for the direct normal irradiance.

As the NOAA responsivities were obtained as an average over a range of zenith angles, they have to be adjusted to responsivities at a 45° reference point. In general for older PSPs, the responsivities averaged over a range of zenith angles are about 1-2% higher than the responsivity determined at 45º. Therefore, it was decided to decrease the NOAA responsivities by 1% to compensate for the difference between average responsivity and that at 45º. Decreasing the NOAA responsivities by 1% makes the Eppley responsivities about 2% higher than the NOAA values. Since the Eppley values are also about 2.3% higher than the NREL pre-2000 responsivity values, the NOAA and NREL, and Eppley adjustments are now consistent.

TABLE 1: ADJUSTMENTS MADE TO RESPONSIVEITIES FROM DIFFERENT CALIBRATION METHODS

Cal. method:	Responsivity Adjustment
Eugene	None
NREL before 2000	changed to zenith angle 45°
NREL after 2000	↑ 2.5%
Eppley	↓ 2.3%
NOAA	↓ 1%

A summary of the adjustments made to responsivity values determined at different calibration facilities are shown in Table 1. The overall reference calibration in Eugene was chosen because it is in the region where the instruments are used and the IR losses should be somewhat similar. Responsivities found at NREL before 2000 were chosen at a zenith angle of 45° instead of 45-55°. Responsivities from calibrations done at NREL after 2000, Eppley Labs, and NOAA are all shifted up or down by a percentage given in Table 1.

6. COMPARISON OF CALIBRATIONS OVER TIME

In addition to adjusting responsivities from different calibration methods for consistency, attention must be given to how instrument responsivities change over time. As a check on responsivities, the UO SRML keeps a record of clear day solar noon irradiance values. It was found that, with the exception of the volcanic eruptions of El Chichón (1982) and Mt. Pinatubo (1991), the clear solar noon values are fairly constant over time with properly calibrated instruments. By removing the calibration changes and utilizing only one responsivity value, the rate of degradation of the pyranometer responsivity is clearly visible as shown in Fig. 4.

6.1 Clear Day Noontime Values

To obtain these clear noon data, clear solar noon periods were identified by looking at continuously plotted back up charts. This method is excellent at identifying clear periods with smoothly varying beam and global irradiance. The clear day solar noon values from each year were then grouped into 25, 15-day bins and normalized the bin's long-term average in order to reduce scatter. An example of these clear day values is plotted in Fig. 4. This shows normalized Eugene clear noon values when each instrument keeps the same responsivity value for the entire period of use. The decreasing responsivity shows up as declining global clear noon values.

6.2 Responsivities from Calibration Records

Special attention was paid to the Eugene instruments labeled P1 and P3 as they have been the primary reference

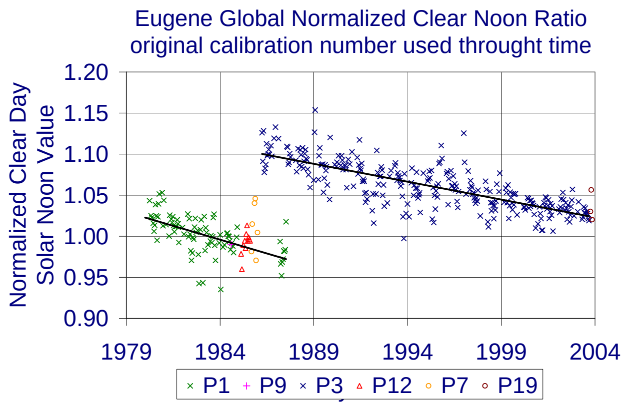

Fig. 4: Clear day solar noon data for Eugene, Oregon from 1980 through 2004. Six different pyranometers were in use during this period. A fixed calibration number was used for each PSP to show rate of change in responsivity.

instruments for all relative calibrations done in Eugene and in the field. Also, they have the most complete calibration records because Eugene is the primary reference and research station in the UO SRML network. The responsivity values for the two instruments were determined by fitting regression lines to the responsivities from historical calibration. Following the convention of Wilcox et al [1], calibration changes were examined based on accumulated exposure to radiation. Fig. 5 shows the responsivities of P1 plotted against the summed irradiance exposure ($MWhr/m^2$) at the time of calibration. The dotted line shows a linear regression fit to the calibration records. The green x's show the annually adjusted responsivities that are now used with the instrument. These values were calculated from the linear regression until 1989. After 1989, around 13 $MWhr/m^2$ in Fig. 5, the regression fit was determined by the many calibration points. There were many more calibration records since 1989 than earlier because P1 started being used as a reference instrument.

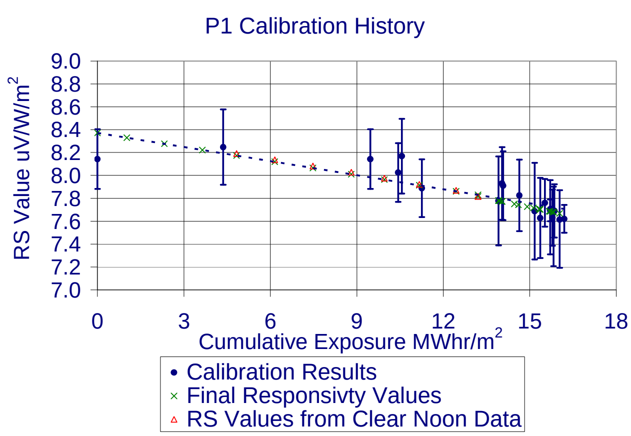

Fig. 5: Calibration record for PSP "P1" plotted over time. The blue dots with the error bars are the various calibrations done over time. The red triangles are the clear day trend. The green x's are the actual responsivity values used.

The green x's plotted in Figs. 5 & 6 show responsivities calculated by fitting a linear regression line to calibration records. The remarkable agreement between responsivities calculated from a linear fit to calibration records and clear noon values, shown with the red triangles, confirms that the responsivity's rate of decrease is due primarily to a change in the sensitivity of the instrument to incoming radiation. Fig. 6 shows the importance of looking at irradiance exposure rather than simply the age of the instrument in determining responsivity change. In this plot, the responsivities from different calibrations are plotted by the date of calibration. Plotting the adjusted responsivities in green x's again, this figure shows distinct differences between slopes when the instrument was being used in the field (until 1987) and later when P1 was brought in to serve as a reference instrument.

Having determined accurate values for P1 over time, relative calibrations for P3 were determined using standardized calibration values. Fig. 7 shows these responsivities plotted against cumulative radiation exposure. As with P1, yearly adjusted responsivity values for P3, shown with green x's, were determined by the linear regression fit to the standarized calibration values. The remaining responsivities for instruments used in Eugene were calculated similarly from adjusted calibration records.

7. ADJUSTMENTS TO DATABASE

Because the responsivities from different calibration methods have been adjusted for consistency, yearly adjusted responsivities can be determined by a regression fit of the calibrations. The clear noon values are plotted with these

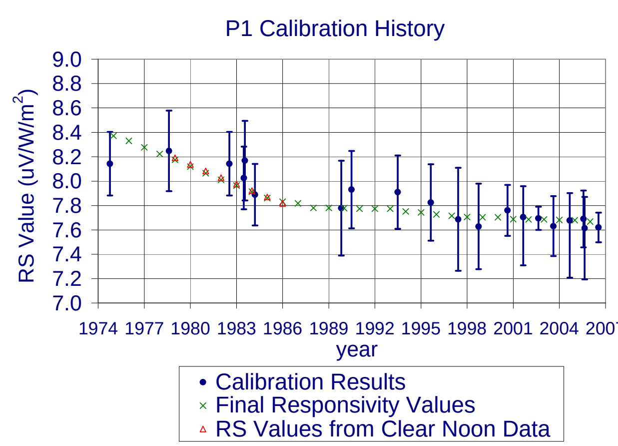

Fig. 6: Same data as plotted in Fig. 5 except plotted against time. In 1987, the pyranometer was removed from daily operation and was used as a reference instrument.

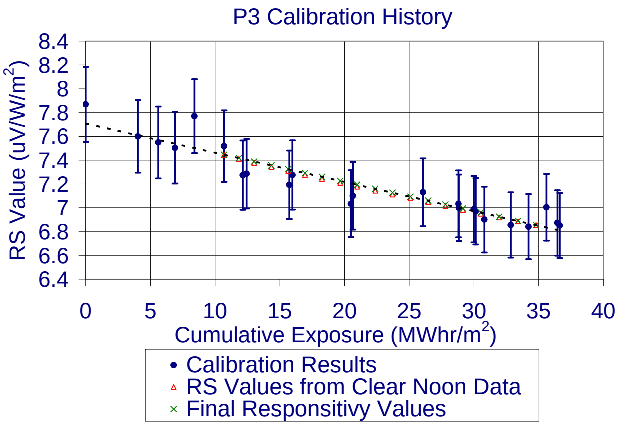

Fig. 7: Calibration history of PSP ("P3") along with averaged clear day trend, regression fit, and indication of the calibration values used in the database.

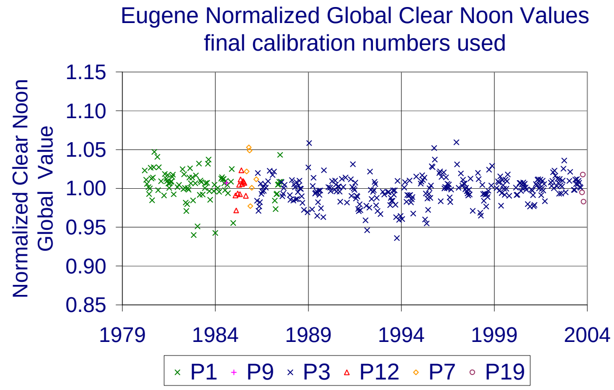

Fig 8. Plot of clean day solar noon values with the calibration values adjusted on a yearly basis and shown in Figs. 5-7.

new responsivities are shown in Fig. 8. The newly derived responsivity values eliminate the trends seen in Fig. 4. The regression fit to the calibration record produces a fairly constant pattern in the clear noon data. This is an independent check on the newly calculated responsivity values. This is particularly shown by the data for P3. P3 was used in Eugene over a period of almost 20 years and has one of the most complete and accurate calibration histories of all the instruments. The consistency of the trend of the clear noon values and the calibration record are also evident in Figs. 5-7. The regression fit to the data (dotted blue line) and the clear noon trend (red triangles) coincide nearly perfectly.

The percent per year decrease in pyranometer responsivity calculated from the clear day values is 0.44% per year. The percent per year decrease calculated from the calibration history plotted by cumulative exposure is on average 0.46% per year. This implies that there is in fact no significant change in the clear day values at solar noon beyond calibration changes of the instruments. This is confirmed by the direct normal plots at clear noon which also show no significant trend over time (Fig. 11).

Because it was found that clear day trends give the same annual responsivity change as calibration records, this allowed us to correct instrument responsivity histories at other sites using clear day records. Using the clear day records is much less work than calculating the cumulative exposure for calibration events, though it shows a similar level of accuracy in responsivity corrections. In cases where only a few calibration records are available for an instrument, correcting the responsivity using clear day records may even be more accurate than using the calibration record. Except for P20, used recently in Burns, instruments used for a significant portion of time at Burns and Hermiston were corrected using clear day data. (P20 changes were calculated based on calibration records because there was not enough clear day data.)

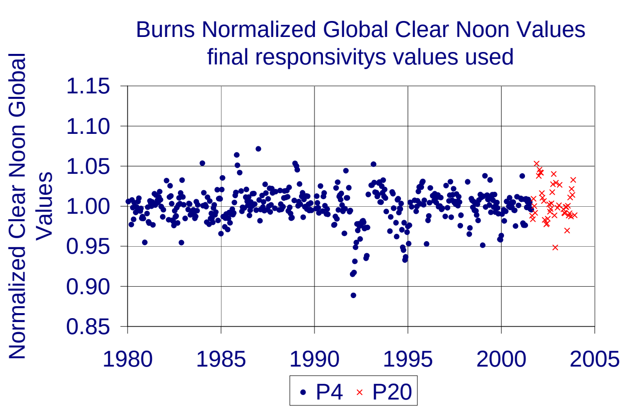

Fig. 9: Clear day solar noon data for Burns, Oregon with updated responsivities.

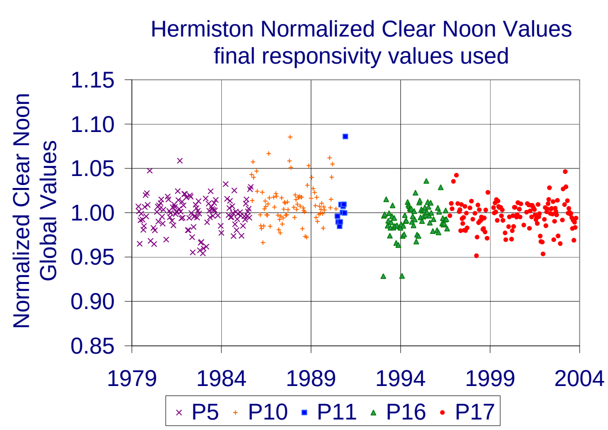

Fig. 10: Clear day solar noon data for Hermiston, Oregon with updated responsivities.

To determine responsivities from clear noon measurements, all the measurements made by a particular instrument were first adjusted so that they were calculated from the same responsivity. The annual change per year was calculated from these normalized values. The absolute values of these responsivities were then checked to make sure they matched corrected calibration records and neighboring clear day measurements from other instruments. The clear day values over time resulting from these corrections are plotted in Figs. 9 & 10 for Burns and Hermiston respectively.

An earlier study showed that the responsivity of Eppley NIPs remained relatively constant over the 25 years in the field. A plot of the clear day solar noon beam data is presented in Fig. 11. The fact that both the clear day solar noon data for the global and direct normal irradiance remain fairly constant over the years helps to confirm that the methodology used to adjust the calibrations does not itself cause or obscure any trends in the data.

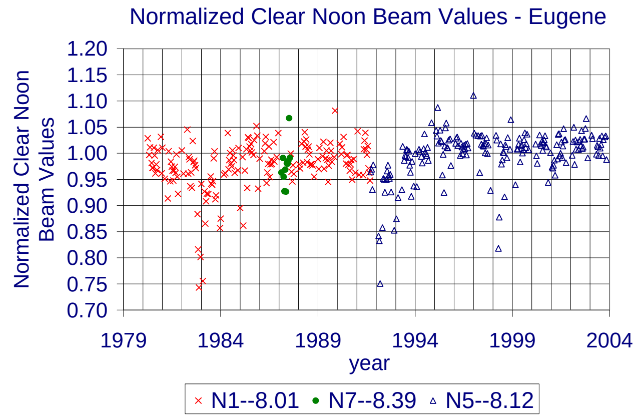

Fig. 11: Plot of clear day solar noon data for direct normal data from Eugene, Oregon. Three different NIPs were used over this period. Volcanic eruptions happened in 1982 and 1992 and show up clearly in the data.

8. CONCLUSIONS

This paper discusses the procedures undertaken to assure that a consistent responsivity was obtained for the UO SRML database for global measurements in Burns, Eugene, and Hermiston database. This work was made necessary because of the way reference calibration methods have changed. A study of the different reference calibration methods was done to determine a relationship among them that would enable the use of different reference calibrations in determining the long-term rate of change of PSP responsivity. The responsivity of pyranometers was found to vary depending on exposure.

The rate of change of field instruments was between a few tenths of a percent to one percent per year. Looking at the long-term trends in the degradation of pyranometer responsivity, it was determined that the deterioration is a slow and steady process that is dependent on exposure over at least a 20 year period. This study confirms the work by Wilcox et al [2].

By taking into account the rate of responsivity change, a more consistent long-term solar radiation database can be obtained. Since all pyranometer calibrations have absolute uncertainties of ±2 to 3%, it is difficult to see a change of a percent or less. Changing the responsivity of the pyranometer after each calibration can introduce additional variability into the dataset. This additional error would be present in networks that move their pyranometers between sites and change them out when they are calibrated.

The long-term solar radiation data sets from Burns, Eugene, and Hermiston, Oregon now have a consistent calibration and these data can now be used to more accurately study the long-term variability and change of the global irradiance in the Pacific Northwest.

9. ACKNOWLEDGEMENTS

Material in this work was supported by a grant from the Engineering and Technology Industry Council of Oregon as part of the UO GK-12 program. We would also like to acknowledge Bonneville Power Administration, Emerald People's Utility District, Energy Trust of Oregon, and the Eugene Water and Electric Board for support of the University of Oregon Solar Radiation Monitoring Laboratory.

10. REFERENCES

(1) Nelson, R.J., J.R. Augustyne, and C. Jennings, "Radiometer Calibration Drift" Solar 94, Proceedings of the 1994 annual conference of the American Solar Energy Society, San Jose California June 27-30, 1994. Burley, Arden, Campbell-Howe and Wilkins Crowder, Ed. ASES 1994.
(2) Wilcox, S., Myers, D., Al-Abbadi, N., Bin Mahfoodh, M., "Using irradiance and temperature to determine the need for radiometer calibrations" in Forum 2001 Solar Energy, the Power to Choose. 2001. Washington D.C., ASES.
(3) Vignola, F. Long, C., Reda, I., "Evaluation of Methods to Correct for IR Loss in Eppley PSP Diffuse Measurements" in SPIE, 2007. San Diego, CA
(4) Myers, D., et al. (2002), Recent Progress in Reducing the Uncertainty in and Improving Pyranometer Calibrations, *J. of Solar Energy Engineering*, 124, 44-50.
(5) Vignola, F. & D.K. McDaniels, Pacific Northwest Solar Radiation Data , UO SRML, 1998