VI. SENSOR CALIBRATIONS

One of the most important aspects of high quality solar radiation measurements is the accurate calibration of sensors and recording instrumentation. To do this, several careful measurements must be made and evaluated. First, the response of the sensors to the incoming radiation must be determined (in volts/watts/meter^2). This is done by simultaneously comparing the measured output of the site instrument with a secondary standard. Next, the response of the recording instrumentation to an input signal must be determined. For the CR-10 data logger this means checking the relation between output value (over a 5-minute interval) and a given input voltage. Having established these calibration constants, it is then necessary to determine the uncertainties involved in each and evaluate what these uncertainties mean to the final results. As a check on the consistency of these procedures, we monitor the solar radiation transmission values on clear days at solar noon. A comparison of these values over the years provides the means for monitoring degradation of the instruments. All of the above procedures are described in detail below.

First, let us look at the procedure whereby the absolute calibration of our sensors is obtained. This is illustrated schematically in Fig. 6. The modern calibration process starts with the international standard, PACRAD III that is kept at Davos, Switzerland. The name PACRAD stands for Primary Absolute Cavity RADiometer. This standard is then compared to the U.S. absolute cavity radiometer, TMI 67502 that was kept at the NOAA laboratory at Boulder, Colorado under the direction of Ed Flowers. This type of sensor is self-calibrating because applying power to an internal heater can exactly duplicate the response to the incident solar radiation. The electrical power used in the heater can be determined very accurately by measuring the voltage and current and thereby yields an absolute measurement of the incident solar radiation.

The next step in the procedure is to transfer the absolute calibration to a secondary standard, the Eppley Normal Incidence Pyrheliometer (NIP 1330). Detailed comparisons at Boulder give the calibration constant for this standard to ±0.4%. The calibration factor was obtained by an extensive series of side-by-side comparisons of the NIP and the Boulder TMI.

(It should be noted that the calibration constant of NIP 1330 obtained from the comparisons with the absolute cavity radiometer was 2.5% higher than that given by Eppley labs. In 1976, Eppley used the international pyrheliometer scale (IPS). This comparison was in accord with the result obtained at Davos, as the IPS scale was 2.2% lower than the absolute one now universally accepted.)

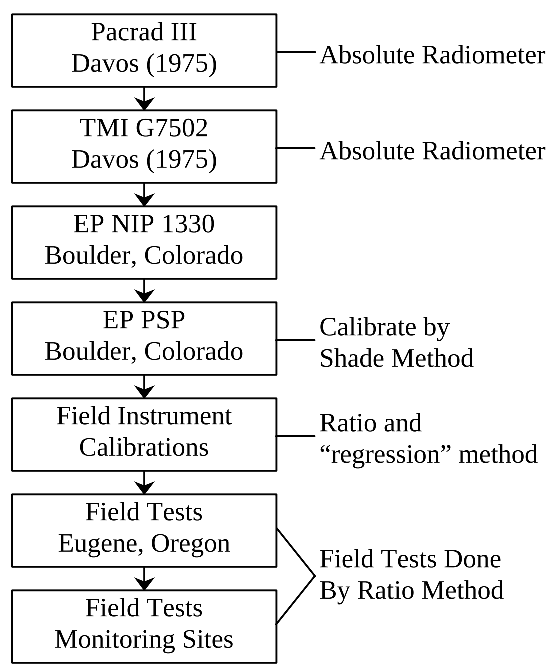


Fig. 6. Flow diagram showing the absolute calibration process.

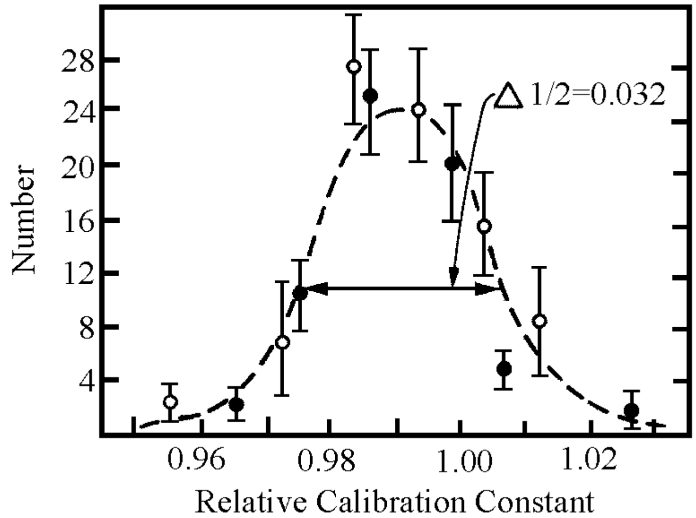


Fig. 7. Comparison of calibration constants for 67 different PSP pyranometers as determined at the NOAA facility at Boulder, with the calibrations obtained at Eppley laboratories. The width at half maximum corresponds to a fractional standard deviation of about 1.4%. The points with the open circles represent similar calibrations performed by our group normalized to the Boulder results.

Once a secondary NIP is established it remains necessary to obtain a calibrated reference pyranometer. The pyranometer to be established as the reference is compared with the direct output from the standard NIP using the shade method. The contribution from direct beam solar radiation to the pyranometer is obtained by alternately measuring the global and the diffuse components by shading the pyranometer for short periods of time. The difference between the global and the diffuse components is the direct component on a horizontal surface.

Standardization of our reference Eppley PSP was then done routinely by comparing the simultaneous outputs from our reference instrument with the NOAA reference pyranometer at Boulder, Colorado. We now have our reference pyranometer calibrated at NREL. This instrument is then brought back to Eugene and used as the secondary standard to calibrate all our other pyranometers.

It is of interest to look at the uncertainty associated with the routine calibrations of pyranometers. One way to study this is to determine the variance associated with the standardization process. This is done by plotting the frequency distributions for the ratio of the calibration constants determined at Boulder to the values determined by Eppley Laboratory. There is a considerable quantity of this type of data available from Ed Flowers at Boulder. For a variety of reasons, the calibration constants determined at Boulder differ from those measured at the Eppley laboratories. The distribution of the calibration constant ratios is shown in Fig. 7 for a sample of 67 Eppley PSP pyranometers. This distribution is centered about a mean of 0.99 with a standard deviation of 1.4%. One can interpret this distribution in two different ways. The Boulder calibrations can be regarded as correct, and the variance in the distribution arises from variations in the Eppley calibration process. Alternatively, the distribution can be regarded as reflecting the uncertainty in the process of obtaining an absolute calibration constant for a pyranometer, regardless of the reasons. We choose to interpret Fig. 7 in this latter fashion. The uncertainty in the calibration constant for our measuring instruments is therefore approximately ±1.4%.

This point of view is strengthened by the variations in our own field calibrations. For each of our pyranometers we have divided the individual calibration determinations by the average value. The frequency distribution of the UO calibrations is also plotted on Fig. 7

(as open circles), with the peak value normalized to the peak value of the measurements made at the NOAA facility at Boulder. Within uncertainty, both data sets are consistent with a half width of 3.2% and a resultant standard deviation of 1.4%.

Uncertainties in the electronic calibration constant (digital pulses/millivolt) arise from temperature sensitivity, non-linearity of response, and long-term instabilities of the associated electronics. Detailed measurements both in our laboratory and in the field indicate that each of these variables contributes an uncertainty of 0.2% at most. Assuming these uncertainties add in quadrature, this gives an overall electronic uncertainty of 0.4%, which is negligible compared to the accuracy of the sensors.

The above results can be combined to give an estimate of the absolute accuracy of our global solar radiation values. The important contributions from the sensors and the electronics are summarized below, with the total uncertainty obtained by adding the individual values in quadrature:

Sensor calibrations	1.4%
Temperature response	1.0%
Cosine response	2.0%
Electronics	0.4%
Total uncertainty	≈2.7%

For daily totals the uncertainty associated with analogue to digital conversion is small, except on very overcast days. For hourly values the percent accuracy of the results on lower intensity days can be somewhat worse than the results quoted above.

Systematic effects can contribute to uncertainties beyond those quoted above. Examples of these are:

- Radio frequency noise that gives rise to spurious input voltages at the analog inputs to the electronics,
- long-term sensor deterioration,
- snow and other contaminants on the surface of the pyranometer domes,
- occasional misalignment of the pyrheliometers,
- the presence of neighboring obstructions that can block the sun's rays from striking the sensor.

Since 1992, we have had our reference pyrheliometer and pyranometer calibrated at NREL using a process similar to that used by Ed Flowers. Instead of transferring the calibration from the absolute cavity radiometer to a NIP and then a reference PSP, the calibration at NREL is performed using the ACR for the beam component and a reference PSP with a shade disk is used for a measure of the diffuse irradiance.

The NREL calibration procedure called BORCAL produces a plot of the calibration factor against cosine of incident angle. Fig. 8 is a plot from a recent NREL calibration for our reference PSP.

Fig. 8. Calibration factor verses zenith angle for PSP.

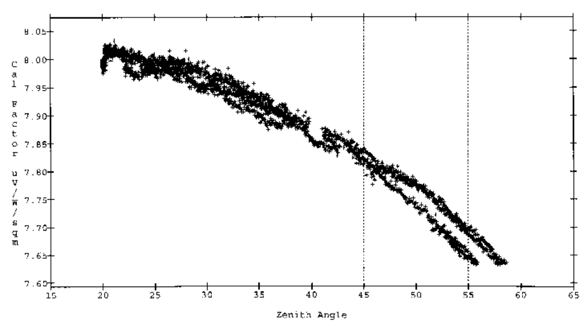
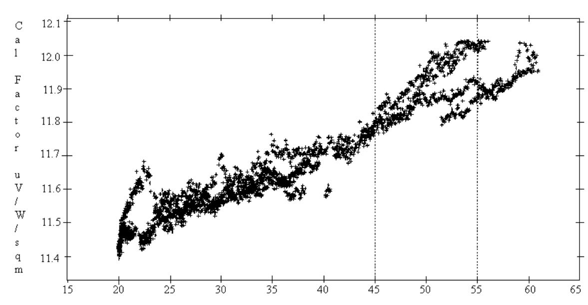


Fig. 9. Calibration factor verses zenith angle for



LiCor pyranometer.

Note that there is a 4.5% change in the calibration factor over the range of zenith angle from 20 to 60 degrees. This change reflects the cosine dependence of the Eppley PSP. (Azimuth and temperature dependence also cause part of the change.) This change is fairly typical of PSPs.

Fig. 8 clearly demonstrates the calibration problems associated with measuring global radiation. What is the best calibration factor for the PSP? Currently NREL selects the values between 45 and 55 degrees to obtain the calibration factor, but this may change.

Fig. 9 shows that calibration factors for our reference LiCor pyranometer obtained during the same calibration run. The changes in the LiCor calibration factor are only slightly larger than for the PSP. However, the LiCor calibration factor increases with zenith angle while those for the PSP decrease. Therefore, calibrating LiCor pyranometers with PSPs can lead to considerable systematic errors.

On a daily basis, LiCor pyranometers track PSPs closely. Therefore we use daily comparisons to obtain the best match between the PSPs and LiCor.

Relative Calibrations

It is difficult to determine the best absolute calibration factor for the PSP because of the deviation from the true cosine response. However, almost all PSPs have similar cosine responses and the relative calibration factors can be obtained more precisely.

Of great value in assessing the relative precision of our results is the comparison of measured solar radiation values on clear days near solar noon with the value of the extraterrestrial solar radiation on a horizontal surface at the top of the atmosphere. The extraterrestrial radiation is equal to the solar constant (1370 w/m^2 is used in this study) times an earth sun distance factor times the cosine of the incident angle. Any differences between the observed and calculated values are due to air mass corrections, water vapor and haze impurities in the atmosphere, and systematic changes in the solar sensor.

The clear-day results for Whitehorse Ranch are plotted in Fig. 10. This figure illustrates a behavior that is typical for all sites in the Pacific Northwest. There is evidence of a consistent seasonal variation superimposed upon an average value characteristic of a given site. This seasonal variation is discussed further in section X.

What is the best calibration factor for the PSP?

From the standpoint of evaluating possible changes in instrument calibrations it is of interest to compare the annual average values for each site. The results for global sensors are given in Table 6 and the results for beam sensors are given in Table 7. Rather than utilizing the values for an entire year, we have chosen instead to use only the period of time from April 15 to August 30, which corresponds to the time period when the clear-day solar noon ratio is highest. The clear day values in Tables 6 and 7 are shown only for 1994 to 1997. While the average values vary considerably between sites, the average values from a given site have only a 1 to 2% variance from year to year. More accurate calibration studies are now being conducted on the pyranometers.

The corresponding results for the direct beam solar radiation measured near solar noon on clear days are presented in Table 7. As with the global results, the agreement from year to year is good. The Burns station on the high desert plateau has an average for the direct ratio of 0.744±0.007 while the Hermiston and Eugene stations are 6 to 7% lower. The difference can be understood on the basis that Burns on the high desert plateau is nearly 1000 meters higher than the other sites.

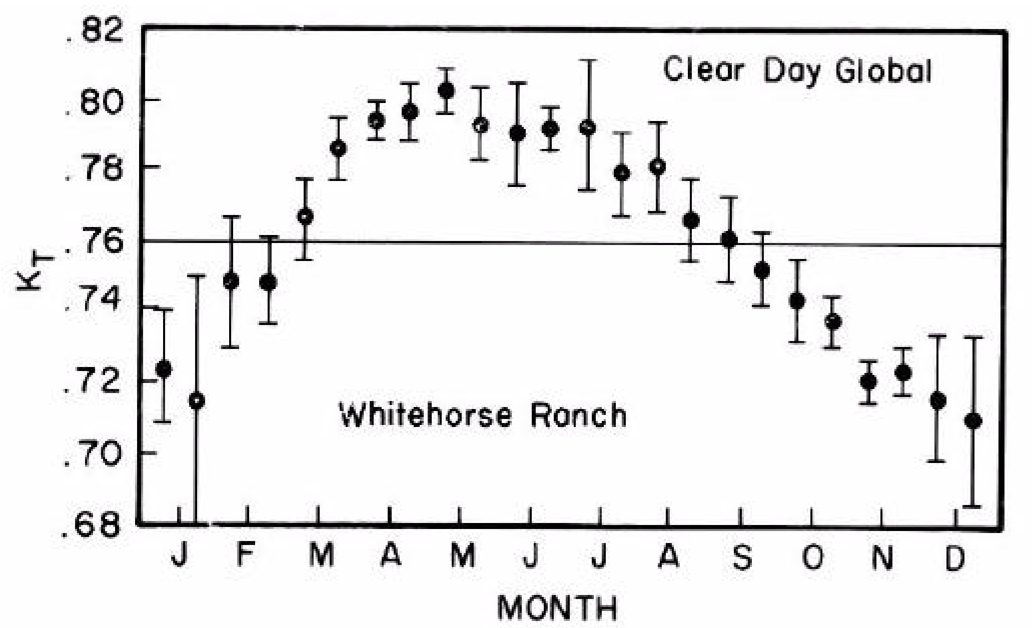


Fig. 10. Solar noon clear-day ratios as a function of the day of the year for Whitehorse Ranch.

Table 6. Ratio of Measured Global Solar Radiation on a Horizontal Surface to Incident Extraterrestrial Radiation. †

Station	1994	1995	1996	1997	Average
Burns	.833±.015	.826±.004	.827±.010	822±.005	.827±.005
Eugene	.765±.015	.757±.011	.772±.013	771±.006	.766±.007
Hermiston	.809±.009	.810±.012	.799±.014	.789±.015	.802±.010

†All values calculated over the time period of April 15 to August 30. The solar constant of 1370 W/m^2 was used.

Table 7. Ratio of Measured Direct Beam Solar Radiation to Incident Extra-terrestrial Radiation. †

Station	1994	1995	1996	1997	Average
Burns	.746±.013	.749±.007	.734±.011	.747±.020	.744±.007
Eugene	.681±.021	.692±.024	.693±.009	.696±.019	.691±.007
Hermiston	.699±.013	.710±.018	.704±.010	.695±.011	.702±.006

†All values calculated over the time period of April 15 to August 30. The solar constant of 1370 W/m^2 was used.