# EFFECTS OF CHANGING SPECTRAL RADIATION DISTRIBUTION ON THE PERFORMANCE OF PHOTODIODE PYRANOMETERS

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ABSTRACT

The direct normal spectral responsivity of the LI-COR photodiode pyranometer is examined, using DNI spectral data from a PMOD Spectroradiometer and the generic spectral response of a LI-COR pyranometer. The spectral responsivity is found to vary over the day as more blue light is scattered as the air mass increases. The SMARTS2 model is used to examine the effect on the full spectral response range of the photodiode based pyranometer and to refine the estimated response changes. The use of this information is discussed relative to improving corrections to Rotating Shadowband Irradiometers. Similar methodology can be used to estimate the spectral effect on the performance of solar modules.

## 1. INTRODUCTION

Accurate knowledge of the solar resource is important for the planning, operating, and financing of a solar electric generating facility and for validating the system performance. Often the biggest source of uncertainty is in the knowledge of the magnitude and variability of the solar resource. While estimates of the solar resource can be deduced from satellite images, higher levels of accuracy are important, especially for optimum financing and accurate validation of system performance.

Monitoring the solar resource with high accuracy at potential locations is expensive and takes time. The most accurate data comes from the highest quality instruments mounted on automatic trackers that are calibrated regularly and maintained on a near daily basis. However, even the most expensive instruments might have significant sources of uncertainties and the instruments more commonly in use have uncertainties that limit or preclude their use for investigations that require high accuracy. Thus the accuracy of solar resource measurements can be improved using comprehensive characterizations that eliminate or significantly reduce these uncertainties.

Cosine response errors and spectral and temperature dependence of the instrument are among many sources of uncertainties that need to be characterized. Comprehensive algorithms taking into account these effects are being developed in order to reduce these uncertainties. The most robust correction algorithms are based upon understanding these deviations and not just on a simple correlation between a field instrument and reference instrument.

An alternative to the most expensive equipment is the Rotating Shadowband Irradiometer (RSI). This instrument measures the global (GHI) and diffuse irradiance (DHI) and calculates the direct normal irradiance (DNI) using a photodiode based pyranometer. There are hundreds of RSI irradiometers deployed around the world, especially in remote locations because they are simple to maintain and operate, are powered by a small solar panel, and appear to be less prone to soiling problems. In addition, they are a fraction of the cost of a high quality solar monitoring station.

The main weakness with the RSI is that they use a photodiode pyranometer, the LI-COR photodiode pyranometer, essentially an instrument that measures the short circuit current of a solar cell; is used in many such instruments. As solar cell performance is dependent on the solar spectrum, the responsivity of a photodiode pyranometer is also dependent on the incoming spectral distribution (see Fig.

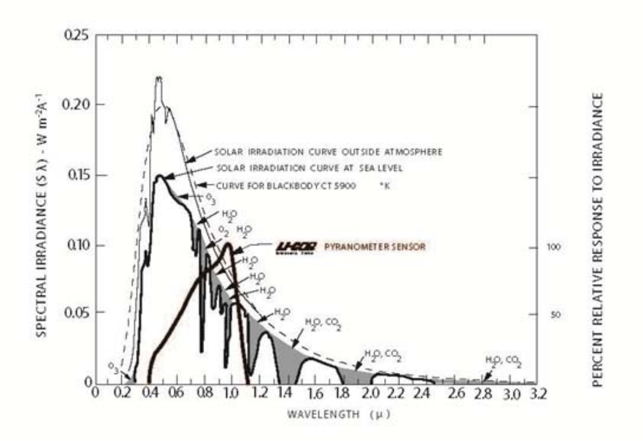


Fig. 1: Typical spectral responsivity of a LI-COR pyranometer as shown by LI-COR

1). The average responsivity of a pyranometer is the micro-volt output signal that is produced by 1 watt•m$^{-2}$ incident energy and is equivalent to the inverse of the calibration factor. The spectral response of a pyranometers is the output signal produced by a fixed (energy) flux of photons of a given wavelength. With spectral response, the relative spectral response if often used as shown in Fig. 1 where a photon with a wavelength of 500 nm will only produce a signal 1/4th the size on a per energy basis as a photon of 1000 nm. The results presented in this article are the relative responsivity averaged over all pertinent wavelengths.

The RSI measures the diffuse radiation by rotating a shield (a shadowband) to block the incoming solar radiation coming directly from the sun, thus measuring the diffuse irradiance from across the sky. Under clear skies, the diffuse radiation consists mainly of blue light that is scattered out of the direct normal radiation mainly by Rayleigh scattering. The spectral distribution from the blue sky is different from the solar radiation coming from the sun and hence the photodiode responds differently to a cloudless sky as opposed to the sky when it is covered by clouds. Clouds are assumed to act as neutral filters, i.e. scattering all wavelengths similarly.

Previously we developed an algorithm to adjust for this change in spectral distribution and hence we were able to correct for the underestimation of diffuse irradiance by the RSI [1]. This algorithm was utilized to correct the spectral shift of the diffuse irradiance and brought the corrected RSI measurements closer to the results produced by the more expensive installation. Other corrections were also made to the GHI measurements that adjusted for other uncertainties such as deviations from a true cosine response [2, 3].

Most RSI irradiometers use photodiode pyranometers because they have extremely fast response time to changes in the solar irradiance. While the corrections made to the GHI measurements were phenomenological in nature (correlations involving the difference between measured values and reference values) it was hoped that better understanding of the sources of uncertainties would lead to more robust and accurate correction algorithms. In an earlier report [4], the change in the average GHI and DHI responsivities over the day of a LI-COR pyranometer was examined. These measurements were made during clear and cloudy periods and showed significant differences between the average DHI and GHI responsivity that was related to differences in the spectral composition of DHI and GHI. Examination of the dependence of the responsivity also indicated that the difference between the DHI and GHI responsivities decreases over the day. Not only was this change observed in the DHI responsivities, but it appeared that the GHI responsivities also changed over the day as the spectral distribution changed.

In order to more accurately determine how the responsivity changes, a much larger dataset was needed that reflected more diverse situations. During a performance evaluation of the RSI and other radiation monitoring instruments at Payerne, Switzerland, a comprehensive direct normal spectral dataset became available. As in the earlier study [4] the DNI spectral responsivity of the LI-COR pyranometer could be determined by convoluting the LI-COR spectral response (Fig.1) with the measured DNI spectral irradiance.

This article is an analysis of the theoretical DNI responsivity of the LI-COR pyranometer. The article is divided into five sections. The first section is the discussion of the methodology used and an evaluation of the experimental dataset. The second section illustrates the relationship of the average DNI responsivity of the LI-COR photodiode based pyranometer as a function of air mass and determines general characteristics of the change in average DNI responsivity as a function of changing spectral distribution over the day. The third section evaluates the ability of a modeled spectral distribution to mimic the spectral distribution and change in responsivity found in the measured data. The fourth section discusses the implications for improving models that enhance the accuracy of RSI irradiometer and discusses future steps.

## 2. DETERMINING THE AVERAGE DNI RESPONSIVITY OF A LI-COR PYRANOMETER RELATIVE TO INCOMING DNI SPECTRAL IRRADIANCE

The LI-COR pyranometer is a photodiode-based instrument which, like solar cells, responds differently to incoming solar radiation depending on its spectral distribution [Fig. 1]. The percent relative responsivity is greatest in the red portion of the solar spectrum around 900-1000 nm. The figure shows that the responsivity of the pyranometer is about four times greater at 1000 nm than at 500 nm. The lens cap on the pyranometer is designed to give the instrument a better cosine response but it also blocks radiation below 400 nm.

One might think that this spectral response variation would significantly affect the instrument's output. However, a properly designed photodiode pyranometer gives a fair determination of the GHI as the spectral distribution doesn't change radically over the day. To determine the magnitude of this effect it is necessary to measure the spectral distribution over the day and see how the average responsivity changes.

The average DNI responsivity resulting from each spectral measurement is determined by multiplying the relative LI-COR spectral responsivity, $R_{LI\text{-}COR}(\lambda)$, by the intensity of the incoming radiation at each wavelength and summing this product over all wavelengths. This sum is divided by the sum over all wavelengths of the incoming spectral solar radiation and yields the average responsivity at the time of the measurement.

$$R_{DNI} = \sum (R_{LI\text{-}COR}(\lambda) * I(\lambda))$$

$$DNI_{tot} = \sum I(\lambda)$$

and

$$R_{av\ DNI} = R_{DNI} / DNI_{tot} \qquad \text{Eq. 1}$$

Where $I(\lambda)$ is the solar intensity at each wavelength and $\Sigma$ is for summing over all wavelengths.

2.1 Spectral Data

The incoming DNI spectral data was obtained using a prototype Precision Solar Spectroradiometer (PSR) built by the "Physikalisch-Meteorologisches Observatorium Davios" (PMOD)[5]. The PSR measures the incoming DNI spectral composition from 320 to 1030 nm with a resolution (FWHM) between 1.6 nm in the ultraviolet and 4.0 nm in the infrared portion of the solar spectrum. A solar spectrum is obtained with an integration time of 500 ms of which an average spectrum composed of 10 individual spectra is stored every minute. Before and after each solar spectrum, the dark counts measured with the shutter closed are used to determine the offset of the instrument for no incident radiation. The instrument has a 2º field of view and a temperature stabilized optical

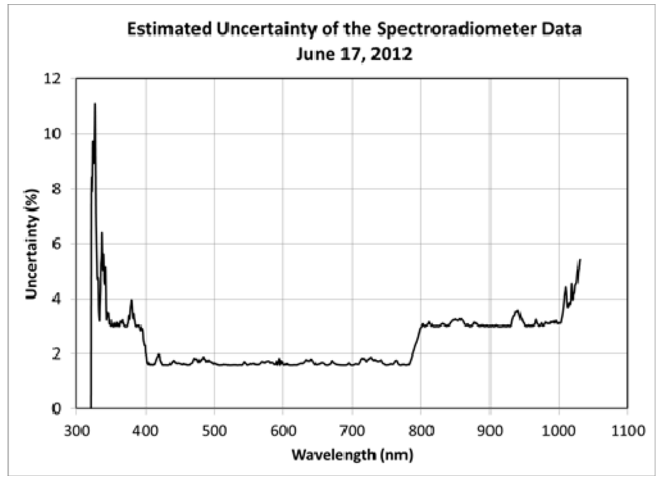


Fig. 2: Typical uncertainty of the PMOD Spectroradiometer. Uncertainty given in percent.

bench. The following data treatment is applied to the solar measurements:

1. The dark counts are subtracted from the solar measurements.
2. A temperature correction based on the temperature of the detector is applied to the spectra resulting from step 1.
3. The solar spectra are compared to a high resolution extraterrestrial solar reference spectrum and the resulting spectral wavelength shifts are applied to the wavelength of the solar spectra.
4. The sensitivity of the instrument, determined prior and after the campaign in the laboratory of PMOD/WRC by measuring the irradiance of a reference source (1000W FEL tungsten-halogen lamp, calibrated at the Physikalisch-Technische Bundesanstalt (PTB)) is applied to the measurements to convert them from counts/s to $W/m^2/nm$.
5. As a final step, the spectra are interpolated in order to bring them on a uniform wavelength grid.

The resulting uncertainties of the solar spectra obtained from the PSR following the procedure outlined in steps 1 to 5 are shown in Fig. 2.

The spectroradiometer was mounted on an automatic tracker with a four quadrant photoelectric sensor to improve the aim of the tracker. Accurate aiming of the PMOD spectroradiometer is important because of its narrow field of view.

A typical plot of the total DNI irradiance from 320 to 1030 nm is given in Fig. 3. Note that about 80% of the total DNI irradiance is from the 320-1030 nm range. The reading in the early morning and late afternoon are decreased by shading from nearby objects. Data occurring when the

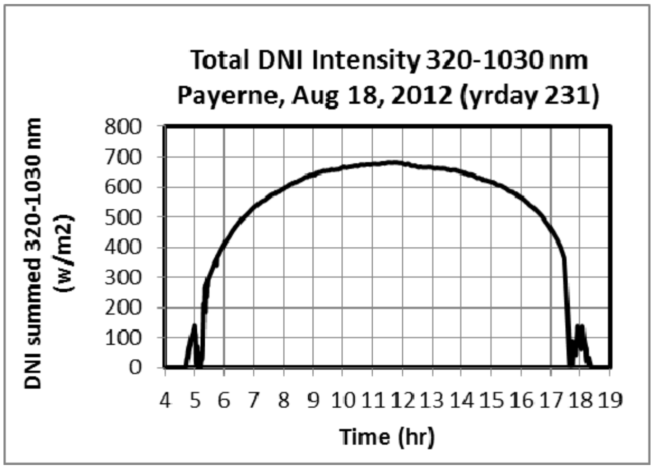


Fig. 3: Plot of the sum of spectral DNI from 320 to 1030 nm under clear skies. Drops in the morning and evening are the results of objects between the sensor and the sun.

spectral radiometer was shaded were eliminated. Five months of data were used in the study, starting on May 12, 2012 and ending on October 12, 2012.

2.2 Average LI-COR DNI responsivity

In addition to the above-mentioned rejection of data collected at a time when the spectroradiometer was shaded, values of DNI less than 10 W/m$^2$ were not used in the analysis. This was done to avoid potential problems when there was not sufficient DNI irradiance for the PSR to make a meaningful measurements.

A plot of the average DNI responsivity is plotted against solar zenith angle in Fig. 4. The average DNI responsivity varied from about 50% to 58% when the solar zenith angle was smaller than 65º. When the sun was lower in the sky,

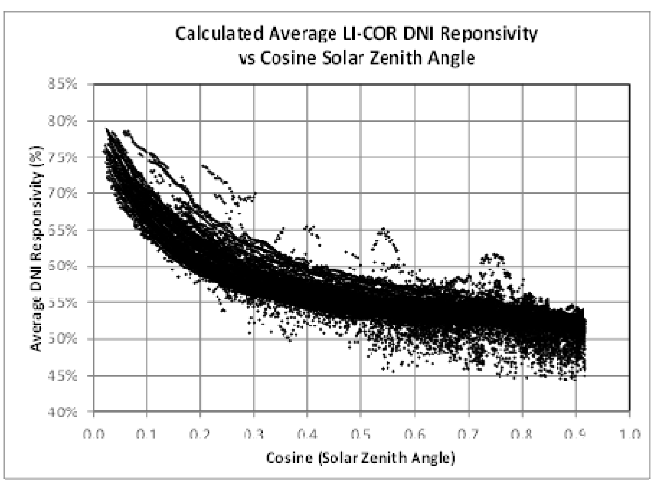


Fig. 4: Plot of average DNI responsivity versus cosine of the solar zenith angle.

the responsivity change increases dramatically, reaching 70 to 75% near sunrise or sunset. This increase is the result of increasing the amount of blue light being scattered out of the DNI irradiance, especially in the late afternoon or early morning. As shown in Fig 1, the LI-COR pyranometer is more responsive to the longer wavelengths and as more short wavelength blue light is scattered, the higher the average DNI responsivity becomes.

3. MODELING THE DNI RESPONSIVITY

Clearly there is a relationship between the average DNI responsivity and spectral radiation distribution that is related to air mass. The plot in Fig. 4 is reminiscent of earlier models of DNI radiation. In these models, the DNI irradiance is a function of air mass [6, 7]. The DNI formulas were respectively given by the following equations:

$$DNI = 1.353 \bullet 0.7^{AM^{0.678}} \qquad \text{(Eq. 2)}$$

and

$$DNI = 1.353 \bullet [(1 - .14 \bullet h) \bullet 0.7^{AM^{0.678}} + 0.14 \bullet h] \qquad \text{(Eq. 3)}$$

where AM is air mass and h is the altitude of the location above sea level in kilometers. Note that Eq. 2 is a the sea level version of Eq. 3.

Taking the core of these models, $0.7^{AM^{0.678}}$, and plotting the average DNI responsivity against this function, leads to a more linear relationship as shown in Fig. 5.

A linear fit to the data in Fig. 5 yields

$$R_{DNI} = 0.7355 - 0.3231 \bullet 0.7^{AM^{0.678}} \qquad \text{(Eq. 4)}$$

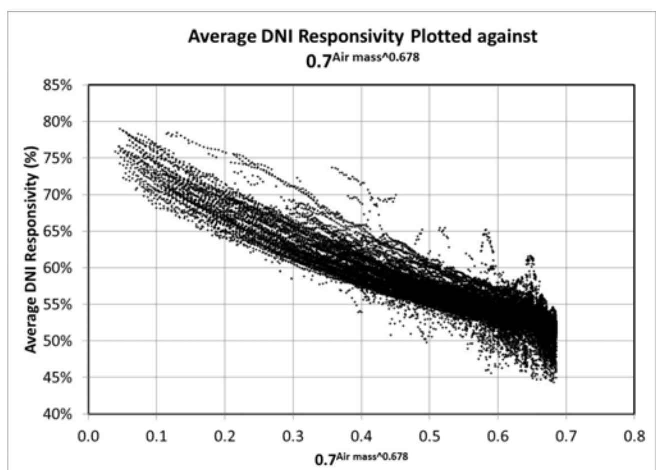


Fig. 5: Plot of the average DNI responsivity verses $0.7^{AM^{0.678}}$.

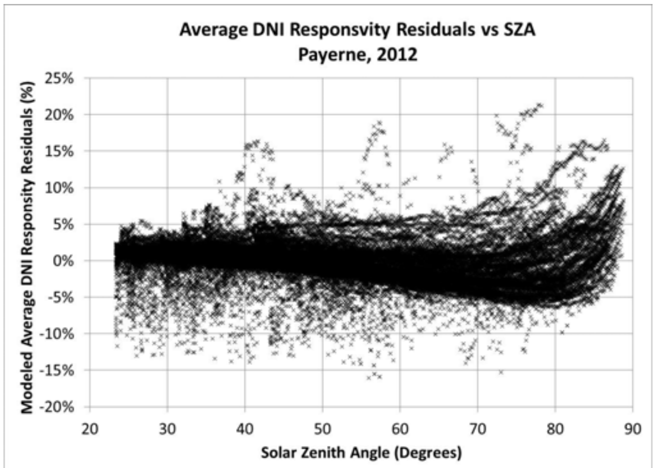


Fig. 6: Residuals from the fit to the average DNI responsivity of a LI-COR pyranometer.

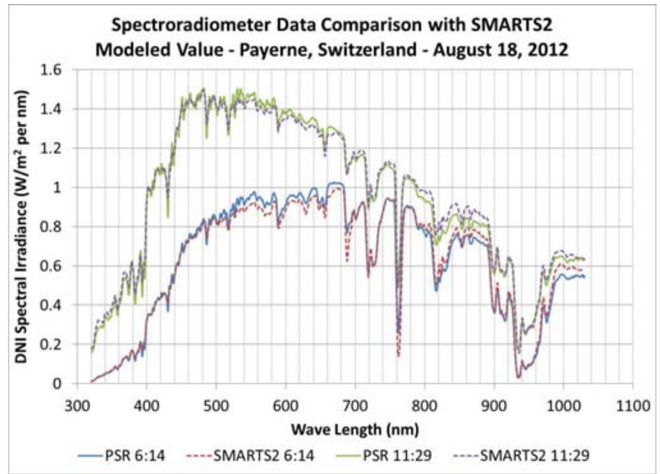


Fig. 7: Comparison of SMARTS2 estimates and PSR data at Payerne, Switzerland on August 18, 2013 at 6:14 am and 11:29 am. Modeled values are the dashed lines.

This gives an $R^2$ value of 0.86 with an uncertainty in the coefficients of less than ±0.2%. The residuals show that for the most part, the average DNI responsivity for the LI-COR pyranometer can be determined to better than ±5% using Eq. 4.

Two problems still remain before this information can become applied. First, the effect of the change in spectral distribution only covers the 320–1030 nm range. The LI-COR responsivity from 1030–1100 nm was ignored in the initial analysis because spectral data in that range was not available. The contribution of the 1030—1100 nm range to the average responsibility is examined using the SMARTS2 model [8]. The Spectral data below 320nm does not affect the average responsivity because the photodiode pyranometer does not respond to wavelengths below 400 nm because the material of the lens is opaque to the shorter wavelengths.

The second question is what happens to the responsivity under atmospheric conditions different from that experienced in Payerne? The answer to both questions can be obtained by using a spectral model such as the SMARTS2 model.

The ground based meteorological, temperature and pressure data from Payerne were used along with radiosonde values for water vapor and satellite derived ozone values. The spectral data at 500 nm was used to obtain the aerosol optical depth [9], and the SMARTS2 model estimated the spectral radiation for all wavelengths. A typical comparison between the PSR measured values and the SMARTS2 estimates is given for a clear day on August 18, 2012 is shown in Fig. 7.

The next step is to compare the estimated average DNI responsivity for the range from 320–1030 nm with the DNI responsivity from the full range seen by the LI-COR pyranometer (320–1100 nm). A sample result is shown in Fig. 8 where the average DNI responsivity from the 300 to 1100 nm range is between 3 and 5% lower than the responsivity calculated from the 320 to 1030 nm range. The reason for the decrease is that the LI-COR pyranometer spectral responsivity drops sharply after 1000 nm and is less than the average LI-COR responsivity. Also notice that the average DNI responsivity obtained from the spectral data (dashed curve in Fig. 8) and the SMARTS2 modeled results, the solid green line, are fairly close. Therefore, given the appropriate meteorological values, the SMARTS2 data results can be used to obtain the spectral

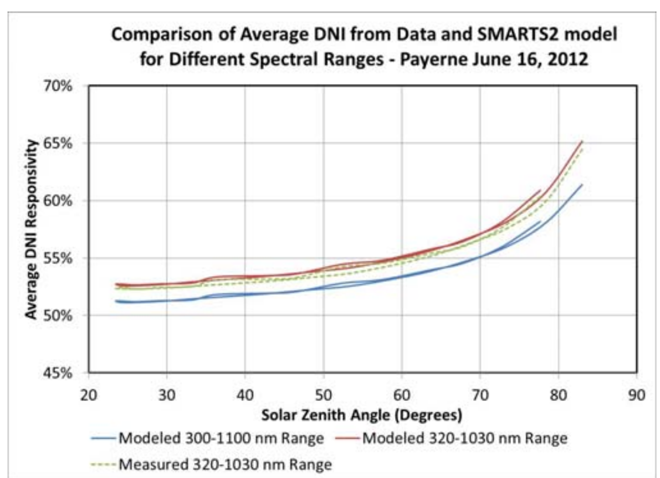


Fig. 8: Comparison of average DNI Responsivity calculated from the 320—1030 nm range with that calculated from the 300—1100 nm range.

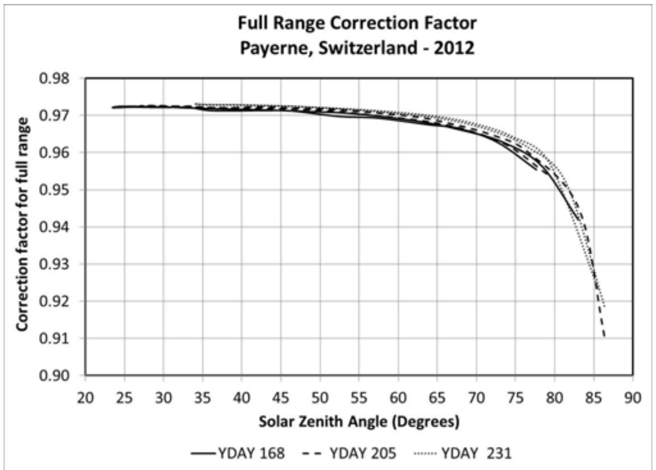


Fig. 9: Average DNI responsivity correction factor for full range.

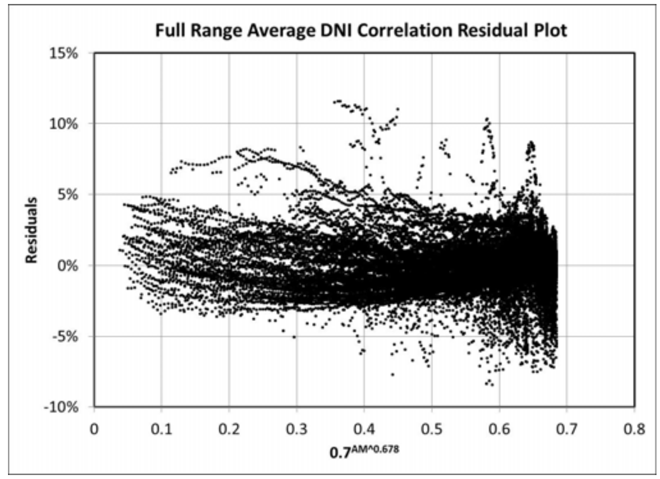


Fig. 10: Residuals from the fit to the average DNI responsivity over the full range of wavelengths of a LI-COR pyranometer.

dependency of the photodiode pyranometer.

The correction factor for the average DNI responsivity for the full spectral range affecting the LI-COR pyranometer can then be obtained by using the SMARTS2 estimates of average responsivity over the 320 nm to 1030 nm range with the estimated average responsivity obtained over the 300 nm to 1100 nm range (Fig. 9). This was done for three different days over the year. The correction factor times the average DNI responsivity determined from the 320 — 1030 nm data equals the full average DNI responsivity that should be used for the LI-COR pyranometer. Fitting the correction factor to the data as air mass power function gives,

Correction Factor =

$$0.8956 + 0.23495 \bullet 0.7^{AM^{0.678}} - 0.1806 \bullet (0.7^{AM^{0.678}})^2$$

Appling the correction to the average DNI responsivity values and correlating the results against the air mass power function yields.

$$R_{DNI} = 0.68613 - 0.26815 \bullet 0.7^{AM^{0.678}} \qquad \text{Eq. 4}$$

The residuals to the fit are shown in Fig. 10. The standard error is 1.6% in terms of the average DNI responsivity. Assuming the average DNI responsivity is 55%, then the uncertainty at the 95% level of confidence of the estimated full average DNI responsivity is on the order of 5.5%. These results are for all weather conditions when the sum of the DNI spectral data is greater than 10 $W/m^2$.

## 4. IMPROVING RSI CORRECTION ALGORITHMS

Application of the DNI responsivity to correct the photodiode measurements is a complex problem because there are other uncertainties such as deviation from true cosine response and temperature effects on the pyranometer output. One must combine the spectral dependence with these other factors to determine the correct appropriate correction factors.

The rationale of this study is to augment the work being done to characterize the uncertainties of RSI Irradiometers and develop correction algorithms to improve the accuracy of the data. The RSIs measure GHI and DHI irradiance. It then subtracts the DHI from the GHI and divides by the cosine of the incident solar zenith angle to obtain the DNI. The spectral dependence on the DHI is complex and has been determined by a phenomenological model. Because we now have a better understanding of the mechanism that causes this spectral dependence, modeling this effect should improve. Under clear skies, the average LI-COR DHI responsivity [1-4] is significant different from the DNI responsivity because the DHI and DNI spectral distributions are different. Under cloudy skies, the DHI and DNI spectral distributions are similar since clouds act as neutral density filters because of the large size of the droplets compared to the incident radiation, leaving the spectral distribution of the radiation passing through the clouds unchanged. With a mixed sky cover, the spectral distribution for the diffuse irradiance is a mixture of the two conditions and the average DHI responsivity lies in between.

Since the SMARTS2 model also calculates the spectral distributions of the GHI and DHI irradiance, it can be used to estimate the spectral distribution effects on these com-

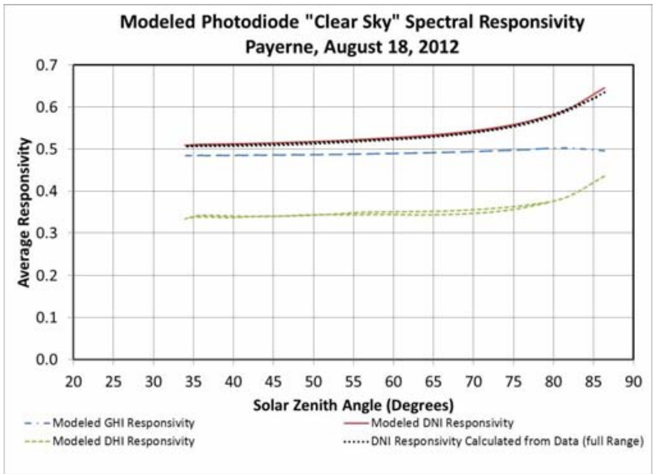


Fig. 11: Estimates of the effect of changing spectral distributions on the average DNI, GHI, and DHI responsivities for a LI-COR pyranometer using the SMARTS2 model.

ponents as well as the DNI component (see Fig. 11).

Theoretical models are the initial step. All these models have to be tested against real data. This is the focus of future work. If this model is shown to improve correction algorithms for RSI data at one location, the question remains as to what correction to apply at a location with different atmospheric conditions than the site under study. Again, the SMARTS2 model or other spectral model can be used if enough data is available to provide an adequate characterization of the local conditions. Then the methodology used here can be applied to the local situation.

All this modeling has been applied to a photodiode pyranometer. However, solar modules also have well defined spectral responsivities. The methodology used here for photodiodes can also be applied to photovoltaic modules by substituting the module spectral responsivities for the photodiode spectral responsivity used here.

Good spectral data from a variety of locations with accurately monitored irradiance and photovoltaic modules could go a long way to providing a significant improvement in performance predictions.

## 5. ACKNOWLEDGEMENTS

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