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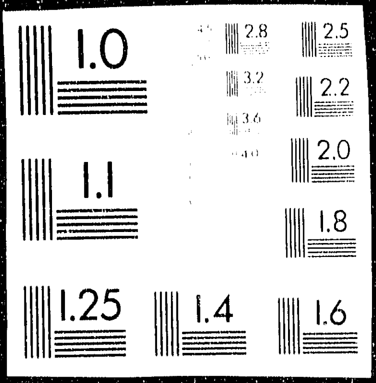

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COSINE RESPONSE CHARACTERISTICS OF RADIOMETRIC AND PHOTOMETRIC SENSORS

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ABSTRACT

Global and diffuse irradiance and illuminance are measured with instruments that are assumed to have true cosine responses. It is known, largely from reports with a limited distribution or by word of mouth, that no instrument is perfect in this regard. This paper reports on measurements of cosine responses for several instrument types and manufacture familiar to the solar radiation measurement community. The measurements were made with an automated cosine response test bench using the same protocol for each instrument. The cosine bench measures with variable angular resolution as fine as 0.25 degrees. The automated rotation is in one plane. A manual rotation allows measurements for other azimuths.

1. INTRODUCTION

The most common measurement in solar radiation research is the global irradiance or the global illuminance, depending on whether one's interest is energy or illumination. To make these measurements, an instrument with a field of view that accepts radiation from any direction within a hemisphere is used. The assumption made when employing these devices is that the response of the instrument is sensitive to the direction of the incident radiation in a clearly defined way. This response is assumed to be Lambertian, i.e., the response decreases as the cosine of the angle of incidence. Fig. 1 illustrates this geometry.

It is generally recognized that global irradiance and illuminance sensors do not have perfect cosine responses. It is also acknowledged that the response is poorest at the highest angles of incidence. This is caused by the specular reflection from the detector or diffuser above the detector as one nears grazing incidence. The assumption is usually made that the measurements are accurate at the highest solar elevations, i.e., the lowest angles of incidence, that the bulk of the irradiation received is at these angles and the lowest elevations do not contribute enough to affect the daily totals in irradiation or illumination appreciably. This is often the practical and acceptable assumption.

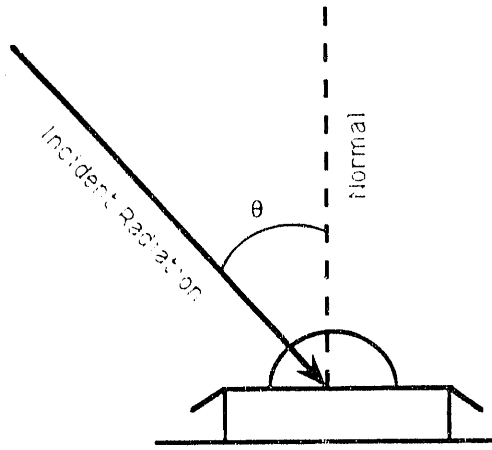


Fig. 1. Cosine response geometry for Lambertian receiver.

However, there are instances when understanding the cosine response is crucial. In lieu of tracking pyrheliometer measurements, direct normal irradiance is often calculated from the measurement of global and diffuse horizontal irradiances. The diffuse is measured with a shadowing band and corrected for blocked sky radiation. By differencing the two measurements one calculates the direct horizontal, and then converts to direct normal by dividing by the cosine of the angle between the zenith and the solar direction. One errs in the calculation of direct by the ratio of the actual cosine response to the true cosine response. Tracking plate or focusing systems may not have their expected performance based on direct solar radiation measured in this fashion.

In this paper we report on measurements made with an automated cosine bench. The bench position and light detection are controlled by a microprocessor-based data acquisition system of our design [1]. We measure three sensors of each type, when available, to illustrate reproducibility within a sensor design. Although the cosine bench was actually constructed to aid us in the development of multispectral rotating shadowband radiometers [1], we will, in this paper, focus on commercial instruments that are commonly used in solar resource assessment. Section 2 describes the cosine response test bench. Section 3 follows with the results of tests of five types of sensors, and section 4 draws conclusions based on these results.

2. COSINE TEST BENCH

Fig. 2 is a schematic layout of the cosine response test bench. The rotating table is a Daedal Model 10001. The table is turned by hand via rotation of a knurled handle. In our application the handle is removed and the shaft on which the handle is normally mounted is coupled to the axis of a stepping motor via a custom-machined plastic coupler. The shafts, which have different diameters, are aligned and the plastic coupler is fixed to each by several set screws positioned on flat spots filed onto each shaft. The table is leveled so that rotation is about a true vertical axis. This rotation axis is centered on the incoming light beam. Custom mounting plates are

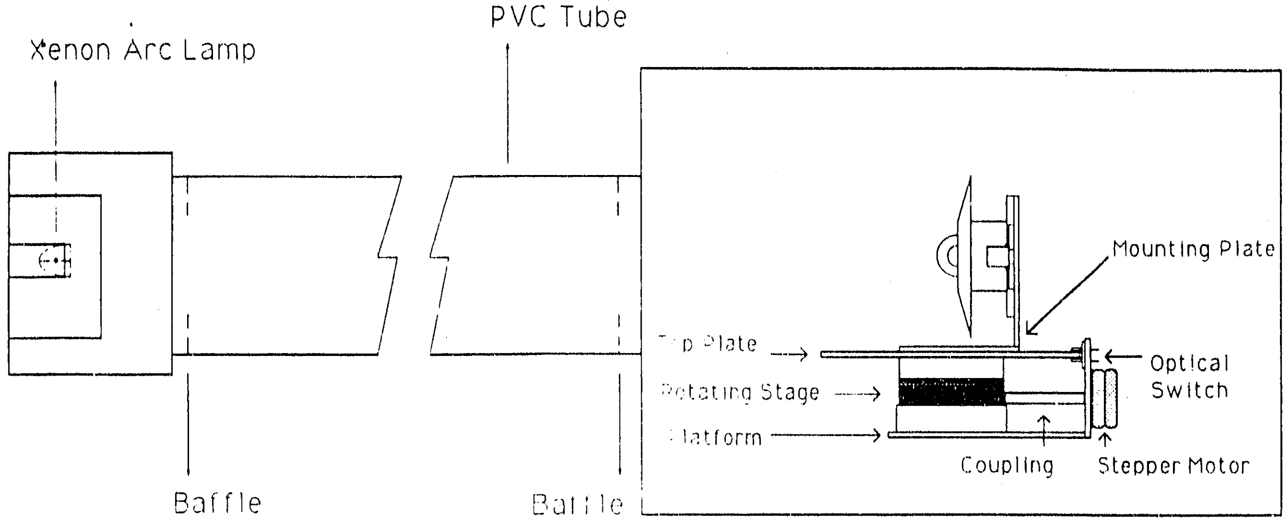


Fig. 2. Schematic layout of the cosine response test bench.

machined so that the sensors may be mounted vertically to rotate in a horizontal plane with the sensor or diffuser, as the case may be, stationary in the beam, i.e., the center of the sensor is on the same axis as the rotation axis of the table. This minimizes sensor wander in the beam.

The beam is formed by a 13-foot (4 m) tube made of 6-inch (15.2 cm) inside diameter polyvinyl chloride (PVC). The inside surface of the tube is painted with a flat black paint and two baffling fixtures consisting of four baffles with 4-inch (10.2 cm) inside diameters are positioned within the PVC tube. The beam terminates in the center of a box that contains the table and measures 4 x 4 x 3 feet (1.22 x 1.22 x 0.91 meters). The box is painted with a very black fiber impregnated paint and black velvet cloth is hung on the walls to further reduce stray light inside the box. The light source consists of a 300-watt, 1-inch (2.54 cm) aperture, axial parabolic confocal xenon arc lamp manufactured by ILC Corporation. The overall distance between detector and source is 15 feet (4.5 m). The working aperture is 2 inches (5.1 cm) with a measured uniformity of about 1%. Except for very large sensors or diffusers we work very near the center of this working aperture.

The table position, sampling interval, sampling dwell time, and number of scans is controlled by a microprocessor-based data acquisition system. This same data logger controls the operation of our rotating shadowband radiometer and is described in [1]. In addition to controlling the operation of the cosine bench, the data acquisition system logs the samples from as many as 16 sensors at each sample position.

A slot that is cut in the rotating platform passes through an optical switch to define the home position 95 degrees from normal incidence. Note that a Lambertian receiver only responds to light incident between 0 and 90 degrees. For the sensors tested, adherence to this characteristic of Lambertian receivers is realized. Dark measurements are made in this position. The dark measurements produce the same values whether the light source is on or off indicating that scattered light within the housing is low. The stepping motor moves the table 0.0625 degrees per step. The table is positioned at 90 degrees incidence angle by stepping from the home position and checking the alignment with a long straight tube positioned on the face of the detector or diffuser. This usually allows alignment to within one step.

One cosine response scan includes sampling from -90 to +90 degrees and back. Four scans are made in a typical measurement. Even though the power supply provides a constant current to the lamp, more that one scan and sampling in each direction are required to average the inevitable fluctuations in our xenon arc lamp output. Samples made be taken with a resolution as fine as every 0.25 degrees, but more often are made at 1 degree intervals. The time spent at each position depends on the response time of the sensor. Silicon cell radiometers and photometers may be sampled relatively quickly, but the response time of thermopile radiometers requires a longer dwell time.

3. COSINE RESPONSE MEASUREMENTS

Some manufacturers of irradiance and illuminance sensors plot the cosine response of their instruments unnormalized. Fig. 3a illustrates one such plot. A perfect cosine response is

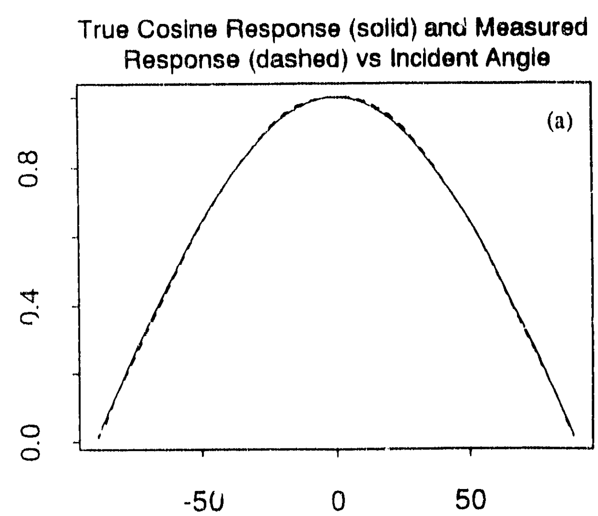


Fig. 3. (a) Unnormalized plot of true and measured cosine responses for a LI-COR photometer.

represented by the solid line. The measured response of a LI-COR LI-200 pyranometer [2] is plotted as the dashed line. Plotted in this fashion the cosine response of the instrument looks remarkably close to perfect. Fig. 3b, on the otherhand, illustrates the response on a normalized plot (the way LI-COR plots their cosine response). This shows directly the bias one would have for a beam incident from a given direction. For example, one would underestimate the irradiance from -75 degrees by about 5% if no corrections were applied.

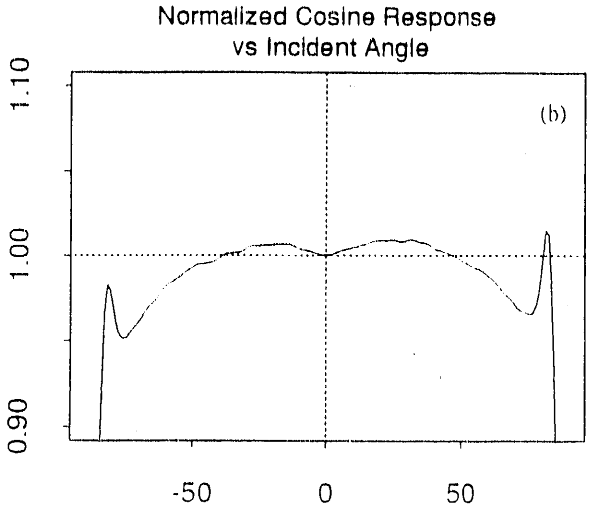


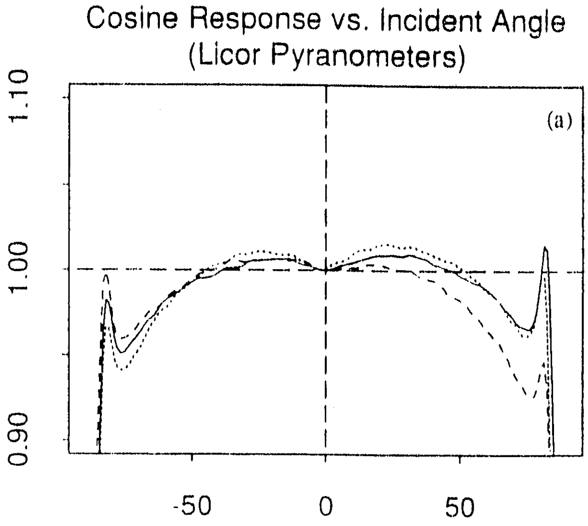
Fig. 3. (b) Normalized plot of measured cosine response for same LI-COR photometer as in Fig. 3 (a).

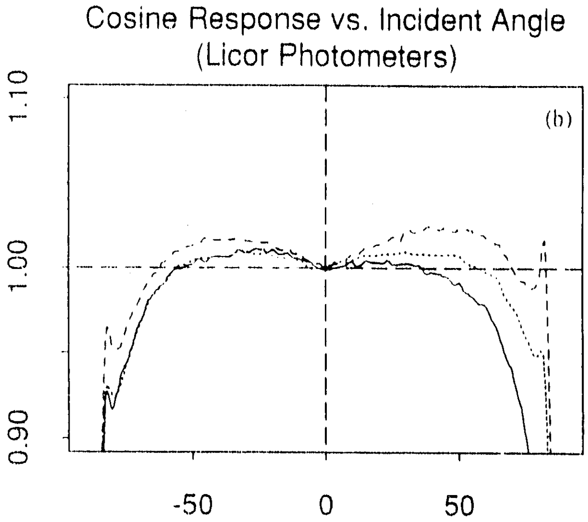
Measurements were made of the cosine response characteristics of a number of sensors. Both irradiance and illuminance sensors were tested. In all of the figures that follow the ratio of the measured cosine response to a true cosine response is plotted. Note that the scale is the same for each instrument tested for easier comparison, and note that the expansion of the scale, compared to a zero-to-one vertical scale, makes discrepancies readily apparent.

Figs. 4a, 4b, and 4c contain the measured cosine responses of three individual LI-COR LI-200 pyranometers, three individual LI-210 photometers, and two individual LI-190 photosynthetically active radiation sensors. These are three different types of instruments in that they measure different portions of the spectrum or with differing weights according to their filtering. They follow the same basic design introduced by Kerr et al. [3] for silicon cell sensors with a silicon cell beneath a diffuser and optical filter as appropriate. The diffuser, which is raised to compensate for the light lost from specular reflection at the top of the diffuser, is surrounded by a shading ring that cuts the light off at 90 degrees incidence angle.

Each instrument shows some asymmetry about normal incidence. If the optical axis of the sensor is not exactly perpendicular to the top of the shading ring, which is used for the alignment within the light beam, then this asymmetry is expected. The angular misalignment error between the actual optical axis of the instrument and the mechanical axis can be estimated by the first moment of the measured angular irradiance function

$$\theta_{error} = \int \theta \, I(\theta) \, d\theta \Big/ \int I(\theta) \, d\theta \qquad (1)$$





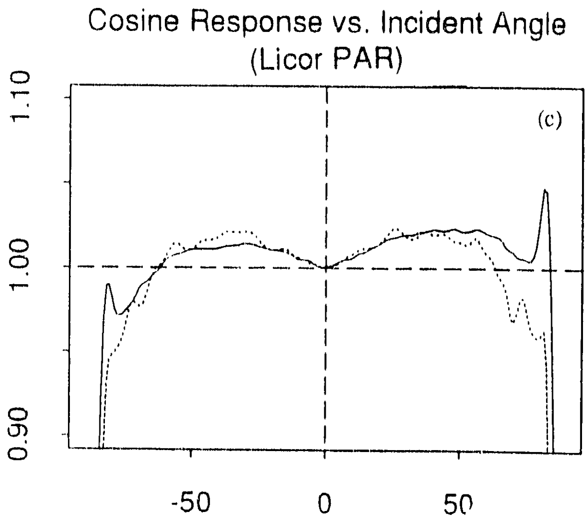


Fig. 4. (a) Normalized plot of cosine responses for three LI-COR pyranometers, (b) for three LI-COR photometers, and (c) for two LI-COR photosynthetically active radiation sensors.

This estimator for the angular error is the maximum-likelihood estimator given uncorrelated normally distributed residuals. After calculating this factor, we have adjusted the sensor position by this angle (to the nearest 0.0625 degrees), rerun the cosine response measurement, and obtained nearly perfect symmetry, thus verifying that this factor represents the asymmetry. The picture emerges, as we shall see further, that every instrument shows some asymmetry. However, in each of these cases this misalignment of optical and mechanical axes is less than 0.5 degrees. Note that the general shape of the LI-COR instrument response corresponds closely to LI-COR's published cosine response [2].

Fig. 5 is the normalized cosine response from three Eppley Precision Spectral Pyranometers (PSPs) [4]. Again there is asymmetry, which in every case is less than 0.5 degrees. The alignment in the light beam in this case was made with the alignment tube on the ring that surrounds the double dome structure. This may explain the asymmetry since this may not be parallel to the detector face, however, this surface would normally be used by us to align the PSP instrument for use outdoors. For the three PSPs that we tested the cosine responses show remarkable reproducibility. The raised response between 60 and 70 degrees is a common feature of this instrument [5], but may be more subdued in our three instruments than others have noted.

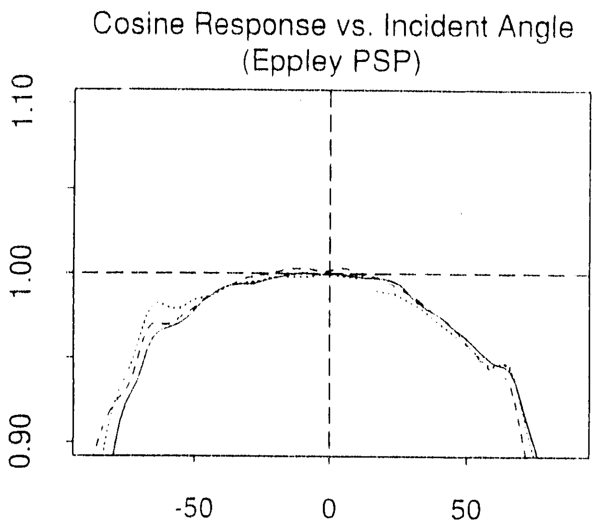


Fig. 5. Normalized cosine responses for three Eppley PSPs.

The final instrument whose cosine response was measured was the Kipp and Zonen CM 11 [6]. This is a thermopile instrument like the Eppley PSP. In Fig. 6 it does not show the enhanced response between 60 and 70 degrees, and its asymmetry is less than 0.5 degrees. Again the alignment tube was positioned on a flat metal support surrounding the dome. Its cosine response is somewhat better than the Eppley PSPs, but we only had a single instrument to test.

4. CONCLUSIONS

The protocol for all instrument testing was identical. Consequently, this study should serve as a fair comparison of the cosine responses of these instruments. In the cosine bench the light source is a xenon arc lamp. These lamps produce

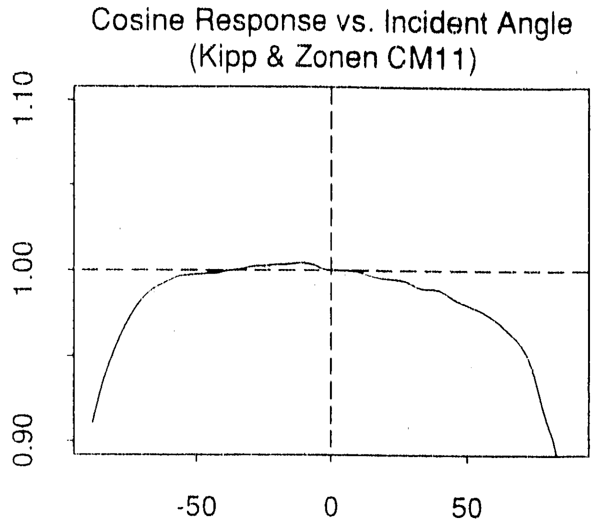


Fig. 6. Normalized cosine response for a Kipp & Zonen CM 11.

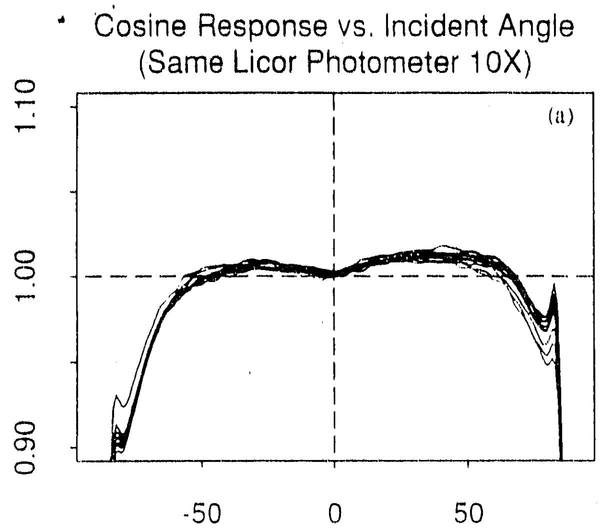
light mainly in the blue and visible and emit poorly in the 1000 to 2800 nm region and, therefore, are red poor with respect to the sun. While thermopile instruments are presumably insensitive to the wavelength of incident radiation, we cannot rule out the possibility that the optical train may produce some cosine response wavelength dependence.

Another point that we wish to stress is the importance of automating these tests. Usually the manual testing of instrument cosine response is slow, tedious and only a few angles are measured. For 1 degree resolution and four to and fro scans, there are 22,912 samples taken, since at each position 16 samples are averaged for each measurement.

We consider the performance of the instruments tested to be among the best of commercial devices. There are some instruments that we tested that had such poor cosine responses, that we elected not to show them so that subtle effects would not be lost. Of course, our tests were not exhaustive. They were limited to the instruments on hand. Performance for a particular instrument could be better or worse than those shown. A point that bears repeating is that we have chosen to greatly expand the scale at which most of these type of plots appear to make our points about asymmetry and reproducibility.

All of the detectors tested had angular misalignment errors between the optical and mechanical axes ranging between 0.1 and 0.5 degrees. While this may appear small, it is quite apparent on the plots. These misalignments are distinctly larger than the limit of operator reproducibility. How well one can align in the laboratory may be assessed by considering Fig. 7. Fig. 7a is the cosine response of the same instrument measured ten times by removing the device and remounting and realigning in the same position. The test was performed by a trainee. The calculated asymmetry from eqn (1) for the ten trials was 0.27 +/- 0.09 degrees. We may consider 0.09 degrees (or 1.5 times the step size of our stepping motor) the upper limit for alignment error in the laboratory. Most instruments mounted in the field are probably aligned less accurately than this.

Errors in the 0.1 to 0.5 degrees range can be very important to a measurement error budget when high accuracy is desired. For instance, 0.25 degrees in hour angle corresponds to one



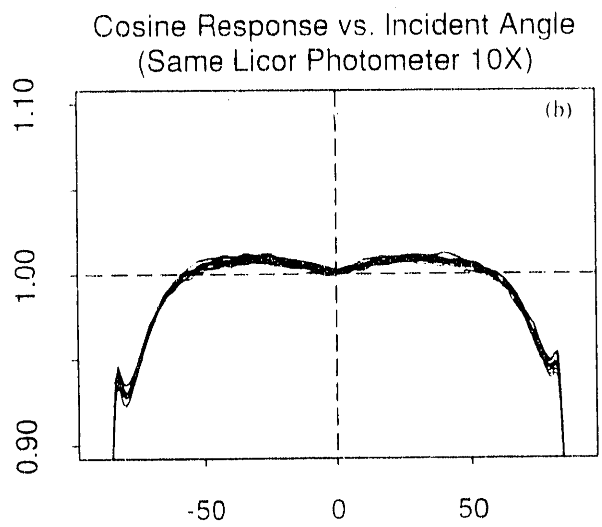


Fig. 7. (a) Normalized cosine response for 10 independent measurements of the same LI-COR photometer. (b) Same plot after correcting by calculated asymmetry factor.

minute of time. Errors in calculating the direct beam component from shaded and unshaded pyranometers may, therefore, be appreciable. The error term also affects global horizontal irradiances when the direct beam dominates. In contrast, the diffuse sky irradiances are less affected. For the artificial case of a uniform sky irradiance and a zero surface albedo, the error is sin (θ_{error}), where an error of 0.25 degrees in alignment causes an error of 0.5%, less but not negligible.

The error in the correction of data that one makes using our bench that may be assigned to random error, rather than the bias that we introduce in aligning the instrument, may be assessed using the same ten measurements. In Fig. 7b we have mathematically corrected the optical and mechanical axis misalignment using eqn (1) and overplotted these. The standard deviation in the ratio of measured to true cosine response at -45 degrees is +/- 0.002, therefore, the random error in the correction factor is on the order of 0.2%.

A final point is that instruments used for global horizontal irradiance or illuminance measurements may actual perform well for integrated values. When the cosine response straddles the perfect cosine response, summed irradiation or illumination should average to nearly the correct value. Instruments whose cosine responses deviate in a monotonic way will produce a bias error that depends on the magnitude of the deviation from true cosine behavior. Since instruments are usually calibrated at zero or near normal incidence angles, the cosine response should not affect calibration. It is, however, crucial that cosine response be understood if one attempts to use these instruments for the calculation of direct irradiance.

5. ACKNOWLEDGMENTS

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