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ACCURATE FIELD CALIBRATION OF PYRANOMETERS

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Abstract—The relative calibration of pyranometers in the field (as opposed to laboratory calibration) is discussed. Measurements performed both for horizontal instruments and for those at normal incidence are analysed. It is found that the normal incidence geometry results in relative calibration constants with a precision of a few parts per mille (for instruments with tilt-independent outputs). This is considerably more accurate than results obtained using the horizontal geometry. The reason for this difference is discussed. It is pointed out that a combination of calibration measurements performed successively at both geometries can serve to identify common instrument deficiencies such as nonlinearity, poor cosine response, and built-in leveling errors.

1. INTRODUCTION

Ideally, all pyranometers should be periodically recalibrated, for example, at a laboratory certified by the World Meteorological Organization (WMO). This need stems from inaccuracies in factory calibrations [1,2,3] as well as from sensitivity degradation of instruments after extended exposure to outdoor conditions. However, this procedure is expensive, and may result in the radiation sensor not being available for use for a considerable period of time. One therefore frequently reverts to the second best option of procuring a separate instrument which is calibrated periodically and is kept as a substandard for local calibration purposes. In this way, local calibration and testing of newly obtained instruments as well as monitoring of possible aging of instruments under continuous use can be conveniently carried out. However, as will be shown below, common field calibrations can be imprecise.

In this note we show how, with quite limited equipment, accurate relative calibration of pyranometers can be performed, and how one can easily separate out linearity errors from cosine response or leveling errors. The proposed method combines two sets of measurements in which the instruments are successively positioned horizontally and at normal incidence to the beam direction. Normal incidence measurements are, of course, necessarily limited to instruments that are tilt-angle insensitive. For such instruments calibration measurements can be performed that are very stable—within a few parts per mille—and thus require only few measurement points. This is not to say that the calibration constant derived in this way is accurate to such a degree of precision, for, as will be explained below, the values obtained tend to vary from one set of measurements to another by more than this amount.

The results reported here were obtained in the course of an experimental program aimed at validating the multipyranometer method [4,5] for measuring the beam and diffuse components of insolation using stationary pyranometers. For such a purpose precise knowledge of the relative calibrations among all the instruments is clearly essential, as is the identification of possible cosine response errors. The data presented in this work were derived from numerous calibration measurements carried out at different seasons over a three-year period. Therefore, possible seasonal and aging effects are expected to be well represented in the results.

Our technique should be applicable for any kind of pyranometer which is considered to have a sensitivity that is independent of the instrument tilt angle. For example, Eppley's PSP (Precision Spectral Pyranometers), used in this work, and Kipp and Zonen's CM10 are suitable instruments [1–3,6].

2. COMPARISON OF PYRANOMETERS

A common method for comparing two or more pyranometers is to place them on a horizontal surface and compare their readings at various times of the day. This is a convenient method if one of the instruments is a calibration substandard. The accuracy of this method is limited by the instruments possibly having poor cosine response and/or leveling errors. The former error causes reduced sensitivity with increasing angle of incidence in excess of the simple geometrical factor. Depending on time of year and latitude of location, a poor cosine response will affect the results differently. On the other hand, subtle leveling errors can occur if the plane of the absorbing surface is not perfectly parallel with the leveling device attached to the instrument. This can cause small differences in the actual incidence angles, and thereby erroneous instrument outputs at large angles.

Figure 1 displays typical results of such a comparison. Four new Eppley PSPs were compared on a cloudless summer day from midday to evening. The results are presented in the form of a relative calibration, namely, the output of each instrument was divided by the output of a "reference" instrument. This was done to mimic the typical situation in which a

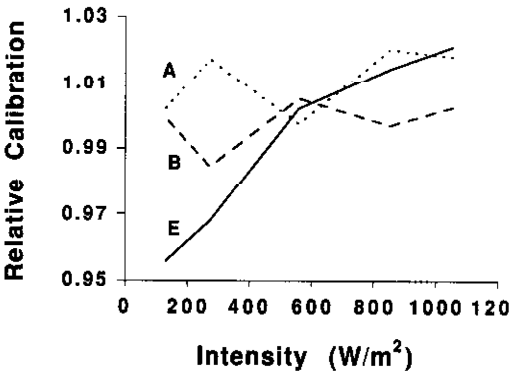

Fig. 1. Results of relative calibration tests obtained at the horizontal geometry. Curves A, B, and E correspond to the outputs of three pyranometers normalized to that of a fourth instrument.

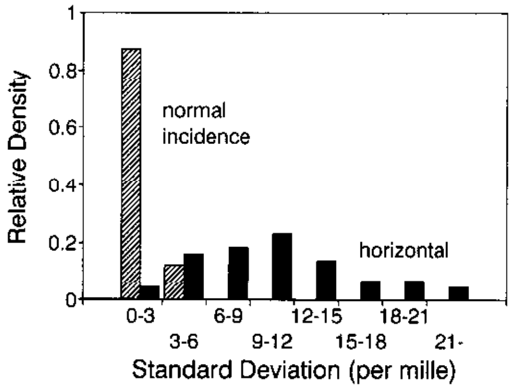

Fig. 3. Histogram of standard deviations observed during calibration tests spanning the full range of solar intensity (200–1000 W/m^2) for normal incidence (shaded bars) and horizontal geometry (solid dark bars).

single instrument is reserved for calibration purposes. The particular choice of the reference instrument is of little importance for our purpose here and was made based on it participating in all subsequent calibration experiments. While instruments A and B show variations relative to the reference instrument of 1 to 2%, which are within the instrument specifications, instrument E appears to exhibit a systematic trend, and the corresponding variations are significantly larger. On the basis of the data of Fig. 1 alone it cannot be determined whether the unsatisfactory performance of instrument E is due to nonlinear output, due to a poor cosine response or due to a leveling error.

In Fig. 2 relative calibrations with the same instruments positioned at normal incidence are shown for varying solar intensities during the course of a day. The measurements were performed a week later on an equally cloudless day, with similar wind and temperature conditions. The constancy of the relative calibration is apparent. The relative calibrations vary throughout the measurement period within only two or three parts per mille. The superior stability is a result of the nominally normal incidence geometry, which virtually eliminates the effect of the cosine response. Moreover, owing to the vanishing of the derivative of the cosine function, any leveling error produces a negligible effect—about 40 parts per million for a deviation of half a degree. For this reason also, it is not even necessary for the instruments to track the sun continuously: one need only set them up at approximately normal incidence to obtain the relative calibration with high accuracy. Thus, complicated tracking devices, typically unavailable in the field, are not required for the method to work. Of course, the instruments under comparison must see the same sky—a condition which is hard to meet at very large tilt angles. Therefore, it is not advisable to carry out such measurements at too large zenith angles when reflected radiation might affect differently the readings of the instruments even if they are set up close to each other. Indeed, the constant curves of Fig. 2 imply that for linear instruments prolonged measurements are not required, and a few data points taken around solar noon suffice to ensure the desired precision. Further evidence for the improved accuracy of normal incidence comparisons will be presented below.

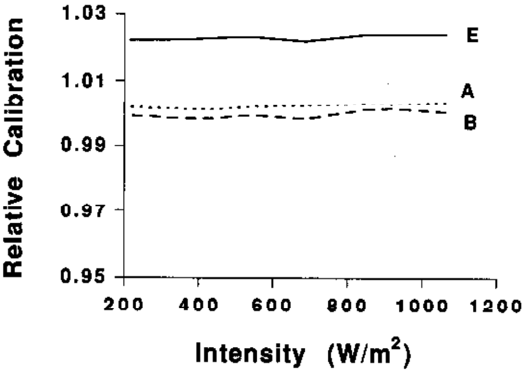

Fig. 2. Results of relative calibration tests obtained at normal incidence. Curves A, B, and E correspond to the outputs of three pyranometers normalized to that of a fourth instrument.

The combined results of measurements carried out at both the normal incidence and the horizontal geometries can now be used to identify the reason for the poor performance of instrument E, shown in Fig. 1. The curve corresponding to this instrument in Fig. 2 appears as constant as the curves of the other instruments, and the 2% difference in the calibration constants is within factory specifications. Thus one would have no reason to suspect any unusual behavior from this pyranometer. Yet, the horizontal test indicates a trend in the output as a function of incidence angle. As the normal incidence results rule out nonlinear output, the combined information of Figs. 1 and 2 suggests a particularly poor cosine response, or a serious leveling misalignment for this instrument. The latter possibility could be discarded on the basis of another horizontal measurement with the instrument rotated by 180° relative to its previous position. After confirming the persistence of the poor cosine response in additional tests, the instrument was returned to the manufacturer for replacement. Previous work by Mohr *et al.*[1] led them to conclude that the cosine response is a characteristic of the individual instrument rather than of a specific brand. Thus, it is strongly recommended to test the cosine response of each instrument before using it in the field.

These conclusions are relevant also for calibration of pyranometers against a precalibrated pyrheliometer, using a shading disc. For improved accuracy, such a calibration is best performed with all instruments at normal incidence. This necessitates the use of at least two pyranometers, so as to eliminate the spurious effects of reflected radiation. If one of the pyranometers is continuously shaded, while the other is not, additional errors associated with the long time constant of the pyranometers[2] can be avoided.

3. LONG-TERM COMPARISON OF PSPs

The behavior displayed in Figs. 1 and 2 is not particular to the instruments included in these figures. Figure 3 summarizes numerous measurements carried over a period of three years with eight pyranometers. The histogram describes two distributions of the standard deviations of the values obtained during the measurements, each conducted over the course of a day. The light colored bars denote the histogram of 26 measurements conducted at normal incidence. The dark colored bars form the corresponding histogram for horizontal measurements. Again, 8 instruments participated in 42 tests. The tests were performed over the intensity range from about 200 W/m^2 to 1000 W/m^2, and the relative calibrations refer to the same "reference" instrument of Figs. 1 and 2. It is seen in Fig. 3 that the standard deviations of the daily relative calibrations for about 85% of the normal incidence tests fall below the three parts per mille level. The horizontal measurements, carried out under similar climatic conditions, have standard deviations that are several times as large.

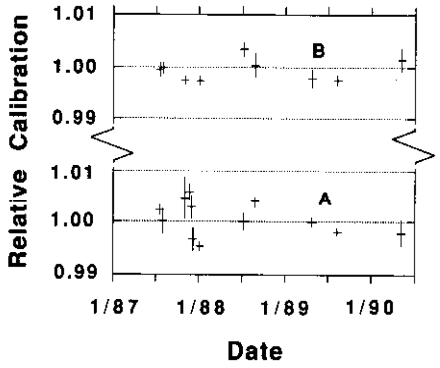

Fig. 4. Variations of relative calibration constants derived at normal incidence versus time of measurement. The data correspond to instruments A and B.

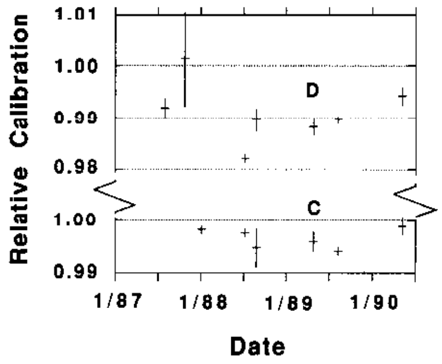

Fig. 5. Variations of relative calibration constants derived at normal incidence versus time of measurement. The data correspond to instruments C and D.

However, this should not distract from the fact that a single measurement does not provide an absolute accuracy of a few parts per mille. Rather, the relative calibration can change from one test to the next, depending on ambient conditions such as temperature or wind. Figures 4 and 5 show normal incidence relative calibrations for four instruments over a period of about three years. The variations in the relative calibrations appear somewhat larger than what would be expected from random fluctuations with the indicated standard deviations. Neither a seasonal trend nor aging could be detected. Instrument D was not exposed to sunlight except during calibration experiments, while the others were in continuous use. Thus, the exact origin of the enlarged variations is not yet clear. Based on the data of Figs. 4 and 5, the value of 0.5% appears as a conservative estimate of the accuracy obtainable with normal incidence relative calibrations.

Perhaps another word of caution is in place here: Since most pyranometers are employed in a stationary mode, their output is subject to cosine and leveling errors. Thus, although the calibration constant can be determined to the accuracy discussed above, the effects of these errors should be considered when assessing the quality of data taken with stationary instruments.

4. SUMMARY AND CONCLUSIONS

This work addresses the problem of accurate field calibration of pyranometers. Both the horizontal and normal incidence arrangements are used for the identification of instruments having nonlinear output, poor cosine response, or leveling errors. It is shown that relative calibration constants of tilt independent pyranometers are best derived under conditions of normal incidence for the solar beam component. Under such conditions, the relative calibration constants are reproducible to a few parts per mille. This precision is typically about a factor of 5 higher than what is obtained when the instruments are compared in the horizontal orientation. However, the precision achieved during a single normal incidence measurement should not be taken as an absolute scale for the instrument accuracy. Over the long term, variations in the relative calibration are observed to be of the order of 0.5%.

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