Evaluation of a New Photodiode Sensor for Measuring Global and Diffuse Irradiance, and Sunshine Duration

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A new integrated device (called the BF3) has been developed, which enables the simultaneous measurement of horizontal global and diffuse irradiance as well as sunshine presence at any time. The sensor needs no specific polar alignment or routine adjustment, and works at any latitude. To evaluate the performance of this new device, a BF3 sensor was installed on the roof of a six-story building in the Merchiston Campus of Napier University, Edinburgh from February 22–July 3, 2001. Horizontal global and diffuse irradiance data were collected from the BF3. To enable a cross check, two Kipp and Zonen CM11 sensors, one with a shade ring, have also been installed beside the BF3 sensor on the same roof. These were used to give a reference measure of the horizontal global and diffuse irradiance. To evaluate the BF3 sunshine duration performance, the direct beam normal irradiance was calculated from the CM11 global and diffuse readings, and compared with a threshold of 120 $W.m^{-2}$ *to give sunshine presence according to the WMO definition. This was compared against the BF3 output, and also with data from two Campbell-Stokes sunshine recorders on the same site. The results show a stable performance on the part of the BF3 sensor for the measurement of horizontal global and diffuse irradiance. The global irradiance measured by the BF3 showed values 4.7% high, with a standard error of 16.5* $W.m^{-2}$ *compared to the Kipp and Zonen sensors. Diffuse values were 1.4% high with a standard error of 13.4* $W.m^{-2}$*. The BF3 sunshine duration was within 2% of that calculated from the WMO definition over the study period, with a typical daily error of less than 20 min. This is well within the WMO requirements for a sunshine recorder. In comparison, the Campbell-Stokes recorders gave readings up to 7% different from the WMO values, with a typical daily error of almost an hour.*

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Introduction

Measurement of Direct and Diffuse components of solar radiation has many applications, e.g., in studying the energy balance of building structures [1], understanding plant growth, or as a meteorological indicator. Instruments that make these measurements have generally been expensive and require considerable attention.

One common approach has been to have two sensors, one measuring radiation from the whole sky (global irradiance), the other measuring the whole sky apart from the sun (diffuse irradiance). The shading is generally done using a shade ring, adjusted to match the track of the sun across the sky for that day. This approach requires accurate alignment to the Earth's axis, and frequent adjustment. In practice, the problems of alignment and frequent adjustment make this a difficult and sometimes unreliable measurement to make.

Another approach has been to use an array of pyranometers, with different fixed orientations, and thus different views of the sun and sky. The known position of the sun combined with the sensor orientation is used to solve for values of global and diffuse from the differing sensor outputs [2]

Another well-established meteorological parameter is sunshine duration, measured using the Campbell-Stokes recorder. This uses a glass sphere to focus the direct solar beam onto a recording chart, causing a burn, which indicates the duration of bright sunshine. This is a very simple and reliable approach, but does rely on daily attention, and the results are very dependent on operator judgement. In addition, the burning process masks much fine detail, and can vary depending on ambient moisture levels and solar elevation.

The object of this study was to evaluate the performance of a new sensor called the BF3 (Fig. 1) designed by John Wood and produced by Delta-T Devices Ltd of Cambridge, UK. The BF3 gives simultaneous outputs of both the horizontal global and diffuse irradiance as well as sunshine presence.

Design of the BF3 sensor

The aim of the BF3 design [3] was to measure the direct and diffuse components of incident solar radiation, and provide a measure of sunshine hours, in a sensor that used no moving parts, and required no specific polar alignment or routine adjustment. The outputs should be compatible with electronic dataloggers, and the sensor should work at any latitude.

The prime requirement for this design was to create a system of photodiodes and a shading pattern such that wherever the sun is in the sky, the following conditions are met:

1. at least one photodiode is always exposed to the full solar beam
2. at least one photodiode is always completely shaded
3. all photodiodes receive an equal sampling of diffuse light from the sky hemisphere

Design of the Shading Pattern. The shading pattern was designed with the help of a computer program. The computer program contained a model of the geometric layout of the sensors,

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with the shading pattern formed on the surface of a hemisphere. The program used a repeated process of test and modification of the pattern. Firstly, a random solar position was chosen, and the pattern tested against the first two rules above (i.e., at least one photodiode exposed, at least one shaded). If either condition was not satisfied, then the pattern was modified, by adding or removing the minimum amount of shading needed to meet the conditions. For example, if at least one photodiode was exposed, but none was fully shaded, then shading was added to cover the photodiode closest to an existing shaded area, or which was most shaded already. After repeated iteration, a stable shading pattern was sometimes found which satisfied the conditions for all solar positions. This shading pattern was then adjusted by hand to ensure that the amount of diffuse sky sampled was 50%, as seen from each photodiode position, to satisfy condition 3.

A layout of six photodiodes on a hexagonal grid with a seventh at the center gave the smallest number of photodiodes necessary for a shading pattern of reasonable size. Given this layout, shading patterns could only be found for a small number of different relative sizes of photodiode and shading hemisphere. One of these has been used which gives a reasonable balance between dome size, photodiode size, and accuracy. This is shown in Fig. 2, plotted in a 180-deg fisheye lens view.

Signal Conditioning and Computation. The BF3 uses GaAsP photodiodes mounted behind opal acrylic diffusers shaped to give a cosine response to incident light. The output from the seven photodiodes is measured by the instrument electronics, and a microprocessor calculates the global, diffuse, and sunshine outputs from the photodiode measurements. These are then converted back to voltage outputs for measurement by a datalogger.

The shadow pattern consists of equal areas of black and clear bands. This means that all of the photodiodes receive 50% of the diffuse radiation, sampled from all over the sky, and at least one photodiode receives only this radiation. At least one photodiode also receives the full amount of direct radiation from the sun. Which particular photodiodes these are depends on the position of the sun in the sky, but the fully exposed one will always receive the most radiation (the direct beam plus half the diffuse), and the fully shaded one the least (half the diffuse).

When a reading is taken, the seven photodiode outputs are measured, but only the largest (MAX) and smallest (MIN) of these values are used in the calculation. Global and diffuse outputs are calculated using the relation:

$$\text{Diffuse} = 2 * \text{MIN}$$

$$\text{Global} = \text{MAX} + \text{MIN}$$

The spectral response of the GaAsP photodiodes used is from 400 nm to 700 nm, which is appropriate for visible light measurements such as PAR or Illuminance. It does however give some variability in measuring energy, especially in the diffuse component, due to the widely differing spectral content of blue sky light compared to overcast light. To compensate for this, the diffuse value is further modified by a function of the direct beam fraction ($\text{Fb} = \text{direct/global}$) which gives an estimate of the amount of cloud cover. So for energy measurement:

$$\text{Diffuse} = 2 * \text{MIN}(1 - \text{Fb}^4)$$

This relation was determined empirically from a series of tests at Winster and Cambridge [3].

The WMO has defined sunshine presence as when the energy in the direct beam is greater than 120 W.m^{-2} measured perpendicular to the beam. This cannot be measured directly using cosine corrected sensors, so the BF3 uses an algorithm based on the measured global and diffuse values that has been found to give good results:

$$\text{Sunshine presence when global/diffuse} > 1.25$$

$$\text{AND global} > 24 \text{ W.m}^{-2}$$

Instrumentation

The BF3 was set up on the roof of Napier University, alongside two Kipp & Zonen CM11 double dome pyranometers, one fitted with a shade ring, and two Campbell-Stokes sunshine recorders.

Kipp and Zonen CM11 Sensors. For the purpose of cross checking, two Kipp and Zonen CM11 sensors (referred to as KZ1 and KZ2) were used to measure the horizontal global irradiance from February 22–July 3, 2001. These data have been compared with the horizontal global irradiance data from the BF3 sensor.

KZ1 was set up with a shade ring to measure sky diffuse irradiance. In general the shade ring must be horizontal and aligned to true north to better than 1 deg to work correctly. The shade ring was adjusted daily, and the measured irradiance corrected for the area of sky obscured by the shade ring, using the formula suggested by Drummond [4].

Campbell-Stokes Sunshine Recorder. The Campbell-Stokes sunshine recorder consists of a 4-in.-dia glass sphere mounted concentrically in a section of a spherical bowl, the diameter of

Fig. 1 BF3 sensor

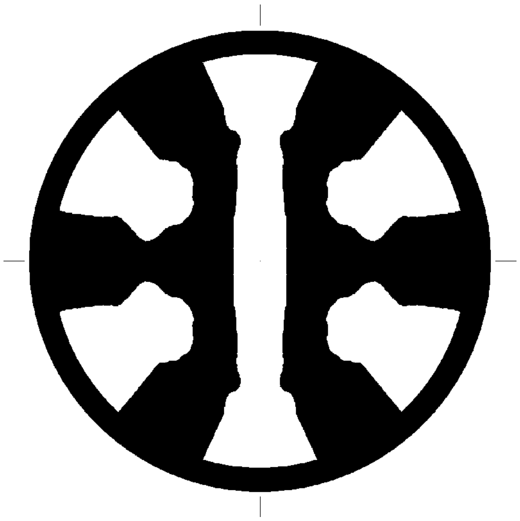

Fig. 2 BF3 shading pattern, plotted using a 180-deg fisheye view

which is such that the sun's rays are focused sharply on a card held in grooves cut into the bowl. There are three overlapping pairs of grooves, each to take cards suitable in shape for different seasons of the year. The 9-in. square×$1\frac{1}{4}$-in.-thick base is made of black slate and the frame is made of black painted aluminum, with an adjustable arc under the sphere and bowl to be set to the latitude, between 40 and 60 deg. As the sun moves across the sky, its focused image burns a trace on the card so that the duration of sunshine is recorded. Varying sets of cards are used for different seasons.

Data Collection. Irradiance values were measured every 10 s using two Grant Squirrel dataloggers. Datalogger A was connected to KZ1 and KZ2. Datalogger B was connected to BF3. Three channels of this logger were used to collect the horizontal global and diffuse irradiance as well as sunshine duration data.

Cards from the Campbell-Stokes sunshine recorders were changed daily on weekdays and measured following the guidelines suggested by the WMO [5]. One set of cards was reanalyzed independently to give an indication of the variation between different operators' interpretations.

Data Processing and Analysis

Ten-second, hourly, and daily data sets were analyzed and plotted within the Microsoft Excel environment.

The beam normal irradiance was calculated from the difference between the Kipp global and diffuse irradiance values, divided by the cosine of the solar zenith angle at that instant. A threshold of 120 W.m^{-2} was applied to this to give sunshine presence as defined by the WMO.

The following comparisons were made:

- BF3 global irradiance with Kipp CM11 global output (10s and hourly)
- BF3 diffuse irradiance with Kipp CM11 diffuse output (10s and hourly)
- WMO standard sunshine presence with BF3 sunshine output, and Campbell-Stokes daily totals

Results

Global and Diffuse Irradiation. Figure 3 shows a typical scatter plot for global and diffuse irradiation for the day, April 27. This was a day of broken cloud, with intermittent strong sunshine. At times, the global irradiation was changing very fast, and some of the scatter can be attributed to the differing time constants of the instruments, and also to drift between the two datalogger clocks. The BF3 diffuse (left hand axis) values are displaced from the BF3 global (right hand axis) in order to separate the plots.

Table 1 Statistical summary of BF3 hourly averages with respect to Kipp CM11 readings, Feb. 22–July 3, 2001

	Calibration error %	R^2	Standard error W.m^{-2}
Global	4.7%	0.994	16.5 W.m^{-2}
Diffuse	1.4%	0.980	13.4 W.m^{-2}

Hourly Averages. Hourly averages of the global and diffuse readings were calculated for the whole period Feb. 22–July 3. There were nine days on which it was obvious from inspection of the data that the shade ring was incorrectly adjusted, and these days have been removed from the series. Figure 4 plots the hourly averages for the whole period.

Table 1 shows the results of regression analysis, using the following indicators:

1. Calibration error. This is the deviation of the slope of the line of best fit from unity (expressed in percentage terms).
2. Coefficient of determination, R^2.
3. Standard error. This is the root mean square deviation of the measured BF3 values from the line of best fit.

These results show a good match between the global and diffuse outputs of the BF3, and those measured using the Kipps and shade ring.

Sunshine Hours. After removing days where the Kipp shade ring was badly adjusted, or no Campbell-Stokes record was made, there were 58 days over the project period with a full set of comparable sunshine hours measurements. There were 90 days when both BF3 and WMO sunshine hours were available.

BF3 Sunshine Output. The WMO has defined sunshine presence when the energy in the direct solar beam exceeds 120 W.m^{-2}, measured perpendicular to the solar beam. The stated

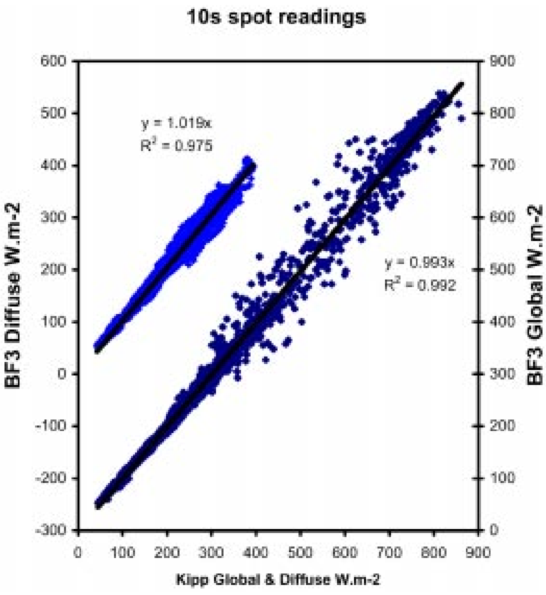

Fig. 3 Global (right hand Y-axis) and diffuse (left hand Y-axis) outputs, logged at 10s intervals on April 27, 2001

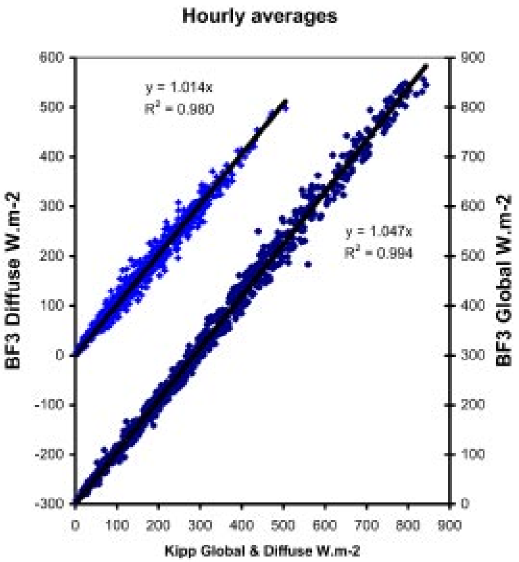

Fig. 4 Hourly averages of global (right hand Y-axis) and diffuse (left hand Y-axis) irradiation for period from Feb 22–July 3, 2001

Table 2 BF3 sunshine output summary, Feb. 22–July 3, 2001

	WMO	BF3	False positive	False negative
Total hours	364.79	358.02	8.56	14.54
Percentage of WMO total		98.14%	2.35%	3.98%
Daily average			0.09 hr 5.6 min	0.16 hr 9.5 min

Regression of BF3 daily totals against WMO

Calibration error %	**R^2**	**Standard error**
−1.00%	0.992	0.287 hr (17.2 min)

Table 3 Sunshine hours regressions

Regression	Calibration error %	R^2	Standard error Hrs
BF3 v WMO	−0.2%	0.993	0.23
CS1(JW) v WMO	1.3%	0.902	0.86
CS1(SYL) v WMO	7.5%	0.893	0.91
CS2(SYL) v WMO	6.3%	0.893	0.90
CS1(JW) v CS1(SYL)	−6.1%	0.980	0.38
CS1(SYL) v CS2(SYL)	−1.1%	0.999	0.09

requirement for sunshine recorders, is that their switching threshold should be within 20% of 120 $W.m^{-2}$, and that the measured sunshine hours should be within 10% over an extended period (several months).

For this study, the WMO reference sunshine state is calculated from the difference between the Kipp global and diffuse spot readings, divided by the cosine of the known solar zenith angle, to give the direct beam normal irradiance. A threshold of 120 $W.m^{-2}$ is then applied to this. Daily totals from the BF3, Campbell-Stokes, and WMO reference were compared.

These values are summarized for all of the days when there was comparable BF3 and Kipp data, in Table 2.

In comparing two quantities with yes/no outputs, it is useful to explore the conditions where they disagree. For this purpose, two other measures were used, based on the 10s spot readings:

1. False positives are defined as times when the BF3 indicates sunshine, but the beam normal irradiance is less than 108 $W.m^{-2}$ (120 $W.m^{-2}-10\%$)
2. False negatives are times when the BF3 indicates no sunshine, but the beam normal irradiance is greater than 132 $W.m^{-2}$ (120 $W.m^{-2}+10\%$)

These are summed for each day, and summarized in Table 2.

Figure 5 plots the distribution of all the false positive and negative readings over the study period, plotted against the measured beam normal irradiance. The two classes closest to the 120 $W.m^{-2}$ beam normal value are still within the ±20% threshold tolerance specified by the WMO. The remaining classes (false positives 1.79%, false negatives 3.38%) are outside this tolerance.

These results show that over the measurement period, about 5% of the BF3 spot readings indicated a sunshine threshold more than 20% away from the WMO 120 $W.m^{-2}$, but the net effect of this was an error of less than 2% in overall sunshine hours. The typical error in daily totals is less than 20 min.

Campbell-Stokes Recorders. There were two Campbell-Stokes recorders adjacent to the other instruments, CS1 and CS2. These are compared to each other, and also to the WMO reference, for the days when all the data are available. Cards from CS1 were independently analyzed by two different people, giving results CS1(SYL) and CS1(JW). Table 3 gives a summary of these different regressions. Figure 6 shows the BF3 and CS1 values plotted against the WMO reference.

These results show that the Campbell-Stokes recorder is a relatively poor performer when judged against the WMO sunshine definition. It shows a typical daily error of nearly an hour, some four times greater than the BF3. While the two adjacent C-S recorders gave fairly consistent results when interpreted by the same person, the two independent operators gave very different interpretations of the same set of record cards, despite working from the same set of guidelines. The variability in interpretation was nearly half as much as the total error relative to the WMO standard, though neither operator was in fact consistently more accurate than the other.

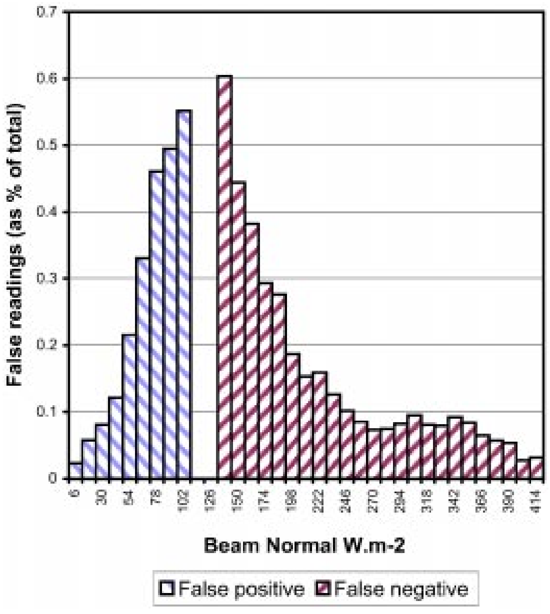

Fig. 5 Distribution of false positive (left hand group) and false negative (right hand group) readings

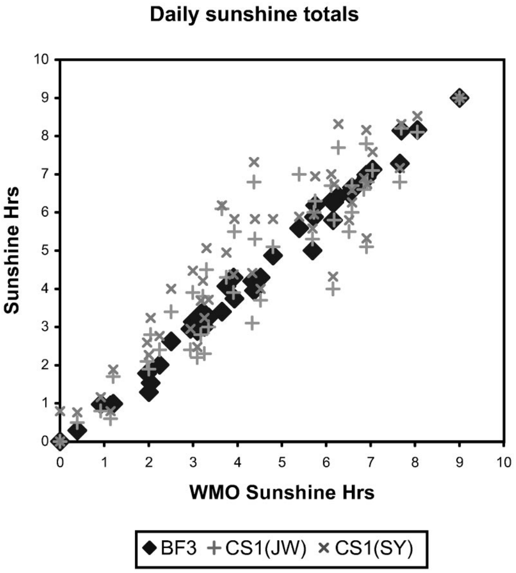

Fig. 6 BF3 and Campbell-Stokes recorders compared to WMO reference

Discussion

Instrument Errors–Global and Diffuse Irradiation. All the instruments were recalibrated at the start or end of the project. The main sources of error are:

- *Differences in sensor leveling and cosine response*. These show up mainly as variations in the direct beam portion of global radiation. The effects of these are greatest at low solar elevations.
- *Shade ring alignment and adjustment*. Inaccurate setting of the shade ring can result in large errors in the diffuse measurement if the diffuse sensor is no longer completely shaded. This was evident on nine days during the project (sometimes for only part of the day). These days were removed from the analysis, but it is possible that there were other borderline cases, which would give errors in diffuse values, even though these were not clearly wrong.
- *BF3 shading pattern*. The diffuse measurement in the BF3 is based on a 50% sample of the diffuse sky. This means that diffuse variability on scales smaller than the shading pattern elements (Fig. 1) may not be measured accurately.
- *Shade ring correction*. We have used the simple geometrical correction from Drummond [4] for the region of sky obscured by the shade ring. However, this may give an inaccurate correction in some conditions [6,7]. However, the improved corrections are not straightforward to apply. In the past decade, a number of alternative shade ring correction methods based on an anisotropic description of the sky-diffuse radiance have been proposed [8–13]. However, the vast majority of meteorological stations world-wide still use Drummond's method, probably because of the lack of consensus on the part of WMO to provide alternate guidance. It appears, therefore, that Drummond's method will remain the default procedure for shade ring correction for the foreseeable future.
- *Timing of readings*. The Kipps and BF3 were logged by two separate data loggers. Their internal clocks did drift over the project period, and there is a relative uncertainty of up to 10s in the exact timing of comparable readings. The Kipps are also much slower in their response (time constant of approx 24 s) than the BF3, which is effectively instantaneous. These differences produce a noticeable amount of scatter in the 10-s spot readings when conditions are changing fast.
- *Spectral response*. The Kipps have a nearly flat spectral response over the solar spectrum, so are relatively unaffected by changes in the spectral content of the incoming radiation. The BF3 uses GaAsP photodiodes, which have a peak sensitivity at 640 nm. This will cause some variability with changes in spectral content of the incoming radiation. This is most pronounced with the diffuse light measurement, where the spectral balance of blue skylight is very different from that of overcast gray.

Errors–Sunshine Hours

- The WMO reference values are based on the difference between the Kipp global and diffuse values, divided by the cosine of the solar zenith angle, to give the direct beam normal value. This is subject to the errors above, but these are magnified when the sun is near the horizon, as we are dividing differences in small quantities by a small amount. This means that the calculation is unreliable when the sun is within a few degrees of the horizon. These errors have been attributed to the BF3, but some of them should more properly be attributed to the WMO calculation.
- The BF3 uses horizontal cosine corrected sensors to measure global and diffuse irradiation, so cannot measure the direct beam normal directly. It uses an algorithm based on the relative magnitudes of global and diffuse to estimate sunshine presence.
- The inaccuracy of the Campbell-Stokes recorder has been well reported elsewhere [14]. It suffers from variations in sensitivity due to solar elevation, recent weather history, and operator interpretation. We have shown that two different operators can produce very different results from the same record cards.

Ease of Use and Reliability. The Kipp plus shade ring combination gives an accurate measurement of global and diffuse irradiation when properly set up. However, the difficulty of the initial polar alignment and regular adjustment make this a difficult system to operate reliably, and problems can pass unnoticed, compromising the data. In this study, even with careful supervision, nine days data were lost due to poor adjustment, and some of the shade ring alignment errors were only obvious when compared with the BF3 output.

The BF3, while showing some variability compared to the Kipps, is very straightforward to set up and maintain, needing no initial polar alignment, and no routine adjustment. This makes it attractive for situations where ease of use and reliability are important.

The BF3 sunshine output gives a consistent measure of sunshine presence, which is substantially more accurate than the Campbell-Stokes recorders, and needs no regular human intervention or interpretation.

Other Studies. As part of the design process, similar comparisons to this one were also carried out at Winster, Derbyshire UK, and Cambridge, UK, giving closely similar results. These are summarized in the BF3 User manual [3].

Conclusion

The BF3 provides a reliable straightforward measurement of global and diffuse irradiation, without needing polar alignment or regular adjustment. It also provides a measure of sunshine hours that is within the WMO accuracy requirements, and is significantly more accurate than the Campbell-Stokes recorder.

Acknowledgments

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