

BF2 Optical Design

| Rev | Date | By | Reason |
|-----|-----------|------|----------|
| 1 | 24-Feb-99 | John | Creation |
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Introduction

Measurement of Direct and Diffuse components of solar radiation has many applications - in modelling the interaction of light with crop canopies, studying the energy balance of structures, 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, the other measuring the whole sky apart from the sun. The shading is generally done using a shade ring, adjusted to match the track of the sun across the sky for that day, or using an occluding disk held on a robot arm. Both of these approaches require accurate alignment to the Earth's axis, and regular adjustment.

Another well established approach is the Campbell-Stokes recorder, which uses a glass sphere to focus the Direct solar beam onto a recording chart causing a burn, which indicates direct beam strength.

Design objectives

The aim of the BF2 design 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 work at any latitude.

How the design evolved

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:

- at least one photodiode was always exposed to the full solar beam
- at least one was always completely shaded
- both photodiodes receive equal amounts of Diffuse light from the rest of the sky hemisphere.

A basic layout of 7 photodiodes on a hexagonal grid, covered by a patterned hemispherical dome was chosen. A computer program was written to model this layout, checking any given shading pattern against the design rules for every position of the sun in the sky hemisphere. The program would also modify the pattern when there was a failure of the design rules, thus evolving towards a solution which satisfied all of the rules all of the time.

These shading patterns varied depending on the relative sizes of the dome and photodiode spacing. Solutions could only be found for a small number of different relative sizes, and one of these has been used which gives a reasonable balance between dome size, photodiode size, and accuracy.

Calculation of Outputs

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, and the fully shaded one the least. All the photodiodes are measured by the electronics, and the maximum and minimum of the seven readings are used. The maximum reading represents the Direct radiation + half of the Diffuse radiation, the minimum reading represents half of the Diffuse radiation. The outputs are calculated as follows:

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

$$\text{Direct} = \text{MAX} - \text{MIN}$$

$$\text{Total} = \text{Direct} + \text{Diffuse} = \text{MAX} + \text{MIN}$$

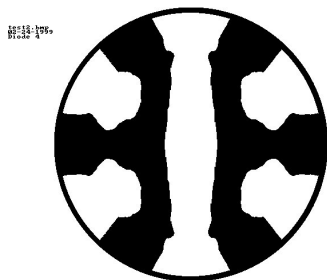
The Total and Diffuse values are used for the instrument output, and the Direct value is used to give an output of sunshine presence compatible with the Campbell-Stokes.

Note: This analysis is independent of the spectral characteristics of the individual photodiode sensors, or their spatial response. In the BF2, cosine corrected PAR photodiodes are used, so the output values represent cosine corrected PAR ($\mu\text{mol m}^{-2} \text{s}^{-1}$). The BF3 (to be released late 1999) has energy response photodiodes (W m^{-2}) with a uniform spatial response, i.e. it measures the strength of the incident radiation independently of angle of incidence.

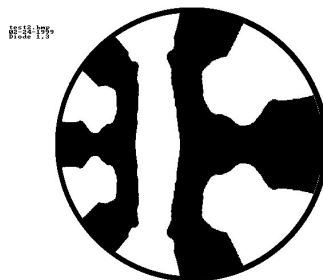
Errors and uncertainties

Diffuse sky sampling

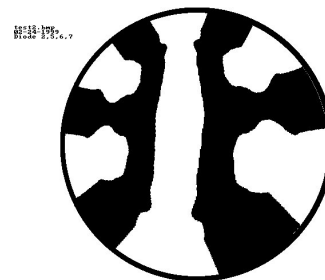
The images below show the parts of the sky hemisphere 'seen' by the different photodiodes. They are plotted using an equiangular projection, where radial distance on the image represents zenith angle on the hemisphere. The three different classes are shown, but specific photodiodes may actually see reflections of these in the horizontal or vertical plane.



Diode 4



Diode 1,3



Diode 2,5,6,7

The exact fraction of diffuse light seen by these diodes depends on its distribution. This is tabulated below (as measured using Delta-T's Hemiview program), for the Uniform Overcast and Standard Overcast sky distributions.

| Diode | UOC diffuse fraction | SOC Diffuse fraction |
|---------------|----------------------|----------------------|
| Diode 4 | 0.503 | 0.508 |
| Diode 1,3 | 0.484 | 0.476 |
| Diode 2,5,6,7 | 0.503 | 0.505 |

This means that with these diffuse sky distributions, the Diffuse value may be in error by +1.6% -5.0%. Under more varied conditions, there may be more difference.

Diffuse sky variations

Because the sensor effectively measures the brightest part of the sky, compared with the dimmest Diffuse sampling, it is also possible in some conditions (e.g. bright reflection off dark thunderclouds) to

give a Direct output where there is in fact no direct beam from the sun. The magnitude of this Direct output will generally be small compared to the real solar beam.

Internal reflections

At low sun angles, there is a cusp of light reflected off the internal surface of the dome. The photodiode spacing has been chosen to avoid these bright spots.

External reflections

Part of the incident light is reflected away from the dome. This is compensated for when the instrument is calibrated, but may change if the dome is allowed to become dirty or scratched in use.

Dome lensing

The clear areas of the dome are curved, and not always of perfectly uniform thickness, so there can be some lensing of light as it passes through the clear areas. These effects show up as variations in the Direct light values, and are included in the performance measurements described later.

Derivation of BF2 Sunshine algorithm

The sensor has a digital output of sunshine presence. This is defined by the WMO as greater than 120 W m⁻² in the Direct beam *measured perpendicular to the beam*. This is no problem for the BF3 which measures this directly. It is not so simple for the BF2, which measures PAR quanta rather than energy, and has horizontal cosine corrected sensors. An algorithm has been devised which gives very good results when compared to the WMO definition.

Defining the threshold in PAR quantum units

There is no direct conversion between W m⁻² and $\mu\text{mol m}^{-2} \text{ s}^{-1}$, because the conversion factor depends on the spectrum of the light involved, and this varies. For example, blue skylight has a blue bias, while direct sunlight has more energy at longer wavelengths. The spectrum of the direct beam is fairly constant, except when the sun is very low in the sky, when it becomes redder. Measurements were made at Burwell, Cambridge UK over 3 weeks in Sept 1998, comparing readings made by Macam Quantum and Energy sensors under a shade ring. This showed that a Direct solar beam strength of 120 W m⁻² was equivalent to a Direct solar beam strength of 200 $\mu\text{mol m}^{-2} \text{ s}^{-1}$ PAR $\pm 10\%$. This compares well with some of the values given elsewhere in the literature.

Defining the algorithm

A long term measurement was made of PAR Total and Diffuse values under a shade ring at Winstar, Derbys. UK, over six months from June to December 1998. From a knowledge of the solar zenith angle, the cosine corrected readings could be 'uncorrected', to give the PAR strength of the Direct beam, as would be measured perpendicular to the solar beam. This was then used to define sunshine presence (Direct beam > 200 $\mu\text{mol m}^{-2} \text{ s}^{-1}$). The BF2 only knows its measured values of Total, Direct & Diffuse light, so any sunshine output must be only a function of these.

It was found that a threshold of 50 $\mu\text{mol m}^{-2} \text{ s}^{-1}$ Total radiation reliably screened out those periods when the sun was below the horizon, and that Total > 1.25 * Diffuse (Direct > 0.25 * Diffuse) gave a very good approximation to the defined sunshine hours. These results are summarised below.

Sunshine hours are based on greater than 200 $\mu\text{mol m}^{-2} \text{ s}^{-1}$ in the Direct beam (no cosine correction)

Algorithm hours are when Total > 1.25 * Diffuse AND Total > 50 $\mu\text{mol m}^{-2} \text{ s}^{-1}$

False positives are when the algorithm gives an output, but no sun is present

False negatives are when the algorithm gives no output, but sun is present

Campbell-Stokes records were also made for much of this period.

| Month | Sunshine hours (WMO based definition) | BF2 Algorithm hours | false positives | false negatives | Campbell- Stokes |
|---------|---|---------------------------|-----------------|-----------------|---------------------|
| June 98 | 84.5 | 82.8 | 1.75 | 3.42 | N/A |
| July 98 | 110.6 | 107.6 | 1.58 | 4.58 | N/A |
| Aug 89 | 149.2 | 148.3 | 1.42 | 2.33 | 163.7 |
| Sept 98 | 36.4 | 36.1 | 0.75 | 1.08 | 48.9 |
| Oct 98 | 59.2 | 59.3 | 1.25 | 1.00 | 69.1 |
| Nov 98 | 13.0 | 13.8 | 1.08 | 0.33 | 9.3 |
| Dec 98 | 35.9 | 36.3 | 1.17 | 0.75 | 40.9 |

| | | | | | |
|---------------------------------|----------------------------|-------|------|-------|---------------------------------|
| Total | 488.8 (293.7 Aug - Dec) | 484.2 | 9.0 | 13.49 | 331.9 |
| % of total sunshine hours | 100% | 99.1% | 1.8% | 2.8% | 113% (of Aug - Dec total) |

This shows excellent agreement between the BF2 algorithm and sunshine hours derived from the WMO definition, and shows that the largest errors are likely to stem from the conversion between Energy and quantum units. Changing the Direct PAR threshold by $\pm 10\%$ only changed the overall measured sunshine hours by $\pm 3\%$, showing that in practise, the results are relatively insensitive to errors in this conversion.

Optical performance validation

Over 20 complete units have been thoroughly tested to make sure the design is working as planned, and to quantify the performance specifications.

Test rig



This consists of a light source, 2 axis tilt rig, BF2, and a datalogging and control computer.

The light sources used are a 500W tungsten halogen spotlight, with electronically stabilised light output, and also a 150W Ceramic Metal Halide discharge lamp. The beams from these have been arranged so that the lamp subtends approximately the same angle as the sun, as viewed from the sensor, and the beam is uniform to $\pm 2\%$ over the area of the photodiodes. The light output was also stable to better than $\pm 2\%$ over the measurement period. The BF2 was shielded from any out of beam illumination.

The 2 axis tilt rig was used to turn the sensor in 1° steps through the whole hemisphere relative to the light beam, so checking all possible sun positions. This process takes some 6 Hrs, and creates a data set of 25000 readings.

The BF2 electronics integrates readings over 20ms to remove any mains frequency variation.

Data interpretation

The incident light is a beam of known strength, which moves through all possible positions relative to the sensor. The sensor is shielded from any diffuse light. The Total and Diffuse outputs of the sensor are measured. The Total output should be proportional to the cosine of the zenith angle. Any deviations from this are due to a combination of:

- failure of the design rule that at least one photodiode be fully exposed
- inaccurate cosine response of the photodiode and diffusers
- lensing by the dome
- other contributions from light scattering, electronics, etc.

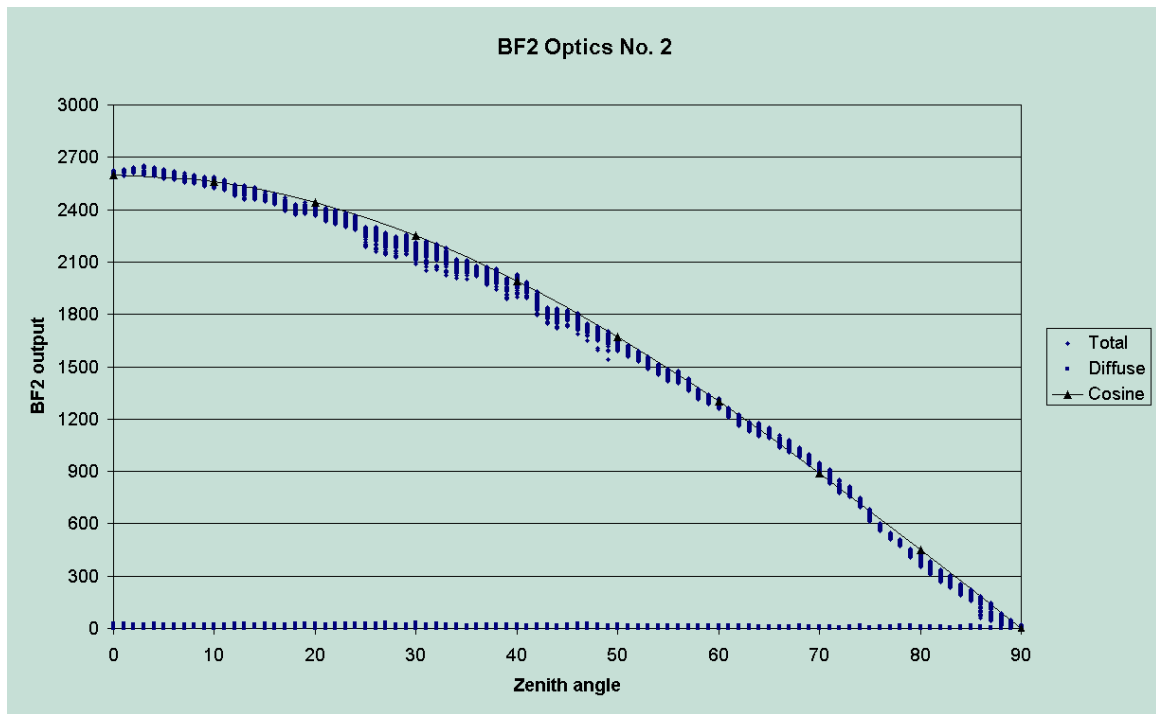
The Diffuse output should always be zero. Any variations from this are due to some combination of:

- failure of the design rule that at least one photodiode be fully shaded
- stray light from scattering, or electronics errors

The directions which produced the greatest errors were then re-examined visually to check for any failures of the design rules.

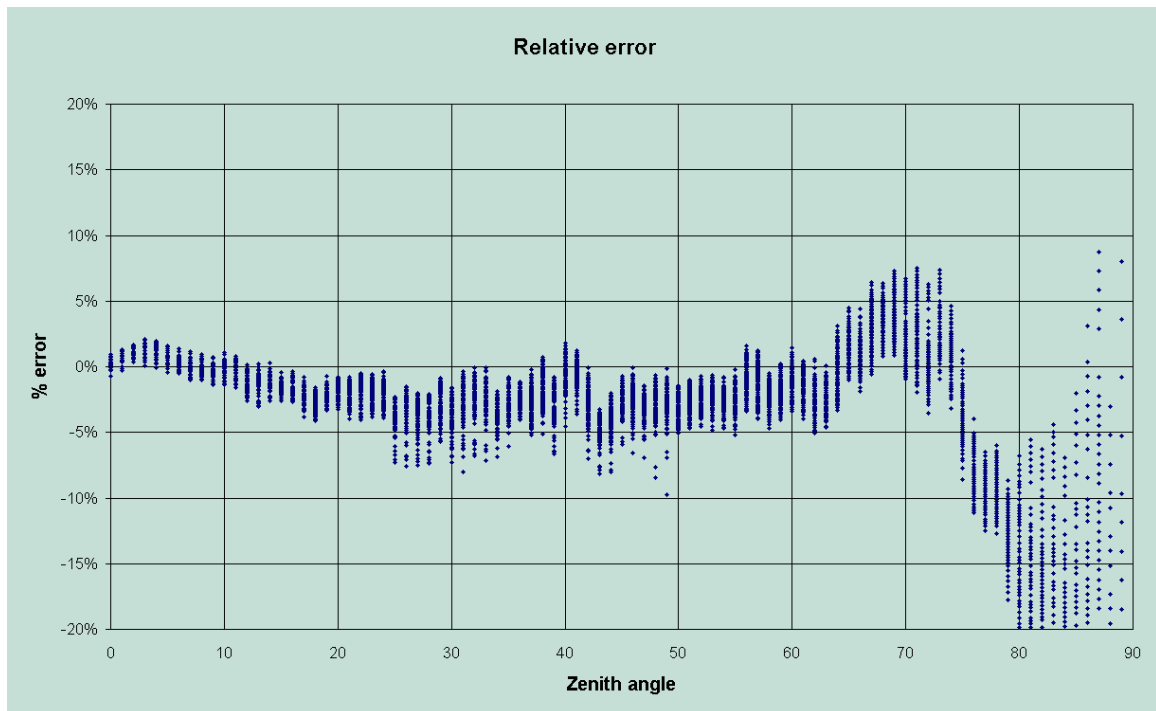
Results

The following graph shows the summary of one such set of results. This shows the output plotted against zenith angle. Each zenith angle shows the outputs over a range of azimuth angles



The RMS error (the standard deviation) of this data set is 2.3% of the intensity of the incident beam.

The data are replotted to show deviations as a percentage of the ideal response below.



These graphs include all errors due to the optical design and electronic measurement, with an additional error due to variations in the test rig light source. They do not include any uncertainties in the calibration standard or due to variations in the Diffuse light distribution.

END

