BF2 & BF3 Optical Design

Rev	Date	By	Reason
1	24-Feb-99	John	Creation
2	6-Nov-2001	John	Amended and updated to include BF3

About this document

This document summarises the design process for the BF2 sunshine sensor (launched spring 1999), with amendments and additions describing the changes made for the upgrade to the BF3 in 2001.

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 on 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:

Diffuse = 2 * MIN

Direct = MAX - MIN

Total = Direct + Diffuse = MAX + MIN

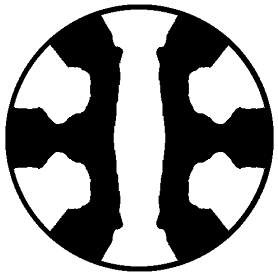
The Total and Diffuse values are used for the instrument output, and the Direct value is used to give an output of sunshine presence compatible with the Campbell-Stokes.

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 (μmol.m^{-2}.s^{-1}).

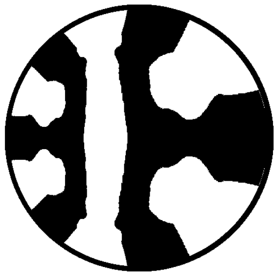
Errors and uncertainties

Diffuse sky sampling

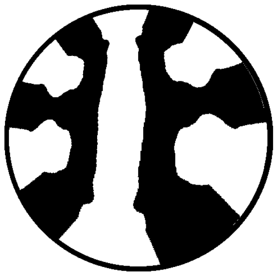
The images below show the parts of the sky hemisphere 'seen' by the different photodiodes. They are plotted using an equiangular projection, where radial distance on the image represents zenith angle on the hemisphere. The three different classes are shown, but specific photodiodes may actually see reflections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

A laser cut metal shadowmask was introduced in spring 2002, with the change to the BF3. This improved the Diffuse light consistency as tabulated below.

Diode	UOC Diffuse fraction	SOC Diffuse fraction
Diode 4	0.501	0.502
Diode 1,3	0.495	0.490
Diode 2,5,6,7	0.499	0.498

This means that with these diffuse sky distributions, the Diffuse value may be in error by up to +0.4% - 2.0%.

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 solar beam*. 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 $\mu mol.m^{-2}.s^{-1}$, 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 $\mu mol.m^{-2}.s^{-1}$ PAR ± 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 Winster, 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 µmol.m^{-2}.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 µmol.m^{-2}.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 µmol.m^{-2}.s^{-1} in the Direct beam (no cosine correction)

Algorithm hours are when Total > 1.25 * Diffuse AND Total > 50 µmol.m^{-2}.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

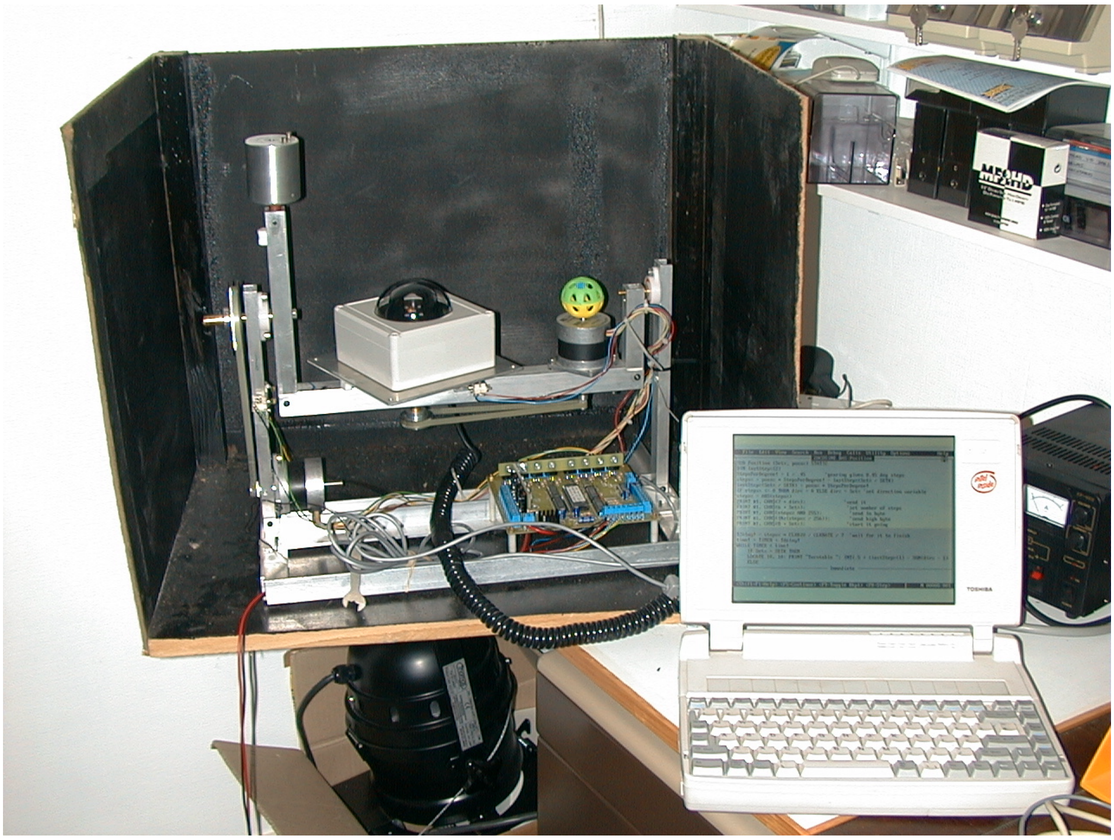
Total	488.8 (293.7 Aug - Dec)	484.2	9.0	13.49	331.9
% of total sunshine hours	100%	99.1%	1.8%	2.8%	113% (of Aug - Dec total)

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 ±10% only changed the overall measured sunshine hours by ±3%, showing that in practice, 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 ±2% over the area of the photodiodes. The light output was also stable to better than ±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.

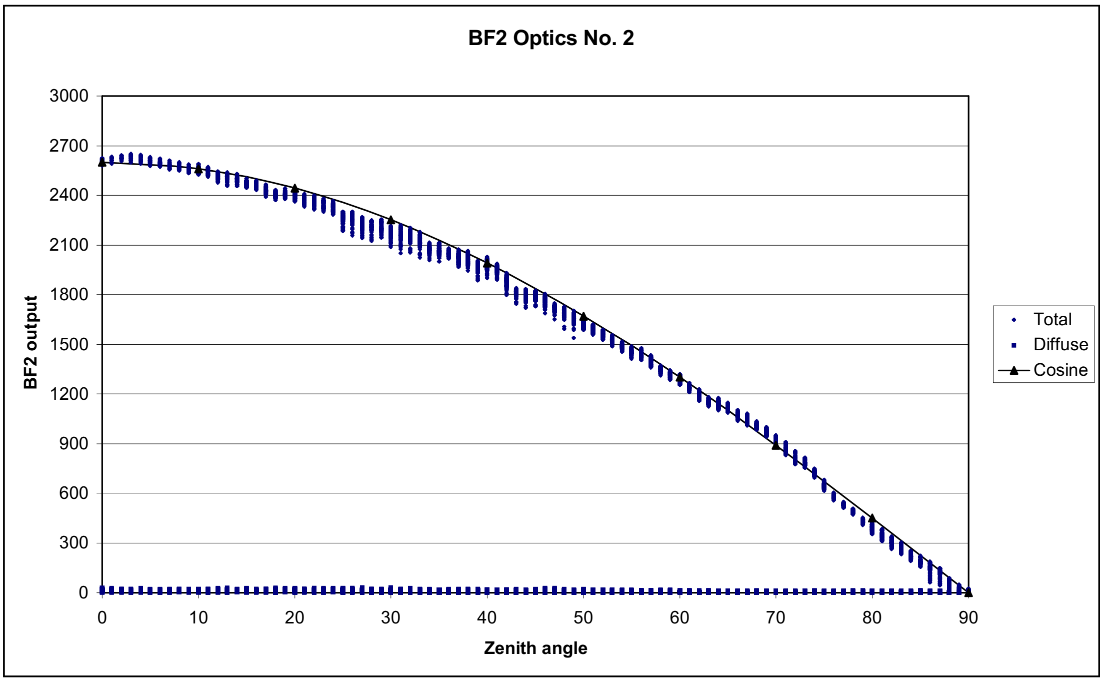
The Diffuse output should always be zero. Any variations from this are due to some combination of:

- 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.

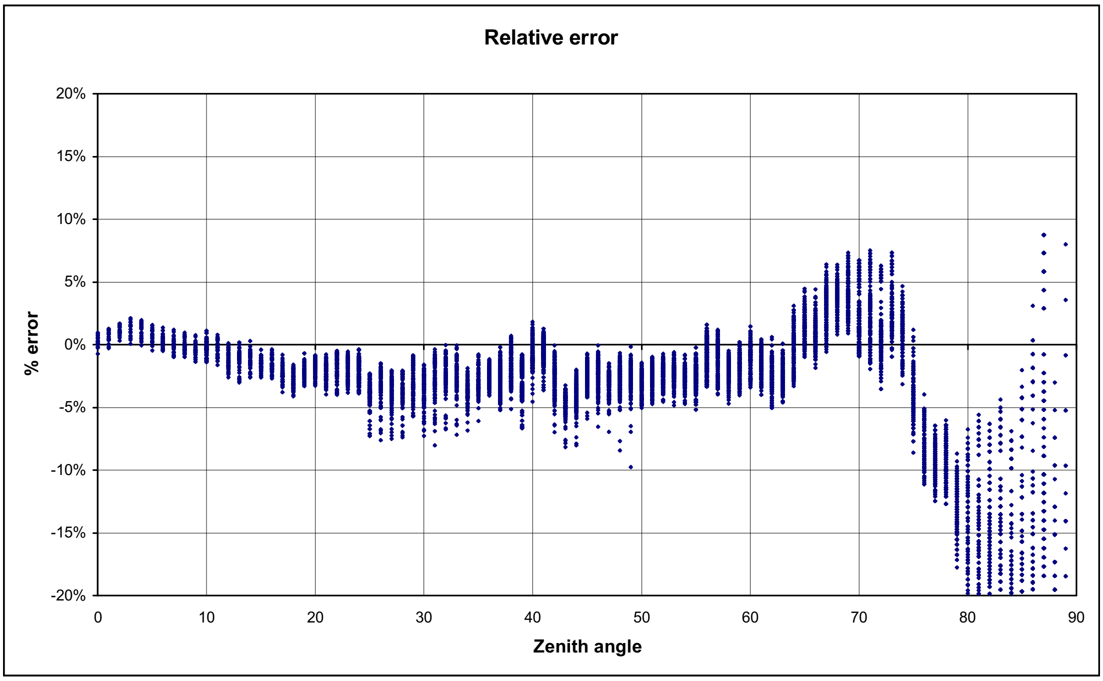
Results

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.

Changes with release of BF3

In spring 2002, the BF2 design was upgraded to the BF3. The main change was the option to have outputs in molar, energy or illuminance units. These additional units required additional processing by the BF3, and the modified algorithms, and their validation, are described here.

Instrumentation

At Winster: BF2, 2 x Kipp CM3 (GS1), one under a shade ring, plus QS as well. All instruments and DL2 recently calibrated by the manufacturers. (One of the CM3s was not recently calibrated, but was compared with the recently calibrated one and the 3% difference corrected in data processing). Data was collected from March 2000 to Sept 2000.

At Burwell: BF2 (measured as 2mV = 1 $W.m^{-2}$), 2 x Kipp CM3 (one under shade ring), 1 x Kipp CM11. Data was collected from Beginning of June to end of August 2000.

All instruments logged at 5s intervals, averaged to 5min.

Algorithm

The algorithm was developed using the Winster dataset, and then validated using the Delta-T dataset. Error values are based on the Delta-T dataset, but the Winster set is very closely similar.

Broad concepts

The BF2 Diffuse value has been given a 5% uplift to compensate for a 5% underreading caused by a combination of: diode calibration variations, and differences in diffuse sky sampling areas between diodes.

Lux values are given by a direct conversion from molar values. The factor is calculated from first principles, based on typical Total and Diffuse spectra taken at Winster in a range of conditions..

Energy values require more complex conversion, due to the very different conversion factors for Diffuse radiation in blue sky and grey sky conditions. The measured beam fraction is used as a predictor (though not particularly accurate) of diffuse sky conditions.

Algorithm – all outputs

Let MAX and MIN be the largest and smallest photodiode reading of the seven photodiodes, after being adjusted for any calibration factors (calibration is done in the solar lamp rig against a standard QS as with the BF2)

Then TOTAL = MAX + MIN gives BF2 TOTAL value, in $\mu mol.m^{-2}.s^{-1}$

DIFFUSE = 2 * MIN * 1.05

IF (DIFFUSE > TOTAL) then DIFFUSE = TOTAL

gives modified BF2 DIFFUSE value, in $\mu mol.m^{-2}.s^{-1}$, with sanity check. This modified DIFFUSE value is used in all subsequent calculations.

Beam Fraction = (TOTAL – DIFFUSE) / TOTAL

SUNSHINE if TOTAL/DIFFUSE > 1.25 AND TOTAL > 50 $\mu mol.m^{-2}.s^{-1}$

Molar $\mu mol.m^{-2}.s^{-1}$ outputs

The TOTAL and DIFFUSE values are then output via the RS232 and Analogue ports, at 1mV = 1 $\mu mol.m^{-2}.s^{-1}$.

Lux outputs

The TOTAL and DIFFUSE values are multiplied by 55.7 lux / µmol.m^{-2}.s^{-1} to give lux. These values are output to the RS232 and analogue ports at a sensitivity of 1mV = 100 lux. This gives an output range of approx 0V to 1.5V for the normal daylight range, with a resolution of 100 lux.

Energy Wm^{-2} outputs

Energy TOTAL = TOTAL * 0.48

Energy DIFFUSE = DIFFUSE * (0.48 – 0.48 * (Beam Fraction)^{4})

(Ie Beam fraction to the fourth power)

These values are then output via the RS232 and Analogue ports, at 2mV = 1 W.m^{-2}.

Validation & Accuracy

Energy

The Energy algorithm was based on the data collected at Winster. The algorithm was applied to the Burwell data set, as a completely independent data set, and the accuracy values calculated from this.(nb this set included relatively few (2) clear blue sky days, which test the spectral and cosine responses most severely)

For Total and Diffuse values, the RMS error relative to the Kipp CM3 & shade ring setup is given, in both absolute (Wm^{-2}) and relative (% of reading) terms. An overall envelope is also given which includes 95% of all daytime readings.

To specify the overall instrument accuracy, the uncertainties in measurement, calibration and traceability, and cosine response of the Kipp & shade ring system also need to be factored in.

Energy output Errors wrt Kipps	Total		Diffuse	
RMS Error (represents the typical error of a reading)	13 W.m^{-2}	4.6%	16W.m^{-2}	12.6%
95% confidence envelope	±5W.m^{-2} ±8%		±20W.m^{-2} ±15%	

A very similar energy performance was obtained from the BF3 comparison run by Napier University – these results are published separately

Lux

The lux conversion from PAR is based on a theoretical calculation using typical spectra of Total and Diffuse light in varying conditions. This was validated at Delta-T by comparing the BF3 Total lux output against a LiCor lux sensor.

Overall accuracy specs for instrument

(95% confidence envelope)

Overall Accuracy	Total	Diffuse
95% confidence Molar output	±10 μmol.m^{-2}.s^{-1} ±12%	±10 μmol.m^{-2}.s^{-1} ±15%
95% confidence Lux output	±600 Lux ±12%	±600 Lux ±15%
95% confidence Energy output	±5W.m^{-2} ±12%	±20W.m^{-2} ±15%

Summary graphs of test comparisons for each of the different outputs are given in the BF3 User Manual.

Analogue output sensitivities

Output units setting	**Sensitivity**	**Resolution**	**Full scale output**
Molar μmol m^{-2} s^{-1}	1mV = 1 μmol.m^{-2}.s^{-1}	0.6 μmol.m^{-2}.s^{-1}	2500mV = 2500 μmol.m^{-2}.s^{-1}
Energy Wm^{-2}	1mV = 0.5 W.m^{-2}	0.3 W.m^{-2}	2500mV = 1250 W.m^{-2}
Illuminance klux	1mV = 100 lux	60 lux	1500mV = 150 klux

END