SPN1 Measurement Best Practices

Solar Irradiance Measurements with

Delta-T Devices SPN1 Sunshine Pyranometer

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Contents

1. Introduction

The SPN1 is a sensor which measures Global and Diffuse horizontal irradiance. The SPN1 contains no moving parts, requires no specific polar alignment, and operates at low power. This makes it suitable for operation in remote sites, or where maintenance is limited, as well as at larger measurement sites.

General considerations for site selection, operation, and maintenance are given in the *Guide to Meteorological Instruments and Methods of Observation* (WMO 2006), or the *Best Practices Handbook for the Collection and Use of Solar Resource Data* (NREL 2010), so are not repeated here. This chapter will describe aspects of site operation that are specific to the SPN1.

2. Principle of operation

The SPN1 consists of an array of 7 thermopile radiation detectors in a hexagonal pattern, underneath a hemispherical shadow mask which has areas cut away, such that for ***any*** position of the sun in the sky:

- At least one detector is always exposed to the direct solar beam
- At least one detector is always completely shaded from the direct beam
- All detectors receive about equal amounts of diffuse light from the sky hemisphere.

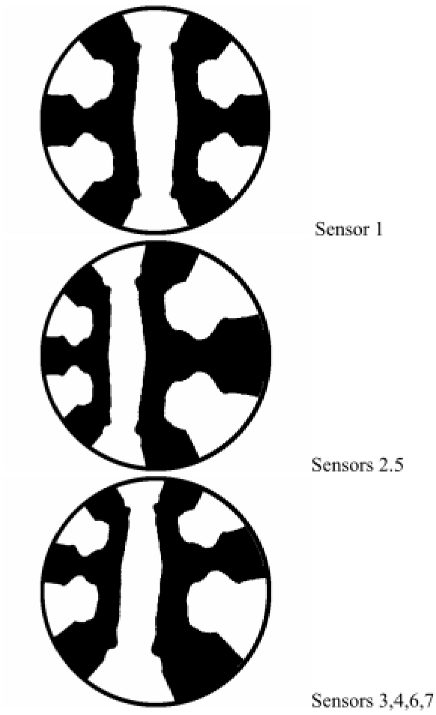


Fig. 1

The pattern of cutaways in the hemispherical shadow mask was generated by computer using an evolutionary algorithm so that, from the viewpoint of each of the 7 detectors, the proportion of diffuse light received is very close to 50% for both a Uniform Overcast Sky, and a Standard Overcast Sky (Moon & Spencer 1943).

Fig.1 shows the view of the sky from the various detectors, using an equiangular projection (where radius on the image is proportional to zenith angle).

At any given time there will always be one or more detectors which are fully shaded from the Direct beam, but are exposed to about half of the diffuse sky; several detectors which are partly exposed to the Direct beam; and one or more detectors which are fully exposed to the Direct beam, plus about half of the diffuse sky. The seven detectors are measured in quick succession. The one with the lowest reading (MIN) will be exposed to only 50% of the diffuse sky, and the one with the highest reading (MAX) will be exposed to the Direct beam plus 50% of the diffuse sky. The Global & Diffuse values can therefore be calculated as follows:

Diffuse = 2 * MIN

Direct = MAX – MIN

Global = Direct + Diffuse = MAX + MIN

There are some additional corrections applied to account for manufacturing tolerances and the detector spectral response, which are described in the SPN1 manual.

Fig.2 shows an example plot of the output of the seven detectors throughout a clear day, and the Global and Diffuse calculated from this.

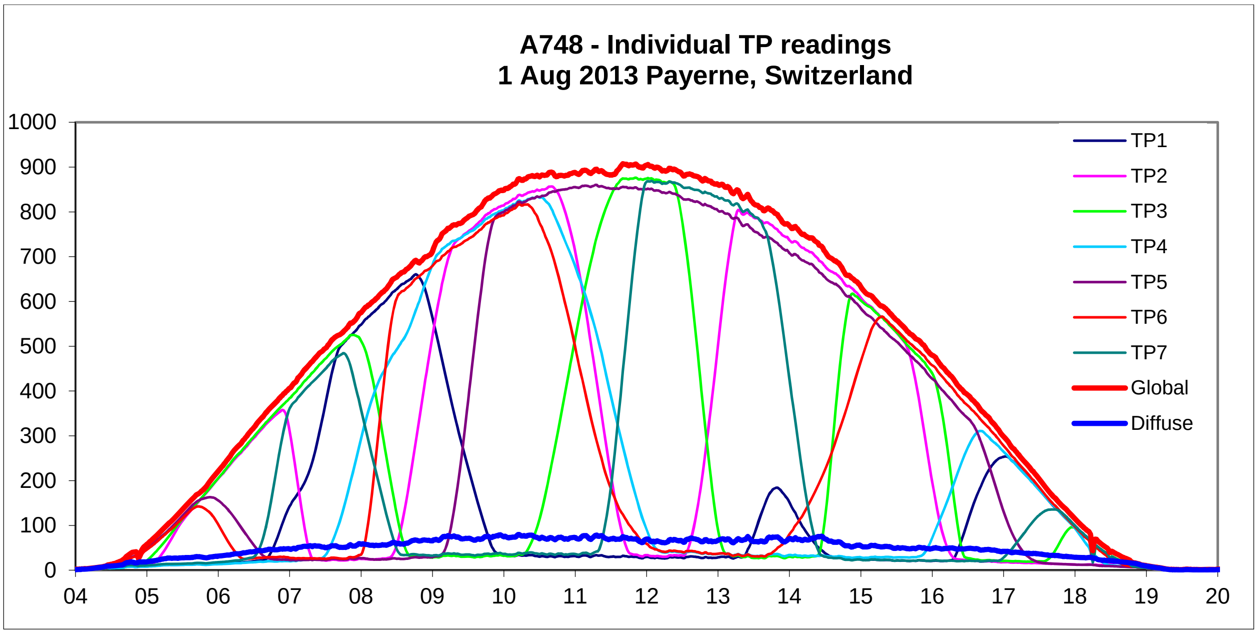


Fig.2

Table 1 – Key specifications provided by the manufacturer

Overall accuracy: Total (Global) and Diffuse radiation	±5% Daily integrals ±5% ±10 W.m-2 Hourly averages ±8% ±10 W.m-2 individual readings
Accuracy: Cosine Correction	±2% of incoming radiation over 0-90° Zenith angle
Accuracy: Azimuth angle	± 5% over 360° rotation
Temperature coefficient	± 0.02% per °C typical
Temperature range	-20 to + 70°C
Stability	Recalibration recommended every 2 years.

Response time	< 200ms
Spectral Response	400-2700nm
Spectral sensitivity variation	10% typical
Non-linearity	<1%
Tilt response	negligible
Zero Offsets	<3 W.m-2 for a change of 5°C/hr in ambient temperature <3 W.m-2 dark reading

3. Measurement site and installation

The general advice in the WMO or NREL guides on site selection should be followed. Use of the SPN1 may allow use of sites with poorer access or facilities than described.

Mounting

The SPN1 should be fixed to a firm support so that it can be accurately levelled, using the indicating bubble fitted inside the dome. Delta-T can supply an adjustable mount which may assist with this. Orientation relative to North is not critical, but it may enable further data analysis if this is recorded, and the sensor can be replaced in the same orientation if it has to be removed for any reason.

Power supplies

For the core measurement function, the SPN1 uses very little power, and is tolerant of a wide range of input voltages (~2mA at 5V – 15V). This means that the installation power needs are mainly determined by the requirements of the data logger, other sensors, and communications equipment.

The SPN1 also contains a built in heater, which is effective in dispersing dew, frost rain and snow. This requires a larger power supply capable of providing up to 1.5A at 12V (9V – 15V). This should be used where the power is available, but will generally require a mains power connection.

Data logger

The SPN1 requires an external data logger. It can give outputs as an analogue voltage in the range 0V – 2V, or as digital values over RS232.

Analogue outputs – the data logger should be capable of measuring over the range 0V – 2V with at least 12 bit resolution. The data logger inputs should be fully differential, otherwise power supply currents in the cables will cause errors in readings of the SPN1 or other connected sensors. This can be a particular problem when the SPN1 heater is used, or if cable lengths are long.

Digital outputs – the data logger should be capable of communicating over RS232 at 9600 baud. The SPN1 uses a simple character-based interface, described in the user manual. The digital outputs are more accurate than the analogue outputs because they do not go through an additional stage of digital-analogue-digital conversion. Additional values of the individual detectors and instrument temperatures are also available. Where there is a choice, the digital outputs should be used.

Lightning

Lightning damage is a risk for any equipment mounted with a clear view of the sky. The SPN1 case should be electrically connected to ground via the mounting tower or frame, and the tower should be grounded to an earthing rod buried underground.

Instrument cable screens should also be connected to ground at the data logger end, but the data logger itself should be free to float relative to ground, otherwise induced currents in the cabling may cause damage to the sensor or data logger.

Cleaning & soiling, heater or ventilator

The SPN1 internal heater is effective at keeping the SPN1 dome clear of dew, frost and ice down to -20°C, and should be used where possible.

The SPN1 has been used by Meteo-Swiss for many years with their own design of ventilator, and this may be more effective at preventing dust deposition.

Fig.3 – SPN1 in MeteoSwiss ventilator

Maintenance

The SPN1 dome should be cleaned regularly using clean water and polished with a dry cloth. Any stubborn deposits can be removed using a mild detergent, or isopropyl alcohol.

The internal desiccant is expected to last for a year or more, depending on climate conditions. Check the internal desiccant indicators every 6 months and renew when they change from blue to pink.

4. Calibration checks, user recalibration

For the SPN1 to measure accurately, there are two conditions that must be satisfied for the seven detectors:

1. All 7 detectors must be accurately matched so that they all give the same output under the same irradiance.

2. The 7 detectors must be accurately calibrated to the world reference scale.

The full calibration process can only easily be carried out by using special lamps and equipment by the manufacturer. However it is possible for the user to check for adequate detector matching, and to adjust the overall calibration if necessary. The protocol described in this section relies on a side-by-side measurement comparison with a reference pyranometer, which allows a calibration check without removing the SPN1 unless absolutely necessary. The protocol relies on having at least some periods during the comparison of bright overcast conditions, which provide a uniform diffuse light distribution.

Manufacturer's original calibration accuracy

SPN1s are calibrated indoors by the manufacturer to give a standard output, but there may be differences outdoors due to climate or manufacturing variation.

106 production SPN1s have been compared outdoors against a Kipp reference pyranometer at various times between 2010 and 2014, either in Winster, UK, or Tenerife, Canary Isles. Comparison periods varied between 8 and 30 days. The slope of the regression line of the SPN1 Global output against the pyranometer is taken as the instrument's calibration.

For these sensors, the mean calibration value is 0.997, with a standard deviation of 2.2%. 97% of the calibrations were within 5% of the reference pyranometer. Fig.4 shows a histogram of these values.

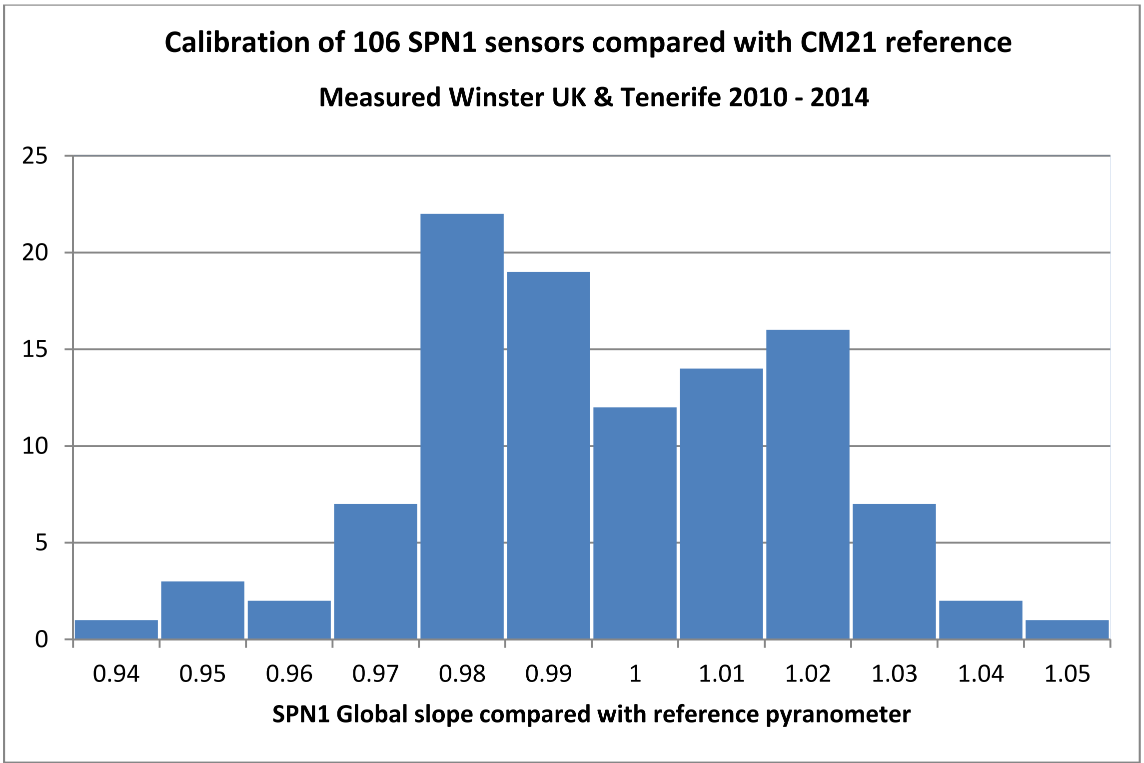


Fig.4 – SPN1 Calibration distribution – data supplied by manufacturer

Calibration stability

Data from the manufacturer on long term calibration drift indicates that this is generally less than 1% per year. The graph in Fig.5 shows drift calculated in percent per year, for 50 SPN1s returned for recalibration after periods of up to 7 years in use.

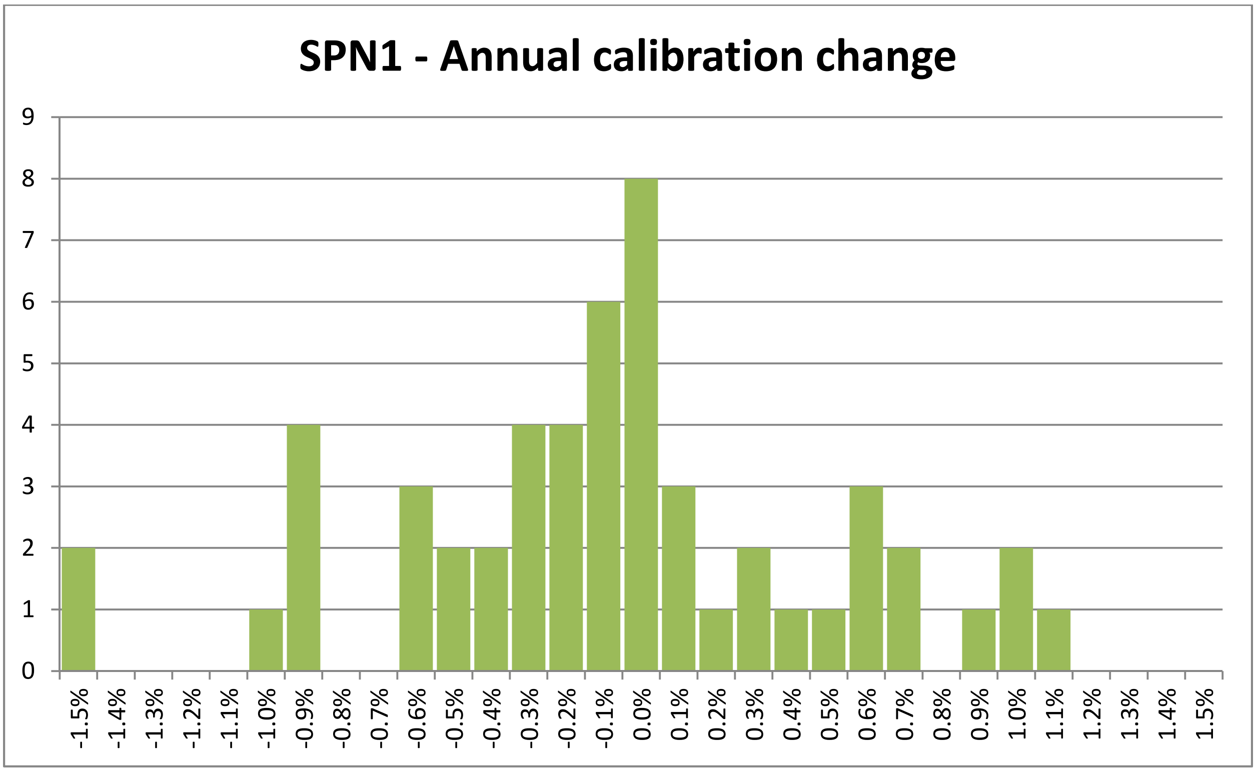


Fig.5 – calibration drift in % per year – data supplied by manufacturer

For the highest accuracy, it is good practice to recalibrate the instrument in similar conditions to its intended use, and to check this calibration regularly. A calibration check every 2 years is recommended.

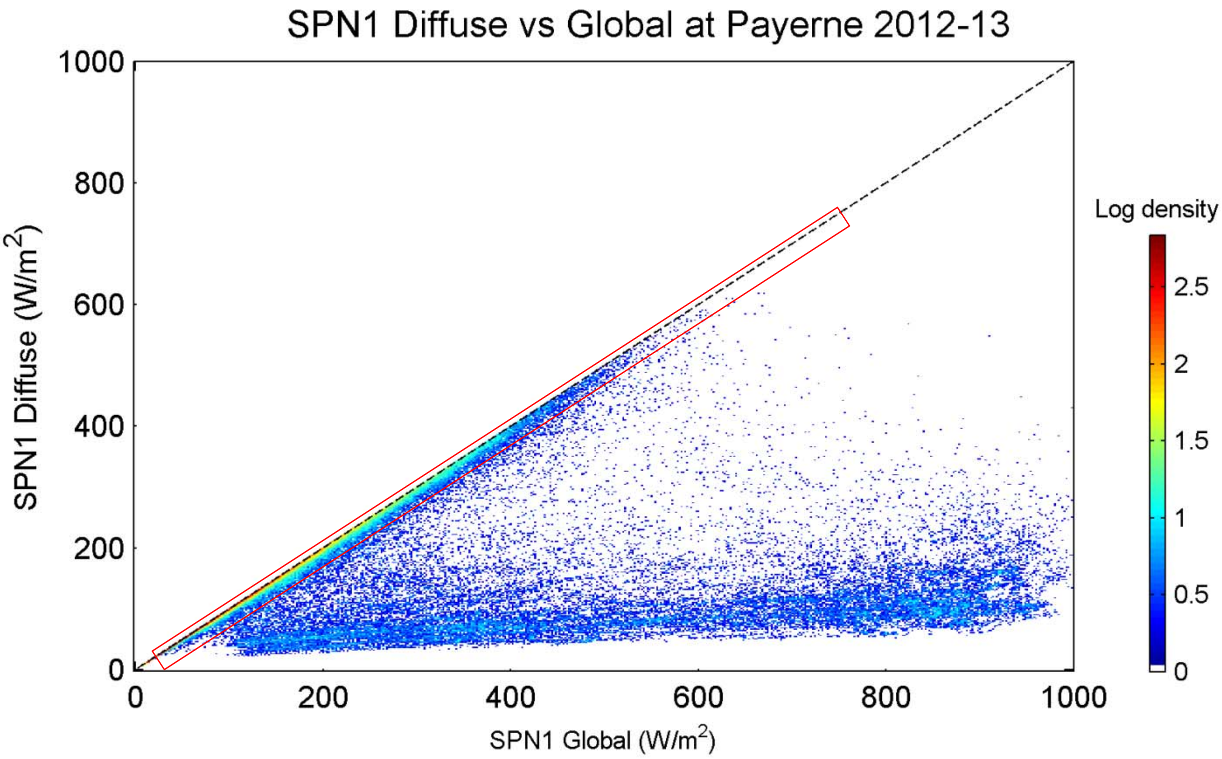
In-situ check for detector matching

Under uniform diffuse conditions, all of the detectors should measure the same light intensity if they are well matched. If this is the case, then the Global & Diffuse outputs will be the same. If the detectors are not well matched, then the Global and Diffuse outputs will differ by half the difference between the MAX and MIN of the 7 detector readings. So as long as the Global and Diffuse outputs are the same in uniform overcast conditions, the detectors must be well matched.

The recommended protocol for checking this is as follows:

- Collect an SPN1 dataset over a period of several weeks (ideally alongside a recently calibrated pyranometer). This must include periods of bright overcast conditions. Data should preferably be 1-minute averages or shorter. The dataset should be as long as possible, and large enough to include at least 5 days with partially overcast conditions.
- Remove all data < 10W.m-2

- Graph Diffuse against Global values (Fig.6 Top). A data density plot gives a much clearer picture of the clustering of data points during overcast conditions.
- Data points in the red box are overcast periods. Points to the right are sunny periods. You need to check the slope of the points during overcast periods.
- Set a limit line at `Global = Diffuse + 3W.m-2` for serial port data, or `Global = Diffuse*1.01 + 3W.m-2` for readings with analogue data logger. (3 W.m-2 is the worst case offset due to internal electronic effects, the additional slope term allows for the specified output error of the digital to analogue converter.)
- If the left hand edge of the densest part of the point cloud falls to the left of the limit line, then the detectors are well matched. If there is a gap between the left hand edge of the point cloud and the limit line, then the detectors are mismatched and need recalibrating by the manufacturer.
- To see more detail, it is clearer to plot Global-Diffuse difference against Global (Fig.6 Bottom)
- Limit line is now `Limit = 3W.m-2 (digital readings)` or `Limit = Global*0.01 + 3W.m-2 (analogue readings.` This is shown as a red dashed line.
- The highest density of points should be below the limit line, with zero slope. This example shows an SPN1 with well-matched detectors.
- Fig.7 shows the same dataset, but with detector matching errors introduced. The upper plot shows a detector mismatch of ±2%, which is just detectable using this technique. The lower plot shows a detector mismatch of ±5%, which is clearly outside the acceptable limit.



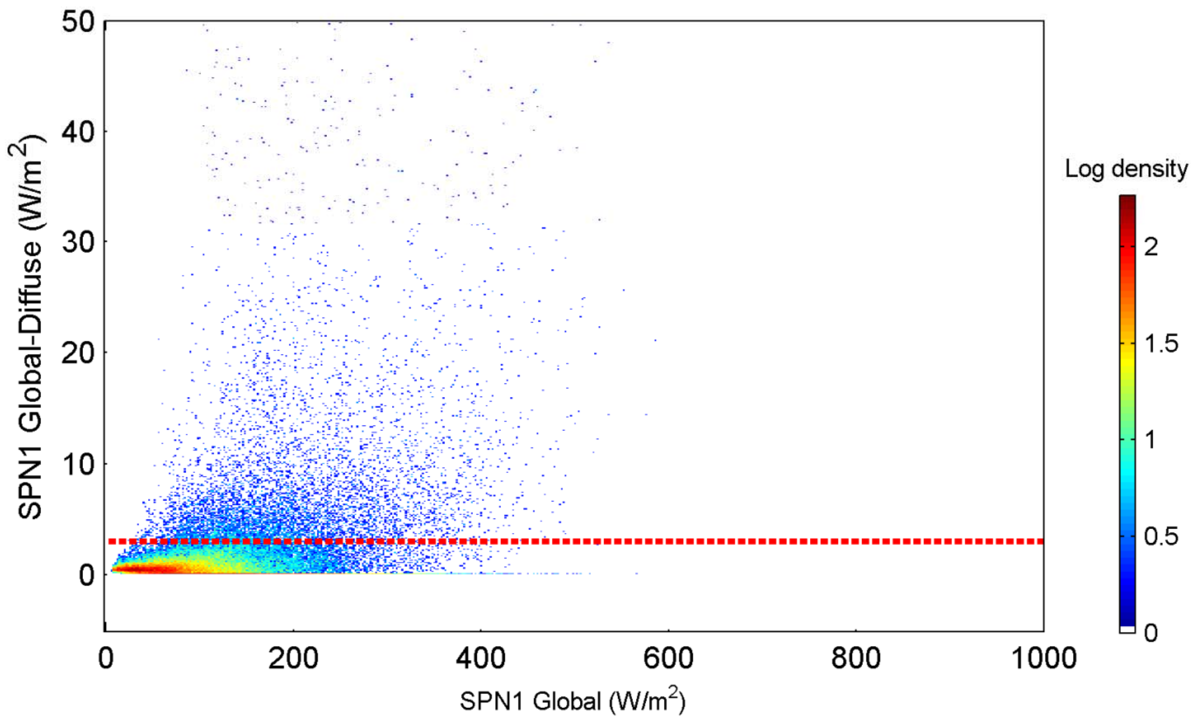


Fig.6 Top - SPN1 Diffuse plotted against Global values

Bottom – Global-Diffuse plotted against Global values

1-minute averages, digitally captured data

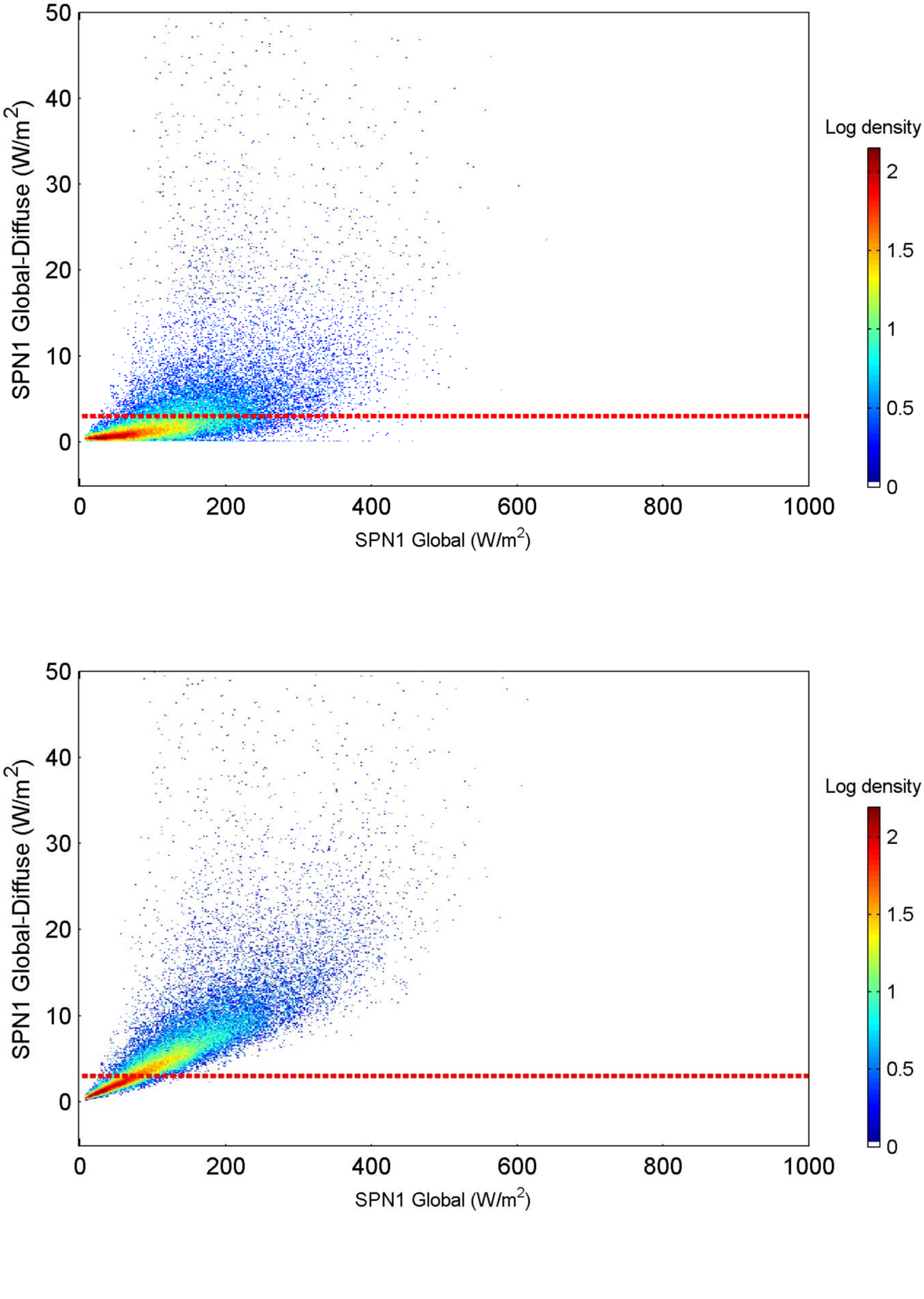


Fig.7 – Global – Diffuse difference plotted against Global values

Top - ±2% detector matching error

Bottom - ±5% detector matching error

In-situ check for accurate calibration

If the detector-matching check is satisfactory, the SPN1 Global output should then be compared with the co-located reference pyranometer with a known good calibration, for a period of (at least) 2 – 4 weeks, and a linear regression fit to the data. If the slope of the linear regression is significantly different to 1, the output of the SPN1 can be adjusted up or down by a constant factor using software available from the manufacturer.

NB – the regression should not be forced through zero. In general there will be an offset of up to 5W.m-2 between the pyranometer and the SPN1 (SPN1 has a small positive electrical offset, and the pyranometer has a small negative IR offset) which will affect the calibration value if the regression is forced through zero.

Calibration variation with period & season

Several long-term datasets have been analysed to show the variability of different calibration periods. Fig.8 shows differences from the long-term mean for all possible calibration periods of 1, 2 & 4 weeks, over 15 months at NREL, Golden, Colorado.

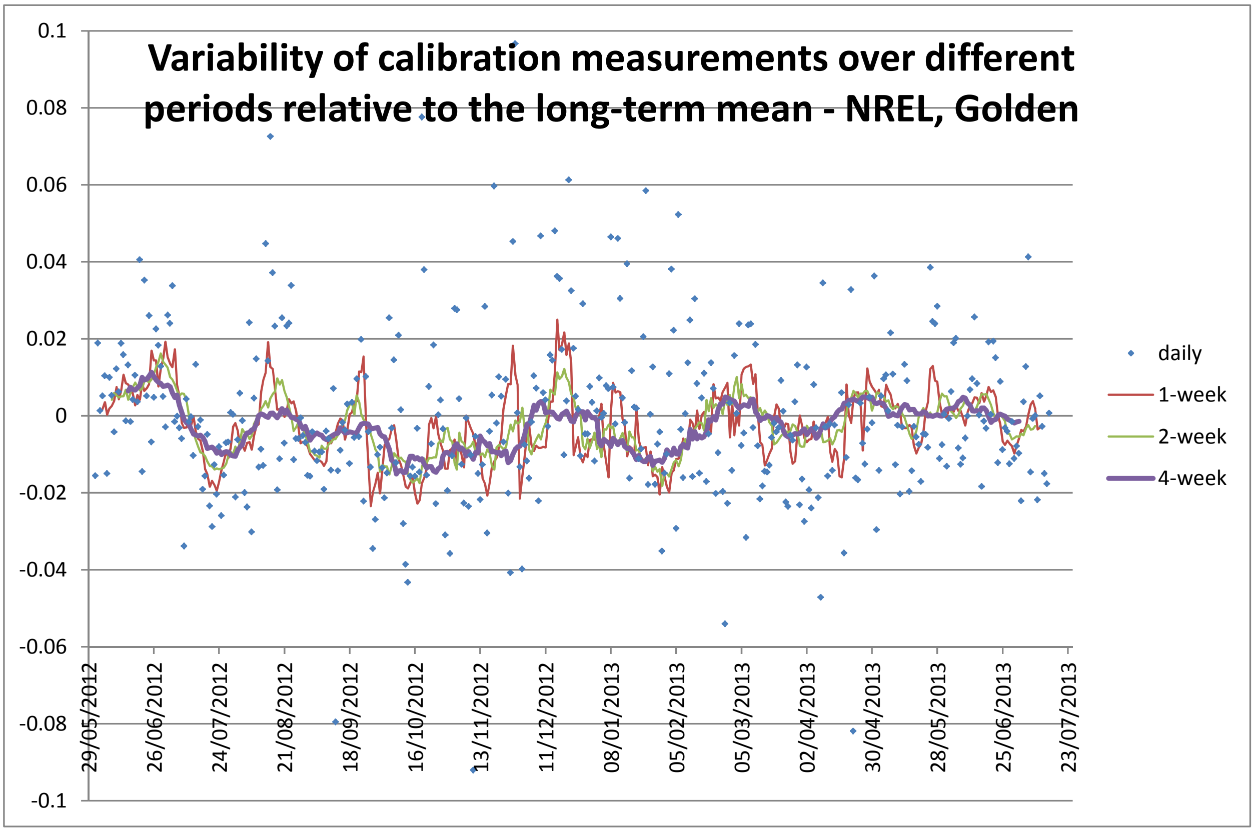


Fig.8 Calibration variability, Golden, Colorado.

A similar analysis has been performed for other sites. Fig.9 shows how the calibration variability reduces with increasing period for all these sites. The boxes show the standard deviation of the complete set of all possible periods, and the whiskers show the greatest extremes. Extending beyond a 4-week period is unlikely to give much further improvement in accuracy.

Calibrations should be carried out during the summer months when the sun is highest. Calibration variability is generally lower during the summer.

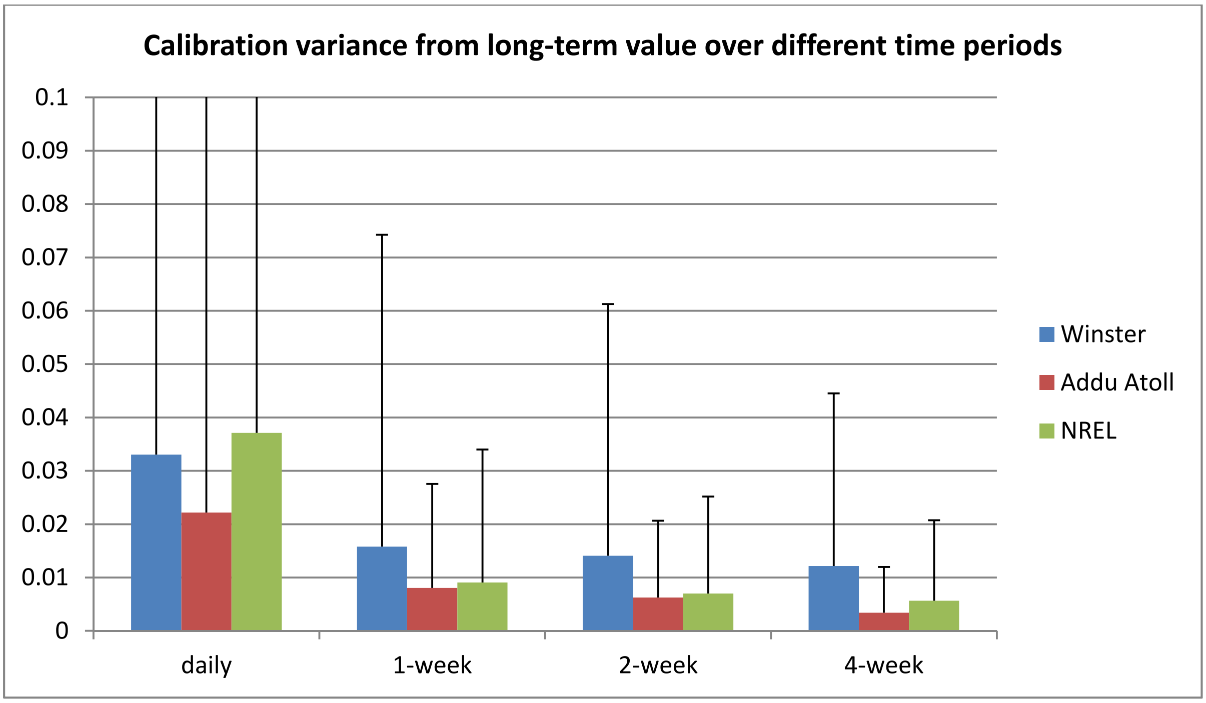


Fig.9 Calibration variability over time period and season (Box gives standard deviation, whiskers the worst case over the dataset)

5. Data validation

Night-time readings

It is good practice to record and review night-time readings. These will often give the clearest indication of problems in the sensor wiring or data logging setup. In normal use the SPN1 will show night-time readings of 0W.m-2 to 3W.m-2 when the temperature is stable, and may be a little higher if the temperature is falling fast. Values greater than 6W.m-2, or less than zero, are indicative of an installation error and should be investigated.

BSRN limits

A subset of the standard BSRN test limits (summarized in Table 2) can be applied to the SPN1 data. This will highlight any gross errors in the output values. It is expected that the SPN1 will pass these tests for >99% of 1-minute values.

Table 2. From BSRN Global Network recommended QC tests, V2.0. C N Long & E G Dutton

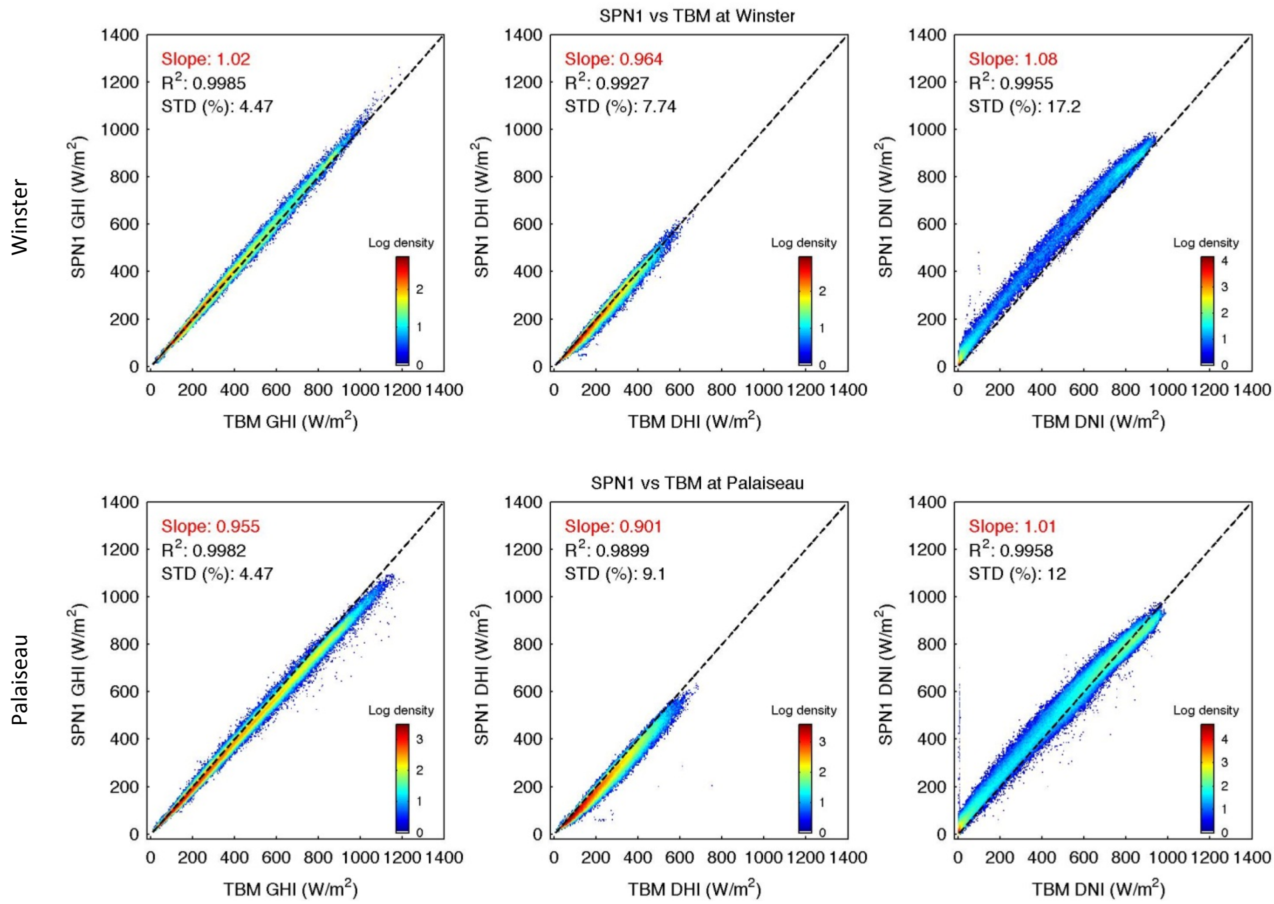
Definitions SZA = Solar Zenith Angle $\mu 0$ = Cos(SZA) NOTE: In the formulas below, if SZA > 90°, μ_0 is set to 0.0 in the formula S_0 = solar constant at mean Earth-Sun distance AU = Earth – Sun distance in Astronomical Units, 1 AU = mean E-S distance $S_a = S_0/AU^2$ = solar constant adjusted for Earth – Sun distance GHI = Global Horizontal Irradiance, short wave 300nm – 3000nm DHI = Diffuse Horizontal Irradiance DNI = Direct beam, Normal Irradiance. Calculated as (GHI – DHI) / Cos(SZA) for SPN1	
Extremely rare limits – GHI	Min: -2W.m-2 Max: S_a * 0.75 * $\mu_0^{1.2}$ + 50W.m-2
Extremely rare limits – DHI	Min: -2W.m-2 Max: S_a * 0.75 * $\mu_0^{1.2}$ + 30W.m-2
Extremely rare limits – DNI (calculated as (Global-Diffuse)/ μ_0)	Min: -2W.m-2 Max: S_a * 0.95 * $\mu_0^{0.2}$ + 10W.m-2
Diffuse ratio	(DHI)/(GHI) < 1.05 for SZA<75°, GHI>50W.m-2 (DHI)/(GHI) < 1.10 for 93°>SZA>75°, GHI>50W.m-2 For GHI<50W.m-2 , test not possible

6. Achievable accuracy

Badosa (2014) gives a detailed analysis of SPN1 accuracy from 6 different sites, with long-term comparisons against tracker-based references. These results are summarized in Table 3 and graphically in Fig.10.

Table 3– GHI, DHI and DNI regression slopes from all sites together with DHI and DNI slopes found after recalibrating for GHI slope

Linear regression slopes	GHI (slope/ std(%))	DHI (slope/ std(%))	DNI (slope/ std(%))	DHI slope after calibration for GHI slope	DNI slope after calibration for GHI slope
Winster	1.017/4.4%	0.966/7.8%	1.076/15.7%	0.950	1.058
Palaiseau	0.955/4.5%	0.901/9.1%	1.009/12.0%	0.944	1.057
Payerne	1.002/3.7%	0.940/8.9%	1.052/10.5%	0.937	1.049
Golden	1.021/4.2%	0.976/9.1%	1.055/8.8%	0.956	1.033
Addu Atoll	1.011/3.4%	0.913/9.2%	1.062/9.5%	0.903	1.051
Roseraye	0.993/3.8%	0.916/9.0%	1.043/11.8%	0.922	1.050



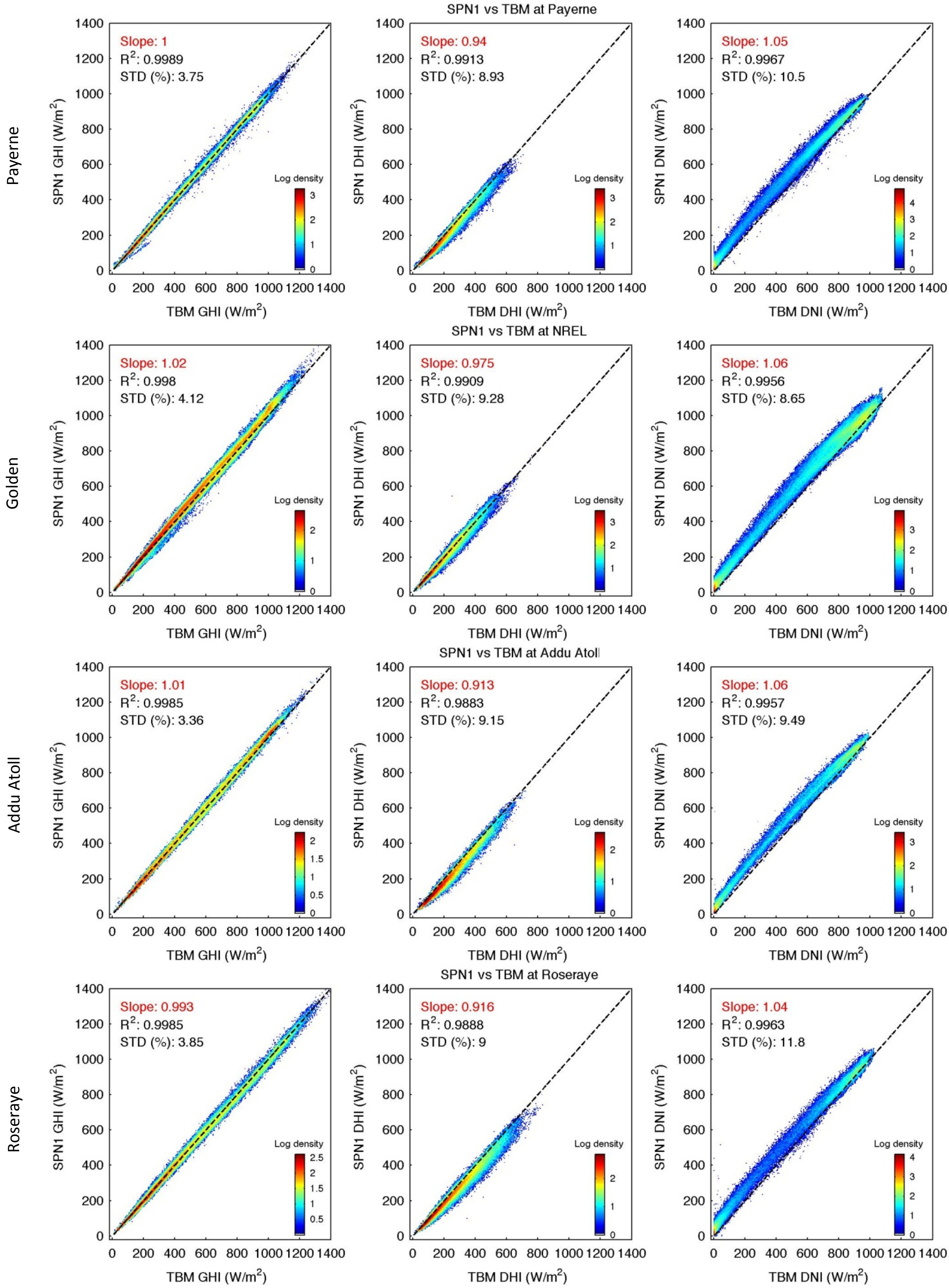


Fig.10 – XY plots of quality controlled data for 6 sites

This shows typical performance of the standard SPN1. The Global accuracy is good, but compared to a tracker-based system, the Diffuse is usually understated, and the DNI overstated, typically by about 5% each.

Much of this difference is due to the larger effective opening angle of the SPN1, which means that the majority of the circumsolar aureole is included in the SPN Direct measurement, whereas a tracker-based system would include this in the Diffuse measurement. The magnitude of the aureole can be up to 100W.m-2 depending on conditions. For some situations (e.g. modelling irradiance on flat panels) it is appropriate to include the aureole with the Direct beam, in others (e.g. modelling CSP systems) it should be included with the Diffuse.

SPN1 agreement with a tracker-based measurement can be improved by applying a simple correction factor to the DHI & DNI values, or by calibrating specifically for the operating conditions against a tracker-based system.

Table 4 shows the measurement differences at all sites for SPN1s as received from the manufacturer, and also with a linear correction for Global & Diffuse slopes on each site.

Table 4: SPN1 vs TBM comparison scores before and after slope calibration (three values at each cell, corresponding to GHI, DHI and DNI irradiances respectively)

No correction applied for SPN1 data

	Mean TBM (W/m^2)	MAE (W/m^2)	rMAE %	MBE (W/m^2)	rMBE %	RMSE (W/m^2)	rRMSE %
Winster	312/183/215	10/11/30	3.3/5.9/14	3.8/-7.6/30	1.2/-4.2/14	15/16/44	4.9/8.8/21
Palaiseau	318/160/281	16/18/22	4.9/11/7.8	-14/-17/14	-4.4/-11/4.8	23/24/34	7.3/15/12
Payerne	358/160/314	8.3/13/28	2.3/ 8/8.9	0.77/-11/27	0.21/-7/8.6	13/18/41	3.8/12/13
Golden	471/154/514	18/10/44	3.7/6.6/8.5	11/-4.6/41	2.4/-3/ 8	23/15/58	4.9/9.6/11
Addu Atoll	532/221/426	15/23/42	2.8/11/9.8	4.6/-22/41	0.86/-10/9.6	19/30/53	3.6/14/12
Roseraye	467/231/326	13/21/31	2.8/9.2/9.4	-2.7/-19/29	-0.58/-8.4/8.9	18/31/44	3.9/13/14

After slope correction of Global & Diffuse SPN1 data

	Mean TBM (W/m^2)	MAE (W/m^2)	rMAE %	MBE (W/m^2)	rMBE %	RMSE (W/m^2)	rRMSE %
Winster	312/183/215	9.3/10/19	3/5.5/ 9	-1.4/-1.4/8.9	-0.44/-0.77/4.1	14/15/30	4.4/ 8/14
Palaiseau	318/160/281	8.8/11/22	2.8/6.7/7.8	0.31/-1.7/10	0.098/-1.1/3.6	15/16/34	4.7/10/12
Payerne	358/160/314	8.2/11/22	2.3/6.6/ 7	-0.023/-1.5/7.8	-0.006/-0.97/2.5	13/15/31	3.7/9.5/9.8
Golden	471/154/514	15/10/30	3.1/6.5/5.8	1.1/-0.92/18	0.23/-0.6/3.4	19/14/42	4.1/9.3/8.1
Addu Atoll	532/221/426	14/16/25	2.6/7.2/5.8	-1.1/-3.3/4.9	-0.2/-1.5/1.1	18/22/32	3.3/10/7.6
Roseraye	467/231/326	13/15/24	2.7/6.6/7.3	0.46/-0.04/4.8	0.097/-0.016/1.5	18/23/33	3.9/9.8/10

Key

TBM: Tracker Based Measurements performed with two pyranometers (for DHI and GHI) and one pyrheliometer (for DNI)

Mean TBM: The mean value of the TBM measured Irradiance for SZA < 80°

MAE: Mean Absolute Error

MBE: Mean Bias Error

RMSE: Root Mean Square Error

rMAE: MAE relative to the mean TBM measurement

rMBE: MBE relative to the mean TBM measurement

rRMSE: RMSE relative to the mean TBM measurement

7. Error sources

Badosa (2014) identifies the main errors and differences in SPN1 measurements in detail. These are summarized here.

1. Calibration mismatch between detectors can cause jumps in the Direct part of the output as the sun moves across the sky, changing which of the detectors are fully exposed.
2. Lensing of light by the glass dome can cause an additional mismatch between detectors which varies with solar position.
3. Detector cosine response can cause a changing Direct beam sensor response which varies with solar zenith angle.
4. The SPN1 diffusers have a reduced transmission of blue light. This causes a variation in Diffuse sensitivity between blue-sky and cloudy conditions which is not fully corrected by the instrument.
5. The shape of the shadow mask pattern gives an effective opening angle which varies with solar position, between ±5° and ±20°. This changes the measured partition between Direct and Diffuse light in conditions with a large solar aureole.
6. There are smaller effects due to temperature change, internal electronics, time response and soiling.

Corrections for some of these effects are being developed.

8. References

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SPN1 Best Practice version 3