UPDATING AND DEVELOPMENT OF METHODS FOR WORLDWIDE ACCURATE MEASUREMENTS OF SUNSHINE DURATION.

Vuerich, E. [1], Morel, J.P.,[2], Mevel, S. [2], Oliviéri, J.[3]

[1] **Italian Meteorological Service** - Centre of Meteorological Experimentations, via Braccianese Claudia, 00062 Bracciano, Italy – Tel. +39-06-99887701, Email: vuerich@meteoam.it;

[2] **Meteo France**, Regional Instrument Centre – Radiation, Chemin de l'Hermitage, 84200 Carpentras, France – Tel. +33-490636967, Email jean-philippe.morel@meteo.fr;

[3]Meteo France, Retire, Email: frvincent@noods.fr

ABSTRACT

An all-seasons bilateral inter-comparison on sunshine duration (SD) measurement methods has been recently conducted by the Italian Meteorological Service (IMS-AF) and Meteo France (MF) during the period 2010-2012. The inter-comparison has been carried out in two different climatological locations (Vigna di Valle, Italy and Carpentras, France) and the SD evaluated by the 1-second measurements of direct solar irradiance by pyrheliometers has been used as reference in both locations. Among those tested, a pyranometric method, primary developed by MF (*Olivieri, Morel*) and improved through the results of this study, has shown high accuracy compared to the reference. Moreover, through the use of data from worldwide available BSRN stations (Basiline Surface Radiation Network), it has been possible to determine suitable coefficients for an universal application of such pyranometric method to estimate SD with reduced uncertainty (*Morel – Vuerich – Mevel, BSRN meeting, Postdam, Germany,1-3 August 2012*). Through the experience of the European Regional Instrument Radiation Centre of Carpentras and quality long-term field measurements, this inter-comparison as a whole has achieved the established goals and its results could permit the development of specific proposals for updating the 7th Chapter of CIMO Guide with regard to the SD daily achievable uncertainty, pyranometric methods and their accuracy, and determine a crucial impact on the related applications.

1. Introduction

1.1 Background and rationale

Representative sunshine duration (SD) measurements are typically used for characterizing the climate of a region. The need of searching for optimal cost-effective solutions with accuracy suitable for the requested application is becoming essential for the scientific community, especially in the field of solar radiation measurements where the use of solar energy for agricultural and industrial reasons represents a wide area of development. Provinding the community with scientific studies on measurements methods and their accuracy will permit the upgrading of methods and techniques and the development of related applications.

The last WMO intercomparisons which evaluated the state of the art of SD instruments and methods were carried out in Budapest in 1984 (Comparison of pyranometers and electronic sunshine duration recorders) and, particularly, in Hamburg from 1988 to 1989 (WMO Automatic Sunshine Duration Measurement Comparison). An very valuable study on a comparison of pyranometric and pyrheliometric methods has been recently proposed by Hinssen and Knap in 2007.

The need to operate a transition from no-more-recommended SD methods (such as the Burn method applied by the Campbell-Stokes recorder) to instruments and methods with improved achievable accuracy, induced the meteorological services to investigate and compare suitable method for selecting those which respects the recommended meteorological requirements (see Chapter 8 of CIMO Guide, WMO 2008). Moreover, as stated during the last WMO CIMO Expert Meeting on Meteorological Radiation and Atmospheric Composition Measurements (Davos, 14-18 September 2009), there is a general need for updating the CIMO Guide, particularly on the uncertainty of sunshine measurements.

The demonstration and evaluation of uncertainty of SD instruments and methods with respect to a recommended reference during a long-term comparison (statistically significant) would be extremely valuable for defining or improving the calibration methods because of the natural variability of measurements conditions. In conclusion, a standardized calibration method for SD measurements is indeed not yet available and agreed in the scientific community, thus the results of a comparison can be used for such purpose.

1.2 Objectives

The primary objective of the present study is to evaluate the daily achievable uncertainty of SD measurements performed through three pyranometric methods (global solar irradiance), two different network sunshine detectors and 1-minute-averaged direct solar irradiance by pyrheliometers; the uncertainty related to a +/-20% variation of the 120 $W*m^{-2}$ threshold has been also evaluated (otherwise referred in the Chapter 8 of CIMO Guide as the "threshold accuracy of 20 per cent").

This study also aimed to use BSRN data for determining suitable coefficients for the best performing pyranometric method (the Carpentras Method or Météo France Algorithm - MFA) and permitting a global use of such method for estimating SD with acceptable accuracy.

2. Procedures and methods

2.1 Definition and meteorological requirements

According to the CIMO Guide the SD during a given period is defined as the sum of that sub-period for which the direct solar irradiance exceeds 120 W m^{-2}. The physical quantity is time and the units are seconds, minutes or hours. For climatologically purposes, and including the present study, the SD will be expressed in "hours per day" or "daily sunshine hours" ([h day^{-1}]) or the relative quantities in case of specific purposes. The measurement period is an important addendum, especially for comparisons of relative performances of SD methods, so it must be always specified when SD data are provided. The primary meteorological requirement on SD measurement is that hours of SD must be measured with an uncertainty of ±0.1 h day^{-1} and with a resolution of ±0.1 h. This paper will basically evaluate the acceptability of such requirement in field conditions for three pyranometric methods and two different network SD detectors (otherwise referred as SD sensors in the text and in figures).

2.2 Intercomparison site and references

As Hinssen and Knap suggested in their paper in 2007, the application of algorithms for estimating SD has been contemporarily carried out in two different climatic sites: Vigna di Valle, Italy (42N lat, 12E lon) and Carpentras, France (44N lat, 5E lon). BSRN measurements from 9 sites has been also used for tuning and adjusting the SD Carpentras method (referred in the text and figures as **M**étéo **F**rance **A**lgoritm - MFA) to improve its performance. The experiment has managed in the form of a bilateral intercomparison, mutually organized by two meteorological services interested in the performance of pyranometric methods and in the improvement of their calibration.

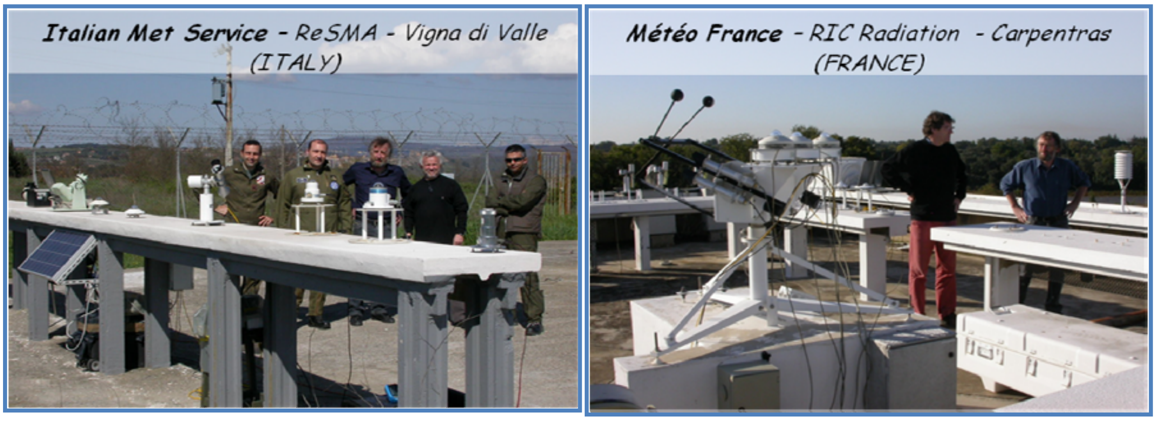


Fig.1 Intercomparison sites: Carpentras, France (right side) and Vigna di Valle, Italy (left side)

As recommended by the CIMO Guide, two pyrheliometers (one in each intercomparison site) were used as the reference sensors for the detection of the threshold irradiance. A model Eppley NIP and a Kipp&Zonen CH1, both operated with automatic sun trackers, have been respectively installed and used in Vigna di Valle and Carpentras. Both instruments have been calibrated on regular base during the intercomparison period by means of a TMI absolute pyrheliometer located in Carpentras and representing the primary reference of Météo France (Regional Instrument Radiation Center of Carpentras).

2.3 SD measurement methods

In both intercomparison sites the pyrheliometric method based on direct irradiance measurement was used as reference for comparing three different algorithms based on global irradiance measurement (pyranometric methods) and the two different SD detectors respectively operated by the Italian Met Service and Météo-France radiation networks.

(1) *Pyrheliometric method*

This measurement principle implies the detection of the transition of direct solar irradiance *(I)* through the 120 W m^{-2} threshold. The CIMO Guide (WMO, 2008) does not specify the time interval but, as described by Forgan (2005) and Hinssen and Knap (2007), the intercomparison measurements reported here have been performed over 1 second time interval (determining the seconds of SD), in order to reduce the uncertainty due to questionable sunshine minutes in case of using 1 minute averages of direct irradiance to detect the transition through the above-mentioned threshold. The seconds of pyrheliometric SD have been cumulated daily to assess the differences and the uncertainty of the other methods and the corresponding physical variable is indicated in the text and figures as SD_{REF}. For the assessment of the daily uncertainty of the SD calculated by 1 minute averages of direct irradiance and the daily uncertainty corresponding to the "SD threshold accuracy" of 20% (96 – 144 W m^{-2}) in instrument specifications admitted by the CIMO Guide (Chap. 8), three additional SD measurements has been derived by the pyrheliometer as follows:

- $SD_{pyrh\ 1m}$, *minutes of SD if the 1 min average of* $I \geq 120$ *W m*$^{-2}$;

- $SD_{thr\ 96}$, *seconds of SD if* $I \geq 96$ *W m*$^{-2}$;

- $SD_{thr\ 144}$, *seconds of SD if* $I \geq 144\ W\ m^{-2}$;

(2) *Pyranometric methods and instruments*

The pyranometric methods described below have been applied to the measurements of two pyranometers Kipp&Zonen CM11, regularly calibrated in Carpentras during the intercomparison period.

a. **S**tep **A**lgorithm (**SA**)

This method consists in an algorithm to estimate minutes of SD through the measurement of 1-min averaged global irradiance *(G)* compared with a *"rough"* threshold. The SA can be expressed by the following formula and test:

If $G \geq G_{THR}$ *then* $SD_{SA} = 1$ *minute, otherwise* $SD_{SA} = 0$ *minute*

where:

- $G_{THR} = 0.4\ G_0$ (*"rough" threshold*) (a1)
- G_0 *(extra-terrestrial global irradiance)* $= I_0 \sin(h)$
- $I_0 = 1367\ W\ m^{-2}$ *(extra-terrestrial irradiance)*
- ***h*** *is the elevation angle of the sun in degrees*

The elevation angle of the sun is calculated every minute contemporary to the sun hour angle, right ascension and geocentric declination according to the astronomical formulas reported in Annex 7.D Chapter 7 of CIMO Guide. The SA is run every minute can be simply described by the following figure:

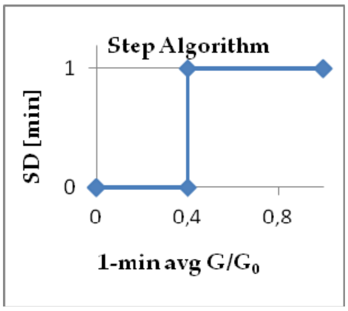


Fig. 2 The Step Algorithm method for estimating minutes of SD

The minutes of SD_{SA} have been cumulated daily to assess the measurement uncertainty of the this method.

b. Carpentras method or **M**étéo-**F**rance **a**lgorithm (**MFA**)

This method has been developed at the European Regional Radiation Centre of Carpentras and described by Olivíeri (1998). It consists in the calculation of minutes of SD through the measurement of 1-min averaged global irradiance *(G)* compared with an accurate threshold value. The MFA is run every minute and can be expressed by the following formula and test:

If $G \geq G_{Seuil}$ *then* $SD_{MFA} = 1$ *minute, otherwise* $SD_{MFA} = 0$ *minute*

where:

- $G_{Seuil} = F_c\ 1080\ (\sin(h))^{1.25}$ *(model)* (b1)
- $h \geq 3°$ *(data filtering)*
- $F_c = A + B\cos(2\pi d/365)$ (b2)

with:

- $\boldsymbol{F_c}$ *representing a fraction of global irradiance in clear sky in mean conditions of atmospheric turbidity;*
- ***h*** *being the elevation angle of the sun in degrees;*

*- **d** being the day number of the annual sequence;*

The **F*c*** factor depends on the climatic conditions of the location and A,B coefficients can be empirically calculated through a long term comparison with SD measurements by means of a pyrheliometer. Météo-France realized tables of A,B coefficients for different location latitudes and the following coefficient have been adopted for the present intercomparison for both locations (due to their similar latitude:

A	***B***
0,73	0,06

Tab. 1 Coefficients used in Carpentras and Vigna di Valle for the SD MFA

The elevation angle of the sun is calculated every minute contemporary to the sun hour angle, right ascension and geocentric declination according to the astronomical formulas reported in Annex 7.D Chapter 7 of CIMO Guide.
The data filtering (***h* ≥ *3°)*** is applied before the execution of the main test and permits the filtering of errors due to the imperfection of the model, height of the sun (low heights) and the atmospheric refraction. The CIMO Guide admits indeed a tolerance of 3° above the horizon for the requirement of an uninterrupted view of the sum at all times of the year for SD detectors. In a further national study, Météo-France scientists in Carpentras demonstrated that the errors introduced by the data filtering on *h* produce a small underestimation that due to their systematic nature can be corrected after a long term period of measurements.
The minutes of SD_{MFA} have been cumulated daily to assess the measurement uncertainty of the this method.

c. Slob and Monna Algorithm (**SM**)

Slob and Monna (1991) developed an algorithm to calculate daily SD from the sum of 10 minutes SD which implies the use of 10 minutes average of global irradiance and the use of its maximum and minimum values during the 10 min interval. The SM algorithm is run every 10 minutes and the daily SD is calculated by the sum of fractions *f* of 10 minute intervals, namely SD = Σ SD_{10}, where $SD_{10} = f \leq 10$ min. The fraction *f* € [0,1], with 0 for no sunshine and 1 for sunshine. The algorithm is based on the assumption that the fraction *f* depends on the solar elevation *h* and the atmospheric turbidity *T*.
The procedure to apply the algorithm is described in the Annex of Chapter 8 of the CIMO Guide (WMO, 2008) and by Hinssen and Knap (2007) who produced the corresponding flow diagram as the one reported in Fig. 3.. In particular the SM algorithm is applied through the parameterization of direct and diffuse irradiance, according to the empirical formulas derived by Slob (1991):

$$I = \left(\frac{r_o}{r}\right)^2 I_0 e^{\frac{-T_L}{(0.9+9.4\mu_0)}} \qquad (c1)$$

$$D/G_0 = \begin{cases} 0.2+\mu_0 & \text{for } 0.1 \leq \mu_0 < 0.3 \\ 0.3 & \text{for } \mu_0 \geq 0.3 \end{cases} \qquad (c2)$$

where:

*- **r_0** and **r** are the mean and actual earth-sun distances*

*- **I_0** = 1366 W m^{-2}*

- $\mu_0 = cos(az)$
*- **az** is the solar zenith angle (Annex 7.D Chap. 8 CIMO Guide)*
- $G_0 = \mu_0 I_0 (r/r_0)^{-2}$ (extra-terrestrial global irradiance)
- T_L is the Linke turbidity factor
(effect of true atmosphere with respect clean and dry atmosphere)

with (in Fig.3):
*- **G**: 10 minute average of the global irradiance;*
- G_{max}: maximum value of the global irradiance during the 10 min interval;
- G_{min}: minimum value of the global irradiance during the 10 min interval;

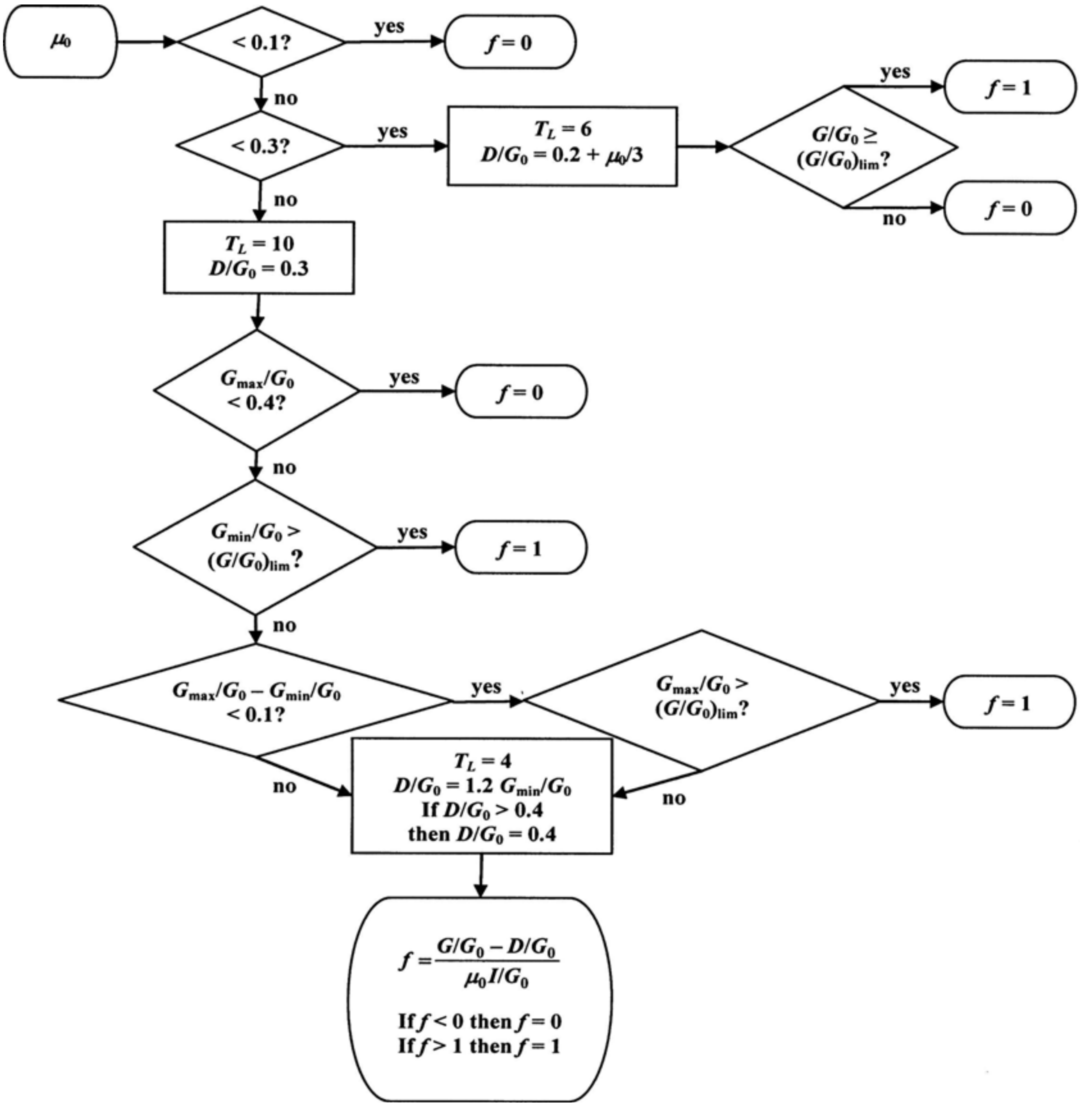


Fig.3 Flow diagram of the Slob and Monna algorithm (Hinssen and Knap 2007)

(3) *SD detectors*

Two SD sensors respectively operated by the Italian Met Service (IMS) and Météo-France (MF) radiation networks has been tested in this bilateral intercomparison to assess the SD network uncertainty and to compare it with the uncertainty of the pyranometric methods.

a. **MF sensor**

The MF sensor is the CIMEL CE181 detector. Its measurement principle is based on the *scanning method* by means of an optical fibre. It has been operating by MF for more than fifteen years.

b. **IMS Sensor**

The IMS sensor is Campbell-Stokes (C&S) recorder and its measurement principle is based on the *burn method*. It has been operating by MF for more than fifty years.It is the case to remember that such method is no longer recommended by the WMO since the duration of bright is not recorded with sufficient consistency, producing quite high inaccuracy in SD measurements.

2.4 Data acquisition and processing

The instrumental set up for each site was represented by one reference pyrheliometer, one pyranometer and one SD network detector. The data acquisition has been carried out in both intercomparison site by means of a Campbell CR10X datalogger which only integrated the measurements of pyrheliometer and pyranometer. The daily SD measured by the detectors were provided separately by the corresponding operating networks. The sampling frequency time was 1 HZ and the global and direct irradiances were calculated at the same frequency through the corresponding calibration coefficients of each instrument and averaged or cumulated over the suitable time interval by the datalogger and stored in different output data files. The algorithms and tests for SD_{pyrh1m}, SD_{SA}, SD_{MFA} are run every minute and stored in the same data file. The 1Hz data are not stored. The algorithm for SD_{SM} is run every 10 minutes by an "offline procedure " through the processing of 10 minutes data (I, G, G_0) and the application of the flow diagram in Fig.3

All astronomical data necessary for the pyranometric estimation of SD are calculated by the datalogger according to the formulas reported in Annex 7.D of the Chapter 7 of the CIMO Guide 8 (WMO, 2008) and their values are reported every minute (or 10 minutes) and stored in the 1 min SD data file (or 10 min SD data file).

The following table shows the physical variables and the main astronomical data used in the data analysis.

	Time interval				
Variable	1s	1 min	10 min	Hour	**day**
I	*sampled*	*Averaged*			
G	*sampled*	*Averaged*	*Averaged*		
G_{max}			*Sampled*		
G_{min}			*Sampled*		
G_0		$I_0 \sin(h)$	$I_0 \sin(h)$		
$\mathbf{SD_{REF}}$	*calculated*	$\Sigma\ SD_{REF}$	$\Sigma\ SD_{REF}$	$\Sigma\ SD_{REF}$	$\Sigma\ SD_{REF}$
$\mathbf{SD_{thr\ 96}}$	*calculated*	$\Sigma\ SD_{thr\ 96}$	$\Sigma\ SD_{thr\ 96}$	$\Sigma\ SD_{thr\ 96}$	$\Sigma\ SD_{thr\ 96}$
$\mathbf{SD_{thr\ 144}}$	*calculated*	$\Sigma\ SD_{thr\ 144}$	$\Sigma\ SD_{thr\ 144}$	$\Sigma\ SD_{thr\ 144}$	$\Sigma\ SD_{thr\ 144}$
$\mathbf{SD_{pyrh\ 1m}}$		*Calculated*	$\Sigma\ SD_{pyrh\ 1m}$	$\Sigma\ SD_{pyrh\ 1m}$	$\Sigma\ SD_{pyrh\ 1m}$
G_{THR}		$0.4\ G_0$			
$\mathbf{SD_{SA}}$		*Calculated*	$\Sigma\ SD_{SA}$	$\Sigma\ SD_{SA}$	$\Sigma\ SD_{SA}$
G_{Seuil}		$F_c\ 1080\ (\sin(h))^{1.25}$			

	Time interval				
Variable	1s	1 min	10 min	Hour	**day**
SD_{MFA}		*Calculated*			
D/G_0			*Calculated*		
SD_{SM}			*Calculated*		
SD_{SENSOR}					*Provided*
TST, sinh, ha,az, dec, Eq		*All calculated*	*TST, sinh, az*	*TST*	*TST*

Tab.2 Sampled and/or calculated physical parameters and astronomical data.

2.5 *Quality control of data*

The quality control of data has been performed by the procedures developed for BSRN global network by Long and Dutton (2002) and mainly consisting in 10 minutes interval checks of physically possible limits, extremely rare limits and ratios of the variables *G*, *D* and *I* mean values. Only good quality data were used in the analysis. Daily SD data with missing values for different reasons (datalogger failures, power supply, ect,) have been also discarded by the analysis dataset such as those data with poor alignment of NIP (located in Vigna di Valle) because the its sun tracker must be regularly checked (every two days) and adjust when necessary.

3. Data analysis

3.1 *Uncertainty of the reference*

The typical uncertainty of a reference pyrheliometer is 0.4 - 0.6% in terms of direct irradiance. This feature can be applied to both pyrheliometers operated during the bilateral intercomparison but to determine how and how much the uncertainty in *I* could influence the daily SD_{REF} uncertainty is not simple. The pyrheliometric uncertainty directly influences the detection of the transition through the 120 W m^{-2} threshold producing an uncertainty interval around the threshold: [120 – 120 *0,6%; 120 + 120*0,6%] = [119.28; 120.72] Wm^{-2}. Therefore one possible method is the empirical determination of SD uncertainty from daily transitions through the threshold due to the *I* uncertainty interval. In Fig.4 a plot of two set of *I* data is represented. The first set is in low turbidity conditions, the second set in high turbidity conditions. Each set of data represents the upward passage of *I* through the threshold of 120 W m^{-2} as obtained from experimental data. Fitting data, applying the linear fit equation to the *I* uncertainty interval and considering a maximum of 50 transitions per day (in very special cases), the time max uncertainty interval can be determined by the formula:

$$U^{MAX} = 50*((\Delta tmin/2)*60h/min)) = 0.06\ h\ day^{-1}\ (d1)$$

This uncertainty value should be combined with the uncertainty of the other SD methods and instrument, but its value is negligible with respect the other uncertainty (see section 3.2).

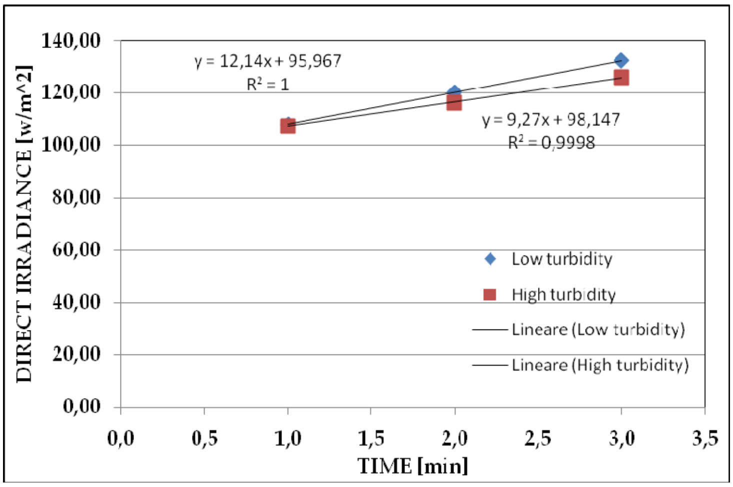


Fig.4 Plot of direct irradiance through 120Wm^{-2} from two sets of experimental data

Low turbidity				High turbidity			
Exp. Data		Linear fit (blue)		Exp. Data		Linear fit (red)	
t	I	I	t	**T**	**I**	I	t
minute	W/m^2	W/m^2	minute	minute	W/m^2	W/m^2	minute
1,0	108,09	**119,28**	1,92	1,0	107,5	**119,28**	2,28
2,0	120,28	**120**	1,98	2,0	116,52	**120**	2,36
3,0	132,37	**120,72**	2,04	3,0	126,04	**120,72**	2,44

tmax - tmin	0,06	tmax - tmin	0,08
U_L [h/d]	**0,05**	**U_H [h/d]**	**0,06**

Tab. 3 Experimental data and calculations for determining the SD_{REF} uncertainty due to *I* uncertainty

In addition to the previous considerations, it has to be noted that CH1 and NIP has a difference field-of-view angles: 5 degrees for CH1 and 5,7 degrees for NIP. Its means that NIP will theoretically sense more diffuse irradiance from the sun aureole and will tend to overestimate *I*. There can be also differences due to ambient temperature and to wind which can be modify the energetic equilibrium of the instrument. Scientists in Carpentras determined the dispersion of SD measurement differences between CH1 and NIP and found that:

$$\textit{Mean difference} = -0.06\ h\ day^{-1}$$

$$\textit{Uncertainty (95\%)} = 0{,}10\ h\ day^{-1}$$

This experimental result may be used for explaining the differences between results in Vigna di Valle and Carpentras corresponding to the same SD method when compared with a different reference pyrheliometer.

3.2 Results

In this section the daily SD values from the 1 min averages of *I*, the daily SD values from the 20 per cent of the threshold 120Wm^{-2}, the daily SD values from pyranometric methods and network detectors are respectively evaluated through the following plots:

a. *scatter plot of SD_x versus SD_{REF} with a linear fit (where x is the measuring principle used);*
b. *time series of SD daily differences ($SD_x - SD_{REF}$);*

c. *the dispersion of SD daily differences with a normal distribution fit.*

The following parameters are provided in this section and in the summary for the interpretation of results in both intercomparison sites:

- Npts = number of experimental points (daily SD values);
- Totals [h] = totals of SD for the intercomparison period;
- Cumulative differences [h/day]
- Relative error [%] of each SD measurement with respect to the total SD_{REF}.
- Bias [h/day] = mean value of the daily differences ($SD_x - SD_{REF}$). The Bias can be used as a measurement of accuracy or **trueness** of the SD method/instrument.
- Std.dev or s[h/day] = standard deviation of each daily SD measurement with respect to the reference. The standard deviation can be used as a measurement of the **precision and repeatability** of SD method/instrument with respect to the reference;
- **U_{95}**[h/day] = 2*s = daily achievable uncertainty of each SD measurement with respect to the reference. If SD daily difference are normally distributed, the 95% of the confidence level (95% of samples) are within 2 standard deviations. Otherwise the achievable uncertainty can be expressed by the next parameter.
- **Achievable uncertainty interval** [h/day] = interval with the 95% of samples, calculated by the experimental data.
- Npts [%] in the range {-0,1 ; +0,1} [h/d]. This value expresses the percentage of SD values within the uncertainty limit recommended by the WMO.
- Daily e avg[%] = averaged relative error of each daily SD measurements with respect the daily SD_{REF}. As the BIAS, it can be used for express the trueness of daily SD method/instrument in relative way.
- Daily st.dev[%] = relative standard deviation of each daily SD measurements with respect the daily SD_{REF}. As the standard deviation of each daily SD measurement of the **precision and repeatability** of SD method/instrument in relative way.
- Npts [%] in the range of 5% of daily relative error. This values expresses the percentage of experimental points within a daily relative error of 5% with respect the reference.
- Npts [%] in the range of 20% of daily relative error. This values expresses the percentage of experimental points within a daily relative error of 20% with respect the reference.
- R^2, Rsqr = coefficients of determination. Their values are a measure used in statistical model analysis to assess how well a model explains or predicts the future outcomes and in our case it is used to express the goodness of the linear and normal fit.
- Skewness = a parameter to measure the symmetry of the sample distribution. A negative skewness indicates that the "left tail" of the distribution is longer than the "right tail" and the median is greater than the mean. A positive skewnes is the opposite case. The formula for calculating the skewness is:

$$Skew = [Npts/(Npts-1)(Npts-2)]*[(\Sigma(x-\mu)^3)/\sigma^3)$$

(1) $SD_{pyrh\ 1m}$ and SD threshold tolerance (96 – 144 Wm^{-2}) - (Vigna di Valle and Carpentras)

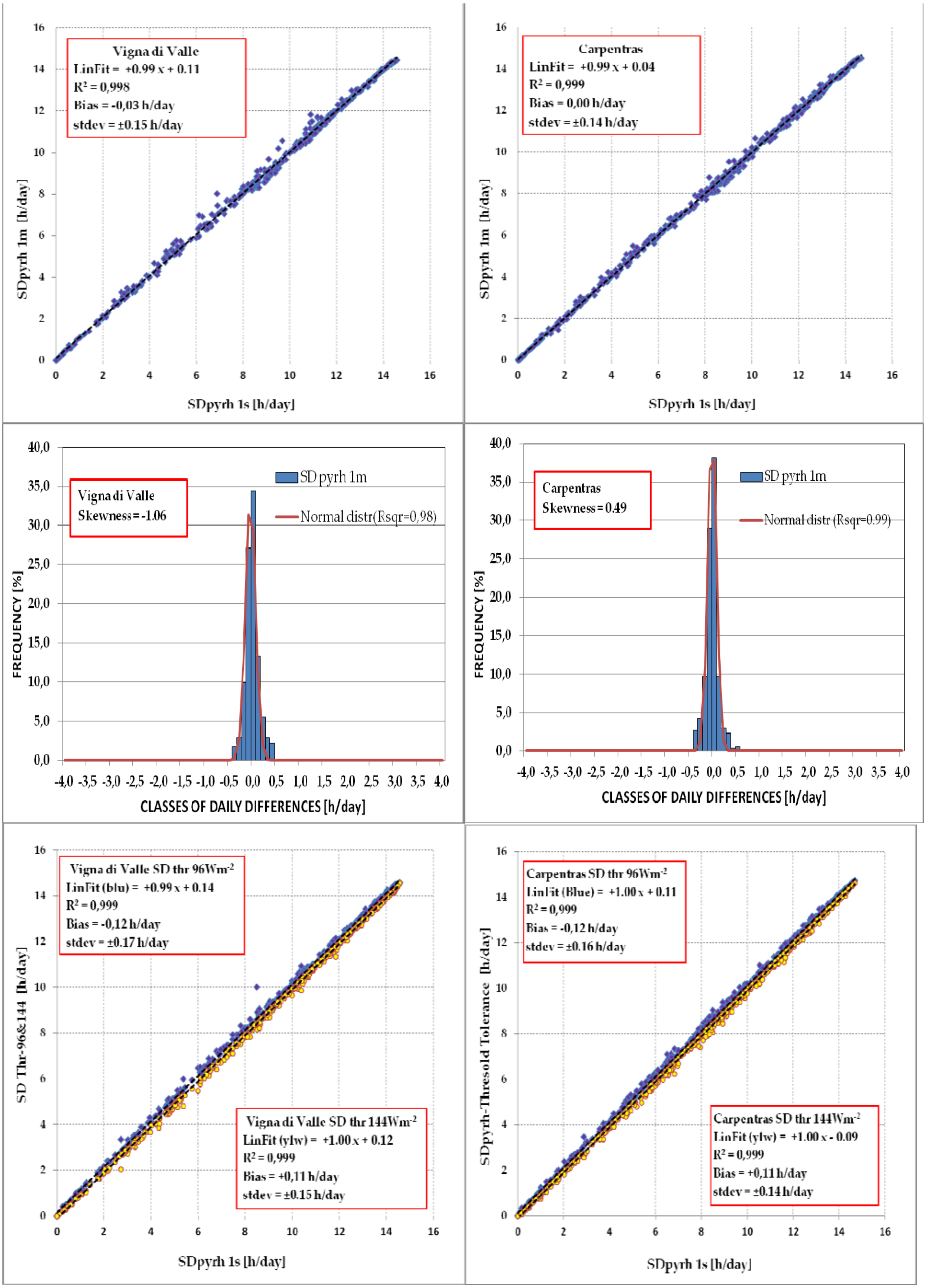


Fig.5 Scatter plot and distribution of differences for $SD_{PYRH\ 1m}$ and scatter plot for $SD_{THR\ 96\text{-}144}$

(2) Step Algorithm (Vigna di Valle and Carpentras)

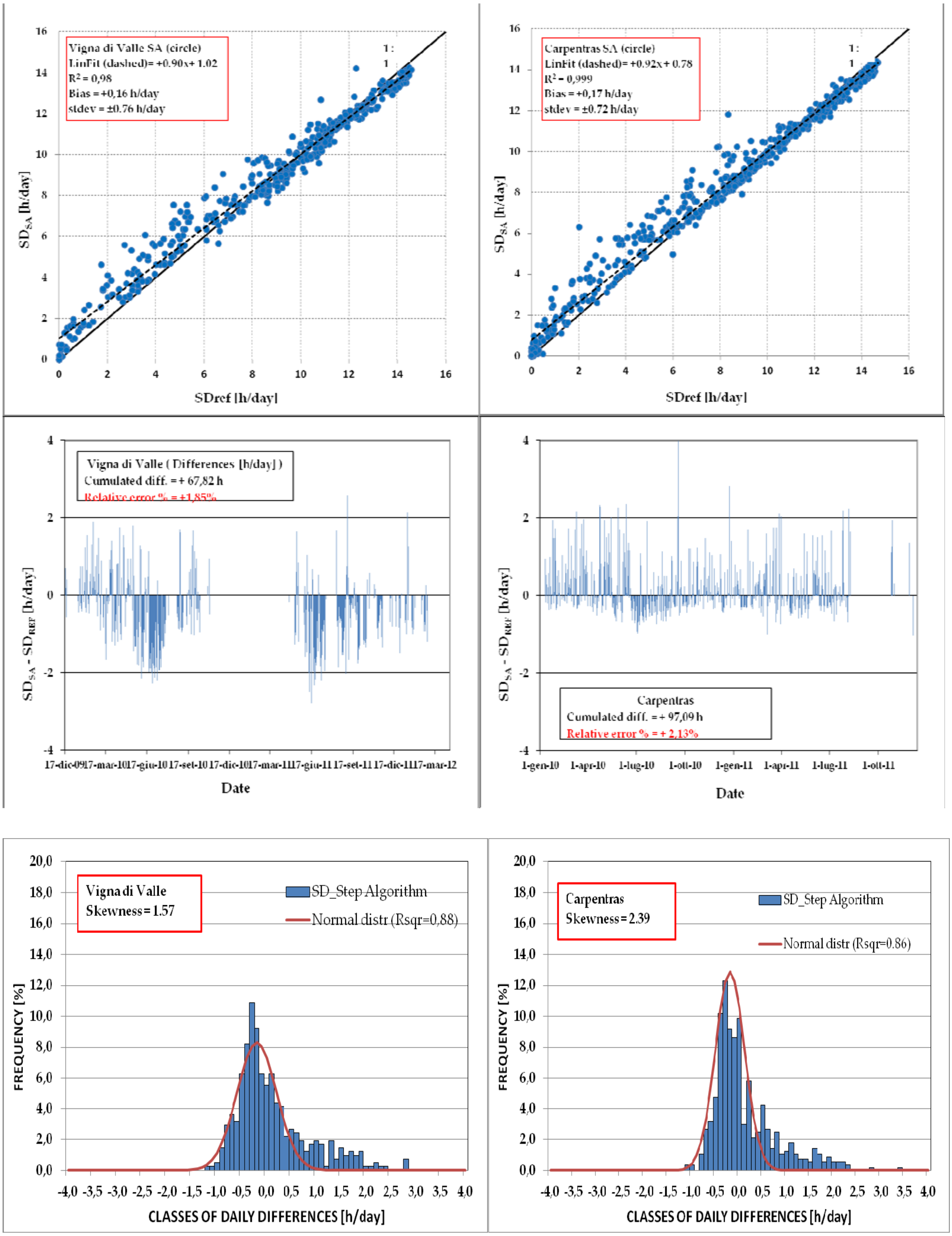


Fig.6 Scatter plot, time series of differences and distribution of differences for SDSA

(3) Météo-France Algorithm (Vigna di Valle and Carpentras)

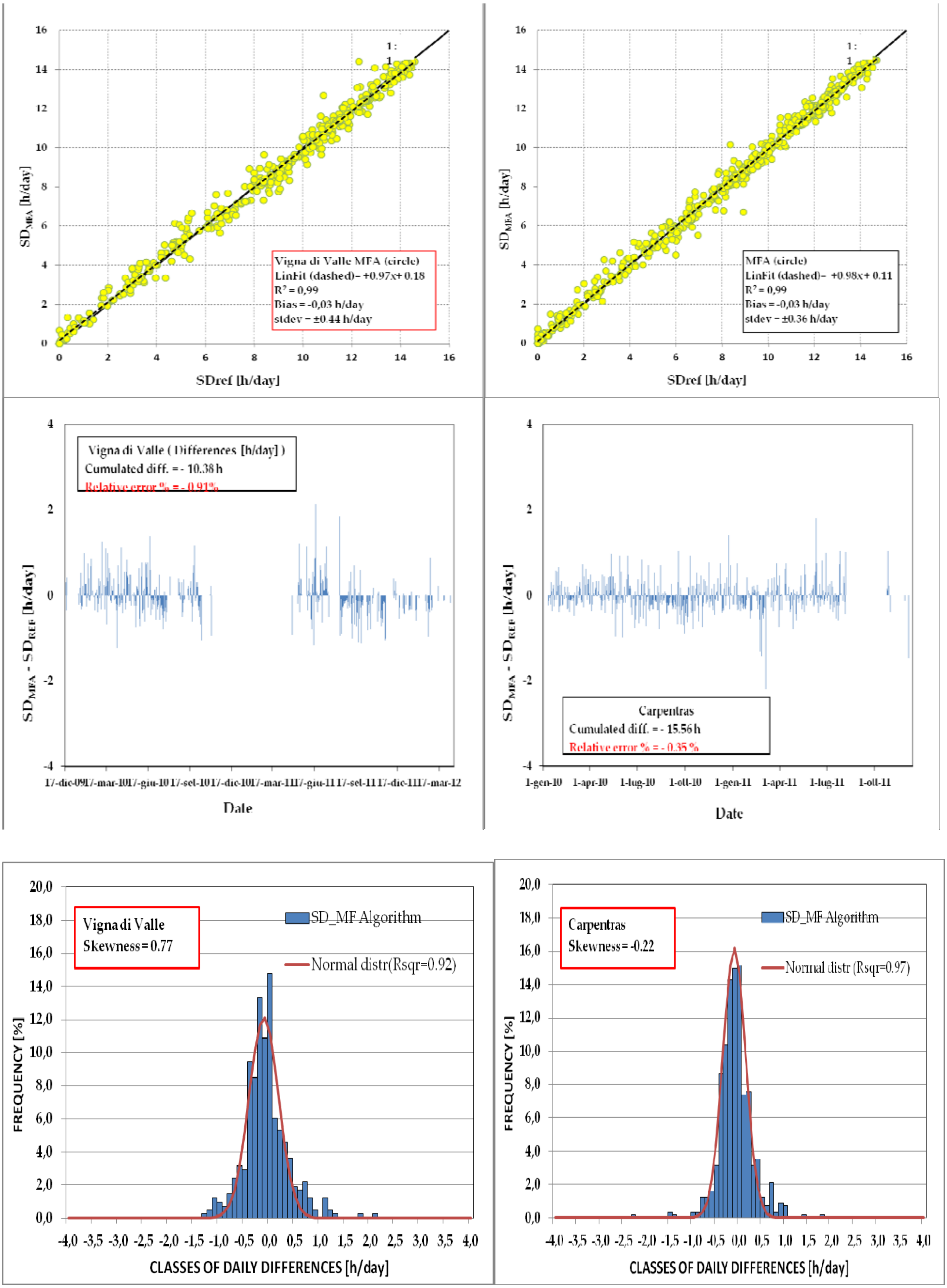


Fig.7 Scatter plot, time series of differences and distribution of differences for SD_{MFA}

(4) Slob ad Monna Algorithm (Vigna di Valle and Carpentras)

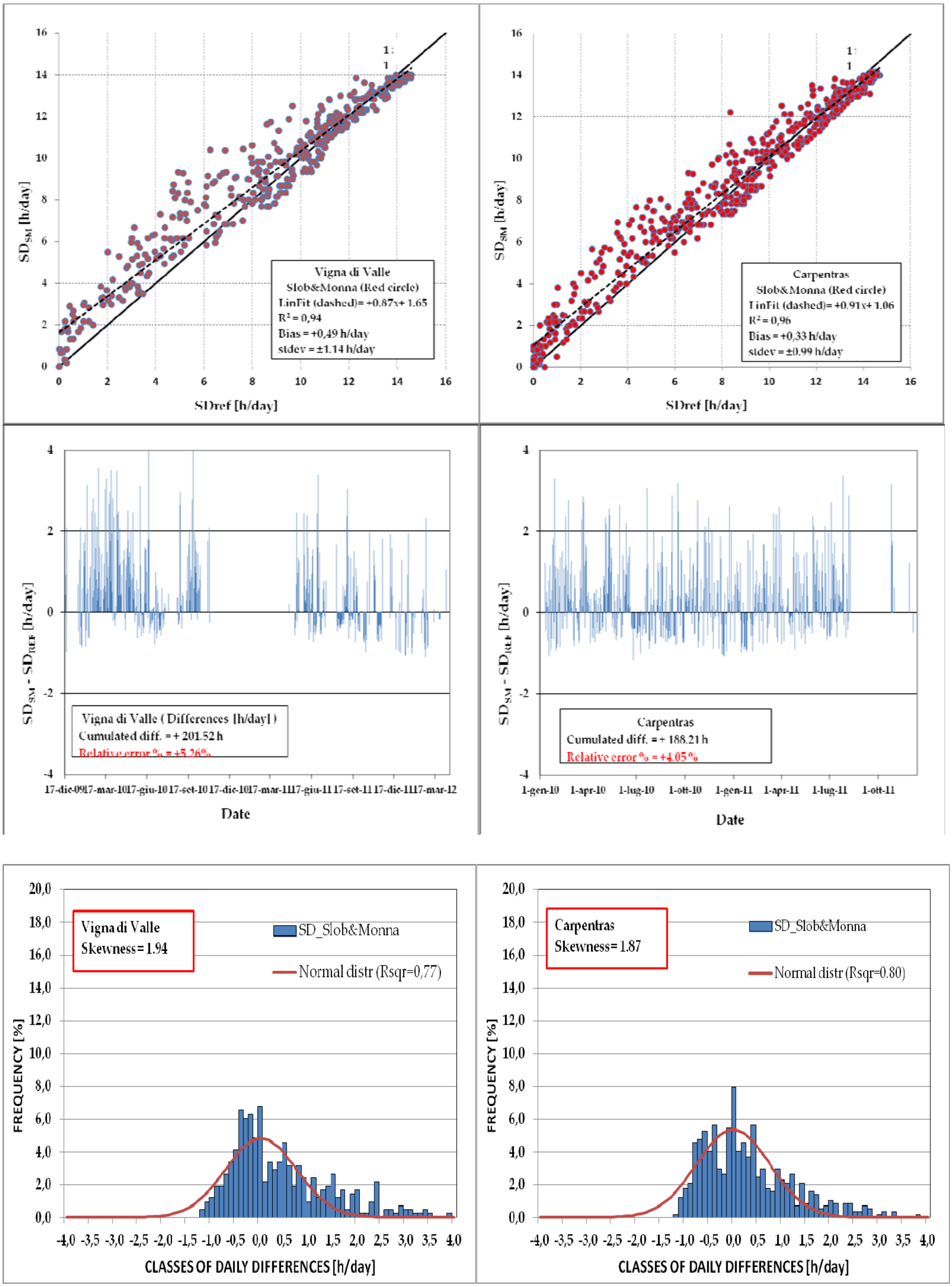


Fig.8 Scatter plot, time series of differences and distribution of differences for SD_{Slob}

(5) MF detector (Carpentras)

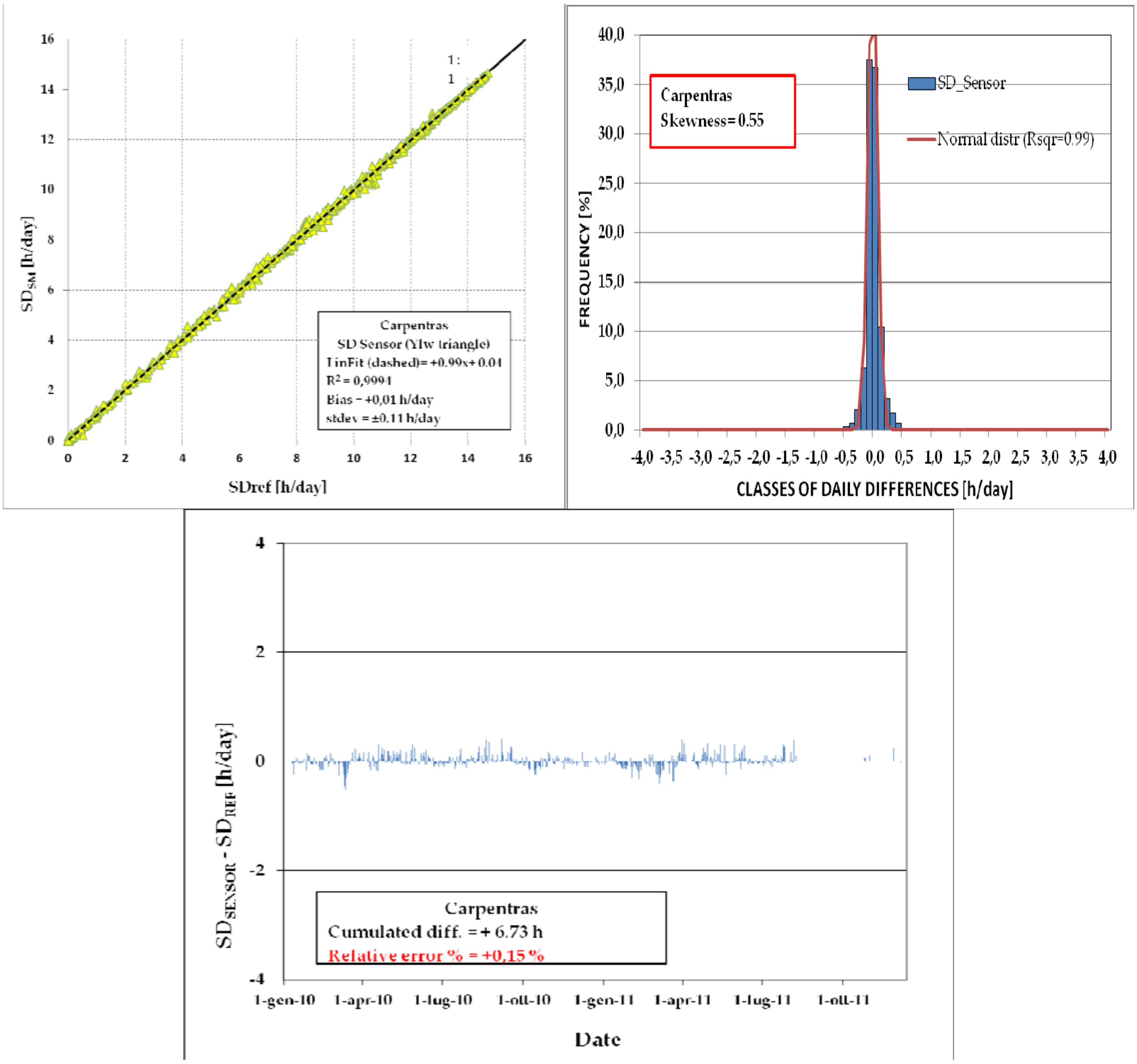


Fig.9 Scatter plot, time series of differences and distribution of differences for the Météo France network detector

(6) C&S recorder (Vigna di Valle)

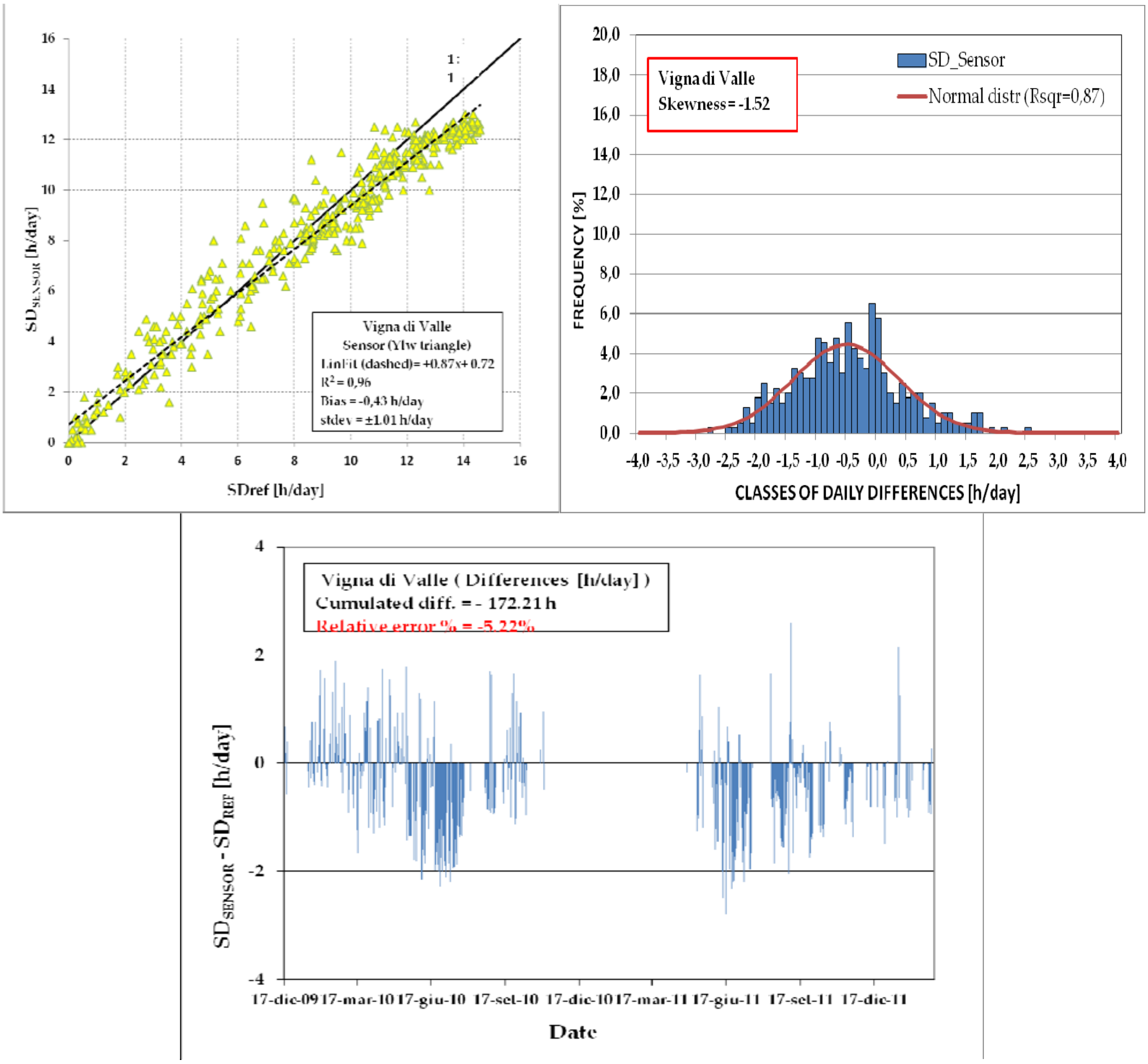
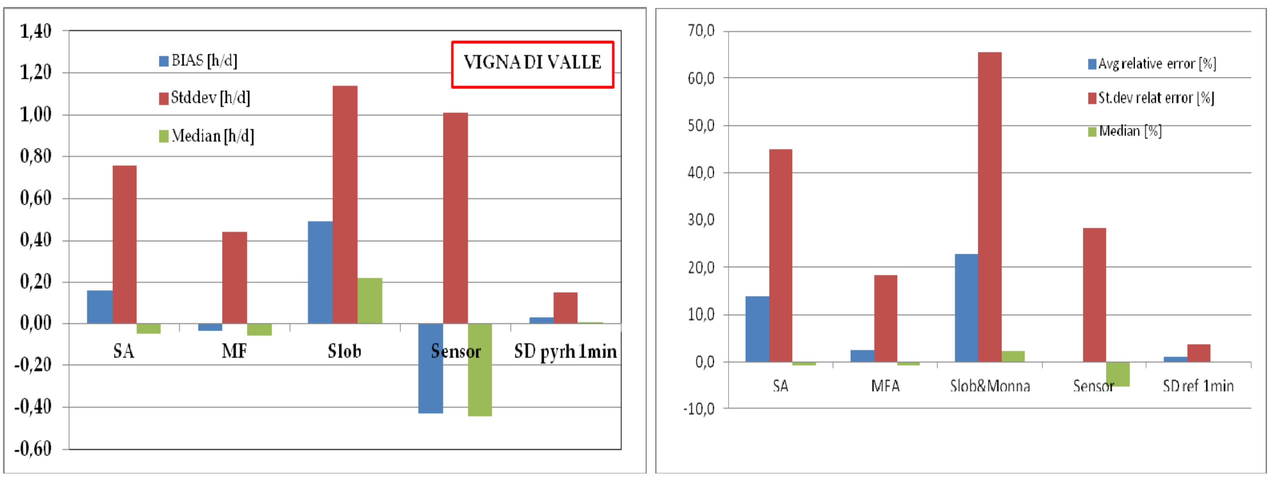


Fig.10 Scatter plot, time series of differences and distribution of differences for the IMS network detector

(7) Summary plots and table with results (Vigna di Valle and Carpentras)



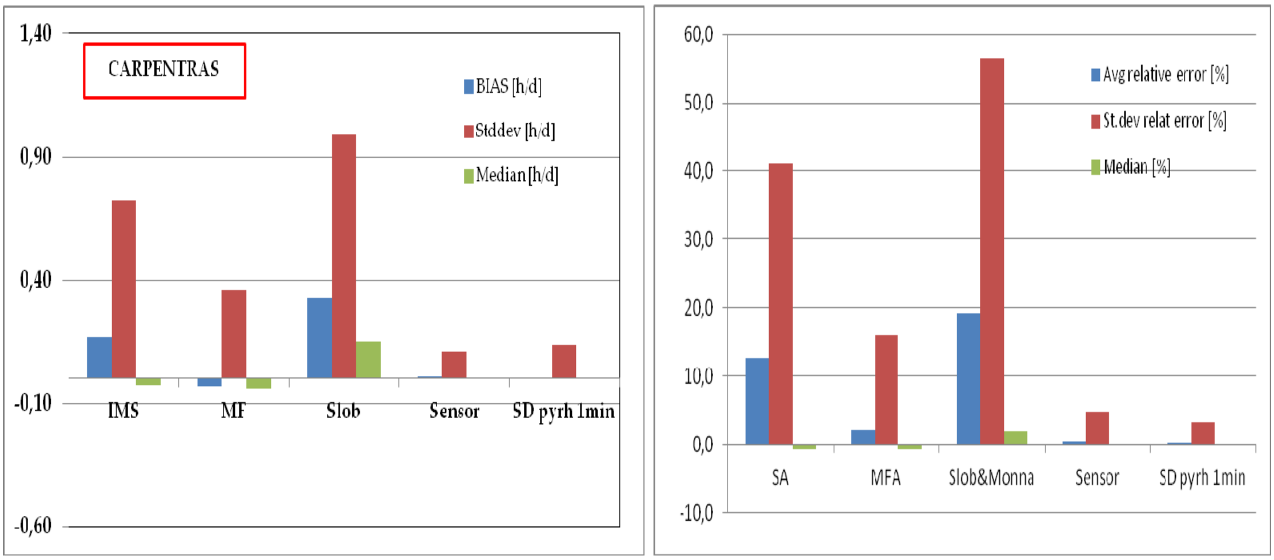


Fig.11 (a) and (b) Bias, st.dev, median [h/d] and average relative error, st.dev and median [%] calculated for both intercomparison locations

SD method	SA		MFA		Slob&Monna		Detector		1m avg direct Irradiance	
Location	Carpentras	Vigna di Valle	Carpentras	Vigna di Valle	Carpentras	Vigna di Valle	Carpentras	Vigna di Valle	Carpentras	Vigna di Valle
Npts	568	413	568	413	568	413	566	398	568	413
Totals [h]	4559,67	3670,23	4447,02	3583,48	4650,78	3828,72	4448,42	3299,40	4463,50	3593,17
Cumulated diff [h]	97,09	67,82	-15,56	-10,98	188,21	201,52	6,73	-172,21	0,93	11,81
Relative Err [%]	2,13	1,85	-0,35	-0,31	4,05	5,26	0,15	-5,22	0,02	0,33
Bias [h/d] (trueness)	0,17	0,16	-0,03	-0,03	0,33	0,49	0,01	-0,43	0,00	0,03
s [h/d]	0,72	0,76	0,36	0,44	0,99	1,14	0,11	1,01	0,14	0,15
U_{95} = 2*s [h/d] (uncertainty)	1,43	1,51	0,73	0,88	1,97	2,29	0,23	2,03	0,27	0,29
Range [h/d] for 95% of Npts (uncertainty)	[-1,37; +1,71]	[-1,36; +1,68]	[-0,75; +0,69]	[-0,91; +0,85]	[-1,41; +2,07]	[-1,45; +2,43]	[-0,21; +0,23]	[-2,35; +1,69]	[-0,28; +0,28]	[-0,27; +0,33]
Npts [%] in the range {-0,1 ; +0,1}[h/d]	21,5	18,2	37,5	31,7	17,4	13,8	84,6	15,3	76,9	74,8
daily eavg% (trueness)	12,6	13,7	2,1	2,4	19,2	22,8	0,6	0,0	0,3	1,1
daily st.dev % (precision)	41,1	44,8	16,0	18,3	56,5	65,4	4,8	28,4	3,2	3,7
Npts [%] in error range of ±5%	70,2	65,6	77,9	75,5	50,3	55,9	96,4	32,5	97,1	96,9
Npts [%] in error range of ±20%	83,3	83,7	93,5	95,4	80,6	76,3	99,4	88,5	99,8	99,7

3.3 Improvement of the MFA by BSRN data

The evaluation of the performance of the MFA algorithm has been also extended to nine BSRN stations by using 1-min average global and direct irradiances for at least 4 consecutive years. The purpose is the determination of the best set of A and B coefficient that minimize the total relative error of SD over a long period of time (years) and a method for an universal application of the MFA for estimating SD from global irradiance at all latitudes.

The technique applied consists in an empirical method that permits to select the A,B from the plot of the cumulative difference between the SD from MFA and SD from 1 min average of direct irradiance (assumed as reference because available from BSRN data). The results have been recently presented at the BSRN meeting in Postdam, 1-3 August 2012. As example, the results obtained for BSRN station of Cabauw (The Netherlands) and Capentras are shown in Fig. 12 and 13. They represent 4-years daily SD data from which the A,B coefficients that minimize the error between SD_{MFA} and reference SD have been derived.

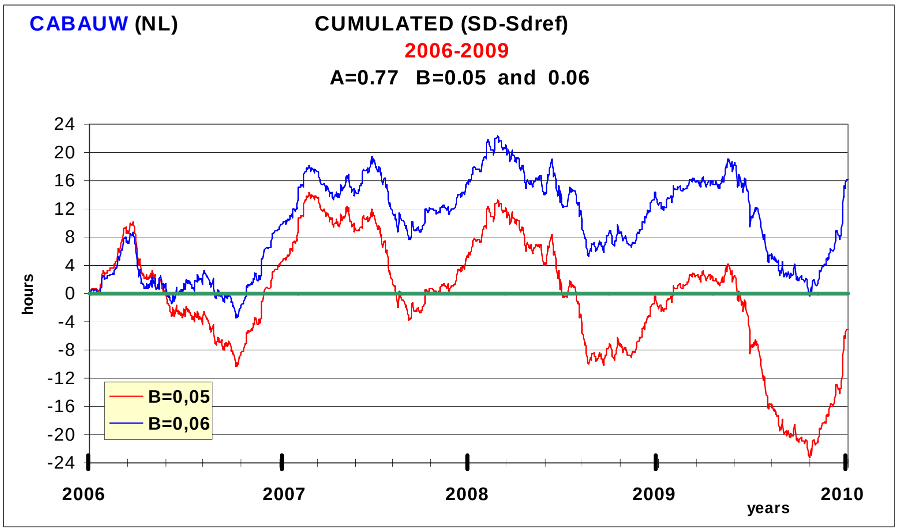


Fig.12 Cumulative differences of SD_{MFA} and SD_{REF} for different B coefficients in Cabauw

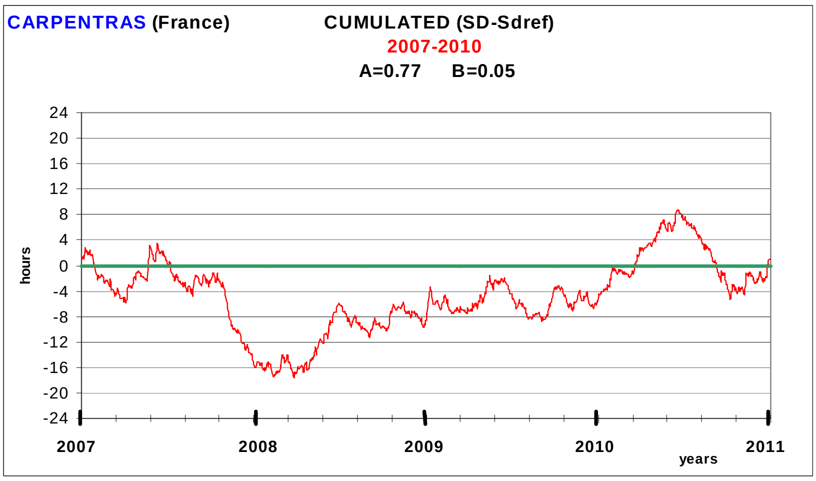


Fig.13 Cumulative difference of SD_{MFA} and SD_{REF} for a set of A,B coefficients in Carpentras

The following plots show the positive effect of the appropriate selection of A and B coefficients on Carpentras and Cabauw.

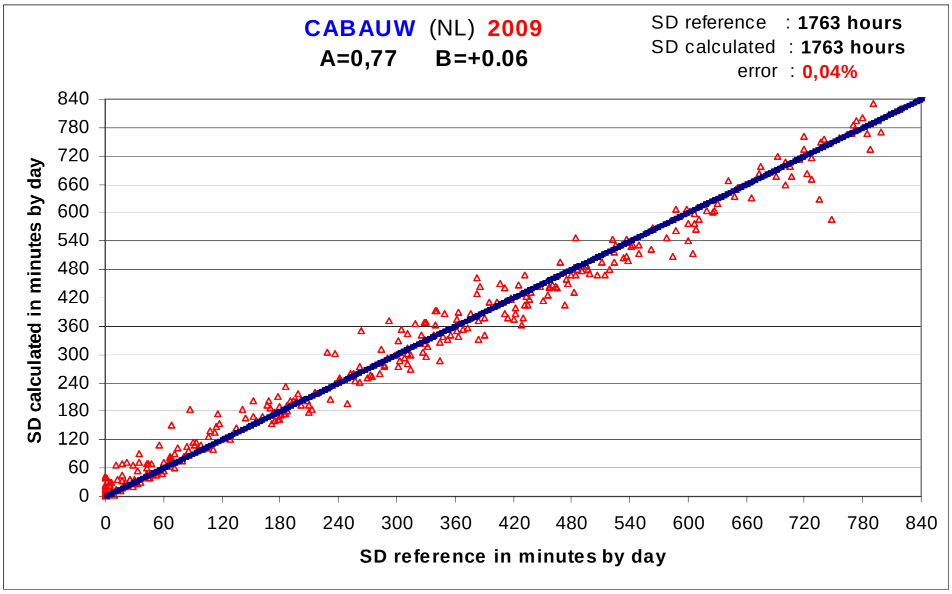


Fig. 14 Scatter plot of SD_{MFA} versus SD_{REF} after selection of appropriate A,B coefficients (Error 0.04%)

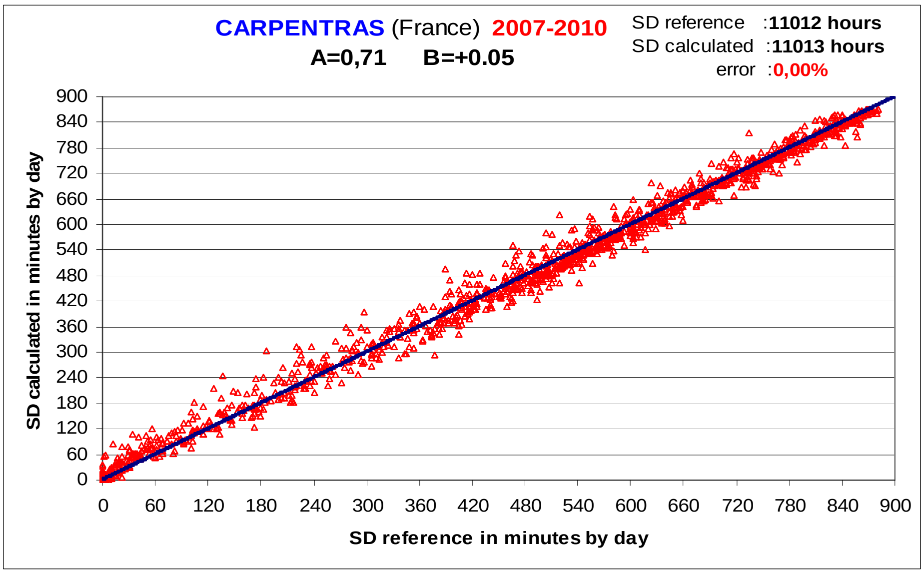


Fig. 15 Scatter plot of SD_{MFA} versus SD_{REF} after selection of appropriate A,B coefficients (Error -0.00%)

The application of this empirical technique on all nine BSRN stations covering the Northen Hemisphere latitudes produced the following results:

BSRN STATION	Latitude	A	B	Err %
MOMOTE	-2	0,67	0	-0,1
TAMANRASSET	22	0,77	0	-0,2
TATENO	36	0,73	0,05	-0,2
BOULDER	40	0,67	0,06	0,1
CARPENTRAS	44	0,71	0,05	0,1
PAYERNE	47	0,75	0,06	0,4
PALAISEAU	48	0,75	0,04	0,2

BSRN STATION	Latitude	A	B	Err %
CABAUW	52	0,77	0,06	0,2
TORAVERE	58	0,74	0,06	0,4

Tab. 5 A and B best coefficients for 9 BSRN stations covering Northern Hemisphere

The re-determination of Carpentras A,B coefficient will thus permit to improve the results obtained from this intercomparison on SD measurements methods and the future application of these new coefficients for local quality SD measurements.

4. Summary and conclusions

The results of the bilateral intercomparison on SD measurements organized by Météo-France and Italian Met Service in two different location (Carpentras and Vigna di Valle) permitted the accurate evaluation of the performance of three pyranometric methods for estimating daily SD from global irradiance. The reference SD value is calculated every second by comparing 1 s direct solar irradiance *I* with the 120 W m^{-2} threshold. The effect due to the application of a threshold tolerance of 20% and the SD calculation from 1 minute averages of *I* have been also investigated. According to the summary plots and table reported in section 3.2.(7) and the variability between Carpentras and Vigna di Valle, the following conclusions can achieved:

- uncertainty of daily SD from 1 min average of *I* is $U_{95}^{pyrh1m} = 0.27 - 0.29 hday^{-1}$, with an absolute relative error of 0.02 - 0.33 % and an average daily relative error of 0.3-1,1%;
- uncertainty corresponding to the tolerance threshold of 20 per cent is $U_{95}^{THR} = 0.28 - 0.30 hday^{-1}$, with a relative error on totals of - 1.39% (VdV) or - 1.45% (Carp.) for 96Wm^{-2} threshold and a relative error on totals of +1.33% (VdV) or +1.37% (Carp.) for 144Wm^{-2} threshold;
- the MFA for daily SD measurements through global irradiance is the best performing pyranometric method with achievable uncertainty $U_{95}^{MFA} = 0.73 - 0.88 hday^{-1}$ (or 95% points in [-0,75;069] h day^{-1} for Carpentras and in [-0.91;0.85] h day^{-1} for Vigna di Valle), with an absolute relative error of -0.33% (-13h) and a daily mean relative error of 2.2% (median -0,76%) considering both locations;
- the Slob and Monna algorithm performed as the worse, even if the large overestimation of SD remained unexplained with consideration to the underestimation obtained by Hinssen and Knap (2007);
- the achieved uncertainties of pyranometric methods and of the tolerance threshold are definitively not comparable to the CIMO Guide required uncertainty ± 0,1h (U_{95}), so the WMO requirement is not appropriate target for routine operational measurements and should be reviewed;
- long time series of BSRN data (1 min averages of global and direct irradiance) can be used for empirically improving the MFA over a large range of latitudes, permitting a global use of such algorithm for accurate determination of SD through global irradiance;
- For Northern Hemisphere A and B coefficient resides in a range respectively of 0,67-0,77 and 0.04 - 0.06, probably depending more on local climatology than on latitude.

- The CIMO Guide should be reviewed for taking into account additional algorithms for estimating SD, for updating the typical achievable uncertainty of those methods and for methods used on BSRN data for calculating daily SD or adjusting coefficient of pyranometric method over a long time base.

5. Acknowledgements

We acknowledge the precious contribution and support of M. Leroy and J. Oliviéri. Special thanks to Didier and A. Oliva for their maintenance and data acquisition activities respectively at the RIC-Radiation in Carpentras and at the ITAF Centre of Meteorological Experimentations in Vigna di Valle.

6. Bibliography

- **Dyson, P., 2003**: Investigation of the Uncertainty of Sunshine Duration in the Solar and Terrestrial Radiation Network, BoM – Instrumeny Test Report 674
- **Forgan, B. W., 2005**:Sunshine duration uncertainty from BSRN station, Exeter (UK), WCRP Informal Rep.4/2005, 68pp
- **Hinssen, Y. B. L., 2006**: Comparison of different methods for the determination of sunshine duration. KNMI Scientific Rep WR-2006-06, 72pp
- **Hinssen, Y. B. L., and Knap, W. H., 2007**: Comparison of pyranometric and pyrheliometric methods for the determination of sunshine duration. *Journal of Atmospheric and oceanic technology*, **24**, 835-846
- **Olivíeri, J. C., 1998**: Sunshine duration measurement using a pyranometer. WMO, IOM no.70, WMO tech doc 877, 385pp
- **WMO, 2008**: Measurement of radiation and sunshine duration. *WMO no.8, 7th Ed., Part I, Cap. 7 and 8*.