Sunshine duration from pyranometer readings

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Abstract.

As more and more meteorological stations are working in a fully automatic mode, the classic Campbell-Stokes (CS) instrument for measuring sunshine duration becomes obsolete. Specialized sunshine meters are usually expensive and not commonly used, whereas global solar irradiance measurements by pyranometers become ubiquitous. Many methods exist for computing sunshine duration from these irradiance readings. This report uses 11 years measurements from meteoLCD to compare several models (Oliviéri, simplified Slob & Monna, Hinssen-Knap, Louche 1/2, Campbell and Glover) and one series of CS readings. The Olivieri and Hinssen-Knap algorithms seem to be good alternatives for the CS instruments, and are probably the most accurate and easy to use for computing the true sunshine duration in accordance with the WMO definition.

Chapters:

1. The Campbell-Stokes instrument

Fig.1. The Campbell-Stokes (CS) sunshine duration recorder.
Source: http://www.adagunes.com/

This antique sunshine recorder was invented by J. F. Campbell in 1853 and modified to its usual shape by Sir G.G.Stokes in 1879. A typical 10 cm diameter glass sphere acts as a convergent lens to focus the sun rays on a time-graduated paper strip. If the irradiance is high enough, a hole will be burnt into the paper strip. Adding the total length of the burned parts gives the sunshine duration of the day.

The CS recorder was for many years practically the sole contender for recording sunshine duration, despite its well known shortcomings and disadvantages:

1. the instrument must be operated manually and a new paper strip mounted every morning before sunrise.

2. the paper strip responds in a different manner to solar irradiance whether the ambient air is humid or dry **[12]**. It is assumed that most CS instruments start burning a hole when the direct irradiance lies between 106 and 285 Wm-2, an extremely large interval. **[3]**

3. the holes are not well formed at sunrise and sunset

4. the holes may be smeared out when cloud cover is patchy, but solar irradiance high (as is often the case in summer)

5. different operators reading the same cards may get very different totals **[6]**

As a consequence, the CS recorder tends to **overestimate** sunshine duration by approx. 7% in winter and up to 20% in summer **[2]**,**[3]**. Nevertheless, the CS sunshine recorder may still have some usefulness in estimating the direct beam irradiance from the width of the burns, as shown in **[5]**

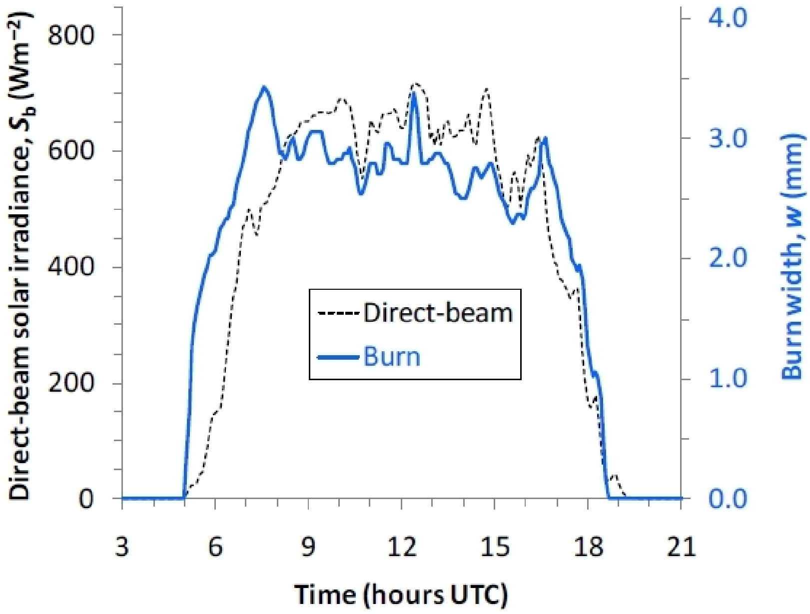

Fig. 2. Correlation between direct beam irradiance and width of the burns on the Campbell-Stokes paper strip [5].

As most modern weather stations operate in a fully automatic manner, the CS recorder becomes obsolete. It is sometimes replaced by electronic sunshine recorders like the CSD3 from Kipp & Zonen [18] or the BF5 from Delta_T Devices Ltd. [19]

Fig.3. The Kipp & Zonen sunshine duration sensor CSD3 [18]

2. Sunshine definition and the algorithms used in this report

2.1. The WMO definition of sunshine

Starting 2003, the World Meteorological Organization has adopted the following definition for the existence of sunshine [7]:

"Sunshine duration during a given period is defined as the sum of that sub-period for which the direct solar irradiance exceeds 120 W/m^{-2} "

To follow this definition by the letter, direct solar irradiance must be measured by a pyrheliometer, which is a rather expensive, usually sun-tracking mounted device not commonly found as a standard equipment of a weather station.

Fig.4 Suntracker with shaded horizontal mounted pyranometer, and two tracking instruments: pyrheliometer (upper instrument) and pyranometer
(Source: http://en.wikipedia.org/wiki/Pyrheliometer)

But many weather stations (like meteoLCD) are nowadays equipped with a pyranometer. This horizontal mounted device measures global solar irradiance, i.e. the sum of direct, diffuse and reflected irradiances. The obvious question is: can the sunshine duration according to the WMO definition be computed from the pyranometer readings and from some other known or commonly measured parameters?

Several authors, by taking simultaneous pyrheliometer and pyranometer readings have found an affirmative answer to that question. The algorithms used are heavily localized and contain fit-parameters that may not give good results at different locations.

Other authors have used algorithms based on the Angström-Prescott formula to obtain a relationship between average daily solar energy and sunshine duration.
This formula states that:

$\mathbf{H/H_0 = a + b*S/S_0}$ [eq. 1]

where

H_0 extraterrestrial solar energy received in a day on a horizontal surface at the top of the atmosphere

H the same energy measured by the pyranometer at ground level

S_0 maximum possible sunshine duration of the day

S measured sunshine duration during the day.

Kadir Bakirci [13] has compiled 66 different models, all based on the Angström-Prescott formula. We will use in this report 2 of those models, one by Glover & McCulloch, the other by Louche; these models will be applied to daily totals, not half-hours average readings.

MeteoLCD at Diekirch, Luxembourg, has used for many years a method established by Jean Oliviéri, a scientist from the French Météofrance “Centre Radiométrie de Carpentras” [8]. Slob and Monna [9] from the Dutch KNMI published a rather complicated algorithm in 1991, which will be used in this paper in a simplified manner. Hinssen and Knap [10] also from KNMI published a report in 2006 on the same problem. Alain Louche from the University of Corsica found a rather simple to use algorithm to derive sunshine duration. Finally this paper will also check a procedure recommended by Campbell Scientific, manufacturer of data loggers and environmental instruments [14]. All these comparisons are based on the semi-hourly pyranometer readings by meteoLCD, which are themselves averages of 30 measurements done every minute.

The models will be applied to the meteoLCD data from 2000 to 2010, spanning eleven years. For a comparison the monthly mean Campbell-Stokes readings from the Luxembourg official weather station located at the Findel airport, about 27 km South from Diekirch will be used. The altitude of meteoLCD is 218m asl, that of the Findel 365m asl. Monthly readings from two meteorological stations of ASTA, a public administration, will also be used, even if these series suffer from many gaps and/or impossible readings. Conclusions will be drawn either on the full eleven year totals, the different yearly totals, the heat-wave year 2003 and on a seasonal analysis of the two months periods of Jun-July and Sept-October

2.1. Some important equations

The following table gives a list of the parameters used in this report; all angles and arguments of trigonometric functions are in degrees! (be aware that many software packages expect the argument of the trigonometric function in radians; in Excel the function RADIANS() can be used to change degrees to rads).

Parameter	Formula or value	Comment	Equation
L = latitude of the station	L = 50° North	[degrees]	
n = day number of the year	n = 1 for the 1st January	[degrees]	
d = solar declination of the day	d = 23.45*sin(360*(n+284)/365)	[degrees]	[eq.2]
w = mean sunrise hour angle	w = arccos(-tan(d)*tan(L))	[degrees]	[eq.3]
S_0 = monthly average day length	S_0 = 2/15*w	[hours]	[eq.4]
k = factor corresponding the yearly variation of the extraterrestrial solar irradiance	k = 1 + 0.033*cos(360*n/365)		[eq.5]

H_0 = daily total extraterrestrial **energy** on a horizontal plane at the same geographic location	$H_0 = (10^{-6}*24*3600/pi)*k*(cos(L)* cos(d)*sin(w)+pi/180*w*sin(L)*sin(d))$	$[MJ*m^{-2}*d^{-1}]$	[eq.6]
H = daily total **energy** on a horizontal plane, as measured by the pyranometer		$[MJ*m^{-2}*d^{-1}]$	
z = solar zenithal angle		[degrees]	
h = solar elevation angle	h = pi/2 - z	[degrees]	[eq.7]
G_0 = extraterrestrial solar **irradiance** on a horizontal plane at the same geographic location	$G_0 = 1080*[sin(h)]^{1.25}$ (Oliviéri, approximate formula) a more precise expression containing also declination, latitude and variable SUN-EARTH distance could also be used.	$[Wm^{-2}]$	[eq.8]

The essential parameter in most of the models is the solar angle, either the horizontal angle h or its complement, the zenithal angle z. Many formulas exist to compute a reasonable accurate approximation of h. In this paper the formulas given by Oliviéri in [15] will be used, as summarized in the following table:

sine of solar angle h	sin(h) = sin(delta)*sin(L)+cos((delta)*cos(L)*cos(t)		[eq. 9]
solar declination delta	delta = 0.006918 - 0.3999912*cos(theta) + 0.070257*sin(theta) - 0.006758*cos(2*theta) + 0.000908*sin(2*theta)	[radians]	[eq. 10]
theta	theta = 2*pi*d/365	[radians]	[eq. 11]
solar angle t	t = 15*(logger_time + longitude/15 + EQ -12)	[degrees]	[eq. 12]
equation of time EQ	EQ = 0.0172 + 0.4281*cos(theta) - 7.3515*sin(theta) - 3.3495*cos(2*theta) - 9.3619*sin(2*theta)	[hours]	[eq. 13]

For leap years the values of the second last day of the year are simply repeated for the 31 December. Situations were the solar angle is smaller than 3 degrees are flagged as "non-sunshine".

The next sub-chapters explain the different methods used to derive sunshine hours from pyranometer readings; five of these methods are applied to the half-hour readings stored in the meteoLCD datalogger: Two use the daily averages computed from the meteoLCD readings.

2.2. The Oliviéri method (half-hour readings)

Jean Oliviéri, a now retired scientist working at the Centre de Radiométrie in Carpentras, France, has published an easy to use procedure for deriving sunshine duration from pyranometer readings. In a personal communication [8] he told the author that correlation calculations between sunshine duration and pyranometer readings have been made in France since 1920. The only conclusion were that these correlations were unusable on short periods (like a day), but could have some validity on longer time spans, like a month or a year.

Comparing the extraterrestrial irradiance G_0 on a horizontal plane, calculated for the same latitude and longitude as those of the pyranometer, to the pyranometer readings G gives the criterion for the existence of sunshine.

Here are the steps involved in Olivieri's method as used at meteoLCD; trigonometric arguments are in degrees.

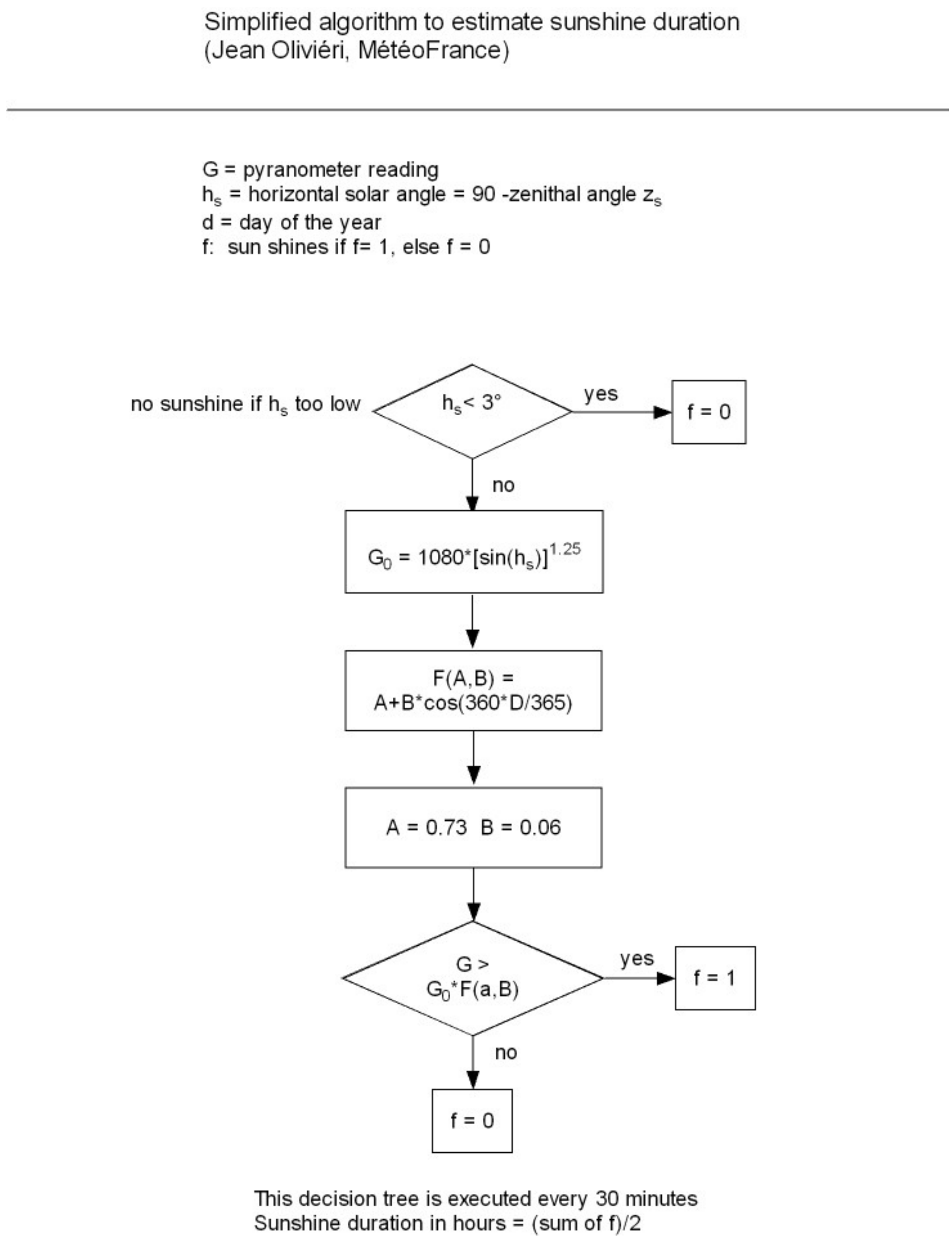

Fig.5. Flow chart of the Oliviéri algorithm

The factor F(A,B) = A+B*cos(360*d/365) where d is the day of the year (01Jan = 1) is based on the scaling factor to apply to the solar constant to obtain the extraterrestrial solar irradiation on a normal plane at day number d (eq.5). A and B are location and latitude dependent parameters. The values for France are A = 0.73, B = 0.06. These will also be used for Diekirch, located at about 60 km North of the French border.

This calculation should ideally be repeated every 10 minutes. At meteoLCD readings are made every minute, but only the 30-minutes average is kept in the data files. So the frequency of all model calculations will be 2 per hour.

2.3. The algorithm of Slob and Monna (half-hour readings)

W.H. Slob and W.A.A. Monna **[9]** from the KNMI published in 1991 a rather complex method to obtain the sunshine duration. This method relies, besides the usual parameters, also on the diffuse irradiance D on a horizontal surface and the Linke turbidity factor T_L. Figure.6 taken from the CIMO guide **[11]** reproduces this algorithm:

<table>
<tr><td>Sun elevation</td><td>sin (h) < 0.1, h < 5.7°</td><td colspan="2">0.1 ≤ sin (h) ≤ 0.3, 5.7° ≤ h ≤ 17.5°</td><td colspan="6">sin (h) ≥ 0.3, h ≥ 17.5°</td></tr>
<tr><td rowspan="7">Other criteria</td><td rowspan="7">No further decision criteria</td><td colspan="2" rowspan="3">Is $G/G_0 \leq \{0.2 + \sin(h)/3 + \exp(-T_L/(0.9 + 9.4 \sin(h))\}$ with $T_L = 6$?</td><td colspan="6">Is $G_{max}/G_0 < 0.4$?</td></tr>
<tr><td rowspan="6">If “yes”</td><td colspan="5">If “no”</td></tr>
<tr><td colspan="5">Is $G_{min}/G_0 > \{0.3 + \exp(-T_L/(0.9 + 9.4 \sin(h))\}$ with $T_L = 10$?</td></tr>
<tr><td rowspan="4">If “yes”</td><td rowspan="4">If “no”</td><td rowspan="4">If “yes”</td><td colspan="4">If “no”</td></tr>
<tr><td colspan="4">Is $G_{max}/G_0 > \{0.3 + \exp(-T_L/(0.9 + 9.4 \sin(h))\}$ and $G_{max}-G_{min} < 0.1\ G_0$ with $T_L = 10$?</td></tr>
<tr><td rowspan="2">If “yes”</td><td colspan="3">If “no”</td></tr>
<tr><td>$c < 0$</td><td>$0 \leq c \leq 1$</td><td>$c > 1$</td></tr>
<tr><td>Result</td><td>$f = 0$</td><td>$f = 0$</td><td>$f = 1$</td><td>$f = 0$</td><td>$f = 1$</td><td>$f = 1$</td><td>$f = 0$</td><td>$f = c$</td><td>$f = 1$</td></tr>
</table>

Fig.6 The Slop and Monna algorithm as given in the WMO CIMO guide ***[7]***

A serious problem with this algorithm is that D and T_L are unknown at many stations, including meteoLCD. Another problem is that S&M asks for 10 minute interval measurements with mandatory knowledge of minimum and maximum readings, conditions that do not apply at meteoLCD. So we will use in this paper a vastly simplified version, whose flowchart is shown in fig.7

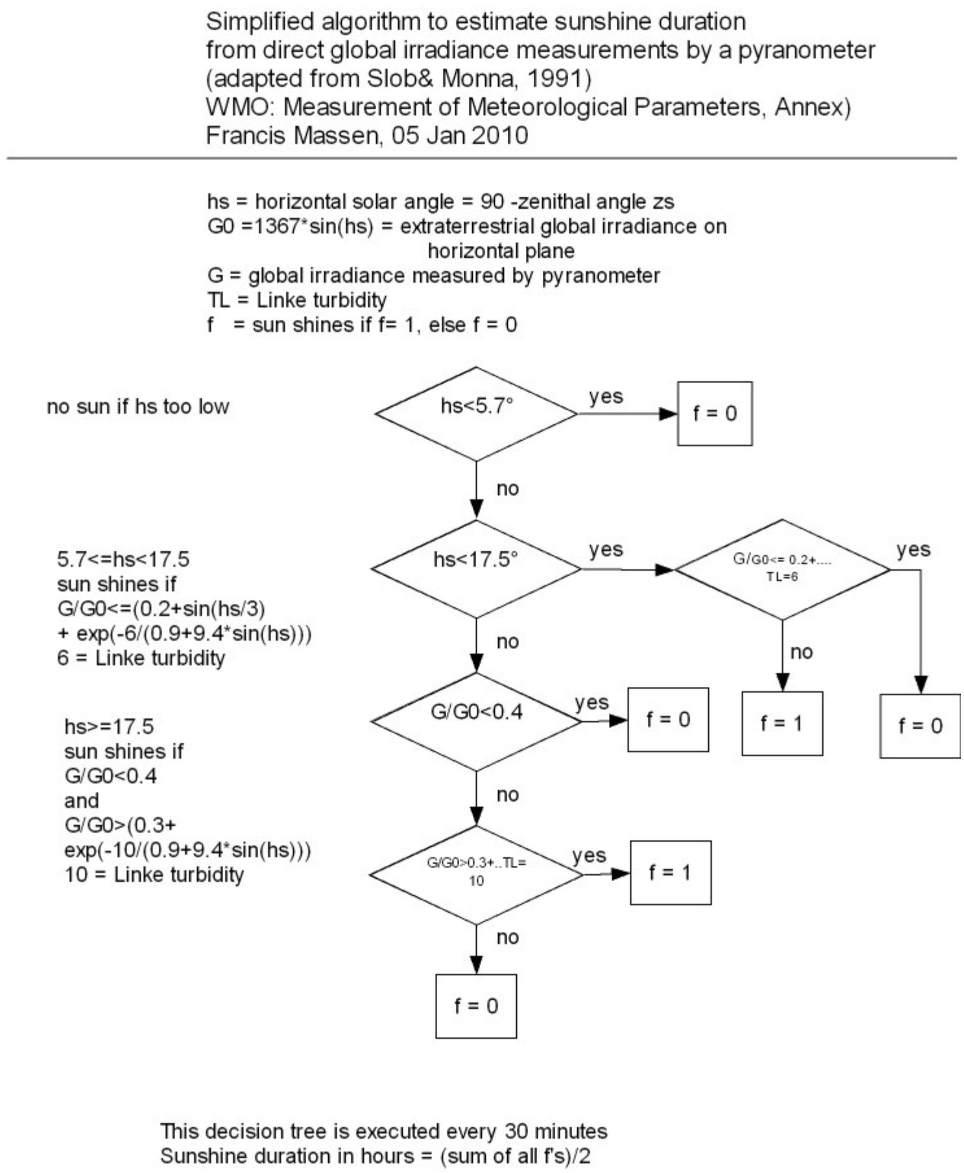

Fig. 7. Simplified S&M algorithm used in this paper.

Only three different solar elevation situations are retained:

- when elevation angle h_s is lower than 5.7°, the sun does not shine.
- when h_s is greater than 5.7° and smaller than 17.°, a turbidity factor of 6 will be assumed
- when h_s >= 17.5, T_L will be 10.

The diffuse radiation parameter **D** and the dependent parameter **c** of the original algorithm will be ignored, which reduces the number of decisions to be made.

2.4. The method of Hinssen and Knap (half-hour readings)

Yvonne B.L. Hinssen and Wouter H. Knap, also from the KNMI, published a paper **[10]** in 2006 where they compared simultaneous pyranometer and pyrheliometer readings made at the Cabauw Baseline Surface Radiation Network (BSRN) from March 2005 to February 2006.

Cabauw is located in the middle of the Netherlands, at latitude 51.97°N and a longitude 4.93°E. These coordinates are close to those of meteoLCD (49.52 N and 6.10 E). Their algorithm is a correlation algorithm, comparing the fraction G/G_0 to 4 different numbers which represent in fact lower and upper limits in the linear relationship between f and the fraction G/G_0. An important parameter is $u_0 = \cos(z_s)$; H&K make a distinction between the situation when u_0 <.0.3 (i.e. $z_s > 72.54°$ or $h_s < 17.46$ °) and when u_0 is equal or higher (h_s >=17.46°). Fig. 8 shows the H&K correlation algorithm as used in this paper. It should be noted that H&K use fractional sunshine hours, what the two preceding algorithms do not.

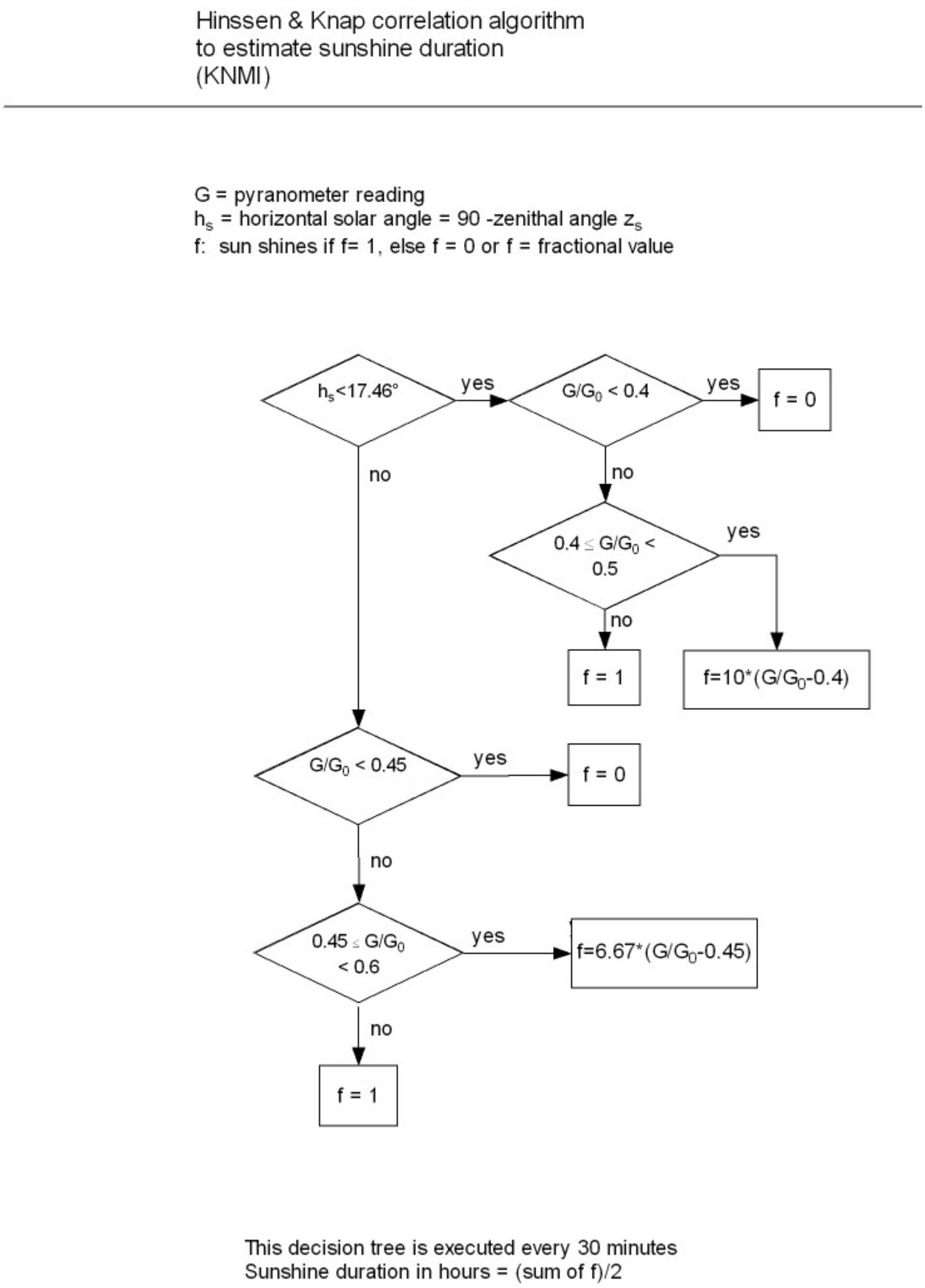

Fig. 8. The Hinssen-Knap correlation algorithm, with the numerical values given in [2]

The H&K method will be used as the "standard" to compare too; four arguments are in favor of this choice:

1. the parameters come from a station that is geographical close to Diekirch

2. the method is based on a comparison of simultaneous pyranometer and pyrheliometer readings

3. it is the most recently published method among the seven retained in this report.

4. the estimated uncertainty in sunshine duration (albeit for measurements done at 10 minutes interval) is known and given as 0.5 to 0.7 hours per day

2.5 The first method of Louche (half-hour readings)

Alain Louche is a professor of the physics department, University of Corsica Pasquale Paoli. The first "Louche" method, published in 1991 is given in **[16]**. Louche uses a 5 degree polynome to express the direct transmittance k_b = **I**/**I**$_0$ = (direct irradiance)/(solar constant) as a function of k_t = G/G$_0$. Knowing k_b, the direct irradiance **I** = k_b***I**$_0$. Now using the WMO definition, the sun shines if **I** > 120 Wm^{-2}.

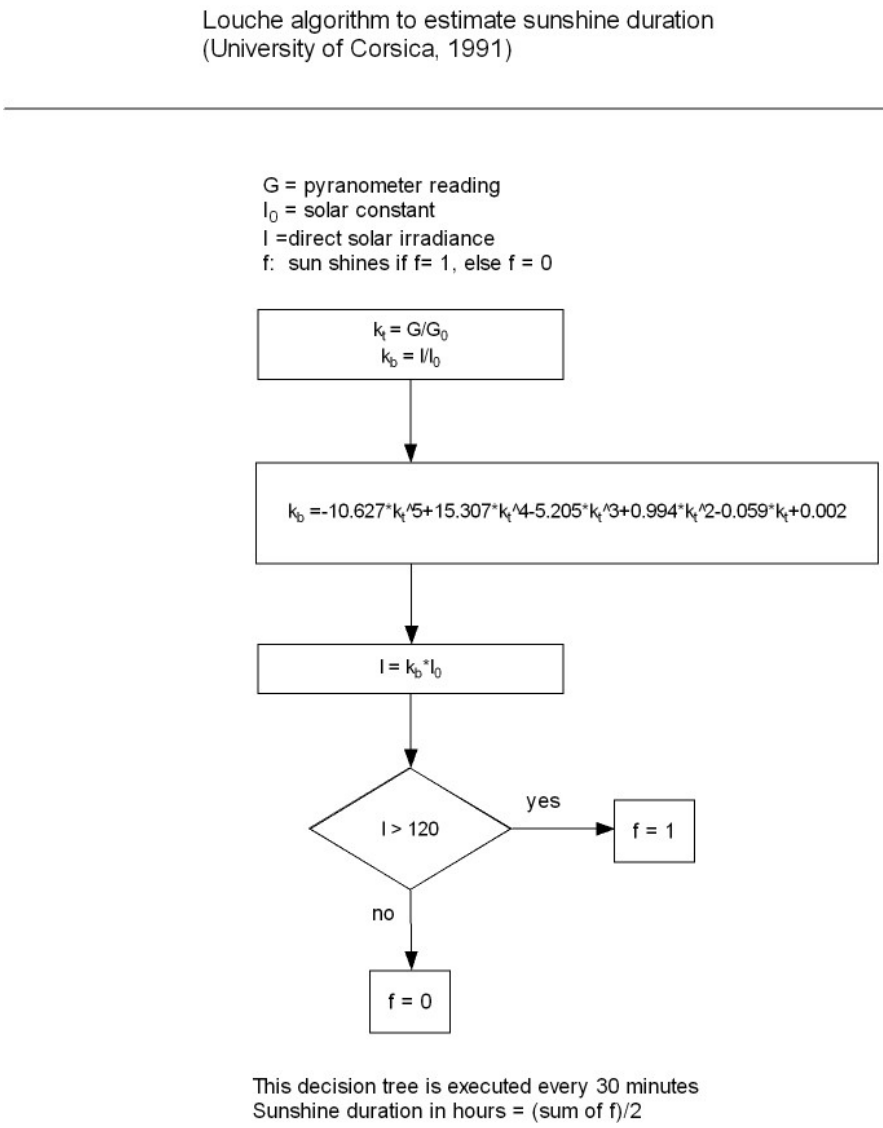

Fig.9: The Louche1 algorithm applied to half-hour pyranometer readings

It should be noted that the numerical coefficients in the expression of k_b were derived from readings made in Corsica, at a latitude close to 41°.

2.6. The method of Campbell Scientific (half-hour readings)

Campbell Scientific, manufacturer of environmental sensors and data-loggers, published a technical note no.18 in 1998 titled "Calculating sunshine hours from pyranometer/solarimeter data" **[20]**. Their method relies on the Slob & Monna paper **[9]** simplified to the extreme by defining that the sun shines if $\mathbf{G > 0.4*G_0}$. As $G = I_0*\sin(h_s)$, the main problem in applying this criterion lies in computing h_s. The Campbell technical note takes a slightly more complicated way for computing h_s, but in this paper the Olivieri method will be retained for all models needing h_s. This means the Campbell method applied here will give f = 0 (no sunshine) when $h_s < 3°$.

2.7. The method of Glover & McGulloch (daily averages)

The next two methods are explained in **[13]**. The Turkish author Kadir Bakirci summarizes a huge number of 66 models, many applying to measurement data made in Turkey. All these models derive from a modified Angström-Prescott relationship between global irradiance G_0 at ground level, extraterrestrial irradiance G on a horizontal plane, average daily hours of sunshine S and average day length S_0:

$$\mathbf{G/G_0 = a + b*S/S_0} \qquad \text{[eq. 14]}$$

In this paper calculations derived from eq.14 will be applied to daily averages, not to half hour readings as done for the previous models.

The Glover & McGulloch model **[17]** is said to be valid for latitudes < 60°, derives from UK measurements and so makes a good candidate for meteoLCD readings. The modified Angström-Prescott formula is augmented by a term containing the latitude::

$$\mathbf{G/G_0 = 0.29*\cos(latitude) + 0.52*S/S_0} \qquad \text{[eq. 15]}$$

From this expression, one can extract S = calculated daily sunshine duration.

$$\mathbf{S = (G/G_0 - 0.29*\cos(latitude))*(S_0/0.52)} \qquad \text{[eq. 16]}$$

The average length of the day S_0 can be computed using equations 2, 3 and 4:

$$\mathbf{S_0 = (2/15)*\cos^{-1}[-\tan(declination)*\tan(latitude)]} \qquad \text{[eq. 17]}$$

The flowchart in fig.10 summaries the Glover & McGulloch method.

2.8. The second method of Louche (daily averages)

The Louche parameters of the modified Angström-Prescott formula are given by Bakirci [13] as:

$G/G_0 = 0.206 + 0.546*S/S_0$ [eq. 18]

which yields a daily sunshine duration of

$S = (G/G_0 - 0.206)*(S_0/0.546)$ [eq.19]

The successive calculations are similar to those of fig. 10.

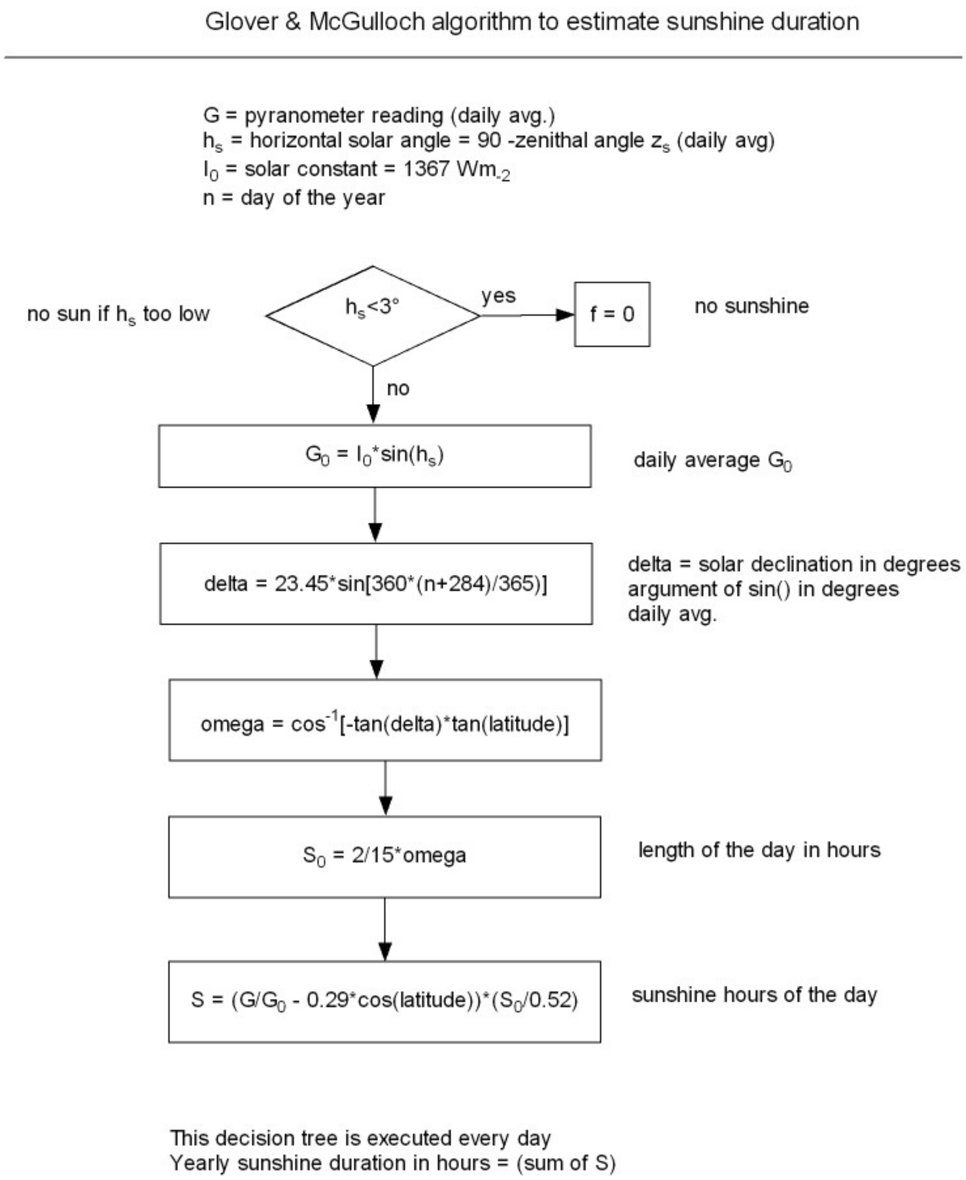

Fig.10. The algorithm of Glover & Mc.Gulloch

3. Sunshine duration data from Luxembourg

Besides the 11 year data series from meteoLCD, 3 other series will be used in this paper:

- the monthly sunshine duration data of the national meteorological station of the Findel airport (EELX, latitude 49.37N, longitude 6.13E, 376m asl), located ca. 27 km from meteoLCD. The Findel measurements are made with a Campbell-Stokes instrument.

- the 10 minute sunshine readings from the ASTA station of Echternach readings. ASTA is the "Administration des Services Techniques de l'Agriculture"; this administration operates a great number of meteorological stations in Luxembourg, but only a subset is equipped with pyranometers and/or sunshine duration sensors. The Echternach station is equipped, at least for the last 3 years with a CSD3 sensor. Prior to this a solarimeter from Haenni was probably used. Echternach is located in a valley, similar to Diekirch. Latitude = 49.817N, longitude = 6.417E, altitude 207m asl, distance from Diekirch ca.19 km.

- the 10 minute sunshine readings from the ASTA station of Luxembourg-Merl: latitude = 49.693N, longitude = 6.096, altitude = 275m asl, distance from Diekirch ca. 25 km. The sunshine sensors used are probably the same as those in Echternach.

It should be noted that the ASTA files have many missing or impossible data, and should be considered with great care. The Findel measurements seem complete and free of these problems.

Comparisons will be made for yearly totals and for the sub-periods June-July and September-October; these periods correspond to summer and pre-autumn climate; the latter period is chosen to distinguish possible different fog situations at Diekirch (and Echternach) which are located in a river valley, and Findel airport (and Luxembourg-Merl) situated on a plateau at a somewhat higher altitude.

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4. The 11 year data 2000 to 2010

4.1. The mean yearly sunshine hours given by the different methods over the period 2000-2010

The following table shows the mean sunshine hours and the standard deviations calculated over the period 2000 - 2011; all values are rounded to the nearest integer. The third column "applied on ... data" shows the frequency of the original data from which the sunshine hours have been computed. For meteoLCD these are the half-hour measurements, for the Glover and Louche2 algorithms the starting data are the daily means of the half-hour pyranometer readings. The Findel data are taken from the monthly reports of that meteorological station. The 2 ASTA stations Echternach and Luxembourg-Merl publish online available data at 10 minutes intervals (registration required). From these the monthly totals of sunshine hours have been calculated.

Station	Algorithm or instrument	applied on... data	mean yearly sunshine hours	standard deviation	number of valid data years	% deviation w.r. to Hinssen-Knap
meteoLCD	Oliviéri	half-hour readings	1655	185	11	+0.8
	Slop simplified	half-hour readings	1859	231	11	+13.2
	Hinssen & Knap	**half-hour readings**	**1642**	**201**	**11**	
	Louche 1	half-hour readings	1837	178	11	+11.9
	Campbell	half-hour readings	1840	179	11	+12.1
	Glover	daily totals	1986	208	11	+21.0
	Louche 2	daily totals	1763	193	11	+7.4
Findel	Campbell-Stokes recorder	monthly totals	1813	185	11	+10.4
Echternach	Haenni and CSD3 recorder	10 minutes readings	1482	177	9	-9.7
Luxembourg-Merl	Haenni and CSD3 recorder	10 minutes readings	1584	173	9	-3.5

The Echternach and Luxembourg - Merl data are obviously very suspicious, and should probably be discarded; they are included in this paper only as indicative The methods that give results closest to the "standard" of Hinssen-Knap are the Olivieri and Louche2 algorithms; one should remember that Louche2 is based on a modified Angstrom - Prescott formula.

Clearly the simplified Slop method delivers values that are much too high, as does the Louche1 method which was probably parameterized to yield values close to the readings that a Campbell-Stokes instrument would have given in Corsica, located at an approx. 9° more southern latitude as Diekirch.

The higher Findel readings seem to confirm the usual critique that the Campbell-Stokes instrument overestimates sunshine hours.

A good criterion to validate the different models would be that the best methods should be those that are closest to HK for the heat-wave year 2003 with its record breaking sunshine hours.

year	method	sunshine hours	% deviation w.r. to Hinssen-Knap
2003	**Oliviéri**	**2138**	**-1.0**
	Slob simplified	2445	+13.2
	Hinssen - Knap	**2160**	
	Louche 1	2278	+5.5

Campbell	2284	+5.7
Glover	2507	+16.1
Louche 2	2252	+4.3
Findel Campbell-Stokes	2278	+5.5
Echternach Haenni, CSD3	1811	-16.2
Merl Haenni, CSD3	1980	-8.3

As in the previous test, the Oliviéri method again compares best.

Figure 11 on next page shows the time-series for the 11 years, for clarity reasons, 3 different methods are each time compared to Hinssen - Knap (H&K). Clearly the Oliviéri method gives results that every year are very close to the H&K calculated totals.

The following table shows the signed differences, rounded to the nearest integer, with respect to H&K yearly totals obtained from the 6 other methods and the Findel station. Sqrt(SSD) = (square-root of the sum of squared differences)/11.
Oliviéri's method beats all others by a wide margin.

	Oliviéri	**Slob**	**Louche1**	**Campbell**	**Glover**	**Louche2**	**Findel**	**H&K total**
2000	+29	+171	+202	+207	+421	+211	+244	1400
2001	+47	+279	+258	+260	+489	+258	+113	1607
2002	+19	+169	+201	+203	+372	+155	+185	1505
2003	-23	+284	+118	+124	+347	+92	+118	2160
2004	+18	+216	+224	+226	+399	+170	+119	1631
2005	+1	+251	+217	+219	+361	+125	+161	1743
2006	-35	+198	+142	+145	+268	+43	+94	1717
2007	-19	+212	+183	+183	+297	+75	+209	1678
2008	+8	+214	+217	+222	+293	+85	+118	1473
2009	+16	+237	+220	+222	+294	+77	+291	1589
2010	+77	+160	+168	+170	+246	+39	+226	1560
average	**+13**	**+217**	**+195**	**+198**	**+344**	**+121**	**+171**	**1642**
sqrt(SSD)	**10**	**67**	**60**	**61**	**106**	**42**	**55**	

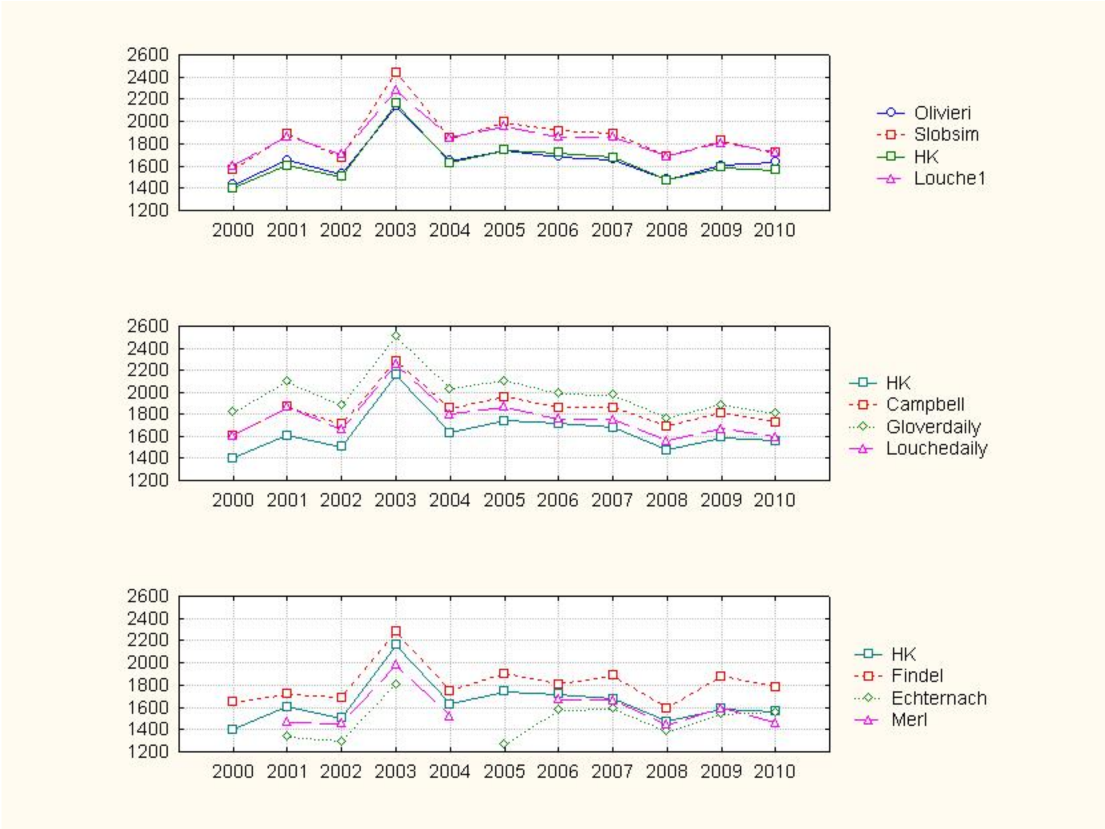

Fig.11. Time series of yearly sunshine hours given by 3 different methods and the Hinssen-Knap (HK) algorithm. The first two graphs apply to the pyranometer measurements made at meteoLCD, Diekirch, Luxembourg. The last graph compares HK to the recorder readings made at Findel, Echternach and (Luxembourg-) Merl by different instruments: Findel = Campbell-Stokes, Echternach and Merl = Haenni solarimeter and Kip & Zonen CDS3:

Fig.12 shows the linear relationship between the sunshine duration hours given by the Hinssen & Knap (HK) and Olivieri's methods: if HK is considered as the "standard", the Olivieri totals should be multiplied by 0.9934 to correspond to HK; for all practical reasons this means that both methods give very close results and both can be considered valid tools.

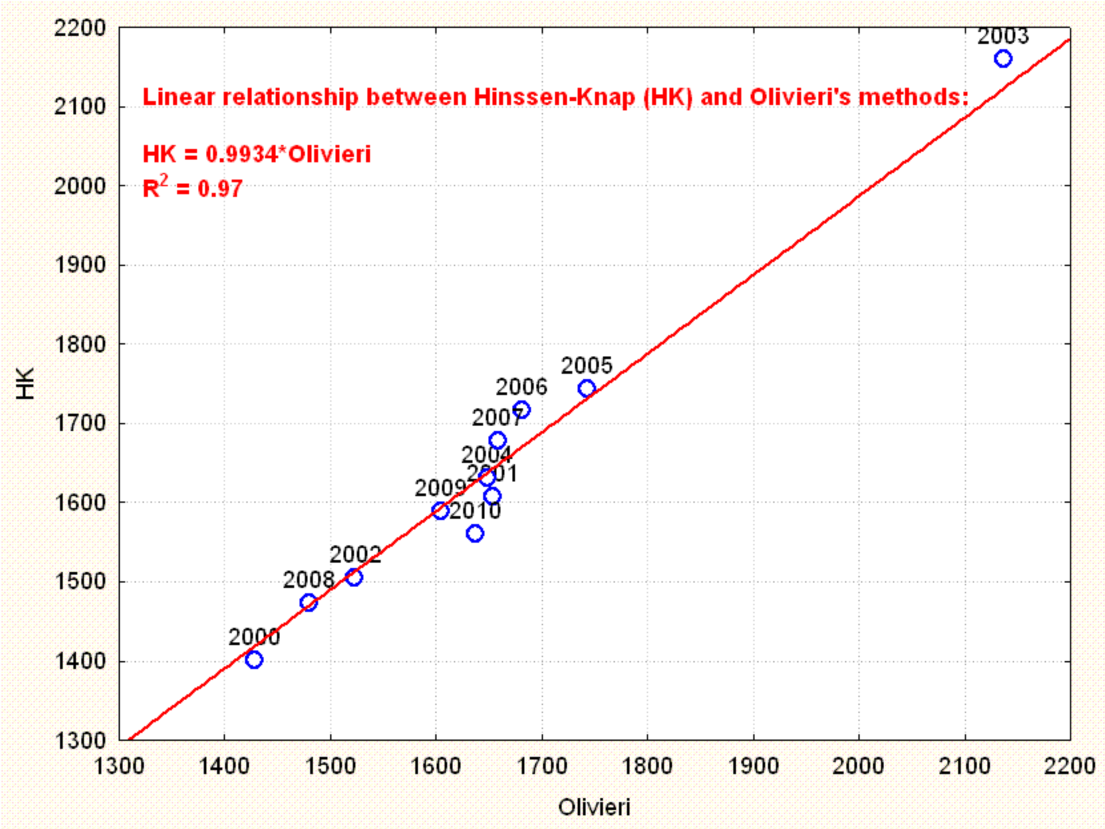

Fig.12. Sunshine hours at meteoLCD computed by the HK method versus those given by Olivieri's algorithm. Excellent linear correlation, with R^2 = 0.97 (linear function explains 97 percent of variation between both methods)

4.3. Does the good concordance between HK and Oliviéri exist also for daily totals?

In his personal communication, Jean Oliviéri warned in using his (or other) pyranometer readings for short time periods: good results will be obtained only on periods of one year or longer. The year 2005 gave nearly identical sunshine totals for both methods: Olivieri = 1744, HK = 1743. Fig.13 shows the daily differences between Olivieri's and HK methods for this year.

Even if most of the time (~82%) the difference in daily sunshine duration is smaller than 1 hour, there remain about 18% of occurrences where it is higher. The biggest "error" which could have been made is about 3.5 hours. The same result of greater variability is given by the square-root of the SSD, which can be compared to that in the table of the yearly totals:

sqrt(SSD) for 2005 daily totals = 15 (rounded)
sqrt(SSD) per year from yearly totals = 10 (rounded)

If 30 days are grouped into **one month** (ignoring the missing 5 days), the greatest difference is 8 hours, which would amount to 8/30 ~0.27 hours per day, considerable less than the 3.5 hours found above.. So the warning of J. Oliviéri should be kept in mind. In no circumstances should one use either HK or Oliviéri's methods on periods smaller than a month; applying them to yearly totals seems to be a good compromise between variability and acceptable length of time period.

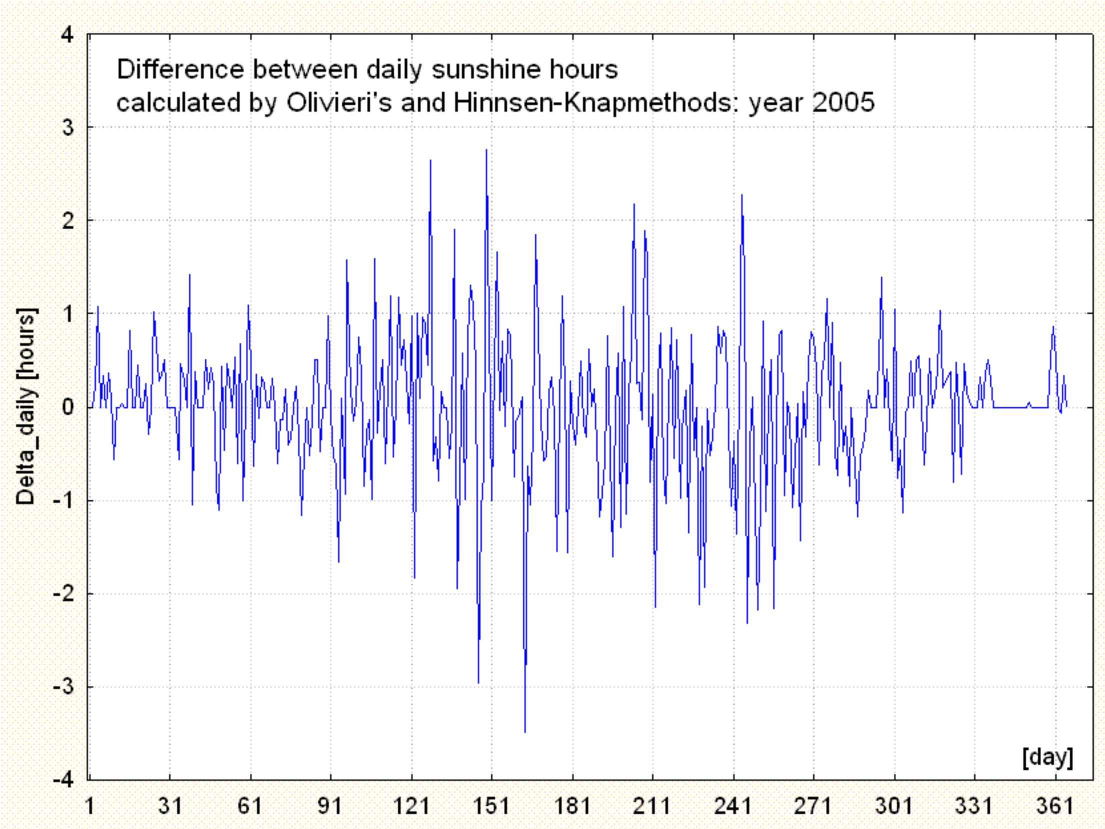

Fig.13. Differences in year 2005 between daily sunshine hours calculated by Olivieri's and Hinssen-Knap methods. Delta = Olivieri - HK

4.3. Comparing summer and fall results.

It is interesting to compare the sunshine totals separately for the 2 approximate summer months June-July and the autumn months September-October. As the meteoLCD station is located at the bottom of a river valley and the Findel airport at a plateau of an altitude about 150m higher, could the greater Findel totals result from clearer sky and less foggy days?

The next table gives the 2000-2010 mean of sunshine hours of these two periods:

station and method	total for June-July	% difference w.r. to HK	total for September-October	% difference w.r. to HK
meteoLCD Oliviéri	475	-2.5	257	-5.5
meteoLCD Hinssen-Knap	487		272	
Findel Campbell-Stokes	513	+5.3	288	+5.9

The overall sky situation in Diekirch and Findel certainly is more similar during the summer months, and could possibly be different during the foggier pre-autumn periods. The small differences between the Findel percentages in columns 3 and 5 suggest that this seems not to be the case. Confirming this conclusion is the relatively closeness of the differences of

Oliviéri and Findel results for the two periods (-38 and -31 hours). Thus the overall higher Campbell-Stokes readings at the Findel airport station are probably not the exclusive result of a locally sunnier sky, but include for a good part the fingerprint of the well known overestimation inherent to the Campbell-Stokes sunshine recorder.

5. Conclusions

In this paper 7 different methods were used to obtain sunshine duration from the pyranometer readings of the meteoLCD weather station in Diekirch, Luxembourg. The most recent method of Hinssen & Knap (HK) was taken as a reference. Oliviéri's method (which is the method used at meteoLCD) was found to give sunshine totals closest to this reference: the global total over 11 years data, the totals calculated year by year as well as the total sunshine hours of the extreme heat-wave year 2003 do not deviate by much more than **±1%** from the H&K computed results. A "calibration" factor very close to 1 was found to transform the Olivieri result into the corresponding HK. The second best contender is the model of Louche2 applied to daily averages with a maximal deviation of +7.4%. All other models give results over the 11 years period different by more than 10%.

The Campbell-Stokes measurements done at the Findel airport suggest a systematic over-estimation of sunshine hours by possibly up to +10% over the 11 years period.

The very easy to apply Oliviéri method can thus be recommended as an alternative to the Hinssen-Knap algorithm for meteorological stations located not too far away from the Netherlands. It seems also to be a good choice to compute sunshine duration if an electronic sunshine recorder like the CSD3 is unavailable, noting that this instrument's accuracy over monthly totals may not exceed 90%.

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