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# On the Use of the Coefficient of Variation to measure Spatial and Temporal correlation of Global Solar Radiation

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## 25 **1.Introduction**

26

### 27 **1.1 Context**

28 Because of clouds, solar radiation is a fluctuating data especially under tropical climate. Indeed,  
29 rapid changes in the local meteorological condition as observed in tropical climate can provoke large  
30 variation of solar radiation. The amplitude of these variations can reach up to  $700 \text{ W/m}^2$ . Moreover,  
31 these solar radiation variations can occur within short time interval (from few seconds to few  
32 minutes), depending on the clouds size, speed and number. The typical time scales associated with  
33 these solar radiation variations also vary significantly with the geographical location.

34 Studies of solar energy systems are traditionally performed using daily or hourly data [1] [2]. These  
35 data do not take into account the fluctuations mentioned previously. It has been shown that the  
36 fractional time distribution for instantaneous radiation differs significantly from that obtained with  
37 daily values.

38 Since solar energy systems are sensitive to instantaneous radiation fluctuations, simulations of  
39 these systems with daily or hourly data can lead to significant error especially under tropical climate.  
40 Indeed rapid variation of solar energy induces rapid and large variation of the output of such  
41 systems. For example solar cells (photovoltaics), used for electrical production, have very short  
42 response time and their electrical output will follow almost instantaneously the variations of solar  
43 radiation.

44 With a high density of photovoltaics generation in a power distribution grid, rapid fluctuations of  
45 the produced electrical power can lead to unpredictable variations of node voltage and power. In  
46 small grids as they exist on islands (such a Guadeloupe, FWI) such fluctuations can cause instabilities  
47 in case of intermediate power shortages with insufficient back-up capacity available. To manage the  
48 electrical network and the alternative power sources requires a better identification of these small

49 time scales variations. This stresses the need for power system operators to develop real time  
50 estimation tools for such disturbances.

51 Over the last years, some work were dedicated in establishing correlation between sites as a  
52 function of distance [3] and in parameterization of short term irradiance variability [4]. There has  
53 been resurgent interest in modeling and quantifying sub-hourly variability using different methods  
54 and metrics. In [4] the authors uses and frequency analysis based on spectral and coherence  
55 functions. This study showed high correlation for time scale greater than 3 hours :24h, 12h , 6h and  
56 4h which are the main component in the irradiance signal.

57 Other studies have quantified the solar radiation variability with a prediction goal. Methods such as  
58 wavelets [6], fractal parameters [7], [8] or hybrid models [9] were used for a given site.

59 The Marquez formula [10] is also used to measure the variability, it is defined with the variation of  
60 the clear sky index CSI,  $diff = CSI(t) - CSI(t - 1)$  and  $V = \sqrt{mean(diff^2)}$ .

61 An extension of this metric (called P) proposed by Perez et al. [5] is based on the dispersion of the  
62 quantity  $diff P = std(diff)$ . Four metrics are used to characterize intra-hourly variability, including  
63 the standard deviation of the global irradiance clear sky index, and the mean index change from one  
64 time interval to the next, as well as the maximum and standard deviation of the latter. Different  
65 time scales are studied from 20 seconds to 15 minutes.

66 In the present work we compare and analyze the statistical moments of the solar radiation  
67 parameters measured at two sites in the Guadeloupean archipelago with a time step of one second.  
68 We have established a correlation model for the coefficient of variation defined over a ten minutes  
69 period.

70 The paper is organized as follow: the theoretical frame is exposed in section 2,

71 This model can be useful in choosing new sites of production not only for establishing correlation  
72 from on site to another, but also in optimizing the geographical distribution of the solar farms within  
73 the territory to favor a smoothing of the overall available solar electricity production. Indeed this  
74 choice should be done not only on the basis of the annual potentiality of a site but also from the  
75 stability of its production.

## 76 **1.2 Methodology**

77 In the present work, we compare and analyze the solar global radiation signals  $G_1$ ,  $G_2$ , measured at  
78 two sites in the Guadeloupean Archipelago. This study put in evidence the existence of a dynamical  
79 correlation between  $G_1$  and  $G_2$ . To do so, we calculate for each signal, the global solar radiation  
80 fluctuation  $G'_{[T_1; T_2]}$  for time scales  $T= 10$  min, 20 min, 30 min, ..., 3 hours. The cross-correlation  
81 coefficient  $C_{G_1 G_2}$  is used for each time scale  $T$ . From this result, we determine the time scale  
82 threshold  $T_{trs}$ : for  $T < T_{trs}$ , the two signals are decorrelated and for  $T > T_{trs}$ , the two signals are  
83 correlated. To evaluate the scattering effect of two sites, we determine the coefficient of variation  
84 for the sum signal  $G_{1+2}$ .

85 Finally we propose, analytical relationship of coefficient of variation  $I_{1+2}$  for two cases i) two signals  
86 statistically independent with different momentum, ii) two signals correlated with different  
87 momentum.

## 88 **2.Theoretical frame**

### 89 **2.1 Decomposition of solar radiation signal using moving average filter**

90 The moving average of the instantaneous solar radiation  $G$ , at a given instant  $t$  for a given averaging  
91 time  $T$ , is defined as(Papoulis):

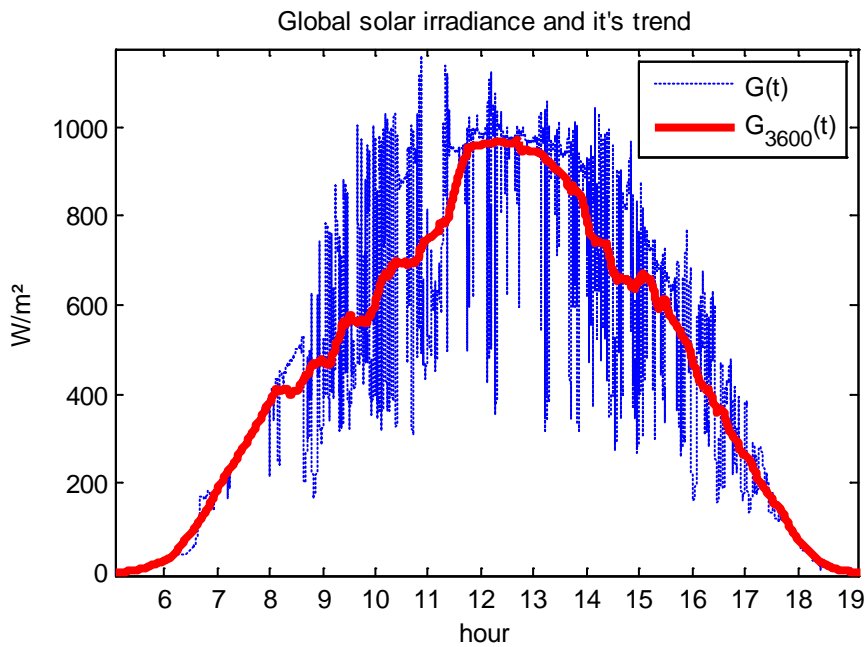
$$92 \quad \overline{G}_T(t) = \frac{1}{N} \sum_{i=t-\frac{T-1}{2}}^{i=t+\frac{T+1}{2}} G(i) \quad (1)$$

93 The instantaneous solar radiation  $G$  can then be expressed as (ref):

94 
$$G(t) = \overline{G_T}(t) + G'_T(t) \quad (2)$$

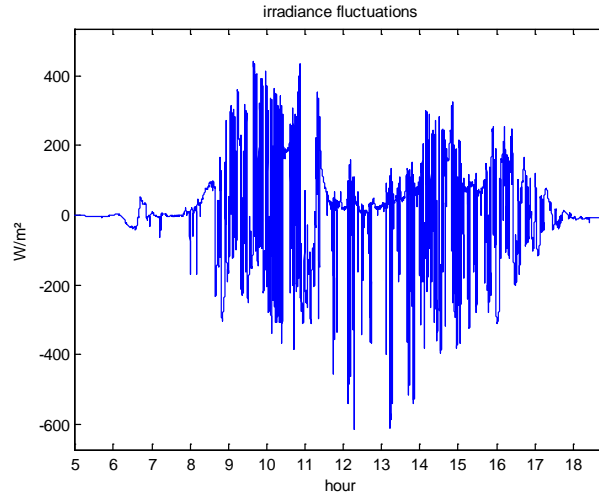
95 Where  $G'_T(t)$  is the solar radiation fluctuation for time scales smaller than  $T$  while the moving  
96 average  $\overline{G_T}(t)$  gives the solar radiation evolution for time scales larger than  $T$ . This decomposition  
97 is illustrated in figure (1), where  $\overline{G_T}(t)$  is superimposed to  $G(t)$  for a measurement duration of one  
98 day and for  $T = 3600s$ . Figure (1.a) illustrates the fluctuations obtained from equation (2).

99



100

101 Figure1: An example of instantaneous solar radiation signal (red line) and it's trend (black line).



102

103 Figure 1a: global solar radiation fluctuations obtained from moving average decomposition

104

105 Besides, the difference between two moving average having respectively averaging time  $T_1$  and  $T_2$ ,  
 106 gives the fluctuation for time scales ranging on  $[T_1, T_2]$ :

107 
$$G'_{T_1-T_2}(t) = \overline{G_{T_1}}(t) - \overline{G_{T_2}}(t) \quad (3)$$

108

109 **2.2 Coefficient of variation defined for two sites.**

110 In this study we consider solar radiation signal of 10 min length defined arbitrary. Let consider  $G_1 \left\{ \begin{matrix} \overline{G}_1 \\ \sigma_1 \end{matrix} \right.$   
 111 and  $G_2 \left\{ \begin{matrix} \overline{G}_2 \\ \sigma_2 \end{matrix} \right.$  two signals measured at site 1 and 2 respectively. We can define, for each  $G_1$  and  $G_2$ ,  
 112 from the two momentums  $\overline{G}$  and  $\sigma$ , the coefficient of variation, a normalized measurement of  
 113 dispersion of a probability distribution as:

114 
$$I = \frac{\sigma}{\overline{G}}$$

115

116 This parameter is a second order statistic moment measuring the degree of variability of a given  
 117 process. In the turbulence and the wind energy communities, it's called turbulence intensity and is  
 118 classically used. Turbulence intensity is a metric characterizing turbulence expressed as a percent.  
 119 For an illustration, an idealized flow of air with absolutely no fluctuations in air speed would have  
 120 a turbulence intensity value of 0%. This idealized cases never occurs on earth. However, the values  
 121 greater than 100% are possible. This can happen, for example, when the average air speed is small  
 122 and there are large fluctuations present. The higher the coefficient is, the more turbulent the flow.  
 123 This parameter is computed for the first time with global solar radiation data. This could be an  
 124 interest for the solar energy community. It could be a simple way in order to qualify and classify the  
 125 variability level of sites.

126

127 Let consider the sum  $G_{1+2}$  is defined by  $G_{1+2} \begin{cases} \bar{G}_{1+2} \\ \sigma_{1+2} \end{cases}$  with  $G_{1+2} = G_1 + G_2$  and  $\bar{G}_{1+2} = \bar{G}_1 + \bar{G}_2$

128 Let us define  $\sigma_{1+2}$ . By definition of standard deviation

129 
$$\sigma_G = \sqrt{(G - \bar{G})^2}$$

130 thus,

131 
$$\sigma_{1+2} = \sqrt{(G_1 + G_2)^2 + (\bar{G}_1 + \bar{G}_2)^2 - 2(G_1 + G_2)(\bar{G}_1 + \bar{G}_2)}$$

132 This equation becomes

133 
$$\sigma_{1+2} = \sqrt{G_1^2 + G_2^2 + 2\bar{G}_1\bar{G}_2 + \bar{G}_1^2 + \bar{G}_2^2 + 2\bar{G}_1\bar{G}_1 - 2\bar{G}_1\bar{G}_2 - 2\bar{G}_2\bar{G}_1 - 2\bar{G}_2\bar{G}_2}$$

134 A) Assuming that  $G_1$  and  $G_2$  are statistically independent and have same moment order:



135 We have

$$136 \quad \overline{G_1 G_2} = \overline{G_1} \overline{G_2}$$

137 And

$$138 \quad \overline{G_1} = \overline{G_2}$$

139 With this assumption equation (2) becomes:

$$140 \quad \sigma_{1+2} = \sqrt{2(\overline{G_1^2} - \overline{G_1}^2)}$$

141 Hence we can define the coefficient of variation of  $G_{1+2}$  as:

$$142 \quad I_{1+2} = \frac{\sigma_{1+2}}{\overline{G_{1+2}}} = \frac{\sqrt{2(\overline{G_1^2} - \overline{G_1}^2)}}{2\overline{G_1}}$$

$$143 \quad I_{1+2} = \frac{1}{\sqrt{2}} \frac{\sigma_1}{\overline{G_1}} \quad (4)$$

144 This result can be extended to n independent signals having the same moments:

$$145 \quad I_n = \frac{\sqrt{(\sum_{i=1}^n \sigma_i^2)}}{\sum_{i=1}^n \overline{G_i}} \quad (5)$$

146

147 *B) Let us now consider  $G_1$  and  $G_2$  two signals statistically independent with different*  
148 *momentum.*

149 We can decompose each signal as  $G = \overline{G} + G'$

150 Where  $G'$  is the fluctuation in the signal around the mean value  $\overline{G}$ .

151 Thus the sum is

152  $G_{1+2} = \overline{G_1} + G_1' + \overline{G_2} + G_2'$

153  $G_{1+2} = \overline{G_1} + \overline{G_2} + G_1' + G_2'$

154  $G_{1+2} = \overline{G_{1+2}} + G_{1+2}'$

155 With

156  $\overline{G_{1+2}} = \overline{G_1} + \overline{G_2}$

157 and  $G_{1+2}' = G_1' + G_2'$

158 The standard deviation of  $G_{1+2}$  is

159 
$$\sigma_{1+2} = \sqrt{(G_{1+2} - \overline{G_{1+2}})^2}$$

160 Elsewhere  $\sigma_{1+2} = \sqrt{(G_1' + G_2')^2} = \sqrt{(G_1'^2 + 2G_1'G_2' + G_2'^2)}$

161

162 As the signals are considered statistically independent and decorrelated, we have

163 
$$\text{Corr}(G_1', G_2') = c = \frac{\overline{G_1'G_2'}}{\sigma_1\sigma_2} = 0$$

164 Where  $c$  is the normalized correlation coefficient

165 Thus  $\overline{G_1'G_2'} = 0$

166 And

167 
$$\sigma_{1+2} = \sqrt{(G_1'^2 + G_2'^2)} = \sqrt{(\sigma_1^2 + \sigma_2^2)}$$

168 And the variation coefficient is

169 
$$I_{1+2} = \frac{\sqrt{\sigma_1^2 + \sigma_2^2}}{\overline{G_1 + G_2}} \quad (6)$$

170 *C) Now let us consider two signals correlated with different momentum as*

171 
$$c = \frac{\sqrt{G_1' G_2'}}{\sigma_1 \sigma_2} \text{ and } \sigma_{1+2} = \sqrt{(G_1'^2 + 2G_1' G_2' + G_2'^2)}$$

172 
$$\sigma_{1+2} = \sqrt{\sigma_1^2 + 2(c \sigma_1 \sigma_2)^2 + \sigma_2^2}$$

173 As said previously  $c$  is the normalized correlation coefficient and the variation coefficient is

174 
$$I_{1+2} = \frac{\sqrt{\sigma_1^2 + 2(c \sigma_1 \sigma_2)^2 + \sigma_2^2}}{\overline{G_1 + G_2}} \quad (7)$$

175 Consequently, using the analytical relation given above, considering two signals  
 176 decorrelated,  $c=0$ , we found the analytical expression given in equation 6. Besides, if we  
 177 consider two signals correlated,  $c=1$ , the analytical relation given 7 becomes:

178 
$$I_{1+2} = \frac{\sqrt{\sigma_1^2 + 2(\sigma_1 \sigma_2)^2 + \sigma_2^2}}{\overline{G_1 + G_2}}$$

179 **3 Solar radiation measurements**

180 In this study, the solar radiation measurements sampled at 1hz were measured during one  
 181 year, from January 2006 to January 2007, at two different sites in Guadeloupe. The daily average  
 182 for the solar load on a horizontal surface is around 5 kWh/m<sup>2</sup>. A constant sunshine combined with  
 183 the thermal inertia of the ocean makes the air temperature variation quite weak, between 17°C and  
 184 33°C with an average of 25°C to 26°C. Relative humidity ranges from 70% to 80% and the trade  
 185 winds are relatively constant all along the year. Two main regimes of cloudiness are superposed:

186 the clouds driven by the synoptic conditions over the Atlantic Ocean and the orographic cloud layer  
 187 generated by the local reliefs.

## 188 4 Results

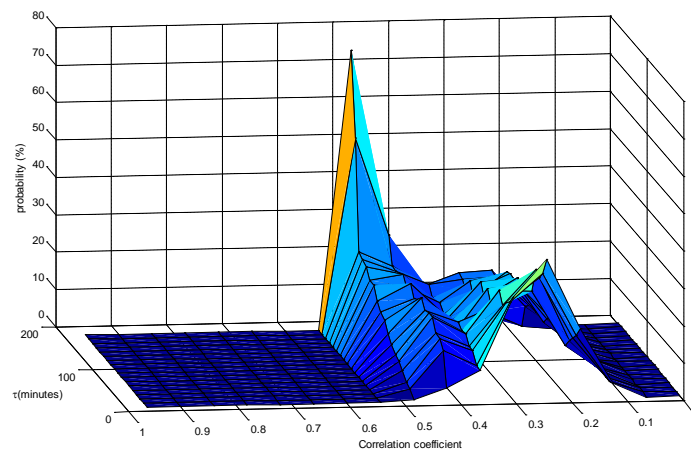
### 189 4.1 Time scale separation

190 To put in evidence an eventually dynamical correlation between the two sites, the cross-  
 191 correlation coefficient  $C_{G'_1 G'_2}$  is defined as [3]:

$$192 \quad R_{G'_1 G'_2}(\tau) = \begin{cases} \sum_{n=0}^{T-\tau-1} G'_{1n+\tau} G'_{2n} & \tau \geq 0, \\ R_{G'_1 G'_2}(-\tau) & \tau < 0 \end{cases}$$

$$193 \quad C_{G'_1 G'_2}(\tau) = \frac{R_{G'_1 G'_2}(\tau)}{\sigma_{G'_1} \sigma_{G'_2}}$$

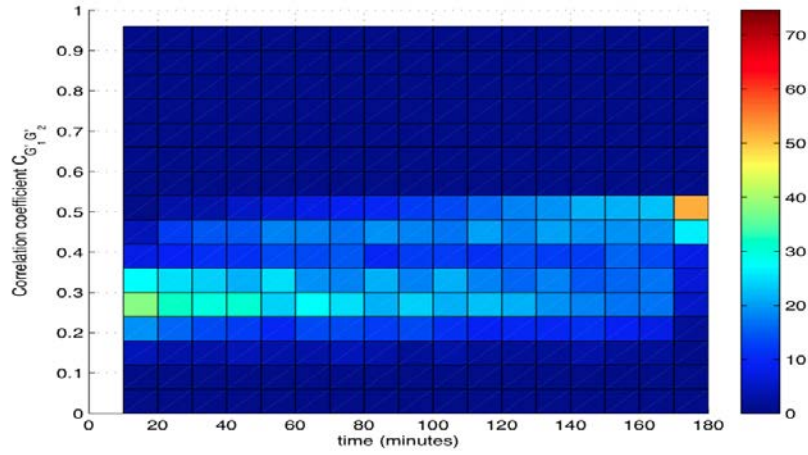
194 Where  $G'_1, G'_2$  are zero-mean stochastic variables,  $\sigma_{G'_1}$  and  $\sigma_{G'_2}$  are the corresponding  
 195 standard deviation . For each day we have calculated this coefficient  $C_{G'_1 G'_2}$  for different  
 196 time scales.



197

198

Figure 2: The conditional probability of the cross correlation.



199

200

Figure 3: percentage of correlation values for different  $\tau$

201

For the highlighting of a threshold time  $T_{trs}$  under which the fluctuations of two sites

202

are not correlated, we determine the correlation coefficient  $C_{G'_1, G'_2}(\tau)$  for the fluctuations

203

$G'_{T_1-T_2}(t)$  defined in equation 3, with  $T_1=10j$  minutes and  $T_2=T_1+10$  minutes, for  $j$  between

204

1 and 18. The figure illustrates the conditional probability  $P(C_{xy}|\Delta t)$ , with  $\Delta t = T_2 - T_1$ . We

205

observe that the maximum value of the probability increase 0.25 to 0.5 for time range

206

[10;170] minutes. We observe a significant correlation for time [160; 170] and  $C_{G'_1, G'_2} = 0,5$ .

207

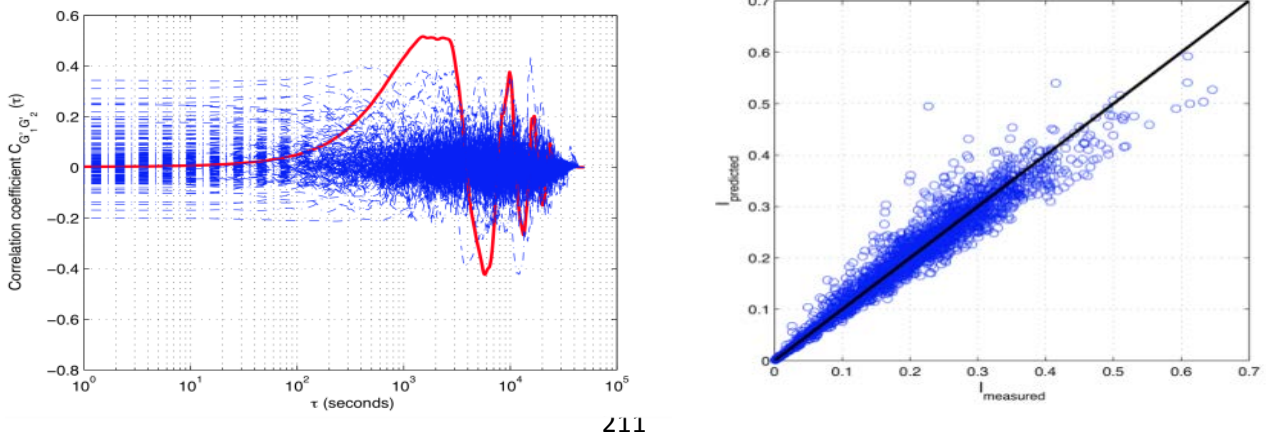
This correlation keeps increasing for higher time scale. Thus the threshold time is estimated

208

to be  $T_{trs} = 170 \text{ min}$ .

209

210 **4.2 Time scales for uncorrelated signals:  $T < T_{trs}$ .**

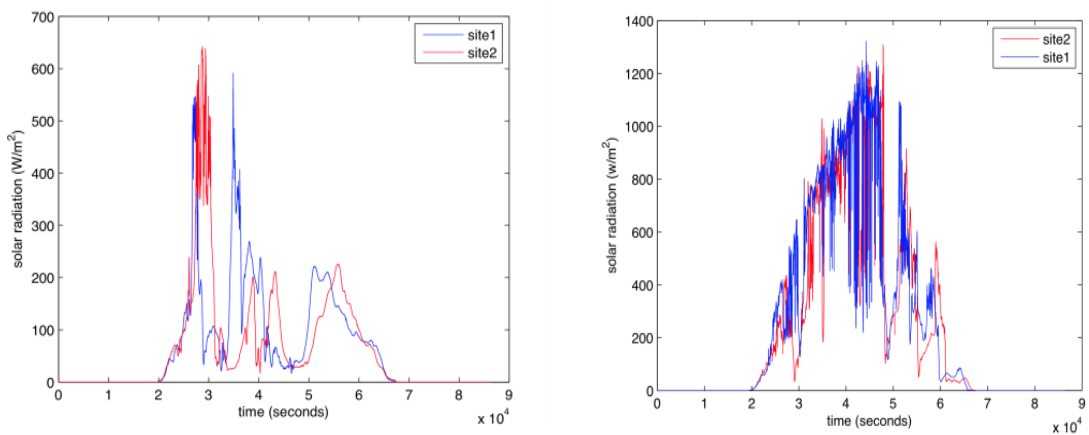


211

212 Figure 4: a (left) The cross correlation function in semi-log diagram. The red curve correspond to the cross  
 213 correlation for an example of a marginal event, and the blue curve represent the cross correlation for the  
 214 majority of the events. b(right) the predicted coefficient of variation versus the experimental coefficient of  
 215 variation.

216 In this section, the figure 3a presents the cross correlation coefficient of the two  
 217 sites, for time scales  $T < T_{trs}$ . In 97% of cases, the value of  $C_{G_1 G_2}(\tau)$  is smaller than 0,4. For  
 218 time going to [10; 50] minutes the maximum correlation coefficient is  $C_{G_1 G_2} = 0,25$ .

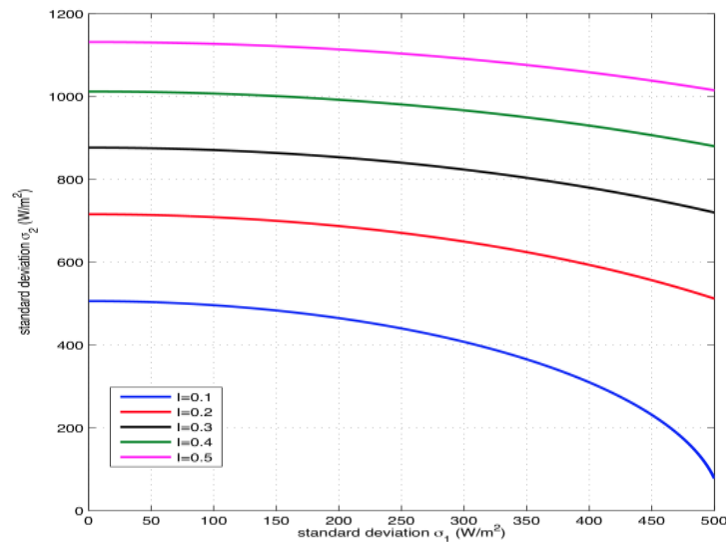
219 A weak value of the cross correlation coefficient for two measurement sites  
 220 indicates that the solar radiation fluctuations are statistically independent. This shows  
 221 that the fluctuations are not correlated on these time scales.



222 Figure 5: Examples of correlated marginal events for small time scales.

223 However, in 2% of cases we observe a dynamical correlation for  $C_{xy}$  values superior to 0,5.  
 224 These marginal events correspond to extreme meteorological situations (clear sky or cloudy  
 225 sky) as illustrated in figure 4.

226 Besides, for these time scales, in figure 3b, we have plotted the experimental coefficient  
 227 variation  $I_{1+2exp} = \frac{\sigma_{1+2}}{G_{1+2}}$  versus the analytical relationship given in equation 6,  $I_{1+2theo} =$   
 228  $\frac{\sqrt{\sigma_1^2 + \sigma_2^2}}{G_1 + G_2}$ . A good agreement is observed between the predicted coefficient variation and the  
 229 measured coefficient variation, confirming a non-synchronous variability of the two sites  
 230 for times scales  $T < T_{Trs}$ .



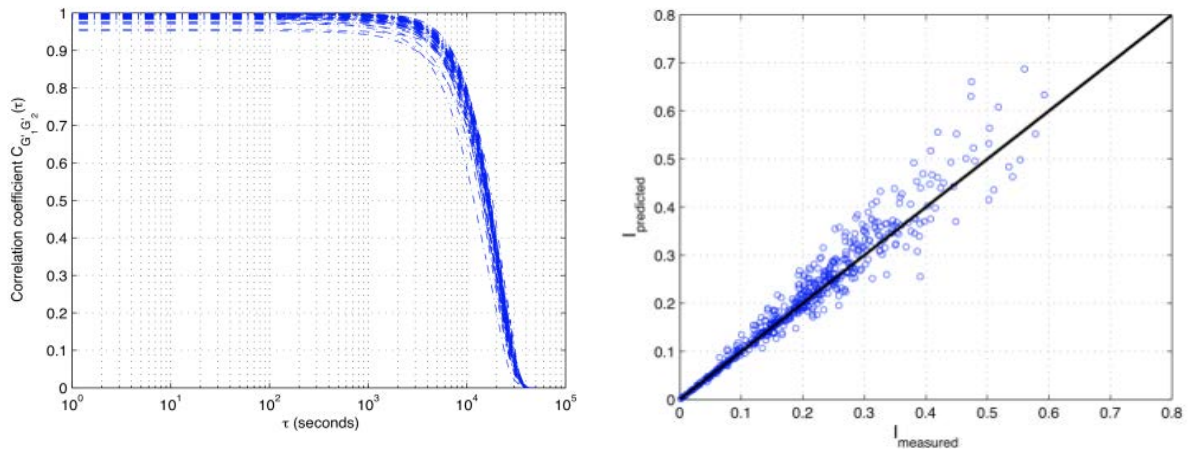
231

232 Figure 6: Diagram of the predicted coefficient of variation determined with the standard deviations of two  
 233 sites, uncorrelated cases.

234 Moreover, in figure 6, we give the evolution of the predicted coefficient variation versus  
 235 the given standard deviation  $\sigma_1$  and  $\sigma_2$ , respectively for a site 1 and site 2.

236

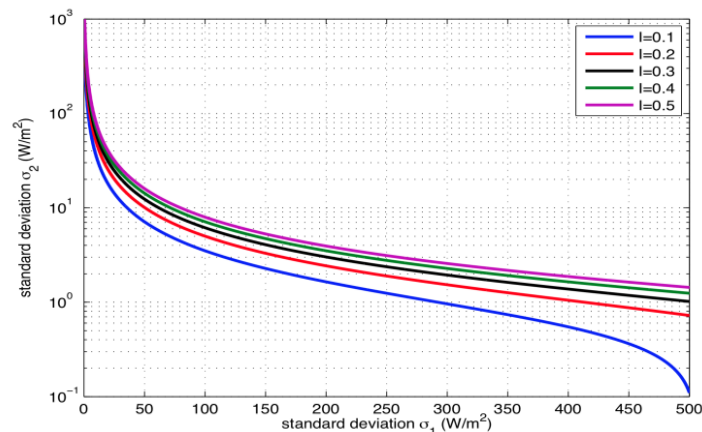
237 **4.3 Time scales for correlated signals:  $T > T_{trs}$**



238 Figure 7: a (left) the cross correlation coefficient in semi-log diagram. b(right) the predicted coefficient of  
 239 variation versus the experimental coefficient of variation.

240 The figure 7a displays the cross correlation of the two sites, for time scales  $T > T_{trs}$ . We can  
 241 observe that the cross correlation coefficients almost are close to 1 obtained for a time  
 242 delay equal to 0.

243 For these time scales, the characteristic length of the convective structure, in the  
 244 atmospheric sub- layer, is of the order of several hundreds of kilometers (ref); we recall that  
 245 the distance between the two sites is around to 40 kilometers.



246

247 Figure 8: Diagram of the predicted coefficient of variation determined with the standard deviations of two  
 248 sites, correlated cases.



249 For these time scales, we illustrated in figure 7b, the predicted coefficient of variation  
250  $I_{1+2\text{theo}}$  given in equation 7, is plotted versus the experimental coefficient of variation,  
251 indicating a good agreement between the predicted values and the measured values. The  
252 figure 8 presents the evolution of the predicted coefficient of variation versus the given  
253 standard deviation  $\sigma_1$  and  $\sigma_2$ , respectively for a site 1 and site 2.

## 254 **5. Discussions**

255 In this study, we attempt to quantify the variability and the coupling of the global solar  
256 radiation for two sites in Guadeloupe, through the coefficient of variation, on ten minutes  
257 interval. This coefficient is defined from the mean and standard deviation of solar irradiance  
258 over the considered interval.

259 We have established a model for the coefficient of variation assuming a time scale  
260 separation. Two cases can be distinguished according to the correlation of the first order  
261 moment (mean).

262 The analysis of the cross correlation coefficient put in evidence à threshold under which  
263 there is no significant correlations of the global solar radiation fluctuations. According to  
264 this assumption we have established a model for the coefficient of variation defined for a  
265 pair of site, each one being characterized by the first and second order momentums  $\bar{G}$  and  
266  $\sigma$ . This is given by the equation (6).

267 When the signal are significantly correlated, the coefficient of variation of a pair of site is  
268 given by equation (7).

269 Hence according to this model we can determine the coefficient of variation of a pair of site  
270 knowing the mean and standard deviation on one of the sites.

271 The model was tested on experimental data for both cases, correlated and non-correlated.  
272 In both cases the predicted values by the model are in good agreement with the calculated  
273 coefficient of variation.

274 For both cases a diagram is proposed to determine the coefficient of variation of a pair of  
275 site. This model can be useful to determine in a very simple and easy way the amount of  
276 energy and the associated fluctuations that may occur on a pair of site knowing the  
277 conditions on one site.

278 When considering the PV production on different sites, it becomes possible to estimate the  
279 smoothing effect of the sum knowing the PV power at one site.

280 This study cans also be helpful in choosing the best places for PV plants to take advantage  
281 of the smoothing effect due to the connection of different sites.

282

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