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ONE MINUTE K_T PROBABILITY DENSITY DISTRIBUTIONS CONDITIONED TO THE OPTICAL AIR MASS AND HOURLY K_T

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Abstract

Present needs in concentrating solar power systems require knowledge of the solar irradiation temporal evolution. Daily or hourly generation of irradiation synthetic series is normally used in the estimation of solar resource, as measured series of radiation are only available for a reduced number of locations. Notwithstanding, the flickering nature of instantaneous solar irradiance is lost in hourly series, and it has a considerable impact on the non-linear behaviour of solar energy conversion systems. The study of the statistical behaviour of short term values of solar irradiation will facilitate more precise one-minute synthetic generation of solar irradiation series, and consequently will facilitate more accurate estimations of concentrating solar power systems performance characterized by a fast and non-linear response to the incoming solar radiation.

In this work, the probability density function of one-minute values of clearness index k_t (solar global horizontal irradiance to extraterrestrial horizontal irradiance ratio) conditioned to the optical air mass m (relative thickness of the air path traversed by a sun's ray when it reaches the earth's surface) and hourly k_t in Carpentras (France) has been investigated. These distributions present a unimodal character, in contrast with bimodal character founded in distributions conditioned only to m . Probability density functions (PDFs) at k_t equal to 0.15 are almost independent of m , indicating a strong dependence of them on cloud conditions. Otherwise, PDFs at k_t equal to 0.75 decrease and widen with higher m values, indicating cloud-free conditions at $m = 1$ and transient situations under partial cloud cover at higher m values. PDFs at k_t equal to 0.3 and 0.45 show a mixed behavior between the last cases, presenting similar peaks and dispersion, and different dependence on m .

Keywords: optical air mass, global irradiation, clearness index, one minute, instantaneous solar irradiance, synthetic generation

1. Introduction

Long-term performances of concentrating solar power (CSP) systems predictions depend on availability of solar irradiation data. Hourly data (both measurements and estimations) of global horizontal irradiation (G_h), diffuse radiation, and direct normal irradiation (DNI) are normally available, being commonly used in these analyses. Unfortunately, hourly time-steps solar irradiation data throws out the intrahourly variability of solar irradiance (due to the effect of clouds intermittently hiding the sun and/or changes in the angular position of the sun).

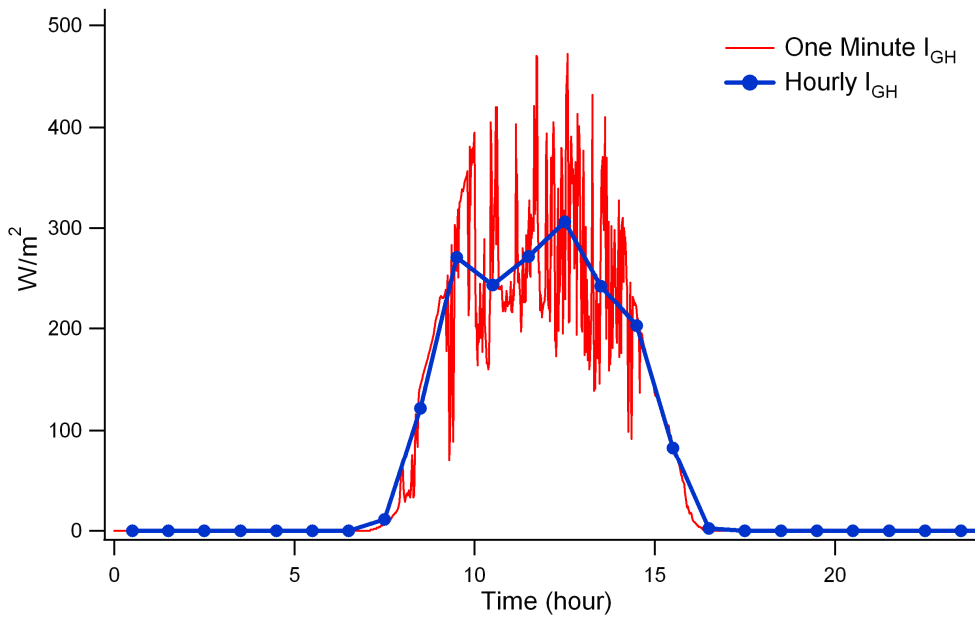


Fig. 1. One-minute and hourly global irradiation values.

When conducting performance analyses of CSP systems, the system response to changes in solar irradiance must be considered. The fluctuating nature of instantaneous solar irradiance has a significant impact on the non-linear behaviour of solar energy conversion systems [1], and could lead to inaccurate estimates of CSP systems performance characterized by a fast and non-linear response to the incoming solar radiation. Hourly solar irradiation data are appropriate only for systems that respond slowly or linearly to changes in solar irradiance [2]. The analysis of probability density function of one-minute values of clearness index k_t (solar global horizontal irradiance to extraterrestrial horizontal irradiance ratio) conditioned to the optical air mass m (relative thickness of the air path traversed by a sun's ray when it reaches the earth's surface) and hourly k_t will allow the ability to quantify the variability of short term solar irradiation data from commonly available hourly averages.

Several works have highlighted the importance of knowing intra-hourly solar irradiation variations ([1-5]). One-minute probability distribution functions of k_t has been investigated in [1] (conditioned to m), and in [5] (conditioned to hourly k_t average). It is worth to highlight here the work of Skartveit and Olseth ([7]), which introduced a stochastic model to reproduce the intra-hourly dynamics of global or beam irradiance.

In this work, the probability density distributions of one minute k_t values at a given location conditioned to m and hourly k_t are investigated. Furthermore, a probability density distribution model using the same type of functions that have been used in previous works ([5-6]) is proposed. This analysis will provide detailed information of k_t variability (at least in the location studied), and will allow a more accurate one minute synthetic generation.

2. Description of experimental data used

The one minute ground-based measurements of G_h used in this study are from the BSRN (Baseline surface radiation network) station of Carpentras (44° 03' N, 5° 02' E, 100 m a.m.s.l.). The measurements used in this work are from the time interval starting in January 2006, and finishing at the end of 2008, including in the order of $1.5 \cdot 10^6$ values of one minute G_h .

The data selected ensures the analysis of a complete range of both seasonal conditions and solar angles. To avoid errors derived from cosine response, data which solar altitude angle is less than 4° have been discarded.

3. Methodology

3.2 Quantities and functions analyzed

The solar global irradiance behaviour was studied by means of k_t . This variable is studied using the probability density function (PDF), given by

$$f(k_t) = \frac{\partial F(k_t)}{\partial k_t}$$

Being $F(k_t)$ the distribution function, which represents the probability that the event $k_t(t)$ (k_t at time t) is smaller than the given value k_t :

$$F(k_t, t) = P\{k_t(t) \leq k_t\}$$

The possible range of k_t (0-1) has been broken-down in 40 intervals of width 0.025.

To determine the best coefficients of the fitting function, we will minimize the value of Chi-square, χ^2 , defined as:

$$\chi^2 = \sum \left(\frac{y - y_i}{\Omega_i} \right)^2$$

Being y a fitted value for a given point, y_i the measured data value for the point and Ω_i an estimate of the standard deviation for y_i .

4. Results

4.1 Density probability distributions of one-minute k_t values conditioned to m

Fig. 2 shows one-minute k_t density probability distributions for the following values of m : 1 ± 0.1 , 1.5 ± 0.1 , 2 ± 0.2 , 2.5 ± 0.2 and 3 ± 0.25 .

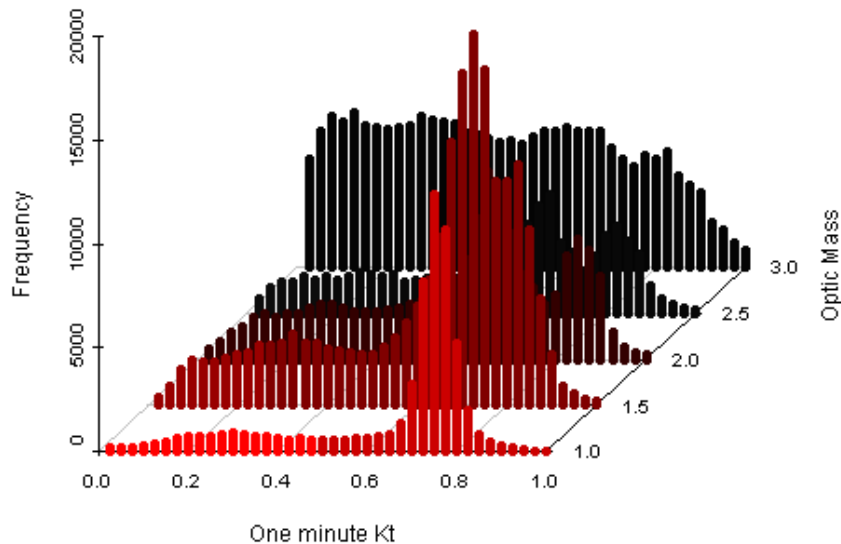


Fig. 2. One-minute k_t density probability distributions conditioned to m .

The study of probability density distributions of one-minute values of k_t , conditioned to m reveals an increasing bimodal character as a function of m . Experimental one-minute k_t probability density distributions conditioned to m has been modelled as the sum of two functions based on Boltzmann's statistics [6]:

$$f(k_t | m) = A_1 \frac{\lambda_1 \exp(k_t - k_{t01}) \lambda_1}{[1 + \exp(k_t - k_{t01}) \lambda_1]^2} + A_2 \frac{\lambda_2 \exp(k_t - k_{t02}) \lambda_2}{[1 + \exp(k_t - k_{t02}) \lambda_2]^2}$$

The bimodal character observed in this study is higher than the one presented in [6], and is lost at $m = 3$. Fitting parameters for probability density distributions of one-minute values of kt conditioned to m found in this study (obtained from data measured in Carpentras, south-eastern France) are different from those shown in [6] (obtained from data measured in Granada, south-eastern Spain). Fig. 3 shows probability density distribution of one-minute values of kt for $m = 1.5$ for data measured in Carpentras, as well as its corresponding fitting curve (red line). Fitting curve for one-minute values of kt for $m = 1.5$ measured in Granada (blue dash line) is also depicted (vertically scaled), showing marked differences between fitting distributions founded in data measured in Carpentras and Granada, as revealed by the fitting parameters (Table 1):

Fitting parameters for $m = 1.5$	Carpentras		Granada
	Value	S Dev	Value
A_1	7378.1	513	0.755
λ_1	17.526	1.52	45.14
Kt_{01}	0.69756	0.00691	0.713
A_2	3462	322	0.245
λ_2	7.1899	0.841	10.0
Kt_{02}	0.29646	0.0166	0.345

Table 1. Fitting parameters of one-minute kt values at $m = 1.5$, measured in Carpentras (France) and Granada (Spain)

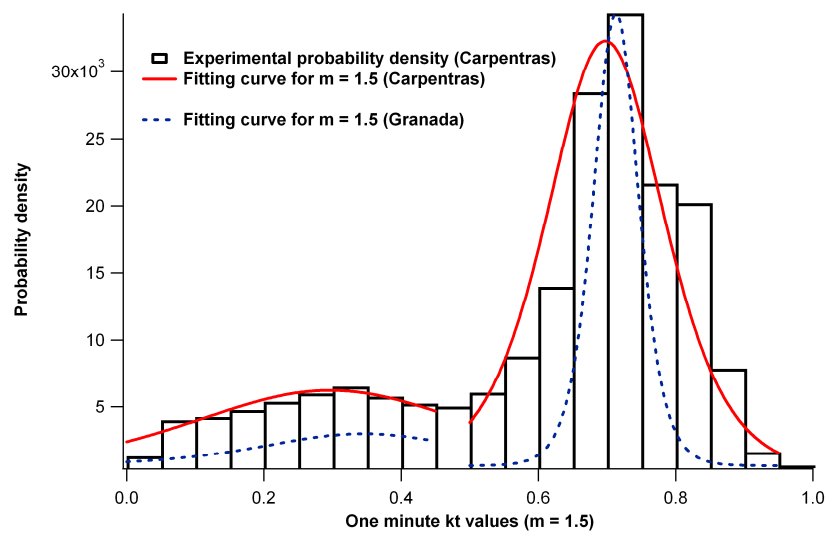


Fig. 3. One-minute kt probability density distribution ($m = 1.5$) for data measured in Carpentras (bars), corresponding fitting curve (red line) and fitting curve for the same distribution found in Granada (blue dashed line).

Assuming that bimodality feature is related to the existence of two levels of irradiation corresponding to two extreme atmospheric situations (cloudless and cloudy conditions), these results indicate a less extreme behaviour between these two levels in data measured in Carpentras, than in those data measured in Granada.

4.2 Density probability distributions of one-minute kt values conditioned to the hourly kt

Fig. 4 shows one-minute kt frequency distributions for different m values according to the following values of hourly kt: 0.15 ± 0.05 , 0.30 ± 0.05 , 0.45 ± 0.05 , 0.60 ± 0.05 and 0.75 ± 0.05 .

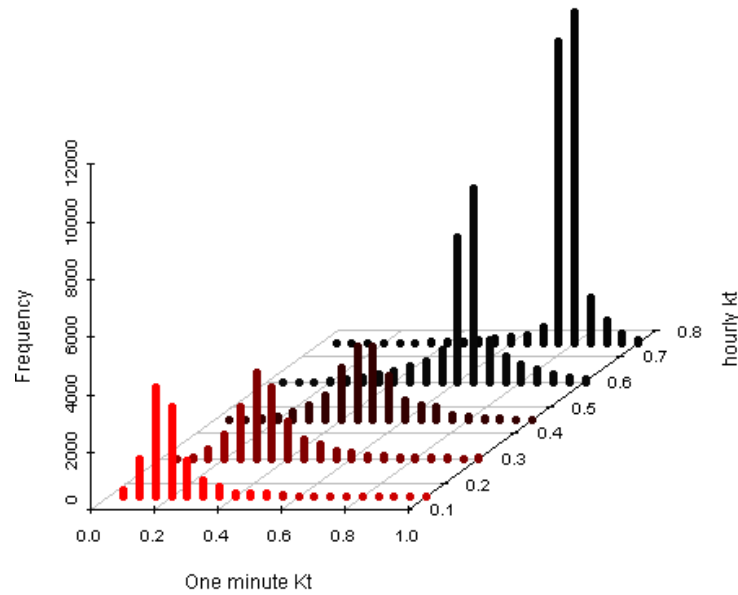


Fig. 4. One-minute kt density probability distributions conditioned to the hourly kt.

PDF of one-minute values of kt (conditioned to the hourly kt) found reveals a unimodal character, in contrast with bimodal character founded in distributions conditioned to m. Furthermore, hourly kt distributions between 0.45 and 0.6 show a marked symmetry around they mode, which is close to the corresponding hourly average value. In contrast, the other distributions analyzed (hourky kt below 0.30 and 0.75) show a slight asymmetry.

Dispersion of different distributions reveals the range of one-minute kt values that corresponds to a given hourly kt. The qualitatively behaviour of one-minute kt distributions conditioned to the hourly kt found in this study (obtained from data measured in Carpentras) is similar to those presented in [5] (obtained from data measured in Granada). In distributions which values of hourly kt are below of 0.45, very high (even near 1) and very low one-minute kt values are found. Those distributions also show an asymmetry toward the higher values. This fact has been previously observed in [5], and it is attributed to the existence of transient situations under partial cloud cover with clouds close to the sun position, which can both block or enhance the sun direct beam. In contrast, in high hourly kt distributions, a narrower range of one-minute kt is appreciated. This fact has been associated to cloudless sky conditions.

4.3 Density probability distributions of one-minute kt values conditioned to m and the hourly kt

Fig. 5 shows one-minute kt density probability distributions for the following intervals of m: 1, 1.5, 2, 2.5, 3, and according to the following intervals of hourly kt: 0.15, 0.30, 0.45, 0.60, 0.75.

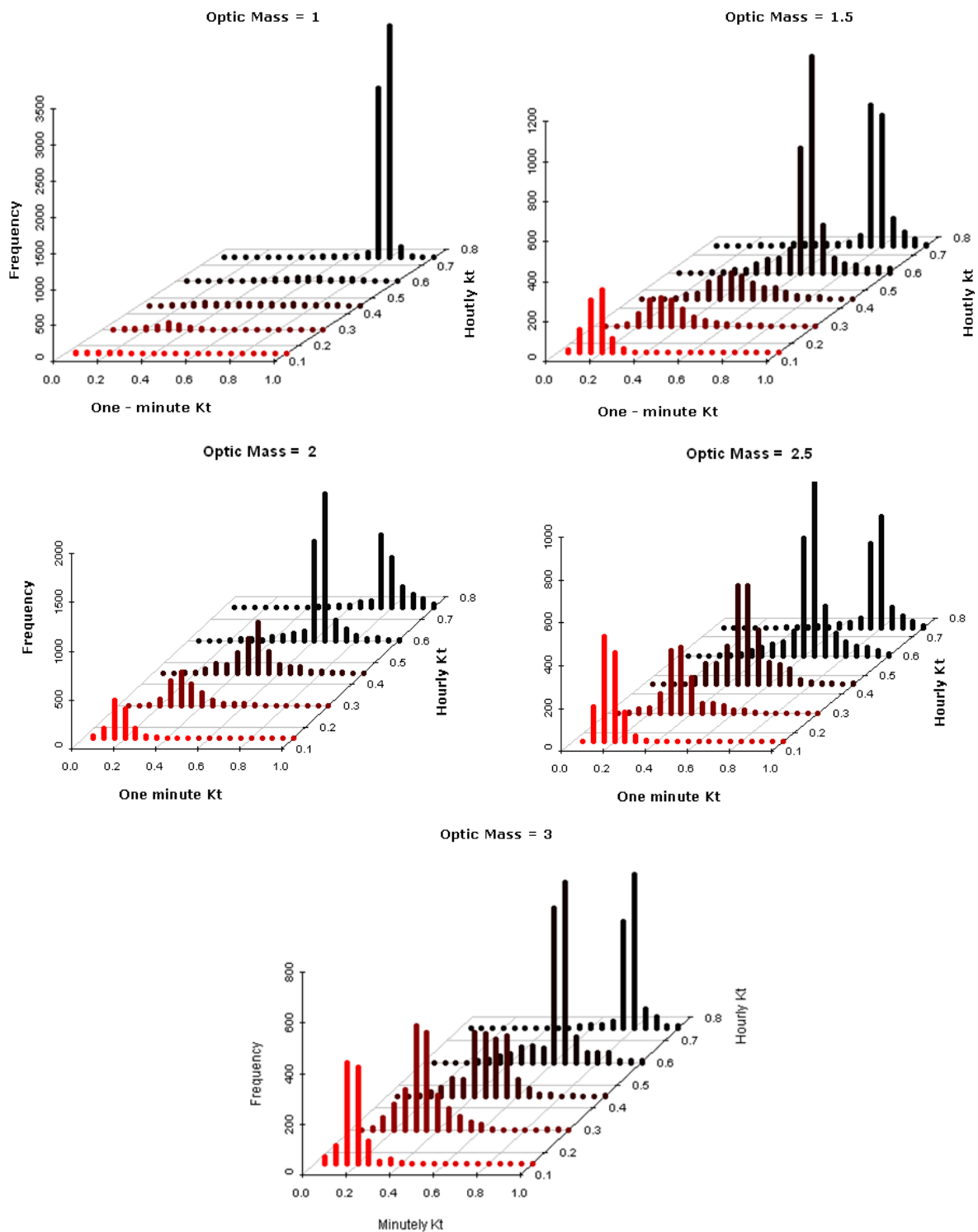


Fig. 5. One-minute kt density probability distributions conditioned to hourly kt and m.

PDF of one-minute values of kt conditioned to m and hourly kt present a unimodal character. PDFs at hourly kt equal to 0.75 decrease and widen with higher m values, indicating cloud-free conditions at m = 1 and

transient situations under partial cloud cover at higher m values. In contrast, PDFs at kt equal to 0.15 weakly depend on m values, indicating a strong dependence of them on cloud conditions. PDFs at kt equal to 0.3 and 0.45 present a mixed behavior between the two extreme cases (kt equal to 0.75 and equal to 0.15), showing similar peaks and dispersion, and different dependence on m values.

For m values equal and higher than 1.5, the maximum PDF of one-minute kt values has been found at kt equal to 0.6, and its maximum increases until m is equal to 2, and decreases at higher m values.

5. Conclusions

In this work, PDFs of one-minute values of kt conditioned to m and hourly kt in Carpentras (France) have been investigated. These distributions present a unimodal character, in contrast with bimodal character founded in distributions conditioned only to m values. PDFs at kt equal to 0.15 are almost independent of m , indicating a strong dependence of them on cloud conditions. Otherwise, PDFs at kt equal to 0.75 decrease and widen with higher m values, indicating cloud-free conditions at $m = 1$ and transient situations under partial cloud cover at higher m values. PDFs at kt equal to 0.3 and 0.45 show a mixed behavior between the last cases, presenting similar peaks and dispersion, and different dependence on m .

Moreover, the comparison of the PDFs conditioned only to m found in this work (in Carpentras station, France), with those calculated in Granada (Spain) suggests different bimodality features in these locations. Notwithstanding, in both locations, bimodality is higher at increasing m values. Distributions conditioned only to the hourly kt in both locations show a similar qualitatively behaviour, as very high (even near 1) and very low one-minute kt values in distributions which values of hourly kt are below of 0.45 are found. Those distributions also show an asymmetry toward the higher values. This fact has been previously attributed to the existence of transient situations under partial cloud cover with clouds close to the sun position, which can both block or enhance the sun direct beam.

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