



**HAL**  
open science

## Comparison of Methodologies to Estimate Direct Normal Irradiation From Daily Values of Global Horizontal Irradiation

Sara Moreno, Silva Manuel, Carlos M. Fernández-Peruchena, Íñigo Pagola

► **To cite this version:**

Sara Moreno, Silva Manuel, Carlos M. Fernández-Peruchena, Íñigo Pagola. Comparison of Methodologies to Estimate Direct Normal Irradiation From Daily Values of Global Horizontal Irradiation. 15th SolarPACES Conference, Sep 2009, Berlin, Germany. pp.16136. hal-00919055

**HAL Id: hal-00919055**

**<https://hal.science/hal-00919055>**

Submitted on 16 Dec 2013

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# COMPARISON OF METHODOLOGIES TO ESTIMATE DIRECT NORMAL IRRADIATION FROM DAILY VALUES OF GLOBAL HORIZONTAL IRRADIATION

Sara Moreno<sup>1</sup>, Manuel Silva<sup>1</sup>, Carlos M. Fernández-Peruchena<sup>2</sup>, Iñigo Pagola<sup>2</sup>

1 AICIA / Grupo de Termodinámica y Energías Renovables. Address: Avda. de los descubrimientos s/n, 41092 Sevilla (Spain). Phone: (+34) 954487233. Fax: (+34) 954 487233. E-mail: [saramt@esi.us.es](mailto:saramt@esi.us.es)

2 Solar Thermal Energy Department, National Renewable energy Centre (CENER). Address: C/ Isaac Newton n 4 - Pabellón de Italia, 41092 Sevilla (Spain). Phone: (+34) 902 25 28 00. Fax: (+34) 954 46 09 07

## Abstract

Daily global horizontal and direct normal irradiation (DNI) measured from the database of the Group of Thermodynamics and Renewable Energies (GTER) of the Seville Engineering School are used to compare three different methodologies to obtain daily DNI values from daily global horizontal irradiation measurements. Methodologies are based on combinations of models to generate hourly radiation series as the one developed by Collares Pereira and Rabl [4] or the Time-dependent Autoregressive Gaussian (TAG) model developed by Aguiar and Collares Pereira [5] with daily and hourly global-to-diffuse or global-to-direct decomposition models [6] developed by GTER from their own database. The estimated data are classified by the clearness index to analyze the influence of cloudiness on the different methodologies. Furthermore, the hourly decomposition model developed by Erbs is used to study how the use of different decomposition models affects the results.

Keywords: solar, irradiation, direct, methodologies, TAG, decomposition models.

## 1. Introduction

The fast development of the solar thermal power sector during the last few years (especially in Spain) makes it necessary to develop methodologies to estimate the direct normal irradiation (DNI) from other magnitudes, more specifically from global horizontal irradiation, which is the radiometric magnitude more frequently measured and that can also be estimated from satellite images.

The purpose of this work is to test and compare three different methodologies to obtain daily DNI values from daily global horizontal radiation data using empirical models. For this purpose, we have compared the results with measured values from the database of the Group of Thermodynamics and Renewable Energies (GTER) of the Seville Engineering School that includes direct normal irradiance and global horizontal irradiance measurements for a period of 25 years.

Methodologies are based on combinations of models to generate hourly radiation series as the one developed by Collares Pereira and Rabl [4] or the Time-dependent Autoregressive Gaussian (TAG) model developed by Aguiar and Collares Pereira [5] with daily and hourly global-to-diffuse or global-to-direct decomposition models [6] developed by GTER from their own database.

The influence of the use of a different global-to-diffuse decomposition model is also explored through the use of the Erbs model [2].

## 2. Database

Solar radiation measurements used in this work have been recorded at the meteorological station installed at the Seville Engineering School, which is operated by the Group of Thermodynamics and Renewable Energies (GTER). The meteo station was installed in 1984. Data recorded during the period 2000-2008 will be used in this work. The reason is that a dual automatic tracker was installed by the end of 1999, providing better DNI measurements. The geographical coordinates of the meteo station are 37.4°N y 6.04°O . A Kipp &

Zonen CM21 pyranometer has been used for the measurement of global horizontal irradiance, while DNI has been measured by a Eppley Normal Incidence Pyrheliometer (NIP) mounted on the Kipp & Zonen 2AP 2-axis tracker. Measurements have been recorded every 5 seconds, but for the purpose of this work only hourly and daily values have been used. After application of the quality control procedures, 2462 valid days resulted, distributed as shown in table 1.

Year	2000	2001	2002	2003	2004	2005	2006	2007	2008
Days	263	340	337	324	254	272	81	327	267

**Table 1. Number of valid days.**

During year 2006, the Kipp & Zonen tracker was sent to the manufacturer for repair, what explains the low number of valid days for this year.

## 2. Methodologies

### 2.1. Method 1. Daily $kt$ - $kd$ and hourly distribution $rd$ - $rg$

The daily clearness index  $kt^d$  is calculated from the daily global irradiation value and the extraterrestrial irradiation, both on a horizontal surface. The corresponding daily diffuse components are calculated through decomposition models (global to diffuse or global to direct) developed by GTER from its own database [5]. The second can be represented by:

$$\begin{array}{ll} kd = 0.999 & kt \leq 0.26 \\ kd = 1.471 - 1.784 \cdot kt & 0.26 < kt < 0.77 \\ kd = 0.111 & kt > 0.77 \end{array}$$

These models have been compared to other models of common use and to other models for other locations in Spain.

The hourly distributions of global and diffuse irradiation are calculated through a very simple empirical model, developed by Collares Pereira and Rabl [4]. The model is based on the hypothesis that the composition of the atmosphere for a given site is reasonably constant during one day, thus the solar radiation-atmosphere interaction variation depends mainly on the relative position of sun and earth. Liu and Jordan [1] suggested that, under these circumstances and for a given surface, the time distribution of the diffuse fraction follows the same pattern as the extraterrestrial irradiance. A coefficient,  $rd$ , is defined as follows:

$$rd = \frac{H_{0d}^h}{H_{0d}^d} = \frac{H_0^h}{H_0^d} = \frac{\pi}{24} \cdot \frac{\cos(w) - \cos(w_s)}{\sin(w_s) - w_s \cdot \cos(w_s)}$$

Collares and Rabl developed the following expression for the calculation of the hourly global horizontal irradiation from the corresponding daily value and  $rd$ :

$$rd = \frac{H_{g0}^h}{H_{g0}^d} = rd \cdot (a + b \cdot \cos(w))$$

Where  $a$  and  $b$  are calculated by means of

$$a = 0.409 + 0.5016 \cdot \sin(w_s - 60^\circ)$$

$$b = 0.6609 + 0.4767 \cdot \sin(w_s - 60^\circ)$$

Where  $w$  is the hourly angle and  $w_s$  the sunset angle. The hourly beam irradiation on horizontal surface is the difference between the hourly horizontal global irradiation and the hourly horizontal diffuse irradiation; the hourly direct normal irradiation is then calculated by trigonometry:

$$H_{bn}^h = \frac{H_{b0}^h}{\cos(\theta_z)}$$

where  $\theta_z$  is the solar zenith angle.

Finally, the daily DNI is calculated by integration of the corresponding hourly values:

$$H_{bn}^d = \sum_{h=1}^n H_{bn}^h,$$

where n is the number of sunlight hours.

## 2.2 Method 2. Hourly distribution rd-rg and hourly correlation kt-kd

The hourly horizontal global distribution is obtained as in 2.1. using the model developed by Collares Pereira and Rabl [4]. Then, for each hourly global horizontal value, its corresponding hourly clearness index  $kt^h$  is calculated. An hourly decomposition model  $kt^h$ - $kd^h$  developed by GTER is used to calculate the corresponding hourly diffuse fraction,  $kd^h$ . This model can be represented by:

$$\begin{aligned} kd &= 0.993 & kt &\leq 0.27 \\ kd &= 1.494593 - 1.789853 \cdot kt & 0.26 < kt < 0.82 \\ kd &= 0.045 & kt &> 0.82 \end{aligned}$$

The hourly beam irradiation on horizontal surface is the difference between the hourly horizontal global irradiation and hourly horizontal diffuse irradiation and the hourly beam irradiation on a normal surface is calculated by trigonometry:

$$H_{bn}^h = \frac{H_{b0}^h}{\cos(\theta_z)}$$

where  $\theta_z$  is the solar zenith angle.

Finally, the daily DNI is calculated by integration the hourly normal beam values.

$$H_{bn}^d = \sum_{h=1}^n H_{bn}^h, \text{ where n is the number of de solar hours.}$$

## 2.3 Method 3. Time-dependent, Autoregressive Gaussian (TAG) model and hourly correlation kt-kd

The TAG model assumes that for each  $kt^d$  and solar hour the probability density of the hourly clearness index  $kt^h$  is a truncated Gaussian function [4].

$$\chi_h = \frac{kt(h) - \bar{kt}(kt^d, h)}{\sigma(kt^d, h)}$$

A first-order autoregressive model is fitted for the  $kt^h$  variable, normalized using parameterizations for the time-dependent average and standard deviation values:

$$\chi_h = \phi \cdot \chi_{h-1} + r$$

$$r = \sigma' \left[ z^{0.135} - (1-z)^{0.135} \right] / 0.1975$$

$$\sigma' = (1 - \phi^2)^{1/2}$$

where z is a random number in the [0,1] interval.

Values generated by this ARMA(1,0) model can then be transformed backwards to generate synthetic sequences of  $kt^h$  values.

$$kt^h = \bar{k}(kt^d, h) + \sigma(kt^d, h) \cdot \chi_h$$

The sequence of  $kt^h$  values is calculated from 1 hour before sunrise. The 1<sup>st</sup> order autoregressive parameter for a given day,  $\phi$ , is estimated through:

$$\phi = 0.38 + 0.06 \cos(7.4kt^d - 2.5)$$

The distribution moments are then determined:

$$\bar{k} = \lambda + \mu \cdot \exp\left(\frac{-\nu}{\cos \theta_z}\right)$$

$$\sigma = A \exp[B(1 - \cos \theta_z)]$$

where  $\theta_z$  is the solar zenith angle and

$$\lambda = -0.19 + 1.12kt^d + 0.24 \exp(-8kt^d)$$

$$\mu = 0.32 - 1.60(kt^d - 0.5)^2$$

$$\nu = 0.19 + 2.27(kt^d)^2 - 2.51(kt^d)^3$$

$$A = 0.14 \exp[20(kt^d - 0.35)^2]$$

$$B = 3(kt^d - 0.45)^2 + 16(kt^d)^5$$

And then, the normalized variable  $\chi$  for the hour h is calculated:

$$\chi_h = \frac{k(h) - \bar{k}(kt^d, h_1)}{\sigma(kt^d, h_1)}$$

Once the initial parameters are known, the hourly series is calculated hour by hour, from sunrise to sunset. If the value of  $kt^h$  is less than zero or higher than the clear sky clearness index, the random number z must be generated again, and all parameters are recalculated. The clear sky clearness index is calculated as

$$kcs = 0.88 \cos\{\pi(h_i - 12.5)/30\}$$

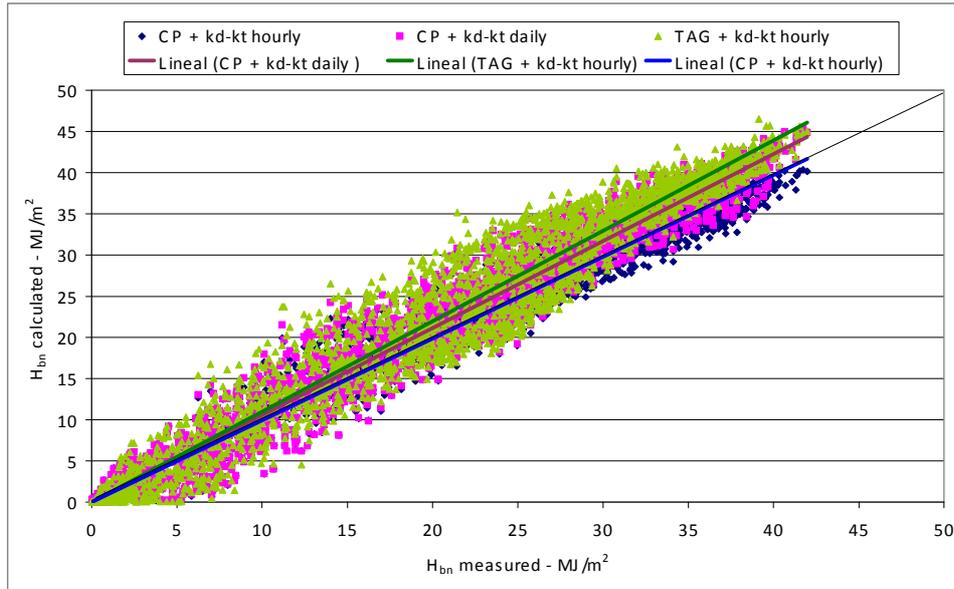
Once the hourly  $kt^h$  values have been obtained, the hourly  $kd^h$  are obtained by application of the daily decomposition model  $kd^h$ - $kt^h$  developed by GTER.

The hourly beam insolation on horizontal surface is obtained, as in previous sections, as the difference between the hourly horizontal global insolation and hourly horizontal diffuse insolation. The hourly beam insolation on a normal surface is calculated by trigonometry. Finally, the daily beam radiation at normal incidence is calculated by integration of the hourly normal beam values.

### 3. Comparison against measured values

#### 3.1. Comparison of methodologies

The three sets of estimated daily DNI values are compared to the daily DNI values registered at the GTER station in figure 1.



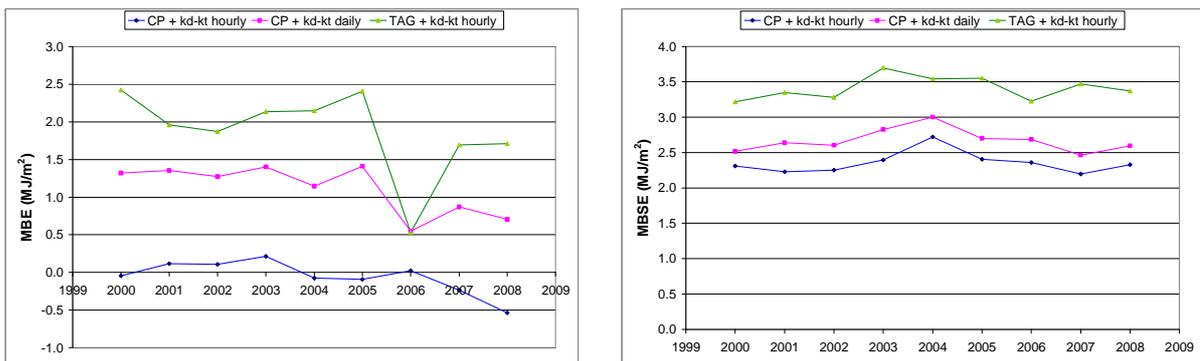
**Fig. 1. Estimated DNI values using three different methodologies compared to measured DNI.**

The best fitting to measured values are obtained through the combination of the Collares-Pereira hourly distribution and hourly  $kd^h-kt^h$  model (Method 2). Method 1 and, significantly, Method 3 overestimate the daily DNI, compared to experimental, registered data. The same trend is observed in table 2, where the Mean bias error (MBE) and Root Mean Squared Error are presented.

Methodology	CP + kd-kt hourly	CP + kd-kt daily	TAG + kd-kt hourly
MBE ( $W/m^2$ )	-0.053	1.168	2.001
RMSE ( $W/m^2$ )	2.354	2.676	3.457

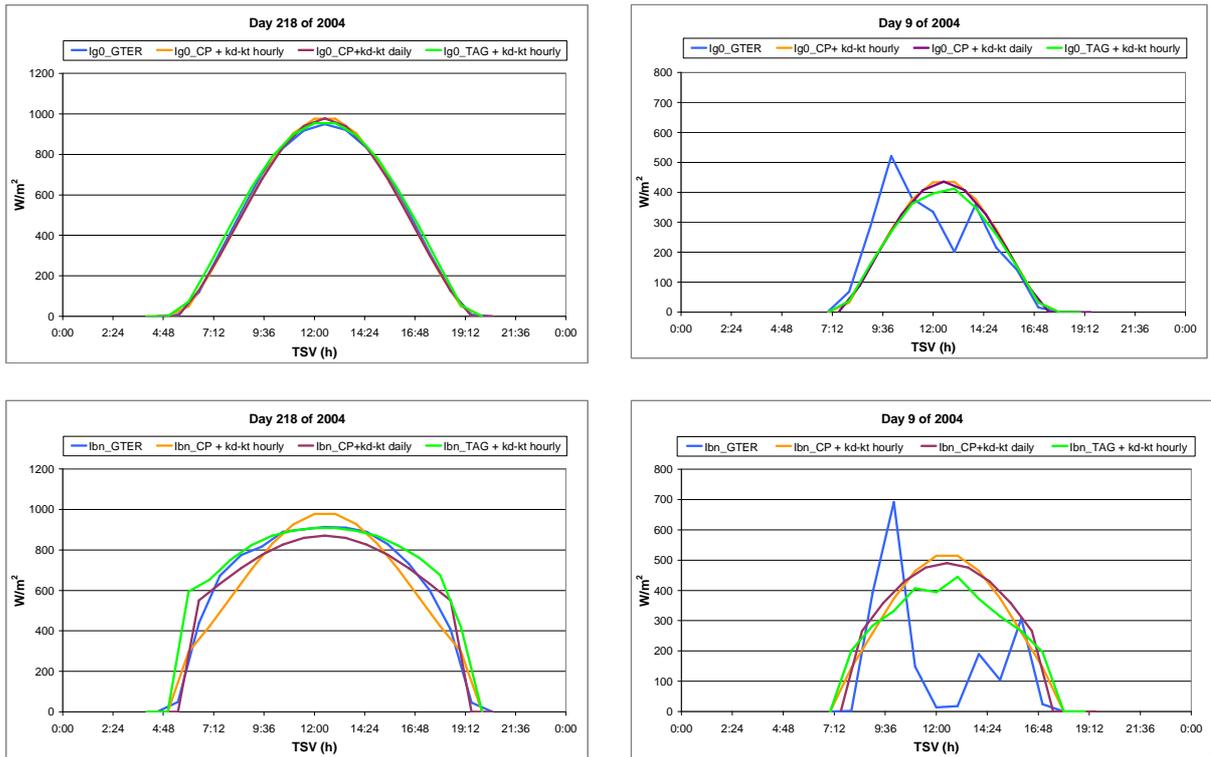
**Table 2. Medidas del error que se introduce al aplicar las diferentes metodologías.**

Figure 2 represents the MBE and RMSE values obtained every year of the “control period”. The estimates of the three methodologies always follow the same order, except for year 2006. This year we had a small number of valid days.



**Fig. 2. MBE and MBSE of the DNI estimates from each of the methodologies for years 200-2008.**

Despite of this fact, the TAG model for generation of hourly values provides more variability or “randomness” that the Collares-Pereira Model, as shown in figure 3. The hourly distribution provided by the Collares-Perira model has the shape of a *scaled* clear day, even for cloudy days.



**Fig. 3. Hourly values of global horizontal insolation and DNI obtained from the application of the three methodologies under comparison and the corresponding measured values.**

Table 2 presents the results of the analysis of the errors as a function of the daily clearness index:

kt	No. of valid days	CP + kd-kt hourly		CP + kd-kt daily		TAG + kd-kt hourly	
		MBE (W/m <sup>2</sup> )	RMSE (W/m <sup>2</sup> )	MBE (W/m <sup>2</sup> )	RMSE (W/m <sup>2</sup> )	MBE (W/m <sup>2</sup> )	RMSE (W/m <sup>2</sup> )
0.1	48	-0.12	0.37	-0.01	0.37	-0.13	0.37
0.2	83	-0.63	1.06	-0.41	1.03	-0.64	1.06
0.3	134	-1.58	1.69	-1.41	1.70	-1.41	1.66
0.4	186	-0.73	2.23	-0.76	2.23	-0.27	2.47
0.5	238	0.23	2.62	-0.01	2.61	1.07	3.06
0.6	491	1.09	2.67	1.90	2.85	2.79	3.71
0.7	1224	-0.16	2.20	1.74	2.51	2.78	3.38
0.8	61	-0.94	1.16	2.07	1.52	3.28	1.98

**Table 2. Errors of the estimates as a function of the daily clearness index.**

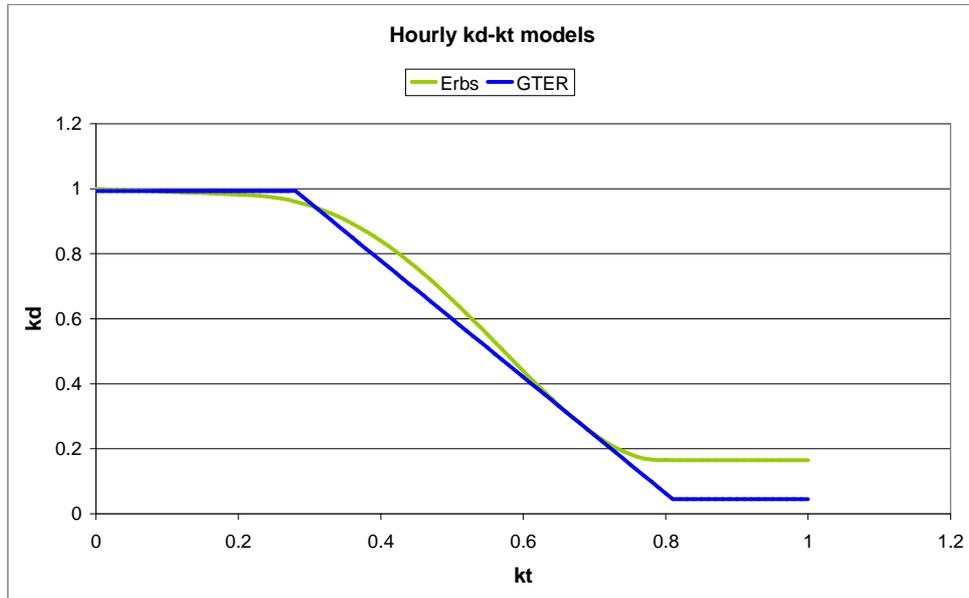
Again the combination of the Collares-Pereira and hourly  $kd^h-kt^h$  models shows the best results; the other two methodologies tend to overestimate DNI, especially for high kt values. The dispersion of results is in general greater for intermediate-high values of kt.

### 3.2 Influence of the decomposition model

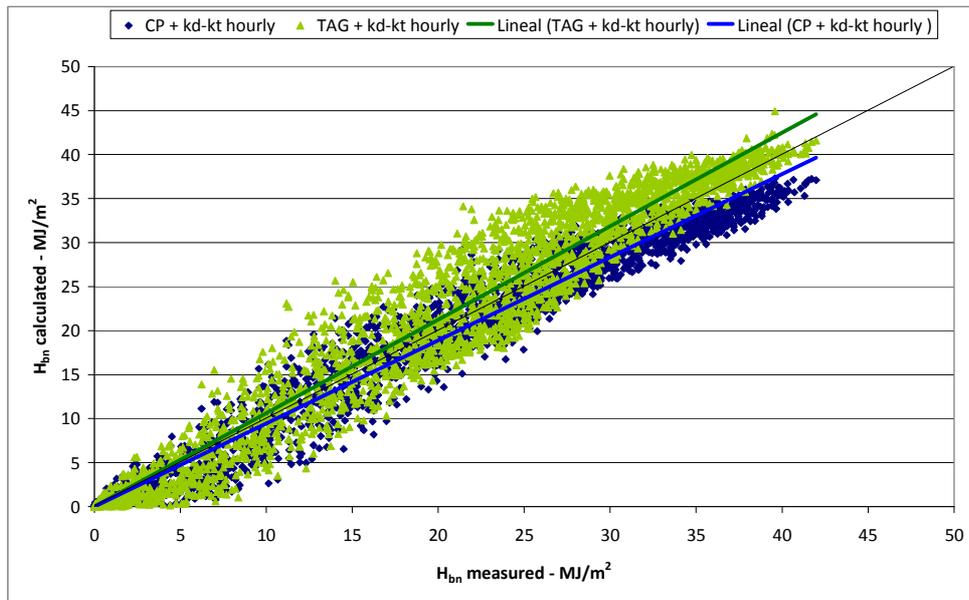
To analyze the influence of the selected decomposition model the GTER model has been replaced the Erbs hourly model [2]:

$$\begin{aligned}
 kd &= 0.993 & kt &\leq 0.27 \\
 kd &= 1.494593-1.789853 \cdot kt & 0.26 < kt < 0.82 \\
 kd &= 0.045 & kt &> 0.82
 \end{aligned}$$

The Erbs and GTER models are shown together in figure 4. The results obtained with the combinations of the Erbs model and the Collares-Pereira and TAG models are shown in figure 5.



**Fig. 4. Erbs and GTER models.**



**Fig. 5. Comparison of 2 sets of estimated DNI values versus measured values.**

The Erbs model results in a larger diffuse fraction (or alternatively, less beam component) for  $kt^h > 0.7$ . As a result, the application of the Erbs model results in lower DNI estimates. The comparative performance of the combination with the Collares-Pereira and TAG models follows the same trend observed when the GTER model was used, this is, the TAG model provides the highest DNI estimates; however, the errors decrease clearly when the Erbs model is used, while the opposite is true for the combination of the Erbs and Collares-Pereira models. This shows very clearly the importance of selecting an adequate decomposition model for the “goodness” of the estimates.

## 5. Conclusions

Three methodologies to estimate DNI daily values from daily global horizontal values have been compared, using nine years (2000-2008) of measured values from the GTER database. The results show that:

- 1) The use of the TAG method for the generation of hourly global insolation from daily values results in more *optimistic* DNI estimates, while the combination of the Collares-Pereira model with a hourly decomposition model results in more *pessimistic* estimates.
- 2) When the methods for generation of hourly values are combined with the GTER model, the Collares-Pereira model provides the best estimates, while the TAG model results in a significant overestimation of the DNI.
- 3) When the methods for generation of hourly values are combined with the Erbs model, the comparative behavior of the Collares-Pereira model and the TAG model is the same as before, but the errors with respect to measured values increase for Collares-Pereira and decrease for the TAG model.

## References

- [1] B. H. Y. Liu and R. C. Jordan, The interrelationship and characteristic distribution of direct, diffuse and total solar radiation. *Solar Energy* 4, 1 (1960).
- [2] D. G. Erbs, S. A. Klein and J. A. Duffie, Estimation of the diffuse radiation fraction for hourly, daily and monthly-average global radiation, *Solar Energy* 28, 293-302 (1982) .
- [3] J.Polo, Estimación de la radiación solar directa para aplicaciones de concentración solar, *Curso sobre Sistemas Solares Térmicos de Concentración*, 6 (2008).
- [4]. M. Collares-Pereira and A. Rabl, The average distribution of solar radiation---correlations between diffuse and hemispherical and between daily and hourly insolation values, *Solar Energy* 22, 155-164 (1979).
- [5] R.Aguiar and M. Collares-Pereira, TAG: A time-dependent, autoregressive, Gaussian model for generating synthetic hourly radiation, *Solar Energy* 49, 167-174 (1992).
- [6] S.Moreno, Obtención de modelos kd-kt horario y diario a partir del análisis de datos medidos en la estación radiométrica de la Escuela Superior de Ingenieros de Sevilla. Proyecto Fin de Carrera. Escuela Superior de Ingenieros de Sevilla (2007)