Fourier Analysis of Daily Solar Radiation Data in Spain

Article *in* Solar Energy · December 1988

DOI: 10.1016/0038-092X(88)90028-X

José M Baldasano
Technical University of Catalonia, Barcelona, Spain

A. Berna
University of Valencia

Solar Energy Vol. 41, No. 4, pp. 327–333, 1988
Printed in the U.S.A.
0038-092X/88 $3.00 + .00

FOURIER ANALYSIS OF DAILY SOLAR RADIATION DATA IN SPAIN

J. M. BALDASANO
Dpt. de Proyectos de Ingeniería, Universidad Politécnica de Cataluña, Spain

and

J. CLAR and A. BERNA
Area de Ingeniería Química, Dpt. de Química, Universitat de les Illes Balears, Spain

Abstract—The aim of this work has been to obtain a Typical Annual Time Function by the application of a calculation procedure based on a Fourier analysis to solar radiation data of 21 stations in Spain. This function allows us to estimate the most probable value of the horizontal daily global solar radiation for every day of the year in a certain geographical point. It is confirmed that the first harmonic presents an important percentage of the total variance, located between 61 and 77% and that none of the other harmonics contributes in a significant form to explain the total variance.

Resumen—El objeto de este trabajo ha sido la obtención de una Función Temporal Anual Tipo, mediante la aplicación de un procedimiento de cálculo basado en un Análisis de Fourier, a los datos de 21 estaciones de medida de la radiación solar en España. Dicha función permite estimar el valor más probable de la radiación solar global diaria sobre una superficie horizontal, para cualquier día del año en una localización geográfica determinada. Comprobándose que el primer armónico representa un porcentaje importante de la varianza total, situándose entre el 61 y el 77%; y que ninguno de los demás armónicos contribuye de forma significativa a explicar la varianza total.

1. INTRODUCTION

A more intensive use of solar energy implies the need to have analyzed and reliable information about solar radiation. The information should be available in a form that is easy to handle.

The design methods and the mathematical models, utilized to calculate and define the solar systems, need to use external meteorological variables. Thus, it is necessary to analyze them thoroughly in order to know the behavior of the former variables and to get the mathematical formulations for them. These formulations could easily be incorporated to the procedures of analysis, design, and simulation of these systems.

In general, the information of the meteorological variables, and particularly of solar radiation, are available in form of data tables with hourly or daily values. This represents a highly numerical information form and therefore difficult and inconvenient to handle.

The treatment of time series by means of Fourier Analysis has been applied to climatic data, such as solar radiation, air temperature, etc.[2,5,6,9,10,18,19], besides other fields, such as water quality data[17,20], and hydrological data[1].

The application of this technique to daily data of solar radiation, air temperature, and air vapor pressure[3,8] has clearly confirmed in all the cases that the yearly harmonic contributes in a very definitive way; without a significant participation of the rest of the harmonics.

This permits to obtain a Typical Annual Time Function that calculates the most probable value of solar radiation, air temperature, and air vapor pressure for any day of the year in a given geographical point.

The aim of this work has been to obtain this Typical Annual Time Function for the Spanish measurement stations of global solar radiation over a horizontal surface using the maximum number of available data.

2. DATA OF SOLAR RADIATION IN SPAIN

The interest in the measurement and the evaluation of solar radiation in Spain is recent, as shown in the first publication of Instituto Nacional de Meteorología (INM) with the data about the mentioned variable, made in 1974[12], with the daily data of global solar radiation over a horizontal surface from 1957 to 1973 and only for 15 stations. The data for the next following years[13–16] with an extension of number of measurement stations to 48, and with the hourly data in some of them, were published later.

The names and the codes of the 24 studied meteorological stations as well as the available years for each of them are indicated in Table 1. The letter D or H appearing after each year indicates that the source data are daily and hourly respectively, although all of them have been used in daily data form.

The adopted criterion consisted of having available as many stations as possible and in each of them the most possible number of years. The limit of the years considered as minimum, not desirable, for each station was four, because the used method was the open type and with the object of containing the maximum geographical extension.

An important part of the solar radiation data used

Table 1. Name, code, and years of the analyzed stations.

ALICANTE	08359	1976D, 1977D, 1978D, 1979D, 1980D	[5]
ALMERIA	08487	1958D, 1959D, 1960D, 1961D, 1962D, 1963D, 1964D, 1965D, 1966D, 1967D, 1976D, 1978D, 1979D, 1980D	[14]
AZNALCAZAR	99008	1971D, 1972D, 1973D, 1974D, 1975D, 1976D, 1977D	[7]
BADAJOZ	08330	1959D, 1960D, 1962D, 1964D, 1965D, 1966D, 1976H, 1977H, 1978H, 1979H, 1980H	[11]
BARCELONA	08180	1965D, 1966D, 1967D, 1968D, 1973D, 1974D, 1975D, 1976D, 1978D	[9]
CACERES	99013	1975D, 1976D, 1977D, 1978D, 1979D, 1980D	[6]
CIUDAD REAL	08348	1976D, 1977D, 1978D, 1979D, 1980D	[5]
GRANADA	08419	1976D, 1977D, 1978D, 1979D, 1980D	[5]
LA PALMA	60005	1976D, 1977D, 1978D, 1979D, 1980D	[5]
LERIDA	08171	1977D, 1978D, 1979D, 1981D	[4]
LOGROÑO	08084	1971D, 1972D, 1973D, 1974D, 1975D, 1977D, 1979D, 1980D	[8]
MADRID	08220	1958D, 1959D, 1960D, 1961D, 1962D, 1963D, 1964D, 1965D, 1966D, 1967D, 1969D, 1971D, 1975H, 1978H, 1979H, 1980H	[16]
MAJADAHONDA	–	1958D, 1959D, 1961D, 1962D, 1963D	[5]
MENORCA	08314	1977D, 1978D, 1979D, 1980D	[4]
M. DE ARAGON	08232	1976D, 1977D, 1978D, 1979D, 1980D	[5]
MURCIA	08430	1973D, 1976H, 1977H, 1978H, 1979H, 1980H	[6]
OVIEDO	08015	1973D, 1974D, 1975H, 1976H, 1977H, 1978H, 1979H, 1980H	[8]
PALMA DE M.	08301	1976H, 1977H, 1978H, 1979H, 1980H	[5]
SALAMANCA	08202	1967D, 1968D, 1970D, 1971D, 1976D, 1977D, 1978D, 1979D, 1980D	[9]
SANTANDER	08023	1974D, 1975D, 1977D, 1978D, 1979D, 1980D	[6]
SAU	–	1972D, 1973D, 1974D, 1975D, 1979D, 1982D	[6]
SEVILLA	08391	1959D, 1960D, 1961D, 1962D, 1966D, 1979H, 1980H	[7]
VALENCIA	08285	1973D, 1974D, 1975D, 1976D, 1977D, 1978D, 1979D, 1980D	[8]
VANDELLOS	99001	1975D, 1976D, 1977D, 1978D	[4]

in this study came from a magnetic tape provided by INM in September 1984 containing information from 1975 to 1980. The published data by INM with the years before 1975[13,14] were taken into account, and therefore were obliged to their mechanization.

Besides the data of INM, the information of other stations were mechanized in order to include the Catalonian area. The data of Barcelona (Dpt. of Air Physics), Tortosa (the Observatory of the Ebro), and Sau (Hydrographic Conf. of the Oriental Pyrenees) were obtained directly from their sources.

In total, a set of 24 meteorological stations have been analyzed. They sum up a total of 168 years and present more than 61,000 points distributed over the whole Spanish geography.

3. FOURIER ANALYSIS APPLICATION

One method for analyzing time series is based on the hypothesis that the mentioned series are formed by a set of sine and cosine waves of different frequencies. The application of a development in Fourier series permits the detection and calculation of the amplitude and the phase angle of each component, its frequency, and the retained variance for each harmonic over the total variance of the series.

The calculation procedure, used to obtain a Typical Annual Time Function for the set of the studied stations indicated in Fig. 1, and it has been used before[3,8].

The method followed, which is used in an independent form for the data of each measurement station, consists of two stages:

1. In the first stage, a Fourier analysis is applied to the set of annual series year after year. This permits the removal of the random phenomena and the obtaining of the representative equation of each year from the retained harmonics in function of the explained variance for each of them. In our case, in a generalized form, only the annual harmonic is retained. Carrying out the analysis year after year allows us to notice quickly if there exists a year with any differences in its behavior with regard to the rest of the years of the studied series and also use less computer time.

2. The second stage consists of obtaining the Typical Annual Time Function from the set formed by the representative equation of each year, analyzed by the application of least squares method for the nonlinear systems. The following expression is obtained from this form:

$$RS_P(t) = VM_T + AM_T \cos\left(\frac{2\pi}{365} t - \theta_T\right) \qquad (1)$$
$$t = 1, \ldots, 365$$

where $RS_P(t)$ represents the most probable value of the global solar radiation in the day t for the correspondent measurement station m, VM_T is the annual average of the daily global solar radiation, AM_T is the typical amplitude, and θ_T is the typical phase angle.

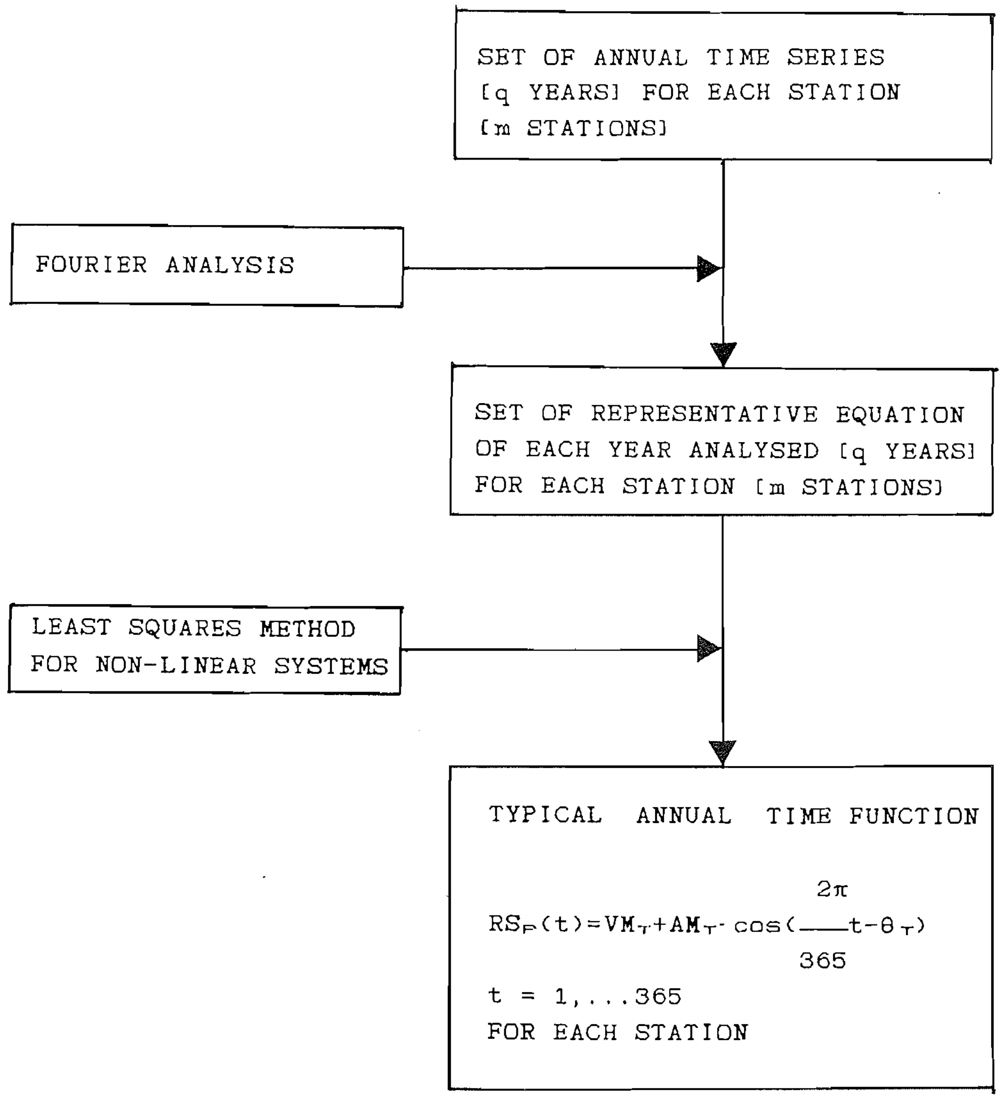

Fig. 1. Procedure used in the data analysis.

4. RESULTS AND DISCUSSIONS

The obtained results confirm clearly that only the annual harmonic contributes in a determinant way to explain the variance of the series, with percentages that range between 61 and 77% (Table 2). Figure 2 shows the daily values of global solar radiation measured in Almeria during 1979 and the equation representative of that year.

With regard to the rest of the harmonics, it is observed that none of them contributes significantly to explain the variance of the series; the majority of them participate with percentages less than 1%. In certain cases, a limited number of harmonics, between 1 and 6, contributes with a percentage between 1 and 4% but without a repetitive character. That is, they are not always the same, although it is the semiannual harmonic that is the most exceptional of all of them, even though not in a constant form.

These results correspond well to those obtained by Balling[4], who carried out a Fourier analysis of the monthly data of solar radiation for 221 stations in the United States, with periods of 24 to 25 years. He found that the average variance for the set of stations explained by the first harmonic was 98.9, varying between 92.9 and 99.9%; and that the second harmonic was explained between 0.01 and 6.56%. These percentages were due to the use of monthly average data.

A Fourier analysis was applied to explain these differences to monthly averaged data from Madrid (14 years), the Nitchequon station in Quebec, Canada, (2 years)[3], and some others. The double objective was to compare the number of years and different climatology. The results obtained reproduced the orders of magnitude of the variance explained by the first and second harmonic found by Balling[4]. The range of variation was between 89.3 and 98.5% for the first harmonic and between 0.01 and 3.8% for the second.

The use of monthly averaged data is the only reason for these differences in the variance percentage explained by the first harmonic, since the background noise of the temporal series is diminished. The values obtained for the amplitude and phase angle are also different. The amplitude is logically some what inferior. The monthly averaged data phase angle is about 15 days later if compared with the phase angle obtained with daily data (the maximum oscillates around the summer solstice, June 22–28).

Phillips[19] applied a Fourier analysis to the hourly data of solar radiation and air temperature in three stations in the United States for a period of 20 years in each of them and discovered that it too was the

Table 2. Parameters of the Typical Annual Time Function for the set of analyzed stations.

STATION	YEARS	VM_T (MJ/m^2)	AM_T (MJ/m^2)	θ_T	%VAR
ALICANTE	5	17.33	8.58	3.0141	75.39
ALMERIA	13	17.29	8.46	2.9898	76.01
AZNALCAZAR	6	16.54	8.79	3.0634	77.27
BADAJOZ	11	15.53	9.13	3.0494	77.08
BARCELONA	9	13.82	7.95	2.9781	67.91
CACERES	5	16.71	8.75	3.0157	72.12
CIUDAD REAL	5	16.20	8.92	3.0775	70.52
GRANADA	5	16.87	8.37	3.0594	69.48
LERIDA	4	14.24	8.79	3.0176	72.95
LOGROÑO	8	14.95	10.05	3.0575	62.74
MADRID	14	16.16	10.38	3.0483	76.59
MAJADAHONDA	5	15.62	9.42	3.0089	74.58
MENORCA	4	15.20	8.46	3.0256	75.01
M. DE ARAGON	5	14.95	8.37	3.0885	65.66
MURCIA	5	16.58	9.21	3.0174	74.10
PALMA DE M.	5	15.28	8.83	3.0277	73.62
SALAMANCA	8	15.03	9.63	3.0537	76.92
SAU	6	12.23	7.12	3.0263	61.37
SEVILLA	7	16.12	8.62	3.0198	76.62
VALENCIA	8	15.99	8.58	3.0219	67.77
VANDELLOS	4	16.62	9.84	3.0227	65.38

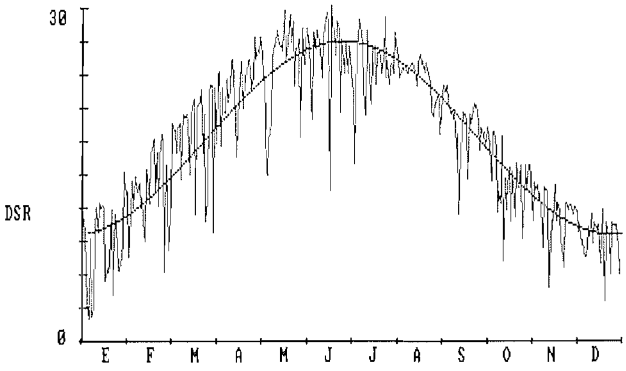

Fig. 2. Annual variation of the daily global solar radiation in Almeria, 1979 (MJ/m^2).

annual harmonic that contributed significantly when explaining the variance of the series with a little but detective component for the semiannual harmonic.

The stations in La Palma, Oviedo, and Santander have not followed the indicated conduct in the previous paragraphs. The annual harmonic explains a smaller percentage of the variance than the shown one—between 30 and 60%—and, besides the number of harmonics that contribute to explain the total variable, increases considerably to a maximum of 19.

To explain this differential behavior, a graphical representation through computer for each of the studied stations was proceeded. It was observed that they represented a bigger background noise than the years with a normal behavior, and besides, very low solar radiation values throughout the whole year for certain years appeared.

Climatic conditions of those stations does not seem to be the reason of this behavior, since although Oviedo and Santander are very similar, Las Palmas climate is totally different. Moreover, the other analyzed stations present strong climatic differences. Results obtained by other authors[4,19] do not justify it either. Because of the important contribution of harmonics of higher order, a possible explanation to this behavior could be attributed to the bad functioning of the measurement apparatus.

A graphical representation of the equations for each year was proceeded for the rest of the stations (Fig. 3). This permitted us to detect five years (one in five different stations and in different years) that differ from the general behavior of their stations. This is well appreciated in the annual parametric values of the average value and the amplitude of the representative equation of that year.

Table 2 indicates the values of the parameters of the Typical Annual Time Function for each of the 21 stations from which concordant results were obtained: the number of years used by a station, the annual average of daily global solar radiation type (VM_T), the amplitude type (AM_T), and the phase angle type (θ_T).

No tendencies in the annual average values in the analyzed stations during the estimated periods of time—from 1958 to 1980—were observed. A complete relation of the obtained results for each station and for each year can be seen in Clar [7].

Figure 4 shows the average value of daily global

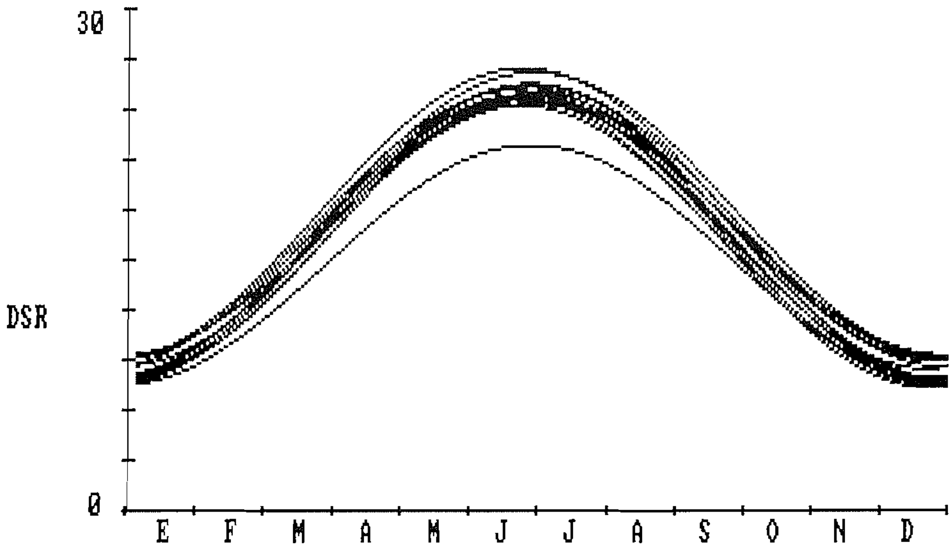

Fig. 3. Almeria. Representative equation of each year analysed (MJ/m^2).

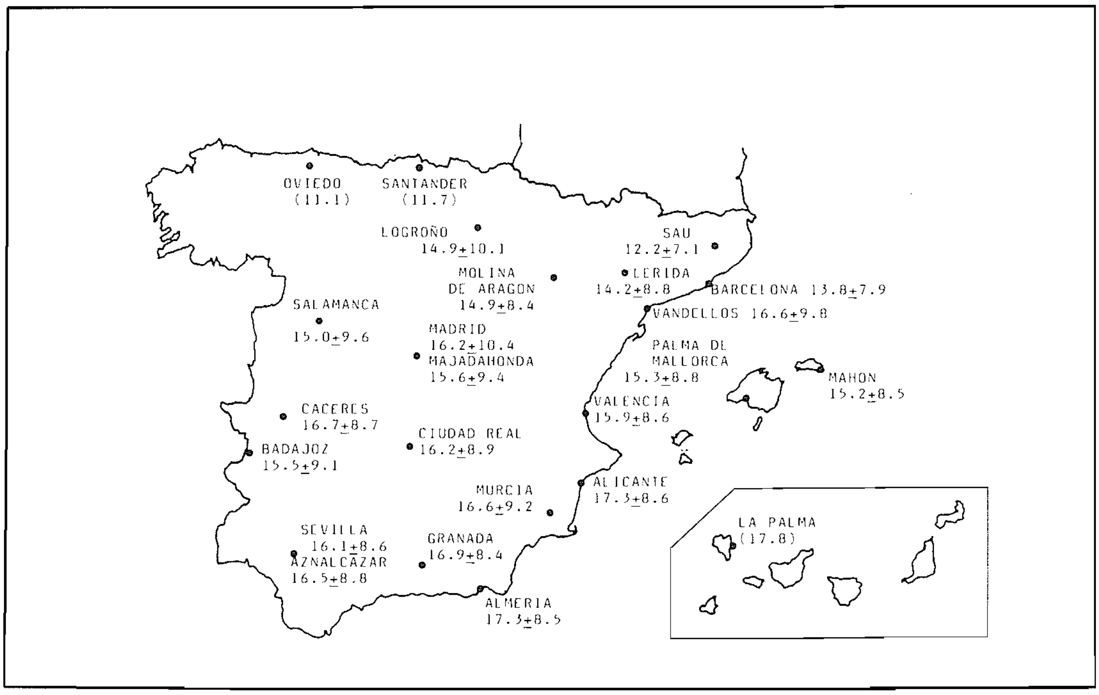

Fig. 4. Solar radiation map for Spain. Average value of daily global solar radiation and the typical amplitude for each of the studied stations (MJ/m^2).

solar radiation and the corresponding amplitude for each of the stations studied. The obtained results permit us to form a map of daily global solar radiation, as well as the variation of it during a year.

The geographical distribution coincides perfectly with the equivalent map of the *Atlas of Solar Radiation in Spain*[11]. However, the obtained values of the annual average of daily global solar radiation are slightly lower than the reflected values on the above-mentioned map, in an average percentage of 5%.

The values of the annual average of daily global solar radiation in La Palma, Santander, and Oviedo are included only in an orientative way. Their values coincide with those of the map, maintaining the mentioned deviation.

Values obtained for the attenuation of solar radiation by the atmosphere (annual average value) are represented in Fig. 5, where they are calculated as the relationship between daily global solar radiation and the theoretically possible solar radiation that would be available if there was no atmosphere.

The obtained values coincide well with those indicated by INM[16], with similar levels, except in Madrid and Sevilla where slightly lower values (in 0.03 and 0.05, respectively) were obtained.

5. CONCLUSIONS

A Typical Annual Time Function was obtained for 21 measurement stations of daily global solar radiation over a horizontal surface through the application of a calculation method based on the Fourier analysis.

The result of the mentioned analysis confirmed that the annual harmonic explains a high percentage of the total variance of the time series—between 61 and 77%—depending on the stations. For the rest of the harmonics, it has been observed that none of them contributes significantly to explain the variance of the series.

The stations in La Palma, Oviedo, and Santander have not followed the indicated behavior. Performing a lower percentage of the variable explained by a higher number of harmonics contributes to explain the total variance. Its graphical representation indicates the existence of certain anomalous points. The data of solar radiation of these stations should be revised.

The Typical Annual Time Function obtained through the analysis and reduction of a great number of data, when synthesized in a simple expression and of easy use, permits us to calculate the most probable value of global solar radiation over a horizontal surface, in a given date of a year for each of the 21 analyzed stations.

The applied method permits its application to the new measurements of solar radiation that are being carried out. This will be necessary because of the number of years used in this study, especially in some stations. That is, that the results are open type. New data will permit us to test the obtained results or to modify them after new available information.

The extent of the analyzed data, of more than 168 years in 24 different geographical points, permits us to confirm the validity of methodolological process to obtain the Typical Annual Time Functions for the

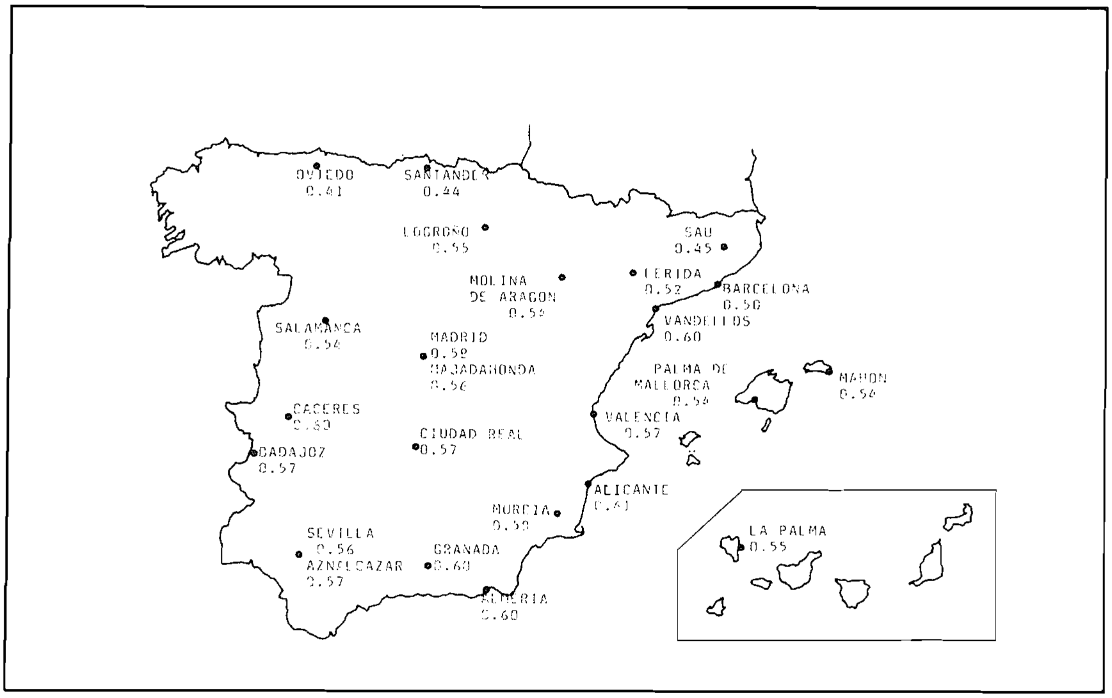

Fig. 5. Annual average value of the attenuation of solar radiation by the atmosphere for each of the studied stations.

meteorological variables with a strong annual component, like air temperature or air pressure.

REFERENCES

1. K. Adamowski, Spectral density of a river flow time series. *J. Hidrology* **14,** 43–52 (1971).
2. J.M. Baldasano, y A. Coronas, Análisis de la radiación solar global. Ecuación "año tipo. *Energía* **VII**(2), 109–112 (1981).
3. J.M. Baldasano, y A. Coronas, Aplicación del análisis de Fourier a datos meteorológicos: Irradiación solar, temperatura del aire y tensión de vapor. International Solor Energy Symposium Solar 83. Palma de Mallorca (1983).
4. R.C. Balling, Jr., Harmonic analysis of monthly insolation levels in the United States *Solar Energy* **31**(3), 293–298 (1983).
5. R.C. Balling, Jr. and R.S. Cerveny, Spatial and temporal variations in long-term normal percent possible solar radiation levels in the United States, *J. Climate and Applied Meteorology* **22,** 1726–1732 (1983).
6. C.E.P. Brooks, and N. Carruthers, *Handbook of Statistical Methods in Meteorology*, 2nd ed., 412 pp. Her Majesty's Stationery Office, London, (1978).
7. J. Clar, Aplicación del análisis de Fourier a datos de radiación solar en España. Tesis de Licenciatura. Universitat de les Illes Balears, Palma de Mallorca (1986).
8. A. Coronas, and J.M. Baldasano, Fourier analysis of meteorological data to obtain a typical annual time function. *Solar Energy* **32**(4), 479–488 (1984).
9. M. Egido, J.M. Yuste, J. Garmendia, y J. Seco, Estudio armónico y estadístico de la radiación solar en salamanca. *Anal. de Edafología y Agrobiología* **XXXIX**(1–2), 277–295 (1980).
10. O. Essenwanger, *Applied Statistics in Atmospheric Science*, 1st ed., 412 pp. Elsevier, (1976).
11. I. Font, *Atlas de la Radiación Solar en España*. Instituto Nacional de Meteorologia, Madrid (1984).
12. Instituo Nacional de Meteorología, *Radiación Solar Global en España. Años 1957 a 1973*. Publicación D-34, 91 pp. Madrid, (1974).
13. Instituo Nacional de Meteorología, *Radiación Solar Global en España. Año 1974*. Publicación D-37, 41 pp. Madrid, (1976).
14. Instituo Nacional de Meteorología, *Radiación Solar Global en España. Años 1975 y 1976*. Publicación D-39, 114 pp. Madrid, (1980).
15. Instituo Nacional de Meteorología, *Radiación Solar Global en España. Años 1977 y 1978*. Publicación D-40, 172 pp. Madrid, (1982).
16. Instituo Nacional de Meteorología, *Radiación Solar Global en españa. Años 1979 y 1980*. Publicación D-41, 216 pp. Madrid, (1983).
17. L.L. Long, Water temperature forecasting and estimation using Fourier series and comunication theory techniques. *Water Resources Research* **12**(5), 881–887 (1976).
18. P. Mateo, *Un Estudio de las Temperaturas Diarias de Gijón*. Instituto Nacional de Meteorología, Madrid, Spain, Serie A, no. 45 (1967).
19. W.F. Phillips, Harmonic analysis of climatic data. *Solar Energy* **32**(3), 319–328 (1984).
20. R.V., Thomann, Time-series analyses of water-quality data. *J. Sanitary Engineering Division* **93**(SA1), 1–23 (1967).