

A New Method for Determining the Ångström Turbidity Coefficient from Broadband Filter Measurements

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ABSTRACT

In this work, a new method for determining Ångström turbidity coefficients is presented. This method is based on broadband filter irradiance measurements. By combining measurements obtained with different filters it is possible to obtain a single value of the turbidity coefficient representative of the whole measurement range of the pyrheliometer. The results provided by this new method are compared with the original Ångström method and turbidity coefficient values derived by spectroradiometric measurements. The results reproduce the actual values, as measured by a spectroradiometer, better than the previous best correlation did, thus demonstrating the advantage of analyzing the optical thickness from bands covering the whole spectral range.

1. Introduction

Turbidity is a dimensionless measure of the opacity of a vertical column of the atmosphere. It is a numerical quantification of the total column extinction of transmitted radiation by atmospheric aerosols for some finite band in the solar electromagnetic spectrum. Turbidity is so closely related to aerosol optical thickness that it is difficult to establish from a historical point of view when these two terms first were used to name different concepts (WMO 1994a).

Monitoring the aerosol optical thickness of the atmosphere, in principle, requires very simple measurements of the relative solar spectral irradiance and the application of the Beer–Lambert–Bouguer law. Although this law is very straightforward, its implementation has as many variations as there are investigators who use it. The central problem is the lack of agreement on the accuracy with which the aerosol optical thickness should be derived. Uncertainties arise in the computation of the air mass, in the calculations of the Rayleigh and ozone optical thicknesses, and in the derivation of water vapor expressed as total column abundance or precipitable water. For a long time, sun photometers, which measure the direct solar irradiance under clear-sky conditions, have been the instruments usually employed to measure aerosol optical thickness, especially since the second World Meteorological Organization ex-

pert meeting on turbidity measurements recommended that the measurements obtained by means of broadband pyrheliometers should be removed from the updated turbidity Background Air Pollution Monitoring Network archive. The lack of agreement on corrections, calibration procedures, data analysis procedures, and so on often caused by divergent error tolerances or the specific requirements of various investigators, however, has rendered questionable many results from these instruments.

Investigators currently are searching for alternatives to the sun photometers that are easier to manipulate, are more accurate, and are less expensive. One such alternative is to reconsider pyrheliometric direct total irradiance measurements, provided that an instrument stability of 0.5% can be maintained over intervals of 1–2 yr (WMO 1994a, 1994b). Another possibility could involve some form of multifilter rotating shadowband radiometer, which determines almost simultaneously the global and diffuse irradiances at various wavelengths (WMO 1994a; Gueymard 1998; Holben et al. 1998).

Given the radiative effects of aerosols, different methods have been developed to deduce atmospheric turbidity indexes that explain the corresponding attenuation of solar radiation. These indexes relate to the ground-level reduction of the extraterrestrial solar irradiance for the whole solar spectrum. Ångström (1961) proposed an expression for the aerosol optical thickness $\tau_{a\lambda}(\lambda)$ including the effects that correspond to absorption and scattering:

$$\tau_{a\lambda} = \frac{\beta}{\lambda^\alpha}. \quad (1)$$

The β coefficient, known as the Ångström turbidity co-

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efficient, expresses the aerosol content of the atmosphere in the zenith direction, and is defined as the aerosol optical thickness corresponding to a wavelength of $1 \mu\text{m}$. The wavelength exponent α is an index for the aerosol size distribution. The Ångström formula is only a convenient approximation. It is not necessarily valid over an extended spectral range, and Ångström parameters that work properly in a given range might not be so appropriate in another. Nevertheless, the Ångström formulas seem to provide a good parameterization of spectral aerosol optical thickness for the 400–670 nm band (Martínez-Lozano et al. 1998).

Although the experimental determination of the Ångström turbidity coefficient should be carried out from spectral measurements of solar radiation, such measurements usually are not available, so sun photometers with one or more measurement bands normally are used. In the case of data from a single filter instrument, the aerosol wavelength exponent α is assumed to be constant and equal to 1.3. It also is possible, however, to determine the values of β and α simultaneously from aerosol transmittances at two wavelengths using sun photometers. Volz (1974) proposed this method, and Bokoye et al. (1997) recently have suggested that the values obtained in this way could be named as turbidity standard coefficients. For identical atmospheric conditions, however, the α , β pairs obtained depend strongly on the method used to derive them, and, even for the same method, they can depend on the wavelength pairs selected (Cachorro et al. 1987, 1989; Cuomo et al. 1993; Bokoye et al. 1997). Bokoye et al. (1997) have shown that the optimum wavelength pair in the 290–900 nm interval is 400 nm and 750 nm when using the Volz method.

If integrated measurements are used that are taken, for example, by a pyrliometer, they may correspond to the whole spectrum (integrated irradiance measurements) or to spectral bands selected by filters (broadband filter irradiance measurements). Several authors (Louche et al. 1987; Pinazo et al. 1995; Gueymard 1998) have proposed different parameterization models for obtaining β from integrated solar irradiance measurements. Because these methods are parametric in the whole spectral range, they cannot be used to determine the values of the couple (α , β) simultaneously.

The methods that use the broadband filter irradiance measurements are based on the original method proposed by Ångström (1961, 1964), which employs normal direct irradiance measurements obtained by cutoff filters. These filters are opaque below a determined wavelength. The cutoff wavelength is the one that causes a reduction of about 50% in the filter transmissivity. The selective use of spectral bands obtained by such filters allows the absorption effects caused by some atmospheric constituents such as water vapor to be eliminated and the evaluations of the turbidity coefficients to be simplified. These methods may be considered to be an intermediate technique between sun photometry

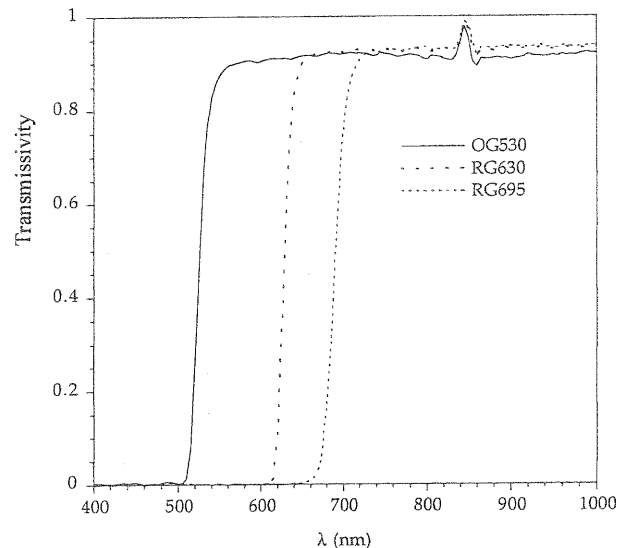


FIG. 1. Transmissivity curves of the filters obtained experimentally.

and the methods that employ broadband measurements and produce lower precision in the optical thickness. Nevertheless, the Ångström method suffers from the same problem that the methods based on photometer measurements employing the Volz technique do, that is, it is highly dependent on the selection of the spectral bands because different band combinations produce different α and β values.

In this work, an alternative to the Ångström method that eliminates this problem is presented. The proposed method, instead of considering the different bands separately and obtaining values of α and β for each, considers all the bands together and so obtains a single value for each of the turbidity coefficients that is representative of the whole measurement range.

2. Instrumentation and measurements

The measurements were taken on the terrace of the Faculty of Physics, Valencia University, Spain, 40 m above sea level (39.5°N , 0.4°W). The obstructions above the horizon were less than 4° , except in a small zone to the northwest. An Eppley Laboratory, Inc., Normal Incidence Pyrliometer (NIP) was used to measure normal direct irradiance I . For the determination of the irradiance corresponding to different spectral bands, the cutoff filters Schott OG1 (spectral band, 530–2800 nm), RG2 (spectral band, 630–2800 nm) and RG8 (spectral band, 690–2700 nm), provided by the Eppley Laboratory and adapted to NIP, were used. Figure 1 shows the actual transmissivity curves of these filters as obtained in the Asociación Industrial de Óptica, Valencia by means of a PerkinElmer, Inc., Lambda 19 spectrophotometer with a spectral range of 380–2500 nm and 1-nm resolution. The average precision of the measurements was estimated to be 0.9%. The peak appearing near 850

nm in the curves of Fig. 1 is caused by a change in the filter of the spectroradiometer, and its effects are less than 0.01% of the values of irradiance obtained from these curves of transmissivity. On the other hand, the transmissivity of these filters shows a nonnegligible dependence on the temperature (Sadler 1978). In the 20°–40°C range, the changes in the effective wavelength from these temperature effects are lower than 5 nm, and the cutoff values of the different curves can be estimated at approximately 530, 630, and 690 nm.

By coupling these pyrheliometric filters, it is possible to evaluate experimentally the integrals

$$\int_{530}^{2800} I_{n\lambda} d\lambda, \quad \int_{630}^{2800} I_{n\lambda} d\lambda, \quad \text{and} \quad \int_{690}^{2700} I_{n\lambda} d\lambda, \quad (2)$$

where $I_{n\lambda}$ is the spectral direct irradiance. By combining them, the following also can be evaluated:

$$\int_{530}^{630} I_{n\lambda} d\lambda, \quad \int_{530}^{690} I_{n\lambda} d\lambda, \quad \text{and} \quad \int_{630}^{690} I_{n\lambda} d\lambda. \quad (3)$$

Last, by combining the measurements obtained by filters with those obtained from the broadband-integrated direct irradiance, the following expressions are deduced:

$$\int_{280}^{530} I_{n\lambda} d\lambda, \quad \int_{280}^{630} I_{n\lambda} d\lambda, \quad \text{and} \quad \int_{280}^{690} I_{n\lambda} d\lambda. \quad (4)$$

For comparison of the spectral characteristics of real and ideal filters, the filter factor is introduced, which is the value by which the real filter transmission must be multiplied to obtain the ideal filter transmission. The effective wavelength λ_{eff} corresponding to each of the filters has also been obtained. Here, λ_{eff} is defined as (Kondratyev 1969)

$$\lambda_{\text{eff}} = \frac{\int_{\lambda_1}^{\lambda_2} I_{0\lambda} P_{\lambda} \lambda d\lambda}{\int_{\lambda_1}^{\lambda_2} I_{0\lambda} P_{\lambda} d\lambda}, \quad (5)$$

where P_{λ} is the transmissivity factor, and I_0 is the extraterrestrial irradiance. A more accurate value of λ_{eff} could be determined taking into account factors such as the ozone absorption and the Rayleigh scattering. The calculation of λ_{eff} considering these factors implies the definition of a different λ_{eff} value for each ozone content and for each optical mass, however (note that the values of both transmissivities depend in turn on these factors). Because this makes the calculation too involved and achieves only a slight increase in precision, the approximation given in Eq. (5) will be used. To solve Eq. (5), the values of $I_{0\lambda}$ proposed by the Simple Model for the Atmospheric Radiative Transfer of Sunshine (SMARTS2) code (Gueymard 1995) have been used. The λ_{eff} values used here are presented in Table 1.

TABLE 1. Width and effective wavelength of the bands used.

Band (nm)	λ_{eff} (nm)
280–530	427
280–630	481
280–690	508
530–630	555
530–690	588
630–690	650
530–2500	998
630–2500	1095
690–2500	1154

3. Methodology

Ångström (1961) suggested a method for the determination of the β coefficient based on broadband filter irradiance measurement. This method uses Beer's law independently on each of the bands, selecting the integration bands in such a way that allowed the exclusion of water vapor. This exclusion in these methods probably was not perfect because, considering that the composition of the atmosphere is steady, the water content becomes the parameter with the highest influence on β , and, for different values of the water content, the variation of β may be near 20% in some cases (Pedrós et al. 1999). With definition of λ_{eff} for each band and consideration of the relation existing between the turbidity coefficients [Eq. (1)], the irradiance corresponding to a band included within λ_1 and λ_2 may be expressed as

$$I_{n\Delta\lambda} = I_{0(\lambda_1-\lambda_2)} \exp[-(\tau_{\text{oz}\lambda_{\text{eff}}} + \tau_{R\lambda_{\text{eff}}})m] \exp(-\beta m \lambda_{\text{eff}}^{-\alpha}), \quad (6)$$

where τ_{oz} and τ_R represent the optical thickness corresponding to ozone and Rayleigh scattering, respectively; m is optical air mass, and $I_{0(\lambda_1-\lambda_2)}$ is the extraterrestrial irradiance integrated within λ_1 and λ_2 . Through use of the irradiance measurements obtained with the different cutoff filters, it is possible to obtain the irradiance for the spectral regions with different wavelength limits. A general expression for each one of these spectral band has the form

$$I_{n\Delta\lambda} = C \exp(-\beta \lambda_{\text{eff}}^{-1.3} m), \quad (7)$$

where C includes the contribution of the nonaerosol atmospheric components that cause some attenuation in the band (in this case, ozone absorption and Rayleigh scattering). To calculate both α and β simultaneously, it is enough to consider the experimental values corresponding to any two bands. To do this calculation, Ångström (1961) obtained the values of C from tables that relate the solar constant in each band to the optical mass and the β coefficient. These days, the methods for the determination of both the solar constant and the cutoff filter transmissivity factors have been improved significantly, and the values of C can be calculated much more accurately (Cachorro et al. 1987; Marco and Iqbal 1987).

The main problem with this method is, as discussed

above, the choice of the most adequate bands. This problem is similar to what happens with the Volz method applied to sun photometers (Cachorro et al. 1987, 1989; Cuomo et al. 1993; Bokoye et al. 1997). With measurements made using three different cutoff filters as well as the whole spectrum-integrated irradiance, and using only the bands without high absorption by water vapor, it is possible to perform up to 15 different combinations of band pairs, with different values of α and β .

As an alternative to this procedure, a new method is described whereby, instead of considering the different bands separately, all the bands are considered jointly to produce a single value for each of the two coefficients. Table 1 presents all the bands used, covering the whole measurement range of the pyrheliometer.

The application of Beer's law to a specified spectral band gives

$$I_{n\Delta\lambda} = I_{0\Delta\lambda} T_{a\Delta\lambda} T_{R\Delta\lambda} T_{g\Delta\lambda} T_{w\Delta\lambda} T_{oz\Delta\lambda} T_{N\Delta\lambda}, \quad (8)$$

and, for the aerosol optical thickness,

$$\tau_{a\Delta\lambda} = -\frac{1}{m} \ln \left(\frac{I_{n\Delta\lambda}}{I_{0\Delta\lambda} T_{R\Delta\lambda} T_{g\Delta\lambda} T_{w\Delta\lambda} T_{oz\Delta\lambda} T_{N\Delta\lambda}} \right). \quad (9)$$

The transmissivities due to Rayleigh scattering $T_{R\lambda}$ and to the absorption of the different atmospheric constituents (ozone $T_{oz\lambda}$, nitrogen dioxide $T_{N\lambda}$, water vapor $T_{w\lambda}$, and homogeneous mix of gases $T_{g\lambda}$) have been evaluated by using the expressions proposed by Gueymard (1995):

$$T_{R\lambda} = \exp[-m_R P / (117.2594\lambda^4 - 1.3215\lambda^2 + 3.2 \times 10^{-4} + 7.68 \times 10^{-5}\lambda^{-2})], \quad (10)$$

$$T_{oz\lambda} = \exp(-A_{oz\lambda} u_{oz} m_{oz}), \quad (11)$$

$$T_{w\lambda} = \exp\{-[(m_{oz} w)^{1.05} A_{w\lambda} B_w f_w^n]^c\}, \quad (12)$$

$$T_{g\lambda} = \exp[-(A_{oz\lambda} u_g m_{oz})^a], \quad \text{and} \quad (13)$$

$$T_{N\lambda} = \exp(-A_{n\lambda} u_n m_n), \quad (14)$$

where $A_{i\lambda}$ are the extinction coefficients corresponding to the different absorption components, and m_i are the corresponding optical air masses; u_i are the reduced path lengths; w is the total precipitable water; B_w is a correction factor that takes into account that the absorption process varies with the distance from the band center; f_w is a pressure scaling factor that compensates for variations in the water path length by applying the Curtis-Godson approximation. The factors n , c , and a are defined in Gueymard (1995).

In theory it is possible to consider the effective wavelength as representative of a specific band, but such an approximation is not valid for the transmissivities because the absorption by different atmospheric constituents is strongly selective and Eqs. (10)–(14) are valid only for the specific wavelength to which the corresponding absorption coefficient is assigned. It is nec-

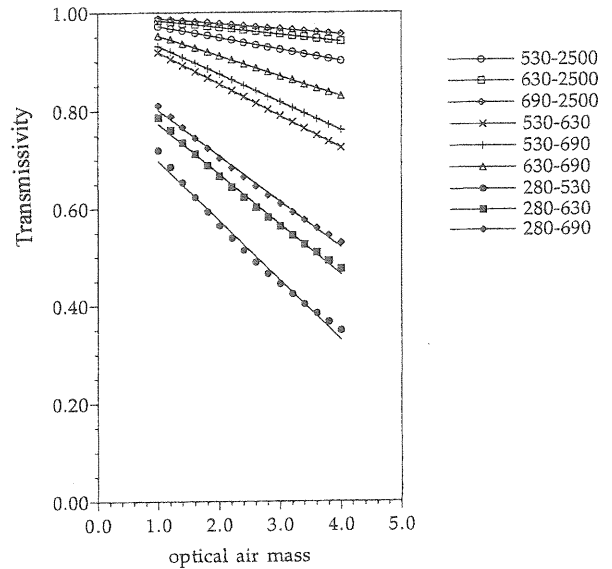


FIG. 2. Rayleigh-scattering transmissivity of the different bands as a function of the optical mass.

essary to work with transmissivities integrated over whole band. Such integrated transmissivities have been determined using a procedure analogous to that employed for the determination of the effective wavelength corresponding to each band. Thus, the transmissivity $T_{i\Delta\lambda}$ of a component i , corresponding to a spectral band with limits λ_1 and λ_2 , is

$$T_{i\Delta\lambda} = \frac{\int_{\lambda_1}^{\lambda_2} I_{0\lambda} T_{i\lambda} d\lambda}{\int_{\lambda_1}^{\lambda_2} I_{0\lambda} d\lambda}. \quad (15)$$

With use of Eqs. (10)–(14) to calculate Eq. (15), the expressions for the transmissivities corresponding to the different extinction processes are linear with the exception of that corresponding to water vapor.

Figures 2–5 show, for different bands, the integrated values of the transmissivities $T_{R\lambda}$, $T_{oz\lambda}$, $T_{N\lambda}$, and $T_{g\lambda}$. As observed, in all cases a linear fit is possible. Although it is difficult to observe in the figures, in most of the cases it also should be possible to perform a higher-order polynomial fitting, but the effort of introducing new coefficients is not rewarded with a higher precision in the results. Table 2 presents the parameters of these fits. In the case of water vapor, the integrated transmissivity presents a double dependence on both optical mass m and the precipitable water content w . To obtain $T_{w\Delta\lambda}$ corresponding to any of the bands, a first fit with the optical mass for determined values of w has been made. As an example, Figs. 6 and 7 show the dependence of $T_{w\Delta\lambda}$ on the optical air mass for different values of w and for the bands 280–530 and 630–2500 nm, respectively. It is observed that, for the spectral bands

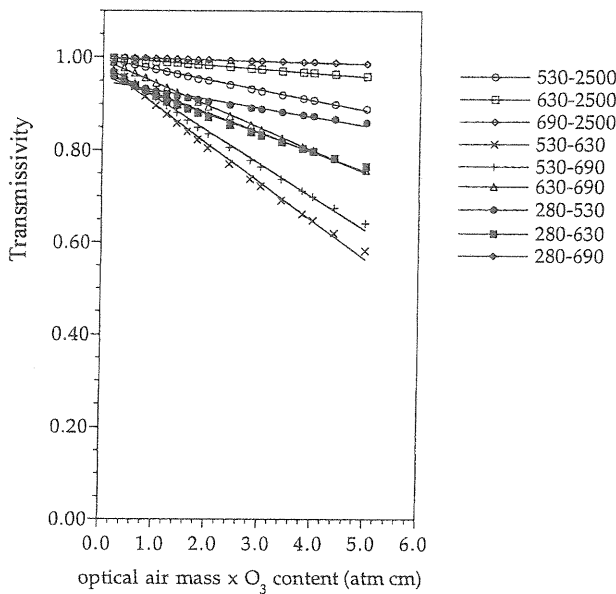


FIG. 3. Ozone (O_3) absorption transmissivity as a function of the product of optical mass times O_3 content.

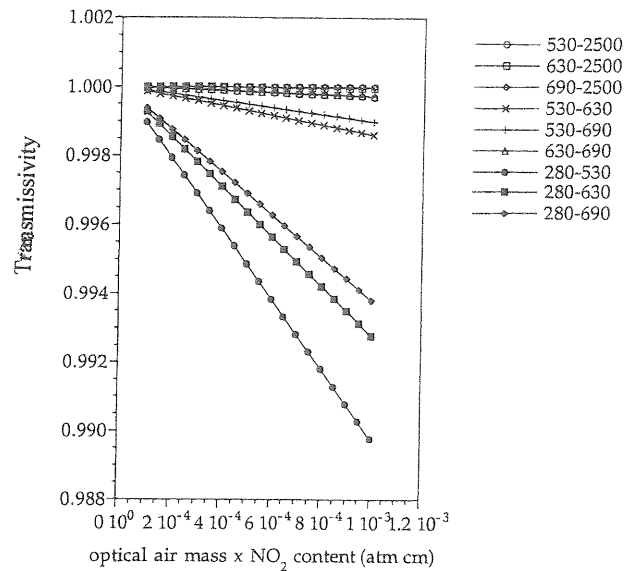


FIG. 4. Nitrogen dioxide (NO_2) absorption transmissivity as a function of the product of optical mass times NO_2 content.

having low absorption by water vapor, the dependence of integrated transmissivity on optical air mass is linear (i.e., 280–530-nm band, Fig. 6). Otherwise, if bands with water vapor absorption in the near infrared are included, the integrated transmissivity presents a logarithmic dependence on m (i.e., 630–2500-nm band, Fig. 7). The dependence of the transmissivity on the precipitable water is introduced afterward by analyzing the slope of the curves as a function of w . Figure 8 shows this dependence for the whole set of bands. In Table 3 the results obtained for the fits of $T_{w\Delta\lambda}$ versus m and w , together with the standard deviation and the root-mean-square deviation (rmsd) for each fitting, are summarized.

Once the integrated transmissivities are determined for any one of the bands, the value of the aerosol optical thickness is obtained from Eq. (9), considering that the different extinction processes have independent transmissivities. If the effective wavelength is representative of the whole band, and with use of Eq. (1), the following expression is obtained:

$$\ln \tau_{a\Delta\lambda} = \ln \beta - \alpha \ln \lambda_{\text{eff}}. \quad (16)$$

Equation (16) represents, for a specific time and a known effective wavelength, the relation between the aerosol optical thickness and the coefficients α and β representing the whole spectral interval. To determine an instantaneous value of the coefficients corresponding to any one of the experimental measurement series, nine pairs of values ($\ln \lambda_{\text{eff}}, \ln \tau_{a\Delta\lambda}$) corresponding to the nine spectral bands defined in Table 1 are available. With these values, it is possible to perform a least squares fitting of $\ln \tau_{a\Delta\lambda}$ versus $\ln \lambda_{\text{eff}}$ to obtain a single pair of values β and α .

4. Results and discussion

Both the Ångström method and the new one proposed in this work have been applied to experimental measurements of 22 clear days in 1995: a total of 126 series of instantaneous measurements corresponding to optical air masses in the interval 1–4.

a. Ångström method

To use the Ångström method, a constant value of 1.3 was taken for the α coefficient, a value that is commonly accepted in the literature (Ångström 1961; Louche et

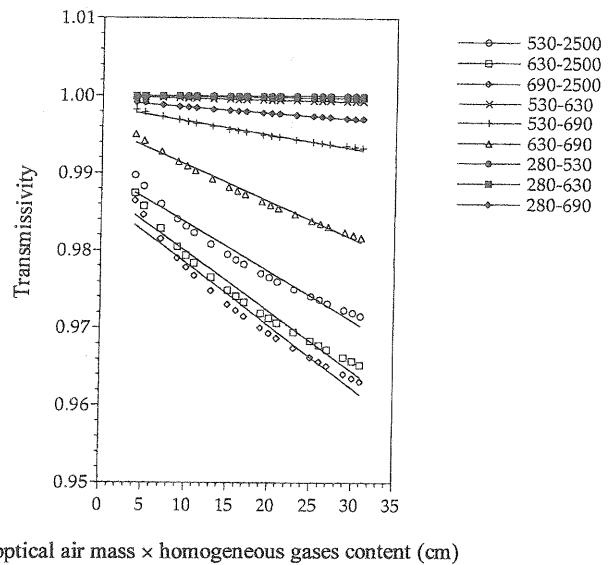


FIG. 5. Homogeneous mix of gases absorption transmissivity as a function of the product of optical mass times gas content.

TABLE 2. Linear regressions of the integrated transmissivities for Rayleigh ($T_{R\Delta\lambda}$), ozone ($T_{oz\Delta\lambda}$), nitrogen dioxide ($T_{NO_2\Delta\lambda}$), and mix of gases ($T_{g\Delta\lambda}$). Correlation coefficient is in parentheses. The variables m and u_i are defined in the text.

Band (nm)	$T_{R\Delta\lambda}$	$T_{oz\Delta\lambda}$	$T_{NO_2\Delta\lambda}$	$T_{g\Delta\lambda}$
530–2500	$0.996 - 0.02m$ (0.99)	$0.996 - 0.02mu_{oz}$ (0.99)	$1 - 0.29mu_n$ (0.99)	$0.990 - 0.0006mu_g$ (0.98)
630–2500	$0.999 - 0.0014m$ (0.99)	$0.999 - 0.008mu_{oz}$ (0.99)	$1 - 0.03mu_n$ (0.99)	$0.988 - 0.0008mu_g$ (0.98)
690–2500	$0.999 - 0.0011m$ (0.99)	$0.999 - 0.003mu_{oz}$ (0.99)	1.0 (1.0)	$0.987 - 0.0008mu_g$ (0.987)
530–630	$0.983 - 0.06m$ (0.99)	$0.983 - 0.08mu_{oz}$ (0.99)	$1 - 1.4mu_n$ (1.0)	$0.999 - 0.0002mu_g$ (0.99)
530–690	$0.988 - 0.06m$ (0.99)	$0.987 - 0.07mu_{oz}$ (0.99)	$1 - 1.0mu_n$ (1.0)	$0.999 - 0.0002mu_g$ (0.99)
630–690	$0.995 - 0.04m$ (0.99)	$0.995 - 0.05mu_{oz}$ (0.99)	$1 - 0.27mu_n$ (0.99)	$0.996 - 0.0005mu_g$ (0.99)
280–530	$0.826 - 0.12m$ (0.98)	$0.948 - 0.02mu_{oz}$ (0.97)	$0.999 - 10.2mu_n$ (1.0)	1.0 (1.0)
280–630	$0.880 - 0.10m$ (0.99)	$0.958 - 0.04mu_{oz}$ (0.98)	$0.999 - 7.2mu_n$ (1.0)	$0.999 - 0.000007mu_g$ (0.99)
280–690	$0.897 - 0.09m$ (0.99)	$0.970 - 0.04mu_{oz}$ (0.99)	$1.0 - 6.2mu_n$ (1.0)	$0.999 - 0.00008mu_g$ (0.99)

al. 1987; Pinazo et al. 1995; WMO 1994a). With this value for α , the β coefficient has been determined for the spectral bands proposed by Ångström. These bands are the same six as the first six bands in Table 1 and correspond to the bands that do not present water vapor absorption. These values of the turbidity coefficient correspond to what Gueymard (1994) proposes to represent as β^* . This nomenclature is employed here. When the turbidity coefficient values β^* calculated for several spectral bands are very different, Ångström (1961) suggests to use the so-called true values (α_0 and β_0) obtained from band pairs following Eq. (6).

In this work, the values of β^* , α_0 , and β_0 have been determined. The values of $I_{0\lambda}$ proposed by the SMARTS2 code (Gueymard 1995) have been used. For the ozone content, the measurements taken in Madrid (40.5°N, 3.7°W) by the Instituto Nacional de Meteorología (INM) using a Brewer spectroradiometer were used. For the NO₂ content, two of the reference atmospheres proposed by the Low-Resolution Transmittance Model and Code (LOWTRAN 7) (Kneizys 1988) have been considered, specifically, the effective path

lengths of NO₂ for midlatitude summer and midlatitude winter.

Table 4 presents, as an example, the results corresponding to the instantaneous values of the turbidity coefficient β^* for three days of different turbidity conditions, low (13 December 1995), high (3 March 1995), and moderate (27 August 1995). The classification made is a relative one within the turbidity range obtained in Valencia. The choice of these three days is based on an analysis of the turbidity in Valencia carried out using integrated direct irradiance measurements (Pedrós 1997). The uncertainties associated with the turbidity coefficient were calculated by the error propagation method, assuming values of 5 nm for the effective wavelength, 0.001 for the ozone absorption coefficient, 3% for the band irradiance measurement at ground level, and 1% for the extraterrestrial solar irradiance. The error associated with the optical mass values depends on the hour of the day and on the time spent in making the measurements. In this case, because this time is about 6 min, we can assume 1.5% for the mean value of the

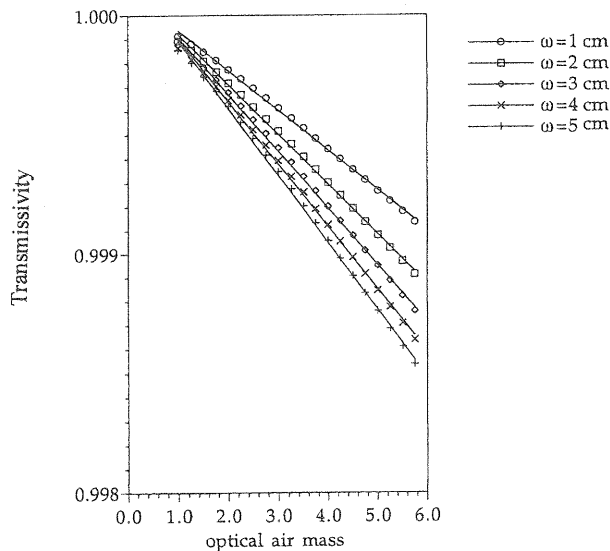


FIG. 6. Water vapor absorption transmissivity as a function of the optical mass for different preset values of the precipitable water vapor amount: 280–530-nm band.

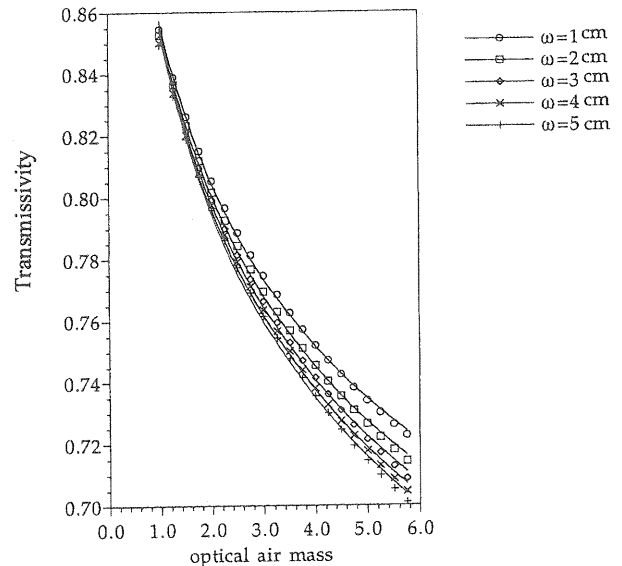


FIG. 7. Water vapor absorption transmissivity as a function of the optical mass for different preset values of the precipitable water vapor amount: 630–2500-nm band.

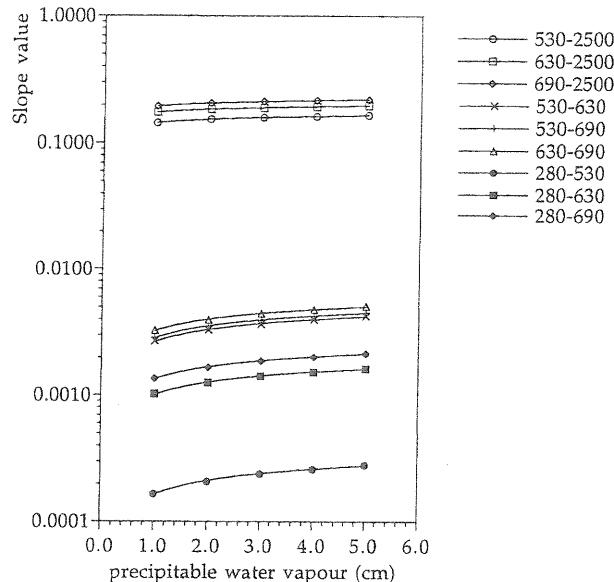


FIG. 8. Dependence of the fit slopes of the water vapor transmissivity as a function of the optical mass against the precipitable water vapor amount.

error associated with the optical air mass. In Fig. 9, the evolution of β^* as a function of the optical air mass for 27 August 1995 is shown as representative of average turbidity conditions. Table 4 and Fig. 9 show big discrepancies among the β^* values obtained for the different bands. The errors associated with β^* are high (about 20%), but the differences between the values determined for different bands are considerably higher, implying that the calculated errors do not justify the differences.

The main error source may be the value 1.3 taken for the α coefficient. Nicholls (1984) shows that this value is correct only if the aerosols follow the so-called power law distribution (Junge 1960) with an exponent value of 4. This hypothesis is approximately valid only for aerosols of the continental type, and even in this case the Junge exponent depends on wavelength. In other circumstances, 4 is not a valid value for the Junge exponent and indeed the validity of the power law distribution is questionable in many particular circumstances. Generally it is accepted that, in the absence of spectral measurements, it is not possible to establish ahead of time what kind of aerosols are present. In such cases, only an idealized Ångström model can be considered, but this model does not represent the characteristics of real aerosols (Gueymard 1998).

The use of the true values (α_0 and β_0) does not produce satisfactory results either. As an example, Figs. 10 and 11 show, respectively, the values of β_0 and α_0 corresponding to 27 August 1995 (the same day shown in Fig. 9). It is observed that, for the same day, the α_0 values corresponding to very different aerosol size distributions take apparently random values.

TABLE 3. Fit parameters of the integrated transmissivities for water vapor ($T_{w\Delta\lambda}$). Rmsd is root-mean-square deviation, and σ is standard deviation. The variables w and m are defined in the text.

Band (nm)	$T_{w\Delta\lambda}$	σ	Rmsd
530–2500	$0.88 - [0.15 + 0.005 \log(w)]\log(m)$	0.004	0.01
630–2500	$0.85 - [0.18 + 0.03 \log(w)]\log(m)$	0.006	0.02
690–2500	$0.83 - [0.19 + 0.03 \log(w)]\log(m)$	0.006	0.03
530–630	$1.0 - [0.003 + 0.002 \log(w)]\log(m)$	0.018	0.03
530–690	$1.0 - [0.003 + 0.002 \log(w)]\log(m)$	0.019	0.04
630–690	$1.0 - [0.003 + 0.003 \log(w)]\log(m)$	0.02	0.05
280–530	$1.0 - [0.0002 + 0.0002 \log(w)]\log(m)$	0.001	0.002
280–630	$1.0 - [0.001 + 0.0009 \log(w)]\log(m)$	0.007	0.01
280–690	$1.0 - [0.001 + 0.001 \log(w)]\log(m)$	0.01	0.02

b. New method

The new method described in this work is summarized in Eq. (16). To calculate the different values of transmissivity, the same approximations proposed in Eqs. (10)–(14) and described above for the Ångström method have been used for the extraterrestrial solar radiation and the NO_2 and ozone contents. The values of precipitable water vapor content have been obtained from measurements made by INM in Valencia. In the linear regressions expressed in Eq. (16), two different kinds of fit have been considered: a simple one and a weighted one. In the second case, a higher weight has been assigned to the points where the solar irradiance I_0 in the absence of the atmosphere is higher. In this way, the weight function is of the form

$$p(\Delta\lambda) = \frac{I_0(\Delta\lambda)}{I_0}, \quad (17)$$

where $p(\Delta\lambda)$ represents the contribution of the irradiance in the considered band to the total irradiance in the employed spectral interval.

The results obtained by this method for the same days considered in Table 4 are shown in Table 5. As is observed, the uncertainty in the turbidity coefficient values always is lower than 0.02, the highest value accepted for the determination of aerosol optical depth in pass bands dominated by Rayleigh and aerosol extinction (Holben 1998; WMO 1994b). The α values oscillate between 0.28 and 1.13 for the 22 days of measurements. This oscillation suggests a highly variable mix of continental and marine aerosols whose composition basically depends on the prevailing wind direction. The city of Valencia is situated on the Mediterranean coast where marine breezes predominate, leading to a high concentration of marine-type aerosols (Utrillas et al. 1998).

Figures 12 and 13 show the evolution of the turbidity coefficient and the wavelength exponent with the optical air mass for 27 August 1995. It may be observed that their evolution does not present, in general, any visible anomalies that invalidate the coherence of this method. Fig. 14 represents the linear regressions between the turbidity coefficient values obtained by a simple fit (β) and a weighted one (β_p). It can be observed that the

TABLE 4. Instantaneous values of the turbidity coefficient β^* for 13 Dec 1995 (low turbidity), 27 Aug 1995 (moderate turbidity), and 3 Mar 1995 (high turbidity) (Ångström method). Here, ε is uncertainty.

Hour (LST)	530–630 nm		530–690 nm		630–690 nm		280–530 nm		280–630 nm		280–690 nm	
	β^*	$\varepsilon(\beta^*)$	β^*	$\varepsilon(\beta^*)$	β^*	$\varepsilon(\beta^*)$	β^*	$\varepsilon(\beta^*)$	β^*	$\varepsilon(\beta^*)$	β^*	$\varepsilon(\beta^*)$
3 Mar 1995												
0845	0.15	0.05	0.15	0.05	0.15	0.04	0.13	0.08	0.17	0.06	0.17	0.06
0900	0.15	0.05	0.15	0.04	0.16	0.04	0.15	0.07	0.18	0.05	0.18	0.05
0915	0.13	0.04	0.14	0.04	0.15	0.03	0.15	0.06	0.17	0.05	0.18	0.04
0930	0.14	0.03	0.14	0.03	0.14	0.03	0.20	0.05	0.21	0.04	0.21	0.04
0945	0.10	0.03	0.12	0.03	0.16	0.03	0.16	0.04	0.17	0.04	0.18	0.03
1000	0.10	0.03	0.10	0.03	0.10	0.03	0.13	0.04	0.15	0.03	0.15	0.03
1015	0.11	0.03	0.11	0.03	0.11	0.03	0.13	0.03	0.15	0.03	0.16	0.03
1030	0.10	0.03	0.09	0.03	0.09	0.02	0.12	0.03	0.15	0.03	0.15	0.03
1045	0.12	0.03	0.12	0.03	0.11	0.02	0.14	0.03	0.17	0.03	0.17	0.03
1100	0.12	0.02	0.12	0.03	0.14	0.02	0.15	0.03	0.17	0.03	0.17	0.03
1115	0.14	0.02	0.13	0.02	0.13	0.02	0.15	0.03	0.18	0.02	0.18	0.02
1130	0.14	0.02	0.14	0.02	0.14	0.02	0.16	0.03	0.18	0.02	0.18	0.02
1145	0.14	0.02	0.15	0.02	0.17	0.02	0.31	0.03	0.28	0.03	0.27	0.03
1200	0.16	0.02	0.16	0.02	0.17	0.02	0.18	0.02	0.20	0.02	0.21	0.02
27 Aug 1995												
0900	0.09	0.03	0.08	0.03	0.08	0.03	0.08	0.04	0.11	0.03	0.11	0.03
0922	0.10	0.03	0.09	0.03	0.10	0.03	0.09	0.03	0.12	0.03	0.12	0.03
0942	0.09	0.03	0.09	0.03	0.08	0.03	0.10	0.03	0.12	0.03	0.12	0.03
0953	0.09	0.03	0.09	0.03	0.09	0.03	0.09	0.03	0.12	0.03	0.12	0.03
1010	0.09	0.03	0.09	0.03	0.08	0.03	0.10	0.03	0.12	0.03	0.12	0.03
1028	0.10	0.03	0.09	0.03	0.10	0.03	0.10	0.03	0.12	0.03	0.13	0.03
1045	0.09	0.03	0.09	0.03	0.09	0.03	0.09	0.03	0.12	0.02	0.12	0.03
1113	0.10	0.03	0.09	0.03	0.09	0.03	0.10	0.03	0.12	0.02	0.13	0.02
1132	0.10	0.02	0.09	0.03	0.09	0.03	0.10	0.02	0.13	0.02	0.13	0.02
1154	0.11	0.02	0.10	0.03	0.09	0.03	0.11	0.02	0.14	0.02	0.14	0.02
1213	0.11	0.03	0.10	0.03	0.10	0.03	0.11	0.02	0.14	0.02	0.14	0.02
1243	0.12	0.03	0.11	0.03	0.11	0.03	0.12	0.03	0.15	0.02	0.15	0.03
1313	0.12	0.03	0.11	0.03	0.12	0.03	0.12	0.03	0.14	0.03	0.15	0.03
13 Dec 1995												
0904	0.01	0.09	0.01	0.08	0.02	0.06	0.01	0.19	0.03	0.12	0.03	0.11
1013	0.02	0.03	0.02	0.03	0.03	0.02	0.02	0.05	0.04	0.04	0.05	0.04
1221	0.03	0.02	0.03	0.02	0.04	0.02	0.04	0.03	0.06	0.02	0.07	0.02
1241	0.04	0.02	0.04	0.02	0.05	0.02	0.05	0.02	0.07	0.02	0.07	0.02
1411	0.04	0.02	0.04	0.02	0.05	0.02	0.05	0.03	0.07	0.02	0.07	0.02
1513	0.04	0.05	0.04	0.05	0.05	0.04	0.06	0.09	0.08	0.06	0.08	0.06

coefficients obtained from both fits are very similar, with slightly higher values for the simple fit.

c. Spectral values of the optical thickness for 1000 nm

In the above sections, three different broadband turbidity coefficients have been considered. Two of these coefficients are evaluated by the Ångström method, that is, by considering α to be constant ($\alpha = 1.3$, β^*) or by considering different band combinations in a way similar to the Volz method employed in sun photometry (α_0 , β_0). The third is calculated by means of the method described in this work for the first time and uses the whole set of the solar spectral bands to obtain single values for α and β . The analysis of the errors associated with each coefficient shows the precision of the corresponding method but does not show the validity of the broadband turbidity coefficients for determining the aerosol optical thickness at 1000 nm, which is also the

turbidity coefficient defined by Ångström. To determine which result comes nearest to this turbidity coefficient, it is necessary to compare the values obtained by the different methods described above with the values obtained from spectral measurements. In this sense, the different broadband methodologies must be checked by analyzing the goodness of the fit between their estimations of the Ångström coefficient and the values obtained by means of a spectroradiometer. Experimental values corresponding to six clear days (50 measurement series) in the months of February and March of 1998 have been used with this aim. The spectral solar irradiance measurements were obtained using a LI-COR, Inc., 1800 spectroradiometer. For the direct irradiance measurements, a radiance-limiting tube (collimator) with a field of view of 4.7° was used. The spectral band of this instrument ranges from 300 to 1100 nm, with a 6.15-nm bandwidth. The characteristics and the calibration protocol of this instrument and the measurement procedure are detailed elsewhere (Cachorro et al. 1997;

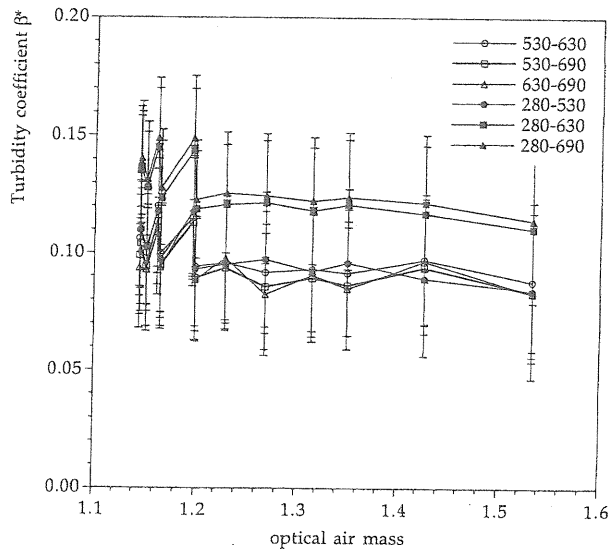


FIG. 9. Evolution of the turbidity coefficient β^* with the optical mass for 27 Aug 1995 (morning).

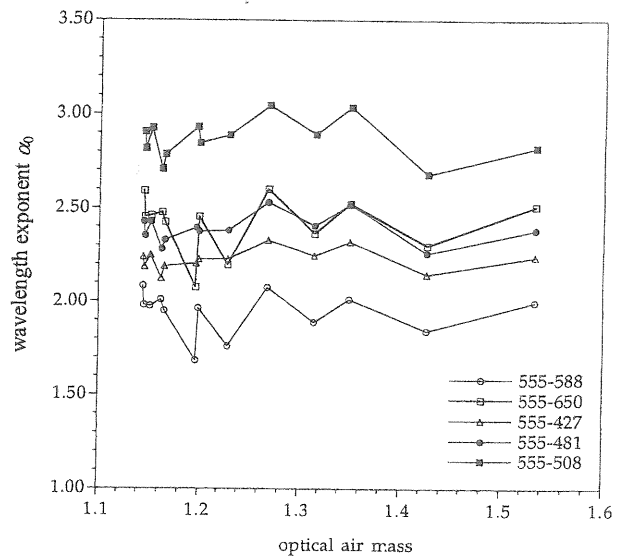


FIG. 11. Evolution of the wavelength exponent α_0 with the optical mass for 27 Aug 1995 (morning).

Martínez-Lozano et al. 1995; Myers 1989; Riordan et al. 1989).

From the spectral irradiance measurements at normal incidence, the aerosol optical thickness for the 1000-nm wavelength β_{1000} was deduced using the Beer law for all the available spectra. At this wavelength, the aerosol optical thickness can be obtained from the total optical thickness by removing only the Rayleigh optical thickness, because the absorption due to the different atmospheric gases may be considered to be negligible (Martínez-Lozano et al. 1998). This consideration is not entirely obvious because wings of lines from nearby absorption bands may still have an influence, but it is

a reasonable approximation. Relative errors associated with the β_{1000} values, obtained by applying the propagation error method, are lower than 5% (Martínez-Lozano et al. 1998).

In Table 6, the parameters of the linear fitting ($y = mx$) of β^* versus β_{1000} for the different bands are shown. It can be observed that, in the best case, the correlation coefficient is lower than 0.75, with the β^* values oscillating between 58% and 79% of the β_{1000} value. If the true values α_0 and β_0 are considered instead of considering α to be equal to 1.3, the results do not improve, as seen in Table 7. This table shows the parameters of

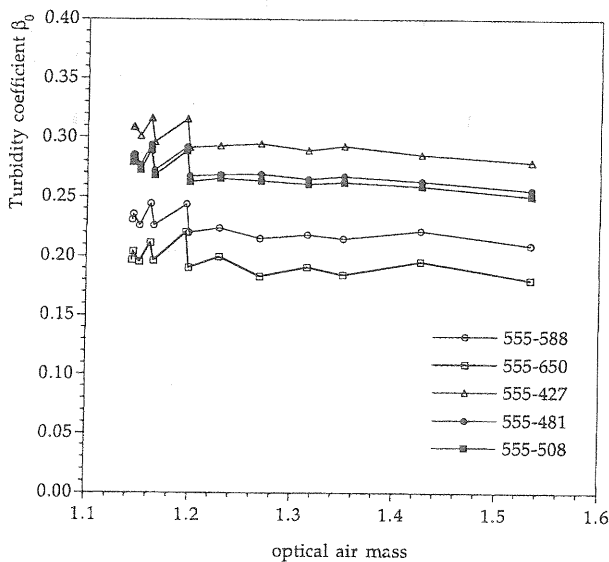


FIG. 10. Evolution of the turbidity coefficient β_0 with the optical mass for 27 Aug 1995 (morning).

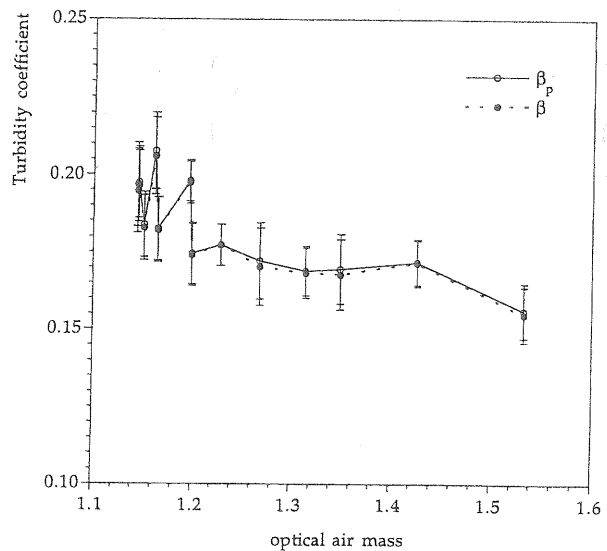


FIG. 12. Evolution, with the optical mass, of the turbidity coefficient values obtained using a simple fit (β) and a weighted one (β_p) for 27 Aug 1995 (morning).

TABLE 5. Instantaneous values of the turbidity coefficient for 13 Dec 1995 (low turbidity), 27 Aug 1995 (moderate turbidity), and 3 Mar 1995 (high turbidity) (new proposed method). The β values correspond to a simple fit, and the β_p values to a weighted one.

Hour (LST)	β	$\varepsilon(\beta)$	α	$\varepsilon(\alpha)$	β_p	$\varepsilon(\beta_p)$	α_p	$\varepsilon(\alpha_p)$
3 Mar 1995								
0845	0.218	0.010	0.67	0.08	0.221	0.010	0.67	0.08
0900	0.240	0.012	0.63	0.07	0.244	0.012	0.63	0.07
0915	0.223	0.011	0.64	0.06	0.228	0.012	0.63	0.06
0930	0.23	0.03	0.78	0.06	0.244	0.035	0.73	0.06
0945	0.22	0.03	0.60	0.05	0.221	0.028	0.60	0.05
1000	0.160	0.017	0.74	0.05	0.166	0.017	0.74	0.05
1015	0.173	0.017	0.68	0.04	0.179	0.017	0.68	0.04
1030	0.16	0.02	0.63	0.04	0.168	0.021	0.63	0.04
1045	0.20	0.02	0.60	0.04	0.21	0.02	0.61	0.04
1100	0.206	0.013	0.60	0.04	0.211	0.013	0.63	0.04
1115	0.215	0.016	0.61	0.04	0.220	0.017	0.62	0.04
1130	0.216	0.013	0.64	0.04	0.221	0.013	0.66	0.04
1145	0.25	0.05	0.98	0.04	0.27	0.05	1.03	0.04
1200	0.259	0.016	0.59	0.03	0.265	0.017	0.61	0.03
27 Aug 1995								
0900	0.154	0.009	0.44	0.05	0.156	0.009	0.45	0.05
0922	0.171	0.007	0.39	0.05	0.172	0.007	0.41	0.05
0942	0.167	0.011	0.41	0.04	0.170	0.011	0.42	0.04
0953	0.168	0.008	0.38	0.04	0.169	0.008	0.39	0.04
1010	0.170	0.012	0.36	0.04	0.172	0.012	0.38	0.04
1028	0.177	0.007	0.33	0.04	0.177	0.007	0.34	0.04
1045	0.174	0.010	0.29	0.04	0.174	0.010	0.30	0.04
1113	0.182	0.010	0.29	0.04	0.182	0.010	0.30	0.04
1132	0.183	0.011	0.32	0.04	0.184	0.011	0.34	0.04
1154	0.194	0.014	0.32	0.04	0.197	0.014	0.33	0.04
1213	0.196	0.011	0.34	0.04	0.197	0.011	0.36	0.04
1243	0.206	0.012	0.40	0.04	0.208	0.012	0.41	0.04
1313	0.197	0.007	0.47	0.04	0.198	0.007	0.49	0.04
13 Dec 1995								
0904	0.021	0.006	0.33	0.06	0.020	0.006	0.57	0.07
1013	0.028	0.004	0.86	0.04	0.029	0.004	0.91	0.04
1221	0.051	0.005	0.80	0.03	0.051	0.005	0.86	0.03
1241	0.056	0.005	0.81	0.02	0.056	0.005	0.87	0.02
1411	0.062	0.004	0.79	0.03	0.062	0.004	0.83	0.03
1513	0.066	0.007	1.00	0.06	0.068	0.007	0.96	0.06

the linear fits of β_0 versus β_{1000} for each of the band pairs (defined by effective wavelength). The results are independent of the effective wavelength, and the correlation coefficient never reaches 0.80.

If the values obtained by the new method are compared with the spectral values, one obtains

$$\beta = 0.914\beta_{1000} \quad r = 0.85, \quad (18)$$

and, if the regression line is not forced to pass through the origin,

$$\beta = 0.958\beta_{1000} + 0.007 \quad r = 0.85. \quad (19)$$

These results are evidently an improvement on those obtained using the other turbidity coefficients.

In previous papers by the authors, several spectral and broadband methods were used to obtain the Ångström turbidity coefficient at Valencia. The results show that the β values obtained from spectral measurements in the 400–670-nm band were systematically lower than the values obtained from a single wavelength of 1000 nm. The lower the turbidity, the greater was the relative difference between them (Martínez-Lozano et al. 1998). On the other hand, the β values obtained using the Louche et al. (1987) method were approximately 50% of the values corresponding to β_{1000} (Pedrós 1977). The values of β obtained using this new method based on band combinations also are lower than the β_{1000} values and intermediate to those obtained using the two previous methods. This result points out that, as the methods lose their spectral character, the results obtained for

TABLE 6. Linear fitting parameters of the β^* vs the β_{1000} values for each of the spectral bands used.

Band	Slope	r
530–630	0.579	0.75
530–690	0.607	0.72
630–690	0.762	0.53
280–530	0.638	0.70
280–630	0.751	0.68
280–690	0.785	0.68

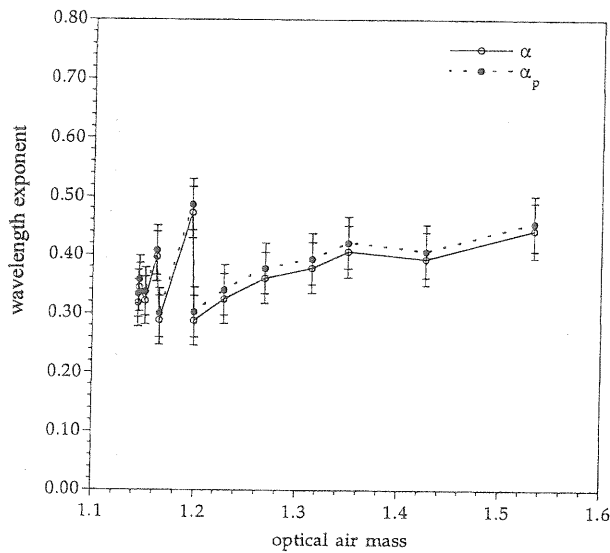


FIG. 13. Evolution, with the optical mass, of the wavelength exponent values obtained using a simple fit (α) and a weighted one (α_p) for 27 Aug 1995 (morning).

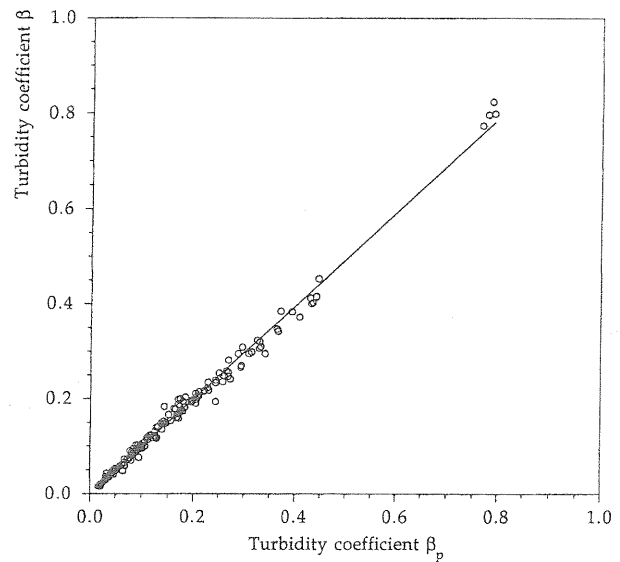


FIG. 14. Linear regression between the turbidity coefficient values obtained using a simple fit (β) and a weighted one (β_p).

β decrease when compared with the corresponding values of β_{1000} .

Last, the ideas of Molineaux and Ineichen (1996), who question whether the effects of different atmospheric attenuating factors really are independent in a broadband equation (as is assumed in the spectral equation), are considered. To establish whether the values of the turbidity coefficients obtained here are conditioned by such a dependence, all the calculations in the proposed new method have been repeated using the Molineaux and Ineichen approximation. The results show that the Molineaux and Ineichen (1996) approximation does not improve the previous ones given by Eqs. (18) and (19).

TABLE 7. Linear fitting parameters of the β_0 values vs the β_{1000} values for each of the considered band pairs (defined by their effective wavelength).

Band	Slope	r
555-588	1.838	0
555-650	1.455	0
555-427	0.729	0.67
555-481	0.720	0.61
555-508	0.608	0.55
588-650	1.319	0
588-427	0.856	0.64
588-481	0.887	0.59
588-508	0.813	0.60
650-427	0.956	0.47
650-481	1.002	0.42
650-508	0.965	0.43
427-481	0.768	0.78
427-508	0.958	0.66
481-508	1.420	0

5. Concluding remarks

A new method aimed at determining the Ångström turbidity coefficients from measurements of broadband direct irradiance with filters has been developed. The results obtained using this method have been compared with those obtained using the Ångström method, and both have been compared with the values obtained from 1000-nm-wavelength spectral irradiance measurements. For values of β_{1000} , the results provided by the proposed method improve significantly on those results obtained using the method developed by Ångström.

These values can be of interest in models used for the determination of the spectral irradiance. In these models, the aerosol optical thickness at a given wavelength (usually at 500 or 550 nm) generally is used as an input parameter. Other possible choices are the turbidity coefficients and the visibility. For the turbidity coefficient, a parameter (β^* , β_0 , or another similar one) named the β Ångström coefficient generally is used, although it is not exactly equal to the value of β_{1000} . In this context, the coefficient obtained using this new method can be employed as an input parameter for solar spectral irradiance models for the whole solar range, in the absence of values of aerosol optical thickness. The new method has two more advantages over the Ångström method: independence of the selected bands and higher precision in the coefficient β .

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