# TECHNICAL NOTE. Error source in AOD retrieval from filter radiometer data in the UV due to filter band function

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## Abstract

The filter band function of filter radiometers is frequently used in AOD retrieval to improve the accuracy of the Rayleigh and gaseous absorption contributions to the total optical depth. These contributions to the total optical thickness are overestimated when the band-pass filter curve used in the computation exceeds the lower limit of the detector response range (around 320nm). It can be the case for some typical band-pass filters used in the ultraviolet region (e.g. 340 or 380nm).

This error can involve a strong impact on the aerosol optical depth accuracy, underestimating its value. Errors as large as 0.047 in the evaluation of ozone optical depth at 340nm, and 0.009 in the Rayleigh optical depth were found, leading to final errors of 50-100% in the AOD for remote locations, like Polar regions or high mountains.
To avoid this significant error, the detector spectral response must be taken into account in the computations. Further, it is recommended to discard the filter band-pass function when the transmittance falls below 1% of its maximum value at the central wavelength.

## 1. Introduction

Cimel sun photometers use silicon photodiode detectors with typical spectral response range between 320 and 1100nm approximately, with a sensitivity peak at a wavelength around 960nm. Interference filters are situated in front of the detector to select the wavelengths of interest. A filter is a device which selectively transmits radiation in a particular range of wavelengths, blocking the others. An ideal filter would only let pass the radiation in one wavelength, but in reality filters used in sun photometry allow passing a narrow range of wavelengths, with typical values for the bandwidth (Full Width at Half Maximum, FWHM) between 2 and 10nm, and a central wavelength in which the maximum transmittance is found. However the filters transmit radiation at wavelengths outside this band, but with very low or negligible transmittance values. These are called the wings of the filter. The out-of-band blocking is typically 1E-04 to 1E-06 in sun photometric applications. We must also bear in mind the technical difficulties for an accurate out-of-band blocking evaluation (of several orders of magnitude), especially at short wavelengths.

To calculate the true radiation passing through the filter and reaching the detector, the band function of the filter, i.e. the transmittance for each wavelength must be known. The manufacture of filters is very complicated and not all filters made by the same company are exactly equal. So supplying the spectral response of each individual filter is an essential element.

In this note we are going to show an example of how the transmittances in the filter wings can affect the accuracy in the AOD retrieval if they are not computed properly. The same effect affects other atmospheric component optical depths, like ozone or water vapor (Mavromatakis et al., 2007), thus having a strong impact in their content determination. For aerosol studies, UV region is especially sensitive due to the strong ozone absorption. This effect can specially be important in clear areas with low level of AOD, like Polar Regions (Ortiz de Galisteo et al., 2008) or high altitude stations where sun photometers are usually calibrated.

## 2. Methodology

The determination of AOD by radiometric measurements is based on the comparison between the absolute direct solar irradiance measured at ground level $I(\lambda)$ and the irradiance at the top of the atmosphere corrected for the sun-earth distance $I_0(\lambda)$, according to the Beer-Lambert-Bouguer law:

$$I(\lambda) = I_0(\lambda) \cdot e^{-\tau(\lambda)\, m} \quad (1)$$

Where m is the air mass and $\tau(\lambda)$ the total spectral optical depth of the atmosphere produced by: Rayleigh molecular scattering, aerosol scattering and absorption, and absorption by ozone, water vapor, and other gases.

The difference between $I_o(\lambda)$ and $I(\lambda)$ at a wavelength $\lambda$ is due to the attenuation throughout the atmosphere. In the case of the Cimel sun photometer $I_o$ is the extraterrestrial signal (the calibration constant) and $I$ is the measured signal (both in digital counts) of the instrument. Note that a calibration to convert raw signals into physical units is not necessary for AOD evaluation.

The AOD ($\tau_a$) is calculated after subtracting from the total optical depth ($\tau$) the contribution of the other atmospheric constituents (Rayleigh, ozone, water vapor and other gases). Thus, its accuracy is affected by errors in the other components. So the AOD at a given wavelength is given by

$$\tau_a(\lambda) = \tau(\lambda) - (\tau_R(\lambda) \cdot P / P_0 + \tau_{O_3}(\lambda) + \tau_{wv}(\lambda) + \tau_g(\lambda)) \qquad (2)$$

Where the contribution due to Rayleigh scattering, $\tau_R(\lambda)P/Po$ (P and $P_o$ are the pressure at site and sea level respectively), and the absorption of ozone $\tau_{O3}(\lambda)$, water vapor $\tau_{wv}(\lambda)$ and other atmospheric gases $\tau_g(\lambda)$ in the affected wavelengths are removed.

This work is focused on sun photometers using filters to select spectral channels at wavelengths which are appropriate for aerosol studies. The spectral width of the filters, typically 10nm in the visible range and 5nm or less in the UV, influences the measurement, since eq. (1) is valid for monochromatic irradiance.

The contribution of Rayleigh scattering in the ultra-violet region is very large, increasing as $\lambda^4$, but especially important is the ozone optical depth because its strong absorption varies various orders of magnitude with wavelength. A small relative error in these quantities can involve a large relative error in the AOD. This is particularly relevant in areas with low AOD levels. So the data processing must be accurately accomplished, otherwise the errors can be as large as the variable that we try to determine.

In the case of ozone its optical depth is estimated from the ozone columnar concentration *c* and the absorption coefficient $A_\lambda$ for each wavelength, according to expression (3).

$$\tau_{\lambda,O_3} = A_\lambda \cdot c_{O_3} \qquad (3)$$

An effective absorption coefficient $\bar{A}$ for the filters is calculated by a convolution of filter band function ($T_\lambda$), the detector spectral response ($D_\lambda$), and the ozone spectral coefficients ($A_\lambda$), according to (4).

$$\bar{A} = \frac{\int_{\lambda_1}^{\lambda_2} T_\lambda \cdot D_\lambda \cdot A_\lambda \cdot d\lambda}{\int_{\lambda_1}^{\lambda_2} T_\lambda \cdot D_\lambda \cdot d\lambda} \qquad (4)$$

In our case, the coefficients $A_\lambda$ with 1nm resolution have been taken from the SMARTS2 model (Gueymard, 1995), whereas the transmittance values $T_\lambda$ are provided by the filter manufacturer.

Similar procedure is used to estimate the effective Rayleigh optical depth $\bar{R}$ .

$$\bar{R} = \frac{\int_{\lambda_1}^{\lambda_2} T_\lambda \cdot D_\lambda \cdot R_\lambda \cdot d\lambda}{\int_{\lambda_1}^{\lambda_2} T_\lambda \cdot D_\lambda \cdot d\lambda} \qquad (5)$$

The $R_\lambda$ coefficients have been calculated for the standard pressure at sea level with the Bodhaine's expression (Bodhaine et al., 1999).

The sensitivity of the detector is normally considered constant in the short spectral range of the filter spectral response. Thus, $D_\lambda$ can be extracted and simplified from the integrals in ec. 4 and 5, not being considered in the AOD calculation procedures.

The procedure described above to calculate the Rayleigh optical depth and the effective ozone absorption coefficient is in principle more accurate than using only the value of the isolated central wavelength of the filter. Nevertheless, we have evaluated these quantities with both methods. In addition, in the first method we use the whole filter band function or only a range around the central wavelength, truncating the filter wings when the transmittance falls bellow certain percentages of its maximum value at the central wavelength. The results are shown in the next section.

On the other hand, to evaluate the contribution of this effect it is necessary to keep in mind the nominal errors associated to AOD determination. As demonstrated by various authors (Reagan et al., 1986; Cachorro et al., 2000, 2008) the absolute uncertainty of the AOD according to eq. (2) and following the error propagation theory is:

$$\Delta\tau_a = \frac{1}{m}(\tau_a \Delta m + \varepsilon(I_o) + \varepsilon(I)) + P/P_0 \cdot \Delta\tau_R + \Delta P/P_0 \cdot \tau_R + \Delta\tau_{O_3} + \Delta\tau_g \quad (6)$$

where Δ and ε represent absolute and relative uncertainties, respectively. *I* is the measured value (digital counts in the case of Cimel), and $I_o$ is the calibration constant of the photometer. Usually the far largest term is the error in the calibration $\varepsilon(I_0)$, and the other terms may be neglected. However, we must point out that neglecting the term ε(I) in (6) depends on the measurement system (photometer, radiometer, spectroradiometer…) and on the other hand significant errors arise from the last terms in case the site pressure is unknown or the Rayleigh or ozone optical depth errors are large.

Furthermore, we must note from eq.(6) that the AOD absolute uncertainty depends on *m* and therefore it is not constant, having a maximum error at solar noon (minimum air mass *m*) and a minimum error at sunrise and sunset, thus producing a diurnal variation on the AOD values (see for details Cachorro et al., 2008). Since the relative uncertainty depends on the absolute AOD value, this gives rise to a wide range of relative uncertainties. Obviously the above equation is also dependent on wavelength, decreasing the error from the UV to the near infrared NIR.

In spite of *m* variation, usually a constant nominal error is taken in the case of Cimel field operating photometers of 0.01-0.02 (Holben et al. 1998; Eck et al, 1999; Cachorro et al., 2008) in the VIS-NIR range. This nominal error is about 0.04 for 340nm, but the errors in the UV region need further assessment in the Cimel photometers.

Keeping in mind the total error of the AOD determination, the above mentioned artifact is only due to the evaluation process and affects mainly the ozone absorption in the UV region, although it is a general problem for selected spectral windows which are close to a strong absorption band. Then, when applied to real measured values it gives rise to anomalous retrieved AOD values independent of the AOD nominal error.

## 3. Results and discussion

We have analyzed the influence on the AOD evaluation of the band function of the ultra-violet filters (340 and 380nm) of four commercial Cimel sun-photometers, which operated in AERONET. In figure 1 are illustrated the band functions in the region of maximum transmittance of the 340nm filters under testing. From them we see how different can be the band function of the filters, even in the vicinity of the nominal wavelength. Even though the FWHM in 340nm is only 2nm, three out four filters (table 1) have significant transmittance values for wavelengths shorter than 320nm (the lower limit of the spectral response range of the photodiode S1336-BK from Hamamatsu manufacturer, used as the silicon detector in the Cimel instruments), and the same happens for one 380nm filter.

Following the procedure described in the methodology section, anomalous values with extremely low AOD in the ultra-violet region is obtained, particularly in 340nm, and even negative AOD values. These were obtained with the data from the Cimel number #419, which is an instrument included in AERONET that it has operated in several locations, including Andenes, NyAlesund, El Arenosillo and Izaña. In figure 2 it is represented the ozone absorption coefficients and the band function of this filter, the one with more extended wings.

The detector spectral response was considered constant and not taken into account. Therefore, the filter is the only element limiting the range of wavelengths. The filter central wavelengths used in sun photometers are within the detector spectral response range, however all filters are not identical and the wings of some of them can spread out of this range. If the filter band function exceeds the limits of the spectral response range of the detector, the radiation out these limits passing through the filter and reaching the detector is not measured by the instrument.

However, if the detector response is not considered, this wavelength range out of the detector limits is computed in the theoretical calculation of the Rayleigh, ozone, and other gases optical depth. Consequently these optical depths are higher than the ones corresponding to the true radiation measured by the detector. As a result, after removing these falsely higher values of Rayleigh and ozone optical depth from the total optical depth obtained from the instrument measurements, the AOD calculated is lower than the real one. This artifact is almost negligible in most cases because the transmittance values in the filter wings are very low. However, in the ultra-violet region of spectrum, where the Rayleigh and specially the ozone absorption increase strongly, the final contribution can be significant.

This artifact can go unnoticed in a non-supervised automatic processing like the one carried out in large networks, thus affecting significantly the accuracy of the AOD. The AERONET version 2 algorithm only uses filter functions, without considering the detector spectral response.

We have calculated the Rayleigh and ozone optical depth for the filters under study with and without taking into account the detector response range. In table 2 and 3 are depicted the values of the ozone effective absorption coefficient and the optical depth for an ozone concentration of 300DU. They are calculated: for the central wavelength of the filter (denoted by C letter, that must be only taken as a reference), taking into account the whole filter band function but without considering the detector spectral response (denoted by F), and finally, taking into account both filter band function and detector spectral response (denoted by F+D). Table 4 is similar to table 3 but in this case the results are given for the Rayleigh optical depth.

Comparing the results between (F) and (F+D) in Rayleigh optical depth we have not obtained significant differences, only an overestimation of 0.009 in 340nm for Cimel #419. But a difference of 0.047 for ozone optical depth for the same filter has been obtained, being this difference much larger than the mean value of ozone optical depth. Even for 380nm, where the ozone contribution is negligible, we have obtained a value for the optical depth of 0.004. Combining both Rayleigh and ozone we have an overestimation of 0.056 in 340nm optical depth and consequently an underestimation in the AOD of the same value, which is comparable to the magnitude of the AOD in low-polluted areas, approximately between 50-100% of the AOD value. Note that in case of using only the transmittance at the central wavelength instead of the whole band function we obtain a better result, a difference of 0.004 in the Rayleigh optical depth and only 0.001 in ozone optical depth.

Finally, figures 3 and 4 show how the value of the ozone and Rayleigh optical depth varies for the tested 340nm filters with the marginal transmittance of the filter wings. We have considered five cases: using the entire filter band function as provided by the manufacturer and truncating it when the transmittance falls below the 5%, 1%, 0.1%, and 0.01% of its maximum value at the central wavelength. We can see that a truncation at 1% of the maximum is enough to eliminate the noise in the filter wings and at the same time to keep as much as possible of the filter spectral response.

This truncation of the filter function when the transmittance goes below a certain value could also prevent another problem: a lack of resolution in the filter transmittance determination by the manufacturer. It is possible that the filter function is not determined over 5 or 6 orders of magnitude in transmittance, i.e. the out of band blocking could exceed the capability of the instrumentation used to determine the filter function. In such a case, below a certain threshold in transmittance we would see the noise of the spectral system used to measure the band-pass, instead of the real filter blocking. In this work we have assumed the filter function provided is true.

## 4. Conclusions

The transmittances in the filter wings can affect the accuracy in the AOD retrieval if they are not computed properly. If the filter band function exceeds the limits of the spectral response range of the detector and its spectral response is not considered in the AOD calculation procedures, the theoretically calculated contribution of Rayleigh scattering and ozone and other gas absorption to the optical depth is overestimated, and consequently the AOD is underestimated. We even achieved better results considering only the filter central wavelength than considering the filter function without the detector spectral response.

Although the transmittance values in the filter wings are very low, the strong absorption of ozone in the ultra-violet region of the spectrum makes significant its contribution to the AOD. This effect may be especially important for low AOD conditions.

This problem is here focused on AOD retrieval but it is a general problem, which affects the optical depth and hence the atmospheric component determination in spectral regions in the vicinity of strong absorption bands.

To avoid this error in automatic processing we recommend rejecting the filter wings when the transmittance falls below 1% of its maximum value at the central wavelength.

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## Figures

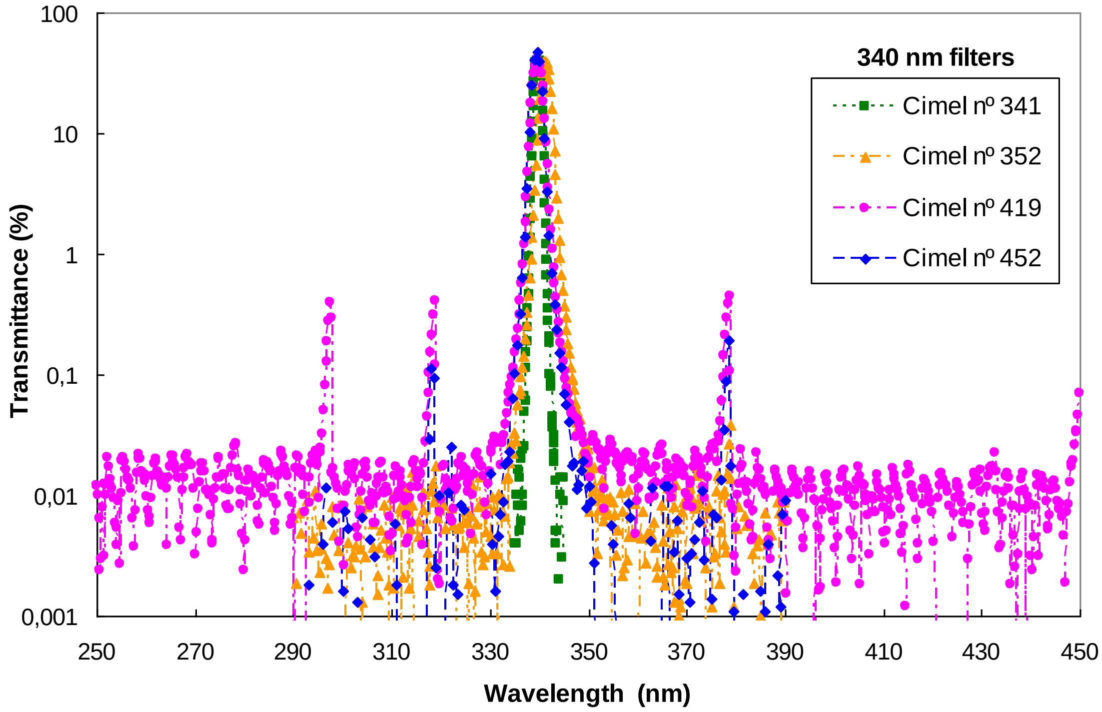


Figure 1. Band-pass function curves (logarithmic scale) in the wavelength range 334-346nm of the 340nm filters of the four Cimel sun photometers under study.

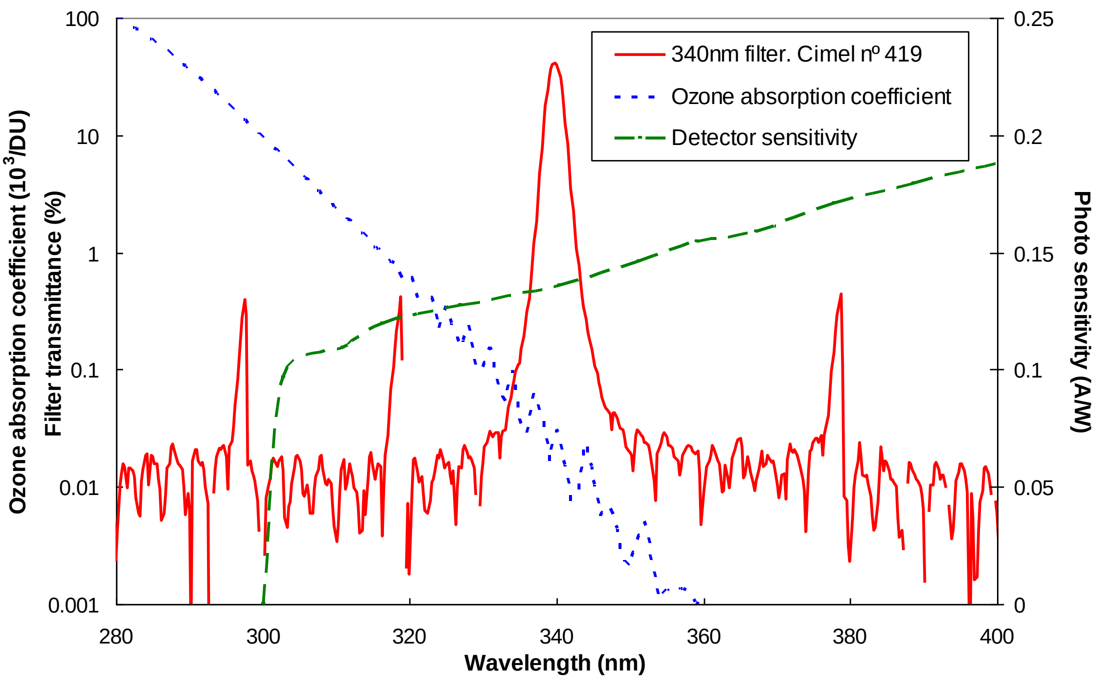

Figure 2. Ozone absorption spectral coefficients from SMARTS2 model and band-pass function of the 340nm filter of Cimel #419 (both in logarithmic scale). The two peaks in the spectral region exceeding the nominal inferior limit of the detector response (320nm), have almost negligible transmittance values, but while the effect of the peak between 315 and 320nm can be rejected because the ozone absorption coefficients are very low, in the case of the one between 295 and 300nm it must be taken into account because in this region the ozone absorption coefficient increases exponentially with a significant contribution.

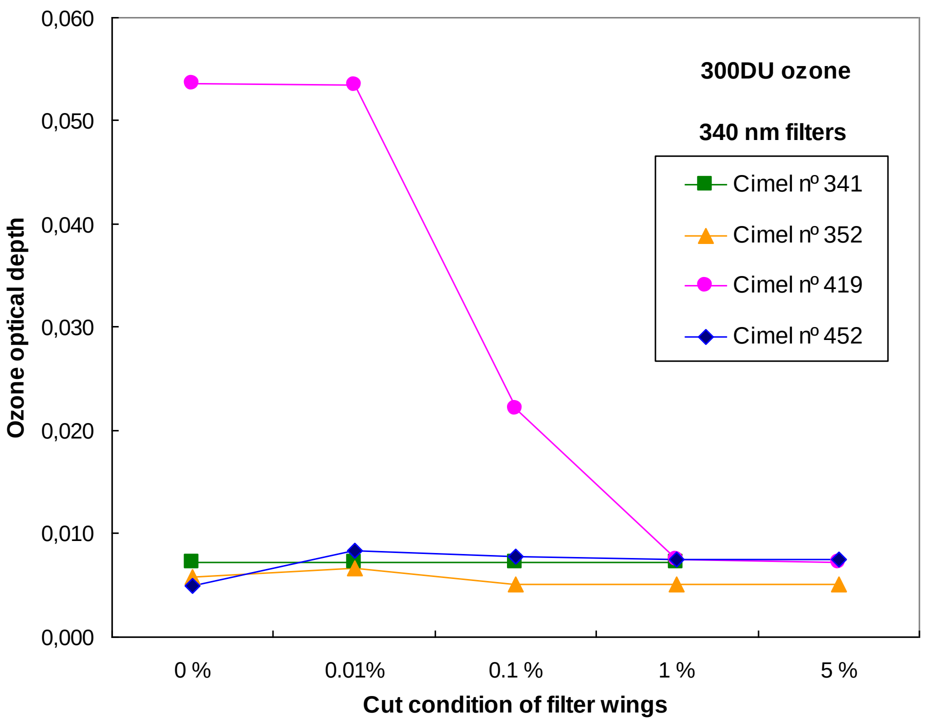


Figure 3. Ozone optical depth for an ozone concentration of 300DU for different truncations of the wings of several 340nm filters. In the calculation of the effective ozone absorption coefficient of a certain filter, its band-pass function has been truncated when the transmittance fell below 5%, 1%, 0.1%, 0.01%, and 0% (entire filter) of its maximum value at the central wavelength, considering zero the transmittance out of these limits .

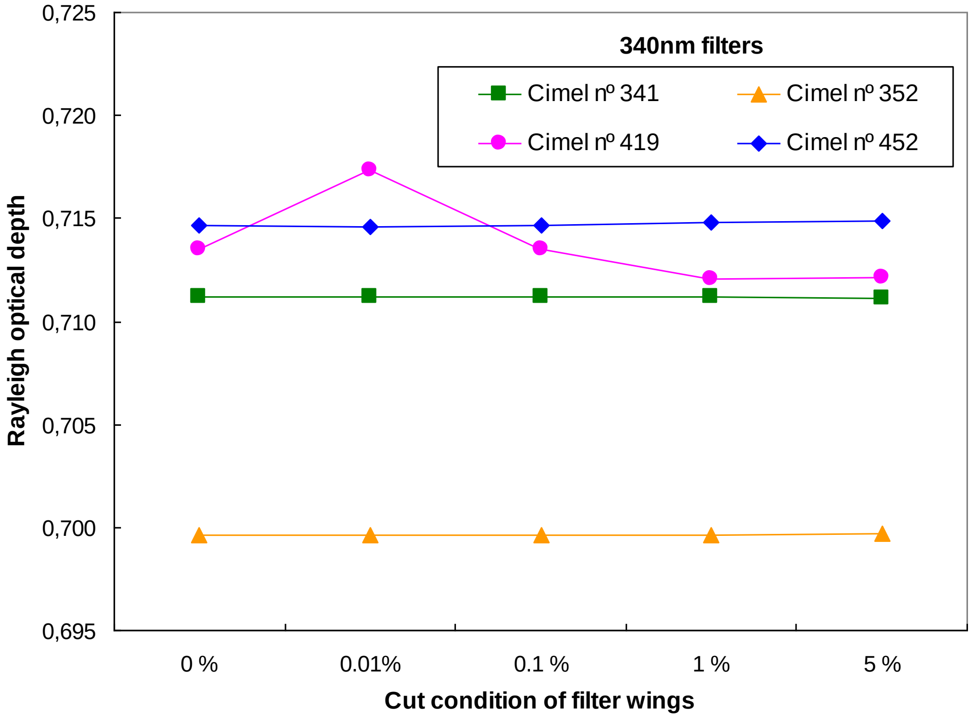


Figure 4. Similar to figure 5 but in this case the Rayleigh optical depth is represented.

## Tables

| | Cimel #419 | Cimel #341 | Cimel #452 | Cimel #352 |
|---|---|---|---|---|
| **380 nm** | 300 – 450 | 330 - 430 | 330 - 430 | 330 - 430 |
| **340 nm** | 250 – 450 | 335 - 435 | 290 - 390 | 290 - 390 |

Table 1. Wavelength ranges of the band-pass functions of the 380 and 340nm filters of four Cimel sun photometers as provided by the manufacturer.

| | Cimel #419 | | | Cimel #341 | | | Cimel #452 | | | Cimel #352 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **C** | F | F + D | **C** | F | F + D | **C** | F | F + D | **C** | F | F + D |
| **380 nm** | 0.0 | 0.0133 | 0.0006 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0001 | 0.0001 |
| **340 nm** | 0.0272 | 0.1792 | 0.0243 | 0.0265 | 0.0242 | 0.0242 | 0.0237 | 0.0289 | 0.0252 | 0.0152 | 0.0237 | 0.0171 |

Table 2. Effective Ozone absorption coefficient (x $10^3$/DU) calculated with the spectral absorption coefficients of the SMARTS2 model and with the band-pass functions of the ultra-violet filters (340 and 380nm) of the four Cimel instruments under study. Columns headed with `C´ mean values for the central filter wavelength only; `F´ means values calculated taking into account the whole filter band function but not the spectral response range of the silicon detector; and in `F + D´ both effects were taken into account.

| | Cimel #419 | | | Cimel #341 | | | Cimel #452 | | | Cimel #352 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **C** | F | F + D | **C** | F | F + D | **C** | F | F + D | **C** | F | F + D |
| **380 nm** | 0.0 | 0.004 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| **340 nm** | 0.008 | 0.054 | 0.007 | 0.008 | 0.007 | 0.007 | 0.007 | 0.009 | 0.008 | 0.005 | 0.007 | 0.005 |

Table 3. Ozone optical depth for an ozone concentration of 300 DU (same notation as in table 2).

| | Cimel #419 | | | Cimel #341 | | | Cimel #452 | | | Cimel #352 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **C** | F | F + D | **C** | F | F + D | **C** | F | F + D | **C** | F | F + D |
| **380 nm** | 0.446 | 0.450 | 0.446 | 0.442 | 0.440 | 0.440 | 0.442 | 0.440 | 0.440 | 0.443 | 0.443 | 0.443 |
| **340 nm** | 0.712 | 0.717 | 0.708 | 0.713 | 0.711 | 0.711 | 0.715 | 0.715 | 0.714 | 0.699 | 0.700 | 0.699 |

Table 4. Rayleigh optical depth at sea level for the standard pressure (1013.25 Hpa) obtained according with Bodhaine's expression and the filter band-pass functions (same notation as table 2) for the 340 and 380nm filters of the four Cimel sun photometers.