Determination of Aerosol Optical Depth and Ångström's Wavelength Exponent Using Sunphotometers and Spectroradiometers: A Preliminary Assessment

C. A. Gueymard

Solar Consulting Services, New Smyrna Beach, FL 32168, USA, Chris@SolarConsultingServices.com

Abstract. Quality measurements from sunphotometers and spectroradiometers are used here to evaluate the aerosol optical depth (AOD) and Ångström wavelength exponent (α) at various sites. Using a few examples, it is shown that, even if collocated instruments agree on AOD, they disagree on α. Knowledge of the latter's variations along the spectrum may be improved by using spectroradiometers, but only if they are high-performance instruments.

Introduction

Aerosol optical depth (AOD) is a rapidly variable characteristic of the atmosphere. Its accurate knowledge is essential for the determination of the impact of aerosols on, e.g., the radiative budget of the earth's atmosphere. For ground-based operation, which is the focus here, multiwavelength sunphotometers (SPMs) or shadowband radiometers offer the possibility of determining AOD by discrete observations in the shortwave direct spectrum. This type of instrument is used in global networks such as AERONET and GAW. Their data is extremely valuable as ground truth for spaceborne sensors and to derive AOD climatologies over the world (e.g., Gueymard and George, 2005). SPM measurements are indirect because of their lack of absolute calibration, most generally.

Spectroradiometers (SRMs), on the other hand, are absolutely calibrated and their output spectra can therefore be directly compared to irradiance predictions from models. AOD can also be derived following a method similar to that outlined above for SPMs, albeit with considerably finer resolution. Unfortunately, SPM or SRM intercomparisons are rare events, and the two types of instrument do not usually coexist on a permanent basis.

This contribution outlines some valuable lessons learned while using and comparing the two types of data, which have been gathered for years on a relatively regular basis at the Atmospheric Radiation Measurement (ARM) Program's Cloud And Radiation Testbed (CART) site in Oklahoma, and at the National Renewable Research Laboratory (NREL) in Golden, Colorado.

Sunphotometry Issues

For proper long-term and automatic monitoring of AOD, a few important issues need to be addressed: (i) filter degradation; (ii) calibration accuracy and stability; and (iii) cloud interferences. The two first issues are such that the absolute uncertainty in individual AOD measurements is about 0.01 at best. This is a known problem, but its incidence on the derivation of the Ångström wavelength exponent, α, is more serious than is usually admitted, as discussed in the next section. Cloud-screening algorithms, such as that used to post-process AERONET data, are very efficient but still not perfect. Instances of cloud contaminated data points have been found occasionally, resulting in slightly overestimated AODs and underestimated α values in monthly-average "climatological" products.

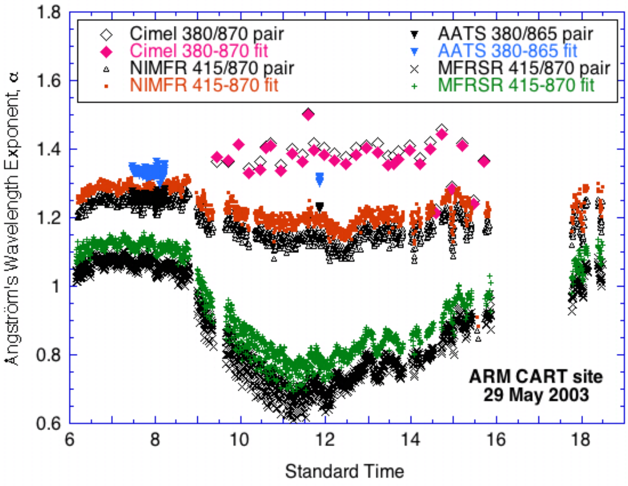

Figure 1. Ångström wavelength exponent obtained by two methods (wavelength pairs and linear fit) with four instruments.

Wavelength exponent Coefficient α can be obtained by either solving Ångström's equation for a pair of judiciously selected wavelengths for which AOD is measured (e.g., 380 and 870 nm), or by linearly fitting the observed AOD at many wavelengths to the log-log transform of Ångström's equation. The limitations and inaccuracies of the first method have been discussed long ago (Cachorro et al., 1987), but it is still being used in the AERONET and ARM datasets, for instance. Figure 1 shows that for a typical mostly-clear day, large differences in the calculated α may result— with a surprisingly large range of 0.6–1.5 near noon in this case—when the two methods are applied to data from four instruments. This considerable scatter occurs even if the measured AODs at 500 nm are relatively similar over time (Fig. 2). In Fig. 1, note also the small difference in the α values obtained by the two derivation methods with any instrument, but particularly the Cimel. This is representative of the best-case scenario only.

The linear-fitting method is potentially more accurate because it compensates (to some extent) for opposite biases in AOD due to the calibration issues mentioned earlier. The accuracy in α may also depend on the number of channels considered, and therefore vary from one SPM to the other. A more ambitious investigation—considering months of ARM data under varied atmospheric conditions—is underway to determine the uncertainty in α resulting from the combination of the instrument-dependent uncertainty in AOD and that of the derivation method.

To characterize the spectral dependency of AOD in the visible, the interval 380–870 nm, or 415–870 nm at the very least, seems the best suited, depending on instrumentation.

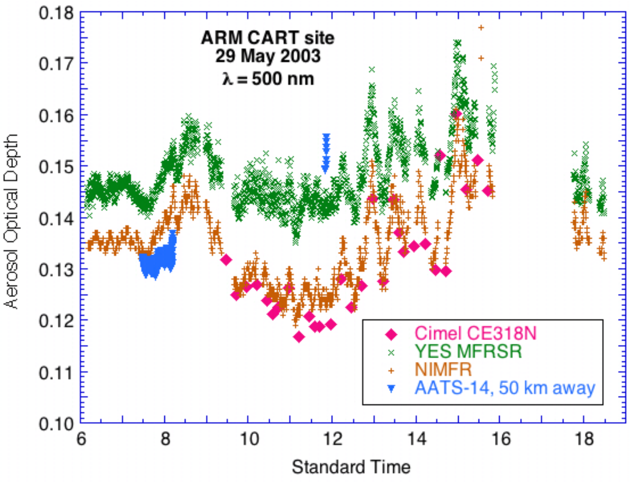

Figure 2. Example of daily course of aerosol optical depth at 500 nm: intercomparison between four instruments. Cloud passages have been filtered out.

Unless specifically designed for the UV, SPMs cover the spectral range 340–1040 nm at most. Whereas the spectral dependency of AOD (through α) is now relatively well known in the visible (to the extent that the uncertainties reported above have not blurred the picture so far), it is less known in the UV or, even more so, beyond 1100 nm. A research SPM, the AATS-14, has 14 channels, including three special channels at 1241, 1558 and 2139 nm (Schmid et al., 2005). The log-log transform of Ångström's law applied to data from these 14 channels indicate that α tends to decrease beyond 1000 nm. It is also found, however, that the behavior of α in the UV differs completely when considering the few UV channels of the AATS-14 and Cimel. More specialized equipment (UV SPM and/or SRM) will therefore rather be used for this task.

Spectroradiometry Issues

A promising application of SRMs is to use their measured irradiance to derive AOD. This is done here by comparing each measured direct spectrum to an ideal spectrum predicted by the SMARTS model (Gueymard, 2005). Inputs to the model are all known atmospheric conditions—but no aerosol. Results are smoothed to simulate the instrument's bandwidth. The spectral aerosol transmittance, $T_{a\lambda}$, is obtained at each wavelength λ by the measured/predicted irradiance ratio. The AOD is then simply $-\ln(T_{a\lambda})/m_a$, where m_a is the aerosol optical mass. (This is valid only outside of strong gaseous absorption bands.)

In theory, this method has the potential to validate Ångström's law over the whole spectral range of SRMs. In practice, however, it is found that this is not so with all SRMs. For instance, Fig. 3 shows the results of this method for different turbidity conditions, using a well-calibrated Licor LI-1800, a largely used SRM. Whereas it appears appropriate for hazy conditions, it is *not* for very clean conditions, due to some inherent spectral instability. This confirms previous findings (Carlund et al., 2003). The same conclusion is also found when the Licor-derived AODs are compared to that obtained (similarly) with a collocated higher-performance instrument, whose range extends to 2.5 µm (Fig. 4). Preliminary results with this SRM also confirm α's tendency to decrease beyond 1 µm.

Work is now underway to analyze recent SRM data at CART (using UV and VIS Rotating Shadowband Spectroradiometers) and NREL (using SRM data from various instruments) in order to validate Ångström's law in the 0.3–2.5 µm spectral range under varied conditions.

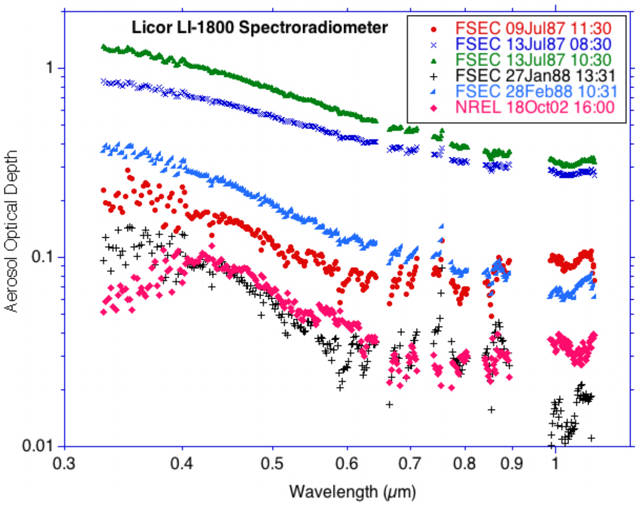

Figure 3. AOD as a function of wavelength using Licor LI-1800 spectroradiometer measurements at two locations.

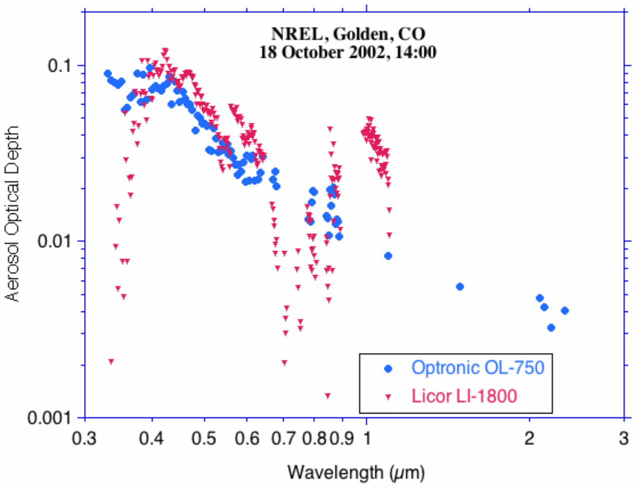

Figure 4. AOD as a function of wavelength using two spectroradiometers (Licor LI-1800 and Optronic OL-750) at NREL.

References

Cachorro V.E. et al., Determination of the Angstrom turbidity parameters, *Appl. Opt., 26*, 3069-3076, 1987.

Carlund T. et al., Comparison and uncertainty of aerosol optical depth estimates derived from spectral and broadband measurements. *J. Appl. Meteorol., 42*, 1598-1610, 2003.

Gueymard C.A., Interdisciplinary applications of a versatile spectral solar irradiance model: A review. *Energy, 30*, 1551-1576, 2005.

Gueymard C.A., George R., Gridded aerosol optical depth climatological datasets over continents for solar radiation modeling. *Solar World Congress*, International Solar Energy Soc., 2005.

Schmid B. et al., How well do state-of-the-art techniques measuring the vertical profile of tropospheric aerosol extinction compare? *J. Geophys. Res.*, 2005 (in press).