The ARM Aerosol Optical Thickness VAP

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Introduction

The aerosol optical thickness (AOT), τ_{aer}, is one the most critical parameters influencing clear-sky, shortwave radiative fluxes. This point has been underscored in numerous publications (Kato et al. 1997; Halthore et al. 1997; Halthore and Schwartz 2000) in which the sensitivity of calculated irradiances to changes in τ_{aer} has been demonstrated. For example, Halthore and Schwartz (2000) have shown that, when compared to other input parameters required by radiative transfer models, τ_{aer} has the greatest effect on diffuse irradiance calculations, for AOT (at 550 nm) less than 0.1.

The need for accurate AOT in radiative transfer calculations has generated a demand for this quantity in the Atmospheric Radiation Measurement (ARM) Program. To meet this demand, a “value added product” (VAP) has been developed to retrieve τ_{aer} from spectral irradiance measurements; the goal of this paper is to describe this VAP.

The VAP retrieval uses measurements from either the multi-filter rotating shadowband radiometer (MFRSR, Harrison et al. 1994) or the normal incidence multi-filter radiometer (NIMFR). These instruments measure the direct normal irradiance (and other quantities, in case of the MFRSR) at six different nominal wavelengths: 415 nm, 500 nm, 615 nm, 673 nm, 870 nm, and 940 nm. The nominal passband for each wavelength channel is 10 nm. Due to the influence of water vapor, the 940-nm channel is not suitable for determining τ_{aer}. At the remaining five wavelengths, the AOT can be ascertained at the sampling rate of the instruments, 20 sec, if the sky is sufficiently clear when the measurements are made.

Calculation of AOT: Some Considerations

With measurements of (virtually) monochromatic direct normal irradiances in hand, it is possible to find the total optical depth, τ_{total}. This process has been discussed in detail in Schmid et al. (1997); for the sake of brevity, we omit most of the details here and sketch out the process in simplified terms.

The total optical depth between the top of the atmosphere and the instruments is calculated using Beer's law:

$$\tau_{total}(\lambda, t) = -\frac{1}{m} \mathrm{Log}\left[\frac{I_{meas}(\lambda, t)}{I_o(\lambda)}\right] \tag{1}$$

where m is the airmass between the sun and the instrument, $I_{meas}(\lambda,t)$, is the measured direct normal irradiance at time, t; and wavelength ☒. $I_o(\lambda)$ is the sun's irradiance at the top of the atmosphere. In this equation both I_{meas} and I_o have been corrected for the eccentricity of the earth's orbit.

Once τ_{total} is found using Eq. (1), the AOT is calculated by subtracting from τ_{total}: (a) the optical thickessess associated with Rayleigh scattering, $\tau_{Rayleigh}$, (Hansen and Travis 1974), and, (b) the optical thickness of ozone and NO_2 absorption, $\tau_{ozone} + \tau_{NO_2}$. The optical thickness of NO_2 absorption is often very small at the MFRSR wavelengths (e.g., less than 0.001 nm at 500 nm, see Schmid and Wehrli 1995) and it is often neglected in optical thickness calculations. With this in mind, the AOT is:

$$\tau_{aer} = \tau_{total} - \tau_{ozone} - \tau_{Rayleigh} \tag{2}$$

While calculation of the τ_{aer} using Eqs. (1) and (2) is simple in principle, in practice it is fraught with difficulty because of inaccuracies in the measurements. Small calibration and/or measurement errors, on the order of a few percent, will cause errors of similar magnitude in total optical thickness but much larger relative errors in τ_{aer}. Specifically, an error of 1% in the measurements translates into an error of about 0.01 in total optical thickness at 415 nm ($m \approx 1$). Under conditions of low aerosol loadings, a typical total optical thickness at 415 nm is 0.35 (at sea level), and a calibration error of 1% corresponds to a percentage error in total optical thickness of about 2%—a seemingly insignificant error.

However, when aerosol loadings are low, the sensitivity of τ_{aer} to measurement errors can be very significant. This error magnification occurs because τ_{aer} is obtained from subtracting two relatively large numbers from one another, τ_{total} and $\tau_{Raleigh} + \tau_{ozone}$, thus leaving a small remainder. For example, at sea level, $\tau_{Rayleigh} + \tau_{ozone}$ is about 0.31 nm at 415 nm, and if the total optical thickness is 0.35, τ_{aer} is about 0.04. A calibration error of 1%, which induces a 2% error in τ_{total}, translates into a relative error of 25% in AOT. Thus, when determining τ_{aer}, the need for accurate measurements is critical.

Fortunately, the calibration of the MFRSR and the NIMFR can be monitored using Langley regressions, thereby significantly reducing the errors of τ_{aer} derived from these instruments. The ability to monitor and then correct for instrument calibration problems forms the cornerstone of ARM's optical thickness VAP.

The VAP

The basis of the ARM AOT VAP has been discussed in Michalsky et al. (2001). The ARM VAP follows the technique presented in Michalsky et al. with just minor differences. These differences do not materially effect the optical thickness retrievals.

The steps used in the ARM VAP are:

- Perform Langley regressions (Harrison and Michalsky 1994) on MFRSR (or NIMFR) direct normal irradiance data to produce a time series of estimated extraterrestrial irradiances, $I_o^{estimated}$, for each of the five wavelength channels suitable for optical depths retrievals.

- Remove outliers from these time series using the method of Forgan (1998).

- Find estimated $I_o^{estimated}$ for each day of the year using a smoothing technique applied to the "cleaned" $I_o^{estimated}$ found above.

- For each day, the measurements can be corrected so that the $I_o^{estimated}$ is equal the measured extra-terrestrial radiation. This correction is done by multiplying the measurements by the correction factor $(I_o / I_o^{estimated})$. (Recall that I_o is the true extraterrestrial irradiance).

- Using the corrected measurements, τ_{aer} can be determined as discussed in Section 2. Alternatively, one can find τ_{total}, the therefore τ_{aer}, by using the uncorrected measurements and substituting $I_o^{estimated}$ for I_o in Eq. (1).

Figure 1 illustrates the first three steps listed above. The figure plots $I_o^{Langley}$ for 415 nm; these are the I_os determined from the Langley regressions as indicated by the violet dots. The direct normal irradiance measurements, from which the $I_o^{Langley}$ are derived, come from the "C1" MFRSR at ARM's Southern Great Plains site. Note that for many days of the year it is not possible to perform a Langley regression because the skies are not clear enough for a regression to take place. This is particularly true during the summer months.

Also shown is this figure are the daily estimates of the extraterrestrial radiation, $I_o^{estimated}$, determined by applying the Forgan method to the $I_o^{Langley}$ and then smoothing the results. These daily values show that the instrument calibration has a slight downward trend with time.

Once the daily $I_o^{estimated}$ are in hand, we correct I_{meas} by multiplication by the correction factor, $(I_o / I_o^{estimated})$, and the total optical thickness is determined using Eq. (1). The AOT follows using Eq. (2). When finding τ_{aer}, the Raleigh optical depth is scaled by the surface pressure to account for changes in the columnar mass of the atmosphere, and TOMS-measured ozone values are used to find the ozone optical thickness, if these measurements are available. In the absence of surface pressure measurements and/or ozone measurements, default values of 977 mb for surface pressure, and 300 Dobson Units for ozone, are used.

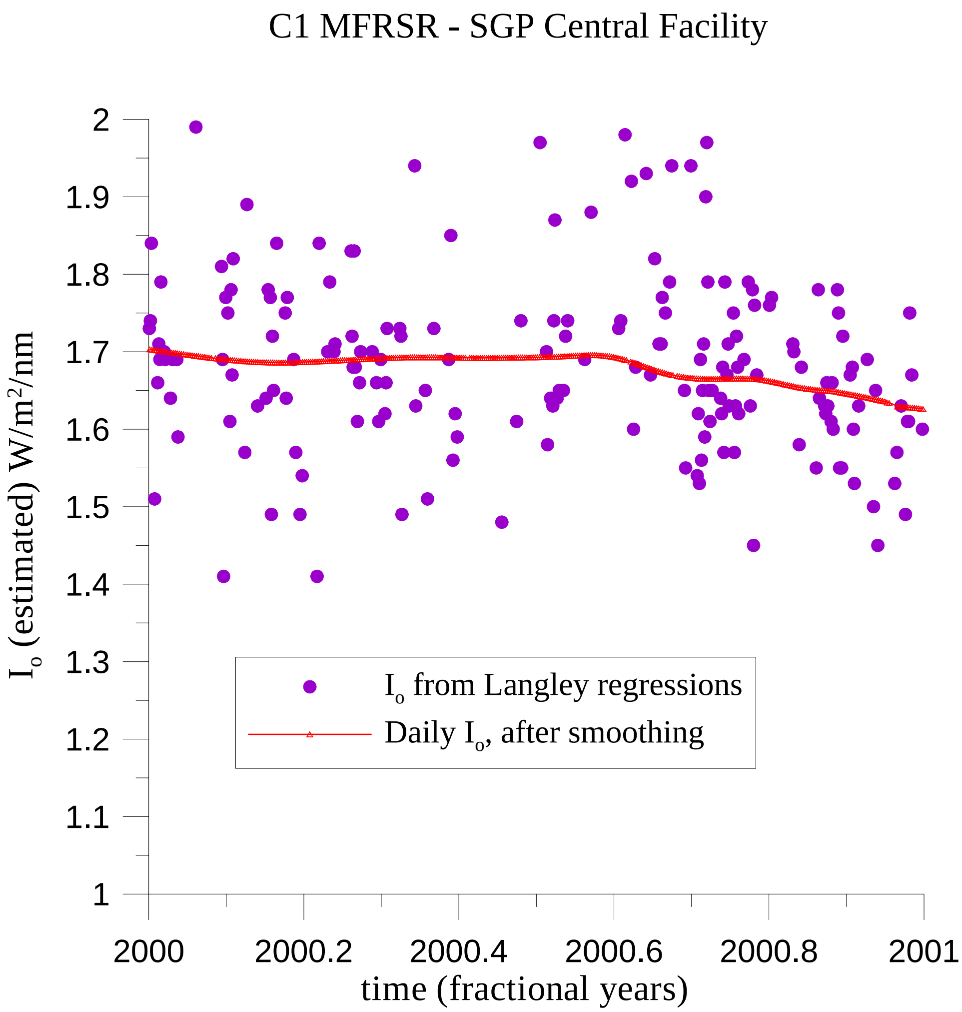

Figure 1. The violet dots show $I_o^{Langley}$, an estimate of the extraterrestrial irradiance determined from the Langley method. The red line indicates the daily $I_o^{estimated}$ determined by removing outliers using the Forgan method and then smoothing these results.

An example of daily time series of AOT is shown in Figure 2 for December 5, 1998. For this particular day, only three of the five MFRSR wavelengths channels were operational because two of the filters had failed (see "caveats" below). Therefore, we show time series of τ_{aer} for only the 415-nm, 500-nm, and 870-nm channels.

We chose this particular day to illustrate that extremely clear days do sometimes occur at the Southern Great Plains (SGP) site. For this particular day, the turbidity is so low that the atmosphere is close to being a molecular scatterer in the morning hours. Exceptionally clear days, as well as other days of scientific interest, can be found by perusing the optical thickness database produced by the ARM VAP. The VAP also calculates a time series of the Ängström exponent, and for this day, the exponent is about 1.5.

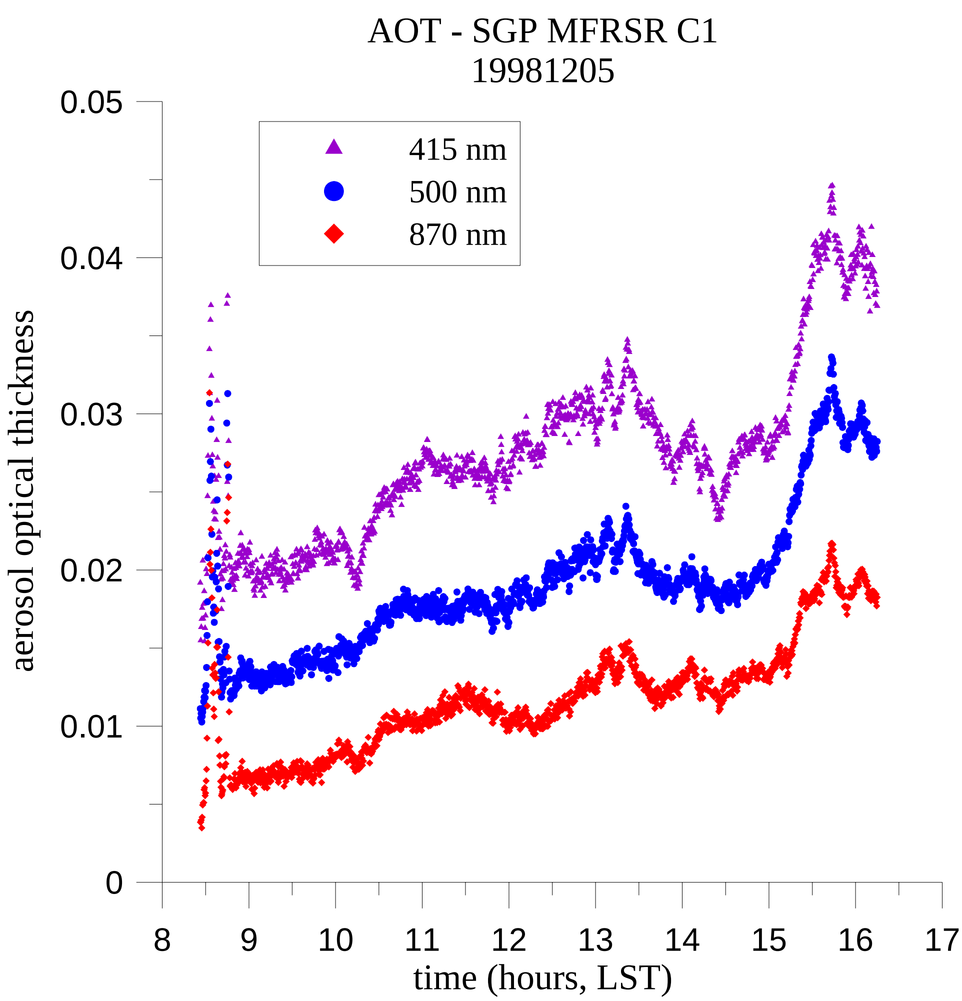

Figure 2. AOT for three wavelengths from the "C1" MFRSR. Note that for this day the atmosphere is exceptionally clear.

An important aspect of any AOT retrievals is an assessment of its accuracy. The accuracy cannot be determined directly, but one can estimate the accuracy by comparing the AOT from various instruments operated coincidentally at the same. To this end, Schmid et al. (1999) examined τ_{aer} obtained from four instruments deployed at the SGP site and determined that over a range of wavelengths, the AOT could be retrieved to an accuracy of about 0.026 (a "two-sigma" limit).

We can also assess the quality of τ_{aer} retrievals by performing a "closure" experiment. For example, we can supply τ_{aer} to a radiative transfer model that calculates direct normal irradiances, and then compare the calculated irradiances with measured irradiances. If the agreement is good, we can conclude that the various measurements employed in the closure experiment are accurate, and that the radiative transfer model is similarly accurate. Using the MOTRAN model, Halthore et al. (1997) have shown that calculated and measured direct normal irradiances agree to about 0.2%. Similarly, Barnard and Powell (2002) have shown that the radiative transfer model SBDART (Ricchiazzi et al. 1998) underpredicts the direct normal irradiance by about 1%.

To perform a closure experiment for the data in Figure 2, we fed the AOT from the ARM VAP, as depicted in this figure, to SBDART and calculate the direct normal irradiance. Figure 3 shows the results of this calculation. We see that the calculated and measured direct normal irradiances are quite close. When averaged over the time period extending from 10 AM to 2:30 PM, the averaged irradiances are 916 W/m^2 and 909 W/m^2, for the measurements and calculations, respectively. SBDART's slight under prediction of the measurements is consistent with past studies. Overall, the results of this closure experiment suggest that the AOT shown in Figure 2 are accurate, probably to a level of 0.01.

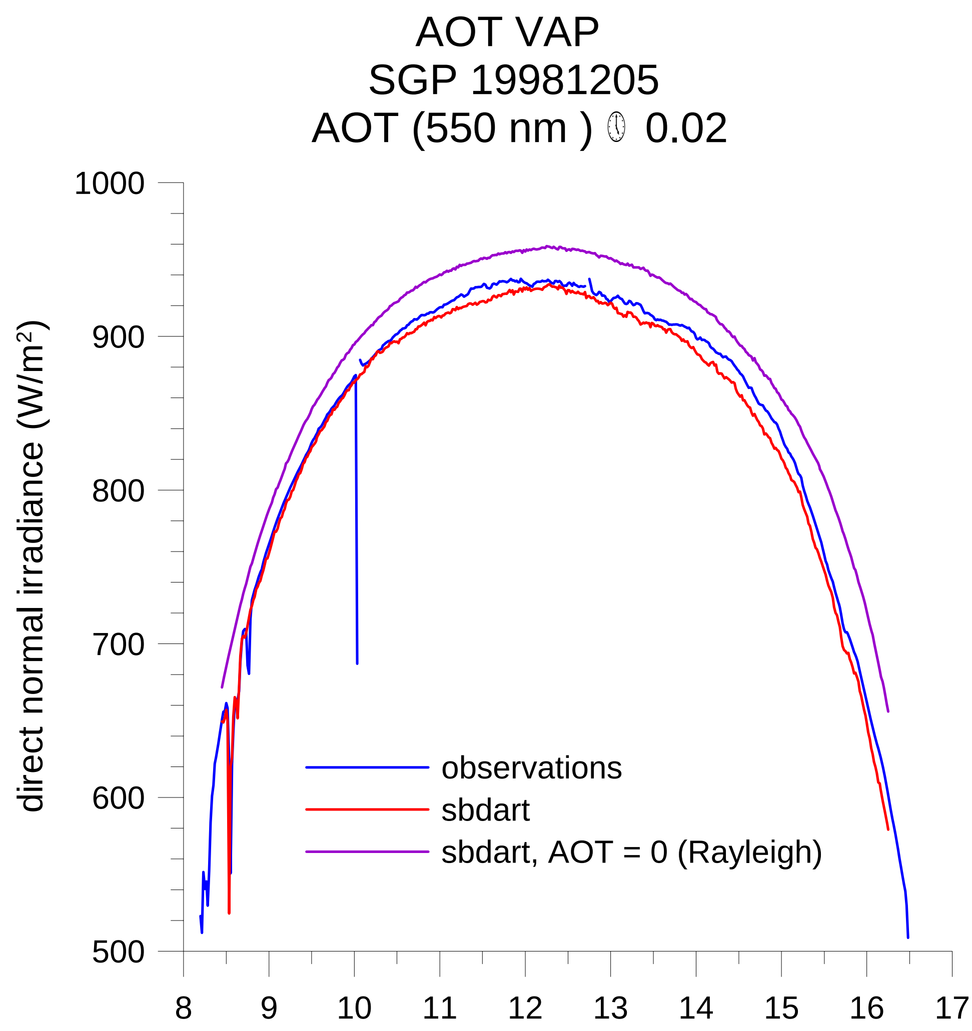

Figure 3. Direct normal irradiance as calculated by the SBDART model (red line) using aerosol properties as depicted in Figure 2. The blue line shows the measurements. For the sake of comparison, a Rayleigh calculation is also shown by the violet line.

Practical Considerations: Where's the Data?

The AOT, in beta-release form, are located at the ARM archive. These data can be found in http://iop.archive.arm.gov/arm-iop/0beta-data; the netCDF files, with names like "sgpmfrsrod1barnmichC1.19981205.00000.cdf" are located here. The optical thicknesses in these files are from the C1 MFRSR and cover the time period of September 18, 1996, through September 19, 2001.

Caveats

There are a few caveats regarding the AOT produced by the ARM VAP. First, the transmission of some of the MFRSR interference filters has degraded rapidly, or occasionally, the filters fail outright. This is particularly true of the 615-nm and 673-nm wavelength channels. When rapid "slippage" or failure occurs, it is sometimes difficult to find the daily $I_o^{estimated}$ with much confidence. In these cases, we do not try to compute τ_{aer} because we know it will be incorrect. Instead, we assign it a value of –9999.0.

Additionally, we have discovered that of the some filters do not have sufficient out-of-band rejection; i.e., the filters "leak." These leaky filters afflict data taken after September 19, 2001 from the C1 MFRSR, and when the data is so affected, the AOT can be far too low. We are now working procedures to correct this problem.

Finally, MFRSR data, taken from the SGP extended facilities, are in generally very poor condition (e.g., among other things, these data suffer from shading problems and slipping filters). Considerable grooming of these data will occur before feeding them the AOT VAP.

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