AERONET Inversion Products (Version 3)

AERONET inversion code provides aerosol optical properties in the total atmospheric column derived from the direct and diffuse radiation measured by AERONET Cimel sun/sky-radiometers. AERONET inversion development and research activities are described in the papers by Dubovik and King, [2000], Dubovik et al. [2000], Dubovik et al. [2002a], Dubovik et al. [2002b], Dubovik et al., [2006], Sinyuk et al. [2007]. The Version 3 (V3) inversion (or retrieval) products are summarized below. These products are available through the internal analysis system "demonstrat" and the AERONET website. For the almucantar retrievals the description of V2 retrieval quality controls provided in Holben et al. [2006] holds for V3 as well. However, the hybrid criterion for the last scattering angle bin has a different minimum scattering angle limit (>=75°) than almucantars (≥80°) and a different minimum number of symmetric scattering angles (N=2) than almucantars (N=3), due to somewhat fewer scattering angle range measurements in the hybrid scan. New developments of V3 AERONET retrieval will be provided in detail in the paper by Sinyuk et al., [2019].

1. Operational Protocol

The AERONET code inverts sky radiances simultaneously at all available wavelengths for the complete solar almucantar scenario or hybrid scenario (Θ>3.2°) together with measurements of aerosol optical depth τ (λ) at the same wavelengths. Depending on the model of Cimel radiometer, the sky radiance measurements may be taken on all or some of the following spectral channels: 0.38, 0.44, 0.5, 0.675, 0.87, 1.02 and 1.64 μm.

2. Inversion assumptions:

- Aerosol particles are assumed to be partitioned into two components: spherical and non-spherical. The spherical component is modeled by an ensemble of polydisperse, homogeneous spheres (complex index of refraction is the same for particles of all sizes). The non-spherical component is a mixture of polydisperse, randomly-oriented homogeneous spheroids [e.g. Mishchenko et al. 1997]. The spheroid aspect ratio distribution is fixed to one retrieved by Dubovik et al. [2006] and fit to the entire scattering matrix of mineral dust (Feldspar) measured in laboratory by Volten et al. [2001]. The importance of using refined surface reflectance properties in the retrieval and possible improvements in retrieved aerosol properties are described by Sinyuk et al. [2007].

- Atmosphere is assumed plane-parallel.

- Vertical distributions of aerosol concentration are adopted from MERRA-2 [Gelaro et al., 2017] global assimilation model simulations, which utilize CALIOP [Winker et al., 2007] aerosol vertical profile measurements.

- Surface Reflectance is modeled by BRDF: Cox-Munk model for over water of Cox and Munk [1954a] and by Li-Ross model over land of Lucht and Roujean [2000]. The BRDF parameters for land sites are adopted from MODIS BRDF/Albedo CMG Gap-Filled Snow-Free Product MCD43FG V005 [see link at the end of publications list]. The land and water BRDF models are mixed using percentage of land and water within 10 km diameter circle centered at AERONET site. NISE SSM/I snow and ice extent by Nolin et al. [1998] and MODIS snow cover map by Hall et al. [2002] are used to account for BRDF of snow. Cox-Munk calculations use wind speed from NCEP/NCAR Reanalysis data, which are acquired from the NOAA National Weather Service NOMADS NCEP server.

- Gaseous absorption by ozone, nitrogen dioxide and water vapor are accounted for in the inversion of the sky radiances. Total column water vapor amount is determined from the AERONET Cimel instrument 940 nm channel retrievals. Total ozone (O3) optical depth is determined utilizing the total column TOMS monthly average climatology (1978–2004) of O3 concentration at 1° X 1.25° spatial resolution, the O3 optical air mass using O3 scale height adjustment by latitude [Komhyr et al., 1989], and the O3 absorption coefficient (Burrows et al., 1999). Similarly, the nitrogen dioxide (NO2) optical depth is calculated using the total column OMI monthly average climatology (2004–2013) of NO2 concentration at 0.25° X 0.25° spatial resolution and the NO2 absorption coefficient [Burrows et al., 1998].

- The statistically optimized inversion and corresponding retrieval error estimates are obtained under the assumption of uncorrelated log-normally distributed errors. This optimization accounts for different levels of accuracy in the measurements (e.g. the standard deviation for error in $\tau(\lambda)$ is assumed 0.01, the standard deviation for error in sky radiance measurements is assumed 5%). The details see in Dubovik and King [2000], Dubovik [2004] and Dubovik et al. [2006b].

3. Inversion results

The V3 AERONET retrieval provides wide number of parameters and characteristics that are important for the comprehensive interpretation of the aerosol retrieval. The output includes both retrieved aerosol parameters (i.e., size distribution, complex refractive index and partition of spherical/non-spherical particles) and calculated on the basis of the retrieved aerosol properties (e.g. phase function, single scattering albedo, spectral and broad-band fluxes, etc.). In addition, the output provides many values that can be helpful for assessment of the retrieval quality. Namely, the output provides estimates for both random and possible systematic (resulted from possible biases in measurements) errors for most of the retrieved characteristics. According to those estimates, 68% confidence interval intervals are presented for most retrieved characteristics. Also, for convenience of data analysis, the retrieval code groups the output based on measured characteristics and their fit.

3.1 Microphysics

The volume particle size distribution $dV(r)/d\ln r$ (μm^3/μm^2) is retrieved for 22 logarithmically equidistant discrete points (r_i) in the range of sizes 0.05μm≤r≤15μm. The real $n(\lambda)$ (1.33≤$n(\lambda)$≤1.6) and imaginary $k(\lambda)$ parts of the complex refractive index (0.0005≤$k(\lambda)$≤0.5) are retrieved for the wavelengths corresponding to sky radiance measurements.

The retrieval provides **the percentage of spherical particles** in the observed aerosol [Dubovik et al., 2006].

In addition to the detailed size distribution, the retrieval provides the following standard parameters for total (t), fine (f) and course (c) aerosol modes:
(*) -the definitions of each parameter are given in the Appendix below.
$\mathbf{C_v}$ – (μm^3/μm^2) volume concentration (t, f, c);
$\boldsymbol{r_v}$- volume median radius (t, f, c);
$\boldsymbol{\sigma}$ - standard deviation (t, f, c);
$\boldsymbol{r_{eff}}$ - effective radius (t, f, c);

Fine and coarse mode separation: The inversion code finds the minimum within the size interval from 0.439 to 0.992 μm. This minimum is used as a separation point between fine and coarse mode particles. Using that separation, the code simulates optical thickness, phase function and single scattering albedo of fine and coarse mode separately. Furthermore, the retrieval provides estimates of Effective Radius $\boldsymbol{r_{eff}}$, Volume Median Radius $\boldsymbol{r_{eff}}$, Standard Deviation $\boldsymbol{\sigma}$ and Volume concentrations $\mathbf{C_v}$ (μm^3/μm^2) for both fine and coarse modes of the retrieved size distribution.

NOTE: The fine and coarse modes of single scattering albedo are technically estimated; however, it is not advised to use these values for the physical interpretation because the retrieval is implemented under assumption that complex refractive index is the same for all particle sizes.

NOTE: These parameters characterize generally a size distribution of any shape. Therefore, they can still be useful even if the size distribution is not bi-modal.

3.2 Radiative properties

$\boldsymbol{\omega_0(\lambda)}$ - single scattering albedo at wavelengths corresponding to sky radiance measurements;

P(Θ; λ) - phase function for 83 scattering angles at wavelengths corresponding to sky radiance measurements;

<COS(Θ)> - asymmetry parameter for each phase function;

Spectral fluxes (W/m^2) at the wavelengths corresponding to sky radiance measurements:

$\mathbf{F^{\downarrow}_{TOA}(\lambda)}$ **and** $\mathbf{F^{\downarrow}_{BOA}(\lambda)}$ **-** down ward flux
$\mathbf{F^{\uparrow}_{TOA}(\lambda)}$ **and** $\mathbf{F^{\uparrow}_{BOA}(\lambda)}$ **-** upward ward flux
(TOA - top of atmosphere and BOA - bottom of atmosphere)

The detailed retrieved aerosol properties are used for calculating broad-band fluxes in spectral range from 0.2 to 4.0 μm. The flux simulation relies on the retrieved $n(\lambda)$ and $k(\lambda)$. The spectral integration uses $n(\lambda)$ and $k(\lambda)$ that are interpolated/extrapolated from the values $n(\lambda)$ and $k(\lambda)$ retrieved at AERONET wavelengths. Similarly, spectral dependence of surface reflectance is interpolated/extrapolated from surface albedo values assumed in the retrieval on the wavelengths of sun/sky-radiometer. The gaseous absorption is accounted using radiative transfer model GAME (Global Atmospheric ModEl) [Dubuisson et al., 1996]. This model performs spectral integration using correlated-k distribution based on line by line simulations [Scott, 1974].

Broadband fluxes (W/m^2):

$\mathbf{F^{\downarrow}_{TOA}}$ **and** $\mathbf{F^{\downarrow}_{BOA}}$ **-** down ward flux
$\mathbf{F^{\uparrow}_{TOA}}$ **and** $\mathbf{F^{\uparrow}_{BOA}}$ **-** upward ward flux

Radiative forcing (W/m^2):

$$\Delta F_{TOA} = F^{\uparrow 0}_{TOA} - F^{\uparrow}_{TOA}$$
$$\Delta F_{BOA} = F^{\downarrow}_{BOA} - F^{\downarrow 0}_{BOA}$$

where $\mathbf{F^{\uparrow 0}_{TOA}}$ and $\mathbf{F^{\downarrow 0}_{BOA}}$ are fluxes calculated with no aerosol

Radiative forcing efficiency (W/m^2):

$$\Delta F^{eff}_{TOA} = \Delta F_{TOA}/\tau(\lambda{=}0.55\ \mu m)$$
$$\Delta F^{eff}_{BOA} = \Delta F_{BOA}/\tau(\lambda{=}0.55\ \mu m)$$

3.2 Uncertainty Estimates

As a new addition to inversion products, V3 includes estimation of uncertainties in retrieved aerosol parameters. The uncertainties are modeled as a variability in retrieved aerosol parameters due to systematic errors (biases) in both measurements (AOD, sky radiances) and ancillary data (solar spectral irradiance, surface reflectance). The detailed description of the procedure for uncertainty estimation can be found at https://aeronet.gsfc.nasa.gov/new_web/Documents/U27_summary_final.pdf

Appendix: The formulas for calculating standard parameters of the particle size distribution.

Effective radius:

$$r_{eff} = \frac{\int_{r_{\min}}^{r_{\max}} r^3 \frac{dN(r)}{d\ln r} d\ln r}{\int_{r_{\min}}^{r_{\max}} r^2 \frac{dN(r)}{d\ln r} d\ln r} \tag{1}$$

We retrieve the aerosol size distribution of the particle volume ***dV*(*r*)/*d*ln*r***. It relates to the distribution of particle number as follows:

$$\frac{dV(r)}{d\ln r} = V(r)\frac{dN(r)}{d\ln r} = \frac{4}{3}\pi r^3 \frac{dN(r)}{d\ln r} \tag{2}$$

Volume median radius (mean logarithm of radius):

$$\ln r_v = \frac{\int_{r_{\min}}^{r_{\max}} \ln r \frac{dV(r)}{d\ln r} d\ln r}{\int_{r_{\min}}^{r_{\max}} \frac{dV(r)}{d\ln r} d\ln r}. \tag{3}$$

Standard deviation from volume median radius (mean logarithm of radius):

$$\sigma_v = \sqrt{\frac{\int_{r_{\min}}^{r_{\max}} (\ln r - \ln r_v)^2 \frac{dV(r)}{d\ln r} d\ln r}{\int_{r_{\min}}^{r_{\max}} \frac{dV(r)}{d\ln r} d\ln r}} . \tag{4}$$

Volume concentration (μm³/μm²):

$$C_v = \int_{r_{\min}}^{r_{\max}} \frac{dV(r)}{d\ln r} d\ln r. \quad (5)$$

Optical Residual (Error)

f* values are measured sky radiance (or AOD).
f values are fit by the model for sky radiance (or AOD).

For sky error, N represents the number of sky radiance measurements for a specific wavelength.

For sun error, N represents the number of wavelengths for AOD.

Using logarithms:

$$\sqrt{\frac{\sum_{i=1}^{n}[\ln f^{*} - \ln f]^2}{N}} * 100 = \%\, Error \quad (6)$$

The spectral sky error average is provided as the sky error of the retrieval.

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