Comparison of the Data of Airborne, Lidar, and Photometric Sensing of Aerosol Parameters in the Cloudless Atmosphere

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Introduction

A comprehensive investigation of the optical and microphysical parameters of tropospheric aerosol dictates the necessity of applying several different methods and devices that have different spatial and temporal resolution. The wide range of size spectrum of aerosol particles is necessary to correctly estimate their radiative properties; hence, it is clear that each of the applied devices has different sensitivities to particles of different sizes. These differences are being studied in conjunction with data from recent experiments investigating the properties of tropospheric aerosol with different remote and local methods (Schmid et al. 2004; Han et al. 2003; Collins et al. 2000).

To develop the technique for comprehensive investigation of tropospheric aerosol and estimation of the information capacity of different devices, we conducted the Aerosol-Radiation Complex Experiment (ARCE–2005), which studied the aerosol properties in the cloudless atmosphere. The main purpose of the experiment was to compare the results of synchronic airborne, lidar, sun-photometer, and ground-based measurements of aerosol parameters.

Instrumentation of Aerosol Measurements

ARCE–2005 took place on July 2, 2005, under cloudless conditions near the village of Zavjalovo (Novosibirsk region). The “OPTIC-E” AN–30 aircraft-laboratory (Zuev et al. 1992) flew for 3 hours over an area of 50 × 50 km and up to 7 km. The following parameters were measured onboard:

- directed aerosol scattering coefficient at the angle of 45° at the wavelength of 0.51 μm (the FAN photoelectric nephelometer)
- mass concentration of black carbon (aethalometer)
- meteorological parameters of air (temperature [T], °C, and relative humidity [RH], %).

All aforementioned aerosol parameters are caused by dry matter of submicron particles. The experimental setup and instrument calibration procedures are described in Panchenko et al. (2000). Ground-based measurements took place at a site directly under the aircraft flight. The following parameters were measured:

- vertical profiles of the aerosol extinction coefficient ε (km^{-1}) at the wavelength of 532 nm up to the height of 4–5 km ("LOZA–M" aerosol lidar)
- aerosol optical thickness (AOT) of the atmosphere at 15 wavelengths in the range 399 to 4000 nm (SP–5 sun-photometer)
- the directed aerosol scattering coefficients at the wavelengths of 0.41, 0.51, and 0.63 µm at the angle 45° and two polarized components of scattered radiation at the angle of 90° at the wavelengths of 0.44 and 0.51 µm (the FAN photoelectric nephelometer, measurements in the near ground air layer).

The multiwavelength sun-photometer SP–5 is capable of measuring the columnar water vapor and the spectral dependence of the AOT. The techniques for calibrating the photometer and calculating the AOT and columnar water vapor are described in Sakerin and Kabanov (2002) and Kabanov and Sakerin (1997). This procedure excludes the contributions of the molecular absorption and scattering by means of normalizing the measured signals to the transmission functions of atmospheric gases calculated using the model LOWTRAN-7 (Kneizys et al. 1988) taking into account spectral instrumentation functions of the photometer are real variability of the columnar water vapor. The error in determining AOT in the shortwave range is 0.01–0.02< and increases up to 0.02–0.03 in the infrared range.

Sensing the vertical profile of the aerosol extinction coefficient at the wavelength of 532 nm was carried out with the mobile lidar "LOZA–M" (Bairashin et al. 2005). The pulse repetition rate was 5 Hz. The lidar makes it possible to reconstruct the aerosol optical characteristics with spatial resolution of 3, 6, or 12 m up to the distance of 3–4 km from an individual return signal, and up to 6–10 km using the method of statistical accumulation. In addition, a nephelometer, mounted on the ground-based mobile station, measured the aerosol scattering coefficients and polarization components of scattering.

Reconstructing the Vertical Profiles of the Aerosol Scattering Coefficient and Other Parameters from Airborne Data

The profiles onboard the aircraft were measured during ascending and descending flights at heights between 500 m and 7000 m. Additional measurements at eight fixed heights (0.5, 1, 1.5, 2, 3, 4, 5.5, and 7 km) were performed between 7 and 10 minutes to estimate spatial variability of the aerosol characteristics.

A nephelometer installed onboard the aircraft measured the scattering coefficient of the dry matter of submicron aerosol particles, and a meteorological sensor measured the RH. The values of the "dry" scattering coefficient were recalculated to the real value of humidity by the well known Kasten-Hanel formula using the value of the parameter of aerosol condensation activity $\gamma = 0.184$ obtained on the ground at the aerosol monitoring station of IAO SB RAS (Kozlov et al. 1997).

$$\sigma_{\mathrm{RH}} = \sigma 0(1 - RH)^{-\gamma},$$

where σ_0 is the aerosol scattering coefficient at zero RH.

To complete the profile, the value of the aerosol scattering coefficient measured on the ground in the region under the aircraft flight was added σ (0.51 μm, RH = 60%) = 0.118 km^{-1}.

Figure 1 shows the vertical profiles of the aerosol scattering coefficient and mass concentrations of aerosol and black carbon (BC). The aerosol mass concentration was derived from the data on the aerosol scattering coefficient using the one-parameter model of atmospheric hazes (Gorchakov et al. 1981), $M_a(\mu g/m^3) = 330 \times \sigma\ (km^{-1})$ for the density of aerosol particles of $\rho = 1.5$ g/cm^3. The profiles of aerosol and BC mass concentrations were used to calculate the profiles of BC fraction of submicron aerosol $P = M_{BC}/M_a$ and the single-scattering albedo, ω. The aerosol absorption coefficient was derived from the data of the aethalometer using the value of absorption efficiency 5.49 m^{2}g^{-1} at the wavelength of 0.53 μm, which was obtained from synchronic optical-acoustic and aethelometric measurements of real aerosol parameters (Tikhomirov et al. 2005). The value P was also used to estimate the absorption index pf particles χ_{dry} is assumption of internal mixture of BC and nonabsorbing aerosol. The estimates of the aforementioned parameters at the height of 0.1 km are shown in the figure. Note that the vertical profile of BC concentration is obtained from measurements at eight fixed heights of horizontal flight. Because of errors in measuring the BC concentration (absorption coefficient), i.e., increasing due to the "jumps" of pressure in the air path, we did not consider the parts of quick ascending and descending.

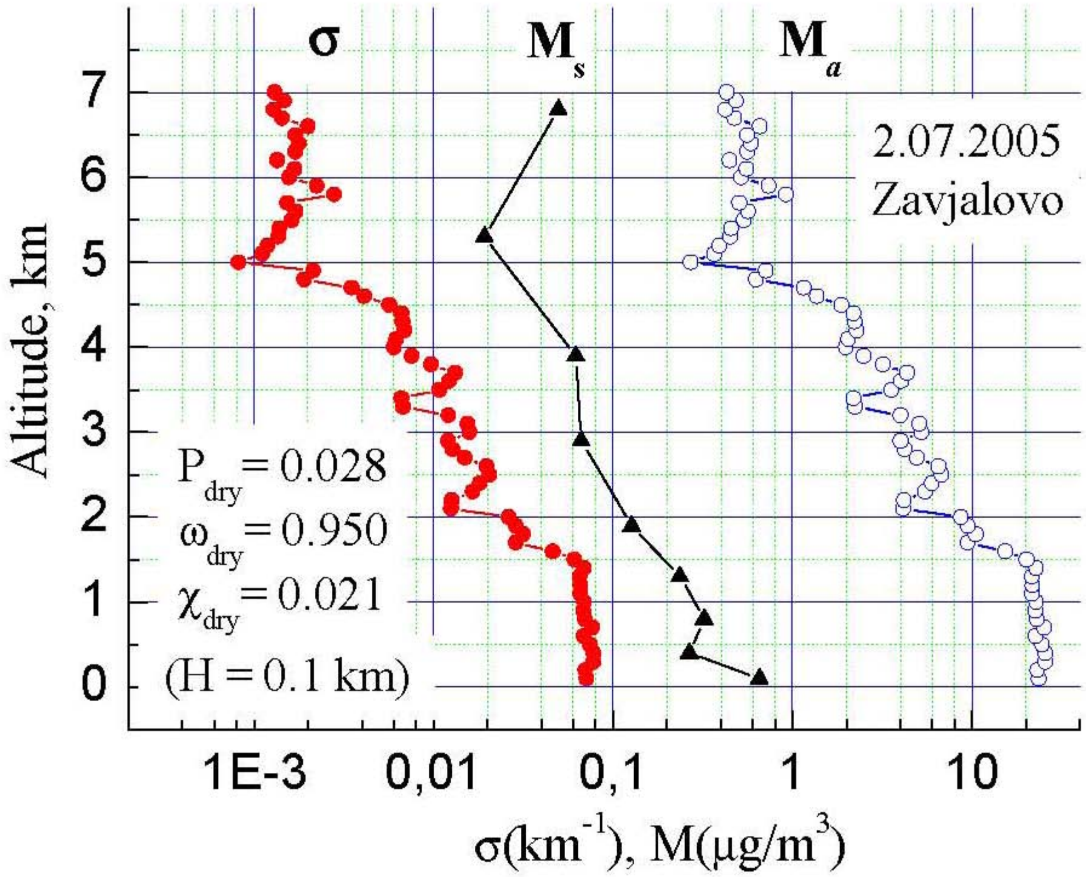

Figure 1. Vertical profiles of the scattering coefficient σ and mass concentrations of aerosol (*M_a*) and Black carbon (*M_{BC}*).

Comparison of Nephelometric and Lidar Profiles

The experimentally obtained profiles of the aerosol extinction ε and scattering σ coefficients (Figure 2) are typical for summer conditions in West Siberia (Panchenko and Terpugova 1994; Bairashin et al. 2005) and are characterized by the near-ground layer, mixing layer, and free atmosphere.

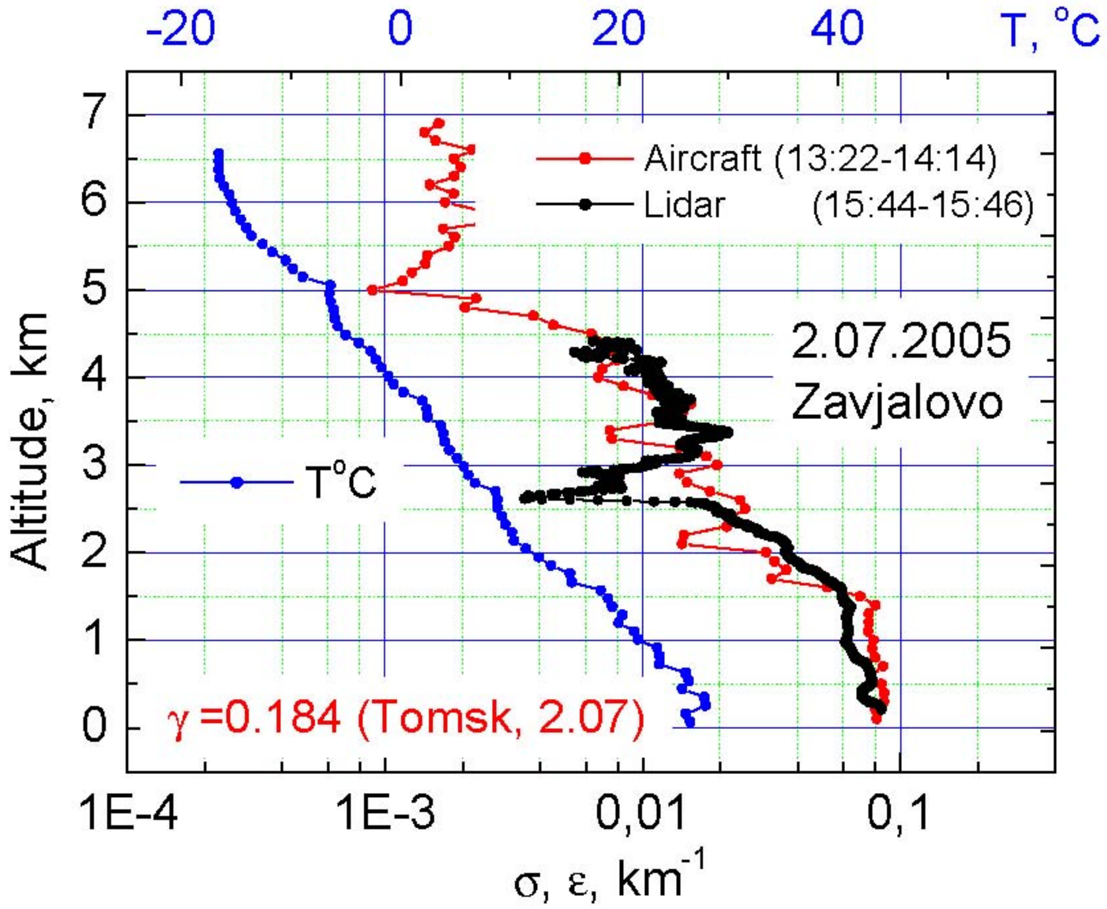

Figure 2. Vertical profiles of the aerosol scattering coefficient at real humidity (onboard nephelometer), aerosol extinction coefficient (lidar) and air temperature.

Comparison of the vertical profiles obtained from onboard the aircraft and with the lidar show good quantitative and qualitative agreement. Some differences in the profiles in the height range 2.5 – 3 km are related probably to the effect of spatial-temporal variability of the aerosol concentration in the region of measurements.

Inverse Problems and Data Processing

The data of the spectral AOT measured with the sun-photometer SP–5 was inverted to the columnar aerosol size distribution in the radius range 0.04 – 4.5 µm. The regularizing algorithm based on construction of a smoothing functional by the A.N. Tikhonov method and direct minimizing in the k-dimension space was applied for inversion. The peculiarities of the inversion technique are considered in Zuev (1983). Then the contributions of fine (0.04 – 0.35 µm) and coarse (0.35 – 4.5 µm) aerosol fractions into the total optical thickness in the considered wavelength range were calculated.

All measured aerosol profiles (scattering coefficient and BC mass concentration measured from onboard the aircraft and the profiles of the extinction coefficient measured with the lidar) were integrated with respect to height to obtain the AOT (τ) of scattering, absorption and extinction, and the height of the homogeneous atmosphere. Then the calculated values τ were used for comparison with the results of spectral measurements with sun photometer and spectral calculations for fine and coarse aerosol fractions.

In addition, the aerosol particle size distributions were retrieved from inverting the data on the spectral aerosol scattering coefficient and its polarized components measured with the ground-based nephelometer. The iteration algorithm (Anikin and Sviridenkov 1999) based on the Twitty method (Twitty 1975) was used for retrieval of the particle size distribution в диапазоне радиусов 0.04-0.7 μm. Measurements of not only the directed scattering coefficients but also the degree of linear polarization make it possible to estimate the refractive index of the aerosol matter together with the size spectrum. Discrepancy of this retrieval (the ratio of the optical parameters calculated using the retrieved refractive index and size distribution to their measured values) is about 5% (i.e., approximately the same as the error in measuring).

Aerosol Extinction Closure

Consideration of qualitative peculiarities of the values AOT in visible wavelength range obtained by different methods (Figure 3) shows the following:

1. values of the AOT obtained from the data of airborne and lidar measurements are is good agreement with each other (points 4 and 5 in Figure 3)

2. airborne and lidar estimates of AOT better correspond to the data of sun photometer obtained for the submicron aerosol fraction (curve 2).

The detailed quantitative comparison of the data presented below confirms the noted peculiarities.

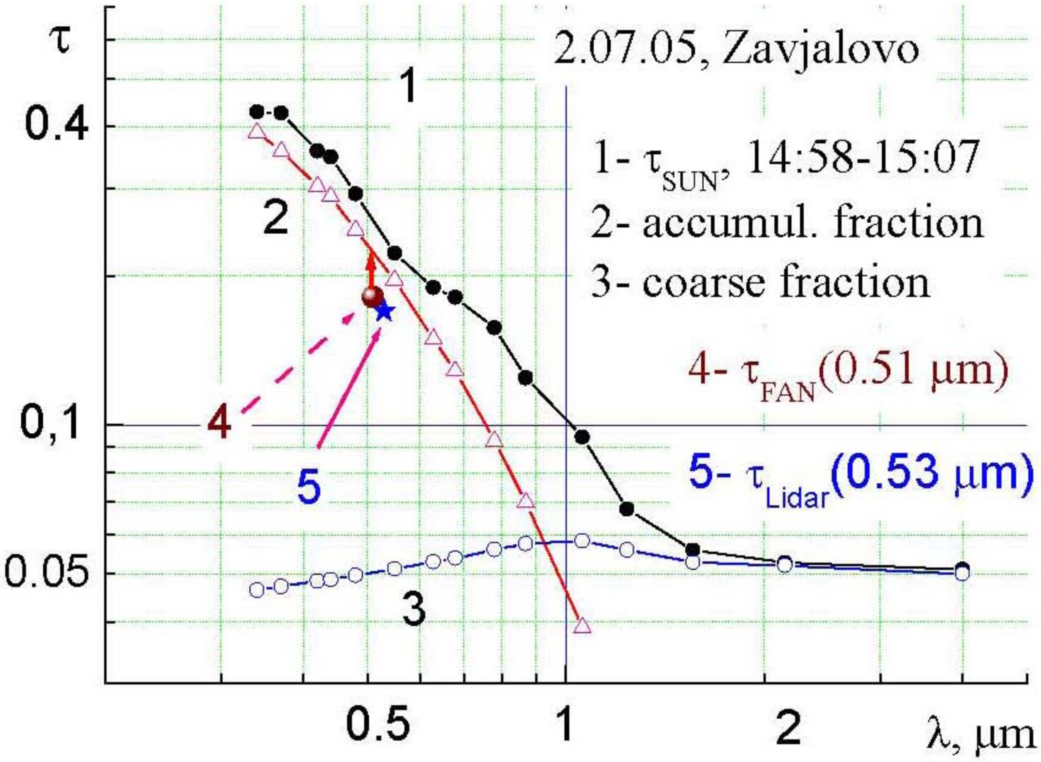

Figure 3. Comparison of spectral AOT of the atmosphere with the data of airborne and lidar sounding (1 – spectral AOT measured with sun-photometer; 2 – estimate of AOT due to fine fraction (r = 0.04 – 0.35 µm); 3 – estimate of AOT due to coarse fraction (r = 0.35 – 4.5 µm); 4 – estimate of AOT (0.51 µm) obtained by integrating of the vertical profile of the aerosol scattering coefficient measured from onboard the aircraft in the height range up to 7 km; 5 – estimate of the AOT (0.53 µm) obtained by integrating of the vertical profile of the aerosol extinction coefficient measured with the lidar from the ground).

Numerical comparison of the AOT obtained by different methods (sun photometry, airborne and lidar measurements)

Results of measurements (see Figure 3):

Sun photometer – $\tau_{phot} = 0.26$; Nephelometer $\tau_n = 0.18$; Lidar – $\tau_l = 0.18$
According to the LOWTRAN–7 model (Kneizys et al. 1988), optical thickness of the layer from 7 km to the top of the atmosphere in midlatitude summer $\Delta\tau_7 = 0.035$,
Hence, $\tau_{phot}(0–7\text{ km}) = 0.26–0.035 = 0.225$

As the nephelometer measures the characteristics of submicron fraction of particles, hence, one needs to exclude the contribution of coarce particles into the total AOT. Two ways for estimating AOT for fine fraction of particles (nephelometer) are as follows:

1. Let us assume that τ in near infrared range (1.5–2 μm) is determined by only the coarse fraction, then τ due to submicron particles $\tau_{fine} = \tau(0.51) - \tau(1.5) = 0.26 - 0.054 = 0.206$
   $\tau_{fine}(0\text{–}7\ km) = 0.206 - 0.035 = 0.171$

2. Contribution of the coarse fraction is estimated from solution of the inverse problem
   $\tau_{coarse} = 0.05$, then $\tau_{fine} = 0.225 - 0.05 = 0.17$

Finally we have

$\tau_n = 0.18$ $\tau_l = 0.18$ $\tau_{phot}(0\text{–}7\ km)_{fine} = 0.17$

Thus, quantitative estimates of AOT if submicron particle fraction by the methods of sun photometry, lidar sounding, and airborne nephelometric measurements are in good agreement.

Columnar and Ground-Based Cross Section Size Distributions of Aerosol Particles

Figure 4 shows the columnar (curve 1) and near-ground (curve 2) particle size distributions reconstructed by solving the inverse problems. The columnar size spectrum was determined assuming the particle refractive index m = 1.45–0.005 i. The complex refractive index of particles in the near-ground layer obtained from the nephelometric data corresponds to the dry matter of submicron aerosol and is equal to m = 1.56–0.02 i. Qualitative comparison of the obtained size distributions shows their satisfactory agreement in the radius range less than 0.4 μm and significant differences in the range of larger particles.

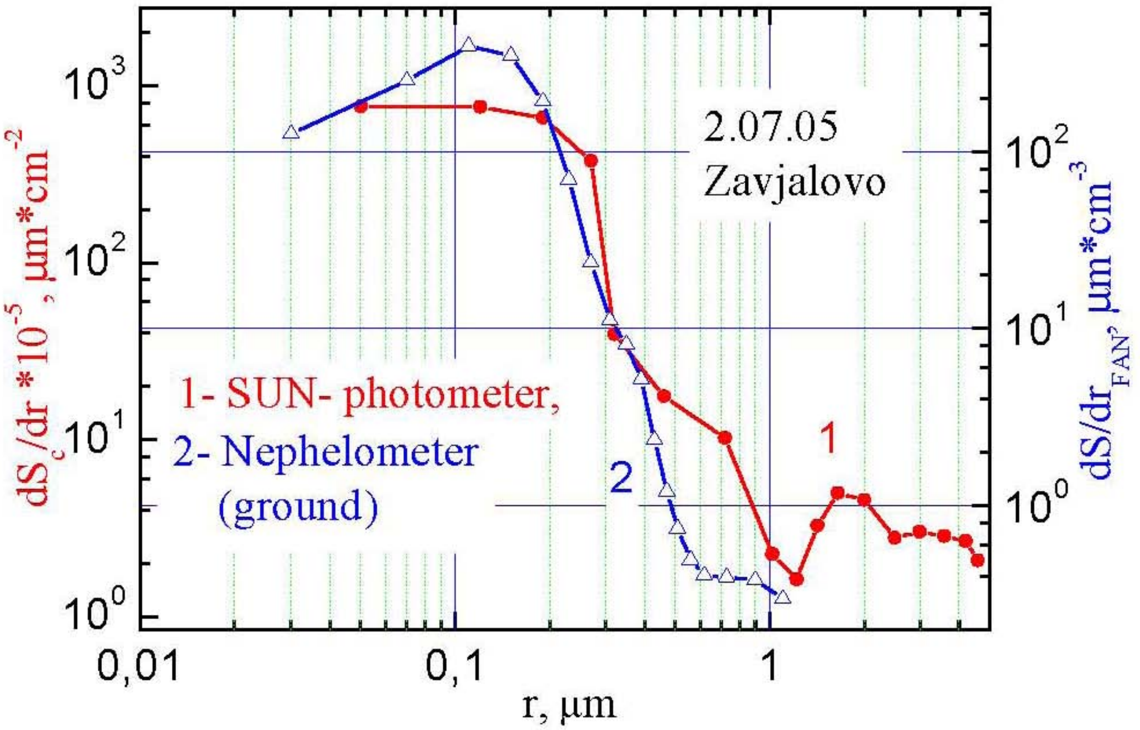

Figure 4. Particle cross section size distributions (1 – columnar, 2 – near-ground)

Conclusion

The results of the study show satisfactory agreement of the data on optical and microphysical characteristics of submicron aerosol particles obtained by different methods. In addition, the results of the comprehensive experiment indicate the necessity of significant extension of the wavelength range of measurements and application of another class of devices for the study of the coarse fraction of particles.

Acknowledgments

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