On uncertainty of determination of particle optical thickness in atmospheric environment

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Abstract. The uncertainty of particle optical thickness retrieval in the Earth's atmosphere is estimated. There are some specific factors, which are notoriously not evaluated i) the intensity distribution on the solar disk, ii) changes of the optical air mass along the solar disk, and iii) diffuse radiation in the solar aureola, which represents an addition to the measured intensity because of the finite instrument field-of-view. It is shown that the first two factors, in general, reduce the final value of the aerosol optical thickness τ_a, so that the corrected value τ_a^C looks to be less than the approximate value τ_a^A obtained by a simple retrieval mechanism. However, diffuse radiation in the aureola region causes an increasing of τ_a^C by a factor Q. The corrected value of τ_a^C can finally be about 2-3 % larger than τ_a^A. This difference varies with modal radius of the aerosol size distribution, due to sensitive dependence of the scattering pattern (in the near-forward scattering region) on particle size. An error level (2-3 %) cannot be ignored, because it is comparable to the standard systematic/random measurement error $\approx$ 4-5 %. It is shown that such a small uncertainty in the aerosol optical thickness can produce large changes in the solution of the inverse problem yielding the size distribution of the aerosol particles $f(r)$. This influences data processing and it is, for instance, a source of new open questions when interpreting the measured brightness of F-corona (to retrieve the number density of interplanetary dust particles). The gained range of the possible solutions of $f(r)$ then has a direct impact on the calculation of radiation fluxes in the atmosphere. The uncertainty in estimation of the radiative balance may change the view of chemical and physical processes in the planetary atmosphere, and may be a reason for partially inaccurate or inadequate physical conclusions.

Key words: particle optical thickness – diffuse radiation – extinction – optical air mass

1. Introduction

The standard ground-based astronomical observational data in visible (VIS) and infrared (IR) need to be corrected due to changes of the optical properties of Earth's atmosphere, which therefore need to be systematically monitored (Burki et al., 1995). The absorption of electromagnetic radiation by the gaseous components is a selective process. The most important absorption bands are well-known, which enables us to perform measurements in spectral regions with no absorption influence. However, the measured data is always affected by the permanent effect of light scattering by air molecules and atmospheric aerosols. Molecules scatter the radiation in a typical manner, which is well described by the Rayleigh theory. Rayleigh scattering brings a symmetry into the scattering diagram (the patterns for the backscattering and forward scattering have the same form). Molecular scattering optical thickness can be calculated accurately by using the hydrostatic approximation for a given surface pressure (Kato et al., 1999). However, Maxwell equations must be explicitly solved to describe the light scattering by objects the size of which is comparable to or greater than the wavelength λ of incident radiation (not less than 0.03 λ). The particles flying in the Earth's atmosphere are different in size, chemical composition, and shape, dependant on of their origin and formation (Lacis and Mishchenko, 1994). At present, several methods are known to solve the problem of light scattering by such particles. Mishchenko and Travis (1998) have developed a fortran implementation of the T-matrix method for randomly oriented rotationally symmetric scatterers. Most frequently used computational methods - DDA (Discrete Dipole Approximation), FDTD (Finite Difference Time Domain), and EBCM (Extended Boundary Condition Method), calculating the light scattering by arbitrarily shaped particles were compared by Wriedt and Comberg (1998). Although the scattering properties of the individual nonspherical particles vary significantly with the particle orientation, the volume scattering characteristics of the planetary atmosphere (consisting of polydisperse populations of the particles) have a different character. The polydisperse ensembles of small spheroids exhibit essentially the same scattering behaviour as their equivalent-volume spheres (Krotkov et al., 1999).

The extinction of aerosol particles is often expressed in terms of a power law corresponding to the Ångström formula (Cachorro and Casanova, 1987). Such an approximation is acceptable for mountain regions - as La Silla (Burki et al., 1995) - Junge's function supplies the particle size distribution with sufficient accuracy in this case. However, this is not true in the lower troposphere (let's say in the atmospheric boundary layer), where the physical and chemical processes change the size distribution of aerosols significantly. There is an evident relationship between emission and particle extinction when ground-based measurements are performed at stations which are not situated in mountain regions. Source emissions are linked to ambient particle concentrations through processes of chemical transformation, particle growth, coagulation, dispersion, transport, and removal. The changes of extinction are then directly related to the changes of the particle size distribution (Lowenthal et al., 1995).

Knowledge of the atmospheric aerosols is important because continuous atmospheric scattering by dust particles affects spectrophotometry and high resolution spectroscopy since atmospheric features are superimposed onto those in stellar spectra (Fluks and Thè, 1992). Also the retrieval of the optical thickness of the water vapour in the planetary atmosphere is directly affected by the accuracy of the retrieval of aerosol optical thickness. The information on water vapour in the planetary atmosphere has an important role in the study of various dynamical and chemical processes, and contributes to the atmospheric radiation balance, and has probably played a crucial role in the climate and biological evolution on the planet (Titov et al., 2000) - therefore, the water vapour has been, the focus of space missions to Mars and ground-based observations (Clancy et al., 1996).

Atmospheric extinction mainly modifies the profile of interstellar extinction or photometric data due to spectral, spatial, and time variability of the aerosol optical thickness $\tau_a(\lambda)$. The information on $\tau_a(\lambda)$ in VIS and IR therefore has high importance. The short-term changes of aerosol optical thickness strictly reflect small fluctuations in particle size distribution function $f(r)$ (r is the particle radius). The sensitive dependence of $\tau_a(\lambda)$ on $f(r)$ can effectively be used to evaluate the particle size distribution. Once the function $f(r)$ is known, the values of $\tau_a(\lambda)$ can be re-calculated over the chosen spectral range.

2. Selected factors affecting aerosol optical thickness retrieval

Observations of the polarization of solar corona at infrared wavelengths is effective when determining the size of interplanetary dust or when significant limits on dust size are imposed (Beard, 1984). Many observations of the solar corona at visible brought the information on light scattering by small particles in the inner solar system. The mechanism of light scattering is related mainly to the Fraunhofer diffraction of sunlight revealing that the radius of particles is larger than 0.1 μm. Determination of absolute intensity of the scattered light in the visible spectrum is notoriously difficult because of atmospheric scattering. Lamy and Perin (1986) have shown that the accuracy of the photometry of F-corona can significantly affect the results related to the study of interplanetary dust particles (IDPs). In general, it is possible to retrieve the number density of the IDPs using the measurements of the brightness of F-corona. However, the precision and effectivity of such retrieval is affected by the accuracy at which the aerosol optical thickness of the Earth's atmosphere is known.

An evaluation of the optical thickness of the atmospheric environment is influenced by many factors, such as an instrumental, environmental conditions, the physical model used and others. Sun photometers usually measure the spectral transparency of the atmosphere. Several techniques are known to correct the measured data and for yielding reliable information on the particle optical thickness. However, there are some specific factors, which are notoriously not taken into account: i) the intensity distribution on the solar disk, ii) changes of the optical air mass along the solar disk, and iii) diffuse radiation in the solar aureola, which represents an addition to the measured intensity because of finite instrument field-of-view.

2.1. A brightness distribution on the solar disk

The spectral brightness distribution around the solar disk can be expressed simply as follows (Link, 1956)

$$b(R) = I_0 \frac{3}{3-\kappa} \left(1 - \kappa + \frac{\kappa}{R_S} \sqrt{R_S^2 - R^2} \right) \quad , \tag{1}$$

where I_0 is the normalized intensity, κ is the spectral parameter ($\kappa \approx 0.73$ at λ=460 nm, $\kappa \approx 0.62$ at λ=540 nm, $\kappa \approx 0.54$ at λ=620 nm), R_S is the angular radius of the solar disk, and R is the actual angular distance measured from the centre of the solar disk. The ratio $\kappa/(3-\kappa)$ results from the condition

$$I_0 \pi R_S^2 = 2 \int_{R=0}^{R_S} \int_{\varphi=-\frac{\pi}{2}}^{\frac{\pi}{2}} b(R)\; R\; dR\; d\varphi \quad , \tag{2}$$

where φ is the polar angle. The couple (φ, R) constructs the polar coordinate system measured from the centre of solar disk.

2.2. The effect of optical air mass changes in the region of the solar disk

The attenuation of solar electromagnetic radiation in the atmospheric environment can be described as a reduction of intensity due to extinction. The measured intensity of monochromatic radiation can then be defined as follows

$$I = I_0\; e^{-\tau M} \quad , \tag{3}$$

where τ is the atmospheric spectral optical thickness and M is an optical air mass. Although the tables or approximations for air mass are well-known (Kasten and Young, 1989; Young, 1994), analytical expressions for optical air mass are frequently necessary (e.g., for fast numerical computations to solve the inverse problems). The Earth's atmosphere is a mixture of gaseous components and aerosols with their own optical air masses, but the spectral dependency of the total optical thickness τ is usually calculated using the optical air mass M for a Rayleigh atmosphere. In such a case the analytical model of M for a horizontally homogeneous atmosphere (Kocifaj, 1996) can be applied for all the computations.

The most unstable part of optical thickness is the particle optical thickness τ_a that can be simply calculated using the equation

$$\tau_a = \tau - \tau_R - \tau_g \quad . \tag{4}$$

The optical thickness of the molecular atmosphere corresponds to the Rayleigh component τ_R, which differs from τ_g related to absorption by gaseous components of the atmosphere (e.g. ozone, water vapour, ...). Optical air mass M depends significantly on the solar zenith angle ζ_0, and therefore the equation (3) need to be expressed in the form

$$I(\zeta_0) = I_0 \; e^{-\tau M(\zeta_0)} \quad . \tag{5}$$

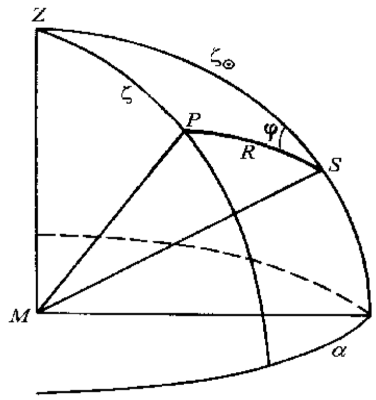

Figure 1. The spatial geometry (M - point of the measurement, Z - zenith, S - centre of the solar disk, R - angular distance measured from S, ζ - zenith angle of the point P, ζ_0 - zenith angle of the Sun, α - azimuth).

Using spherical geometry (Fig. 1), the actual zenith angle of any point on the solar disk (the position of which is determined by couple φ, R) equals

$$\zeta(R, \varphi, \zeta_0) = \arccos\left(\cos\zeta_0 \cos R + \sin\zeta_0 \sin R \cos\varphi\right) \quad . \tag{6}$$

Including the brightness distribution over solar disk, the theoretical intensity of the radiation is as follows:

$$I(\zeta_0) = I_0 \frac{6}{3-\kappa} \int_{R=0}^{R_S} \left(1 - \kappa + \frac{\kappa}{R_S}\sqrt{R_S^2 - R^2}\right) R$$
$$\int_{\varphi=0}^{\pi} \exp\left\{-\sum_{i=1}^{N} \tau_i M_i(\zeta)\right\} \, d\varphi \, dR \quad , \tag{7}$$

where the sum combines all the atmospheric components (indexed by i) with their own optical mass M_i. Using a simple formula (5) , the approximate particle optical thickness τ_a^A is obtained. This quantity differs from the corrected value τ_a^C - related to Eq. (7). Comparing both equations, (7) and (5), the relationship of τ_a^C and τ_a^A is found

$$\tau_a^C = Q \tau_a^A \quad . \tag{8}$$

The correction factor Q can be tabulated, so the corrected value of the particle optical thickness may easily be calculated using τ_a^A. This fact accelerates the calculation significantly while the integral (7) need not be calculated.

2.3. The diffuse radiation in the solar aureola and effect of instrument aperture

An evaluation of particle optical thickness may also be affected by diffuse radiation in the solar aureola. The influence of diffuse radiation varies significantly with the characteristics of the particle population in the atmosphere, such as the size distribution function $f(r)$, and the refractive index m. The total intensity measured by a solar photometer with its own aperture angle θ_a is then

$$I_{tot}(\zeta_0) = I(\zeta_0) + D(\zeta_0) \quad , \tag{9}$$

where the diffuse component D can be simulated by the first scattering order with a high accuracy

$$D(\zeta_0) = 2I_0 \int_{\theta=0}^{\theta_a} \cos\theta \sin\theta \int_{\varphi=0}^{\pi} M(\zeta) \int_{h=0}^{\infty} \beta(h,\theta)$$

$$\exp\left\{ -M(\zeta_0) \int_{z=h}^{\infty} b(z)\ dz - M(\zeta) \int_{z=0}^{h} b(z)\ dz \right\} dh\ d\varphi\ d\theta \quad , \tag{10}$$

where θ is the scattering angle measured from the center of the solar disk up to instrument field-of-view $\theta_a/2$, $b(z)$ is the volume extinction coefficient at an altitude z, and β is the scattering coefficient.

The particles flying in the atmosphere are assumed to be non-absorbing, with flat dependence of refractive index on wavelength in the visible. However, this can be true for continental aerosols (Zuev and Krekov, 1986). Some experimental studies (Wendisch and von Hoyningen-Huene, 1992; Kabanov et al., 1988; Asaturov et al., 1986) conclude that the real part m_r of the particle refractive index $m = m_r$-$i.m_i$ is much greater than the imaginary part m_i in the visible spectrum ($m_i \approx 10^{-3}$). In particular, the retrieval techniques are often based on the assumption $m_i = 0$ (Gobbi, 1995; Stramski and Sedlák, 1994). Taking into account these facts, the volume scattering coefficient simply equals volume extinction coefficient, and the scattering coefficient β is calculated as follows

$$\beta(h,\theta) = \frac{P_R(\theta)}{4\pi}\ b_R(h) + \frac{P_a(\theta)}{4\pi}\ b_a(h) \quad , \tag{11}$$

where the total volume extinction coefficient $b(h)$ equals

$$b(h) = b_a(h) + b_R(h) + b_g(h) \quad , \tag{12}$$

(b_a for aerosols, b_R and b_g are related to the Rayleigh scattering and absorption by gaseous components), and $P_R(\theta)$ and $P_a(\theta)$ represent the normalized phase functions for Rayleigh and Mie scattering, respectively. In general, the aerosol phase function is a complex function of particle shape. The calculation of the light scattering by inhomogeneous particles of arbitrary shape is a time-consuming procedure, which is notoriously hard to solve. However, Mie's substitute is applied for a statistically large amount of randomly oriented particles.

Mie's component in the small scattering angle approximation is most important because

$$\frac{P_a(\theta)}{4\pi}\ b_a(h) \rangle\rangle \frac{P_R(\theta)}{4\pi}\ b_R(h) \quad . \tag{13}$$

The aerosol scattering coeeficient can be expressed as follows

$$\frac{P_a(\theta)}{4\pi}\ b_R(h) = \frac{\lambda^2}{4\pi^2}\int_{r=0}^{\infty} \frac{|S_1(r,\theta)|^2 + |S_2(r,\theta)|^2}{2}\ f(r,h)\ dr \quad , \tag{14}$$

where $f(r,h)$ is the vertical profile of the particle size distribution function, and S_1 and S_2 are Mie dimensionless functions, which depend significantly on the wavelength λ. These functions may be replaced by a Bessel function with a relatively good accuracy in a small scattering angle approximation. Such approximation of diffraction theory is well-known – the smaller the scattering angle, the higher the importance of the large particles. Kokodij (1994) has derived an asymptotic formulae for scattering characteristics of large particles (with scattering parameter $x = kr > 5$, wavenumber $k = 2\pi/\lambda$), which can be simply applied in inversion procedures. For particles whose characteristic length is of the order of, or greater than, the wavelength λ, the Mie function $|S_1(r,\theta)|^2$ is dominated by a peak in the near-forward direction. This peak may be modelled, or derived on the basis of Fraunhofer diffraction. Box and Viera (1990) show that the differential-kernel method does provide distinctly superior retrievals to the normal method. For example, the aerosol characteristics can successfuly be obtained by using a small scattering angle approximation when aureole data is measured in the region $3^o < \theta < 30^o$ (Tonna et al., 1995). The near-forward light scattering problem has been well elaborated over the past few years. For instance, Mroczka (1993) showed that a particle size distribution can be obtained by the direct inversion of light scattering data, in particle, without the necessity of pre-supposing the form of the distribution function.

Fraunhofer diffraction related to the Mie theory in small scattering angle approximation brings a simple equality

$$S_1(r,\theta) = S_2(r,\theta) = \frac{2\pi r}{\lambda \sin\theta}\ J_1\left(\frac{2\pi r}{\lambda}\ \sin\theta\right) \quad , \tag{15}$$

which reflects in the expression

$$\frac{P_a(\theta)}{4\pi}\ b_a(h) = \frac{1}{\sin\theta}\int_{r=0}^{\infty} r^2\ J_1^2\left(\frac{2\pi r}{\lambda}\ \sin\theta\right)\ f(r,h)\ dr \quad . \tag{16}$$

Assuming the exponential profile of the particle concentration stratification

$$f(r,h) = F(r)\ G(h) = A\ F(r)\ e^{-\gamma h} \quad , \tag{17}$$

the equation (10) yields a new form

$$D(\zeta_0) = 2\ I_0\ A \int_{\theta=0}^{\theta_a} \frac{1}{\sin\theta} \left\{ \int_{r=0}^{\infty} r^2\ J_1^2 \left(\frac{2\pi r}{\lambda}\ \sin\theta \right)\ F(r) \right\} \int_{\varphi=0}^{\pi} M(\zeta)$$

$$\int_{h=0}^{\infty} e^{-\gamma h}\ \exp\left[-M(\zeta_0) B_1(h) - M(\zeta) B_2(h) \right]\ dh\ d\varphi\ d\theta \quad , \tag{18}$$

where

$$B_1(h) = \frac{b_R(0)}{\delta}\ e^{-\delta h} + \frac{b_a(0)}{\gamma}\ e^{-\gamma h} \quad , \tag{19a}$$

$$B_2(h) = \frac{b_R(0)}{\delta}\ \left(1 - e^{-\delta h}\right) + \frac{b_a(0)}{\gamma}\ \left(1 - e^{-\gamma h}\right) \quad , \tag{19b}$$

because

$$b_R(h) = b_R(0)\ e^{-\delta h} \tag{20a}$$

and

$$b_a(h) = b_a(0)\ e^{-\gamma h} \quad . \tag{20b}$$

3. Correction of the aerosol optical thickness

The accuracy of the atmospheric optical thickness determination using the spectral transparency data depends mainly on experimental errors. A random error with the values $I(\lambda)$ (Eq. 3) could occur during observations. The root-mean-square measurement error is usually about 4 % in the whole visible and is reduced by increasing the wavelength. A systematic error with uncertainty of the instrument solar constant can be minimized by periodical calibration of the device. Small variations of aerosol optical thickness calculated according to Eq. (4) may also reflect the uncertainty of the Rayleigh component of the optical thickness. However, this error can be reduced by monitoring the actual meteorological data (pressure, temperature), which makes it possible to minimize the error of the Rayleigh component.

The accuracy of evaluation of aerosol optical thickness also depends also on the Sun's elevation. The smaller the elevation the bigger the uncertainty of the optical air mass, and the bigger the differences between the optical mass corresponding to individual atmospheric components. Nevertheless, some astronomical observations performed near the horizon are based on simple the approximation $M = 1/\cos\zeta_0$ (Titov et al., 2000). Unfortunately this is not true for small elevations (or for $M > 5$).

We have analysed the influence of all three effects (itemized in chapter 2):

– changes of the optical air mass along the solar disk

In general the changes of the optical air mass don't have a large influence on the retrieval accuracy of the aerosol optical thickness. There is no evident difference in Q for various aerosol types over the whole visible spectrum. The factor Q (Eq. 8) varies mainly with elevation (near the horizon). Omission of changes of the optical air mass along the solar disk reduces the final aerosol optical thickness, because of the reduction of the factor Q with increasing zenith angle ζ_0 (Tab. 1). Assuming that the observations of the Sun are usually not performed near the horizon ($\zeta_0 \geq 10^o$, the maximum deviation of the corrected τ_a^C from the approximate aerosol optical thickness τ_a^A (Eq. 4) is less than 1 %, and therewithal $\tau_a^C < \tau_a^A$.

Table 1. Q factor (inside) defined as the ratio of corrected and approximate aerosol optical thickness (τ_a^C/τ_a^A): only the effect of optical air mass changes in the region of the solar disk is taken into account. The value of Q in principle doesn't depend on the wavelength in the visible spectrum and the particle size distribution.

	solar zenith angle ζ_0 [deg]				
τ_a^A	0	30	60	70	80
0.01	1	1.002	1.017	1.043	1.175
0.02	1	1.001	1.008	1.019	1.070
0.03	1	1.001	1.004	1.011	1.039
0.04	1	1.001	1.003	1.007	1.024
0.05	1	1	1.002	1.005	1.015
0.06	1	1	1.001	1.003	1.009
0.07	1	1	1.001	1.002	1.005
0.08	1	1	1	1.001	1.002
0.09	1	1	1	1.001	1
0.10	1	1	1	1	0.998
0.15	1	1	0.999	0.999	0.993
0.20	1	1	0.999	0.998	0.990
0.25	1	1	0.999	0.997	0.988
0.30	1	1	0.999	0.997	0.987
0.35	1	1	0.999	0.997	0.986
0.40	1	1	0.998	0.997	0.986
0.45	1	1	0.998	0.997	0.985
0.50	1	1	0.998	0.996	0.985

– intensity distribution on the solar disk

The effect of nonhomogeneous intensity distribution on the solar disk has a measurable effect on the retrieval accuracy of the aerosol optical thickness if τ_a^A is less than about 0.2. The difference of the corrected and approximate aerosol optical thickness is less than 1 % if $\tau_a^A > 0.2$. For all that, the correction due to the changes of wavelength in the visible doesn't exceed 0.5 %. The final effect of the discussed physical quantity is the reduction of the aerosol optical thickness by the factor $Q < 1$, where the error of the aerosol optical thickness may be about 4 % if $\tau_a^A < 0.1$ (Tab. 2).

Table 2. Q factor (inside) defined as the ratio of corrected and approximate aerosol optical thickness (τ_a^C/τ_a^A; $\lambda = 0.46\ \mu m$): only the effect of intensity distribution of the solar disk is taken into account. The value of Q in principle doesn't depend on the particle size distribution.

	solar zenith angle ζ_0 [deg]						
τ_a^A	0	20	40	50	60	70	80
0.01	0.751	0.764	0.798	0.825	0.856	0.894	0.929
0.02	0.858	0.866	0.888	0.904	0.922	0.944	0.963
0.03	0.901	0.906	0.922	0.934	0.947	0.962	0.975
0.04	0.924	0.928	0.940	0.949	0.960	0.971	0.981
0.05	0.938	0.942	0.952	0.959	0.967	0.977	0.984
0.06	0.948	0.951	0.959	0.966	0.973	0.980	0.987
0.07	0.955	0.958	0.965	0.970	0.976	0.983	0.989
0.08	0.960	0.963	0.969	0.974	0.979	0.985	0.990
0.09	0.964	0.967	0.973	0.977	0.982	0.987	0.991
0.10	0.968	0.970	0.975	0.979	0.983	0.988	0.992
0.11	0.971	0.973	0.977	0.981	0.985	0.989	0.993
0.12	0.973	0.975	0.979	0.983	0.986	0.990	0.993
0.13	0.975	0.977	0.981	0.984	0.987	0.991	0.994
0.14	0.977	0.978	0.982	0.985	0.988	0.991	0.994
0.15	0.978	0.980	0.983	0.986	0.989	0.992	0.994
0.20	0.984	0.985	0.987	0.989	0.992	0.994	0.996
0.25	0.987	0.988	0.990	0.991	0.993	0.995	0.996
0.30	0.989	0.990	0.992	0.993	0.994	0.996	0.997
0.35	0.991	0.991	0.993	0.994	0.995	0.996	0.997
0.40	0.992	0.992	0.994	0.995	0.996	0.997	0.998
0.45	0.993	0.993	0.994	0.995	0.996	0.997	0.998
0.50	0.993	0.994	0.995	0.996	0.996	0.997	0.998

– diffuse radiation in the solar aureola

The effect of diffuse radiation, which significantly depends on the aerosol population seems to be the most important. The reason is the rapid change of near-forward scattering pattern for different types of aerosol particles (Eq. 18). The correction of τ_a^A is small enough (about 0.2 %) if the atmosphere consists of small particles, the modal radius of which is about $r_m = 0.03\ \mu m$. Such a size defines the bottom limit of the applicability of Mie's theory, and therefore the relation (13) is already not true and need to be transformed into

$$\frac{P_a(\theta)}{4\pi}\, b_a(h) \ > \ \frac{P_R(\theta)}{4\pi}\, b_R(h) \quad .$$

In such a case the Rayleigh component cannot be omitted and Eq. (18) is no longer accurate. The correction factor continuously increases with particle size, so that the difference of τ_a^C and τ_a^A is about 1 % with $r_m = 0.07\ \mu m$, 2 % with $r_m = 0.16\ \mu m$, and 3-4 % with $r_m > 0.3\ \mu m$ (Tab. 3 and Tab. 4). The factor Q decreases with wavelength λ little. The absolute value of correction factor is $Q > 1$ and in principle doesn't depend on τ_a^A.

Table 3. Q factor (inside) defined as the ratio of corrected and approximate aerosol optical thickness (τ_a^C/τ_a^A; $\lambda = 0.46\ \mu m$): only the effect of diffuse radiation in solar aureola is taken into account. The modal radius of the size modified gamma distribution is $r_m = 0.07\ \mu m$.

	solar zenith angle ζ_0 [deg]				
τ_a^A	0	30	60	70	80
0.01	1.009	1.010	1.010	1.011	1.012
0.10	1.008	1.008	1.009	1.009	1.010
0.20	1.008	1.008	1.008	1.009	1.009
0.30	1.008	1.008	1.008	1.008	1.008
0.40	1.008	1.008	1.008	1.008	1.007
0.50	1.008	1.008	1.008	1.008	1.007

Table 4. Q factor (inside) defined as the ratio of corrected and approximate aerosol optical thickness (τ_a^C/τ_a^A; $\lambda = 0.46\ \mu m$): only the effect of diffuse radiation in solar aureola is taken into account. The modal radius of the modified gamma distribution is $r_m = 0.32\ \mu m$.

	solar zenith angle ζ_0 [deg]				
τ_a^A	0	30	60	70	80
0.01	1.030	1.031	1.032	1.033	1.036
0.10	1.029	1.029	1.030	1.031	1.032
0.20	1.028	1.029	1.030	1.030	1.030
0.30	1.028	1.029	1.030	1.030	1.029
0.40	1.028	1.029	1.029	1.029	1.027
0.50	1.028	1.029	1.029	1.029	1.026

As for the real measurement all the effects need to be incorporated. The final behaviour is the continuous increase of the factor Q with the particle size and with τ_a^A. Analysing the data tabulated in Tab. 5 and Tab. 6 one can see that the error can be about 2-3 % when neglecting all three effects. This value cannot be ignored although it looks to be relatively small. The obtained result is quite important, as such a value is comparable to the systematic/random error of the measurements as was previously described. The problem addressed to diffuse radiation will always occure when the field-of-view of sun-photometer is bigger than R_S. Russel et al. (1993) used an airborne autotracking sunphotometer to monitor Pinatubo and pre-Pinatubo optical-depth spectra. The field of view of the detector used was about 2.2^o. The air mass was calculated using different formulae for aerosols, and other constituents of the atmosphere. It was shown that their own specific correction factor increased during the Pinatubo incident up to 10% in UV and 5% in IR, and then continuously decreased (in 3 months - to 5% in UV, 1% in IR). Faizoun et al. (1994) used apparatus consisting of a 3^o field-of-view optical head when monitoring the Sahelian aerosol and atmospheric water vapor content. However, Beer's law was assumed to be valid when processing the signal measured by a sun photometer, and the optical air mass was derived simply as $1/\cos\zeta_0$. The random error of the measurement was estimated to be about 4%. Both the instruments operate with their apertures big enough in comparison with R_S, therefore diffuse radiation plays an important role in data processing.

Table 5. Q factor (inside) defined as the ratio of corrected and approximate aerosol optical thickness (τ_a^C/τ_a^A; $\lambda = 0.46\ \mu m$): the effect of all three factors - i) optical air mass changes in the region of the solar disk, ii) the intensity distribution on the solar disk, and iii) diffuse radiation in the solar aureola, are taken into account. The modal radius of the modified gamma distribution is $r_m = 0.07\ \mu m$.

	solar zenith angle ζ_0 [deg]								
τ_a^A	0	10	20	30	40	50	60	70	80
0.01	0.757	0.760	0.769	0.784	0.804	0.831	0.864	0.903	0.939
0.02	0.864	0.866	0.873	0.882	0.894	0.911	0.930	0.951	0.964
0.03	0.907	0.909	0.913	0.920	0.929	0.941	0.954	0.968	0.973
0.04	0.930	0.932	0.935	0.941	0.947	0.956	0.967	0.977	0.977
0.05	0.945	0.946	0.949	0.953	0.959	0.966	0.974	0.982	0.980
0.06	0.955	0.956	0.958	0.962	0.967	0.973	0.979	0.986	0.982
0.07	0.962	0.963	0.965	0.968	0.972	0.977	0.983	0.988	0.983
0.08	0.968	0.968	0.970	0.973	0.976	0.981	0.986	0.990	0.984
0.09	0.972	0.973	0.974	0.977	0.980	0.984	0.988	0.992	0.984
0.10	0.975	0.976	0.978	0.980	0.982	0.986	0.990	0.993	0.985
0.11	0.978	0.979	0.980	0.982	0.985	0.988	0.991	0.994	0.985
0.12	0.981	0.981	0.982	0.985	0.987	0.989	0.993	0.995	0.986
0.13	0.983	0.983	0.984	0.986	0.988	0.991	0.994	0.995	0.986
0.14	0.984	0.985	0.986	0.988	0.989	0.992	0.995	0.996	0.986
0.15	0.986	0.986	0.987	0.989	0.991	0.993	0.995	0.997	0.986
0.16	0.987	0.988	0.989	0.990	0.992	0.994	0.996	0.997	0.986
0.17	0.988	0.989	0.990	0.991	0.993	0.995	0.997	0.997	0.986
0.18	0.989	0.990	0.991	0.992	0.993	0.995	0.997	0.998	0.987
0.19	0.990	0.991	0.992	0.993	0.994	0.996	0.998	0.998	0.987
0.20	0.991	0.992	0.992	0.994	0.995	0.996	0.998	0.998	0.987
0.25	0.994	0.995	0.995	0.997	0.997	0.998	1.000	0.999	0.987
0.30	0.997	0.997	0.998	0.998	0.999	1.000	1.001	1.000	0.987
0.35	0.998	0.998	0.999	1.000	1.000	1.001	1.001	1.000	0.987
0.40	0.999	1.000	1.000	1.001	1.001	1.001	1.002	1.001	0.987
0.45	1.000	1.000	1.001	1.002	1.002	1.002	1.002	1.001	0.987
0.50	1.001	1.001	1.001	1.002	1.002	1.002	1.003	1.001	0.987

As was stated before, the correction of retrieved aproximate values of τ_a^A has a typical character. This fact enables us to construct a successful correction

Table 6. Q factor (inside) defined as the ratio of corrected and approximate aerosol optical thickness (τ_a^C/τ_a^A; $\lambda = 0.46\ \mu m$): the effect of all three factors - i) optical air mass changes in the region of the solar disk, ii) the intensity distribution on the solar disk, and iii) diffuse radiation in the solar aureola, are taken into account. The modal radius of the modified gamma distribution is $r_m = 0.32\ \mu m$.

	solar zenith angle ζ_0 [deg]								
τ_a^A	0	10	20	30	40	50	60	70	80
0.01	0.768	0.772	0.781	0.797	0.818	0.846	0.880	0.921	0.960
0.02	0.880	0.882	0.888	0.898	0.911	0.928	0.948	0.971	0.986
0.03	0.924	0.926	0.931	0.938	0.947	0.959	0.973	0.989	0.995
0.04	0.948	0.950	0.953	0.959	0.966	0.976	0.986	0.998	0.999
0.05	0.963	0.964	0.968	0.972	0.978	0.986	0.994	1.003	1.002
0.06	0.973	0.975	0.977	0.981	0.986	0.993	1.000	1.007	1.004
0.07	0.981	0.982	0.984	0.988	0.992	0.997	1.004	1.010	1.005
0.08	0.987	0.988	0.990	0.993	0.996	1.001	1.007	1.012	1.006
0.09	0.991	0.992	0.994	0.997	1.000	1.004	1.009	1.013	1.006
0.10	0.995	0.995	0.997	1.000	1.003	1.006	1.011	1.014	1.007
0.11	0.998	0.998	1.000	1.002	1.005	1.008	1.012	1.015	1.007
0.12	1.000	1.001	1.002	1.005	1.007	1.010	1.014	1.016	1.007
0.13	1.002	1.003	1.004	1.006	1.008	1.011	1.015	1.017	1.007
0.14	1.004	1.005	1.006	1.008	1.010	1.013	1.016	1.017	1.008
0.15	1.006	1.006	1.007	1.009	1.011	1.014	1.016	1.018	1.008
0.16	1.007	1.008	1.009	1.011	1.012	1.014	1.017	1.018	1.008
0.17	1.008	1.009	1.010	1.012	1.013	1.015	1.018	1.019	1.008
0.18	1.009	1.010	1.011	1.013	1.014	1.016	1.018	1.019	1.008
0.19	1.010	1.011	1.012	1.013	1.015	1.017	1.019	1.019	1.008
0.20	1.011	1.012	1.013	1.014	1.015	1.017	1.019	1.020	1.008
0.25	1.015	1.015	1.016	1.017	1.018	1.019	1.021	1.021	1.008
0.30	1.017	1.017	1.018	1.019	1.020	1.021	1.022	1.021	1.007
0.35	1.018	1.019	1.019	1.020	1.021	1.022	1.022	1.021	1.007
0.40	1.020	1.020	1.021	1.021	1.022	1.022	1.023	1.022	1.007
0.45	1.021	1.021	1.021	1.022	1.022	1.023	1.023	1.022	1.006
0.50	1.021	1.021	1.022	1.023	1.023	1.023	1.023	1.022	1.006

mechanism, where the tabulated values of Q can be utilized. In general Q increases with τ_a^A, which brings an increase of the corrected values of τ_a^C. The bigger τ_a^A the bigger Q. We can demonstrate such behaviour in two examples (Fig. 2), for the measured aerosol optical thickness in two different regions, Bratislava (Slovakia, continental region), and Zingst (Germany, maritime region) (Kocifaj and Lukáč, 1994).

On the other hand, the random error takes place when all the possible errors are combined - random/systematic measurement errors and the random uncertainty of the evaluation of aerosol optical thickness due to the three factors analysed in this paper. Such a fact brings the random fluctuations of the corrected aerosol optical thickness (dashed curves) around the approximate profile of τ_a^A (solid curve), which can be seen on Fig. 3.

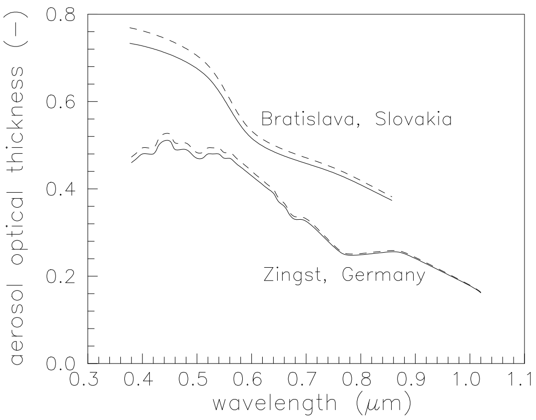

Figure 2. Spectral dependence of aerosol optical thickness τ_a measured in Bratislava (Slovakia) and Zingst (Germany): aproximate value τ_a^A (solid curve), corrected value τ_a^C (dashed curve) - accepting a monotoneous increasing of τ_a^C with τ_a^A.

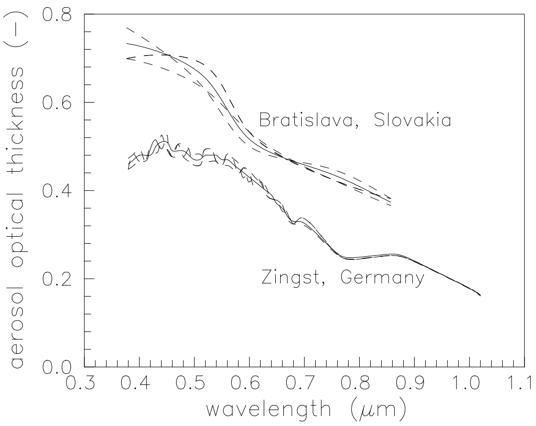

Figure 3. Spectral dependence of aerosol optical thickness τ_a measured in Bratislava (Slovakia) and Zingst (Germany): aproximate value τ_a^A (solid curve), corrected value τ_a^C (dashed curve) - accepting a random character of uncertainty of aerosol optical thickness, amplitude is related to the factor Q .

4. Uncertainty of the aerosol distribution function, and its effect on radiation balance in the atmosphere

The error of the aerosol optical thickness at the level 2-3 % can affect retrieved number density of the IDPs using the measurements of the brightness of F-corona. Such an uncertainty of τ_a^A can modify the solution of the inverse problem of the optics of atmosphere, when determining the aerosol size distribution function $f(r)$. This problem is notoriously difficult to solve, and it is typical that small changes in the input data can produce very large changes in solutions. Such instability is responsible for the existence of multiple solutions and for difficulties in interpretating the gained results. Some other knowledge about the expected solution can support the inversion method. An ambiguousity of $f(r)$ will be reflected in the variability of the scattering pattern in the near-forward scattering region. This is the source of new open questions when interpreting the measured brightness of the F-corona.

Horvath and Dellago (1993) systematically analysed the accuracy of inversion techniques for extinction data. They reached the best results in the inversion of extinction data if the mean diameter of the accumulation mode is between 0.3 and 0.8 μm, and the extinction measurements cover the visible spectral range. It was also shown that the inversion of light scattering data brings better results than the inversion of extinction data, because the variety of possible solution function's is less.

The effect of 2-3 % uncertainty of aerosol optical thickness arises mainly when accepting its random character. The examples described above (the measurements of the aerosol optical thickness in Bratislava and Zingst) may simply demonstrate this fact. Let assume that the mean square-root measurement error of the aerosol optical thickness is about 5 %, which is a good representative value. Usually it is in principle impossible to gain much better accuracy.

Retrieval of the columnar particle size distribution $f(r)$ $[\mu m^{-1}\ m^{-2}]$ using the spectral values of aerosol optical thickness significantly depends on such an error level. The solution of Fredholm integral equation of the first kind is:

$$\tau_a(\lambda) = \pi \int_{r_1}^{r_2} Q_{ext}(r,\lambda)\ r^2\ f(r)\ dr \quad , \tag{21}$$

where $Q_{ext}(r,\lambda)$ is the efficiency factor for extinction, and a crucial amount of particles have a radius larger than r_1 and smaller than r_2, is an ill-posed inverse problem. Equation (21) can numerically be solved by using Tikhonov's regularization (Tikhonov and Arsenin, 1979), when minimizing the functional

$$M_\alpha = \sum_{i=1}^{m} \left[\sum_{j=1}^{n} A_{i,j} s_j - \tau_{a,i} \right]^2 + \alpha \left\{ p_0 \sum_{j=1}^{n} \Delta'_j s_j^2 + p_1 \sum_{j=1}^{n-1} \frac{(s_j - s_{j-1})^2}{\Delta_j} \right\} \quad , \tag{22}$$

where $s(r)$ equals to $\pi\ r^2\ f(r)$ $[\mu m^{-1}]$, m is total number of measured values $\tau_a(\lambda_{i=1..m})$, n number of nodes $r_{j=1..n}$, in which the function $s(r)$ is calculated, and the components of matrix A, Δ_j, Δ'_j, p_0 and p_1 are defined in (Kabanov et al., 1988).

Results of the inversion of both, τ_a^A (solid curve) and τ_a^C (dashed curve) are presented on Figs. 4 and 5, where the systematic character of τ_a^C is accepted ($\tau_a^C = k\tau_a^A$, and k is a monotoneous function of τ_a^A). The behaviour is quite similar for both examples (Bratislava, Zingst): the amount of the particles the size of which is close to the modal radius increases, while the amount of large particles is a little bit reduced. This result doesn't depend on the refractive index of the particles. However, the differences between distribution functions retrieved using τ_a^A and τ_a^C are not so critical.

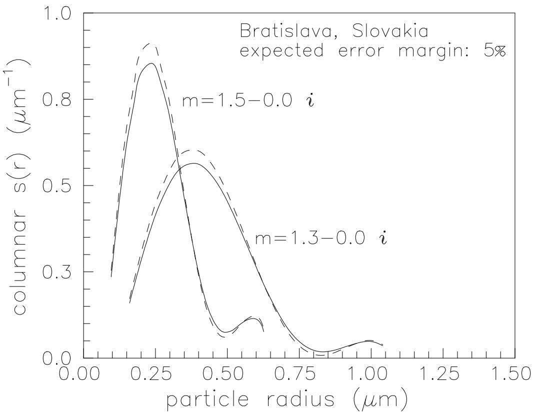

Figure 4. Retrieval of columnar aerosol distribution function using the measured data in Bratislava according to Fig. 2. The standard mean square-root mearurement error is chosen to be about 5 %. Two results for different refractive index m of the particles are presented.

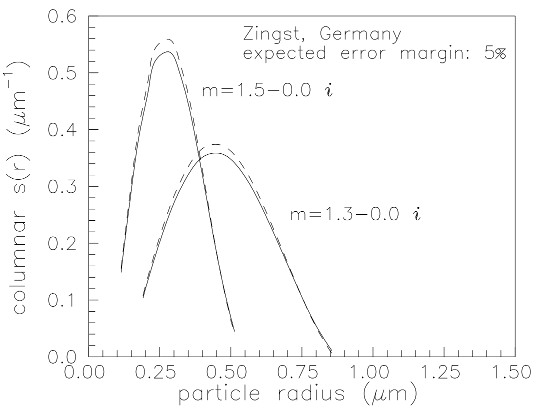

Figure 5. Retrieval of columnar aerosol distribution function using the measured data in Zingst according to Fig. 2. The standard mean square-root mearurement error is chosen to be about 5 %. Two results for different refractive index m of the particles are presented.

On the other hand, we should accept random character of the uncertainty of aerosol optical thickness, due to the type of measurement errors. In such a case, the retrieval of aerosol optical thickness (Fig. 3) results in significant ambiguousity of the distribution functions (Fig. 6 and 7) due to the changes of the slope of function τ_a^C.

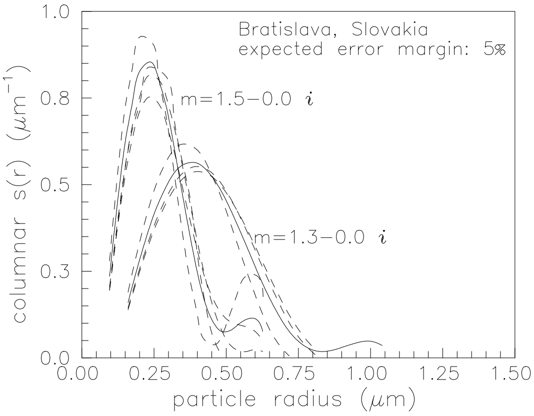

Figure 6. Retrieval of columnar aerosol distribution function using the measured data in Bratislava according to Fig. 3. The standard mean square-root mearurement error is chosen to be about 5 %. Two results for different refractive index m of the particles are presented.

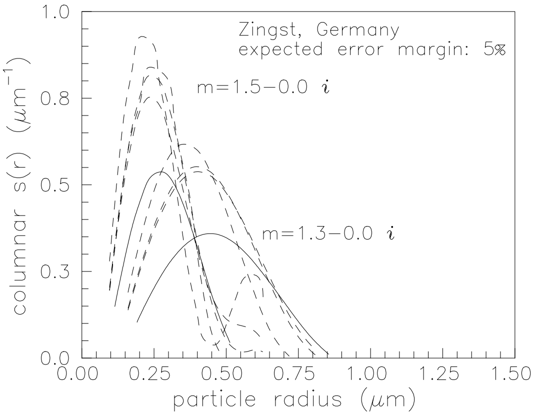

Figure 7. Retrieval of columnar aerosol distribution function using the measured data in Zingst according to Fig. 3. The standard mean square-root mearurement error is chosen to be about 5 %. Two results for different refractive index m of the particles are presented.

The obtained range of the possible solutions has a direct impact on the calculation of radiation fluxes, because they are modified significantly by the changes in the discussed aerosol population. The bigger the abundance of the aerosols the bigger the influence of the discussed effect (e.g. in Martian atmosphere). The radiative balance changes many chemical and physical processes in the planetary atmospheres, and therefore an inaccurate estimation of the radiation budget can result in inadequate physical conclusions. The radiation fluxes were calculated using the MRSM method (Kocifaj and Lukáč, 1998). It was shown that the differences in the global, diffuse and direct solar radiation can vary over a wide range. The variability of the total downward and upward radiative fluxes calculated over the whole visible and near infrared (300 nm $< \lambda <$ 1000 nm) can reach several tenths of a percent. The fluctuations in selected spectral bands are much larger and highly sensitive to the profile of the actual distribution function.

5. Conclusion

The astronomical photometric observations are a source of valuable data to study the interplanetary environment, or the planetary atmospheres. The most frequently used physical quantity is extinction, which is measured over a wide spectral range. The dependency of extinction on the wavelength of incident radiation is often utilized to retrieve information on the size distribution of particle polydisperse systems. The measured brightness of F-corona is, for instance, directly related to the number density of interplanetary dust.

The processing of photometric data is affected by random/systematic measurement error, which is usually about 5 %. From this point of view, knowledge of atmospheric transparency is most important. Its short-term/spatial fluctuations are related mainly to atmospheric aerosols and their optical thickness τ_a. However, there are some specific factors, which are notoriously not evaluated when determining aerosol optical thickness. We focused on three of them, i.e. i) the intensity distribution on the solar disk, ii) changes of the optical air mass along the solar disk, and iii) diffuse radiation in the solar aureola, which represents an addition to the measured intensity because of finite instrument field-of-view. Astronomical observations need to be corrected due to atmospheric optical thickness, which is often related to the simple formula (3). By using this equation, the approximate aerosol optical thickness τ_a^A is calculated using Eq. (4). However, the discussed factors may modify aerosol optical thickness, so that the corrected final value τ_a^C will differ from τ_a^A. This has a direct impact on the processing of photometric data.

As the first two factors, in general, reduce the final value of the aerosol optical thickness, the corrected value τ_a^C is likely to be less than an approximate value τ_a^A - obtained by a simple retrieval mechanism. However, diffuse radiation in the aereola region causes an increasing of τ_a^C by a factor Q. Its value varies with the modal radius of the particles, due to the sensitive dependence of the scattering pattern (in the near-forward scattering region) on particle size. Astronomical devices have different fields-of-view, usually much bigger than the angular radius of the source of radiation (i.e. the Sun). In such a case, diffuse radiation cannot be ignored. It was found that the uncertainty of the aerosol optical thickness may be about 3 %, when incorporating all three analysed factors. This value cannot be ignored because it is comparable to the random/systematic experimental error level typical for standard photometric measurements (4-5 %). Assuming a random character of uncertainty of aerosol optical thickness at the level 3 %, a significant ambiguousity of solution of inverse problem could occur - when determining the particle size distribution $f(r)$.

The gained range of the possible solutions of $f(r)$ then has a direct influence on the calculation of radiation fluxes. The uncertainty in estimation of the radiative balance can change the view of chemical and physical processes in the planetary atmospheres, and may be a source of inaccurate or inadequate physical conclusions.

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