Numerical methodology for the assessment of asymmetry coefficient of aerosol scattering in near IR region of spectrum

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Abstract. Based on the aerosol model of IAP RAS, a methodology has been developed for determining the aerosol coefficient of asymmetry of scattered radiation for natural particles. The source of information is the calculation data for the brightness of the cloudless sky in solar almucantarat with different spectral transparency of the atmosphere and the albedo of the underlying surface. By solving the radiation transfer equation by the Monte Carlo method, the asymmetry coefficients of diffuse fluxes were calculated, including the effects of single and multiple scattering, as well as light reflection from the earth's surface. Tables of average values of the asymmetry coefficients are presented that assume the use of interpolation methods for calculating atmospheric parameters. A technique is proposed for determining the aerosol asymmetry coefficient from the results of observations of a similar integral coefficient, optical depth, and terrain albedo without using an apparatus of solving inverse problems. In this case, the brightness can be observed in any units, including directly the readings of the photometer. Software has been developed that implements this technique.

1. Introduction
Global warming observed in many regions of the Earth [1-3], of course, requires the construction of appropriate physical models. This requires a careful study of not only optical parameters, but also processes that affect the temperature of the lower layers of air and the earth's surface. First of all, it is the receipt of solar energy, its absorption and reflection from the underlying surface. Both incoming to the Earth and reflected radiation can be strongly transformed by clouds, atmospheric gases and aerosols.

Speaking about the role of aerosol, it should be noted that in the process of scattering of sunlight, not only the number and size of particles, but also their dispersed composition, as well as the refractive index play an important role. In further calculations, we used the aerosol model developed at the Institute of Atmospheric Physics of the Russian Academy of Sciences [4]. It includes three fractions of particles: finesdispersed, submicron and largedispersed. Each of the fractions has its own optical characteristics, in particular, has its scattering indicatrix. In practice, the following approximation is often used: in the near IR region of the spectrum, the real part of the refractive index of particles is about 1.5, and the imaginary part is close to zero. In other words, an aerosol over territories far from cities, industrial centers, and dark sand deserts in the wavelength range of 0.65 ≤ λ ≤ 1.2 μm has a low absorption coefficient [5].
In the physics of dispersed media, especially in atmospheric optics and climatology, the often scattering properties of aerosol particles are characterized by the magnitude of the asymmetry coefficient of scattered light fluxes

$$\Gamma_a = \frac{\int_0^{\pi/2} f_a(\varphi) \sin(\varphi) \, d\varphi}{\int_0^{\pi/2} f_a(\varphi) \sin(\varphi) \, d\varphi}$$

(1)

The following notation is used here: \(\varphi\) – the scattering angle, \(f_a(\varphi)\) – the directed coefficient of a single aerosol scattering. If the last quantity to summarize to the analogous molecular scattering coefficient \(f_m(\varphi)\), then, taking into account \(\varphi\), we obtain the absolute indicatrix of the one-fold scattered light \(f_1(\varphi)\)

$$f_1(\varphi) = f_a(\varphi) + f_m(\varphi)$$

(2)

The measurements of the brightness of a cloudless sky in solar almucantrate make it possible to find the absolute indicatrix of brightness [6-7]

$$f(\varphi) = f_1(\varphi) + f_2(\varphi) + f_q(\varphi)$$

(3)

Accordingly, the observed asymmetry coefficient of scattered light fluxes obtained in practice has the form

$$\Gamma = \frac{\int_0^{\pi/2} (f_1(\varphi)+f_2(\varphi)+f_q(\varphi)) \sin(\varphi) \, d\varphi}{\int_0^{\pi/2} (f_1(\varphi)+f_2(\varphi)+f_q(\varphi)) \sin(\varphi) \, d\varphi}$$

(4)

The quantities \(f(\varphi)\) and \(\Gamma\) include the components of the one-fold scattered light \(f_1(\varphi)\), the multiple scattered light \(f_2(\varphi)\), and the light \(f_q(\varphi)\), reflected from the underlying surface that enters the photometer. The \(q\) symbol indicates the albedo of the underlying surface.

The numerical values of \(f_2(\varphi)\) and \(f_q(\varphi)\) are determined by solving the radiation transfer equation. In this case, it is usually assumed that the component \(f_q(\varphi)\) is orthotropic in nature.

2. Formulation of the problem. Input data

The transport equation was solved for specific values of aerosol depth \(\tau_a\) and molecular \(\tau_m\) optical atmospheric depth. The latter was set by the wavelength. The aerosol depth quantitie varied from 0.05 to 0.3. Such limits of variation are typical of natural aerosol in the near IR region of the spectrum. The zenith angles of the Sun varied in the range 65° ≤ \(Z_0\) ≤ 75°, which allows using a plane-parallel atmospheric model with a uniform height in the calculations of sky brightness and \(f(\varphi)\) [7].

In order to take into account the role of aerosol in the formation of the angular dependence \(f(\varphi)\), the IPA RAS model was used [4]. The values of Ga, recommended in these articles [8-9] and used in our calculations were 6.00 for the finely dispersed, 8.65 for the middling dispersed and 13.85 for the coarse dispersed fractions. The aerosol scattering indicatrices \(f_a(\varphi)\) for each of the fractions are also given. The software for solving the radiation transfer equation [8-9] was kindly provided by the authors to our disposal, which allowed studying in detail the angular move \(f(\varphi)\) for different \(f_a(\varphi)\) and \(f_m(\varphi)\), for different solar zenith angles \(Z_0\) and various optical depths of the atmosphere \(\tau_a\) and \(\tau_m\) and the albedo of the underlying surface \(q\). Cases of combinations of aerosol fractions are also considered. As a result, tables [10] were published that can be used in the development of practical methods for determining the aerosol coefficients of asymmetry of light fluxes by single scattering in the simplest way. Wherein it does not require the use of mathematical methods for solving inverse problems [11]. Such a technique is presented in this work.
3. Linear links between some optical parameters of the atmosphere. Technique for determining Ga

At the first stage of building the model, the connections between the parameters used in the calculations and the computed quantities were analyzed [12]. In most cases, the relationship is linear or close to it. The density of the calculations is high enough, which eliminates significant errors in the final results. The main advantage of the proposed technique is that in its practical use, measurements of the intensity of the scattered light in absolute units are not necessary. This circumstance is due to the fact that the value of G is dimensionless, which eliminates errors associated with the calibration of the equipment.

Let us turn to the results of calculations of the values of G in three wavelengths: 675, 870, and 1020 nm, as is customary in the AERONET system [13]. The advantage of these spectral regions when studying the optical properties of an aerosol is the absence of absorption bands by atmospheric gases. A detailed analysis of the series of calculated values of G in the range of solar zenith angles of 65° ≤ Z₀ ≤ 75° leads to the conclusion that they depend weakly and without any system on Z₀ in all three parts of the spectrum. This can be judged by the histograms of deviations of G from the average values (in %) calculated for a specific set of parameters. The histograms are present in figure 1.

![Figure 1. Histograms of deviations of G from average values.](image)

The largest deviations are observed at q = 0.1, Ga = 10.65 and Ga = 13.85. The roof-mean-square deviation is: for 675 nm σ = 1.4, for 870 nm σ = 2.1 and for 1020 nm σ = 2.9. If we take into account that when measuring the atmospheric transparency coefficient by the Bouguer method with an accuracy of 1% (which is very rare), the relative error in determining the optical depth will be at least 10%, then it is quite possible to use the values of G, averaged over Z₀ while maintaining other parameters. In this case, the volume of the tables [10] will decrease by 5 times. The findings results are presented in tables 1-3.
Table 1. The average values of G in the range of zenith angles 65°–75°. Wavelength is 675 nm.

| Ga  | 7.1  | 8.65 | 10.65 | 13.85 |
|-----|------|------|-------|-------|
| 6   | 0.05 | 0.05 | 0.05  | 0.05  |
| 0   | 1.96 | 2.18 | 2.29  | 2.42  |
| 0.1 | 1.89 | 2.10 | 2.21  | 2.32  |
| 0.2 | 1.84 | 2.03 | 2.13  | 2.24  |
| 0.3 | 1.79 | 1.97 | 2.06  | 2.17  |
| 0.4 | 1.74 | 1.82 | 2.01  | 2.10  |
| 0.5 | 1.71 | 1.87 | 1.95  | 2.10  |
| 0.6 | 1.67 | 1.92 | 2.01  | 2.10  |
| 0.7 | 1.64 | 1.82 | 1.95  | 2.04  |

| q   | 65 nm | 70 nm | 75 nm |
|-----|-------|-------|-------|
| 0   | 1.44  | 1.23  | 1.02  |
| 0.1 | 1.26  | 1.05  | 0.84  |
| 0.2 | 1.08  | 0.87  | 0.66  |
| 0.3 | 0.90  | 0.70  | 0.50  |
| 0.4 | 0.72  | 0.52  | 0.32  |
| 0.5 | 0.54  | 0.34  | 0.14  |
| 0.6 | 0.36  | 0.16  | 0.06  |
| 0.7 | 0.18  | 0.08  | 0.00  |
Table 2. The average values of $G$ in the range of zenith angles $65^\circ$-$75^\circ$. Wavelength is 870 nm.

| Ga | $\tau_a$ | $q$ | 0   | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 |
|----|---------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 6  | 0.05    | 3.10 | 2.93 | 2.78 | 2.66 | 2.55 | 2.45 | 2.37 | 2.29 |
|    | 0.1     | 3.61 | 3.40 | 3.21 | 3.06 | 2.92 | 2.80 | 2.69 | 2.59 |
|    | 0.15    | 3.75 | 3.52 | 3.33 | 3.16 | 3.02 | 2.89 | 2.78 | 2.68 |
|    | 0.2     | 3.74 | 3.53 | 3.34 | 3.18 | 3.03 | 2.91 | 2.79 | 2.69 |
|    | 0.25    | 3.68 | 3.48 | 3.30 | 3.14 | 3.00 | 2.88 | 2.77 | 2.67 |
|    | 0.3     | 3.60 | 3.41 | 3.24 | 3.09 | 2.96 | 2.84 | 2.73 | 2.63 |
| 7.1| 0.05    | 3.44 | 3.25 | 3.07 | 2.93 | 2.80 | 2.69 | 2.59 | 2.50 |
|    | 0.1     | 4.13 | 3.87 | 3.64 | 3.45 | 3.28 | 3.14 | 3.01 | 2.89 |
|    | 0.15    | 4.33 | 4.05 | 3.82 | 3.61 | 3.44 | 3.28 | 3.14 | 3.02 |
|    | 0.2     | 4.34 | 4.07 | 3.84 | 3.64 | 3.46 | 3.31 | 3.17 | 3.04 |
|    | 0.25    | 4.29 | 4.03 | 3.80 | 3.61 | 3.44 | 3.29 | 3.15 | 3.03 |
|    | 0.3     | 4.19 | 3.95 | 3.74 | 3.55 | 3.39 | 3.24 | 3.11 | 2.99 |
| 8.65| 0.05   | 3.88 | 3.64 | 3.44 | 3.27 | 3.11 | 2.98 | 2.87 | 2.76 |
|    | 0.1    | 4.81 | 4.49 | 4.21 | 3.97 | 3.77 | 3.59 | 3.43 | 3.29 |
|    | 0.15  | 5.12 | 4.76 | 4.46 | 4.20 | 3.98 | 3.79 | 3.61 | 3.46 |
|    | 0.2   | 5.19 | 4.84 | 4.54 | 4.28 | 4.06 | 3.86 | 3.68 | 3.53 |
|    | 0.25 | 5.12 | 4.79 | 4.51 | 4.26 | 4.04 | 3.85 | 3.68 | 3.52 |
|    | 0.3 | 5.01 | 4.70 | 4.43 | 4.19 | 3.98 | 3.79 | 3.62 | 3.47 |
| 10.65| 0.05 | 4.34 | 4.06 | 3.82 | 3.62 | 3.44 | 3.29 | 3.15 | 3.03 |
|    | 0.1  | 5.70 | 5.27 | 4.91 | 4.61 | 4.35 | 4.13 | 3.93 | 3.75 |
|    | 0.15 | 6.22 | 5.73 | 5.33 | 4.99 | 4.69 | 4.43 | 4.21 | 4.01 |
|    | 0.2 | 6.42 | 5.91 | 5.49 | 5.13 | 4.83 | 4.56 | 4.33 | 4.12 |
|    | 0.25 | 6.40 | 5.91 | 5.50 | 5.15 | 4.85 | 4.58 | 4.35 | 4.14 |
|    | 0.3 | 6.21 | 5.76 | 5.37 | 5.05 | 4.76 | 4.51 | 4.28 | 4.09 |
| 13.85| 0.05 | 4.93 | 4.59 | 4.31 | 4.06 | 3.85 | 3.66 | 3.50 | 3.35 |
|    | 0.1 | 6.85 | 6.28 | 5.81 | 5.41 | 5.08 | 4.79 | 4.53 | 4.31 |
|    | 0.15 | 7.79 | 7.11 | 6.54 | 6.07 | 5.68 | 5.33 | 5.03 | 4.77 |
|    | 0.2 | 8.11 | 7.39 | 6.80 | 6.30 | 5.88 | 5.52 | 5.21 | 4.93 |
|    | 0.25 | 8.24 | 7.52 | 6.93 | 6.43 | 6.01 | 5.64 | 5.33 | 5.05 |
|    | 0.3 | 8.15 | 7.45 | 6.87 | 6.39 | 5.97 | 5.61 | 5.30 | 5.02 |
To implement the developed technique, a set of programs was written that carried out:

- the least squares method to a scattering angle value $\geq 150^\circ$.

The average values of $G$ in the range of zenith angles $65^\circ\div75^\circ$. Wavelength is 1020 nm.

| $\tau_a$ | $q$ | 0     | 0.1   | 0.2   | 0.3   | 0.4   | 0.5   | 0.6   | 0.7   |
|---------|-----|-------|-------|-------|-------|-------|-------|-------|-------|
| 6       | 0.05| 3.93  | 3.66  | 3.44  | 3.25  | 3.08  | 2.94  | 2.82  | 2.71  |
|         | 0.1 | 4.21  | 3.93  | 3.68  | 3.47  | 3.29  | 3.13  | 3.00  | 2.87  |
|         | 0.15| 4.17  | 3.89  | 3.65  | 3.45  | 3.28  | 3.13  | 2.99  | 2.87  |
|         | 0.2 | 4.04  | 3.79  | 3.57  | 3.38  | 3.22  | 3.07  | 2.94  | 2.82  |
|         | 0.25| 3.90  | 3.67  | 3.47  | 3.29  | 3.13  | 2.99  | 2.87  | 2.76  |
|         | 0.3 | 3.76  | 3.54  | 3.36  | 3.19  | 3.05  | 2.92  | 2.80  | 2.69  |
| 7.1     | 0.05| 4.54  | 4.21  | 3.93  | 3.70  | 3.50  | 3.32  | 3.17  | 3.04  |
|         | 0.1 | 4.96  | 4.60  | 4.29  | 4.03  | 3.80  | 3.60  | 3.43  | 3.28  |
|         | 0.15| 4.92  | 4.56  | 4.26  | 4.01  | 3.79  | 3.60  | 3.43  | 3.28  |
|         | 0.2 | 4.78  | 4.46  | 4.18  | 3.94  | 3.73  | 3.55  | 3.38  | 3.24  |
|         | 0.25| 4.61  | 4.30  | 4.04  | 3.82  | 3.62  | 3.45  | 3.30  | 3.16  |
|         | 0.3 | 4.43  | 4.15  | 3.92  | 3.71  | 3.52  | 3.36  | 3.21  | 3.08  |
| 8.65    | 0.05| 5.24  | 4.86  | 4.52  | 4.24  | 4.00  | 3.79  | 3.60  | 3.44  |
|         | 0.1 | 6.00  | 5.53  | 5.13  | 4.79  | 4.50  | 4.25  | 4.03  | 3.84  |
|         | 0.15| 6.02  | 5.56  | 5.14  | 4.81  | 4.52  | 4.27  | 4.05  | 3.86  |
|         | 0.2 | 5.84  | 5.41  | 5.04  | 4.72  | 4.45  | 4.21  | 4.00  | 3.81  |
|         | 0.25| 5.59  | 5.20  | 4.85  | 4.56  | 4.30  | 4.08  | 3.89  | 3.71  |
|         | 0.3 | 5.38  | 5.02  | 4.70  | 4.42  | 4.18  | 3.97  | 3.78  | 3.61  |
| 10.65   | 0.05| 6.42  | 5.87  | 5.42  | 5.05  | 4.73  | 4.46  | 4.22  | 4.02  |
|         | 0.1 | 7.53  | 6.85  | 6.27  | 5.80  | 5.40  | 5.07  | 4.78  | 4.53  |
|         | 0.15| 7.60  | 6.91  | 6.35  | 5.88  | 5.48  | 5.15  | 4.85  | 4.60  |
|         | 0.2 | 7.54  | 6.87  | 6.30  | 5.84  | 5.44  | 5.10  | 4.81  | 4.56  |
|         | 0.25| 7.17  | 6.56  | 6.06  | 5.64  | 5.28  | 4.96  | 4.69  | 4.45  |
|         | 0.3 | 6.75  | 6.22  | 5.77  | 5.39  | 5.05  | 4.77  | 4.52  | 4.38  |
| 13.85   | 0.05| 7.90  | 7.14  | 6.54  | 6.03  | 5.62  | 5.26  | 4.96  | 4.69  |
|         | 0.1 | 9.98  | 8.86  | 8.01  | 7.32  | 6.76  | 6.28  | 5.87  | 5.52  |
|         | 0.15| 10.37 | 9.15  | 8.32  | 7.60  | 7.00  | 6.50  | 6.08  | 5.71  |
|         | 0.2 | 10.08 | 9.03  | 8.17  | 7.47  | 6.89  | 6.39  | 5.98  | 5.62  |
|         | 0.25| 9.83  | 8.87  | 7.99  | 7.32  | 6.77  | 6.31  | 5.91  | 5.56  |
|         | 0.3 | 9.36  | 8.47  | 7.70  | 7.07  | 6.29  | 6.09  | 5.70  | 5.37  |

4. Software brief
The initial data for the calculations are the azimuthal angles, scattering angles and brightness indicatrixes obtained earlier in [14], depending on the chosen parameters: wavelength $\lambda$, zenith angle of the Sun $Z_0$, albedo of the underlying surface $q$, aerosol optical depth $\tau_a$, and molecular scattering depth $\tau_m$, albedo of single aerosol scattering, aerosol scattering asymmetry coefficient $G_a$.

To implement the developed technique, a set of programs was written that carried out:

- Selection and copying into the input data array of scattering angles and the corresponding brightness indicatrixes depending on the current values of $\lambda$, $\tau_a$, $Z_0$, $G_a$ and $q$.
- Extrapolation of scattering angle values and brightness indicatrixes (linear extrapolation by the least squares method to a scattering angle value $\geq 150^\circ$ is performed).
- Data loading and control of the integrator module.
- Checking the linearity of the dependence of $G_a$ on $G$.
- Output of arrays with intermediate results for analysis.
- Recording the obtained values in the array $G$, followed by copying to the output table.
- Finding average $G$, deviations from average $G$, standard deviations.

The block diagram of the algorithm for calculating $G$ at change $q$ for the set values of $\lambda, \tau_a, Z_0$ and $G_a$ is presented in figure 2. Similar actions are performed for the full range of each of the mentioned quantities.

The integrator module is a separate program previously written by the authors. The integrator is designed to calculate the optical depth, burdened by the influence of multiple scattering and reflection of light from the underlying surface

$$\tau_n = 2\pi \int_0^\pi f_n(\phi, \tau_m, \tau_a, Z_0) \sin \phi d\phi$$

where $f_n$ is the indicatrix of brightness in the almucantar of the Sun.

To determine the coefficient $G$, the calculation of the integrals was performed $\int_{\varphi_{max}}^{\pi/2} f_n(\varphi) \cdot \sin(\varphi) d\varphi, \int_{\pi/2}^{\pi} f_n(\varphi) \cdot \sin(\varphi) d\varphi$ and their difference, which are used in further calculations [5].

When calculating the integrals, it is necessary to interpolate the quantities $f(\varphi)$ in the range of angles from $\varphi_{max}$ to $\pi$. Since the maximum scattering angle $\varphi_{max}$ for the solar almucantar is $2Z_0$, the error of the interpolated value $f(\varphi)$ in the above range of angles is significant, and at $Z_0 \leq 60^0$ the calculation procedure becomes fundamentally impossible. When interpolating, a polynomial of the third degree is used with the addition of a point corresponding to $\varphi = \pi$. Since the experimental data, as a rule, do not contain data on the brightness of the sky at angles from 0 to 2, and in some cases up to 4 degrees, extrapolation of the brightness indicatrix is performed in this range of angles. The interpolation method also calculates the brightness indicatrix at 1800 points and with a scattering angle equal to $\pi/2$. The calculation of the integrals is carried out by the trapezium method.

The integrator is controlled by a program, whose functions include:

- Definition of application descriptors and integrator controls involved.
- Selection and loading of current values of scattering angles and brightness indicatrixes into the corresponding integrator text fields using the operating system clipboard.
- Manipulations with controls similar to user actions, such as starting processing, reading results and placing them in the output data array.
- The formation of the necessary time delays to eliminate data loss.

The linearity of the dependence of $G_a$ on $G$ is checked by determining the coefficients of the equation of the straight line $y = ax + b$, where $x = G$, $y = G_a$, at two points for each albedo $q$. Then, the relative errors in % are calculated as the deviations of the tabular $G_a$ from $G_a$, obtained by the equation of the line, referred to the latter.

The data for plotting the histograms are obtained as follows: for certain values of $\lambda, G_a, \tau_a, q$ the average $G$ is found for all zenith angles $Z_0$. Further, for each $G$ deviations from the average in percent are calculated, and standard deviations were also calculated.
Figure 2. The block diagram of the calculation algorithm G for the set values of $\lambda$, $\tau_a$, $Z_0$ and Ga.

5. Practical recommendations
After all the above simplifications, the method of determining Ga becomes quite accessible. At solar zenith angles of 65-75° in three narrow-band spectral regions with maximums of 675, 870, and 1020 nm, the angular variation of the brightness of the daytime cloudless sky in solar almucantar is measured. Brightness can be measured in any units. In parallel, the albedo of the underlying surface and the spectral transparency of the atmosphere are determined in the same spectral regions. From these data the values of G, q, and $\tau$ are determined. The molecular component $\tau_m$ is subtracted from $\tau$ and the aerosol optical depth $\tau_a = \tau - \tau_m$ is determined.

It is natural that the measured values most often will not coincide with the tabular data. In this case, one should use linear extrapolation with respect to the parameters $\tau_a$ and q. The accuracy of the final result will be determined to a lesser extent by the method, and to a greater extent – by experimental errors.
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