MULTIMODE AEROSOL MIXTURE PARAMETERS RECOVERING METHOD BASED ON SPECTRAL POLARIMETRIC MEASUREMENTS OF THE SKY. O. S. Ovsak, Main Astronomical Observatory of the NAS of Ukraine, Zabolotnoho Street 27, Kyiv, 03142, ovsak@mao.kiev.ua.

Introduction: This method bases on spectral phase dependence analysis of the cloudless sky degree of linear polarization (DoLP). Some algorithms was been modified for this aim which were in use for giant planets atmospheres cloud particles parameters determination. One can recover the probable particles microphysical parameters for detected aerosol modes as well a specific weighting coefficients of every mode in the aerosol mixture. Test processing by proposed method the spectral polarimetric measurements data of sky in zenith over the Kyiv (Ukraine) was performed.

Main part: The majority researches of altitudinal distribution and parameters of Earth atmospheric aerosol component are performed with photometric measurements by lidars and solar photometers [1-5]. At the same time, the spectral photo-polarimetric measurements data for Solar system planets are used successfully for aerosol parameters estimation in upper atmospheric layers of celestial bodies [6-9]. Therefore, one may use the methods of skylight polarization analysis for the Earth atmospheric aerosols parameters recovering [9-12].

Observed spectral DoLP value of solar light it penetrated to the Earth atmosphere is determined by scattering at gas molecules and on aerosol particles [13]. The dependence of molecular (Rayleigh) single scattering DoLP $P_R^{'}(\alpha)$ on phase angle α is well known (blue stroke line at Fig.2). The DoLP of sunlight scattered by aerosol particles $P_a(\alpha,\lambda,\rho,m)$ has a complex phase dependence (the yellow stroke line and the green dotted line at Fig.2). It depends much on the wavelength λ; on the particles shape and nature (the value $m = n_r - in_i$ is the particle complex refractive index (CRI) and n_r, n_i are the real and the imaginary components of CRI); on the kind and parameters of particles size distribution function (the effective radius a and the dispersion σ^2 as well as the Mie-parameter $\rho = 2\cdot\pi\cdot a/\lambda$) [13-15].

Spectral and phase DoLP dependence for the light scattered in atmosphere is given by formula:

$$P(\alpha,\lambda) = \beta(\lambda)\cdot P_R^{'}(\alpha) + (1-\beta(\lambda))\cdot P_a(\alpha,\lambda), \quad (1)$$

where $\beta(\lambda)$ is the spectral value of molecular scattering relative contribution:

$$\beta(\lambda) = \sigma_R(\lambda)/[\sigma_R(\lambda)+\sigma_a(\lambda)] \equiv \tau_R(\lambda)/[\tau_R(\lambda)+ +\tau_a(\lambda)], \quad (2)$$

where $\sigma_R(\lambda)$, $\tau_R(\lambda)$ and $\sigma_a(\lambda)$, $\tau_a(\lambda)$ are the volume scattering coefficients and optical thicknesses of gas and aerosol components at the wavelength λ [7].

One can calculate the value of $\beta_{calc}(\lambda)$ at wavelength λ by expression from [7,15] which was been modified to consider a multimode aerosol component of the atmosphere:

$$\beta_{calc}(\lambda) = [\frac{\sum_{i=1}^{N} k_i\sigma_{ai}(\lambda)}{\sum_{i=1}^{N} k_i\sigma_{ai}(\lambda_0)}\cdot\left(\frac{\lambda}{\lambda_0}\right)^4\cdot\left(\frac{1-\beta(\lambda_0)}{\beta(\lambda_0)}\right)+1]^{-1}, \quad (3)$$

where $\sigma_{ai}(\lambda)$ is the volume aerosol scattering coefficient at the wavelength λ and k_i is the weighting coefficient for i-th aerosol mode; N is the total number of aerosol modes in the mixture; $\sigma_{ai}(\lambda_0)$, $\beta(\lambda_0)$ are the corresponding values at wavelength λ_0.

One may calculate the $P_a(\alpha,\lambda)$ value of two-mode aerosol component for atmospheric model by formula:

$$P_a(\alpha,\lambda) = k_1\cdot P_{a1}(\alpha,\lambda,\rho_1,n_{r1}) + +(1-k_1)\cdot P_{a2}(\alpha,\lambda,\rho_2,n_{r2}), \quad (4)$$

where $P_{a1}(\alpha,\lambda_0,\rho_1,n_{r1})$ is the DoLP of aerosol mode 1; $P_{a2}(\alpha,\lambda_0,\rho_2,n_{r2})$ is the same for aerosol mode 2 and k_1 is the mode 1 weighting coefficient.

Note that aerosol constituent $P_a(\alpha,\lambda)$ in sky DoLP includes both the single scattering component and the fraction generated by multiple scattering. Value of the last is insignificant at long wavelengths, however it increases noticeably at short wavelengths range [13,16].

Model limitations and assumptions:

- The log-normal particle size distribution function is a most common for aerosols particles size distributions in the Earth atmosphere [17].
- We assume a zero light absorption by the aerosols particles ($n_i = 0$) and we neglect the dispersion of n_r at the analyzed visual spectral band [16, 18, 19].
- We employ the homogeneous spherical aerosol particles model with using of Lorenz-Mie theory.
- Thanks to numerous remote and contact soundings of aerosol particles properties in the Earth's troposphere the ranges of most widespread values of their parameters are well known [19]. So, we can perform the fitting of the model aerosol parameters within these margins.

The analysis method features: The main highlight of proposed method is the way for determining the $\beta(\lambda)$ values and the weighting coefficients of aerosol modes in total mixture. Also, criterias for assessing the additional aerosol fractions possible presence in the studied atmospheric column were formulated.

Set of special computer program codes to simulate the DoLP of light scattered by Earth's atmosphere in a physically acceptable range of aerosol parameters was been created in accordance to above mentioned atmosphere model limitations and assumptions.

Calculations the DoLP values of model gas-aerosol mixture were performed using formulas (1) and (4). A closeness of agreement is determined by comparison sums of square deviations (SDS) between the model and measured DoLP dependences for all the phase angles. This algorithm was employed for aerosol parameters $\ln(\rho(\lambda))$, n_r and σ^2 recovering as well as for $\beta(\lambda)$ and k_1 values. The tabular spectral values of $\tau_R(\lambda')$ and $\tau_a(\lambda')$ for the Earth atmosphere (see e.g. [18]) one can use for calculate the value of $\beta tab(\lambda')$ by (2). The value of $\beta(\lambda')$ may be calculated by (3). Then the values of $\beta tab(\lambda')$ and $\beta(\lambda')$ may be compared.

The testing results: Trial testing of the method's algorithms was carried out when analyzing the measurements data of the sky DoLP at zenith above Kyiv [20]. Fig.1 shows the coarse-grained aerosol mode parameters recovering. The aerosol fine-grained mode parameters were recovered analogously.

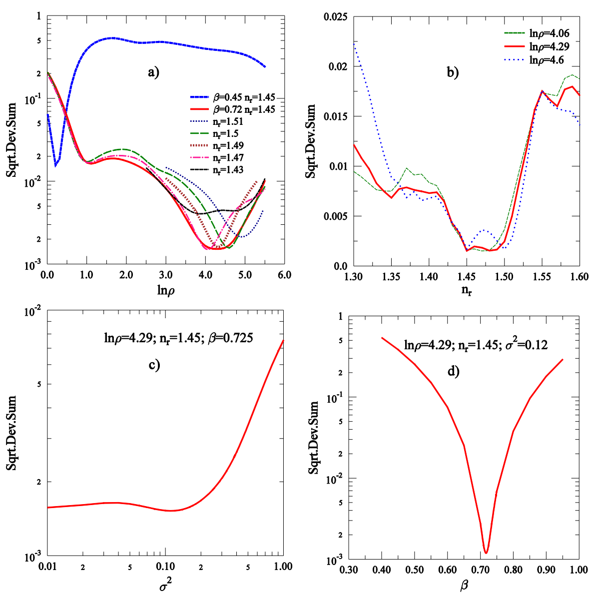

Fig. 1. Dependences the SDS at all phase angles for model and experimental DoLP values on aerosol coarse-grained mode parameters changes (at λ = 578 nm): a) $\ln(\rho)$; b) n_r; c) σ^2; d) β.

Fig. 2 shows the curves of DoLP phase dependences at wavelengths λ = 578 nm and λ = 390 nm. The dependences were constructed according to the measurement data [20] and calculated separately for the gas component and for the two modes of aerosol component as well as for the model atmospheric medium.

Here are the aerosol parameters determined for a logarithmic-normal particles size distribution function with dispersion $\sigma^2 \approx 0.1$: the *coarse-mode* with weighting coefficient $k_1 = 0.22$, $n_{r1} \approx 1.45$ and the average geometric radius $r_{01} \approx 6.7$ μm; the *fine-mode* with $n_{r2} \approx 1.45$ and $r_{02} \approx 0.11$ μm.

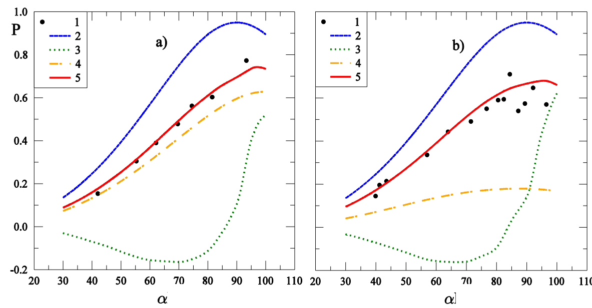

Fig. 2. Spectral phase dependences of skylight DoLP value (P) for the two-mode model of atmospheric aerosol component: 1 – measurements data [20]; 2 – Rayleigh component; 3– aerosol coarse-mode; 4 – aerosol fine-mode; 5 – model gas-aerosol mixture. Wavelength: a) λ = 578 nm; b) λ= 390 nm.

Conclusion: An efficient practical method proposed for feasible atmospheric aerosol parameters determination averaged over the whole atmospheric column.

References: [1] Huige D. et al. (2018) *Remote Sens., 10*, 1753. [2] Veselovskii I. et al. (2015) *Meas. Tech., 8*, 4111. [3] Johnathan W.H. et al. (2008) *Appl. Opt., 47*, 673. [4] Huige D. et al. (2017) *JQSRT, 188*, 28. [5] Shuang Z. et al. (2020) *Earth–Sc. Rev., 200*, 102986. [6] Hansen J.E. and Hovenier J.M. (1974*) J. Atmos. Sci., 31*, 1137. [7] Morozhenko A.V. and Yanovitskij E.G. (1973) *Icarus,* ***18****, 4*, 583. [8] Dlugach J.M. and Mishchenko M.I. (2008) *Mon. Not. R. Astron. Soc., 384*, 64. [9] Morozhenko A. and Vid'machenko A. (2004) *Kluwer Academic Publishers, Dordrecht/Boston/ London.*, 369. [10] Dubovic O. et al. (2019) *JQSRT, 224*, 474. [11] Morozhenko A.V. et al. (2013) *Kin. Phys. Celest. Bod.* ***29****, 5*, 243. [12] Tanré D. et al. (2011) *Atmos. Meas. Tech., 4*, 1383. [13] Hulst van de G. (1961) *M.: IL*, 536 p. [14] Mishchenko M.I. (1991) *J. Opt. Soc. Amer.,* ***8****, 5*, 871. [15] Klimenko V.M. et al. (1980) *Icarus.* ***42****, 3*, 354. [16] Shifrin K.S. (1951) *M., Gostechteoretizdat*, 288p. [17] Horvath H. (1990) *Aeros. Sci. Technol., 12*, 964. [18] Allen C. W (1955) *The Athlone Press, London*. [19] Ivlev L.S. and Dovgaluk J.A. (1999) *St.-Pet.Nat.Univ Press*. [20] Avramchuk V.V. (1965) *Voprosy astrofiziki. Kiev: Naukova dumka*, 112.