Comparing Products of processing airborne NASA and Russian Cloud Data

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Abstract – Data from airborne experiments with NASA′s Cloud Absorption Radiometer and old air-borne spectral data obtained in the USSR is analyzed. Earlier authors presented the algorithm and first results of NASA data processing. Here the regularization of solution is accomplished and final data are compared with optical parameters obtained from old Russian experimental data. NASA observations are in 8 spectral channels. In this study the analytical approach of inverse asymptotic formulas of the transfer theory is used. The method is free from a priori restrictions and links to parameters. Obtained results from NASA and Russian data are used for calculating radiative cloud characteristics: reflection, transmission and radiative divergence.

Keywords: solar radiation, intensity, radiation field, inverse problem, cloud optical parameters

1. INTRODUCTION

The goal of this paper is processing observational data, obtained in the NASA, Goddard Space Flight Center in according with the algorithm for solving the inverse problem of the atmospheric optics proposed earlier (ISRSE-2009). There is a considerable volume of experimental data obtained in different geographical sites in NASA Goddard space flight center (King, 1987; King et al., 1990).

In the 2 section observational data are described and the formulae for processing experimental datasets above and below cloud layer is presented. In the 3 section the approach for retrieving optical parameters (optical thickness, single scattering albedo, scattering and absorption coefficients) of cloud and their vertical profiles is realized and results of retrieving optical parameters are considered. In the 4 section comparing optical parameters obtained from NASA's radiance and Russian irradiance observations is presented.

2. OBSERVATIONAL DATA AND BASED FORMULAS

2.1. Observational data

Considered NASA's data have been obtained below, above and inside a cloud layer during the «Southern African Regional Science Initiative 2000» 13 September 2000 above the South Africa beach at latitude 20.0–21.7°S and longitude 13.0–13.7°E. The solar incident angle θ_0 was about 37.6°. The flight altitude range from 354 to 1170 m. Measurements are fulfilled in the plane with azimuth angle 51.64° relative to the Sun. Stratus cloudiness is extended and has thickness 400 m: cloud top and base are at 800 and 400 m. Duration of the experiment was around 1 hour. Observational data include radiance values in viewing angles from 0 to 180° with a step of 1°. Measurements were made in 8 spectral channels: 340, 381, 472, 682, 870, 1.035, 1.219, 1.273 nm with Cloud Absorption Radiometer (CAR) (King, 1987, King et al., 1990). Every spectral channel corresponds to one file data. It consists from scans, one scan contains geographical coordinates of the observation site, local time, solar zenith angle θ_0, azimuth angle relative to the Sun φ, altitude of the observation, and 182 vales of radiance in reflectance units I_i in zenith viewing angles θ_i from -1 till 181° through 1°. The azimuth angle relative to the Sun changes during the experiment in the ranges φ = 27 – 53°. At every altitude several scans (till 12) are obtained that allows averaging of radiance. There are sounded more than 100 altitude levels Altitudes of observation below cloud layer are from 343 till 404 m, inside cloud 405–790 m and above cloud 800-1178 m. Data inside cloud are obtained too close to the top and do not satisfy to diffuse domain condition thus they are not used here.

2.2. Approach for data processing.

Different strict analytical approaches are proposed for obtaining cloud optical parameters: optical thickness τ_0, single scattering albedo ω_0, scattering and absorption coefficients, asymmetry parameter g (Minin, 1988; Duracz and McCormick, 1989; McCormick and Leathers, 1996; Melnikova and Vasilyev, 2004). Observational data at cloud top and base separately and in combination, are processed for the problem solution.

Note cloud optical parameters desired as: s^2=(1-ω_0)/[3(1-g)] – similarity parameter and τ' = 3(1-g)τ_0 – scaled optical thickness (Melnikova and Vasilyev, 2004).

1) Multiangular data of reflected radiance at the cloud top give the intensity in reflectance units as ρ_i observed at viewing angles arccosμ_i. Consider the ratio of two differences [$\rho_\infty(\mu_1,\mu_0,\varphi)$-$\rho_1$]/[$\rho_\infty(\mu_2,\mu_0,\varphi)$-$\rho_2$], where ρ_1 and ρ_2 are observed intensities at two viewing angles arccosμ_1 arccosμ_2 and $\rho_\infty(\mu_2,\mu_0,\varphi)$ is the reflection function of semi-infinite conservative atmosphere (τ_0=∞). After algebraic transformation it is possible to obtain the following:

$$s^2 = \frac{[\rho_0(\varphi,\mu_1,\mu_0)-\rho_1]K_0(\mu_2)-[\rho_0(\varphi,\mu_2,\mu_0)-\rho_2]K_0(\mu_1)}{[\rho_0(\varphi,\mu_2,\mu_0)-\rho_2]K_0(\mu_1)\left(\frac{K_2(\mu_1)}{K_0(\mu_1)}-\frac{K_2(\mu_2)}{K_0(\mu_2)}\right)-\frac{1{,}91a_2(\mu_0)K_0(\mu_1)K_0(\mu_2)}{2q'(1+g)}[\mu_1-\mu_2]},$$

$$\tau' = (2s)^{-1}\ln\left\{\frac{m\bar{l}K(\mu_1)K(\mu_0)}{\rho_\infty(\varphi,\mu_1,\mu_0)-\rho_1}+l\bar{l}\right\}, \quad (1)$$

where: q′ = 0.714; $K(\mu)$, $K_0(\mu)$ and $K_2(\mu)$ are escape function and coefficients of its expansion over the small parameter s;

$a_2(\mu)$ is the second coefficient in expansion of plane albedo. Their values are known and possible to find in tables or to calculate with approximations and known parameter s (Minin, 1988; Melnikova and Vasilyev, 2004).

2) Observational data below cloud. The analogous expression could be obtained for multiangle radiance below cloud:

$$
s^2 = \left[\frac{\sigma_1 \bar{K}_0(\mu_2)}{\sigma_2 \bar{K}_0(\mu_1)} - 1\right] \frac{1}{\dfrac{\bar{K}_2(\mu_1)}{\bar{K}_0(\mu_1)} - \dfrac{\bar{K}_2(\mu_2)}{\bar{K}_0(\mu_2)}} ,
$$

$$
\tau' = s^{-1} \ln\left[\frac{\sqrt{l\bar{l} + r^2} + r}{l\bar{l}}\right], \quad r = \frac{m\bar{K}(\mu_{1,2})K(\mu_0)}{2\sigma(\tau, \mu_{1,2}, \mu_0)} \tag{2}
$$

Constants m and l are determined by properties of the considered media Here $\bar{K}(\mu)$ and $\bar{l}$ depends on ground albedo A. It is to point out that in our case observations includes radiance and there is difficulty of calculating albedo, defined in terms of irradiances. However, the relation A =I(48°)/I(132°) has been obtained by Melnikova et al. (2000), that used here for ground albedo calculation.

Observations at the cloud top and base considered in combination give for retrieving s and τ' the following (Melnikova and Vasilyev, 2004):

$$
s^2 = \frac{\bar{K}_0(\mu)^2(\rho_0-\rho)^2 - K_0(\mu)^2\sigma^2}{16K_0(\mu)^2\left[\bar{K}_0(\mu)^2K_0(\mu_0)^2 - \left(\dfrac{A\sigma}{1-A}\right)^2\right] - \dfrac{24q'AK_0(\mu)}{1-A}\left[\bar{K}_0(\mu)(\rho_0-\rho)^2 - \dfrac{AK_0(\mu)\sigma^2}{1-A}\right] - J},
$$

$$
\tau_0' = \frac{1}{2s}\ln\left[\bar{l}\left(l + \frac{mK(\mu)K(\mu_0)}{(\rho_0-\rho)}\right)\right]. \tag{3}
$$

$$
J = \frac{2A\bar{K}_0(\mu)}{1-A}\left[a_2(\mu) + n_2 - \frac{K_2(\mu)}{K_0(\mu)}\right](\rho_0-\rho)^2 + \frac{a_2(\mu)a_2(\mu_0)}{6q'}\bar{K}_0(\mu)(\rho_0-\rho)
$$

3. RESULTS OF DATA PROCESSING

Two parameters (similarity parameter s^2 and scaled optical thickness τ') are derived with above formulas for three cases of observation: above cloud top (T) at the altitude 800 m, below cloud base (B) at the altitude 400 m and in combination (T+B). Ten scans are taken at every level, and radiance for every viewing angle is averaged over scans before processing. Table A presents results obtained.

Table A. Results of the retrieval from airborne observations.

λ, µm		0.340	0.381	0.472	0.682	0.870	1.035	1.219	1.273
A_s		0.0774	0.0588	0.0577	0.0481	0.0461	0.0472	0.0452	0.0441
$\tau_{Conserv}$	Base	34.62	23.00	21. 84	16.85	14.34	15.22	17.66	19.39
	Top	18.62	18.00	16.99	23.22	18.88	18.02	9.66	10.39
	Top+Base	22.44	18.46	20.77	22.85	19.88	18.44	16.91	16.33
τ	Base	20.4	18.10	19.00	17.20	14.71	15.25	14.25	15.00
	Top	27.7	23.30	27.7	32.20	16.71	10.30	5.62	7.41
	Top+Base	25.06	20.94	20.22	16.53	16.64	15.47	15.53	14.47
σ km^{-1}	Base	50.1	45.3	47.5	43.0	36.7	40.5	35.8	37.4
	Top	69.2	62.7	69.4	58.4	40.6	25.9	13.9	18.4
	Top+Base	62.66	52.35	50.55	41.33	41.60	38.68	38.82	36.18
r	Base	0.0046	0.0071	0.0051	0.0061	0.0057	0.0062	0.0064	0.0059
	Top	0.1487	0.0241	0.0413	0.0356	0.0329	0.0694	0.0774	0.1994
	Top+Base	0.0150	0.0150	0.0153	0.0153	0.0152	0.0155	0.0155	0.0169
MSD τ		0.7986	0.7249	0.7260	0.6826	0.6748	0.6668	0.6697	0.6638
ω_0	Base	0.99838	0.99850	0.99877	0.99886	0.99904	0.99895	0.99854	0.99885
	Top	0.99539	0.99423	0.99738	0.99715	0.99730	0.99551	0.99512	0.99507
	Top+Base	0.99677	0.99740	0.99828	0.99649	0.99786	0.99683	0.99674	0.99547
$1-\omega_0$	Base	0.00162	0.00150	0.00123	0.00114	0.00096	0.00105	0.00146	0.00145
	Top	0.00461	0.00577	0.00262	0.00285	0.00270	0.00449	0.00488	0.00493
	Top+Base	0.00323	0.00260	0.00172	0.00361	0.00214	0.00317	0.00326	0.00453
κ km^{-1}	Base	0.0812	0.0678	0.0582	0.0491	0.0352	0.0425	0.0523	0.0542
	Top	0.3202	0.1937	0.1790	0.1685	0.0971	0.1028	0.0607	0.0811
	Top+Base	0.1506	0.1094	0.0814	0.1687	0.0937	0.1196	0.1249	0.1638
MSD ω		0.00037	0.00032	0.00026	0.00024	0.00018	0.00022	0.00025	0.00026

Exhaustive searching of all suitable pairs of radiance at different viewing directions is possible to find the value s^2. However, the number of such pairs becomes too large for 90 directions. Hence, the random choice of certain numbers of pairs was provided. At the end desired parameters are obtained with averaging over all considered pairs for regularization with assuming observational errors not depending on viewing direction. Mean square deviations are estimated and presented in the table A.

The asymmetry parameter g is needed for obtaining the single scattering albedo ω_0, optical thickness τ_0 and scattering coefficient α. It was shown the parameter g weak variation in different stratus clouds and over spectrum, thus we took the value g=0.854 from calculations by (Stephens, 1979 and Lobanova et al., 2010). The optical thickness with assuming the conservative scattering calculated during the algorithm is shown in results for estimating the incorrectness of such assuming that often used in shortwave spectral region for clouds.

The special parameter r is introduced, which takes into account the shadow effect (heterogeneity of the cloud top) with following formula:

$$r = \frac{1}{N\bar{\tau}}\sqrt{\sum_{i=1}^{N}\left|\tau_i - \bar{\tau}\right|^2}\ , \qquad (4)$$

where N is number of viewing directions and the optical thickness is obtained with assuming conservative scattering at the first stage of processing.

4. THE ANALYSIS OF CLOUD OPTICAL PARAMETERS

The relation for the volume absorption coefficient is the following $\kappa = s^2\tau'/\Delta z$, where Δz is the geometrical thickness between observational levels, and the phase function parameter is not need for retrieval of the value κ. The volume scattering coefficient is calculated with the expression $\alpha = \tau'(3-3g)/\Delta z-\kappa$

Obtained values are different for processing data above and below cloud that reflect the vertical heterogeneity of cloud layer. The scattering coefficient and optical thickness demonstrate transparent spectral dependence. The figure 1 shows spectral dependence of the optical thickness obtained from Russian airborne spectral observation (GATE-program) of diffused irradiance in stratus clouds above Atlantic close to North-West Africa (solid and dotted lines) (Melnikova and Mikhailov, 1994) and results obtained from NASA observation with CAR instrument (triangles). The dependences of the optical thickness is power approximated.

The figure 2 presents spectral values of the single scattering co-albedo (1-ω_0) obtained from the same observational data. It is to point out that the airborne experiment is accomplished after sand storms in the Sahara desert (Kondratyev et al., 1976), thus true absorption in cloud is higher than in case of NASA observations in 2000.

The surface albedo is shown in the figure 3. Spectral dependence in case of GATE-1974 observation points to atmospheric influence in the interval of the oxygen absorption 0.762mkm band. High dust aerosol content provoked strong scattering and higher albedo values.

The results of 1974 and 2000 are consistent with each other.

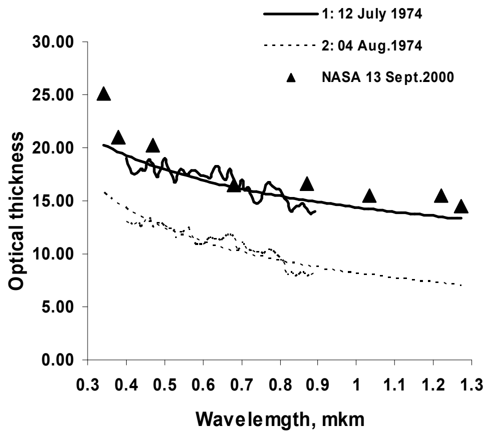

Figure 1. Spectral optical thickness of extended clouds close to North-West and South-West Africa.

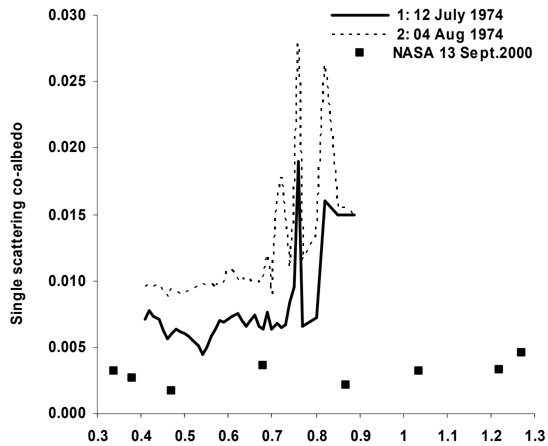

Figure 2. Spectral values of the single scattering co-albedo (1-ω_0) of extended clouds close to North-West and South-West Africa.

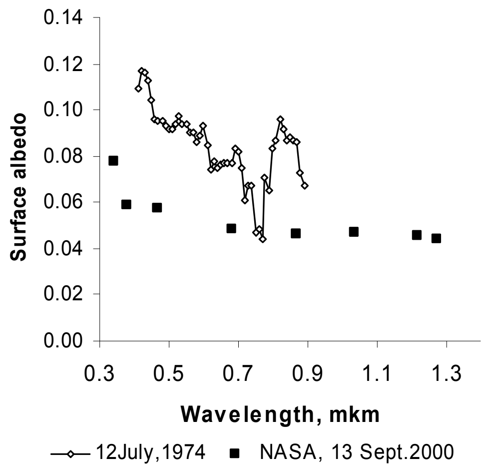

Figure 3. Spectral values of the surface albedo

Formulas for uncertainties of processing and applicability ranges of proposed approach are detailed considered in (Melnikova and Vasilyev, 2004). These formulas are used for regularization of result. It seems useful to calculate the radiation divergence from obtained optical parameters defined as:

$$dR(\mu_0)=[(F^{\downarrow}(\mu_0) - F^{\downarrow}(\mu_0))_{\mathrm{top}} - (F^{\downarrow}(\mu_0) - F^{\downarrow}(\mu_0))_{\mathrm{base}}]/\Delta z \quad , \quad (5)$$

In case of observed irradiance the Eq.(5) might be used. It is done for observation 12 July, 1974, (the cloud thickness 0.9 km) and for observation 20 Apr., 1985 above Ladoga Lake (cloud thickness 1.1 km). Corresponding results are presented in the figure 4 with solid and dotted lines. In case of NASA observation radiative divergence is calculated with Eddington method on the base of obtained cloud optical parameters and marked with black squares.

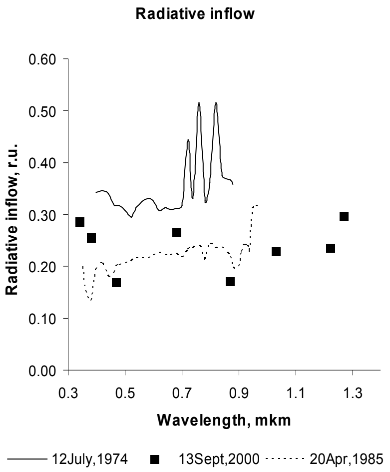

Figure 4. Radiative divergence in the layer 1 km in relative units of the incident solar flux.

The heating rate of the atmospheric layer with clouds in shortwave range is possible to estimate as

$$\left(\frac{\partial T}{\partial t}\right)_p = \frac{S_\lambda}{rC_p}\frac{dR}{dz} \qquad (6)$$

where

dR/dz is the radiative divergence in the layer 1 m, here it is $0.2\ 10^{-3}$;

∂T is the temperature change during the day;

S_λ = 1000 J/(s m^2)is the solar constant in shortwave spectral range (0.3 – 1.0 μm);

r = 1kg/m^3 is the air density at the level 800 mb;

Cp = 1005 J/(kg deg) is the specific heat of the dry air, Cp = 1952 J/(kg deg) is the specific heat of water vapor at constant pressure; 4218 J/(kg deg) is the specific heat of liquid water at 0 °C (Wallace and Hobbs, 1977); take the average value Cp = 2392 J/(kg deg) for calculation.

Approximate estimation of the heating rate of the 400 m thick atmospheric layer with clouds in shortwave range during the day (12 hours – light time) yields ΔT~0.16 deg/day.

5. CONCLUSION

Considered airborne data is a very rich matter and allows a comprehensive cloud analysis from point of view of the strict radiation transfer theory. The considered experiments were the base for elaborating more suitable processing algorithm and it shows results very close to obtained earlier from another kind of data. A diversity of viewing directions allows more thorough regularization of results. Data processing are determined also by observational uncertainties. It should be particularly emphasized that the analytical approach for solving the inverse problem (retrieving cloud optical parameters and their vertical profile) has an advantage comparing with numerical methods. In particular it does not put additional restrictions and links to desired parameters and provides the result adequate to real nature. The analyzing the radiation field angular transformation with deepness in the cloud makes possible to select the diffuse domain, where the asymptotic formulas' using is correct.

The comparison of cloud optical parameters obtained from different airborne experiments USA and Russian demonstrates a good agreement in values and dependences.

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