ALTITUDE ASSIGNMENT OF DATA OBTAINED FROM TANGENT SENSING OF THE ATMOSPHERE FROM SPACE IN THE UV SPECTRAL RANGE

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The accuracy of altitude assignment of the line of sight is estimated for the tangent sensing of the Earth's atmosphere from space. The two methods of assignment are considered: by positions of the spectral brightness maxima of the atmosphere at the Earth's limb (for the reflected and scattered solar radiation) and by the altitude dependence of radiation attenuation for different sources outside the Earth's atmosphere (for radiation transmission). The calculations were performed for the UV spectral range, corresponding to the Hartley ozone absorption band, where the multiple scattering, cloudiness variability, and albedo of the underlying surface are negligible. It is shown that random "weather" variations of density, ozone concentration, and aerosol scattering in the upper atmosphere lead to relatively small error of the altitude assignment.

For tangent sensing of the atmosphere from onboard a spacecraft, the accuracy of determination of the atmospheric components under study depends on a number of factors, in particular, on the accuracy of altitude assignment of measured data.[1–3] To achieve high accuracy of measurements, one needs to estimate the ballistic parameters and the parameters of spacecraft orientation with high accuracy at the time of signal recording. However, often the ballistic data allow determination (with sufficient accuracy) of only the rate of variation of the line-of-sight altitude. A position (shift) of the observed curve of atmospheric brightness at the Earth limb about the altitude axis remains uncertain. In such situations, special methods of altitude assignment are used. Thus, the accuracy of altitude assignment of the data of limb measurements from the turning satellite SME (Solar Mesosphere Explorer) of ± 1 km was obtained by using two horizon meters and a specialized technique for analysis of the pitching angles averaged over five or six satellite turns.[2,3]

The limb altitudes were refined in Ref. 2 by comparing the experimental brightness curve with the model one on the assumption that purely Rayleigh scattering takes place at the altitude of 65 km, and the error of assignment is determined by ± 4% level of atmospheric density variations at this altitude. Similar uncertainty may arise when the method of transmittance is used. In Ref. 4, when observing the attenuation of radiation from the solar disc in the atmosphere, the altitude assignment was made by the value of refraction compression of the solar disc. In Ref. 5 the altitude assignment of stellar ray perigees, when observing star brightness attenuation in the visible spectral range through the atmosphere, was made on the basis of the calculated model curves of star brightness attenuation. The use of special methods for altitude assignment is usually accompanied with special works on their justification.

This paper presents the results of model calculations of the accuracy for some methods of altitude assignment of the line of sight when using the tangent sensing scheme and the UV spectral range. According to the model calculations and experimental data,[6] the spectral brightness of the scattered solar radiation, observed on the Earth's atmospheric limb at the tangent sensing in the UV range of 200–300 nm, has a pronounced maximum at altitudes of 48–63 km depending on wavelength. Figure 1 shows the calculated positions of maxima of the spectral brightness curves as functions of wavelength in the 205–300 nm range.

As seen from Fig. 1, the altitudes of brightness maxima correlate well with the corresponding values of absorption cross sections of the ozone molecules.[7]

The brightness curves were calculated in the single scattering approximation. In the spectral range under consideration, double scattering contributes from several fractions of a percent to several percents of the value of the single scattering intensity.[6,8]

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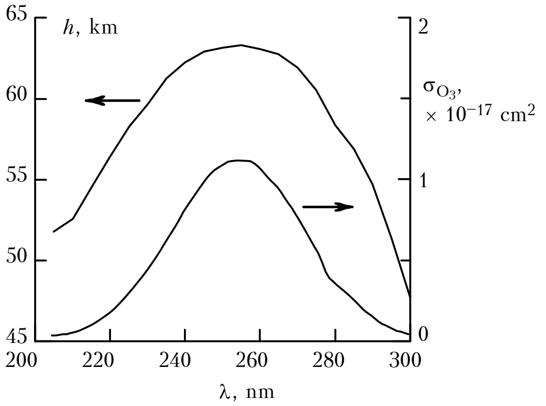

FIG. 1. Altitude h of the maxima of spectral brightness at the Earth's atmospheric limb for the UV spectral range. For comparison, the spectral dependence of absorption cross section of the ozone molecule σ_{O_3} is presented.

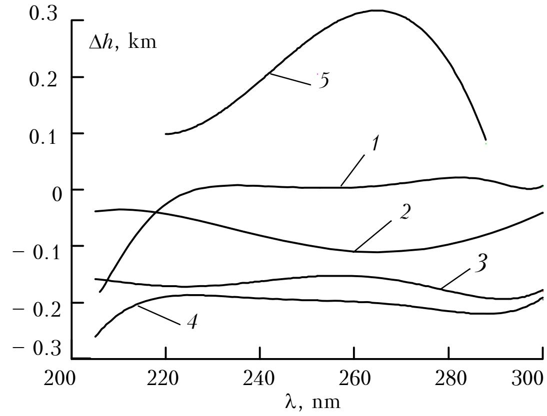

FIG. 2. Shift in the position of the maxima of brightness at the Earth's atmospheric limb Δh due to influence of random "weather" variations of the atmospheric parameters and at different choice of atmospheric models vs. wavelength.

The model ozone distribution from Ref. 9 was used. The absorption cross sections of ozone and molecular oxygen were borrowed from Ref. 7. The molecular scattering characteristics were calculated with the use of the Rayleigh scattering cross sections calculated, according to Ref. 10, based on the model of the atmosphere from Refs. 11 and 12. The aerosol scattering was calculated from the data of the "medium cyclic" model from Ref. 13. The values of altitudes shown in Fig. 1 correspond to the following conditions: the equator, March, the sun in the zenith, the scattering angle of 90°.

The method of altitude assignment consists in the following: the position of the maximum at the experimental brightness curve is assigned the value of altitude obtained as a result of model calculations. This method was used in Refs. 6, 14, and 15 as an element of the combined altitude assignment of data obtained from tangent sensing of the atmosphere in the UV range from onboard the *Astron* astrophysical spacecraft.

The models of the atmosphere used allows us to take into account the effect of seasonal and latitudinal variations of the ozone and the air density, as well as diurnal variations. Besides, the observation geometry and the illumination conditions of the atmosphere are taken into account in calculations. The accuracy of altitude assignment is determined by both the accuracy of atmospheric models themselves, being the results of averaging of the data of long-term observations, and the influence of the neglected random "weather" variations inf the atmospheric parameters, characterizing the difference between the particular and average values of the parameters.

Figure 2 shows the estimation of influence of random "weather" variations of the atmospheric density (curve *1*), aerosol scattering (curve *2*), and ozone concentration (curve *3*) on the altitude of the maximum of atmospheric brightness at the Earth's limb versus wavelength.

The parameter Δ*h* characterizes the shift in the position of the brightness maximum relative to the average value *h*, shown in Fig. 1 depending on the wavelength. Curve *1* corresponds to the maximal deviation (decrease) of the atmospheric density from the average value because of the "weather" component of variability of the atmosphere by the model from Refs. 11 and 12. According to this model, the relative value of "weather" variations of density at altitudes of 40–70 km is within ± 10%. Curve *2* corresponds to 50% decrease in the parameters of aerosol scattering relative to the average values, what characterizes the value of rms deviations according to the model from Ref. 13. It should be noted that, according to the model from Ref. 16 and the results of our research,[6,15] variations of the aerosol scattering parameters in the mesosphere are somewhat smaller, being about ± 30%. Curve *3* corresponds to 4% decrease in the ozone concentration for all altitudes above 40 km. By the model from Ref. 9 the rms value of the "weather" variations of ozone concentration is ± 4% at altitudes of 40–55 km. We might assume that this value of variations is characteristic at least up to 60–65-km altitudes; and above these altitudes the ozone variability is of the same order of magnitude. Thus, the estimation of Δ*h* presented can be considered to be sufficiently accurate. The total value of "weather" and seasonal components of the ozone concentration variability (± 3 – ± 6% at altitudes of 40–60 km) determined by the model from Ref. 15 are in a good agreement with the data of systematic observations in 1982 (Ref. 2). According to these data, ozone variations at the equator at altitudes about 50 km are about ± 10% of the annual mean value of the ozone concentration. As perturbations of the atmospheric density, ozone concentration, and aerosol scattering parameters alternate their sign, the corresponding curves of the shift in the position of brightness maximum versus wavelength are close to curves *1*, *2*, and *3* shown in Fig. 1, but with the opposite sign of the shift.

As seen from Fig. 2, variations of the atmospheric density have the minimal effect on the position of the brightness maximum. This is caused by the fact that in the spectral range under consideration the optical depths for light beams are formed mainly due to absorption by the ozone, while the relatively uniform change of density only leads to overall change of brightness due to the change in the intensity of Rayleigh scattering. The increase in the sensitivity of the maximum's position to density variations at $\lambda < 220$ nm is caused by the increasing part of the molecular oxygen (as compared with the ozone) in the absorption of solar radiation. It should be noted that within the framework of the model from Refs. 11 and 12, in the equatorial region and in the middle latitudes, diurnal, seasonal, and latitudinal changes in the density have relatively weak effect upon the position of the brightness maxima.

The brightness maxima shift most strongly in altitude due to the "weather" variability of the ozone concentration (curve *3*). It should be noted that for the equatorial region and up to the latitude of 30° the shifts in the position of maxima due to seasonal ozone variations, being calculated in accordance with the data of the model from Ref. 9, do not exceed the values presented by curve *3* in Fig. 2.

Because of the layer structure of the atmospheric aerosol by the "medium cyclic" model[13] and the large relative value of "weather" variations, the variability of aerosol scattering produces greater effect upon the position of the brightness maxima at the atmospheric limb (curve *2*) than the "weather" variability of the atmospheric density does.

Thus, according to the presented results calculated within the framework of the above-mentioned models, the altitude assignment of the tangent sensing data by the position of the brightness maximum in the UV 210–300 nm range gives average errors related to random "weather" variations of the atmospheric parameters. These errors do not exceed about ± 0.2 km (curve *4*). Curve *4* corresponds to the total (in the rms sense) shift in the maximums' position under the effect of all perturbations of the atmospheric parameters.

The aerosol scattering was calculated by our averaged data of tangent sensing of the atmosphere from space in the UV range.[6,15] According to these data, at altitudes of 50 and 65–100 km thick aerosol layers are observed, while at altitudes of 55–65 km the atmosphere is relatively clear. According to calculations made for the 220–285 nm range, shifts in maximums' positions due to 30-% (spread in the obtained data) "weather" variations of aerosol scattering practically do not exceed the corresponding shifts calculated by the model from Ref. 13 and shown by curve *2* in Fig. 2. However, the average values of the brightness maxima themselves change as compared to the values obtained with the use of the model from Ref. 13 for calculation of the aerosol scattering. Curve *5* in Fig. 2 demonstrates just this change in the average values. As seen from Fig. 2, the change in the altitude of the brightness maxima varies within 0.1 to 0.3 km in the spectral range of 220–285 nm. For the wavelengths shorter than 220 nm and longer than 290 nm, the change reaches ~1 km, what is caused by influence of the thick pronounced aerosol layer near 50-km altitude.

Figure 3 demonstrates the atmospheric transmission coefficient $I_\lambda/I_{0\lambda}$ versus the altitude of the line of sight of the extraterresrial radiation source for four wavelengths (220, 250, 280, and 300 nm) of the 205–300 nm wavelength range under consideration. In calculations, we use the same average model data for the density of the atmosphere, aerosol scattering, and ozone, as in calculations of the functions shown in Fig. 1. The dependence was calculated for the equator, 24:00 L.T., March 21. However, the ozone concentration was taken according the altitude distribution of ozone for daytime.

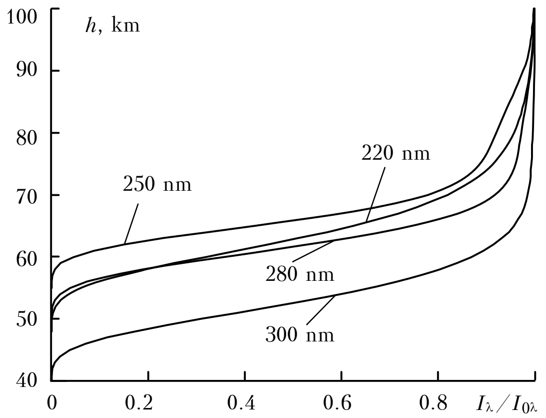

FIG. 3. Altitude dependence of the atmospheric attenuation $I_\lambda/I_{0\lambda}$ of brightness of stars and other extraterresrial radiation sources for different wavelengths in the UV range.

As seen from Fig. 3, radiation from a source is mainly attenuated in the altitude range of 50–70 km. As our calculations show, radiation extinction in the spectral and altitude ranges under consideration is determined, to a great extent, by the absorption by ozone: for $\lambda = 250$ nm, the relative contribution from molecular scattering into the optical depth is about 1–5%, while for $\lambda = 300$ nm it is 3–30%. At $\lambda \approx 220$ nm, the contributions into radiation attenuation from absorption by ozone and molecular oxygen become comparable. The aerosol contribution is usually smaller than the molecular one or comparable with it. The radiation extinction due to refraction is relatively small for the considered altitudes.

The problem of change in the ozone concentration in nighttime as compared to daytime is rather complicated. As known, the ozone concentration in the mesosphere increases during nighttime[17] due to recombination

$$O + O_2 \xrightarrow{M} O_3. \quad (1)$$

The Table I gives the factors of the ozone concentration increase in nighttime as compared to daytime. The values are those calculated within the framework of different models[18,19] and obtained in the rocket experiments.[20] We supplemented the model results with one dependence more. The fourth column of the Table I presents the results calculated using the data of model calculations[17] of the daytime concentration of oxygen, ozone, and atomic oxygen, as well as the photochemical lifetime τ_0 of atomic oxygen in the mesosphere. Up to altitudes of 80 km, the night-to-day factor of the ozone concentration increase is calculated under the assumption that all atomic oxygen transforms into ozone and no reactions of odd oxygen loss take place. Above 80 km, this factor was calculated under similar assumptions, but with regard for the finite lifetime of atomic oxygen τ_0. In this case, it was assumed that the oxygen concentration changes in nighttime following the exponential law with the characteristic time τ_0. Then the rate of n_3 formation was integrated over time according to the reaction (1) with the use of the reaction rate constant presented in Ref. 21. The temperature values were borrowed from Ref. 21 as for the standard atmosphere of the USSR.

As seen from the Table I, up to altitudes of 55–65 km some qualitative agreement is observed between the model and rocket data. Above 70 km, the physico-chemical processes governing the diurnal variability of the ozone concentration are still unclear. This is apparent from the spread in the predictions of diurnal variability within the framework of different photochemical models. The night-to-day factor of the ozone concentration increase at the altitude of 80 km is equal to 2 to 100 according to different estimates.[20]

TABLE I. The night-to-day factor of the ozone concentration increase according to the model calculations and the experimental data.

Altitude, km	Model			Rocket data, Vaughan, Ref. 20
	Herman, Ref. 18	Fabian et al., Ref. 19	Based on the data from Brasseur, Solomon, Ref. 17	
35	0.97	~1	1.00	1
40	0.94	~1	1.00	1
45	1.03	~1	1.01	1
50	1.15	~1.15	1.07	1.09
55	1.33	~1.30	1.26	1.32
60	–	~1.80	–	1.63
65	–	–	2.56	2.05
70	–	–	5.00	2.63
75	–	–	12.8	3.42
80	–	–	101	4.53
85	–	–	109	6.11
90	–	–	121	8.38
95	–	–	182	11.68

The simple estimate of the night-to-day factor of the ozone concentration increase presented in the column 4 of the Table I was obtained when completely neglecting the reactions of odd oxygen loss in nighttime. Being compared with the rocket data, it allows us to assume that the values of this factor obtained in some photochemical models are underestimated due to neglecting some of these reactions.

The shift Δh in altitudes of the same level of the spectral coefficient of atmospheric transmission (relative to attenuation of brightness of stars and other heavenly bodies) in nighttime as compared to daytime for λ = 280 and 300 nm is shown in Fig. 4 (curves *1*) as a function of altitude of the initial level in daytime.

We used the night-to-day factor of the ozone concentration increase obtained from the rocket data. This factor is presented in the fifth column of the Table I. Figure 4 presents the shifts of altitudes under the effect of random “weather” variations of the atmospheric parameters. Description of “weather” perturbations of the atmospheric parameters corresponds to that presented when discussing Fig. 2. Curve *2* presents the density perturbation, while curves *3* and *4* are for the aerosol scattering according to the model from Ref. 2 and the data of our research,[6,15] respectively; curve *5* is for ozone, and curve *6* for the total (in the rms sense) shift of the altitude due to “weather” variations of the atmospheric parameters. The right vertical axes in Fig. 4 present the corresponding values of the attenuation coefficients $I_\lambda/I_{0\lambda}$ themselves.

The parameter Δh characterizes the corresponding contribution into the error of altitude assignment of the line of sight of heavenly bodies from a spacecraft by observation of their brightness attenuation in the UV range because of influence of different atmospheric factors. The requirement of minimization of inevitable influence of measurement error on the assignment results leads to a restriction on the range of measured transmission coefficient vaslues to be used, for example, from 0.1 to 0.9.

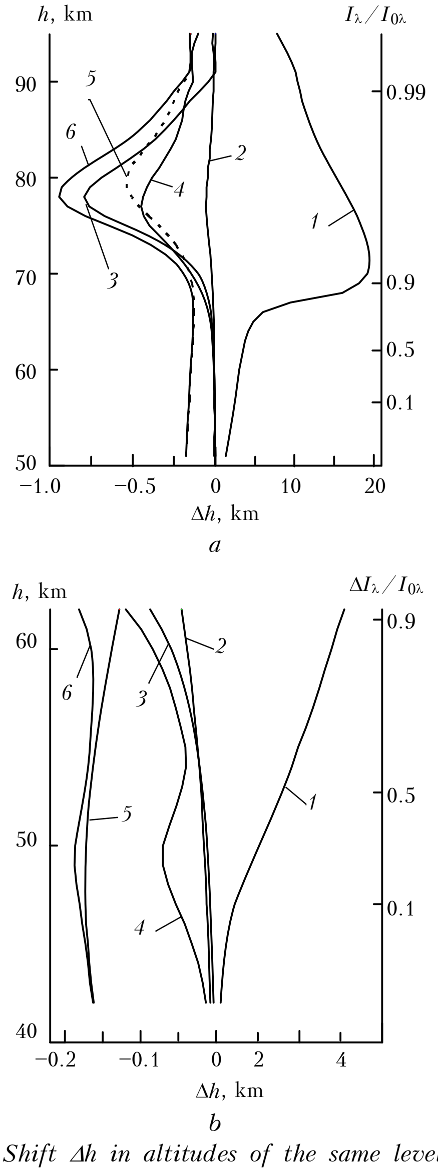

FIG. 4. Shift Δh in altitudes of the same level of the spectral coefficient of atmospheric transmission (relative to attenuation of brightness of stars and other heavenly bodies) in nighttime as compared to daytime under effect of random "weather" variations of atmospheric parameters: for λ = 280 *(a) and* 300 nm *(b).*

As seen from Fig. 4, for this variability range of the transmission coefficient, the influence of neglected "weather" variations leads to the assignment error of ± 0.2 km. This value of the error leads, for example, when using the method of star brightness attenuation in the UV range for autonomous spacecraft navigation,[22] to the angular error in line-of-sight determination from geostationary orbits about ± 1 second of arc.

The problem on accurate altitude assignment of lines of sight of heavenly bodies (stars) in nighttime is much more complicated. If diurnal changes of the ozone concentration are estimated by the data of photochemical models or few rocket experiments, this gives, as seen from Fig. 4*b*, the shift of attenuation curves for λ = 300 nm about 0.5–2 km in the case of assignment at altitudes about 50 km ($I_{\lambda}/I_{0\lambda} \approx 0.1$–$0.55$). For geostationary orbiting, the error of 10 seconds of arc corresponds to 2-km altitude error. From the viewpoint of increase in the accuracy of autonomous spacecraft navigation by the measurements of star brightness attenuation in the UV range, it is important that this is a systematic error. Construction of more adequate models of the ozone concentration variability in the upper atmosphere may significantly decrease the errors in determination of navigation parameters.

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