SOME RESULTS OF VISUAL OBSERVATIONS AND SPECTROPHOTOMETRY OF THE TWILIGHT HALO OF THE EARTH' S ATMOSPHERE FROM THE "SOYUZ-5" SPACECRAFT

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Abstract

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The rapid development of studies of near-Earth space by means of automatic equipment installed on artificial Earth satellites, crewed spacecraft, and interplanetary stations now makes it possible to formulate and solve a whole series of important theoretical and applied problems in the field of atmospheric space optics. In this connection, over a number of years Soviet and American cosmonauts have carried out corresponding visual observations, and black-and-white and color photographs have also been obtained of the twilight horizon of the Earth' s atmosphere at various angles of the Sun' s depression below the horizon ([1–4]). It should be noted, however, that at best the twilight halo was photographed using two or three light filters. This did not make it possible to study the complete pattern of the distribution of spectral brightness over the twilight sky and to establish its dependence on variations of the optical parameters of the atmosphere.

On the other hand, the development of theoretical studies based on the use of analytical and numerical methods for solving the equation of radiation transfer in an aerosol spherical atmosphere has made it possible to obtain sufficiently complete information on the spectral, angular, and spatial distribution of the brightness of the twilight halo for various models of the vertical distribution of the optical parameters of the atmosphere ([4–9]).

Thus there arose a need to carry out a comprehensive optical experiment from space, making it possible to study the spectral (color), angular, and spatial evolution of the brightness pattern of the twilight atmosphere. Such a program was first implemented during the flight of the "Soyuz-5" spacecraft. In the field of optical studies it provided for the simultaneous photographing and spectrophotometry of the twilight halo of the Earth' s atmosphere in the wavelength range 400—650 mμ, as well as the performance of a set of corresponding visual observations.

1. For the experiment, a specially designed hand-held spectrograph with a telephoto lens was used, making it possible to carry out spectrophotometry of distant objects with a spectral resolution of 5 mμ and an angular resolution of about 2′. The design of the instrument makes it possible, simultaneously with the spectrum, to obtain a photographic image of the object being studied. The optical scheme of the instrument is shown in Fig. 1.

The program of work with the hand-held spectrograph provided for photographing the twilight halo of the Earth' s atmosphere in the direction toward the Sun from the moment the halo appeared until the spacecraft had completely emerged onto the illuminated side of the Earth. In addition, the twilight halo was also photographed on black-and-white and color film with a "Zenit-3M" camera. Visual observations included an assessment of the vertical evolution of the brightness and color of the twilight halo as the Sun emerged from behind the horizon.

In accordance with the experimental program, visual observations, photography, and spectrophotometry were carried out on three orbits: 2, 6, and 15. The optical experiment was conducted under cloudless conditions···

cloudless atmosphere (orbit 2), continuous cloud cover (orbit 6), and broken cloud cover (orbit 15). Over the regions where the experiment was carried out, a stable synoptic situation was observed (there were no hurricanes, storms, etc.).

2. The visual observations under cloudless-atmosphere conditions, which preceded the spectrophotometry, may be summarized as follows. At large angles of depression of the Sun below the horizon, red-orange tones are observed near the Earth' s surface (the edge of which is clearly visible). As the altitude of the layer being viewed increases, the color of the halo gradually changes to orange-yellow, adjoining which is a narrow dark-blue band of reduced brightness, located at approximately a height equal to 1/3 of the visible size of the halo. The dark-blue band passes sharply into a rather extensive region colored light blue, which in turn rapidly transforms into dark blue and black-violet at greater heights. As the angle of depression of the Sun below the horizon decreases, the brightness of the halo increases and the dark-blue band disappears. At the same time, the saturation of the color tones of the twilight halo increases. This color pattern differs in some details from the corresponding descriptions by K. P. Feoktistov ([1]), V. V. Nikolaeva-Tereshkova ([2]), and J. McDivitt and E. White ([4]). This circumstance is important in the sense that, first, it emphasizes the different character of the meteorological situation during the visual observations from the spacecraft Soyuz-5, Vostok-6, Voskhod, and Gemini-4. Second, it establishes the fact that colorimetric data obtained from space are a sensitive indicator of vertical inhomogeneities in

Fig. 1. Optical layout of the hand spectrograph.

Figure 1: Fig. 1. Optical layout of the hand spectrograph.

the Earth' s atmosphere.

Fig. 1. Optical layout of the hand spectrograph.
1 —entrance objective of the spectrograph channel, 2 —entrance objective of the phototie-in channel, 3 —shutter of the phototie-in channel, 4, 5, 7, 8 —flat rotating mirrors, 6 —photographic film, 9 —collimating objective, 10 —diffraction grating, 11 —entrance slit of the spectrograph, 12 —shutter of the spectrograph channel

3. As a result of the spectrophotometry carried out by E. V. Khrunov on January 15 (orbits 2 and 6) and January 16, 1969 (orbit 15), respectively at 13 hr 52 min, 18 hr 23 min, and 7 hr 23 min Moscow time, 15 frames were obtained containing spectra and photographs of the twilight halo under different conditions as the Sun emerged from behind the horizon. The geographic coordinates of the Soyuz-5 spacecraft at the time of the spectrophotometry were as follows: orbit 2, 30° S and 157.4° E (near the eastern coast of Australia); orbit 6, 51.69° S and 147.13° E (region of the Auckland Islands); and orbit 15, 4.29° S and 131.66° E (region of the island of New Guinea). The photography was carried out in the direction toward the Sun, with the azimuth of the spectrograph entrance slit relative to the Sun equal to 8°. In this case the entrance slit of the spectrograph was arranged perpendicular to the horizon line.

The spectra obtained were processed with a step of 1 km in altitude and 10 mµ in wavelength. The altitude referencing of the spectral curves was carried out from photographs of the halo, with an absolute error in determining the zero level of about 2 km. In cases where the horizon was covered by clouds, the altitude referencing was carried out according to the maximum of the monochromatic brightness curve (λ 450 mμ). The random error in determining the absolute brightness values is approximately 10%.

4. The results obtained may be briefly summarized as follows. Near the Earth' s surface, the principal contribution to the brightness of the twilight halo is made by long-wavelength radiation. As the altitude of the sighted layer increases, the atmospheric density decreases, and the brightness of the twilight halo is determined by the scattering and absorption of short-wavelength radiation. The maximum brightness of the twilight halo occurs at a wavelength of $\sim$ 480 mμ. A brightness minimum is observed at a wavelength of $\sim$ 600 mμ, caused by ozone absorption in the Chappuis band. The depth of this minimum depends on the altitude of the atmospheric layer under consideration above the Earth' s surface. The spectral brightness depends strongly on the azimuth of the viewing direction and on the angle of depression of the Sun below the horizon, increasing sharply

as the latter decreases. The altitude corresponding to the maximum of the spectral brightness also depends on the angle of depression of the Sun below the horizon and on the wavelength, decreasing as the latter increases.

5. Analysis of the brightness curves obtained shows that they contain no appreciable depressions caused by aerosol layers localized at different levels in the atmosphere (for example, 11 and 19 km). To establish agreement with the conclusions obtained in [2], numerical calculations were carried out in order to determine the influence of aerosol concentration at different altitudes and of the magnitude of the angle of depression of the Sun below the horizon on the absolute values of the indicated depressions, as well as on the color pattern of the twilight halo. It turned out that a twofold increase in the volume concentration of aerosol at an altitude of 20 km (Elterman model [10]) does not produce noticeable depressions on the corresponding brightness curve. They appear only when the volume concentration of aerosol at this altitude is increased by a factor of 4. The usual value of the aerosol volume concentration given by the Elterman model [10] leads to the appearance of depressions on the monochromatic brightness curves only at angles of depression of the Sun below the horizon exceeding 3°.

The analysis of colorimetric calculated data obtained for the Elterman model [10] may be summarized as follows. At small angles of sunset of the Sun below the horizon, ozone has a substantial influence on the color of the twilight sky ("blueing" of the twilight sky in the altitude range 25–30 km). At large angles of sunset of the Sun below the horizon, brightness depressions appear, caused by aerosol layers. Such brightness depressions should be sighted from space as dark bands of reduced brightness.

6. Comparison of the experimental brightness values of the twilight halo with calculated values obtained in the single-scattering approximation for the Elterman model [10], for the orbital parameters of the Soyuz-5 spacecraft, and for viewing directions corresponding to the optical experiment carried out from space, made it possible to estimate the contribution of multiple scattering to the brightness of the twilight halo at different altitudes. As was to be expected, the contribution of multiple scattering to the brightness of the twilight halo near the Earth' s surface proved to be determinative. With increasing altitude of the sighted layer, the role of single scattering increases; above 30–40 km the experimental and calculated brightness curves for λ 450 mμ practically coincide (see Fig. 2).

7. The results obtained make it possible to estimate the optimal possibilities for photography and spectrophotometry of the twilight atmosphere

from spacecraft for solving inverse problems of atmospheric optics. As was indicated above, at small angles of the Sun' s setting below the horizon the vertical depressions of the brightness of the twilight aerosol atmosphere are

Figure 2: graph of monochromatic brightness of the twilight aureole versus height h

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small or absent. This makes it difficult to solve the problem of reconstructing the vertical profile of the aerosol scattering coefficient from the brightness of the twilight aureole measured from a spacecraft. However, the color pattern of the twilight aureole is highly sensitive to the presence of such

Fig. 2. Experimental and calculated values of the monochromatic brightness of the twilight aureole of the Earth' s atmosphere $I_\lambda^{(1)}$ (wavelength $\lambda = 450$ mμ, 6th orbit, spacecraft orbit altitude $h = 252.3$ km, angle of the Sun' s setting below the horizon $\delta_\odot = 0°$, viewing-direction azimuth $\varphi = 8°$). 1 –Elterman model [10] (single scattering), 2 –molecular atmosphere (single scattering), 3 – experimental data ("Soyuz-5")

vertical inhomogeneities, such as, for example, the ozone layer. Therefore, in solving inverse problems of atmospheric optics it is necessary to combine the colorimetric analysis of optical data obtained from space with an analysis of the absolute values of the depressions on the curves of the monochromatic brightness of the twilight aureole. In this connection, the implementation of a space experiment for the independent determination, by direct soundings, of various characteristics of the vertical structure of the atmosphere (vertical profiles of ozone, aerosol, etc.), with the simultaneous assessment of the altitude evolution of the color of the twilight sky, is of exceptional importance.

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Note: Figure translations are in progress. See original paper for figures.