Airborne studies of aerosol trail from detachable stages of a carrier rocket

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An artificial aerosol cloud formed above the tropopause due to emission of propellant components from a falling expendable stage of a carrier rocket has been studied. The scattering coefficient, geometry, and direction of movement of this anthropogenic cloud have been determined.

It is known that separated expendable stages of carrier rockets contain some warranty amount of propellant (heptyl or asymmetric dimethylhydrazin) and oxidant (nitrogen tetraoxide). Remaining propellant components can make up to several hundreds kilograms. In the process of their forced extrusion from tanks and possible destruction of the second stage as it enters dense atmospheric layers, both components are emitted into the atmosphere and dissipate in it.[1]

Because of the high toxicity, propellant components (PC) and the products of their decomposition in the atmosphere are a threat to the environment. In this connection, experimental data on the time of appearance and behavior of the PC in the atmosphere are of considerable importance. The available models of dissipation and sedimentation of aerosol PC have a significant ambiguity in the initial conditions.[2] Therefore, the most complete information could be obtained in airborne lidar sensing of the PCs.

Such an experiment has been conducted on June 16, 2001 during Proton-K rocket launch from the Baikonur Cosmodrome. The Optik-E aircraft-laboratory[3] (AN-30 aircraft) was flown at the altitude of 7 km in the assumed region of the stage descent (to the south-east from Teletskoe Lake in Altaiskii Krai). The PC trail and leavings of the second stage were detected visually at 06:01, Moscow Time, in the direction to north-west from the predicted place of fall. According to the estimated fall trajectory, at that time the second stage should be at the altitude of about 13 km. The visible cloud-like plume of PC emission lied above this altitude and, as the following observations showed, did not descend for 30 min. A lidar designed to operate at horizontal paths from aboard an aircraft unfortunately could not hit the plume lying at such altitudes and sensed only the cloudless atmosphere. Therefore, further studies were based on video records and visual estimates.

Figure 1 depicts the flight route with the time reference of observations along with the ballistic trajectory of the stage fall and the zone of the aerosol plume in projection onto the Earth's surface as estimated based on triangulation marks of aircraft navigation equipment for roughly 35 min. As can be seen, the falling stage deviated considerably from the calculated trajectory. According to the tentative telemetry data, the excess heptyl was forcedly extruded from fuel tanks at the altitudes of about 40 km. The visible plume at lower (roughly by 20–10 km) altitudes is most likely due to oxidant outflow from breaking fuel tanks of the second stage. The meteorological data given in Table 1 evidence of the presence of a pronounced temperature inversion at the altitudes from 11 to 14 km, which favored the stable state of the atmosphere at the level of the tropopause. In contrast to the assumed model of plume dissipation,[2] the aerosol cloud was concentrated above the tropopause. In the process of observation, it elongated and displaced along the horizon above the tropopause level along the wind direction at these altitudes.

Figure 2 shows some video frames of the plume in the black-and-white representation. Figure 2*a* corresponds to the observation time immediately after the appearance of the plume at 06:01:30. Here the camera's field of view is fixed and known, therefore we succeeded in estimation of the plume size. Analysis of the route in Fig. 1 suggests that for the frame in Fig. 2*a* the distance from the aircraft to the plume was (45 ± 5) km. In this case, the inclined length of the central, the brightest part of the plume was 4.5–5 km. Its thickness (diameter) was roughly 0.8–1.0 km. The plume inclination angle in this projection was close to 30° about the vertical. Analysis of the soft part of the color image reveals a weak 3 to 4 km long trail going upward from the central core and an even weaker 1 to 2 km trail below the core. Assumingly, the latter enters the tropopause due to dynamic processes from the stage fall. The spiral structure of the plume is clearly seen in Fig. 2*b*, but here we cannot estimate its size, because the camera zoom lens was in an intermediate position. This spiral or, rather, spin is connected with the fact that the stage body turns by a cone generatrix while falling. The thickness of the aerosol jet forming the spin was equal to 100–200 m at the first moments.

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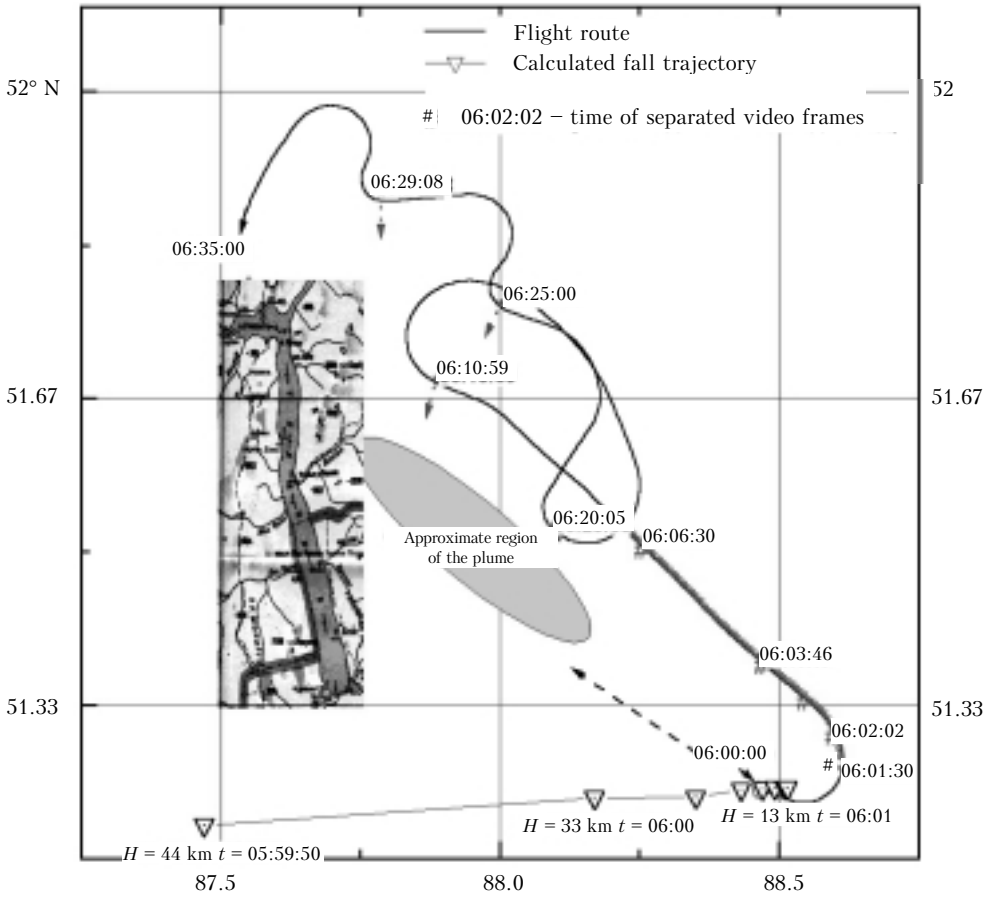
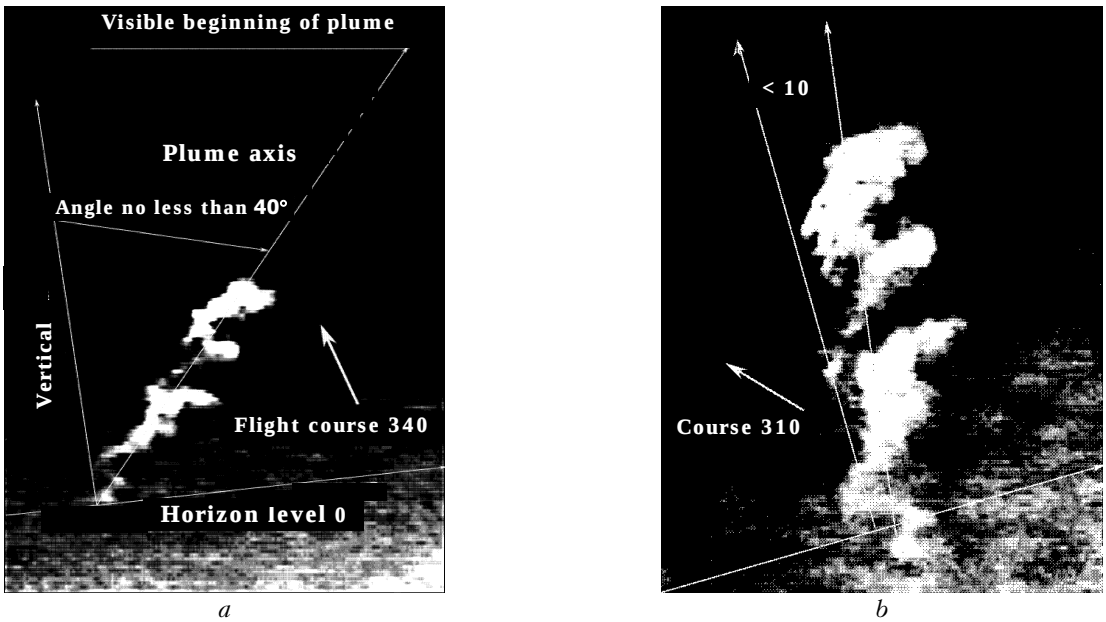


Fig. 1. Flight route. Coordinates are given in geographic degrees. The time shown on the route is Moscow Time, at which the aircraft passed through selected points, a fragment of the Teletskoe Lake map is given on the left.



a *b*

Fig. 2. Images of nitrogen tetraoxide aerosol cloud at the first minutes of its existence: fixed camera field of view (*a*) and magnified image of the cloud in other perspective (*b*).

The estimate of the altitude, the visible part of the plume lies at, proves to be somewhat ambiguous. This is connected with the errors in determination of the camera orientation and the distance to the plume. In the first approximation, the lower boundary of the plume (assuming that its shape is a barrel or spindle) can be referenced to the tropopause. In this case, the core at the initial moment of observation was at the

altitude from 11 to 15–16 km. In further processing of video frames, we estimated the brightness of individual parts of the image at the initial stage of the plume dissipation, when the matter concentration in it is maximum. We compared the spectral brightness of the brightest part of the plume B_p and that of the neighboring (at the same angle of altitude) part of the sky having the same area B_a. The effect of clouds and the surface on the illumination conditions can be neglected in this case.

Table 1. Meteorological information for the site of high-altitude laser sensing of the Novosibirsk atmosphere dated to June 16 of 2001 at 00:00:00 GMT

Altitude H, m	Temperature t, °C	Wind velocity V, m/s	Wind direction, deg
0	16.8	1	120
1006	14.4	5	190
5650	−14.7	11	245
7206	−28.8	13	215
8812	−37.7	12	245
9320	−43.3	13	240
10520	−53.7	13	225
11167	−55.5	13	250
11727	−54.4	14	260
13820	−47.7	9	260
15087	−49.9	5	280
15812	−50.5	6	280
16470	−51.9	5	270

The ratio B_p/B_a was calculated for the red, green, and blue visible spectral regions. Table 2 gives the mean values of B_p/B_a for the time series of video frames from 06:02:57 to 06:06:35. It should be noted that for these several minutes of measurement, no regularity was mentioned in the variation of B_p/B_a.

Table 2. Ratio of the plume brightness to the background brightness of the atmosphere

Spectral region	B_p/B_a
Red	1.664 ± 0.117 (7%)
Green	1.458 ± 0.10 (7%)
Blue	1.378 ± 0.054 (4%)

We can say that the plume is somewhat redder than the ambient atmosphere, although visually it was white resembling an ordinary cloud. This red color is significant, since the confidence intervals of coloration do not overlap. This phenomenon can be caused by the presence of nitrogen oxides, which are known to be red-brown, in the plume. On the other hand, it can be caused by differences in spectral light scattering for the natural aerosol-molecular atmosphere at the altitudes of about 12–15 km and anthropogenic aerosol consisting of particles (droplets or crystals) of watered nitrogen tetraoxide or products of its decomposition.

The further analysis of the image was carried out on the assumption that the brightness of the plume B_p and the neighboring part of the sky B_a is simply proportional to their optical thickness, because the conditions of their illumination by the sun are the same, that is, $B_p = \tau_p I_{sun}$ and $B_a = \tau_a I_{sun}$, where I_{sun} is the intensity of solar illumination. We have estimated the geometric diameter of the central barrel-like part of the plume to be roughly $d = 0.9$ km. Correspondingly, $\tau_p = d\,\sigma$, where σ is the mean scattering coefficient in this plume cross section.

The situation with the optical thickness of the clean atmosphere τ_a is more complicated. This thickness should be estimated from the altitude of 7 km above the ground (aircraft flight level) upward and in the direction of about 30° to the horizon. Our estimate was based on Ref. 4, in which the optical model of the atmosphere suitable for lidar studies was synthesized based on experimental and calculated data. The model accounts for the inhomogeneous, in height, stratification of the continental atmosphere for a wide set of wavelengths.

From this model, we took data on the atmospheric optical thickness τ_a starting from some altitude H above the ground and up to the boundary of the optically active layer 30 km high. We used the wavelength of 0.53 μm both as a laser wavelength and as the center of the band in the visible spectral region. According to Ref. 4, the vertical optical thickness in the zenith direction with the aircraft flying at the altitude of 7 km as in our case is $\tau_{a,zenith} = 3.69 \cdot 10^{-2}$. The camera angle of elevation was about 30° when sighting the plume core. Thus, with the allowance for the angle of 30°, the slant optical thickness is $\tau_a = 7.38 \cdot 10^{-2}$.

Based on the data of Table 2, we can assume that the brightness ratio of the plume and the aerosol-molecular atmosphere in the green region is $B_p/B_a = 1.5$, i.e., $\sigma_p d / 7.38 \cdot 10^{-2} = 1.5$. With the allowance for the fact that $d = 0.9$ km according to our estimate, we obtain $\sigma_p = 0.12$ km^{-1}. Remind that this central part of the plume initially had the spiral or, rather, spin structure. In this case, $\sigma < 0.1$ km^{-1} in other parts of the plume. This is roughly 30–50 times larger than for the natural atmosphere at the altitudes of 13–14 km and falls within the physically justified common sense.

Thus, the results of this experiment allow the following conclusions to be drawn.

The major part of the emitted propellant components does not reach the ground at the places of second stage fall, but stays above the tropopause.

Immediately after the emission, the aerosol cloud of nitrogen tetraoxide can be approximated as a nearly vertical cylinder with the height of 4–6 km (or even larger taking into account the trails) and the diameter of 1 km.

The scattering coefficient of such an acid anthropogenic cloud is about 0.1 km^{-1}.

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