Neutrons from thunderstorms at low atmospheric altitudes and related doses at aircraft

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Abstract. We conduct a simulation of thunderstorm neutron flashes at the lowest atmospheric altitudes below 10 km. The neutron generation mechanism is based on the nowadays conventional idea of possibility for photonuclear reactions to proceed on the atmospheric components owing to TGF photons. Our modeling includes generation of neutrons from TGF and their further propagation with account of interaction with background nuclei. Using the calculation results we investigate the neutron flux properties with respect to problem of their registration, and predict the radiation environment caused by thunderstorm neutrons on altitudes of civil airflights. It is shown, that good conditions for the neutron flashes observation are provided from the 3 km altitude, and, possibly, the neutrons can be registered at ground level. We also found that thunderstorm-neutron-related effective dose can reach the value of 0.5 mSv in the region close to the TGF source if it is located at an altitude of 10 km.

1. Introduction
Our atmosphere is thought to generate powerful neutron bursts (TNF's, “Terrestrial Neutron Flashes” [1], [2]) owing to nowadays conventional phenomenon of Terrestrial Gamma Flashes (TGF) through photonuclear reactions of the gamma photons on the atmospheric components. The amount of neutrons per gamma flash can be substantial so that the correspondent neutron flux is detectable on low orbit [3]. These neutrons are attributed to rises of neutron count rate, registered in a number of on-ground [4], [5] as well as space experiments [6]. They can also provide additional means for investigation of TGF phenomenon and its underlying physics, and along with electrons and gammas can contribute to the radiation environment caused by thunderstorm activity at small atmospheric altitudes, which has been shown to be potentially meaningful for aviation flights [7]. In order to put the last proposition on the solid ground, in this paper, we model the thunderstorm neutron generation and propagation processes with account of our current knowledge of TGF source properties and confront the obtained neutron flux with the neutron albedo background. We also measure the neutron fluence, convert it to dosimetric units and compose a map of the dose distribution.

2. Modeling
In our study, we used the Geant4 package as a modeling tool, realized at the “Chebyshev” supercomputer of the MSU. Also, for the atmosphere, the MSIS-90 model was used [8]. To have a consistent picture of neutrons distribution in space and time one has to start with a γ-ray (TGF) source, which would generate initial spatial and energetic neutron distributions (the neutron source) by the bremsstrahlung gamma-rays. Thus, the modeling of propagation of the γ-rays through atmosphere was
carried out with an appropriate choice of the $\gamma$-ray source structure. As such, the point $\gamma$-ray source was used with the spectrum taken in accordance with the usual RREA bremsstrahlung generation scheme [9]. At that, $\gamma$-rays with energy between 10 MeV and 30 MeV were only used since below almost exactly 10 MeV the photonuclear neutrons are not produced and above 30 MeV the fraction of photons is insignificant [10] and correspondent photonuclear reaction efficiency is low. According to various possibilities, considered in literature, we singled out the cases of upward-, downward-directed (within the 90º solid cone) and isotropic $\gamma$-ray source. For the source altitude, we considered 10 km, 15 km and 20 km to cover most important for civil airflights region. For a TGF event, we 10$^{17}$ photons at the input, which is the current upper estimate. The generated neutrons were detected in the whole calculation area.

At the next step, the obtained on the previous stage data was used to simulate propagation of neutrons through the atmosphere. To obtain the neutron flux a number of neutrons reaching particular altitude was measured. To obtain dosimetric picture, the neutrons were registered by spherical detectors, which had 1 km in diameter and a horizontal and vertical spacing of 2 km between their centers. The spherical shape provides natural way of neutron fluence measurement, needed for dose calculation.

3. Neutron flux analysis
First of all we shall dwell on the spatial and temporal scales of the neutron flash. The characteristic size of the generated neutrons distribution (of the order of several kilometers) appeared to be much larger than the conceivable size of the $\gamma$-ray source, and this justifies the choice of point-like source. Duration of the neutron flash in the simulations at any point of the considered volume was very short, around several microseconds. So that, the characteristic time scale of the flash should be considered to match the one for TGF, i.e. around 1ms. This fact enables us to ignore the plane motion in dose estimation at airflights as a civil aircraft traverses the distance just of a few meters during this time. Neutron arrival time distributions at the 1 ms resolution for two different space points near the source positioned at 10 km are given in Figure 1 (left).

**Figure 1.** Neutron arrival time distributions (left) and spectra of thunderstorm and albedo neutron fluxes (right). The $\gamma$-source is at 10 km.

The spectral composition of the flux at an altitude of 10 km from the downward-directed source is presented in the right-hand side of Figure 1, where spectrums of first four milliseconds are singled out. Shown also is the neutron albedo spectrum for the close altitude level. As it is seen from the picture, the flux of thunderstorm neutrons well exceeds the background. In fact, at the limit of accuracy (connected with input statistics restriction) our calculations show that the excess over background exists at least from altitudes of 3–4 km. However the visible trend is so that one can assume that
thunderstorm neutrons prevail at the ground level. Besides, we note the thunderstorm neutron spectrum ranges to several MeV, where the main part of the neutrons is allocated. So in common, a high-speed and high-energy detector may be required to register them.

4. Assessment of the radiation dose

The radiation equivalent dose was found for the each point by means of the formula:

$$D = \int_{E_{min}}^{E_{max}} K(E) \Phi(r,E) dE$$

(1)

where $\Phi(r,E)$ is the differential energy neutron fluence (number of neutrons of the specific energy intersecting a sphere of unit cross section in all directions during the time of observation), $K(E)$ – the equivalent Kerma of neutrons in specific tissue matter [11], $r$ – the coordinate of observation point. In this investigation, we consider soft biological tissue and the corresponding Kerma factor.

The formula (1) can be transformed to:

$$D = \frac{1}{S} \sum_i K(E_i)$$

(2)

with $E_i$ being the energy of the $i$-th neutron and $S$ is the detector area. The sum is over all neutrons which were caught by spherical detector during the simulation. The $1/S$ coefficient of the sum is needed to convert the neutron flux on the scale of the spherical detector into the local value in accordance with the definition.

The resulting dose distributions for the downward- and upward-directed sources positioned at 10 km altitude are presented in Figure 2. It is seen, that the characteristic length of the dose decrease is about 2 km. The maximal value that can be obtained due to single TGF event constitute around 0.5 mSv. This number is close to the crucial values (the annual dose limit for members of public is 1 mSv), however due to very local manifestation the effect on aviation, in common, must be insignificant. In principle, this conclusion can be changed if one takes into account the multiplicity of TGFs in close time and space scales. However such an investigation is not possible to conduct reliably since this question is poorly known at present.

![Figure 2](image.png)

Figure 2. Maps of the dose distribution near the $\gamma$-ray source. Left: downward-directed emission. Right: upward-directed emission.

5. Conclusions

We have shown that the thunderstorm neutron flashes can be important for near-ground particle composition. They can be responsible for considerable doses that can be received by individuals at aircraft operating. Being undoubtedly a rare event they can have the meaning at least for air crew
Concerning the physical aspect, we have demonstrated that the experimental investigation of the thunderstorm neutron flashes is in principle possible. We also assume that the experimental study of this phenomenon can be effective with the involvement of aviation and, possibly, can be undertaken at the orbital altitudes in space experiments. Being ultimately related to the physics of RRAE the neutrons from thunderstorms can carry an additional opportunity to study TLE, TGF and thunderstorm activity in general.

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