Interrelation between energy and time distributions of high-energy electrons during the observation of the particle bursts in the near-Earth space

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Abstract. Many satellite experiments showed interrelation between changes of particle fluxes in the near-Earth space and various magnetospheric and geophysical phenomena. In this report we focus on temporal and energy characteristics of bursts of high-energy electrons in the inner zone of the Earth’s magnetosphere ($L<2$). In order to study the variations of electron characteristics during the observation of the bursts, caused by local disturbances of the radiation belt (e.g. lightning or seismic events), numerical modelling the propagation of particle cloud formed by electrons, precipitated from radiation belt, has been carried out. It was shown a relationship between energy distribution and temporal profile of electrons of burst in case of their local precipitation. The results of simulation are analyzed and compared with the data obtained in ARINA and VSPLESK satellite experiments.

1. Introduction
High-energy electron bursts in the near-Earth space have been actively studied for the past 20 years. According to completed studies most of the particle bursts have shown to have geophysical origin and are associated with seismic and thunderstorm activities [1-9]. It is necessary to mention a number of satellite experiments: MARIYA, MARIYA-2 [1,2], DEMETER, PET/SAMPEX, POES, ARINA and VSPLESK [10-16], which are aimed to study electron bursts and geophysical effects causing them.

Physical model of electron burst formation is the following. Low-frequency electromagnetic emission is known to be generated a few hours prior to powerful earthquakes in their epicentres and above them. Propagating through atmosphere and ionosphere, it may cause the local disturbance of electron trajectories in the radiation belt (RB), making electrons to precipitate below RB into altitudes of low Earth orbital (LEO) satellite. The formation (cloud) of precipitated particles drifts along $L$-shell around the Earth if the altitudes of their local mirror points higher than ~100 km [17]. The disturbance envelopes entire $L$-shell with time period of longitudinal drift. For high-energy particles this time is ranging from a few dozens of seconds to several minutes. When a LEO satellite crosses the disturbed $L$-shell, on-board particle instruments detect a sharp short-term increase in particle flux (a particle burst). In this case the $L$-shell parameter of bursts coincides with the $L$-coordinate of the local RB disturbance. In fact, as shown in [2, 4, 14], study of particle burst characteristics gives the possibility to determine the location of RB disturbance and thus to search for the place of geophysical event (thunderstorm or earthquake).

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Two experiments ARINA and VSPLESK are important to be distinguished from the others, because their acceptance are more than an order of magnitude than acceptance of instruments in other satellite experiments. It allows to identify weak bursts, and thus to increase the number of detected bursts. The ARINA and VSPLESK experiments are carried out on board the low-orbit spacecrafts. The ARINA instrument operates on board of Resurs-DK1 satellite with an altitude of 350-600 km and an orbit inclination of 70° since 2006[18]. The VSPLESK instrument measurements were carried out from 2008 to 2013 on the International Space Station (altitude is 350-400 km, orbit inclination is 51°) [14].

2. Numerical simulation of electron burst formation

As it was described above, the part of precipitated particles drifts along the L-shell around the Earth. Longitudinal drift velocity of particles depends on their energy. The average drift period (i.e., the time required to perform a complete rotation around the Earth) is [19]

\[ T_{dr}^{\text{earth}} \approx K_1 \frac{(1+\varepsilon)}{\varepsilon} \cdot \frac{K_2}{L} \]

(1)

where \( \varepsilon \) is the ratio of the kinetic energy of the particle to its rest energy, \( L \) – drift shell coordinate. In this work we used \( K_1 = \frac{4\pi}{3} \cdot \frac{Ze^2}{m_0 c^2 r_0} \) where \( M \) – the Earth's magnetic dipole moment, \( m_0 \) – mass of the particle, \( Z|e| \) – electric charge of the particle, \( r_o \) – distance from centre of the Earth. \( K_2 \) - the ratio of the drift period for particles with their mirror points at \( \varphi_m \) to that for particles moving in the equatorial plane only. The quantity of \( K_2 \) depends on latitude of a particle's mirror point \( \varphi_m \), it varies from 1 to 1.5. \( K_2 = 1.0 \) as it is on geomagnetic equator.

Particle drift time \( (T_{dr}) \) from the precipitation region to the place of registration of particles by a satellite is defined by the formula (2),

\[ t_{dr} = T_{dr}^{\text{earth}} \cdot \frac{\Delta \lambda}{360} \]

(2)

where \( \Delta \lambda \) is the longitudinal distance passed by the particle, \( \Delta \lambda \) – in degrees. A drifting cloud of precipitated electrons contains the particles with various energies. Their energy spectrum is defined by interaction processes resulting to precipitation of electrons. In this work spectrum was set by power function \( E^\gamma \). Simulation of processes of electron cloud propagation and its registration by satellite, basing on the Monte-Carlo technique, include the following assumptions. The number of precipitated electrons, space position of particle precipitation zone and satellite orbit are given. The trace of each electron of the cloud from region of precipitation to place of its registration by satellite is calculated. RB disturbance is local. Particle precipitation from RB occurs instantaneous, it means that the time of precipitation \( (\Delta t_{pr}) \) is much less than longitudinal drift time \( (\Delta t_{dr}<<t_{dr}) \). The energy range 3–30 MeV was chosen for simulation to compare its results with ARINA and VSPLESK experimental data, which have such energy range. Period of the longitudinal drift for electrons in this energy range is in the frame of 2-20 minutes. The spectrum of precipitated electrons is defined by power function \( E^\gamma \), with \( \gamma = 3.0 \), as it is observed in ARINA experiment [20]. Width of disturbed L-shell was taken \( |\Delta L| = 0.07 \) [5]. Under this condition the satellite crosses disturbed L-shell for 2-5 minutes in dependence on L value. Albedo electrons form background flux, which is taking into account in modeling. By tracing the motion of each electron, various statistical distributions of drifting cloud particles were evaluated. In particular, time profile and energy spectrum of a particle burst were analyzed.

Figure 1 is presented an example of temporal profile of simulated burst of electrons. Such shape of profile can be observed, if the satellite could be fixed in space at given place of disturbed L-shell. Longitudinal distance \( \Delta \lambda \) between precipitation zone and place of burst registration by satellite, width \( (\Delta L) \) disturbed L-shell has influence on total burst duration. In particular, the burst duration of a cloud of electrons passing 180° longitudinal distance to the registration point will be about 12 minutes. But in a reality the satellite moves and crosses fast the region of a drifting electron cloud less than several
minutes [21]. In this case only a small part of cloud electrons can be registered by satellite. Figure 2 shows the modeling burst of electrons for crossing of disturbance $L$-shell by satellite.

**Figure 1.** Temporal profile of an electron burst in ideal observation conditions for immovable satellite approximation (simulation result, $L=1.2$, $\Delta \lambda=180^\circ$, $T=0$ - electron burst registration start time).

**Figure 2.** Temporal profile of an electron burst observing by orbiting satellite (simulation result, altitude 600km, inclination 70°, $L=1.2$, $\Delta \lambda=180^\circ$, $T=0$ - electron burst registration start time).
In this work time profiles and electron distributions in $E$-$t$ space for their various simulation parameters ($L$, $\Delta \lambda$, $\gamma$) were calculated. Analysis of the simulation results and their comparison with the experimental data is convenient to analyze in a two-dimensional energy ($E$) and time ($t$) space. The $E$-$t$ distribution of albedo electrons is shown in Figure 3 [22], as you may see there is no correlation between electron energy and its registration time by instrument on board of the satellite. However, in case of burst particles their drift period is known to be dependent on their energy (1). Difference in particle drift velocity for different energies lead to expansion of particle cloud along the $L$-shell.
Evaluations show that the particles of burst can be well distinguished from background albedo particles (Figure 4) because high-energy burst electrons are registered on satellite first, and group along the line which is defined by formula (2). Also it necessary to take into account that there is no accurate way to separate burst electrons from background albedo particle flux at the end of the burst.

3. Events selection criteria and experimental data analysis
The results of numerical simulation allowed developing basic criteria for burst selection in experimental data in order to plot time and energy distributions of particle bursts, their relationship with location of RB disturbance.

ARINA and VSPLESK experiments have collected database of several hundred electron bursts. A few bursts being of interest for correlation analysis E-t distributions were found in experimental data. As an example, in Figure 5 an electron burst observed with the ARINA instrument in August 24, 2009 (29° N, 2° E, L=1.55) lasting about a minute is shown. Not high statistic in case of real experiment did not allow to plot E-t diagram like in Figure 4. So it is necessary to calculate the average time of registration electrons for each energy channel of ARINA instrument. This E-t plot for the burst is presented in Figure 6. The free parameter (Δλ) of curve function (2) is longitudinal distance between location of RB disturbance and position of burst registration on board of satellite. The moment of particle precipitation is unknown in experiment, but the method only depends on characteristics of differential change of registered particles energy in time, so we selected the time t₀ = 0 to be the beginning of the burst and introduced additional free parameter t_{off} - time offset between start of burst registration and some unknown time of particles precipitation. An approximation curve on Figure 6 connecting particle registration time with its energy was obtained by regression analysis (ordinary least squares) [23].

![Figure 5. E-t electron registered distribution during the burst (the 24th of August, 2009) (29° N, 2° E, L=1.55).](image-url)
Figure 6. $E$-$t$ electron distribution for the burst. (the 24$^{th}$ of August, 2009) (29$^{o}$ N, 2$^{o}$ E, $L=1.55$)

Figure 7 shows electron burst (marked with a black square on the Northern Africa), $L$-shell (grey line in the southern and northern hemispheres), which corresponds to the burst registration location and two estimated magnetically conjugated RB disturbance regions (marked in grey). One of them contains a part of the Mid-Atlantic ridge [24] and the other one includes region with high thunderstorm activity in South America [25]. Its relatively large size is defined by instrument characteristics (acceptance defines low particle statistics, and instrument energy resolution defines time of registration errors, etc.) and the width of disturbed $L$-shell where the burst was registered.

Figure 7. Black square (1)– location of electron burst registration (29$^{o}$ N 2$^{o}$ E) August 24, 2009, grey bands (2) – estimated places of particle precipitation, grey line (3) – $L$-shell (1.55), corresponding to the burst registration location.
4. Conclusion
Time and energy characteristics of high-energy electron bursts generated by the local RB disturbance of geophysical origin have been studied by numerical simulation of electron propagation in the magnetosphere. The possibility to determine RB disturbance region by measuring variation of particle energy distribution in time during the burst observation was examined.

The analysis of the electron burst obtained by ARINA experiment on the 24th of August, 2009 over the Northern Africa region was carried out. Using simulation results for this burst the magnetically conjugate regions of local RB disturbance were determined. Both of them are geophysically active. The north zone contains seismic Mid-Atlantic tectonic ridge, and another one is the region in South America characterized by heavy lightning activity.

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