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SHORT COMMUNICATIONS

Results of Monitoring Variations of Absorbed Dose Rate onboard the *International Space Station* during the Period 2005–2011

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The radiation control system (RCS) almost continuously operates on the service module of the *International Space Station* (*ISS*) since August 2001. The data obtained with its help are used to estimate daily the radiation environment onboard the station. Variations of the absorbed dose rate onboard *ISS* can be caused by three sources [1–3]: solar proton events, galactic cosmic rays (GCR), and the Earth's radiation belt (ERB). In this paper, we consider the contribution of protons of the Earth's radiation belt to the variation of absorbed dose rate onboard the station in the period 2005–2011.

Equipment. The radiation control system, whose data are under analysis, has been described in several papers [4–6]. The RCS includes: dosimeter R-16, four dosimetric units DB-8, and two units of digital data processing. In this paper, we consider the results obtained with the dosimetric units DB-8 with silicon semiconductor detectors as sensitive elements. As was noted in [6], the unit DB-8 no. 1 is the least shield. It is located at the *ISS* Service Module in a compartment of small diameter in the region of the Central post. The most shielded unit is the unit DB-8 no. 4 located in the *ISS* Service Module in a compartment of large diameter in the region of work table. The data of these units is considered below in this paper. The RCS measurement results are accumulated in units of digital data processing and transmitted to the Earth by the *ISS* telemetry system.

Data processing method. Functioning of the radiation control system on the *ISS* allows one automatically to determine the beginning and the end of zones of increased radiation, as well as the total dose accumulated during this time. Moreover, the dose rate and particle flux density are recorded in the region of increased radiation with a time resolution of 10 s.

By this means, the telemetry data received from the RCS allow one to determine both the detailed distribution of the dose rate while passing the South Atlantic Anomaly (SAA), and the dose accumulated in a single intersection of the increased radiation region. As parameters characterizing the trajectory, along which *ISS* intersects the SAA region, we have chosen the point of intersection of latitude of –30° specified by the longitude and altitude of passing through this point, as well as by the direction of motion from north to south or vice versa. A part of the trajectory characterized by motion from south to north is designated as ascending, and from north to south as descending. The RCS telemetry data processing together with the ballistic data allows us to associate a numerical value of the absorbed dose for each of the SAA passages with time instant and geographical coordinates, which *ISS* had when intersecting the latitude –30°, which we further designate as the reference latitude.

Off-line processing of the *ISS* RCS data was performed using the specialized software package written in visual programming National Instruments LabView 8.2 (http://www.ni.com/labview/).

Results. Off-line processing of the *ISS* RCS data was performed for the time interval from July 1, 2005 to November 30, 2011.

The results of processing are shown in Fig. 1 as a dependence of the dose recorded by the DB-8 units in a single pass of SAA versus the longitude of intersection by the station of reference latitude 30° south . One can see a very large scatter of recorded readings of the detectors. We assume that this scatter is due to a considerable range of altitudes of passing the SAA region by the *International Space Station*. In order to eliminate this effect, it was decided to divide the entire range of altitudes, at which the intersection by *ISS* of reference latitude 30° south occurred, into the following intervals: 320–330 km, 330–340 km, 340–350 km, 350–360 km, 360–370 km, 370–380 km, 380–390 km, 390–400 km, 400–410 km, and 410–420 km, and to perform the appropriate partitioning (corresponding to these altitude ranges) of experimental

Table

Descending orbits		Ascending orbits	
The worst shielded detector DB-8 no. 1	The best shielded detector DB-8 no. 4	The worst shielded detector DB-8 no. 1	The best shielded detector DB-8 no. 4
$k = 0.0015$ $b = 0.028$ $\lambda_m = -46.34$ $\sigma = 12.41$	$k = 0.00073$ $b = 0.0079$ $\lambda_m = -46.55$ $\sigma = 12.13$	$k = 0.00066$ $b = 0.0038$ $\lambda_m = -43.06$ $\sigma = 16.5$	$k = 0.00032$ $b = 0.00088$ $\lambda_m = -47.06$ $\sigma = 15.95$

dependences of doses received by *ISS* in the SAA in one passage on longitude of the *ISS* passage of the reference latitude. Thus performed data partitioning significantly reduced the scatter. As a result, bell-shaped longitude distributions were obtained. For some ranges of altitudes in the same plot, several bell-shaped distributions describing the experimental data could be distinguished. The obtained distributions were approximated by a function of the form:

$$f(\lambda) = A\exp[-(\lambda - \lambda_m)^2/2\sigma^2], \qquad (1)$$

where A, σ are numerical coefficients, λ is longitude, λ_m is the longitude, where this approximating function reaches its maximum numerically equal to A.

For the case, when several experimental bell-shaped distributions could be singled out in the same plot, the approximation was carried out by several functions $f(\lambda)$ using the numerical parameters differing for the different experimental distributions. An example of the obtained approximation results for the altitude interval of 360–370 km is shown in Fig. 2.

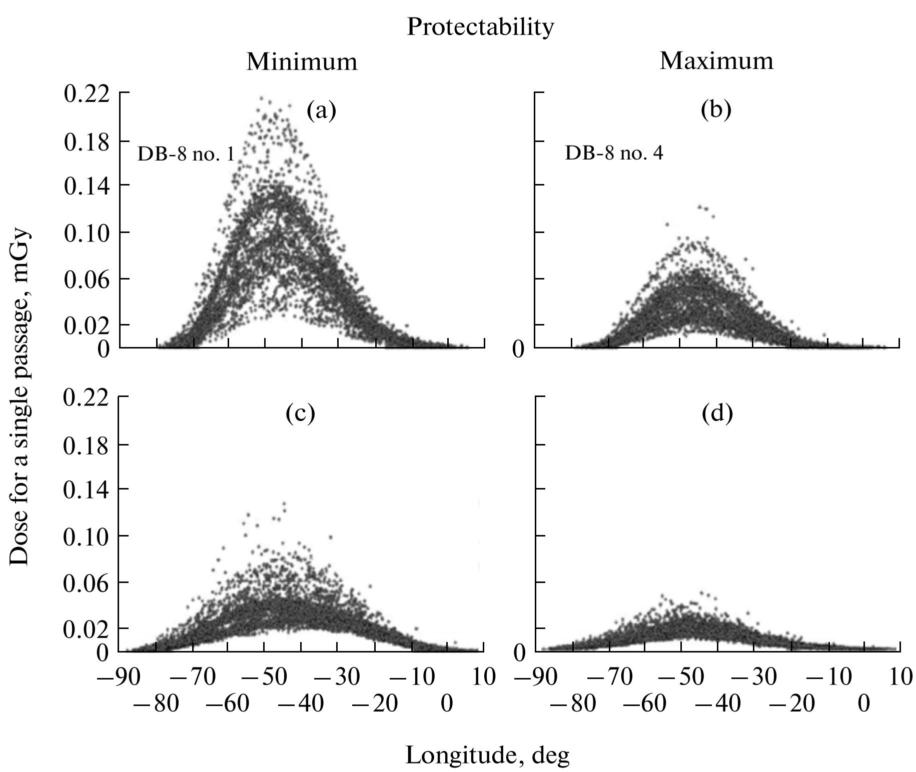

Fig. 1. The dose obtained by *ISS* in the region of SAA for a single passage versus longitude of the *ISS* intersection of the reference latitude for descending orbits (a, c) and ascending orbits (b, d).

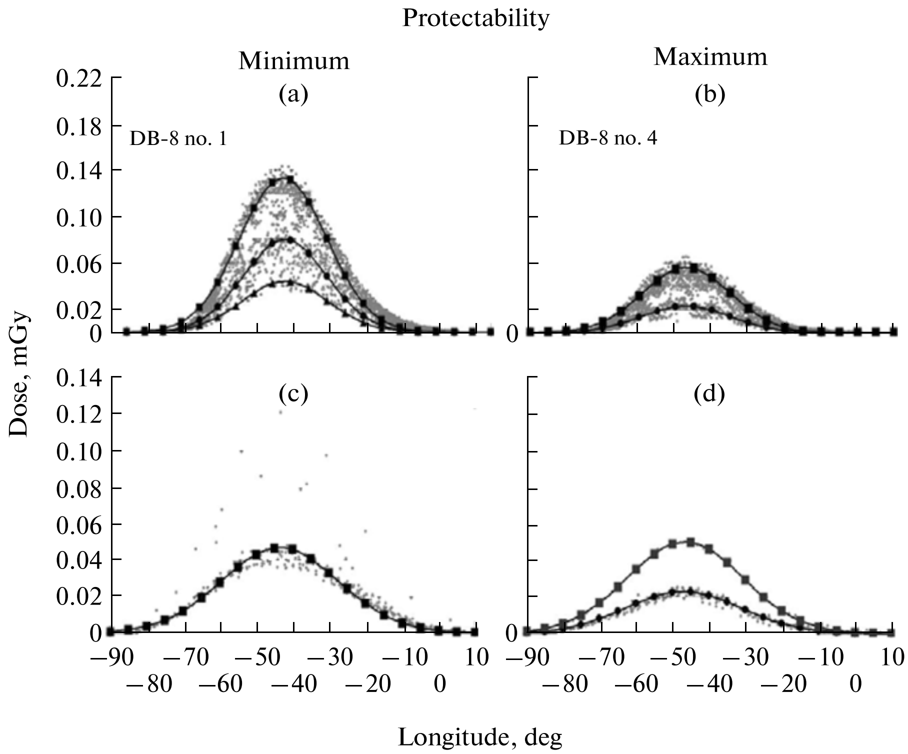

Fig. 2. The result of approximation of empirical dependences of absorbed dose in SAA on longitude of the *ISS* intersection of the reference latitude.

Further on, we have constructed dependences of coefficient A, which characterizes the maximum of approximation function $f(\lambda)$, on the altitude, at which *ISS* was located when intersecting the reference latitude. The results are shown in Fig. 3. For the cases, when several experimental bell-shaped distributions with different coefficients A were singled out for the same altitude range, on the plots of dependences of coefficient A on altitude of *ISS* intersection of the reference latitude all these values were displayed for the corresponding altitude range. The dependence of coefficient A on the altitude of *ISS* intersection of the reference latitude was approximated by a linear function of the form:

$$A(h) = k(h - h_0) + b, \tag{2}$$

where k and b are numerical coefficients, h is altitude (in kilometers) of *ISS* intersection of the reference latitude, and h_0 is the minimum altitude equal to 300 km.

Practically for all altitude ranges for ascending or descending orbits it was found that there were several (2 or 3) values of coefficient A corresponding to different bell-shaped distributions, as it is shown, for example, in Fig. 2a. In this case, for further analysis, the values of parameter A showing the best correlation with the straight line were selected.

From thus obtained sets of points (A, h) the coefficients of approximating straight lines were calculated by the least squares method. The values of coefficients are presented in Table. It turned out to be possible to select the same values of coefficients λ_m and σ in formula (1) for all altitude ranges, but different for descending and ascending orbits, and also for the most and least shielded detector units. The obtained values are also presented in Table.

Using formulas (1) and (2) together with coefficients from Table, we have obtained an empirical dose dependence for each *ISS* passage of the SAA region as a function $D_{emp} = f(h, \lambda)$ (the function of altitude and of the longitude of *ISS* intersection of the reference latitude 30° south). This allowed us to compare measured values of absorbed dose rate for each of the *ISS* passages of the SAA region (D_{exp}) with corresponding calculated values of function D_{emp}. The time dependence of obtained ratio D_{exp}/D_{emp} is shown in Fig. 4.

It can be seen that most points are clustered near a certain region varying with time in the range of values D_{exp}/D_{emp} from 0.5 to 1.5. However, many points deviate from this region rather strongly. The performed analysis has shown that the largest deviations are observed at the edges of bell-shaped distributions at the largest differences between λ and λ_m.

In order to reduce the influence of this effect, an analysis was performed for the central part of the SAA, the most significant from the standpoint of the dose recorded on the *ISS*. We selected the longitude range $-50 < \lambda < -30$. The corresponding dependence D_{exp}/D_{emp} is shown in Fig. 5.

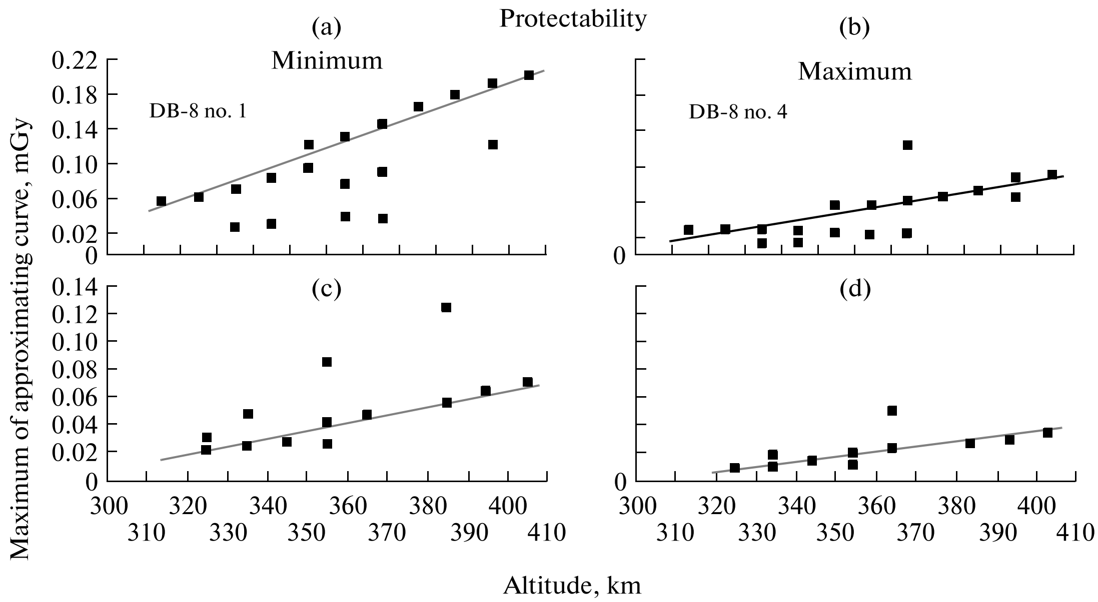

Fig. 3. The dependence of parameter *A* on altitude of the *ISS* intersection of the reference latitude.

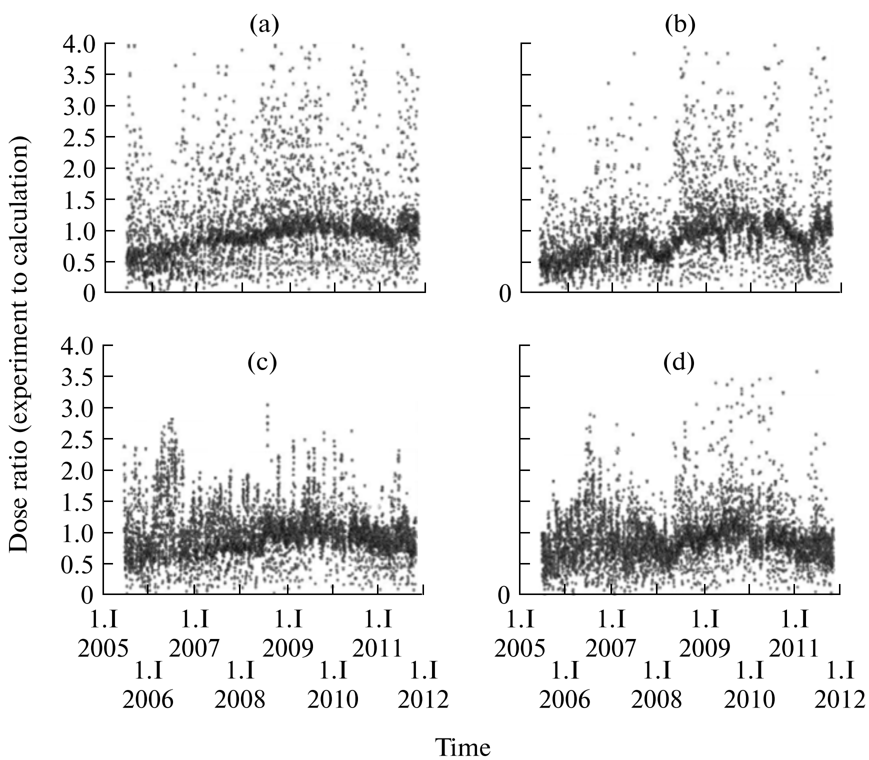

Fig. 4. The dependence of the ratio of experimental absorbed dose for the passage of the SAA region to the calculated one.

One can see that the scatter of data significantly decreased, which indicates to more stable values of proton fluxes in the central SAA zone in comparison with its peripheral regions. Separate groups of points outlying from the general sequence are associated with periods of joint flights of the *ISS* with *Space Shuttles*. This effect is analyzed in [7–10], and further it is not considered here.

There are also variations of the mean ratio D_{exp}/D_{emp} with time, but the scatter of points within a

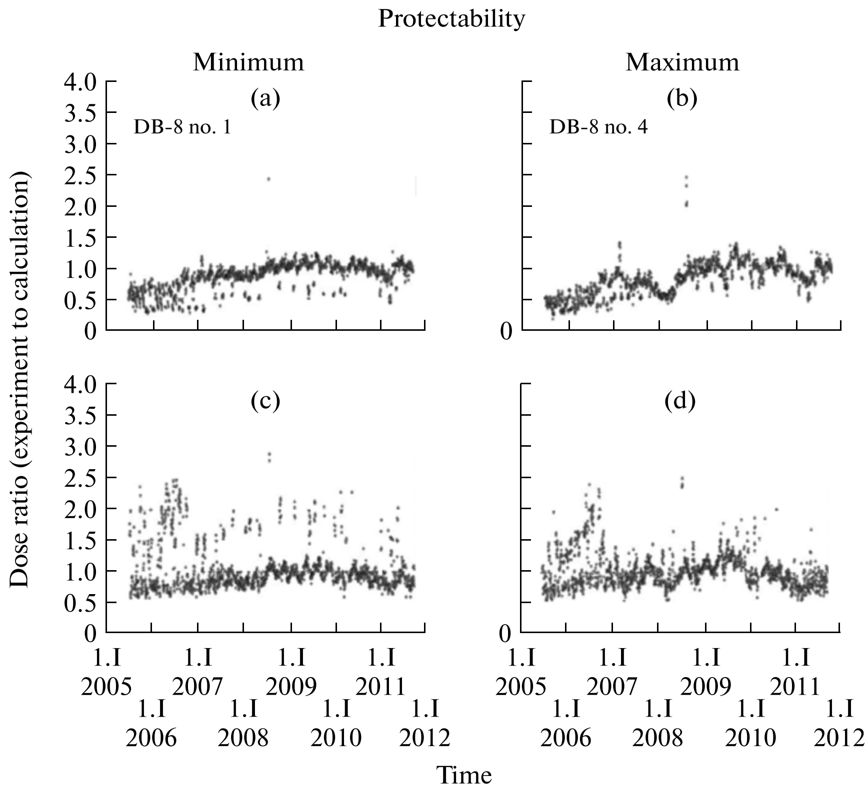

Fig. 5. The dependence of the ratio of experimental absorbed dose for the passage of the SAA region to the calculated one after isolating in longitude the central part of the SAA region.

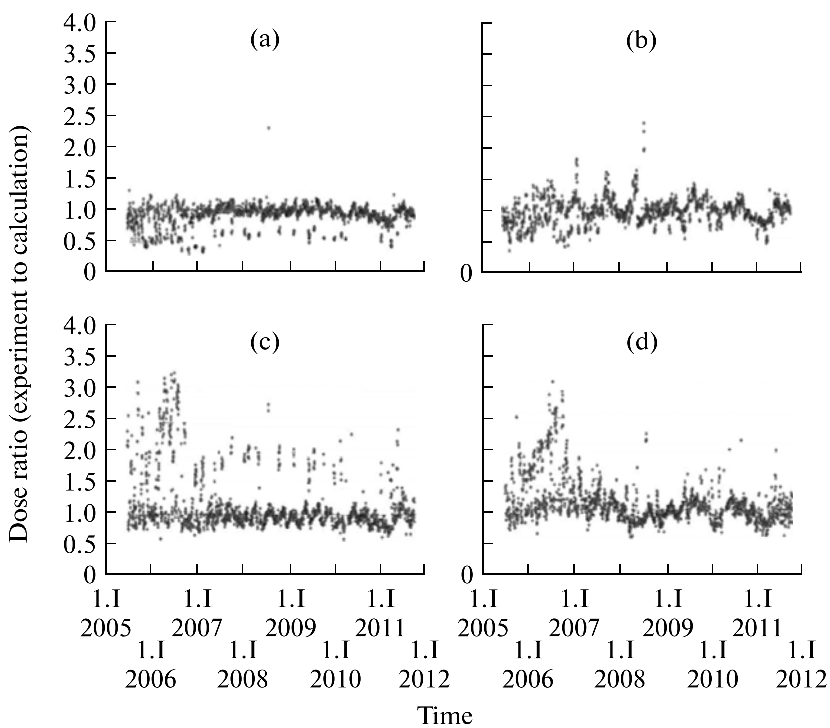

Fig. 6. The same dependence as in Fig. 5 after fitting coefficients in formula (2).

small (2–3 months) time period does not exceed 20–30%. This suggests that variations in the dose rate for different trajectories (within the selected longitude range) and different altitudes of the SAA passage occur proportionally. One can assume that the parameters k and b defining the altitude dependence of amplitude A of the bell-shaped dose distribution in a single pass of SAA characterize the degree of population of the Earth's proton radiation belt at low altitudes and can be used to verify the corresponding model descriptions. Variations of the ratio $D_{\text{exp}}/D_{\text{emp}}$ can be interpreted as variations of parameter A characterizing the state of the lower zone of the Earth's inner radiation belt.

We have made an attempt to take into account this effect by introducing for formula (2) different values of coefficients k and b for different time intervals (6 time intervals were selected in total). This made it possible to obtain the time dependence of the ratio $D_{\text{exp}}/D_{\text{emp}}$ presented in Fig. 6, which show that the ratio $D_{\text{exp}}/D_{\text{emp}}$ is close to 1 (for example, in case of the least shielded detector unit DB-8 no. 1 the characteristic deviation of the measured dose values from the calculated dose does not exceed 20%).

This confirms the assumption that the parameters of the linear approximation of the altitude variation of coefficient A in formula (1) characterize the population of the Earth's proton radiation belt at low altitudes, and it makes sense to look for variations in these parameters in connection with characteristics of heliogeophysical situation.

CONCLUSIONS

The analysis of data of the radiation control system for *ISS* from 2005 to 2011 is performed. We have considered in detail the contribution to the absorbed dose on *ISS* due to protons of the Earth's radiation belt penetrating into the station flight altitude in the region of the South Atlantic Anomaly. The empirical rations are obtained that allow us to calculate the dose rate for a single intersection of the SAA zone. The input parameters for calculation are the longitude and altitude, at which the *ISS* trajectory intersects the SAA. The typical deviation of measured values from the calculated doses does not exceed 20% (for the DB-8 unit, which has the least protection.)

The obtained empirical relations can be useful when comparing with model descriptions of the Earth's radiation belt at low altitudes, as well as when developing new variants for short-term forecasting procedure of radiation environment on the *ISS*.

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