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Radiation Aspect of Two Orbit Inclination Options of the *Russian Orbital Service Station*

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Abstract—The contribution to the effective dose from cosmic radiation of the Earth's radiation belts, galactic cosmic rays, and solar proton events for astronauts located in the large-diameter working compartment of the service module of the *ISS* is considered. It is shown that for quasi-stationary sources of cosmic radiation, a change in the orbital inclination of 51.6° by 97.0° does not lead to significant variations in the average daily effective dose rate. When considering the contribution to the effective dose from solar-flare protons, the dose load on astronauts can increase by ten or more times.

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INTRODUCTION

Prospects for the creation of the *Russian Orbital Service Station* (*ROSS*) are being discussed among space-industry professionals. In this case, two variants of the orbit inclination are considered: 51.6° and 97.0°. Regarding the second option, in an interview with the *Russian Space Journal*, D.O. Rogozin stated, "Of course, such an orbit implies a higher level of radiation, and this will affect the duration of the flight of the expeditions" (https://www.roscosmos.ru/media/pdf/russianspace/rk2022-01-single.pdf).

Let us see if this statement is true.

METHODOLOGY

The highest average daily effective dose rate for the *ISS* was recorded in August–September 2020. The average altitude of the *ISS* orbit at that time was H_{av} = 424.0 ± 1.6 km, and the average value of the A_{p} index was 10.1 ± 6.7. For this period, calculations of dose loads on astronauts were performed when they were in the large-diameter working compartment (LDWC) of the service module (SM) of the *ISS* during the flight of the station in orbit with an inclination of 51.6° and 97.0°.

According to the current standards for ensuring radiation safety (RS) [1], to control the levels of radiation exposure to astronauts, it is necessary to use the value of the effective dose, which, according to RS ground-based standards [2], is defined as

$$E = \sum_T W_T H_T, \tag{1}$$

where H_T is the equivalent dose in the organ or tissue T,

$$H_T = \frac{1}{N}\sum_{i=1}^{N} H(r_i); \tag{2}$$

N is the number of points in the organ, for which the calculation is carried out; and W_T is the weighting factor for an organ or tissue T (Table 1).

According to [3], the absorbed dose at point r_i of organ T is calculated by the formula

$$D_T(r_i) = \int_0^\infty D(\xi)\omega_T(\xi, r_i)\, d\xi, \tag{3}$$

where $D(\xi)$ is the specific dose at depth ξ and $\omega_T(\xi, r_i)$ is the screening function of point r_i in organ T:

$$\omega_T(\xi, r_i) = \frac{1}{4\pi\Delta\xi}\int_{4\pi} \eta(r_i, \Omega)\, d\Omega, \tag{4}$$

where $\eta(r_i, \Omega)$ is unit function on the interval from ξ to $\xi + \Delta\xi$.

The screening function of a selected point inside the object under consideration is understood as the probability-density function of encountering a thickness of the protection in the range from X to $X + dX$ in any direction from the considered point. Shielding functions are calculated in accordance with the State Standard [4]. The results of [5, 6] are used as a model of the human body (phantom), and the results of [7] are used as the *ISS* model. Equivalent dose H included in equality (1) is related to absorbed dose D in expression (2) by a simple relation:

$$H = D \times QF, \tag{5}$$

where QF is the quality factor.

Table 1. Number of points in organs and tissues N and weighting coefficients W_T for determining the effective dose

No.	Organ	W_T	N
1	Gonads	0.20	11
2	Bone marrow (red)	0.12	14
3	Large intestine		10
4	Lungs		36
5	Stomach		15
6	Bladder	0.05	7
7	Breast		2
8	Liver		19
9	Esophagus		3
10	Thyroid gland		
11	Skin	0.01	2
12	Cells of the bone surfaces		34
13	Lens of the eye	0.007	2
14	Central nervous system		3
15	Heart		7
16	Left kidney		
17	Right kidney		
18	Spleen		6
19	Rectum		7

In this study, we used the following dependence of the quality factor on linear energy transfer of charged particles in matter $S(E)$ in MeV cm^{-1}:

$$QT = \left.\begin{array}{ll} 1.0, & S(E) \leqslant 35, \\ 0.02858S(E) & 35 \leqslant S(E) \leqslant 70, \\ 7.31 \times 10^{-2} S(E), & 70 \leqslant S(E) \leqslant 230, \\ 4.9 \times 10^{-2} S(E)^{0.848}, & 230 \leqslant S(E) \leqslant 530, \\ -42.53 + 19.28 \ln S(E), & 530 \leqslant S(E) \leqslant 1750, \\ 20.0, & 1750 \leqslant S(E). \end{array}\right\}$$

We substitute expressions (3) and (5) into equality (1) and, using the linearity of expression (1), change the order of integration and summation. As a result, we express the effective dose as

$$E = \int_0^\infty H_{\text{eff}}(\xi)\omega_{\text{eff}}(\xi, r_i)\, d\xi, \qquad (6)$$

where $\omega_{\text{eff}}(\xi, r_i)$ is the shielding function for calculating the effective dose:

$$\omega_{\text{eff}}(\xi, r_i) = \sum_T W_T \omega_T(\xi, r_i). \qquad (7)$$

With this approach, the certainty of a particular point is lost, but the need to calculate the radiation effect on each organ is eliminated. The shielding functions of various organs were calculated for four spatial orientations of the phantom: forward, backward, left, and right. For each spatial orientation, a different number of points were used in accordance with Table 1. At the same time, in the calculations of the shielding functions of the red bone marrow, its percentage at various points was taken into account.

The partial contributions to the effective dose from electrons and protons of the Earth's radiation belts (ERBe and ERBp) [4, 8] and from galactic cosmic rays (GCRs) [9] were determined. No solar proton events (SPEs) were recorded in the period under consideration. The results of [10], in which the standards were modified [11, 12], were used as models of ERB particle fluxes. As a model description of the spectral distributions of GCR charged particles, the representation for individual GCR groups from [13] is used. At the same time, proton fluxes with energies of more than 100 MeV were normalized to the experimental values obtained on *Geostationary Operational Environmental Satellite* (*GOES*) satellites (geostationary operational satellites for monitoring the environment, http://www.swpc.noaa.gov/). Geomagnetic disturbances were taken into account according to the data of http://wdc.kugi.kyoto-u.ac.jp/dst_realtime/.

RESULTS AND DISCUSSION

The results of calculations of the absorbed and effective doses are presented in Table 2.

It follows from the analysis of the results of Table 2 that the effective dose rate in microsieverts per day changes little—when moving from an orbital inclination of 51.6° to an orbital inclination of 97.0°, by only 1–2%. At the same time, the absorbed dose rate in microgray per day changes by 15–17%. This difference can be explained by looking at the *ISS* flight paths for both variants of orbit inclination in Fig. 1.

It follows from consideration of Fig. 1 that with an orbit inclination of 51.6°, the total time that the *ISS* SM stays in the South Atlantic Anomaly (SAA) zone is approximately 150 min/day; and with an orbit inclination of 97.0°, it is about 100 min/day. In the SAA zone, a contribution from ERB protons is formed, which is practically proportional to the time spent in it. The contribution to the effective dose from GCRs is formed mainly in the region of the polar caps. This contribution to the absorbed dose rate in microgray per day increases by ~12%, but this increase is not enough to compensate for the decrease in the contribution to the absorbed dose from ERB protons. The same increase almost completely compensates for the decrease in the contribution of ERB protons to the effective dose rate per megasievert per day. The opposite picture is observed for electrons. For an orbit with an inclination of 97.0°, the contribution from electrons of the outer electron ERB becomes more significant, but in absolute value it remains very small.

As was noted in [14], "at present, there is no unified analytical model for describing the behavior of electrons in the outer radiation belt of the Earth, therefore, for a specific event, it is impossible to predict the expected dynamics of electron fluxes based on

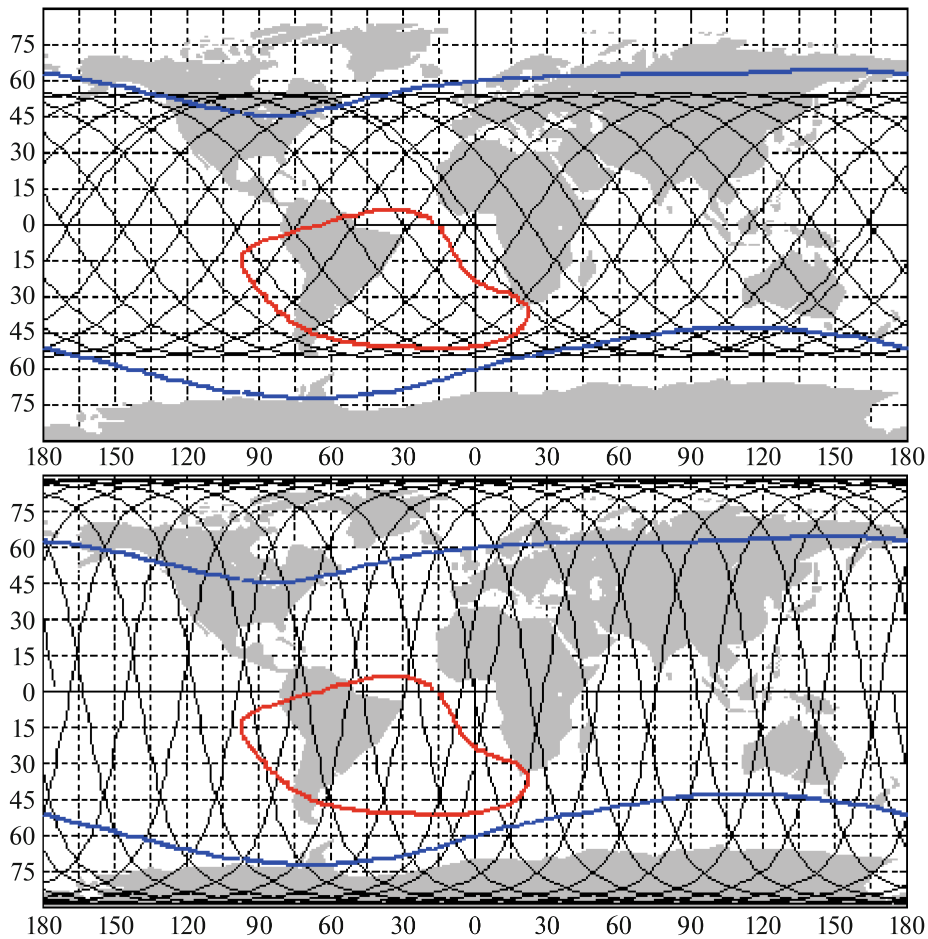

Fig. 1. Flight paths of the *ISS* SM for an orbital inclination of 51.6° (top) and for an inclination of 97.0° (bottom). The curve in the center of figures denotes the isoline of constant magnetic intensity $B = 0.24$ G, which approximately corresponds to the boundaries of the SAA of the inner ERB. The curves in the upper and lower parts of figures indicate isolines $L = 3.0$, which approximately correspond to the boundaries of the outer electron ERB.

the proposed mechanisms of acceleration and transportation." It is possible that the use of the electron model according to [12] is not always correct, especially in the case of geomagnetic disturbances. However, as noted above, during the considered period of time, the geomagnetic situation was quite calm, and the value of the A_p index was 10.1 ± 6.7.

A different picture emerges for solar proton events (SPEs). The largest SPE for the entire period of *ISS* operation occurred on October 28, 2003, in a series of flares over the period of October 26–November 6, 2003. The flux of protons with energies above 30 MeV for the entire event of October 28, 2003, was 3.1×10^9 protons/cm^2.

Table 2. Partial contributions to the dose received by astronauts while they are in the *ISS* SM LDWC

	Orbit inclination of 51.6°				Orbit inclination of 97.0°			
	Absorbed dose, μGy/day							
2020	ERBe	ERBp	GCRs	Σ	ERBe	ERBp	GCRs	Σ
August	0.6	193.2	107.5	301.4	1.0	130.0	126.7	257.8
September	0.7	187.0	107.6	295.3	1.1	128.8	127.3	257.2
	Effective dose, μSv/day							
2020	ERBe	ERBp	GCRs	Σ	ERBe	ERBp	GCRs	Σ
August	0.6	237.5	503.8	742.0	1.0	159.9	563.9	724.8
September	0.7	229.3	503.2	733.1	1.1	158.0	564.6	723.6

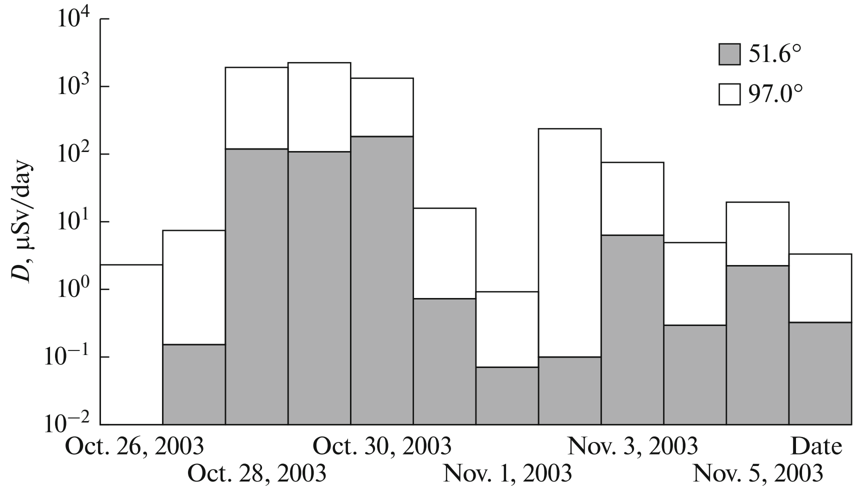

Fig. 2. Dynamics of the effective dose for the astronaut in the *ISS* SM LDWC. Shaded histogram for orbital inclination 51.6°; transparent histogram for orbital inclination 97.0°.

The effective dose for astronaut in LDWC from all proton flares of the period under consideration at an orbit inclination of 51.6° was 407.5 μSv. For an orbital inclination of 97.0°, the effective dose increased by about 14 times and was 5761.7 μSv. It should be noted that, even for the SPE on November 4, 2003 (the flux of protons with energies above 30 MeV was 3.1×10^7 protons/cm), for the 51.6° orbit, the effective dose was only 3 μSv, but this dose increases up to 27 μSv for the 97.0° orbit. The dynamics of the effective dose for both variants of the orbit inclination is shown in Fig. 2.

Specific values of the effective dose are presented in Table 2. From the consideration of the results of Table 3 it follows that even for large SPEs, the established standards for ensuring radiation safety [1] will not be exceeded.

Table 3. Dynamics of contributions to the effective dose (in μSv/day) of astronauts during their stay in the *ISS* SM LDWC from the SPE series during October 26–November 6, 2003

	Orbit inclination of 51.6°	Orbit inclination of 97.0°
Oct. 26	–	2.2
Oct. 27	0.2	7.6
Oct. 28	115.5	1904.5
Oct. 29	103.7	2213.6
Oct. 30	177.8	1273.9
Oct. 31	0.7	15.9
Nov. 1	0.1	0.9
Nov. 2	0.1	243.9
Nov. 3	6.4	74.8
Nov. 4	0.3	4.9
Nov. 5	2.4	18.6
Nov. 6	0.3	3.3
Σ	407.5	5761.7

At the same time, it should be noted that in small modules of the *ISS*, the thickness of the protection is close to 1 g/cm^2. This means that the effective dose for astronauts in small modules will be significantly greater than for astronauts in the LDWC. It is noted in [15] that, beyond a shield thickness of 1 g/cm^2 of aluminum, the additional radiation risk is 55% of the demographic risk. With an increase in the shielding thickness to 20 g/cm^2, the radiation risk decreases to 14%. It follows from this that it is necessary to provide a radiation shelter with a shielding thickness of ~20 g/cm^2 at the *ROSS*.

A separate consideration is required to assess the radiation load on astronauts when conducting spacewalks and performing extravehicular activities (EVAs). As an example, one of the spacewalks in 2014 was considered. When conducting this spacewalk, the average orbit height was 424.7 km and the value of the A_p index was 5. When performing EVAs, the main attention from the effective dose shifts to the assessment of the equivalent dose to the skin (SK) [1]. The effective dose practically coincides with the dose to the hematopoietic system, and the average depth of which is 5 cm. For this depth, the contribution to the dose from electrons is practically insignificant. Table 4 shows the results of calculations of partial contributions to the equivalent dose to the skin from cosmic radiation sources during an EVA from the *ISS* in orbit with an inclination of 51.6° and with an inclination of 97.0°.

It follows from Table 4 that the dose from GCR radiation at an orbital inclination of 97.0° increases by 27%, the dose from ERB protons decreases by 17% and the dose from ERB electrons increases by almost six times. Particular attention during EVAs should be

Table 4. Partial contributions to the equivalent dose in μSv to the skin of astronauts during an EVA from the *ISS* in orbit with an inclination of 51.6° and with an inclination of 97.0°

	Orbit inclination of 51.6°	Orbit inclination of 97.0°
ERBe	103.2	131.1
ERBp	190.9	158.5
GCRs	27.2	164.1
Σ	321.3	453.7

paid to the state of the magnetosphere. After magnetic storms, precipitation of electrons from the outer ERB can occur, which can lead to a significant increase in the dose load on astronauts. In [16], T.P. Dachev notes that, even in the *ISS* orbit with an orbital inclination of 51.6°, the average absorbed dose rate behind the protection of 0.3 g/cm^2 from electrons in a quiet magnetosphere is 80–90 μGy/day. During periods of magnetic disturbances, such as on March 20–22, 2015, the average absorbed dose rate reached 2700 μGy/day.

CONCLUSIONS

During periods of minimum solar activity, when there are no spots on the Sun and, accordingly, there are no SPEs, the radiation situation on the *ROSS* will be practically the same as on the *ISS*.

During periods of maximum solar activity, it is necessary to provide a well-protected compartment as part of the *ROSS*, which should serve as a radiation shelter for astronauts.

When ensuring radiation safety of astronauts on the *ROSS*, the role of forecasting both solar-flare activity and magnetospheric disturbances increases significantly.

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CONFLICT OF INTEREST

The author declares to have no conflicts of interest.

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