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Результаты мониторинга радиационной обстановки на средней круговой орбите

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В данной статье описаны методы и средства измерений ионизирующего излучения космического пространства (ИИКП), проводимых с помощью экспериментального комплекса контроля дозы (ЭККД), расположенного на экспериментальном космическом аппарате (ЭКА) «Скиф-Д», который был выведен на орбиту Н=8070 км и наклонением 90°. Произведен сравнительный анализ результатов расчётов и экспериментальных данных, полученных в ходе летной эксплуатации за один год исследования. Следует отметить, что данная орбита для российских производителей КА с точки зрения воздействия факторов космического пространства (ФКП) является малоизученной. Основная идея измерений ЭККД заключается в создании различных условий массовой защиты для каждого из девяти модулей регистрации интегральной накопленной дозы (МРИНД).

При освоении нового типа орбиты для эксплуатации КА, актуальной является задача обеспечения стойкости бортовой аппаратуры и КА в целом к воздействию факторов ионизирующего излучения космического пространства, характерных на данной орбите. Для этого необходимо экспериментальное подтверждение или уточнение на базе полученных натурных данных расчётной радиационной модели воздействия.

Основной задачей, которая решается в статье, является проведение мониторинга уровней интегральной накопленной дозы за различными массовыми защитами при воздействии ионизирующего излучения космического пространства на орбите с Н=8070 км и сравнение результатов экспериментальных данных с расчётными оценками, проведенными по ОСТ134-1044-2007 изм. 1 (2017 г.).

Практическая значимость заключается в том, что экспериментальные результаты подтвердили расчётную модель. Получено экспериментальное подтверждение больших радиационных нагрузок в диапазоне типовых защит для ЭКБ 0,5–3 г/см², круговой орбиты с Н=8070 км по сравнению с орбитами ГСО и Н=1500 км. Модернизированные датчики МРИНД получили летную квалификацию и подтвердили свою эффективность в части выполнения задач мониторинга факторов ионизирующего излучения космического пространства.

Ключевые слова: космический аппарат, радиационные эффекты, ионизирующее излучение космического пространства, мониторинг радиационной обстановки, полупроводниковый чувствительный элемент.

Results of monitoring the radiation environment in medium circular orbit

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Problem definition – these data will form the basis for the development of technical solutions that will minimize mass, time and financial costs while ensuring the radiation resistance of on-board equipment and the spacecraft as a whole.

Goal – the experimental dose control complex measures the level of absorbed ionizing space radiation doses in the sensitive element, assesses the radiation effects influence on the spacecraft, determines spacecraft's residual radiation resource and refines impact models of the ionizing space radiation, located on an experimental spacecraft “Skif-D”, which was launched into orbit H=8070 km and inclination 90°.

Results – flight experiment demonstrated high convergence of the comparative analysis' results of the experimentally obtained impact levels in orbit of the operation of the “Skif-D” spacecraft with the impact model stated in the Russian Federation Scientific and Technical Documentation (OST134-1044-2007 amend.1 (2017) “Methods of the calculation of radiating conditions on-board of spacecrafts and specification of requirements for resistance of radio-electronic equipment of spacecrafts to the action of the charged particles from the space of natural origin”);

Practical value – successful modernization of the ICDRM integral accumulated dose sensors in terms of their miniaturization and transition to a digital output (flight qualification of the sensors was obtained); the prospects of the concept of monitoring the integral accumulated radiation dose using semiconductor detectors with individual mass protection; experimental confirmation of a higher radiation exposure in the range of typical protections for ECB equal to 0.5–3 g/cm², on a 8000 km circular orbit compared to the GEO and 1500 km circular orbit.

Keywords: spacecraft, radiation effects, factors of outer space, monitoring on-board equipment, semiconductor-sensing element.

Introduction

The development of the satellite constellation of the space system “Sphera” determined the need to develop a circular orbit with H ~ 8000 km. The first Skif-D spacecraft, launched on October 22, 2022, was launched into an orbit of H = 8070 km and an inclination of 90°. The results of its flight tests are planned to be used to deploy a standard orbital constellation of a broadband Internet access system.

This orbit for domestic spacecraft manufacturers from the point of view of the impact of space factors is little studied, in connection with this, monitoring the radiation situation [1–4] is the most important task, the solution of which will allow formulating requirements and ensure the resistance of the unmanned vehicle and spacecraft as a whole to the effects of ionizing radiation from space. It should be noted that currently only a small amount of information from the 03B satellites with H = 8063 km and an inclination of ~0° is available in open sources [5–7].

In order to clarify the levels of exposure to ionizing radiation from outer space, equipment for monitoring dose loads on the electronic component base was integrated on the Skif-D spacecraft of JSC Academician M. F. Reshetnev “Information Sattelite Systems” together with Novosibirsk State University. The information obtained from the equipment of the experimental dose control complex

(EDCC) will form the basis for clarifying the radiation situation, which will further help supplement existing research in various orbits [8; 9] and develop technical solutions to minimize mass, time and financial costs while ensuring the radiation resistance of on-board equipment and the spacecraft as a whole.

Description of the experiment

EDCC provides measurements of the levels of absorbed doses of ionizing radiation from outer space in the sensitive element and is intended to assess the influence of radiation impacts on the spacecraft, determine the residual radiation resource of the spacecraft, and refine the models of the impact of ionizing radiation from outer space (IROS).

EDCC is designed as a monoblock, which includes a matrix of modules for recording the integral accumulated dose (ICDRM matrix) (Fig. 1). Registration of ionizing radiation is carried out using a matrix of identical sensitive elements ICDRM, located on a 3x3 grid.

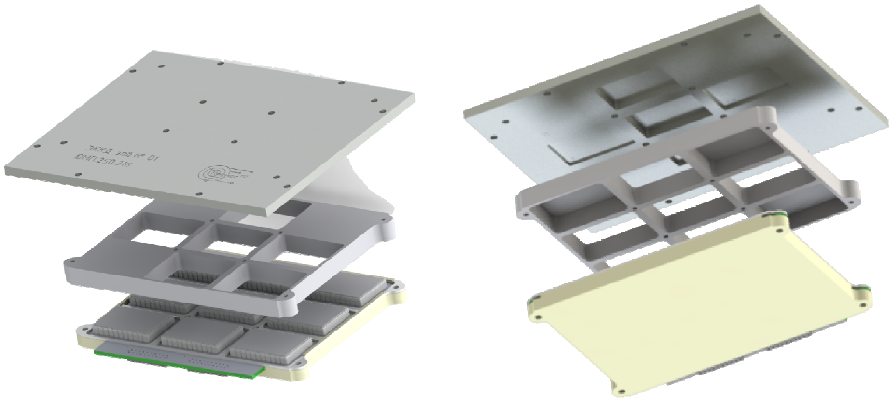
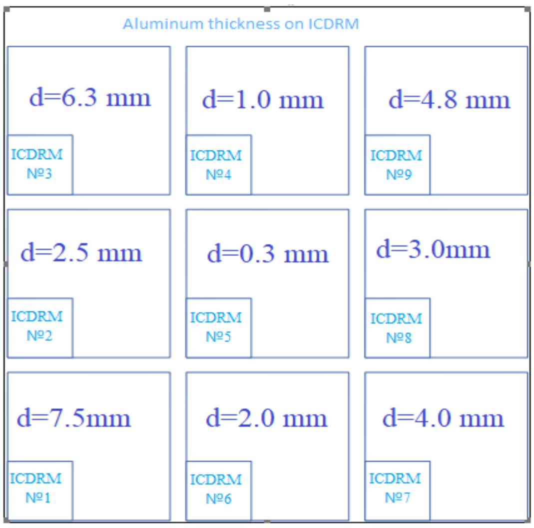


Рис. 1. Матрица МРИНД под разной массовой защитой

Fig. 1. ICDRM matrix under different mass protection



Aluminum thickness on ICDRM

d=6.3 mm ICDRM №3	d=1.0 mm ICDRM №4	d=4.8 mm ICDRM №9
d=2.5 mm ICDRM №2	d=0.3 mm ICDRM №5	d=3.0mm ICDRM №8
d=7.5mm ICDRM №1	d=2.0 mm ICDRM №6	d=4.0 mm ICDRM №7

Рис. 2. Соответствие порядкового номера МРИНД и его массовой защиты

Fig. 2. ICDRM and mass protection sequence number matching

A separate ICDRM represents a microelectronic assembly from a semiconductor sensitive element and a radiation-resistant crystal of an analog-to-digital smart converter. ICDRM has a digital output for external control and reading of measured data. Information exchange between ICDRM and EDCC is carried out via the internal digital interface SPI.

ICDRM registers the integral flux of all main types of ionizing radiation (photons, electrons, protons) incident on its sensitive element. The response of ICDRM to each type of radiation is known thanks to calibrations under ground conditions. The sensor was tested in the γ radiation field of the ^{60}Co radionuclide from the GET 38-2011 source and in the β radiation field of the Sr-Y-90 radionuclide at the UPB-ID installation using the equivalent field method in the range of absorbed doses from 0.50 Gy to $1.20 \cdot 10^3$ Gy (FSUE VNIIFTRI).

Each sensitive element is subject to specific radiation conditions – mass protection weakens the flow of ionizing radiation and changes its spectrum (differently for each type of radiation). Mass protection varies thanks to the installation of steel grating with different cell thicknesses (Fig. 2).

As a result of long-term monitoring of the dynamics of the readings of each of ICDRM, a curve of dose loads is formed depending on the level of protection, characteristic of a given type of orbit.

Technical characteristics are presented in Table. 1.

Table 1

Technical characteristics of EDCC

Parameter	Meaning
Estimated service life	3 years
Dimensions	134 mm × 134 mm × 82.5 mm
Weight, no more than	1.4 kg
Power consumption, no more than	6 W
Operating temperature range	from –20 to +50 ºC
Supply voltage	from 23 to 32 V
Information exchange highway	Multiplex exchange channel GOST R 52070–2003
Number of ICDRM modules	9 pcs.
Cumulative dose range of ICDRM	0.05 до 120 kRad

Measurement technique

The operating principle of EDCC is based on various studies of the effect of ionizing radiation on the electronic component base [10–12]. Under the influence of radiation in the sensitive element, the conductivity of the channel in the built-in field-effect transistor degrades. Thus, by measuring the voltage drop across the sensitive element when direct current is passed through it, one can judge the value of the integral accumulated radiation dose.

The scatter at a fixed dose over a sample of fitting curves (σ) is calculated as the standard deviation from the average fitting curve. The value of the relative standard deviation of resistance at a given accumulated dose according to a sample of calibrations of a series of ICDRM sensors does not exceed ±2.5 % in the operating range of the absorbed dose. The range of ±σ spread of the electrical resistance value from the resistance value corresponding to the average calibration curve is shown in Fig. 3 dotted lines.

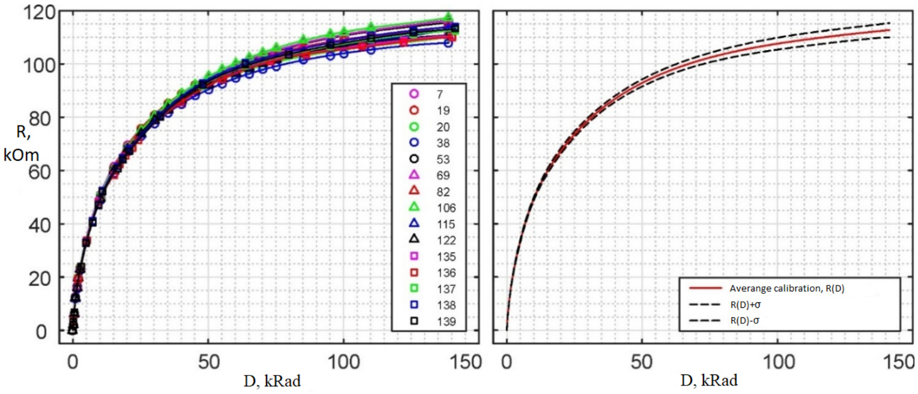


Рис. 3. Зависимости изменения значения электрического сопротивления чувствительного элемента МРИНД от поглощенной дозы на основе данных, полученных в результате проведения калибровок в наземных условиях

Fig. 3. Depending on the change in the value of the electrical resistance of the ICDRM's sensitive element and absorbed dose based on data obtained from ground-based calibrations

Results of experimental data and their comparison with calculated estimates

The experimental data obtained make it possible to estimate the dynamics of the growth of the absorbed dose for each value of mass protection. Graphs characterizing the dynamics of changes in the drain-source voltage of ICDRM sensitive elements when exposed to ionizing radiation from outer space are shown in Figures 4–6.

The readings of the drain-source voltage of ICDRM have the expected dynamics, due to the appropriate mass protection of the sensitive element, except for of ICDRM No. 5 (protection 1 mm for aluminum). The differences in the readings of of ICDRM No. 4 can most likely be explained by the lower value of the initial resistance of the transistor channel of the sensing element of ICDRM No. 4. The average value of the initial resistance of the drain-source channel is about 31±1 kOhm, while the initial resistance of ICDRM No. 4 was 28. 1 kOhm.

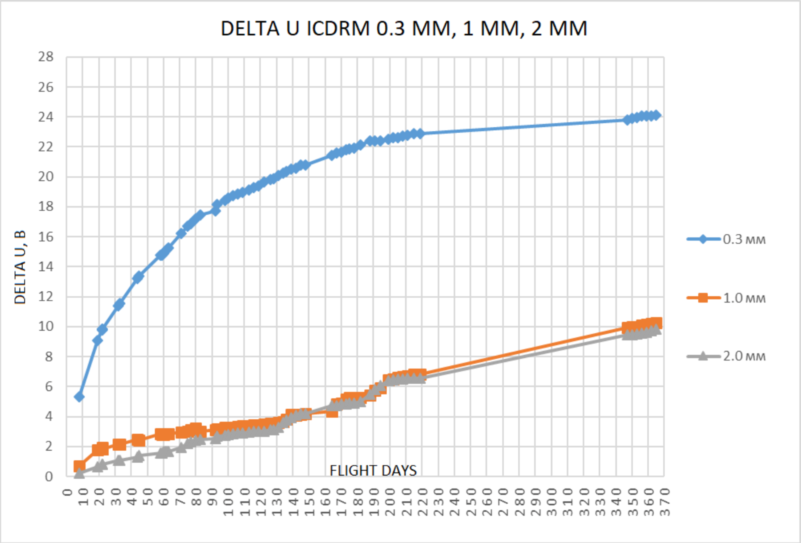


Рис. 4. Динамика изменения напряжения сток-истока
чувствительного элемента МРИНД № 4, 5 и 6

Fig. 4. Dynamics of drain-source voltage changes
in the ICDRM's sensitive element No. 4, 5 and 6

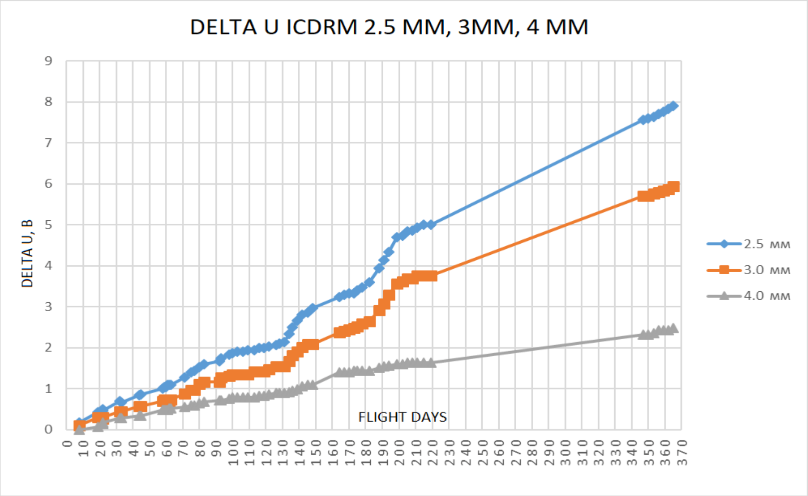


Рис. 5. Динамика изменения напряжения сток-истока
чувствительного элемента МРИНД 2, 7 и 8

Fig. 5. Dynamics of drain-source voltage changes
in the ICDRM's sensitive element No. 2, 7 and 8

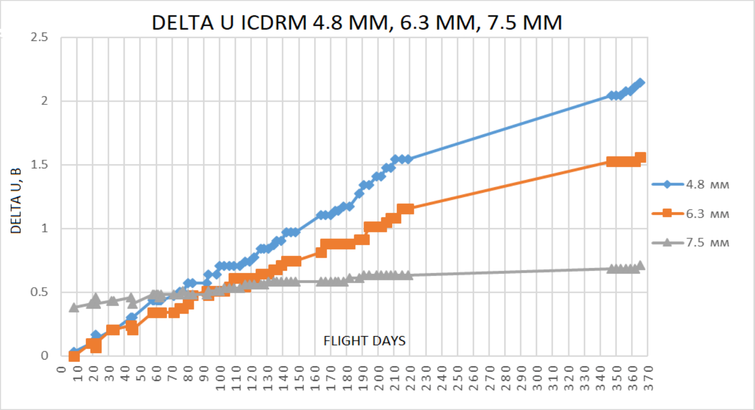


Рис. 6. Динамика изменения напряжения сток-истока
чувствительного элемента МРИНД № 1, 3 и 9

Fig. 6. Dynamics of drain-source voltage changes
in the ICDRM's sensitive element No. 1, 3 and 9

Simultaneously with dose measurement, the current temperature was monitored on the ICDRM matrix. The monitoring results are shown in Fig. 7, the temperature varies from –5 to +15°C, the average temperature of the ICDRM matrix is about 5°C. With a relatively small temperature spread, the spread of ADC readings when taking telemetry in one session could be ±2 units of ADC.

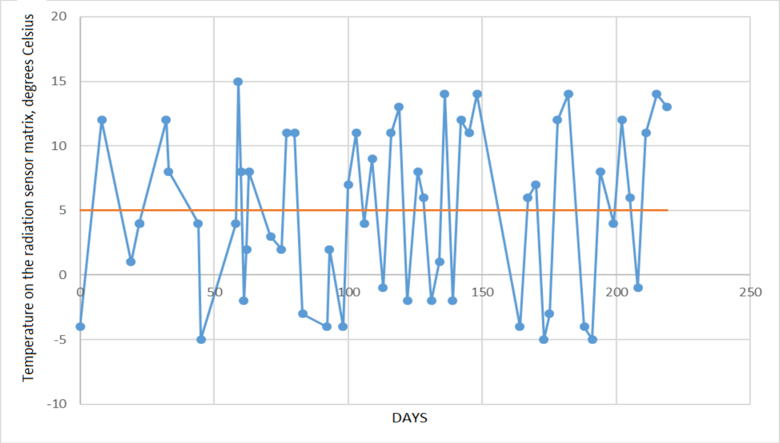


Рис. 7. Регистрация температуры на матрице МРИНД в разные дни

Fig. 7. Temperature registration on matrix the ICDRM on different days

To calculate the levels of accumulated doses as a model of the impact in orbit of the spacecraft operation (H = 8070 km, i = 90°, mission life is 3 years), the data from OST134-1044 amend. 1 "Methods for calculating radiation conditions on board spacecraft and establishing requirements for the resistance of radio-electronic equipment of spacecraft to the effects of charged particles from outer space of natural origin" were used.

The levels of absorbed doses, in accordance with the OST model representation, for an irradiation angle of 4π sr are given in Table 2 [13].

Table 2

Absorbed dose levels per mission life

Amount of protection, g/cm^2	Dose behind spherical protection, rad			
	electrons of NERB, rad	protons of NERB, rad	protons of SCR, rad	Total value, rad
1.00E-02	3.02E+07	2.84E+08	3.77E+04	3.14E+08
1.00E-01	3.18E+06	4.26E+06	9.11E+03	7.45E+06
2.00E-01	8.92E+05	8.55E+05	5.17E+03	1.75E+06
3.00E-01	4.24E+05	3.43E+05	3.57E+03	7.71E+05
4.00E-01	2.20E+05	1.63E+05	2.67E+03	3.86E+05
5.00E-01	1.29E+05	9.02E+04	2.07E+03	2.21E+05
6.00E-01	8.36E+04	5.69E+04	1.63E+03	1.42E+05
7.00E-01	5.79E+04	3.89E+04	1.32E+03	9.81E+04
8.00E-01	4.21E+04	2.85E+04	1.10E+03	7.17E+04
9.00E-01	3.18E+04	2.16E+04	9,33E+02	5.43E+04
1.00E+00	2.47E+04	1.69E+04	8.05E+02	4.24E+04
2.00E+00	5.96E+02	3.04E+03	3.06E+02	3.94E+03
3.00E+00	4.57E+02	1.13E+03	1.72E+02	1.76E+03
4.00E+00	3.79E+02	5.40E+02	1.14E+02	1.03E+03
5.00E+00	3.25E+02	3.44E+02	8.22E+01	7.51E+02
6.00E+00	2.84E+02	2.37E+02	6.26E+01	5.84E+02
8.00E+00	2.25E+02	1.28E+02	4.09E+01	3.94E+02
1.00E+01	1.83E+02	7.81E+01	2.89E+01	2.90E+02

As a result of the calculation estimates, the exposure levels were determined for each sensitive element of ICDRM, which made it possible to construct an absorbed dose curve (the dependence of the absorbed dose on the protection value), and further verify the calculated values with the experimental ones.

The calculation results for all ICDRM for 3 years of mission life are presented in Table 3.

Table 3

Calclation results for 3 years of mission life

Sensor number	Protection value, mm Al	Absorbed dose, rad
5	0.3	1.42E+06
4	1	1.07E+05
6	2	2.07E+04
2	2.5	1.26E+04
8	3	8.31E+03
7	4	4.04E+03
9	4.8	2.29E+03
3	6.3	1.12E+03
1	7.5	7.96E+02

The results of a comparison of calculated and experimental data for 220 days and 1 year of operation are shown in Tables 4, 5 and in Figures 8, 9, respectively.

Based on the data presented in Figures 8, 9, it can be concluded that the curves of the dependence of absorbed doses on the value of mass protection obtained during field measurements and calculated estimates are qualitatively the same. Minor discrepancies are apparently due to insufficient experimental data (more time is needed to carry out measurements).

Table 4

Calculation results for mission life 220 days

Sensor number	Protection value, mm Al	Absorbed dose, rad (calculated)	Absorbed dose, rad (experimental)
5	0.3	2.86E+05	1.19E+05
4	1	2.15E+04	5.22E+03
6	2	4.16E+03	4.91E+03
2	2.5	2.53E+03	3.12E+03
8	3	1.67E+03	1.99E+03
7	4	8.11E+02	6.14E+02
9	4.8	4.60E+02	5.68E+02
3	6.3	2.24E+02	3.94E+02
1	7.5	1.60E+02	1.96E+02

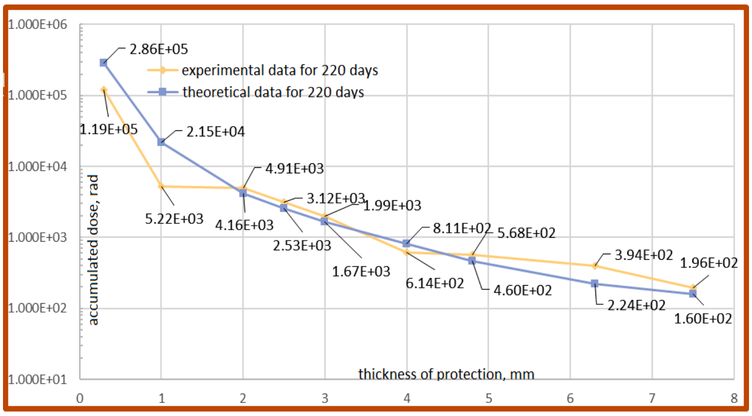


Рис. 8. Накопленная доза различных датчиков МРИНД за 220 дней

Fig. 8. Absorbed dose of ICDRM over 220 days

Table 5

Calculation results for mission life 1 year

Sensor number	Protection value, mm Al	Absorbed dose, rad (calculated)	Absorbed dose, rad (experimental)
5	0.3	4.75E+05	2.95E+05
4	1	3.57E+04	1.12E+04
6	2	6.91E+03	1.02E+04
2	2.5	4.20E+03	6.78E+03
8	3	2.77E+03	4.13E+03
7	4	1.35E+03	1.09E+03
9	4.8	7.63E+02	8.82E+02
3	6.3	3.72E+02	5.77E+02
1	7.5	2.65E+02	2.23E+02

The available data confirm that a circular orbit of 8000 km is a sufficiently rigid orbit, from the point of view of radiation exposure, for the operation of a spacecraft with a long-term mission life. The calculated values of the accumulated dose for various values of protection for geostationary orbit, circular orbits of 8000 and 1500 km for mission life 10 years are shown in Figures 10 and 11 [14].

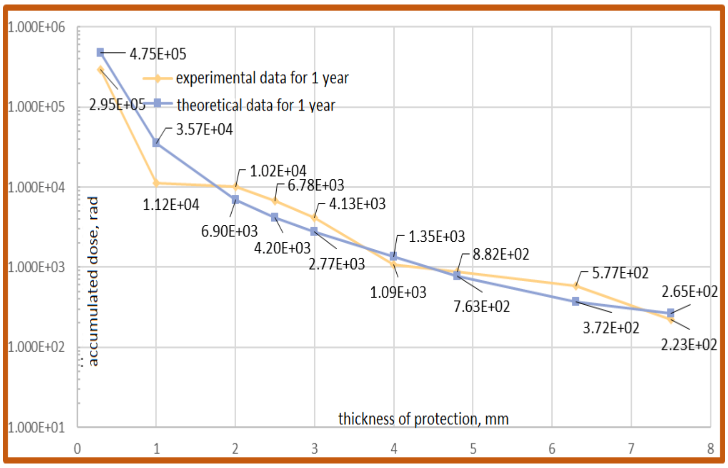


Рис. 9. Накопленная доза различных датчиков МРИНД за 1 год (365 дней)

Fig. 9. Absorbed dose of ICDRM over 1 years (365 days)

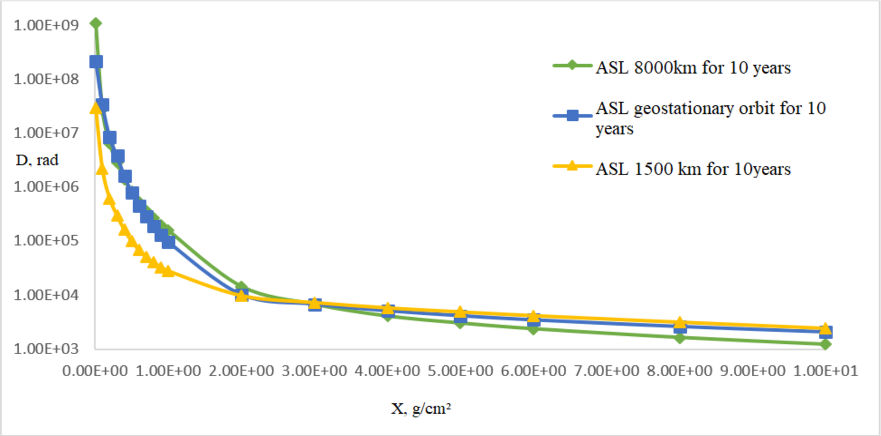


Рис. 10. Сравнительный график ГСО, 8000 и 1500 км

Fig. 10. Comparative graph of GEO, 8000 and 1500 km circular orbits

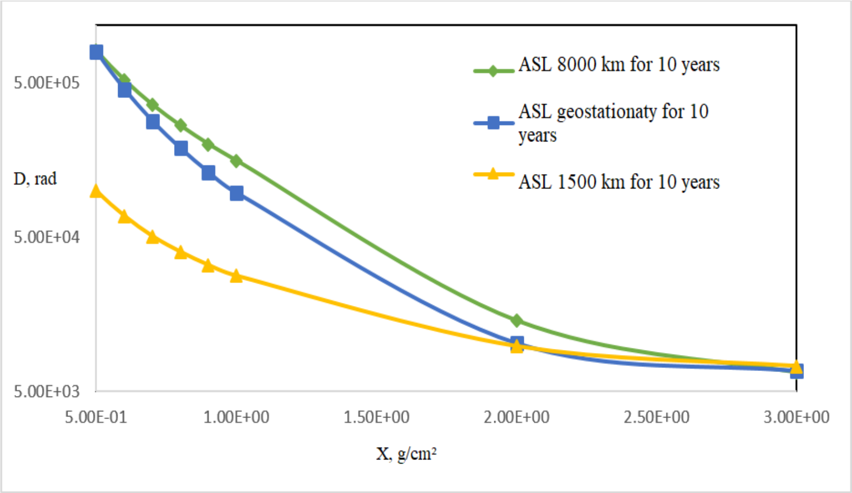


Рис. 11. Сравнительный график ГСО, 8000 и 1500 км для диапазона защит 0,5–3 г/см^2

Fig. 11. Comparative graph of GEO, 8000 and 1500 km circular orbits
for the protection range of 0.5–3 g/cm²

Based on the data presented in graphs 10, 11, it can be concluded that the impact levels for the 8000 km orbit in the range of typical protections for ECB 0.5–3 g/cm^2 exceed the requirements for the GEO orbit and the 1500 km circular orbit for a similar mission life.

The level of impact outside the spacecraft for an 8000 km orbitis ~ 5 times higher than the level of impact in GEO and ~ 1.5 orders of magnitude higher than the level of impact in an orbit of 1500 km, which in turn imposes great restrictions on the list of non-metallic materials that can be used outside the spacecraft.

Conclusion

The results of the flight experiment as part of the Skif-D spacecraft demonstrated:

1) successful modernization of the ICDRM integral accumulated dose sensors in terms of their miniaturization and transition to a digital output (flight qualification of the sensors was obtained);

2) the prospects of the concept of monitoring the integral accumulated radiation dose through the use of semiconductor detectors with individual mass protection;

3) high convergence of the results of a comparative analysis of the experimentally obtained levels of impact in orbit of the operation of the Skif-D ESA with theimpact model set out in the Scientific and Technical Documents of the Russian Federation (OST134-1044-2007 amend. 1 (2017) “Methods for calculating radiation conditions on board space devices and establishing requirements for the resistance of radioelectronic equipment of spacecraft to the effects of charged particles of outer space of natural origin”);

4) experimental confirm at ion of a higher radiation load in the range of standard protections for an ECB of 0.5–3 g/cm^2 for a circular orbit of 8000 km compared to the GEO and 1500 km orbits.

Further work with the EDCC equipment within the framework of the orbital experiment of the Skif-D spacecraft will make it possible to accumulate more voluminous statistics on the radiation situation in the 8000 km orbit, including various phases of solar activity. In the future, it is planned to develop mathematical models that make it possible to calculate the spectra of the influencing outer space nuclear radiation based on the analysis of multi-channel EDCC data.

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