Solar particle events contribution in the space radiation exposure on electronic equipment

Vasily S Anashin\textsuperscript{1}, Grigory A Protopopov\textsuperscript{1,3}, Olga S Kozyukova\textsuperscript{1}, Ninel N Sitnikova\textsuperscript{2}
\textsuperscript{1} Branch of JSC “URSC”-“ISDE”, Moscow, Russia
\textsuperscript{2} JSC “Academician M.F.Reshetnev” Information Satellite Systems”, Zheleznogorsk, Russia

E-Mail: conf@niikp.org

Abstract. The article presented the on-board measurement results of dose sensors. We carried out the estimation of the contribution of solar protons in a dose rate value during solar events. We determined the solar proton events conditions when these events can markedly affect the reliability of on-board equipment operation.

1. Introduction
Space radiation is the most critical natural influencing factor which limits spacecraft’s electronic equipment life time. The main components of space radiation are particles from Van Allen belts, solar and galactic cosmic rays [1]. Space radiation accounts from 30 to 50 per cent of qualified failure (because of total ionizing dose, displacement damage and single event effects), even though this percentage is higher due to the stimulation of other types of failures, first of all, electrostatic [2]. At the present time there is a need for carrying out permanent monitoring of space radiation characteristics for the determination of the degree of space radiation exposure on electronic equipment and for the forecast of spacecraft operability. For these purposes, the monitoring system of space radiation exposure on spacecraft electronic equipment was made on demand of Roscosmos [3].

2. Space radiation exposure on the radio-electronic equipment engineering monitoring system

2.1. The monitoring system aim and tasks
The main aim of the monitoring system is the increase of spacecraft active shelf life. The monitoring system is not the alternative and is an addition to the existing scientific monitoring system and is used, generally, for:

- Measurement of space radiation impact on the spacecraft electronic equipment.
- Calculation and control of the spacecraft remaining lifetime.
- Management of the structural and algorithmic approach for active lifetime increase.
- Forecasting of space radiation impact changes (including dangerous) on the spacecraft radio electronic equipment.
- Receiving the flight data on spacecraft electronic equipment hardness.

3 To whom any correspondence should be addressed.
• The understanding of space radiation influence mechanisms on the spacecraft electronic equipment.
• Improvement of charge particles flux models.
• Forecasting of “space weather” characteristics.

2.2. The monitoring system structure and elements
The monitoring system structure is presented in figure 1. The monitoring system includes space borne and ground segments. The main elements of the space borne segment are sensors which are based on the MNOS-dosimetry principle (metal-nitride-oxide-semiconductor transistor is used as a sensitive element). The sensors were calibrated at the certified stand “GU-200” with $^{60}$Co isotopes [3]. The ground segment includes several stations for the input, data processing and information output among other the on-board measurements. At the moment there are 42 sensors on the board of 21 spacecrafts developed by JSC “Information Satellite Systems” which are functioning on the circular orbit ~ 20000 km (outer radiation belt). The engineering sample of the monitoring system ground segment was developed (website www.kosrad.ru).

![Figure 1. The monitoring system structure](image)

3. Experimental and calculation results

3.1. Abrupt increase of dose rate event
The analysis of the received data from October 2008 to September 2013 allows us to find out the periods with sharp increase of dose rate and definite value of such an increase. We also analysed space radiation characteristics data from other monitoring systems (such as GOES [4]) in dates of anomalous increase of dose rate. As you can see from the table 1, the increase of high-energy electron fluxes is observed on all dates and also geomagnetic storms are observed (Kp index is from 5) for all dates, while there are only two solar proton events which can contribute to the dose rate increase.
Table 1. The characteristics of space weather on the date of sharp increase of dose rate

| Date       | Dose rate before event (a.u. s\(^{-1}\)) | Dose rate after event (a.u. s\(^{-1}\)) | Dose rate increase (times) | GOES proton fluxes >10 MeV (cm\(^2\) day\(^{-1}\) sr\(^{-1}\)) [4] | GOES electron fluxes > 2 MeV (cm\(^2\) day\(^{-1}\) sr\(^{-1}\)) [4] |
|------------|-----------------------------------------|-----------------------------------------|----------------------------|-------------------------------------------------|-------------------------------------------------|
| 05.04.2010 | 1.22 \(10^{-4}\)                        | 1.34 \(10^{-4}\)                       | 1098                       | 1.6 \(10^{4}\)                                    | 5.4 \(10^{6}\)                                    |
| 03.08.2010 | 2.67 \(10^{-4}\)                        | 3.08 \(10^{-3}\)                       | 11                         | 1.1 \(10^{5}\)                                    | 2.5 \(10^{8}\)                                    |
| 01.03.2011 | 1.29 \(10^{-4}\)                        | 1.02 \(10^{-3}\)                       | 79                         | 1.4 \(10^{4}\)                                    | 7.8 \(10^{8}\)                                    |
| 02.05.2011 | 1.06 \(10^{-4}\)                        | 1.89 \(10^{-3}\)                       | 17                         | 1.2 \(10^{4}\)                                    | 6.8 \(10^{8}\)                                    |
| 09.09.2011 | 1.26 \(10^{-4}\)                        | 2.18 \(10^{-3}\)                       | 17                         | 4.2 \(10^{4}\)                                    | 3.2 \(10^{8}\)                                    |
| 23.01.2012 | 2.01 \(10^{-4}\)                        | 1.59 \(10^{-3}\)                       | 8                          | 1.4 \(10^{8}\)                                    | 2.5 \(10^{8}\)                                    |
| 08.03.2012 | 3.61 \(10^{-4}\)                        | 2.35 \(10^{-3}\)                       | 7                          | 2.0 \(10^{8}\)                                    | 5.9 \(10^{8}\)                                    |
| 08.10.2012 | 6.08 \(10^{-4}\)                        | 9.90 \(10^{-3}\)                       | 16                         | 1.4 \(10^{8}\)                                    | 4.8 \(10^{8}\)                                    |

\(^a\) a.u. are arbitrary units

\(^b\) Maximum value during the week

3.2. Computation algorithm of dose rate value from solar protons

In this work we examined the largest solar particle event during the period of absorbed dose measurements (08.03.2012). The following algorithm was applied to assess the contribution of this flare in dose rate on the considered orbit of 20000 km.

- The integral spectrum of solar protons on the Geostationary Earth Orbit (GEO) was determined for the period from 5.03.2012 to 17.03.2012. For this purpose, the daily data of the solar proton fluxes for different energy ranges were used [4].

- The differential spectrum of solar protons was calculated for this event. We considered the energy range from 1 to 100 MeV (protons with this energy give the main contribution in the absorbed dose). The differential spectrum, (in the MeV s\(^{-1}\) cm\(^{-2}\) sr\(^{-1}\)) was estimated for the range from 1 MeV to 10 MeV on the formula (1), for the range from 10 MeV to 100 MeV – (2) and from 100 MeV – (3):

\[
f_1 = \frac{F_1 - F_{10} - F_{100}}{13.2\pi} \\
f_2 = \frac{F_{10} - F_{100}}{36\pi} \\
f_3 = \frac{F_{100}}{360\pi}
\]

Where \(F_p, F_{10}, F_{100}\) are the corresponding integral proton fluxes with energy more than 1 MeV, more than 10 MeV and more than 100 MeV, respectively.

- We recount the differential spectrum of solar protons for the 20000 km orbit with the help of correction indices for the consideration of geomagnetic cutoff rigidity (\(R_c\)). These indices are the ratio of solar protons fluxes for the 20000 km orbit and for GEO at same energies. Calculations were carried out using the COSRAD software [5]. The software is the main certified tool in Russia for space radiation environment calculation and is used for the establishing radiation hardness requirements for electronic equipment developed by the order of Roscosmos. Table values of \(R_c\) are used in the software for different altitudes and inclinations, which were precalculated for average geomagnetic activity (K index ~2-3). So changes of the Earth’s geomagnetic field are not taken into account, and that is the limitation of our method. Figure 2 shows the correction indices.
Figure 2. Correction indices for proton fluxes with certain energy from the 36000 km orbit to 20000 km orbit

- We calculated dose rate values behind the shielding of 1 g cm\(^{-2}\) (the value of the effective thickness shielding was determined taking the spacecraft’s frame and MNOS transistor’s case into account) during the period of solar proton flare with received spectrum by the «OMERE» software \[6\]. The calculation results are presented in table 2.

Table 2. The calculation results of dose rate values

| Data       | GOES proton flux > 10 MeV, proton(cm\(^2\) s sr\(^{-1}\)) | GOES proton flux > 100 MeV, proton(cm\(^2\) s sr\(^{-1}\)) | Dose rate from solar protons, a.u. s\(^{-1}\) | Contribution to the total dose % |
|------------|-------------------------------------------------------|--------------------------------------------------------|---------------------------------------------|----------------------------------|
| 25.09.2001 | 12900                                                 | 30                                                     | 4.3 10\(^{-4}\)                             | \~5\(^{a}\)                      |
| 06.11.2001 | 31700                                                 | 200                                                    | 9.52 10\(^{-4}\)                           | \~10\(^{a}\)                    |
| 24.11.2001 | 18900                                                 | 4                                                      | 1.59 10\(^{-4}\)                           | \~1\(^{a}\)                     |
| 02.10.2001 | 2360                                                  | 0.2                                                    | 1.08 10\(^{-5}\)                           | \~0.1\(^{a}\)                   |
| 28.10.2003 | 29500                                                 | 200                                                    | 1.15 10\(^{-3}\)                           | \~11\(^{a}\)                    |
| 24.01.2012 | 6310                                                  | 2                                                      | 4.28 10\(^{-5}\)                           | \~0.5\(^{a}\) (27\(^{b}\))      |
| 08.03.2012 | 6530                                                  | 70                                                     | 4.82 10\(^{-4}\)                           | \~6\(^{a}\) (21\(^{b}\))       |

\(^{a}\) comparison with the maximum dose rate value for whole period of measurements (\~10\(^{-2}\) a.u. s\(^{-1}\) according to Table 1)

\(^{b}\) comparison with the dose rate value measured for certain day

The calculated value of dose rate from solar protons on the circular orbit 20000 km was 7.12 \(10^{5}\) a.u. s\(^{-1}\) during the period from 5.03.2012 to 17.03.2012 (the maximum increase of solar proton flux during the whole period of dose measurement). If we compare the data of table 2 (right column) with the data of table 1, it may be concluded that during this flare the solar protons didn’t give the considerable contribution to the dose rate increase.
4. Contribution to dose rate values of solar protons according to different models
We also made the analysis of contribution to dose rate values of model events which are used in the software «OMERE» and in software «OSOT» [7] (Nymmik model [8]). Figure 3 shows the dose rate from solar protons reached the value of ~ $10^{-2}$ to $10^{-1}$ a.u. s$^{-1}$ which is comparable to and even more than trapped electron contribution to the dose rate value.

![Figure 3](image)

**Figure 3.** The dependence of dose rate value from solar protons vs. shielding thickness for different modeled events

5. Determination of critical solar proton flare class
In terms of obtained data it is possible to determine the classes of solar proton events which can deposit important contribution in dose rate increase on the 20000 km orbit (more than 10 % of the maximum dose rate value $10^{-2}$ a.u. s$^{-1}$; note that the average dose rate for the 20000 km orbit and shielding 1 g cm$^{-2}$ is approximately equal to $10^{-3}$ a.u. s$^{-1}$). These classes are S4 and S5 [10], but with the condition that the proton flux at energies above 100 MeV exceeds the value of 200 proton (cm$^2$ s sr)$^{-1}$. Characteristics and a probability of these events are presented in the table 3.

| Solar proton event | Integral flux $>$=10 MeV$^a$ | The annual event occurrence probability |
|--------------------|-----------------------------|-----------------------------------------|
|                    |                             | Observed between 1994-2014 $^b$ | All events |
| S5 Extreme         | 100000                      | < 0.1 times during the year          | |
| S4 Severe          | 10000                       | 0.2 times during the year            | 0.3 times during the year |

$^a$ Average value of integral flux within 5 minutes, proton(cm$^2$ s sr)$^{-1}$

$^b$ Upon condition proton flux $>$100 MeV more than 200 proton(cm$^2$ s sr)$^{-1}$

The dose rate abrupt increase can cause the abnormal operation of on-board equipment because of the total ionizing dose effect in case an electronic component has accumulated dose which is close to its failure level. Also the stimulation of other effects (internal charging and etc.) is possible. It should be
noted that there are orbits (low-altitude, polar) where the protons influence exceed the electrons one. There are also orbits which are more shielded by the Earth’s geomagnetic field.

6. Conclusion
The analysis of space-borne measurements of dose rate on the middle-Earth orbit and proton and electrons fluxes from the GEO for 2008 – 2013 showed that the main contribution to the dose rate increase is given by trapped electrons. However, two proton events were seen (with class S3) which gave the contribution more than 20%. The direct in-flight measurements and calculations showed that it is necessary to consider the proton flux not only with the energy >10 MeV (which is used for event type classification), but with greater energy (first of all, 100 MeV) upon condition of flux more than 200 proton (cm² s sr)⁻¹. In this case, solar protons give the contribution more than 10% in comparison with the maximum measured dose rate and future probable events will be able to contribute more than 50% in comparison with the same value. Consequently, the assurance of reliable operation of on-board equipment demands the control of the S4-class events, when the >100 MeV proton flux exceeds the value of 200 proton (cm² s sr)⁻¹. Further, it is necessary to estimate the solar proton contribution to the dose rate on the other orbits (low-altitude orbit, polar orbit) on which dominates the influence of protons, not electrons.

7. References
[1] J. Mazur “The radiation environment outside and inside a spacecraft”. IEEE NSREC 2002 Short Course, pp. II-1 – II 69, 2002.
[2] Koons H.C. et al. The Impact of the Space Environment on Space Systems // AEROSPACE REPORT NO.TR-99 (1670)-1, 1999.
[3] V. S. Anashin, G. A. Protopopov, and Y. A. Milovanov, “Monitoring of space radiation in Russian federal space agency,” 12th European Conference on Radiation and Its Effects on Components and Systems, Sep. 2011.
[4] http://www.swpc.noaa.gov
[5] http://cosrad.sinp.msu.ru/manual.html
[6] http://www.trad.fr/OMERE-Software.html
[7] Anashin Vasily, Protopopov Gregory, and Milovanov Yury, “SEE testing for exposure of space ionizing radiation on radio-electronic equipment,” Proceedings of 5th International Conference on Recent Advances in Space Technologies - RAST2011, Jun. 2011.
[8] R. A. Nymmik, “Probabilistic model for fluences and peak fluxes of solar energetic particles,” Radiation Measurements, vol. 30, no. 3, pp. 287–296, Jun. 1999.
[9] http://umbra.nascom.nasa.gov/SEP/
[10] http://www.swpc.noaa.gov/noaa-scales-explanation