(Abstract No# (ex: 205)

Protection of the Spectr-R Spacecraft against ESD Effects using "Satellite-MIEM" computer code

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Abstract **- There are two competing tendencies in spacecraft design and manufacturing. On the one hand, it is a never ceasing upgrading of the spacecraft electronics to lower energy consumption and increase its functionality, which in turn makes it more susceptible to electrostatic discharges (ESDs). On the other hand, designers constantly seek to improve electronics protection against ESDs. "Spectr-R" spacecraft features on-board equipment, which is highly sensitive to possible ESDs. To exclude ESD-related failures, the following protection measures have been taken. Based on the "Satellite-MIEM" computer code, we developed the lump-element model of the "Spectr-R" body currents and cable-affected electronics response. This model made it possible to compute spacecraft body currents initiated by ESDs originating at various structural sites. For various cable harnesses, we measured transformation coefficients converting body currents into the amplitude of the noise voltages appearing in a cable (a patented methodology was used for this purpose). Afterwards, these transformation coefficients together with the ESD-induced currents have been fed into the "Satellite-MIEM" software to compute noise voltages appearing in electronics input circuits, connected via these cables to the satellite exterior surface. Comparing protection efficiency of cables and electronics equipment allowed us to select suitable cable harnesses and the appropriate equipment protection to insure reliable in-flight performance of the space vehicle. From the launch in July 2011 and up to the present time, there were no failures of the "Spectr-R" electronics, which could be traced to ESDs.**

Keywords* — *Spacecraft Spektr-R; protection; electrostatic discharges; lump-element model;

Space radio telescope Spektr-R has been launched on July 18 2011 from Baikonur Cosmodrome into highly elliptic orbit (apogee 330 000 km, perigee 600 km, inclination 51,3 degree and period of revolution about 9 days). During one revolution, the Satellite spends 5 hours in Earth radiation belts. This spacecraft is the main part of the Radio-Astron international project, which allows seeing the Universe in the radio frequency range with a uniquely high resolution- to the millionth part of the angular second. Such a resolution has been achieved by uniting directed antennas, high-sensibility sensors and electronic blocks into systems. These systems are highly sensitive to radio frequency signals while ESD-induced noise pulses can even put them out of order. That is why so much attention has been given at the design stage of Spectr-R to electronics protection against ESD and ESD-induced pulse currents in cable harnesses.

In present work, we report the entire methodology of spacecraft (SC) electronics protection against ESD-induced pulse currents in cable fragments laid out on the outer surface of the space vehicle. The basic idea of this approach is as follows. ESD are still happening on the SC outer surface as existing materials selection procedure allows only decreasing the ESD discharge rate and its power but not its elimination. ESD-induced voltages appearing in space vehicle cable harnesses laid out on its outer surface may reach volts or even tens of volts. These noise signals are expected to be fed into electronics input circuits. That is why SC electronics should be manufactured in such a way as to guaranty its faultless operation under flight conditions.

Noise levels should be evaluated beforehand on the sketch stage of the space vehicle design. In this case, electronics engineers will have the necessary design information. First, the most probable sites of ESD initiation should be located. NASA uses for this purpose the famous NASCAP computer code. A similar code (developed by L. Novikov and colleagues) is used in Russia. The software specifically adapted to Spectr-R is preserved for the whole service life to be retrieved for establishing the reason of its inadvertent in-flight malfunction.

Second, pulse noise levels at electronics input circuits connected with the SC exterior surface via fragments of the cable harness should be assessed. As a preliminary result of this design stage may be the body current distribution arising from an ESD localized at a specified point indicated by an earlier analysis. For this purpose, we used a variant of a general «Satellite-MIEM» computer code adapted for modeling and computing noise signals generated in cable harnesses and electronics inputs of Spectr-R. We base this approach on the formal similarity of differential equations describing thermal, vibrational and structural processes in various devices.

The Satellite-MIEM computer code is a lumped element model (LEM) of the SC charging originally used for evaluating SC exterior potentials due to space particle fluxes [1, 2].

LEM codes allowing evaluation of the SC differential charging are essentially electrical circuits comprising capacitors C, inductances L and resistors R. Besides these, they usually include current sources imitating both the primary particle fluxes and the secondary particles emitted from the SC surfaces.

Configuration of the space vehicle defines the way the linear circuits or electronic units are treated by these models.

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The application of LEM codes revealed their inability to account for the influence one charged surface element exercises on the secondary fluxes emitted from the other, which results in the overestimated surface potentials [2].

Nevertheless, this drawback prompted further diversification of LEM. We still use LEM codes to evaluate ESD-induced body currents subsequently employed to estimate noise voltages emerging in cable harnesses residing on the outer surfaces of the space vehicle.

Formulation of a LEM roughly involves two phases. First, it is necessary to represent SC surface as consisting of a number of lumped elements (see Fig. 1). Nominal values of them are calculated taking into account both material properties and space vehicle configuration. Using our code, we find possible ESD sites and evaluate induced currents in the SC body and attached units as well. As mentioned above, the ESD was modeled by an equivalent pulse current source. These current sources connect points of likely ESD initiation.

This methodology has been realized based on a special dialogue computer system allowing one to create the SC LEM interactively and carry out the necessary modeling of body currents for various types of ESD including the blow-off discharge into space plasma. This computer system uses Windows 7 and plus.

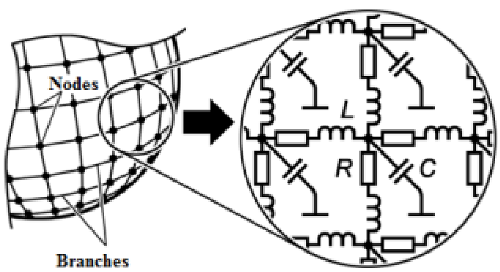

Fig.1. Formulation of the LEM.

As already mentioned, the body current distribution is not an aim in itself but rather serves to predict the noise signals at the electronic input circuits. The body currents as well as the transformation coefficient transforming them into noise voltages were used for this purpose. Analysis and experimental results show that the voltages scale almost linearly with the current and the length of the cable fragment laid on the SC outer surface. Due to this circumstance, it became possible to combine computer blocks responsible for the body currents and the cable output voltages.

Fig. 2 illustrates an experimental set-up realizing this approach. To compute noise voltage it is necessary to indicate an exact cable positioning and provide information for the transformation coefficient. Such a unified approach combining computational and experimental techniques allowed us to achieve prediction accuracy of +/- 30%.

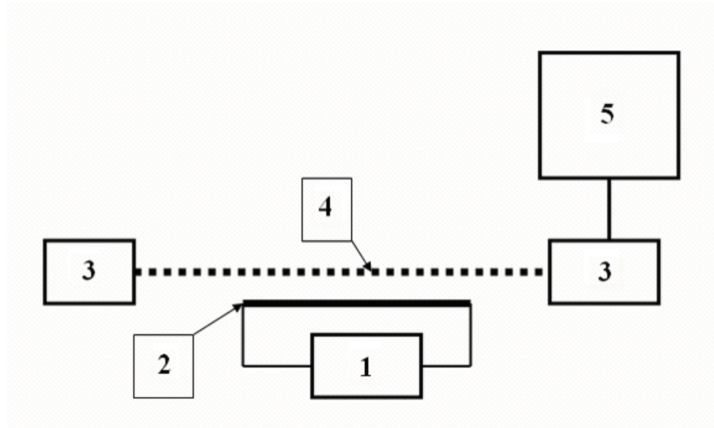

Fig.2. Block diagram of the experimental set-up for testing SC electrical cable harnesses. 1 – pulse current driver; 2 – metallic plate supporting the current; 3 – equivalent load resistor in shielded cable; 4 – harness fragment to be tested; 5 –Tektronix 3032B oscilloscope. Peak discharge current – (10…100) A; pulse length – (30…150) ns; pulse rise time – (3…5) ns; discharge energy – (0,02…0,2) J.

The above guidelines allow one to formulate perspective tolerance specifications for SC electronics regarding the emf noise pulses expected in their input circuits.

The above approach applied at the SC design stage allows one to formulate the noise susceptibility requirements for electronic units connected with the exterior surface via cable harnesses. Fig. 3 shows an experimental set-up used to determine the cable transformation coefficients. The method and its experimental realization are protected by a patent [4].

Fig.3. An experimental set-up intended for determining transformation coefficients converting ESD-induced structure currents into pulse voltages generated in cable harnesses. From left to right: a left set of equivalent load resistors for a cable to be tested, high voltage pulse generator, metal plate to provide an appropriate pulse current, a right set of equivalent load resistors for a cable and a Tektronix 3032B oscilloscope.

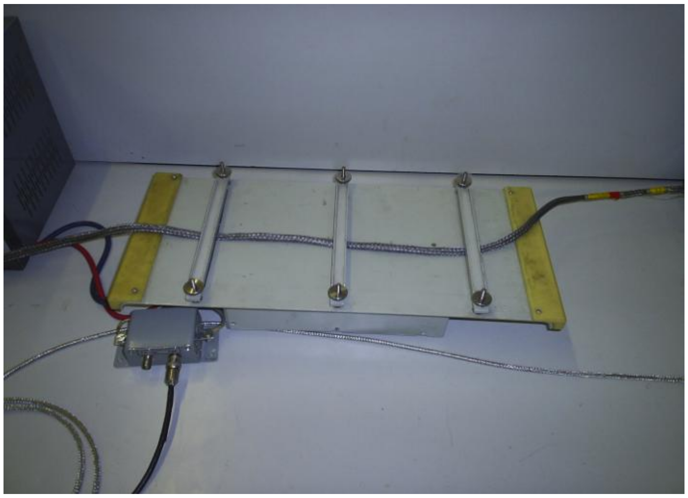

Fig.4. Experimental table, which is effectively a metallic plate to pass a pulse current. A cable harness is tightly pressed to the plate by dielectric planks. A current driver is placed under the plate, which is fabricated from the same alloy as the SC structure.

The «Satellite-MIEM» code is fully compatible with other CAD-systems including «Salome» computer code (in DXF, IGES, ACIS formats). In this sense, our computer code is user friendly. Indeed, one may dispense with the SC geometric model as this may be taken from the sketch phase of its design. In all cases, we are able to generate the final model based on a given configuration. Material characteristics may be specified by the user or can be borrowed from the appropriate built-in libraries. Besides, our code may readily incorporate other commercial finite element models using proper interfaces.

The «Satellite-MIEM» code provides a complete visual control at all modeling phases. For convenience, and to redress inadvertent errors, the code allows for retracting them and re-executing the repealed commands of all levels. In case one needs an additional information or help, the built-in reference library is at hand.

We have developed a new-generation «Satellite-MIEM» computer code (its interface is presented on Fig. 5). This code is based on the finite element model and is intended to evaluate peak voltages in SC cable harnesses traced on its outer surface. Manipulation with the interface is very simple. First, download the geometric model. Second, the code computes painted ESD-induced structure currents. At last, the program provides peak voltages appearing in the cables laid on the SC exterior surface.

Before starting any computations, it is essential to be confident that the model to be used is correct. Accordingly, the «Satellite-MIEM» code envisages the continuous supervision of the simulation process which helps to exclude possible errors, which might have crept into the model at its development phase.

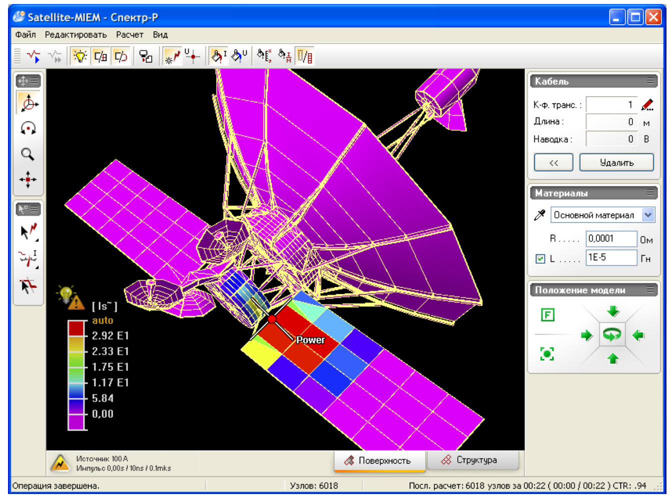

Fig.5. Interface of the «Satellite-MIEM» computer code.

For this purpose, we use the visual feedback for the user. Additionally, the code provides an automatic user-free capability for revealing and redressing inadvertent errors, which are otherwise difficult to spot visually. Thus, it allows one to find coincident (duplicating) geometrical objects or detect wrong connections in electrical circuits. Each of these methods may be used at any time for detecting possible mistakes, which otherwise would have caused an unwarranted time loss.

Boundary frequency in the ESD spectrum is defined by the rise time of the ESD pulse and equals 200 MHz for a 5 ns rise time (an equivalent wavelength is λ = 1.5 m). For acceptable computation accuracy, the grid mesh size, which is equivalent to the branch length on the SC exterior surface, should not exceed λ /10, that is 0.15 m. In this case, the application of the LEM is permissible. However, for Spektr-R with a characteristic dimension of about 10 m this would mean that the number of grid nodes would approach 10^5. It should be noted that computer Spice codes such as OrCad, Pspice, Micro-Cap 8 and LTspice compute R, L, C circuits with this number of nodes using common multi-core PCs very slowly (up to several weeks).

In this situation, we had to develop accelerating procedures greatly decreasing computation times of the existing computer codes. Our colleagues (N. Borisov and A. Vostrikov) proposed two such procedures. The first one, the so-called method of *separated* regions, is based on a heuristic approach and is employed when computation accuracy of 3 to 5% suffices. The main idea here is to apply the Kirchhoff's law at every node of the equivalent circuit. A node gives rise to 5 branches, 4 of which connect with other nodes while a fifth connects to the common ground through a condenser. Therefore, the current falls drastically after several mesh sizes from the ESD site (node), for example it will drop from 100 A to 1 A or less. ESD-induced cable voltage in this place may be neglected.

Computer experiments involving «Satellite-MIEM» code show that a separated region encompasses about 400 nodes centered on the ESD site. Other nodes feature currents that constitute less than 1% of the peak discharge current and as such are insignificant because noise signals induced by these currents in cables will be too weak to affect SC electronics.

Based on matrix analysis, an accurate accelerated method of creating equivalent geometric macro models of a space vehicle and accelerated numerical routines to compute them have been developed. These approaches relying on the implicit and explicit Euler methods allowed reducing LEM computation times of up to two orders of magnitude. At present, these innovations are part of the «Satellite-MIEM» computer code.

We envisage that the new-generation «Satellite-MIEM» computer code adapted for the characterization of a specific spacecraft will be in service until the end of the SC active operation. Such an extended service life of the code is stipulated by a standing need to conduct an expert investigation of any minor malfunction of the SC electronics. In case of such an emergency (soft fault or a complete failure), the following steps are justified.

It is necessary to perform computation of the potential relief on the SC exterior surface at a specific orbit position and at the exact time when the failure occurred. At present, such calculations are being performed in Science and Research Institute of Nuclear Physics at MSU (Moscow). Given the potential relief, one finds the ESD site and its parameters. Further analysis is carried out using our code.

As a result, one ascertains the cable voltage at the input circuit of the electronic unit, which suffered a failure. The value of this voltage allows to judge if an ESD was the real cause of the failure.

During Spectr-R design and fabrication, a complete cycle of simulations have been accomplished. Initially, a soft code analogous to NASCAP has been applied to locate most probable sites of ESD initiation and calculate ESD parameters. Then, peak voltages emerging in surface laid cables due to ESDs occurring in specified sites have been estimated. As a result, cables have gone through a particularly strict selection procedure.

Totally, we tested 26 cables with various shields. Transformation coefficients for every cable have been experimentally determined and included into the «Satellite-MIEM» database. The final decision about cable acceptance relied on the correlation between their mass and size on the one hand and the transformation coefficient on the other. Computed peak voltages have been included in technical specifications for the perspective Spectr-R electronic blocks.

Preflight SC ground testing for ESD susceptibility and the faultless Spectr-R in-flight operation for almost three years proved the consistency of the proposed SC computer modeling of the spacecraft charging effects.

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