Development of risk assessment technology for small spacecraft based on a space weather heat map

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Abstract. This study focuses on the development and implementation of a specialized technology to address the challenges posed by space weather on the performance and operational reliability of small spacecraft, particularly CubeSats and nanosatellites in Low Earth Orbit (LEO). The research emphasizes the importance of data acquisition, processing, and visualization of energy particle fluxes in near-Earth space, with a web application demonstrating visualization of average electron values in a heat map format. The proposed technology, in conjunction with space weather prediction methods, allows for quick response to adverse conditions, contributing to increased longevity and operational efficiency of small spacecraft. In the absence of comprehensive protection systems, the research suggests simple organizational methods as an effective approach for risk mitigation and reliability improvement, applicable even to spacecraft already in orbit.

1 Introduction

The continuous improvement and miniaturization of electronic components have led to the development and proliferation of small spacecraft, particularly CubeSats and nanosatellites. One of the applications for these small spacecraft is their exploitation in Low Earth Orbit (LEO) missions. However, the performance and operational reliability of these small spacecraft are influenced by their exposure to space weather phenomena. Some of them will be considered below.

Solar radiation, including ultraviolet (UV) radiation, X-ray emissions, and extreme ultraviolet (EUV) radiation, can affect the performance and longevity of small spacecraft in several ways. Ionizing radiation from the Sun can cause degradation of materials such as polymers, insulation, and solar cells. In a study [1], the authors highlighted the significant degradation in the performance of multi-junction solar cells under high levels of UV radiation-induced degradation.

Galactic Cosmic Rays (GCRs) and solar energetic particles (SEPs) are primarily composed of high-energy protons and heavy ions, and both can significantly influence small spacecraft in Low Earth Orbit. These energetic particles can cause several phenomena in the spacecraft's electronics, including:
- Single Event Effects (SEE), as described above.

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- Total Ionizing Dose (TID) effects, where an accumulation of ionizing radiation over time causes incremental damage to materials, potentially leading to failure.

- Displacement damage, as high-energy particles dislodge atoms in semiconductor materials, degrading their performance.

A study [2] revealed that small spacecraft with thinner shielding materials are more susceptible to the effects of GCRs and SEPs. However, increased shielding often comes with increased mass and cost, a trade-off that must be carefully balanced when designing small spacecraft.

Geomagnetic activity refers to fluctuations in Earth's magnetic field, predominantly driven by solar wind and the Sun's magnetic field interactions. Geomagnetic activity can lead to a phenomenon known as charging, which can affect spacecraft's electrical systems. Differential charging occurs when plasma in the Earth's magnetosphere differentially charges the surface materials; as well as the spacecraft body, leading to discharges and subsequent potential damage to the electronic systems. Similarly, internal charging occurs when penetrating radiation causes charging within dielectric materials, resulting in electrostatic discharges (ESD) that can cause permanent damage to the electronics. A study [3] revealed that geomagnetic activity-induced charging could lead to anomalies in CubeSats and nanosatellites.

Taking into account the possible harmful consequences of space weather events on small spacecraft, it is essential to apply appropriate countermeasures for maintaining spacecraft robustness. Such methods can be divided into three primary groups, as explained below.

- Passive shielding: This involves utilizing materials like aluminium, polyethylene, or combinations thereof, to shield the spacecraft from ionizing radiation. The effectiveness of the shielding must be balanced with the increased mass and power consumption associated with increased shielding thickness [4]. Passive shielding is generally less effective against heavy ions, as the material may generate secondary radiation.

- Active shielding: Active shielding refers to the generation of an artificial magnetic or electrostatic field around a spacecraft to deflect incoming charged particles. Although this technique is still at a conceptual stage, it promises an effective, but complex, method to protect small spacecraft from space weather factors [5].

- Radiation-hardened electronics: Designing and utilizing radiation-hardened electronics can enhance spacecraft resilience to space weather effects. This can be achieved through various techniques, including redundancy, error detection and correction mechanisms, and latch-up protection circuits [6].

Additionally, having a good understanding of the space environment and predicting space weather events is crucial in developing effective radiation mitigation strategies for small spacecraft [7].

2 Methodology

To solve the problems of analysing space weather factors and the influence of space weather factors on small spacecraft, it was necessary to automate the acquisition and processing, followed by visualization of data on energy particle fluxes, as well as X-ray and gamma radiation fluxes from sensors of small spacecraft.

Data on energy particle fluxes, X-ray and gamma radiation fluxes from sensors of small spacecraft are provided by the D.V. Skobeltsyn Moscow State University named after M.V. Lomonosov [8]. The Meteor-M2 spacecraft was chosen as the main source of data due to the fact that it performs global observation of the earth's atmosphere and surface, allowing systematically obtaining hydrometeorological and heliogeophysical information on a planetary scale.
The PHP programming language is used to implement automation of receiving and processing with subsequent visualization of data on energy particle fluxes, X-ray and gamma radiation fluxes from sensors of small spacecraft. Data from small spacecraft were taken from the FTP server of the D.V. Skobeltsyn Moscow State University named after M.V. Lomonosov. The file tree is represented by a directory with the name of the satellite in the root directory, which contains the directories with the years of the received data, which contains the directories with the numbers of the months of the received data. Month directories contain files with data from a specific time range. The described structure of files and directories is shown in Figure 1.

![Fig. 1. Structure of files and directories.](image)

To get data for a specific month, you need to pass a parameter with the year and month, from which a link to a specific directory with files of the required time range is formed. Due to the fact that the FTP server has a web interface, in order to obtain specific files, the final directory should be parsed to obtain hyperlinks to the required data files. This procedure was performed using a regular expression of the form: `<a[^>]* href =([^>]*[^>])[^>]*>(.*)</a>`.

After receiving links from the document, it is required to exclude links to possible directories from the array using a loop, as well as searching for the absence of directory attributes and searching for the presence of the required file extension.

Due to the fact that the structure of the received files is a CSV document with identical attributes of each of the files, the data is converted into a structured array using parsing by key delimiter characters. An example of the structure of CSV files is shown in Figure 2.

![Fig. 2. An example of the structure of CSV files.](image)
Then, using the loop, iterates over the lines of each of the files, excluding comments and isolating the headers of data attributes. The structured data of each file forms an associative array for further processing and API presentation.

To visualize data, you need to prepare an array for its representation in a heat map. At first, you should exclude attributes that are not of interest for visualization. A heat map visualization will require a latitude, longitude, and a measure of the data to be displayed. An attribute with electrons with an energy of ~0.13 keV (which was transmitted as a GET parameter through a request to a web server) was chosen as an example under study. For uniform coverage of the heat map, it was decided to form an array with a step of one degree in latitude and longitude with the calculation of the average value of the indicator from the original data array.

Direct visualization was performed using the Yandex API Maps [9]. A JSON object is formed from the processed array using a loop, which is passed to the JavaScript script by direct embedding into the HTML structure. In the future, the data (coordinates and quantitative indicator of the displayed data (weight)) are put into a variable, which later forms an instance of the Heatmap class.

3 Result

As a result of the application of the developed technology, a heat map with specified parameters is generated (Figure 3).

![Image](image.png)

**Fig. 3.** The result of applying the technology.

Obviously, the areas marked in purple are areas of particular risk for small spacecraft in low Earth orbit. The image clearly shows the zone of the South Atlantic magnetic anomaly, as well as the polar regions.

Taking into account the collected data in relation to the present position of the small spacecraft within Earth's orbit is crucial. As is commonly known, TLE format contains orbit parameters as regularly updated information and is supplied by the Space-Track service [10].
The conversion of TLE into orbital parameters follows the SGP4 model. The PyOrbital software library was employed for performing the calculations. The results of these calculations are depicted using a geographic information system (Figure 4).

![Figure 4. Location of small spacecraft in orbit.](image)

**4 Discussion**

As stated in [3], the percentage of malfunctions and failures in full-sized spacecraft attributed to space weather factors can amount to 60% of the total failures. For small satellites in low Earth orbit, this figure is even higher because of the susceptibility of certain systems to space weather impacts (the inability to install additional protection, the absence of duplication systems, etc.).

The study studied the issue of automating the acquisition, processing, visualization of data on the fluxes of energy particles in near-Earth space. To demonstrate the developed technology, a web application was created that visualizes the average electron values for a month in the format of a heat map of the near-Earth space.

Such visualized data is important for small spacecraft operators in order to make decisions on satellite management and reduce the risks of its operation.

**5 Conclusion**

This research introduces a specialized technology aimed at mitigating the adverse effects of space weather on small spacecraft functionality and prolonging their orbital lifespan. Utilizing this technology and space weather forecasting methods enables rapid response to unfavorable conditions, substantially enhancing the small spacecraft's longevity. In the absence of comprehensive protection systems for small spacecraft, straightforward organizational strategies for risk reduction and improved reliability prove to be the most effective approach to safeguarding them, as these measures can be applied to spacecraft already in orbit.

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References


