Chapter 8

The relation of high- and low-orbit satellite anomalies to different geophysical parameters

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Abstract Satellite anomaly data in the period 1971-1994 were analyzed in the search of possible influence of different space environmental parameters. The database was created by combining, beyond the malfunction information, various characteristics of space weather: geomagnetic activity indices, fluxes and fluences of electrons and protons at different energy, high energy cosmic ray variations, solar wind characteristics and other solar, interplanetary and geophysical data. Satellites were divided on several groups according to the orbital characteristics (altitude and inclination). It was found, that the relation of satellite malfunctions to the environmental parameters is different for various orbits. This fact should be taken into account for the developing of malfunction frequency models.

Keywords Space weather, satellite anomalies, geomagnetic activity, proton enhancements, relativistic electrons

1. INTRODUCTION

Satellites usually spend several years in the space under the influence of variable electromagnetic fields, plasma and different radiations. Since satellites are not protected by the atmosphere and to some extent also by the magnetosphere, they are much more exposed to the cosmic radiation than ground level devices. This is one of the reasons why space weather changes can be hazardous for satellites. It is known that high energy cosmic rays (CR) of galactic and solar origin lead to single-event upsets (SEU) in

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microelectronic devices; low energy electrons create electric charge on the satellite surface and can cause solar battery degradation; and high energy electrons may create volume charging inside the satellite and damages to the operating electronic (see e.g., Adams et al., 1981; Gussenhoven et al., 1985; Wilkinson et al., 1991; Shea et al., 1992; Wrenn, 1995; Baker et al., 1998). Geomagnetic storms are also dangerous for satellites, not only because of electromagnetic field variations, but also because of their influence on the charged particle access to a particular orbit and on particle precipitation from radiation belts (Lanzerotti, 1979; Wilkinson, 1994). During magnetic storms the density of the upper atmospheric layers increases; this may cause changes in the orbit for the low-orbit satellites, and even the loss of their orientation. The fuller listing of satellite failures with space weather association can be found in the literature (see e.g., Stephen, 1993; Fredrickson, 1996; Koskinen et al., 1999; Feynman and Gabriel, 2000). Anyway, it is clear from all results, that the influence of space weather on satellites is complicated and variable. Besides, a degree of this influence and possible damages depend significantly on the satellite location and characteristics (e. g. Vampola, 1994; Hastings, 1995). Two basic methods can be used to estimate the probability of satellite anomalies: 1) a search for relation between anomalies and global characteristics of space weather to create the models suitable for all satellites or for groups of satellites; 2) an environmental monitoring on separate satellites and the estimation of danger based on these local observations. Both approaches seem to be insufficient. On one side, computations cannot replace measurements in situ. On the other side, single satellite observations cannot furnish a complete picture of the environmental variations. It would be convenient to combine the two approaches.

In this paper we analyze the relationship between satellite malfunctions and different geo- and helio-physical parameters. For this work we use either environmental characteristics out of magnetosphere, or global characteristics of magnetosphere, as the planetary indices of geomagnetic activity. We will also take into account the main specific features of satellites represented by their orbital characteristics.

2. DATA AND METHODS

Data on satellite anomalies and different characteristics of space weather were combined into a special database (Belov et al, 2003). The main part of satellite malfunction data was taken from NGDC satellite anomaly database (Wilkinson, 1994). A substantial contribution was also given by "Kosmos" satellite data (circular orbit at 800 km altitude and 74° inclination). The majority of anomalies in 1994 were taken from NASA report (Thomas, 1995). The satellite characteristics have been taken from different Internet sources (http://spacescience.nasa.gov/missions/, http://www.skyrocket.de/, http://www.astronautix.com, http://hea-www.harvard.edu). Our database is formed by a total of ~300 satellites and ~6000 anomalies. Since the information on satellite anomalies before 1971 and after 1994 was rather fragmented, we limited our study for the period 1971-1994. However, within this interval the information on malfunctions is not uniform (see Figure 1).

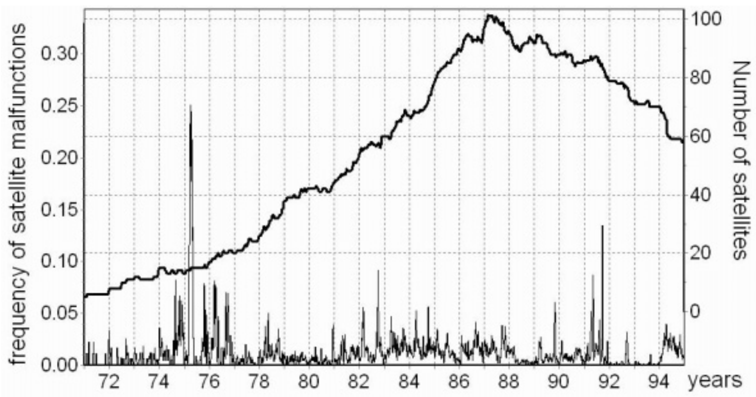

Figure 1. Number of satellites giving information about malfunctions, and frequency of satellite malfunctions ($day^{-1} \cdot satellite^{-1}$) in the period 1971-1994.

The high frequency of anomalies in 1974-1976 is caused by very small number of satellites operated in this period. The maximum number of satellites occurred in 1987; this feature and the following decrease does not look real. Unfortunately, the data incompleteness (the majority of satellite owners prefer not to give information on malfunctions) poses additional problems to the analysis.

All satellites were divided into different groups according to the altitude and inclination of their orbits. In Figure 2 each orbit is presented by a different mark. Sometimes, one point represents many satellites with very close orbits, as the majority geostationary satellites (>100), and 49 "Kosmos" spacecrafts. Since there are no satellites within the wide range 1500-15000 km, the altitude division of satellites was rather easy. It was more difficult to divide satellites according to the orbital inclination. On one hand, it was important to separate orbits fully inside the magnetosphere from those only partly inside. On the other hand, we admit that the "Shuttle" spacecrafts are too specific to be combined with the other satellites. Finally we chose 58^{o} as the inclination boundary.

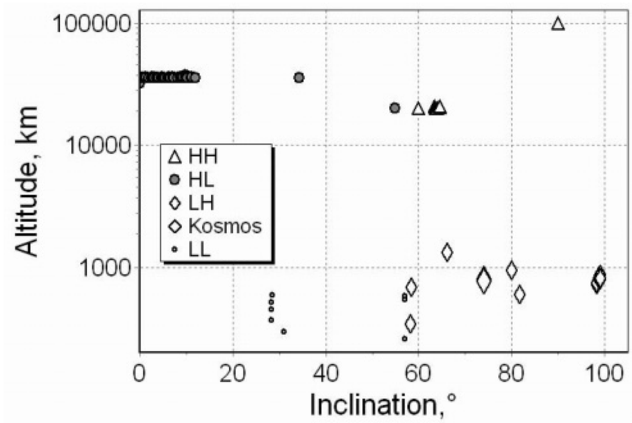

Figure 2. Altitude-inclination distribution by the of the satellite orbits.

As a result, four groups were obtained, with essentially different physical conditions on the orbits: HL (high altitude-low inclination), HH (high altitude-high inclination), LH (low altitude-high inclination) and LL (low altitude-low inclination). HL group contains all GEO satellites and is the most abundant. LH group is approximately the half of HL in number, and it is formed with important share of "Kosmos" satellites. HH group comprises only 14 spacecrafts, but they displayed more than 1000 anomalies. We have here mainly MEO satellites, but the main difference of this group from LH is not in the altitude but in the orbit inclination. LL group (mainly piloted spacecrafts with the special price of malfunctions) is also important. Unfortunately, this group is too small to be discussed here. Sometimes we combined all low and all high orbital satellites together. Satellite malfunctions, unlike the satellites, were not divided on the groups and were not filtered.

We calculated the mean frequency of malfunction (i.e. the number of malfunctions per day and per satellite) for all satellites and for every separate group (only satellites having more than one malfunction were considered). We analyze only daily mean data. This defines the possibilities and peculiarities of our research. We cannot study short-time features (for example, the local time effect) because our data are not so detailed. They have to be better correlated with large-scale effects and with global rather than local conditions. Naturally, this kind of approach limits the possibilities of analysis. Nevertheless, it has some advantages: daily mean data are more reliable, diverse and available and less dependent on occasional factors.

2. RELATION OF SATELLITE ANOMALIES TO DIFFERENT SPACE WEATHER PARAMETERS

2.1 Two examples

Satellite malfunctions are very irregularly distributed by the time. Some days there is no anomalies, in other days, tens malfunctions are given by several satellites. One famous period (e.g. Allen et al., 1989) with high frequency of malfunctions was October 19-26, 1989 (see Figure 3).

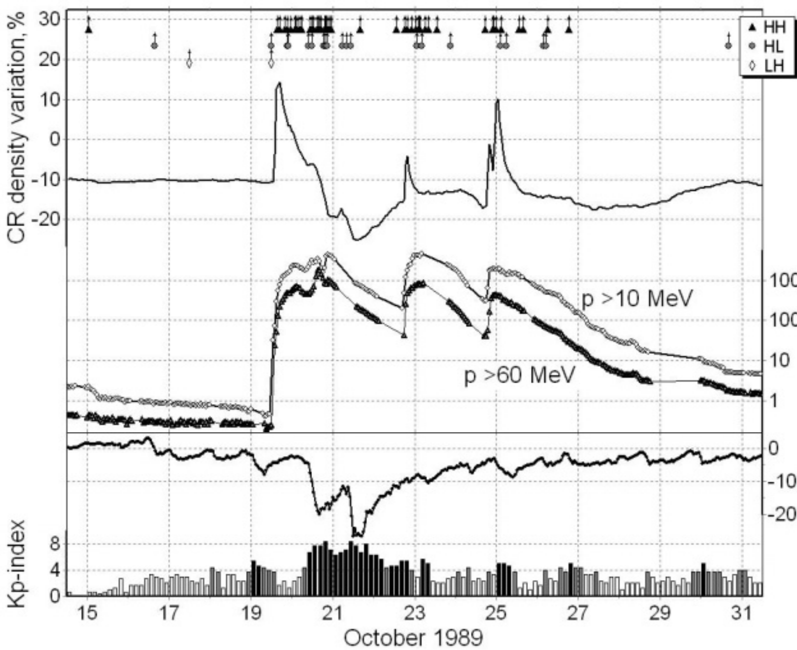

Figure 3. Period with large number of satellite malfunctions in October 1989. Upper panel – cosmic ray activity near the Earth: variations of cosmic ray density, obtained from neutron monitor network; solar proton fluxes (>10 MeV and >60 MeV) recorded by IMP-8. Lower panel – geomagnetic activity: Kp- and Dst-indices. Vertical arrows with points on the upper panel indicate the malfunction in different satellite groups.

In this period we observed several proton events, three Ground Level Enhancements (GLE) of solar cosmic rays (on October 19, 22 and 24), big Forbush-effects, strong geomagnetic storms, including a severe (maximal Kp =8+ and minimal Dst-variation –268 nT) storm on October 20-21. CR variations, derived from neutron monitor data by the global survey method (Belov et al., 1999a), correspond to 10 GV rigidity of galactic CR and to ≈3

GV during GLE. Malfunctions look to be coincided immediately with the maximum of proton enhancements. This connection becomes more evident if we consider the satellite groups. Only one from 73 malfunctions occurred at low altitude, 19 anomalies were recorded at geostationary orbits, and the majority occurred in the HH group, which is maximally exposed to the solar cosmic ray effect. There is usually much smaller number of satellites in this group than in HL (GEO) group, and in this period it was 5.5 times smaller. Thus, on 20 October the malfunction frequency in high altitude-high inclination group was higher than in GEO group by a factor 30.

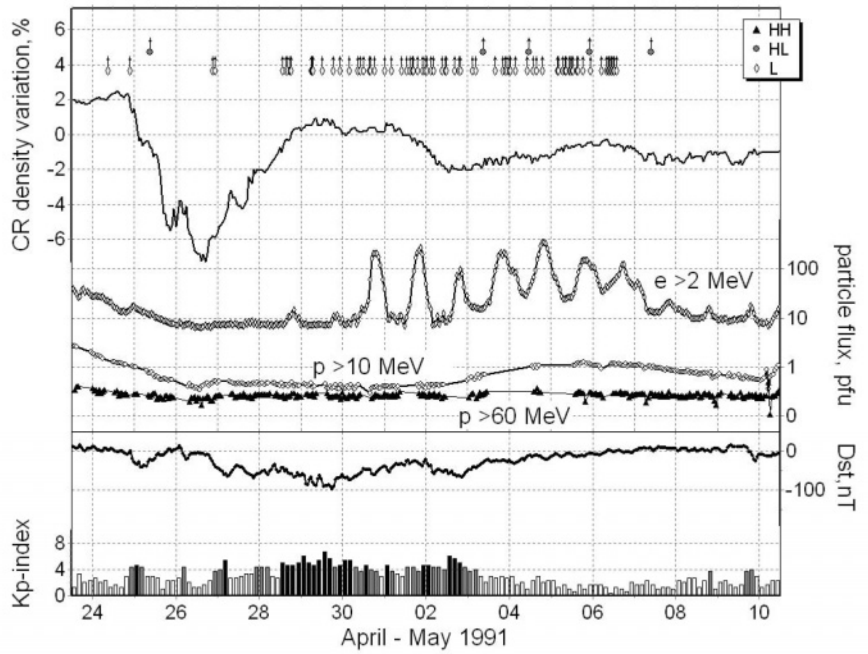

Figure 4. Period with large number of satellite anomalies in 1991. Upper panel – cosmic ray activity near the Earth: variations of cosmic ray density, obtained from neutron monitor network, solar protons of >10 MeV and >60 MeV (IMP-8) and electron fluxes of >2 MeV (GOES). Lower panel – geomagnetic activity: Kp- and Dst-indices. Vertical arrows with points on the upper panel indicate the anomaly in different satellites groups.

Another sample of high frequency satellite malfunctions is presented in Figure 4 for the period April-May, 1991. Here we see a strong magnetic storm (maximal Kp =7- and minimal Dst-variation –97 nT) and big Forbush-effect. There was no significant proton increases, but the flux of relativistic electrons retained on high level during a week. The main amount of malfunctions happened during the magnetic storm and high electron flux period.

The main feature of this period is that malfunctions were entirely absent in HH group, which played the main role in previous example, and majority of anomalies was observed in low orbital satellites with share of GEO group.

These two examples illustrate a relation between satellite malfunctions and space weather, but this relation is different for different satellite groups. Low correlation has been found between anomaly frequencies at high and low altitudes not only in these examples. Considering the events from our whole database we found out that satellite malfunctions appeared usually on different days at high and low altitudes. Through the period 1975-1994 there was 948 days with ≥2 malfunctions at high and 154 days – at low altitudes. Only 11 days from these subsets coincide. Correlation coefficient between malfunctions at different altitudes over the 1975-1994 was found <0.01. It was close to 0 for any long enough period (3 years or more). The only exclusion were 1992-1994 years, when correlation coefficient increased up to 0.19, that is very probably associated with the increased electron fluxes. Low correlation between anomalies in different satellite groups is the evidence either of the effect of different factors on different groups, or of different character of the same factor influence.

2.2 Seasonal dependence

It is well known that satellite malfunctions have a seasonal dependence, and this is considered as one of the evidences of the relation of anomalies to environmental parameters (e.g. Allen, 1990). In Figure 5 the annual behavior of the malfunction frequency averaged over the period 1975-1994 is presented. To reduce the effect of short-term variations the 27-day running means have been computed. The main feature of this dependence is a semi-annual variation with maxima close to equinoxes. This seasonal behavior is characteristic for the geomagnetic activity indices. We processed Ap-index of geomagnetic activity for the same period and by the same method as the malfunction frequency (see Figure 6).

The comparison between Figures 5 and 6 indicates the similarity of seasonal variations in geomagnetic activity and in satellite malfunctions. Both of them are much higher during spring and autumn than during summer and winter. In these 20 years the spring geomagnetic activity dominated the autumnal one, and the same feature is repeated in the behavior of satellite anomaly frequency. It should be noted that seasonal dependence in the satellite anomalies is better pronounced than in Ap-index. The effect is so big, that it appear to be reasonable that significant amount (or possible, the majority) of satellite anomalies are associated with the environmental changes. Seasonal dependence was calculated separately for different satellite groups. It was mostly pronounced in HL (GEO) group. In the LH (low altitude – high inclination) group this dependence is approximately in 3 times less, and it is almost absent in HH group.

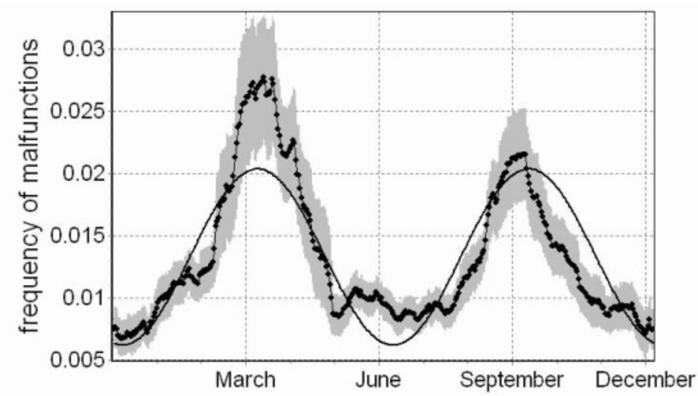

Figure 5. Seasonal dependence of satellite malfunction frequency averaged over the period 1975-1994. The curve with points is the 27-day running mean of frequency; the grey band corresponds to the 95 % confidence interval. The sinusoidal curve is a semidiurnal wave with maxima in equinoxes best fitting the frequency data.

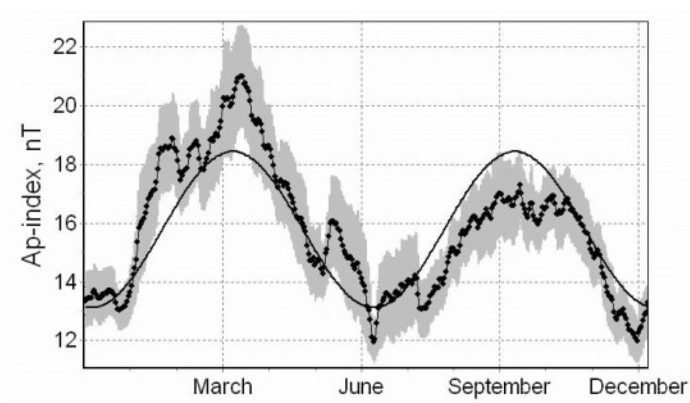

Figure 6. The same as in Figure 5 for the Ap-index of geomagnetic activity.

2.3 Space-weather environmental parameters

The behavior of the daily mean frequency of satellite malfunctions was compared with different characteristics of solar, interplanetary, geomagnetic and cosmic ray activity connected with space weather conditions on the satellite orbits.

Solar activity. As total characteristics of solar activity we used daily sunspot numbers and radio flux at 10.7 cm, as provided by NOAA (ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA). Since the relation of satellite malfunctions with daily solar characteristics was found to be very weak, we used in addition the running means of sunspot numbers, averaged over one year and one solar rotation.

Geomagnetic activity. Ap-, AE- and Dst-indices of geomagnetic activity (ftp://ftp.ngdc.noaa.gov) have been used. We used daily means, and the extreme values of indices: daily maximum value of the 3-hourly Ap and AE indices and minimum hourly value of Dst-index.

Interplanetary medium. Daily mean and maximal hourly solar wind speed and daily interplanetary magnetic field (IMF) intensity were taken from OMNI database (http://nssdc.gsfc.nasa.gov/omniweb/ow.html) as characteristics of near Earth interplanetary space. Some indices were based on the B_z-component of IMF, determined in GSM-coordinates: daily mean and minimal hourly B_z-component and daily sum of negative B_z values. Besides, for all days with sufficient IMF and solar wind velocity data, we estimated the energy transferred into the Earth's magnetosphere, according to Akasofu (1981).

Protons and electrons. Daily fluences of protons of different energies (>1, >10 and >100 MeV) and electrons of >2 MeV energy, calculated from the GOES (ftp://ftp.ngdc.noaa.gov) measurements, have been used as main cosmic ray characteristics. Unfortunately, these data are available only from January 1987 (protons) and from June 1987 (electrons). Together with GOES data, we used the proton fluxes of >10 MeV and >60 MeV, measured by IMP-8 and available in OMNI base for the whole period. To analyze some separate periods we used also electron fluxes >2 MeV from GOES satellites. These data were not included in the model calculations because they are probably contaminated by proton fluxes.

Ground level cosmic rays. We used cosmic ray activity (CRA) indices (Belov et al., 1999b), which characterize the behavior of CR of 10 GV rigidity. They are calculated on the basis of hourly means of CR density and parameters of the first harmonic of CR anisotropy derived from the neutron monitor network by the Global Survey Method. Two different indices were compared with the satellite anomalies: CRA-index based on the CR density and anisotropy, and a simplified index, accounted by density variations only.

CRA indices are strongly connected with the interplanetary and geomagnetic disturbances, and sometimes the greatest proton enhancements are visible in their time behavior.

2.4 Satellite anomalies and SSC

The frequency of malfunctions should vary significantly under sharp changes of the environmental conditions. Space weather strongly changes at the moment of sudden commencements of magnetic storm (SSC), when the interplanetary shock and the solar wind disturbance behind of shock start to interact with the magnetosphere. By analyzing the average behavior of satellite malfunctions by the epoch method, we found that the malfunction frequency increases after SSC.

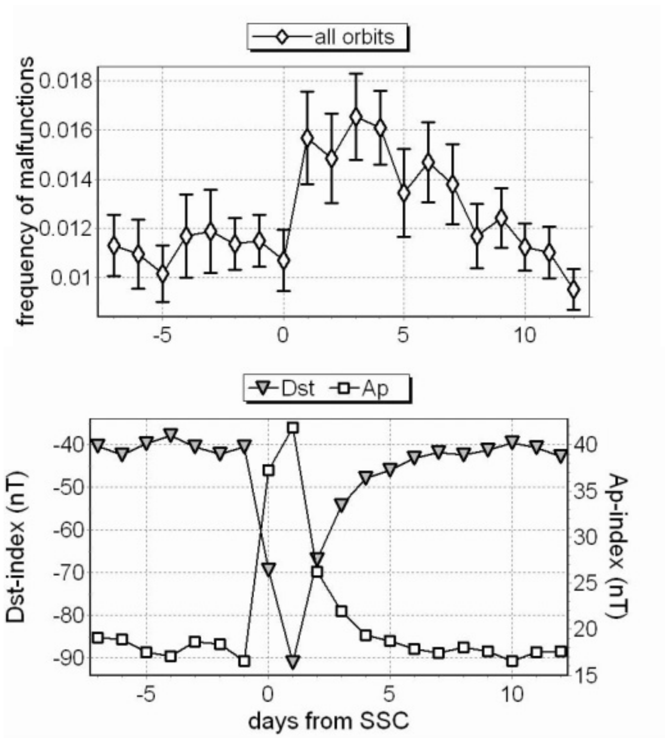

Figure 7. Average behavior of the satellite malfunction frequency, Ap- and Dst-indices in periods of sudden storm commencements. The average was done by epoch method (0 – day of SSC) for 388 magnetic storms with maximal Ap-index >50 nT during 1975-1994.

The largest malfunction frequency increase is observed after SSC in HL-group at geostationary orbits, and it grows with the increase of the magnetic storm power. In Figure 7 the average variations of the malfunction frequency are presented for magnetic storms with maximal Ap-index >50 nT. For less powerful storms the variations were smaller, for more powerful – bigger. This relation between the magnitude of the effect and the storm power could indicate a direct influence of geomagnetic activity on the malfunction probability. However, one can see from Figure 7 that the frequency increase starts after the magnetic storm onset and lasts much longer. Hence, satellite malfunctions seem to be not always directly related to geomagnetic activity, but depends on some other factors.

2.5 Relation of anomalies to protons and electrons

Space weather changes rapidly not only during SSC, but also during proton increases. Analysis done by epoch method showed that the

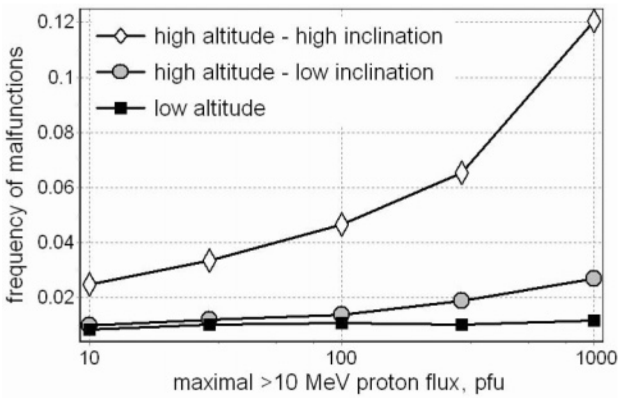

Figure 8. Mean normalized anomaly frequency in the first two days of proton enhancement at different orbits in dependence on maximal >10 MeV proton flux.

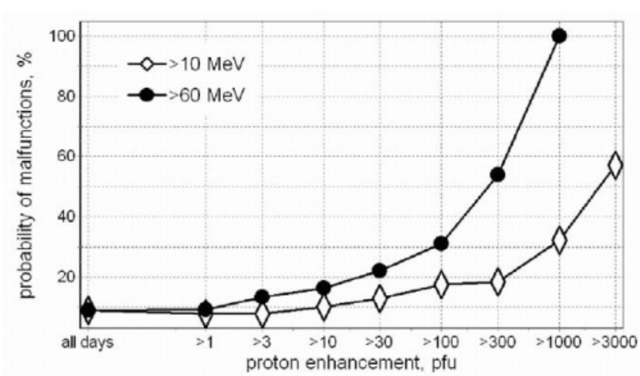

Figure 9. Averaged probability of satellite anomalies in high altitude – high inclination group for days with different maximal proton fluxes of > 10 and >60 MeV (IMP8 data).

frequency of anomalies at high altitudes was significantly larger in the first day of the proton event and also the next day. Moreover, the frequency of anomalies increased with increasing the proton flux. This effect is especially pronounced in the HH group (see Figure 8).

A further evidence of linkage between anomalies registered in HH-group of satellites and proton enhancements is given in Figure 9. As an average, one anomaly per 10 days is registered for satellites in this group, but the anomaly probability increases with the proton flux increasing, and goes to 100% for the days of very big proton events

Electron enhancements, in contrast to the sharp proton enhancements, very often start in a gradual manner. For their study we used a different version of the epoch method, in which the day of each anomaly was chosen as zero-day. Figure 10 shows that the mean fluence of relativistic electrons was maximal in the day when the anomaly was registered. It is important that the electron fluence arises significantly some days before the malfunction. The electron flux variations appeared to be crucial for HL (GEO) and LH groups, but not for the HH group of satellites.

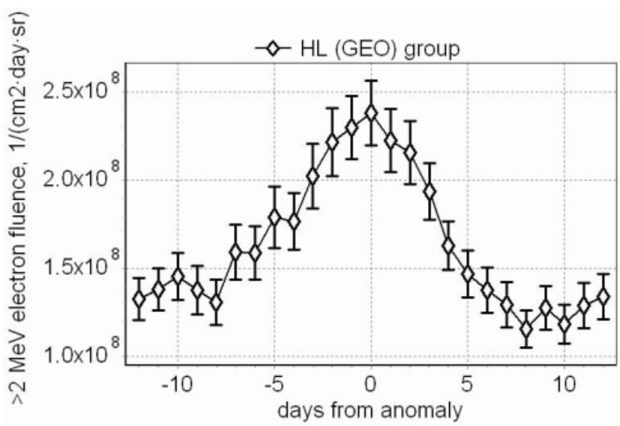

Figure 10. Electron fluences in 1987-94 averaged by the epoch method. 0-day is the satellite anomaly day.

Fig. 11 shows a difference in proton and electron result on anomalies for different orbits. In the anomaly day the mean proton fluence is much higher in HH group than in other groups. LH group is mainly electron-dependent, and HL group may be considered as mixed one.

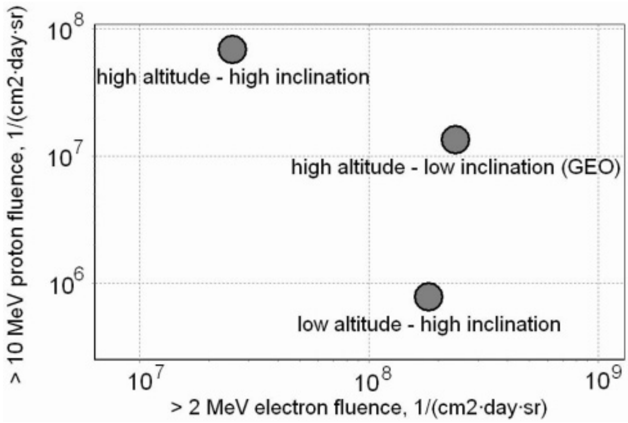

Figure 11. Mean proton and electron fluences in the anomaly day (1987-1994).

2.6 Modeling of satellite anomaly frequency

We examined a relation between different space weather parameters (>30 in total) together with their combinations, and satellite anomalies at different orbits in 1987-1994. This period of time was chosen, because of the presence of electron fluence data, that is very important for the modeling.

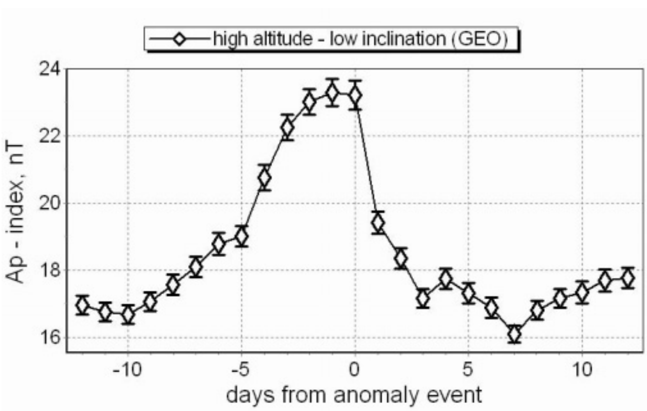

Figure 12. Averaged Ap-index in 1975-94 obtained by the epoch method. 0-day is the anomaly day.

An increase of the environmental index some days before the satellite anomaly, as shown in Figure 10, is a characteristic behaviour not only for electrons, but also geomagnetic activity (see Figure 12), solar wind speed and some other indices as well. It leads to a conclusion, that there are special recurring conditions lasting several days in space environment, which may be considered as a factor contributing to initiate satellite anomalies. Independently on the reasons or nature of this kind of anomaly precursors, it is possible and necessary to use them for modeling and forecasting. Thus, in our modeling we used space weather parameters for the anomaly day, and for several preceding days. The simple linear regression simulation was used. However, links of registered anomalies with electron, and especially with proton indices appeared to be non-linear (see Figure 8). Therefore, we applied, as an exception, power law dependence for the proton and electron fluxes and fluences.

Models of anomaly frequencies were obtained in three steps due to big number of space weather characteristics. Firstly, for each index simple regression analysis was performed and those that demonstrated the higher correlation with frequency of anomalies were chosen. Such indices for HL group of satellites, for example, were solar wind velocity, >2 MeV electron fluence, geomagnetic activity indices Ap and Dst, flux of proton with energy >60 MeV. Then 3-5 indices that show the best correlation were combined in a many-parameter model. The best indices from the first step not always retained the best at the next stage. For instance, solar wind velocity can show better correlation than electron fluence when they are correlated separately, but in a model comprising both parameters, solar wind index become of the second importance. On the last phase we added remaining indices one by one and if the model was improved significantly, these characteristics were kept in the model. Some peculiarities of obtained models, simulating the frequency of satellite malfunctions by means of 5-8 different indices, are presented in Table 1. Index sequence and letter size in the names of parameters reflect the contribution of this index to the model.

Table 1. Models of the satellite malfunction frequency.

Group	HL	HH	LH
Parameters of model	**e2** p100, p60d sf, Ap, Vsw Bz, da10	p60d, p100 Eak SSN365, Bzns	**e2** Dst,AE,sf,CRA,Bz Vsw

Explanations to the Table: e2 and p100 – >2 MeV electron and >100 MeV proton fluences (GOES); p60d – daily mean flux of >60 MeV protons (IMP8); Ap and AE –indices of geomagnetic activity, Eak – estimation of energy incoming to the magnetosphere (Akasofu, 1981); Vsw – solar wind velocity; Bz – daily mean B_z-component of IMF, Bzns – sum of negative values Bz- component; SSN365 – yearly running averaged sunspot number;

CRA and da10 - cosmic ray activity indices, obtained from neutron monitor network data. Seasonal factor sf (semi-annual variation with maxima on equinoxes) was used as one of the independent parameters.

Correlation coefficients k between observed and simulated values of anomaly frequencies are k= 0.24 for LH satellites, k= 0.39 for HL and k= 0.7 for HH – satellite groups. The model examples for frequency of anomalies f in different satellite groups are given by the following expressions in 10^{-4} $day^{-1}satellite^{-1}$ units:

$$f_{HL} = -54 + 1.4\cdot 10^{-9}\langle e2\rangle_4^{1.2} + 0.83\langle Ap\rangle_5 + 0.19\langle Vsw\rangle_2 - 0.15\langle Bz\rangle_3$$
$$+ 1.1(p100)^{0.35} + 1.6(p60d)^{0.75} + 20sf + 1.5da10;$$
$$f_{LH} = -16 + 2.2\cdot 10^{-7}e2 + 0.29\langle AE\rangle_2 - 26\langle Bz\rangle_7 + 0.83\langle Dst\rangle_6$$
$$+ 45\cdot sf + 8.9\langle CRA\rangle_4 + 0.23\langle Vsw\rangle_2;$$
$$f_{HH} = -85 + 6.5(p100)^{0.35} + 2.6(p60d)^{4.4} - 0.53\langle Bzns\rangle_4 + 14\langle Eak\rangle_4$$
$$+ 0.09\cdot SSN365.$$

where $\langle a\rangle_n$ is the a parameter averaged by the day of anomaly together with n-1 preceding days. The units used in this expression are: nT for Ap, Bz and Bzns, km/s for Vsw, % for da10, $electrons\cdot day^{-1}\cdot cm^{-2}\cdot sr^{-1}$ for e2, $protons\cdot day^{-1}cm^{-2}\cdot sr^{-1}$ for p100, and in $protons\cdot sec^{-1}\cdot cm^{-2}\cdot sr^{-1}$ for p60d. SSN365 and normalized Eak are in dimensionless units, dimension of the coefficients and parameters in the equations is omitted.

These equations are presented here as model illustration. They should not be considered as accurate or the only possible description. This is a basis for more advanced models. The coefficients and even kind of model clear to be strongly dependent on chosen time period and satellite set. They will be dependent on many occasional factors as, for example, data gaps. More stable are the sets of parameters involved in the models for different satellite groups and presented in Table 1.

3. CONCLUSIONS

The obtained models describe the relation of the occurrence of satellite anomalies to the space weather parameters in rather complex way and they differ significantly for different satellite groups. They combine the cosmic ray and geomagnetic activity indices, solar wind characteristics and some other parameters. The characteristics of the obtained models allow them to be used for the satellite anomalies forecasting. However, it is difficult to apply these models to the majority of present satellites. The models are obtained for the anomalies registered 10 years ago or even earlier. Nowadays, satellites, and especially their electronic parts, are completely different. However, some features of the obtained models, as their multi parameter nature, accounting for the global characteristics of space weather and difference for various orbits, should be still valid. Models of satellite anomaly frequency should be improved. First of all it is necessary to increase the malfunction database; during our analysis we were permanently aware that our anomaly database was not representative enough. Moreover, the models can be improved by combining global and local (registered in situ or calculated for the location of the satellite) parameters; by taking into account in more details the satellite position at the time of the anomaly occurrence (local time, latitude); and considering the individual characteristics of satellites (mass, lifetime and others) and the type of anomaly.

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