Astronomical and Astrophysical Transactions (*AApTr*), 2024, Vol. 34, Issue 4, pp. 325–342,
ISSN 1055-6796, Photocopying permitted by license only, ©Cambridge Scientific Publishers

The International Space Station as an indicator of space weather processes

V.H. Komendant*

Space Research and Technology Institute, Bulgaria, Acad. Georgy Bonchev Str., Bld. 1, Sofia, 1113

Received 12 March, 2024; accepted 18 June, 2024

The analysis of the International Space Station (ISS) drag data during the period from 2005 to 2019 was carried out. In the analysis the B-star drag term was applied. This coefficient reflects the influence of changes in the state of the atmosphere on the movement of artificial objects in the Earth's orbit. The correlation analysis of the B-star drag term with the indexes of solar and geomagnetic activity at different time intervals and phases of 23 and 24 solar activity cycles was carried out. The time periods of the ISS movement when significant adjustments were not made to the station's orbit and the reception of planned missions were selected. The periodograms were built for these periods. The influence of the indexes of the wave component of solar activity have a longer trend character, while the indexes of the corpuscular component are short-period. For the selected observation intervals, the identification of the majority of the found periodicities in the drag coefficient B-star and the indexes of solar and geomagnetic activity was carried out on the basis of data on the correlation coefficients. This study is the initial stage of work of the construction of multiple correlation models.

Keywords: ISS, atmosphere, ISS drag, solar activity, geomagnetic activity, space weather

1 Introduction

The International Space Station (ISS) is an important and unique research facility. Many biological, meteorological, astronomical, physical and cosmological experiments associated with the presence of unique conditions that have no analogues on the Earth's surface are conducted in the station. It is subject to drag due to changes in the density of the atmosphere, like any object launched into low-earth orbit. The position of the station in orbit is constantly monitored and if it is necessary its height is corrected. The change in the ISS altitude occurs as a result of its drag in the Earth's atmosphere, which changes its density under the influence of solar wave and corpuscular activity.

*Email: votan1360@gmail.com

To ensure the safety of the crew and the stability of its orbit the station is continuously monitored. The ISS orbital parameters can be found in the two-line orbital element set (TLE). This format is freely available from NORAD (North American Aerospace Defense Command). These orbital elements are given from three to 5 times a day (after 5–3 turns of the station around the Earth).

The works about changes in the ISS orbital parameters [1] and episodic changes in the station's orbital period at times of strong solar flare activity (M and X class flares in January 2014) [2] were published in 2014. The first study shows the possible influence of the non-sphericity of the Earth's gravitational field and its compression on some elements of the ISS orbit. In the second, an attempt is made to find out what caused the drag and rise of the station, when the influence of external factors is not obvious. The paper by T. Mendaza et al. "Influence of interplanetary coronal mass ejection on the density of the thermosphere according to the orbital data of the International Space Station" (2017) [3] provides information about the reaction of the total neutral density of the thermosphere to the impulse effect of solar activity from 2001 to the end of 2006. Their results (obtained by the General Perturbation Method) show that the parameters of the ISS orbit can be used to determine the density of the thermosphere and analyze the solar impact on it.

These three works reflect the fact that solar and geomagnetic activity significantly affects the state and basic parameters of the Earth's upper atmosphere. In this case, the influence of solar activity is manifested in two main factors: wave radiation and corpuscular flows. However, a complete analysis of the periodic and anomalous decelerations of the ISS has not yet been carried out.

In this paper, the International Space Station is used as an indicator of the impact of space weather on the Earth's upper atmosphere [4, 5].

2 Data used

The ISS is a manned station with a mass of 418 tons and a length of 109 meters, located at an altitude of about 400 km. Orbital inclination i = 51.6°; e = 0.00037; r_{min} = 372 km; r_{max} = 382 km, where i – the inclination of the orbit, e – the value of the eccentricity of the orbit, r_{min} and r_{max} – the average value of the minimum and maximum distances from the Earth's surface.

These observations cover the period of a prolonged minimum at the end of the 23rd solar cycle, the growth, maximum and decline phases of cycle 24 (04.03.2005–31.12. 2019). The B-star drag coefficient (drag term) is used in this work. This coefficient is used in the SGP and SDP models to take into account the atmospheric drag on the satellite motion and illustrates the satellite's susceptibility to atmospheric drag in orbit [6].

SGP models are applied to objects near the Earth with orbital periods of less than 225 min. These models take into account the influence of perturbations caused by the shape of the Earth, the resistance of the atmosphere and radiation from the Sun [7, 8]. The SDP models are applied to objects with orbital periods greater than 225 min that correspond to the altitude of 5877.5 km, assuming a circular orbit. These models take into account the gravitational perturbations caused by some other objects such as the Sun and the Moon [7, 8].

Since the solar wave and corpuscular radiation increase the temperature of the atmosphere, the density increases in its higher layers, therefore, the drag force affecting the satellite increases.

In these models the ballistic coefficient B is calculated by the formula:

$$B = \frac{C_D \cdot A}{m};$$

where B – the ballistic coefficient, C_D – the aerodynamic drag coefficient. If the mean free path of air molecules is much larger than the geometric size of the satellite, then C_D is close to 2, A – the midsection area (cross-sectional area of the satellite), m – the satellite mass.

The B-star drag term coefficient is related to the ballistic coefficient by the formula:

$$B^* = B \cdot \frac{\rho_0}{2};$$

where B^* – the modified ballistic coefficient or B-star drag term, B – the ballistic coefficient, ρ_0 – some standard density value for a given altitude. The B-star drag term coefficient has the dimension of $1/R_E$, where $R_E = 6\ 371$ km is the radius of the Earth.

A number of difficulties arise, some of which are associated with calculation of the atmospheric wind speed perpendicular to the cross-sectional area of the satellite, and the impossibility of accurately taking into account the C_D parameter. Thus, all models, when estimating the B parameter, correct it so that the calculated parameters correspond to the observed positions of the object in the best way. For this reason, this work uses just this coefficient. The coefficient reflects only the atmospheric effect on the object under study [9].

Many factors of gravitational and non-gravitational nature affect the flight of artificial objects in near-Earth orbit. In this work, the factors associated with the gravitational nature are excluded by choosing the B-star coefficient as the analyzed parameter. Solar and geomagnetic activity have a significant impact on the change in the satellites orbit among the disturbing factors of a non-gravitational nature.

The wide range of indices reflecting the state of space weather are used in this work: W – Wolf numbers; S_p – the total area of the sunspots, F10.7 – the radio emission from the Sun at the wavelength of 10.7 cm, TSI (total solar irradiance) – the solar constant, L_α – the Lyman alpha radiation, E – the fluxes of electrons with energies greater than 0.6 MeV and 2 MeV, the solar wind parameters, IMF – the interplanetary magnetic field, A_p – the planetary geomagnetic index, D_{st} (Disturbance Storm Time Index) – the index of the intensity of geomagnetic storms.

The Wolf number and the total area of the sunspots characterize the 11-year cycle of solar activity.

The F10.7, TSI and L_α indexes characterize the wave component of the solar ionization radiation.

The radio emission from the Sun at the wavelength of 10.7 cm, F10.7, characterizes the wave flux, which correlates with the ultraviolet and the X-ray fluxes of the Sun.

The TSI is a measure of the amount of solar energy received by a body located at a certain distance from the Sun. For the Earth, TSI is defined as the solar energy received per unit area in the upper atmosphere with an average distance from the Earth to the Sun equal to 1 AU. The TSI is approximately 1.35 kW/m^2. This

"constant" changes every day, as does sunspot activity, and over longer periods of time depending on the solar cycle This constant reflects the change in the total energy flux of solar radiation.

The Lyman alpha radiation, L_α, is a spectral series in the spectrum of the hydrogen atom, was named after the physicist Theodore Lyman, who discovered this series in 1906. The series is formed during transitions of electrons from the high energy levels to the first one in the emission spectrum and from the first level to all others during absorption. At normal conditions, L_α is located in the ultraviolet region of the spectrum.

The electron fluxes with energies greater than 0.6 MeV and 2 MeV, E, and the solar wind parameters reflect the corpuscular component of the Sun's activity. They reflect the effect on ionospheric currents, which forms the magnetosphere.

The indexes IMF, A_p, and D_{st} show the disturbance of the interplanetary environment, the magnetosphere reaction to changes in the conditions in the interplanetary environment, and the intensity of disturbances in the magnetosphere, respectively.

The interplanetary magnetic field, IMF, is a component of the solar magnetic field, which is pulled from the solar corona by the flow of the solar wind and fills the solar system.

The planetary geomagnetic index, A_p, characterizes the degree of the solar activity effect on the magnetosphere.

To analyze the magnetic storms, the D_{st} index is used. It is an axisymmetric component of the perturbed magnetic field with respect to the geomagnetic dipole and is determined on the basis of magnetic field measurements at four near-equatorial stations: San Juan, Hermanus, Kakioka, Honolulu.

A detailed graph of the change in the drag coefficient for the period 2005 is shown in Fig. 1(A). It shows a character of the change in the value of the B-star coefficient. The sharp increases in the coefficient (which can be seen on the graph) are the evasion maneuvers or moments of docking and undocking to the space station. The deceleration of the ISS as an object for analysis is very specific. It can be seen from these data. Its height is regularly corrected in addition to evasive maneuvers of the station and docking with it of planned missions. They are clearly demonstrated by the graph of the change in the major semiaxis of the international station in Fig. 1(B).

The time periods between two successive corrections of the altitude of the international station were selected for the analysis. These periods have as few maneuvers as possible. The longest periods between the ISS orbit adjustments were selected. As a result, five periods were obtained for analysis: 1) 28.03.2005–11.05.2005; 2) 16.01.2009–17.03.2009; 3) 31.03.2009–28.06.2009; 4) 15.09.2012–04.10.2012; 5) 03.11.2012–16.12.2012.

The correlation coefficients of the B-star parameter with the indexes of solar and geomagnetic activity were calculated for these five periods. All anomalous points in the B-star coefficient data were removed prior to this. An example of a change in the coefficient excluding periods of orbit corrections and station maneuvers is shown in Fig. 2.

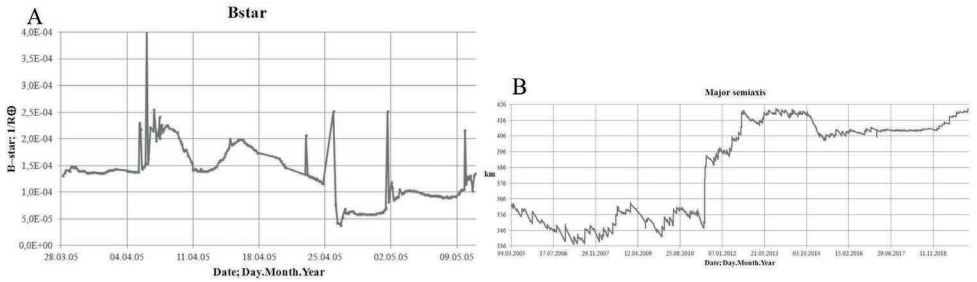


Figure 1 Change in: B-star for the ISS for April–May 2005 **(A)**; The major semiaxis for the ISS for the period 2005–2019 years **(B)**. The B-star coefficient data was taken from the archive (https://celestrak.com/NORAD/archives/).

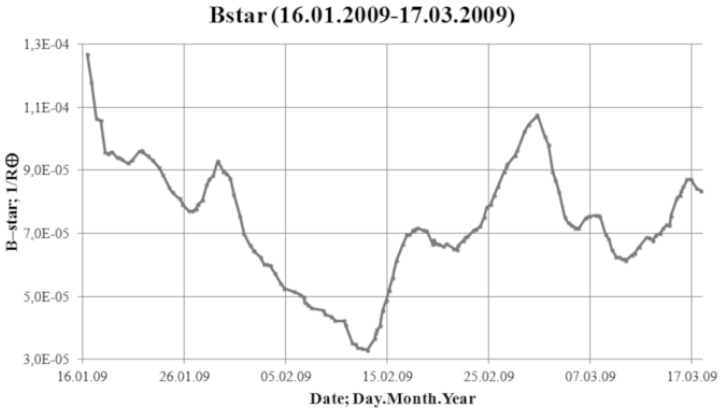


Figure 2 Change in B-star for ISS without data of adjustments and maneuvers for January–March 2009.

3 Results

3.1 Correlations for initial data

The most significant correlation coefficients of B-star with the indexes of solar and geomagnetic activity are shown in Table 1. There is no strong correlation of B-star with the indexes of solar and geomagnetic activity in the periods falling into the transition minimum between cycles (except for the inverse relationship with the solar irradiance). The main influencing factors are: electron fluxes, TSI, radio emission at a wavelength of 10.7 cm and the total area of sunspots – at the decay phase of the 23rd activity cycle in 2005 (based on Table 1).

Electron fluxes showed significant correlation coefficients with B-star at the decay phase of the 23rd activity cycle (2005) and the maximum phase of the 24th activity cycle (January–December 2012), and during the 2009 minimum solar activity insignificant correlation coefficients (less than –0.13).

Table 1 Table of correlation coefficients of the B-star with the indexes of solar and geomagnetic activity (in the rows) at the selected time intervals (in the columns) for the initial data.

ISS (B-star)	28.03.–11.05. 2005	16.01.–17.03. 2009	31.03.–28.06. 2009	15.09.–04.10. 2012	03.11.–16.12. 2012
A_p	–0.15	–0.23	–0.1	–0.02	0.18
E > 0.6 MeV	0.47	–0.03	–0.13	–0.22	0.66
E > 2 MeV	0.61	0.07	–0.04	–0.56	0.66
Radio flux 10.7 cm	–0.51	0.01	–0.05	0.75	0.58
Sp total	–0.62	–0.06	0.31	0.79	0.37
W-T	–0.14	–0.14	0.14	0.41	0.56
Proton density	–0.03	–0.39	–0.04	0.3	–0.38
Flow speed	–0.21	0.34	–0.19	–0.68	0.54
Flow pressure	–0.2	–0.13	–0.19	–0.21	–0.07
IMF	–0.26	–0.03	–0.12	0.03	0.04
D_{st}	–0.01	0.05	0.13	–0.15	–0.4
L_α	0.02	–0.15	0.32	0.76	0.62
TSI	0.69	–0.59	–0.14	0.19	0.23

Radio emission at a wavelength of 10.7 cm and total sunspot area had negative correlation coefficients with the B-star parameter in 2005 (–0.51 and –0.61, respectively). The radio flux shows insignificant values of the correlation coefficient 0.01 (January–March 2009) and –0.5 (March–June 2009) at the minimum of solar activity. Significant correlation coefficients from 0.75 (September–October 2012) to 0.58 (November–December 2012) are achieved at the maximum phase of the 24th solar activity cycle. The correlation coefficient of B-star with the sunspot area index at the phase of minimum of solar activity was insignificant, and at the maximum phase of the 24th solar activity cycle it varied from 0.79 (September–October 2012) to 0.37 (November– December 2012). The correlation coefficient of the B-star with the Wolf numbers is insignificant (–0.14) during the decay phase of the 23rd cycle of activity and during January–March 2009. It begins to increase to values of 0.41 (September–October 2012) and 0.56 (November–December 2012) at the maximum phase of the 24th solar cycle.

The correlation coefficient of the B-star with the proton density was insignificant throughout the selected time intervals. Also, it was not significant and did not exceed the values of –0.39 (January–March 2009), 0.3 (September–October 2012) and –0.38 (November–December 2012).

The correlation coefficient shows strong changes with the speed of the solar wind flow. During the decline phase of the 23rd cycle of solar activity it is insignificant (–0.21), at the minimum phase it increases to 0.34 (January–March 2009) and drops sharply to –0.19 (March–June 2009). At the maximum phase it reaches –0.68 (September–October 2012) and rises to 0.54 (November–December 2012).

The correlation coefficients of the B-star with the solar wind pressure are insignificant at all studied time intervals and do not exceed –0.21. With the index of the interplanetary magnetic field is the same situation as with the pressure of the solar wind. The correlation coefficient of B-star with IMF is insignificant at the decay phase

of the 23rd solar cycle and the minimum (do not exceed –0.26) and at the maximum phase of the 24th solar cycle (0.03).

The correlation coefficient of the B-star with the D_{st} index is insignificant at all studied time intervals 0.05 (January–March 2009) and 0.13 (March–June 2009). At the maximum phase of the 24th solar cycle –0.4 (November–December 2012).

The correlation coefficient of the B-star with the L_α index is insignificant at the decline phase of the 23rd cycle and the minimum (0.02 and -0.15, respectively). Its growth starts from March–June 2009 (0.32) to September–October 2012 (0.76) and decreases in November–December 2012 (0.62).

The highest correlation coefficient of B-star with the solar constant reaches 0.69 at the decay phase of the 23rd solar cycle, then drops to –0.59 (January–March 2009) and –0.14 (March–June 2009) at the minimum of solar activity. At the maximum phase of the 24th cycle it increases to 0.19 (September–October 2012) and 0.23 (November–December 2012).

3.2 Correlations for data with excluded trend

Based on Table 2, at the decay phase of the 23rd cycle of activity in 2005, the main influencing factors are: electron fluxes, L_α index and radio emission at a wavelength of 10.7 cm.

Electron fluxes showed significant correlation coefficients with B-star at the decay phase of the 23rd solar cycle (2005) and the maximum phase of the 24th solar cycle (January–December 2012), and during the 2009 minimum solar activity insignificant correlation coefficients (not more than 0.18).

The radio flux shows insignificant values of the correlation coefficient 0.06 (January–March 2009) and 0.15 (March–June 2009) at the minimum of solar activity. A significant correlation coefficient of 0.6 (September–October 2012) is achieved at the

Table 2 Table of the correlation coefficients of the B-star with the indexes of solar and geomagnetic activity (in the rows) at the selected time intervals (in the columns) for the data with the excluded trend.

ISS (B-star)	28.03.–11.05. 2005	16.01.–17.03. 2009	31.03.–28.06. 2009	15.09.–04.10. 2012	03.11.–16.12. 2012
A_p	–0.20	–0.16	–0.02	–0.15	–0.05
E > 0.6 MeV	0.52	0.41	0.17	0.18	0.34
E > 2 MeV	0.55	0.4	0.04	–0.15	0.37
Radio flux 10.7 cm	0.16	0.06	0.15	0.6	0.1
Sp total	–0.03	–0.08	0.21	0.31	–0.11
W–T	0.23	–0.14	0.06	–0.02	0.13
Proton density	–0.08	–0.48	–0.21	0.21	–0.18
Flow speed	–0.25	0.21	0.23	–0.41	0.24
Flow pressure	–0.24	–0.26	–0.19	–0.29	–0.01
IMF	–0.22	–0.16	–0.23	–0.04	–0.03
D_{st}	0	0.02	–0.10	0.15	0.08
L_α	0.31	0.09	–0.11	0.54	0.22
TSI	0.16	0	–0.15	0.24	0.31

maximum phase of the 24th solar cycle. The correlation coefficient of B-star with the sunspot area index at the phase of minimum solar activity was insignificant, and at the maximum phase of the 24th solar cycle it varied from 0.31 (September–October 2012) to –0.11 (November–December 2012 of the year).

The correlation coefficient of B-star with Wolf numbers is insignificant (0.23) at the decay phase of the 23rd cycle and does not exceed 0.13 during the remaining time intervals.

The correlation coefficient of the B-star with the proton density was insignificant throughout the selected time intervals. It was not significant and did not exceed the values –0.48 (January–March 2009), 0.21 (September–October 2012) and –0.18 (November–December 2012).

The correlation coefficient shows strong changes with the speed of the solar wind flow. During the decay phase of the 23rd solar cycle it is insignificant (–0.25), at the minimum phase it increases to 0.21 (January–March 2009) and continues to grow to 0.23 (March–June 2009). In the maximum phase reaches –0.41 (September–October 2012) and rises to 0.24 (November–December 2012).

The correlation coefficients of the B-star with solar wind pressure are insignificant at all studied time intervals and do not exceed –0.01.

With the index of the interplanetary magnetic field is the same situation as with the pressure of the solar wind. The correlation coefficient of B-star with IMF is insignificant at the decay phase of the 23rd solar cycle and the minimum (does not exceed the value –0.16) and at the maximum phase of the 24th solar cycle (–0.03).

The correlation coefficient of the B-star with the D_{st} index is insignificant at all studied time intervals 0.02 (January–March 2009) and –0.10 (March–June 2009). At the maximum phase of the 24th solar cycle 0.15 (September–October 2012). The correlation coefficient of the B-star with the L_α index is insignificant at the decay phase of the 23rd cycle of activity and the minimum (0.31 and 0.09, respectively). Its growth starts from September–October 2012 (0.54) and decreases in November–December 2012 (0.22).

The highest correlation coefficient of B-star with the solar constant reaches 0.31 at the maximum phase of the 24th solar cycle (November–December 2012). At the minimum of solar activity (January–March 2009 and March–June 2009) it has insignificant correlation coefficients. At the decay phase of the 23rd solar activity cycle (March–May 2005) it has a value of 0.16.

The data of the results of the correlation analysis (given in Tables 1 and 2) are showing how the influence of various factors of space weather on the drag of the ISS changes at different phases of solar activity (if the trend component of the initial data is not taken into account and taken into account). If the trend is not taken into account, the main influencing indexes are the indexes of the wave component of solar activity at all the time intervals under study. If the trend is taken into account, the main influencing indexes are indexes of the corpuscular component of solar activity at all selected observation intervals except 15.09.2012–04.10.2012 (the main influencing parameters are the F10.7 and L_α indexes).

From Tables 1 and 2 it can be seen that when the trend is taken into account at all selected time intervals, the correlation coefficients of the solar and geomagnetic activity indexes with the B-star coefficient change significantly. This is clearly seen for the indexes: F10.7; W; L_α and TSI. For indexes: F10.7; W and L_α – the correlation

coefficients with B-star significantly decreased at the maximum phase of the 24th solar activity cycle (November–December 2012). For TSI the correlation coefficients decreased at all selected time intervals except for the periods: September–October 2012 and November–December 2012. On the indicated intervals, the correlation coefficients increased, but insignificantly and did not exceed 0.31. For the electron flux indexes the correlation coefficients remain significant for the time interval March–May 2005 and increase for the period January–March 2009. For the maximum phase of the 24th solar cycle (November–December 2012) the correlation coefficients with the B-star index are halved. For the rest of the indexes the changes in the values of the B-star correlation coefficients with the indexes of solar and geomagnetic activity are insignificant.

For further consideration of the ISS drag periodograms were constructed and episodes of an increase in the drag coefficient were considered.

3.3 Frequency analysis – periodograms building for the initial data

Since our data (from the TLE format) is a series of the values which are distributed with an unequal time step we need the values of the series to be located relative to each other with the same step in order to apply frequency processing. For this the data were interpolated using the cubic B spline method. An example of the data obtained is shown in Fig. 3.

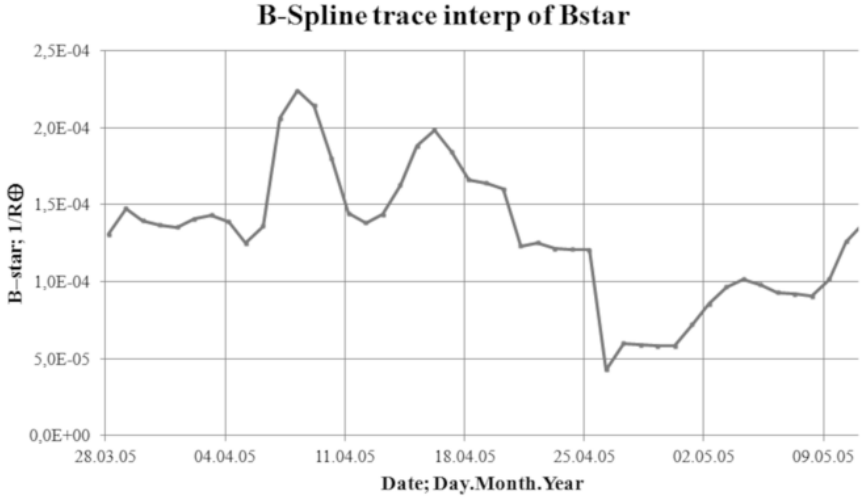


Figure 3 Change in the interpolated B-star coefficient for the ISS for April–May 2005.

After obtaining series with an equable step, a periodogram analysis was carried out. This analysis is used to find hidden periodicities in the data. Periodogram is a method for estimating power spectral density based on calculating the square of the modulus of the Fourier transform. Periodograms were plotted for all indexes of solar and geomagnetic activity selected in this work at selected time intervals, and also for the B-star coefficient. As a result, a set of periods from 2 to 15 days was obtained, and for some selected periods up to a month. The results are shown in Figs 4–7.

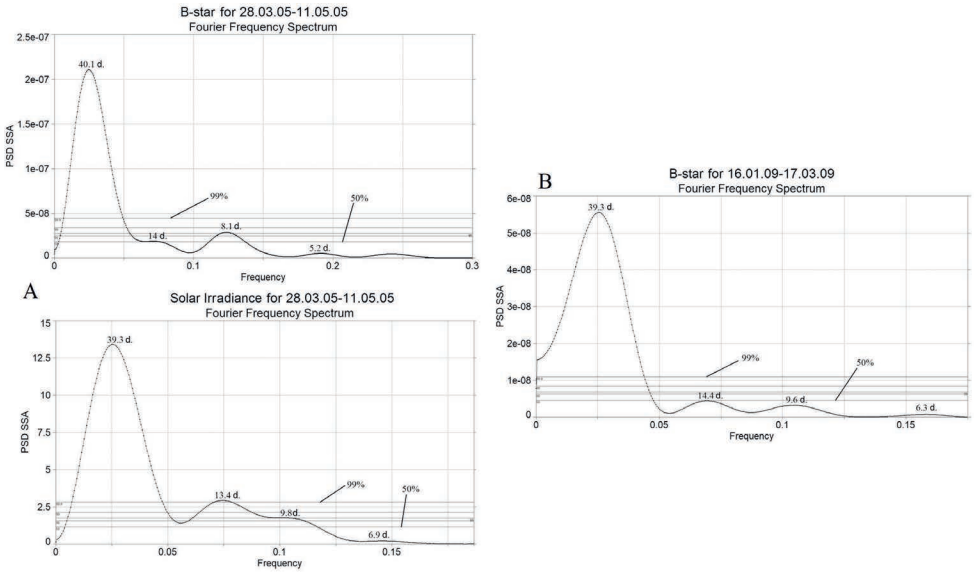


Figure 4 Periodogram for the initial data of: The B-star coefficient and the TSI for the period 28.03.2005 – 11.05.2005 **(A)**; The initial data of the B-star coefficient for the period 16.01.2009–17.03.2009 **(B)**.

Figure 4(A) shows the periodograms of the drag coefficient and the TSI. For the ISS (28.03.2005–11.05.2005), the following periods were found (maximums of period in order of the periodogram value decreasing with a confidence level in %): 40.1 days (99.9%); 8.1 days (95%); 14 days (50%); 5.2 days (<50%). The predominant period for the ISS drag coefficient is the period of 8.1 days. The period of 40.1 days – artifact of computing. The periods shown in Fig. 4(A) were found in periodograms for all indexes (E> 0.6 MeV; E> 2 MeV and the TSI) which have the highest correlation coefficients with the B-star coefficient at this time interval. For the index of the solar constant (TSI), the following periods were found (maximums of period in order of the periodogram value decreasing with a confidence level in %): 39.3 days (99.9%); 13.4 days (99.9%); 9.8 days (95%); 6.9 days (<50%). The period of 39.3 days is the artifact of computing. The predominant period is 13.4 days. Based on the correlation table (Table 1), we can conclude that the short period of 8.1 days could be caused by electron flux.

For the ISS in the period January–March 2009, the following periods were found (maximums of period in order of the periodogram value decreasing with a confidence level in %): 39.3 days (99.9%); 14.4 days (50%); 9.6 days (<50%); 6.3 days (<50%). The predominant period for the ISS drag coefficient is 39.3 days. Figure 5(B) shows the indicated periods of the B-star coefficient for the period 16.01.2009–17.03.2009 (without the subtracted trend).

Based on Table 1, the B-star correlation coefficients with these indices of solar and geomagnetic activity are insignificant. For this period of time, it is not clear what caused these periodicities.

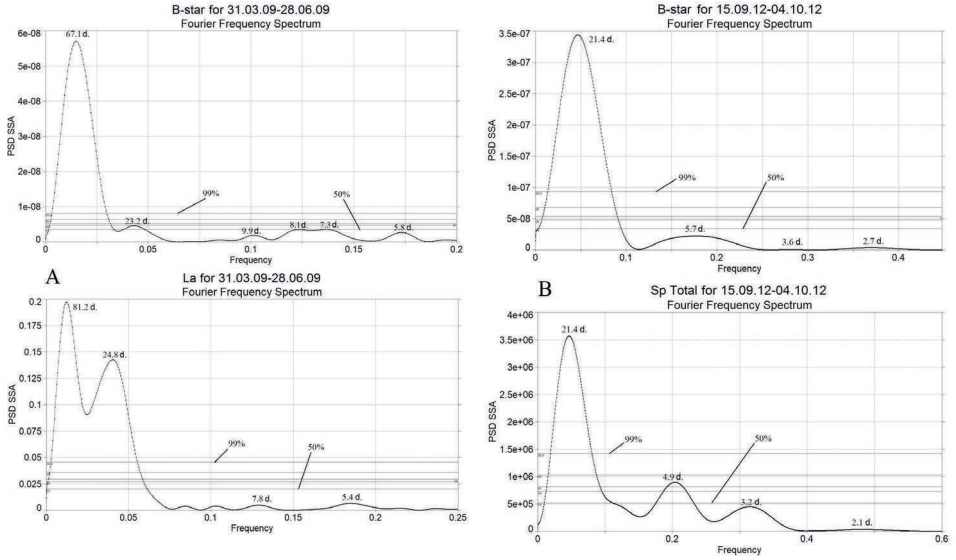


Figure 5 Periodogram for the initial data of: the B-star coefficient and the Lyman alpha index for the period 31.03.2009–28.06.2009 **(A)**; The initial data of the B-star coefficient and the Sp index for the period 15.09.2012–04.10.2012 **(B)**.

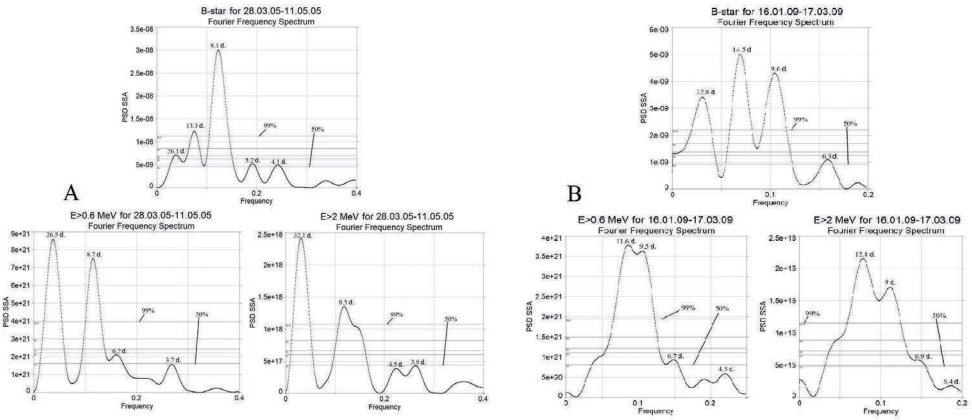


Figure 6 Periodogram for: The B-star coefficient and electron fluxes for the period 28.03.2005–11.05.2005 with the excluded trend **(A)**; The B-star coefficient and the electron flux indexes for the period 16.01.2009–17.03.2009 with the excluded trend **(B)**.

Figure 5(A) shows examples of periodograms for the period 31.03.2009–28.06. 2009. For the ISS in the period from March to June 2009, the following periods were found (maximums of period in order of the periodogram value decreasing with a confidence level in %): 67.1 days (99.9%); 23.2 days (90%); 8.1 days (50%); 7.3 days (50%); 5.8 days (<50%); 9.9 days (<50%). The predominant period for the ISS drag coefficient is 67.1 days. The obtained periods in the B-star drag coefficient are present in all indexes of solar and geomagnetic activity, which show highest correlation

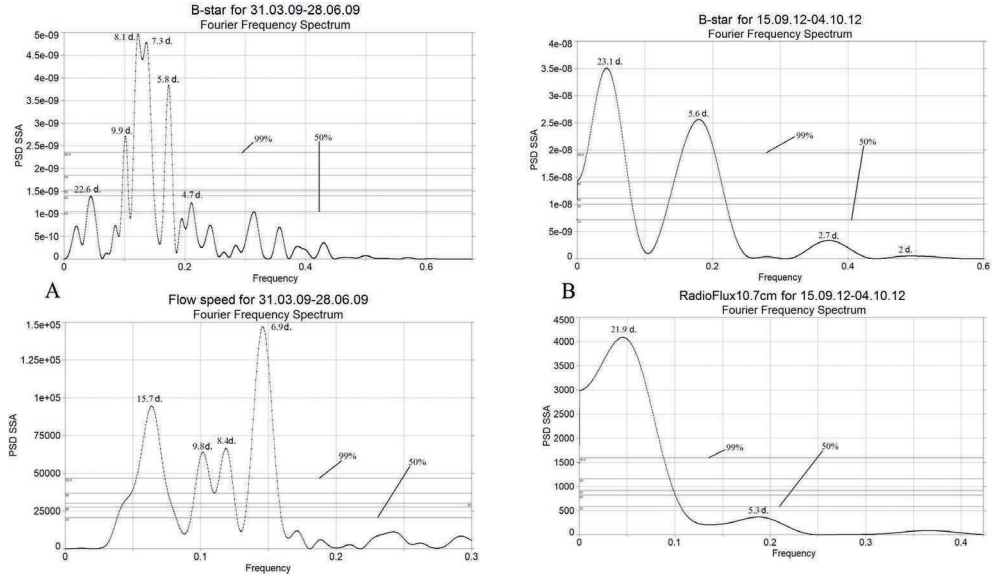


Figure 7 Periodogram for: The B-star coefficient and the flow speed index for the period from 31.03.2009–28.06.2009 with the excluded trend **(A)**; the B-star coefficient and the F10.7 index for the period 15.09.2012–04.10.2012 with the excluded trend **(B)**.

coefficients with B-star. The highest correlation coefficients are with indexes L_α = 0.32 and Sp = 0.31. For the Lyman alpha index the following periods were found (maximums of period in order of the periodogram value decreasing with a confidence level in %): 81.2 days (99.9%); 24.8 days (99.9%); 5.4 days (<50%); 7.8 days (<50%). The period of 81.2 days – artifact of computing. Most likely periods: 23.2; 7.3 and 5.8 days were caused by changes in the L_α index; 8.1 days by changes in the Sp index; 9.9 days with changes in D_{st} (correlation coefficient with B-star = 0.13).

For the ISS 15.09.2012–04.10.2012 the following periods were found (maximums of period in order of the periodogram value decreasing with a confidence level in %): 21.4 days (99.9%); 5.7 days (<50%); 2.7 days (<50%); 3.6 days (<50%). The last three periods are below the 50% confidence level. The periodogram shown in Fig. 5(B) corresponds to the shortest observation period of all those considered in this work. The highest correlation coefficients are with the Sp, F10.7 and L_α indexes (from 0.75 to 0.79). The period of 21.4 days was found only for the Sp index; 21.2 days for the F10.7 index and 20.4 days for the L_α index. In this case these periods are artifact of computing. The period of 2.7 days is present in the F10.7 index, but it is also below the 50% confidence level.

Based on the correlation coefficients presented in Table 1, this period was caused by joint influence of the indexes of wave component of solar activity.

For the drag of the ISS for the period 03.11.2012–16.12.2012 for initial data the following periods were found (maximums of period in order of the periodogram value decreasing with a confidence level in %): 31.3 days (99.9%); 8.5 days (<50%); 4.8 days (<50%); 2.7 days (<50%).

The predominant period for the ISS drag coefficient is 31.3 days. The last three

periods are below the 50% confidence level. The highest correlation coefficients with the B-star coefficient have the following indices: electron fluxes (0.66 for both); F10.7 (0.58); Wolf number (0.56); Flow speed (0.54); L_α (0.62). All the periods which found in the B-star were found in the above indexes as well. For the L_α index the following periods were found (maximums of period in order of the periodogram value decreasing with a confidence level in %): 31.1 days (99.9%); 7.1 days (<50%); 4.4 days (<50%). The last two periods are below the 50% confidence level. The predominant period is 31.1 days.

We can assume (using Table 1) that the period of 2.7 days was caused by changes in electron fluxes (only these indices had periods of 2 days, albeit below the 50% confidence level). All indexes have periods close to 4.8 days. The period close to 31.3 days was found only in the L_α index, taking this into account and the correlation coefficient, we can say that this period in the ISS drag is caused by a change in the Lyman alpha index.

3.4 Frequency analysis – periodograms building for data with excluded trend

After subtracting the trend component from the ISS drag data and the solar and geomagnetic activity indices, we obtained that the main parameters influencing the drag of the International Station are electron fluxes. The correlation coefficient of B-star with them was 0.55 (E> 2 MeV) and 0.52 (E> 0.6 MeV). It also rises with the L_α index of 0.31.

Figure 6(A) shows the periodograms of the drag coefficient and electron fluxes for the data with the subtracted trend. For the ISS (28.03.2005–11.05.2005), the following periods were found (maximums of period in order of the periodogram value decreasing with a confidence level in %): 8.1 days (99.9%); 13.3 days (99.9%); 26.1 days (95%); 5.2 days (> 50%) and 4.1 days (> 50%). The predominant period for the ISS drag coefficient is 8.1 days.

The periods indicated in Fig. 6(A) were found in periodograms for all indexes (E> 0.6 MeV; E> 2 MeV) which have the highest correlation coefficients with the B-star at the given time interval, except for the period of 13.3 days. The corresponding, close in value, period was found in the L_α index (12 days – 95%). For the index E > 0.6 MeV the following periods were found (maximums of period in order of the periodogram value decreasing with a confidence level in %): 26.5 days (99.9%); 8.7 days (99.9%); 6.2 days (> 50%); 3.7 days (50%). The predominant period is 26.5 days.

For the E > 2 MeV index the following periods were found (maximums of period in order of the periodogram value decreasing with a confidence level in %): 32.1 days (99.9%); 8.5 days (99.9%); 3.8 days (50%); 4.5 days (<50%). The predominant period is 32.1 days. Based on the correlation table (Table 2), we can conclude that the period of 26.1 days was caused by changes in the E> 0.6 MeV index. A short period of 8.1 days could be caused by electron fluxes, and a period of 13.3 days by a change in the L_α index (since only it had a period close in value among the indexes with the highest correlation coefficients).

For the ISS 16.01.2009–17.03.2009 (Fig. 6(B)), the following periods were found (maximums of period in order of the periodogram value decreasing with a confidence

level in %): 14.5 days (99.9%); 9.6 days (99.9%); 32.8 days (99.9%); 6.3 days (> 50%). The predominant period for the ISS drag coefficient is the period of 14.5 days.

The periods indicated in Fig. 6(B) were found in the periodograms of all the indexes (E > 0.6 MeV; E > 2 MeV) which have the highest correlation coefficients with the B-star coefficient in the given time interval, except for the periods of 14.5 days and 32.8 days. For the index E > 0.6 MeV the following periods were found (maximums of period in order of the periodogram value decreasing with a confidence level in %): 11.6 days (99.9%); 9.5 days (99.9%); 6.7 days (> 50%); 4.5 days (> 50%). The predominant period is 11.6 days.

For the E > 2 MeV index, the following periods were found (maximums of period in order of the periodogram value decreasing with a confidence level in %): 12.8 days (99.9%); 9 days (99.9%); 6.9 days (> 50%); 5.4 days (> 50%). The predominant period is 12.8 days. Based on the correlation table (Table 2), we can conclude that the periods: 9.6 and 6.3 days were caused by changes in the electron flux indexes (E > 0.6 MeV and E > 2 MeV). It is not clear what indexes could cause periods of 14.5 days and 32.8 days.

After subtracting the trend component, the correlation coefficients of B-star with the indexes of solar and geomagnetic activity for the period from 31.03.2009 to 28.06.2009 decrease. The highest (but not significant) coefficients of correlation with the drag coefficient are for the flow speed (0.23), Sp (0.21) and F10.7 (0.15) indexes. Figure 7(A) shows the periodograms for the B-star coefficient and the flow speed index, taking into account the trend component.

For the ISS, the following periods were found (maximums of period in order of the periodogram value decreasing with a confidence level in %): 8.1 days (99.9%); 7.3 days (99.9%); 5.8 days (99.9%); 9.9 days (99.9%); 22.6 days (90%); 4.7 days (> 50%). The predominant period for the ISS drag is 8.1 days. The obtained periods in the drag coefficient B-star were present in the following indexes: flow speed, Sp and F10.7. For the Flow speed index the following periods were found (maximums of period in order of the periodogram value decreasing with a confidence level in %): 6.9 days (99.9%); 15.7 days (99.9%); 8.4 days (99.9%); 9.8 days (99.9%). The predominant period is 6.9 days. Possible periods: 8.1 and 22.6 days are caused by changes in the F10.7 index; 9.9 days by changes in the Flow speed index; 4.7 days of Sp changes, despite their insignificant correlation coefficients.

For the ISS 15.09.2012–04.10.2012, the following periods were found (maximums of period in order of the periodogram value decreasing with a confidence level in %): 23.1 days (99.9%); 5.6 days (99.9%); 2.7 days (<50%); 2 days (<50%). The last two periods are below the 50% confidence level. The corresponding periodogram is shown in Fig. 7(B). The highest B-star correlation coefficients with the F10.7 (0.6) and L_α (0.54) indexes.

The periods were found for the F10.7 index (maximums of period in order of the periodogram value decreasing with a confidence level in %): 21.9 days (99.9%); 5.3 days (<50%). Periods of 23.1 days and 21.9 days are artifacts of computing.

After subtracting the trend, the highest correlation coefficients of the solar activity indexes with the B-star coefficient do not exceed 0.37. The correlation coefficients with electron fluxes are 0.34 (E > 0.6 MeV); 0.37 (E > 2 MeV). With the TSI of 0.31 (these correlation coefficients are shown in Table 2).

For the drag of the ISS (03.11.2012–16.12.2012) the following periods were found

(maximums of period in order of the periodogram value decreasing with a confidence level in %): 23.6 days (99.9%); 8.5 days (99.9%); 4.8 days (95%); 2.7 days (<50%). The predominant period for the ISS drag coefficient is the period of 23.6 days. The period of 2.7 days is below the 50% confidence level. For the TSI index the following periods were found (maximums of period in order of the periodogram value decreasing with a confidence level in %): 9.8 days (99.9%); 23.3 days (99.9%); 4.5 days (95%); 6.9 days (> 50%). The predominant period is 9.8 days. We can assume (using Table 2) that the period of 2.7 days was caused by changes in electron fluxes (only these indices had periods of 2 days, albeit below the 50% confidence level). Periods close to 4.8 days and 23.6 days are present in the Solar constant index, taking this into account and the correlation coefficient, we can say that this periods in the drag of the ISS were caused by a change in this index.

Thus, from Tables 1, 2 and the periodogram analysis, it can be seen that the influence of the indexes of the wave component of solar activity (F10.7; TSI; L_α) have a longer trend character, and the indexes of the corpuscular component are short-period.

4 Discussion

The drag of the ISS at 5 time intervals was considered. Correlation coefficients and periodograms were calculated for these intervals. The ISS is a popular object for research and discussion, but it is difficult to analyze its drag data. Since the station periodically adjusts its orbit, such values must be excluded from the data analysis. Not all such adjustments or maneuvers are publicly available, making analysis difficult. When it is possible to find the period of time more or less suitable for analysis, often it is quite short and, as a result, uninformative for drawing up a more comprehensive picture of the influence of solar activity on the movement of an object in the atmosphere. The analysis performed is based on Pearson correlations. They cannot show us how the drag coefficient depends on changes in the selected indexes. These correlations should be supplemented with analysis using other statistical methods, such as, for example, multiple correlation models and cross-correlation spectra. These methods will help to show how the drag coefficient and indexes of solar and geomagnetic activity depend on each other. Also, instead of the ISS, 25 artificial objects that move in Earth's orbit in an uncontrolled mode have already been selected for such an analysis. Data on the drag of such objects do not require searching and excluding data on their adjustments. This makes it possible to analyze longer time intervals and if there is a need to select shorter periods of data for analysis. Also, using multiple correlation models, it is possible to identify dates and data periods that are described unsatisfactorily by the selected indexes. As a result, we will analyze them in more detail. In subsequent work we can try to use algorithms of neural networks or deeper machine learning to the analysis of these time intervals, which have become very popular these days. The method of constructing spectrograms will also be used to obtain time intervals within which the found periodicities exist. This article shows some of the initial data analysis that is already underway.

5 Conclusions

- The TSI with a correlation coefficient of 0.69 was the main parameter affecting the ISS motion for the initial data at the decay phase of the 23rd solar activity cycle (28.03.2005–11.05.2005). The B-star correlation coefficient with the index of E $>$ 2 MeV (0.61) for this time interval was also high. Periodogram analysis showed short-period changes (8.1 days) most likely caused by changes in the indexes of E $>$ 2 MeV.
- By excluding the trend component from the initial data at the decay phase of the 23rd solar activity cycle (28.03.2005–11.05.2005), it is possible to identify the parameters that affect the short-period variations in the movement of the international station. They are the indexes of E $>$ 2 MeV (correlation coefficient 0.55) and E $>$ 0.6 MeV (correlation coefficient 0,52). Fourier analysis of these data (28.03.2005–11.05.2005) showed that the variation of 26.1 days (most likely were caused by E $>$ 0.6 MeV); 13.3 days (most likely were caused by changes in the L_α index despite a low correlation coefficient); 8.1 days (most likely were caused by fluxes of E$>$2 MeV).
- In the minimum phase of solar activity (16.01.2009–17.03.2009 and 31.03.2009–28.06.2009) for the initial data, none of the applied indexes showed significant correlation coefficients with the drag coefficient. The TSI index showed an inverse relationship with the drag coefficient in the period from January 16, 2009 to March 17, 2009. The correlation coefficient was –0.59. The highest correlation coefficient of the B-star (0.34) was with the solar wind speed index. The highest correlation coefficients of the B-star (0.32) was with the Lyman alpha index and (0.31) with the total sunspot area index between March 31, 2009 and June 28, 2009. It is difficult to say which of the selected indexes could affect the movement of the ISS due to the low correlation coefficients. Apparently, in the period from 16.01.2009 to 17.03.2009, changes in the drag of the station could cause fluctuations in the solar wind speed. The variations: 23.2; 7.3 and 5.8 days most likely were caused by changes in the L_α Index; 8.1 days by changes in the Sp index; 9.9 days with changes in D_{st} (correlation coefficient with B-star = 0.13) in the period 31.03.2009–28.06.2009.
- Due to the exclusion of the trend component from the initial data of the minimum solar activity, it was found that the highest correlation indexes with the B-star were: the indexes of E $>$ 0.6 MeV (0.41) and E $>$ 2 MeV (0.4) in 16.01.2009–17.03.2009 period; in the period of 31.03.2009–28.06.2009 with the indexes of the solar wind flow speed (0.23) and the total sunspot area (0.21). Periodogram analysis for the time interval 16.01.2009–17.03.2009 showed that the variations that were found of 9.6 and 6.3 days, most likely were caused by changes in the electron flux indexes (E $>$ 0.6 MeV and E $>$ 2 MeV). It was not possible to identify, with the help of correlation coefficients, the variations of 14.5 days and 32.8 days which was found in the drag data of the international station with the changes in the indexes selected for the analysis. The variations which were found in the ISS drag coefficient in the period of 31.03.2009–28.06.2009: 8.1 and 22.6 days most likely were caused by changes in the F10.7 index; 9.9 days by changes in the Flow speed index; 4.7 days by Sp changes, despite their insignificant correlation coefficients.

- At the growth phase of the 24th solar activity cycle 15.09.2012–04.10.2012, for the initial data, the main indexes affected the ISS drag (with the highest correlation coefficients) were: Sp total (0.79); L_α (0.76); F10.7 (0.75). Fourier analysis of the ISS drag data showed the presence of a variation of 21.4 days (artifact of computing) and three others, which are described in Section 3.3 and were below the 50% confidence level.
- By eliminating the trend component for the period 15.09.2012–04.10.2012, it was revealed that the F10.7 and L_α indexes also affect the appearance of short-period variations in the ISS drag. The correlation coefficients, at the same time interval, were: F10.7 (0.6) and L_α (0.54). Analysis of periodograms showed the artifacts of computing of 21 days and 23.1 days.
- In the period 03.11.2012–16.12.2012, for the initial data, the highest correlation coefficients with the B-star were with the E $>$ 0.6 MeV and E$>$2 MeV (0.66), as well as the Lyman alpha index (0.62). The indexes also had high correlation coefficients: F10.7 (0.58); W (0.56); flow speed (0.54). The main variation of the ISS drag of 31.3 days (found using the periodogram analysis) was found only in the L_α index. The rest of the variations were below the 50% confidence level. The variation of 2.7 days with a confidence level below 50% was found only for the electron flux indexes (E $>$ 0.6 MeV and E $>$ 2 MeV) also below the 50% confidence level.
- The exclusion of the trend component from the initial data for the period 03.11.2012–16.12.2012 showed that the correlation coefficients of the B-star with the indexes of solar and geomagnetic activity became insignificant. The highest values of the correlation coefficients of the B-star with the indexes were for the E $>$ 2 MeV (0.37) and E $>$ 0.6 MeV (0.34). In the same range were the values of the correlation coefficients for the indexes of: solar constant (0.31); solar wind flow velocity (0.24) and Lyman alpha (0.22). Close to the variations which were found in the drag of the international station (23.6 days and 4.8 days) were found for the solar constant index, and variations close to 2.7 days only for the electron flux indexes (variations of 2 days, as well as for the variations of the ISS drag below the 50% confidence level).

References

[1] Shupletsov V. I. 22.06.2014, International Space Station. Orbit tremors [Web resource], Space Research Laboratory of Ulyanovsk State University. URL: http://www.spacephys.ru/mezhdunarodnaya-kosmicheskaya-stantsiya-drozh-orbity

[2] Shupletsov V. I. 24.11.2014, ISS orbit – an indicator of the state of the atmosphere [Web resource] // Space Research Laboratory of Ulyanovsk State University. URL: http://www.spacephys.ru/orbita-mks-indikator-sostoyaniya-atmosfery

[3] Mendaza T., Blanco-Ávalos J. J., Martín-Torres J. Interplanetary Coronal Mass Ejection effects on thermospheric density as inferred from International Space Station orbital data. Advances in Space Research Volume 60, Issue 10, 15 November 2017, Pages 2233-2251.

[4] Beletsky V. V. The movement of an artificial satellite relative to the center of mass. M., 1965, 416 p.
[5] Roy A. Orbital movement. M., 1981, 544 p.
[6] Kelso T. 1998, Frequently Asked Questions: Two-Line Element Set Format, [Web resource] // CelesTrak. URL: https://celestrak.com/columns/v04n03/
[7] Felix R. Hoots, Ronald L. Roehrich. Models for Propagation of NORAD Element Sets // Spacetrack Report № 3, December 1988.
[8] allado, David A.; Paul Crawford; Richard Hujsak; Kelso T. S. "Revisiting Spacetrack Report No 3. // Astrodynamics Specialist Conference. April 29. 2017.
[9] Picone J. M., Emmert J. T. and Lean J. L. Thermospheric densities derived from spacecraft orbits: Accurate processing of two-line element sets // Journal of Geophysical Research, Vol. 110, A03301, 2005.