APPLICATION PROSPECTS OF THE RUSSIAN HAZARD ALARM SYSTEM SUPPORTING SAFE FLIGHTS OF OPERATED SPACE VEHICLES

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ABSTRACT

The issues are considered of elaboration and development of the Russian hazard alarm system to provide safe flight of operated space vehicles and life activities on Earth under the conditions of increasingly congested near-Earth space environment. The results are given characterizing the appearance intensity of hazardous approaches of space vehicles with space debris in the different areas of near-Earth space. The estimated probabilities are given of space vehicles collisions with the space objects, and also the statistical data on safety zone violations of space vehicles, performance of avoidance maneuvers, coordinates and time of deorbiting of the falling space objects. There is also a description of development prospects of the hazard alarm system.

1 INTRODUCTION

The flight safety problem of operated space vehicles and life activities on Earth have become of exceptional importance with a rising population of space debris in the near-Earth space (NES). There is a dissimilar numerous population of space debris in the near-Earth space- hundreds of thousands pieces. The qualitative distribution pattern of large-size space objects over the apogee altitudes and their orbit inclinations are presented on the figures 1, 2.

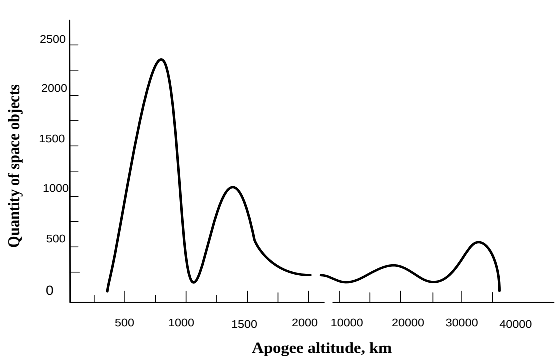

Figure 1. Apogee altitude distribution of space objects

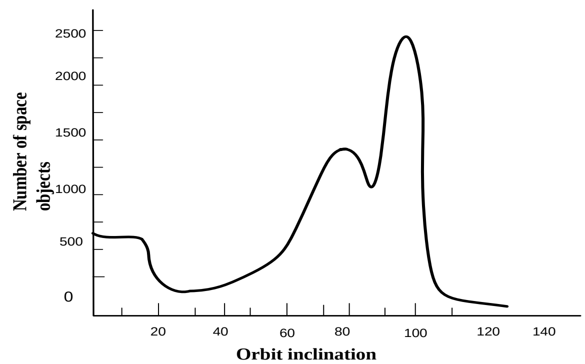

Figure 2. Space objects orbit inclination distribution

One can see that the NES areas in the range from 800 up to 900 km and inclination from 70° up to 100° are mostly congested. There are registered cases of space vehicle destruction as a result of collision with the space debris and the fall of heavy space debris on the Earth. [1,2].

The planned large-scale development of satellite constellations with the steady growth of space debris in the near-Earth will probably demand problem solution to provide safe international space activities.

The whole range of safety measures is being implemented by the world community and national space agencies to provide safe space activities, such as:

– elaboration of organization-technical procedures aimed at space debris mitigation;

– verifying compliance with international obligations during space activities;

– development of utilization technology of space vehicles after their end of life;

– elaboration and realization of measures for space debris removal from the NES;

– development of high-force materials to protect spacecraft from collisions with space debris, etc.

One of the main aspects to provide safe space activities is the whole new level of on-line monitoring and forecasting of space debris situation in the NES.

Proc. '6th European Conference on Space Debris'
Darmstadt, Germany, 22–25 April 2013 (ESA SP-723, August 2013)

2 THE PURPOSE AND MAJOR TASKS OF THE HAZARD ALARM SYSTEM

The works are under way in the Russian Federation to create and develop an automated hazard alarm system in the NES (ASPOS OKP) with the leading role of Mission Control Centre of the Federal Unitary State Enterprise «Central scientific research institute of machine building» and with the participation of Keldysh institute of applied mathematics (of the Russian Academy of science), Institute of Earth magnetism, ionosphere and radiowaves propagation (IZMIRAN), joint stock company “MAC “Vympel”. It consists of the main information-analytical centre (the central core), monitoring segments of hazardous situations in different areas of the NES, calculation of solar and geomagnetic activity, analysis of non-coordinate information about space objects.

The main tasks of the system are as follows:

- constant control of the NES debris environment;
- detection, forecasting and warning of the hazardous approaches of operated spacecraft to space debris fragments, recommendations of avoidance maneuvers;
- forecasting of uncontrolled risk objects entering the atmosphere, their position measurement and time of their fall on the Earth’s surface;
- information and analytical support of interested parties on space debris environment;
- compliance with the Russian Federation international obligations concerning space debris issues.

The system was accepted for testing operation in November 2012.

The process of detection of hazardous situations in the NES is realized stage-by-stage. First of all, the potentially dangerous space objects are determined for every operated space vehicle with the use of space debris catalogue and forecasting methods of their motion. Then according to the requests from the Main information-analytical centre, the motion parameters of detected risk space objects are specified by means of measuring tools of system segments. Then the refined calculations of spacecraft and space debris relative motion are conducted and the decision is made on whether to conduct an avoidance maneuver.

The detection of collision probability of space vehicle and space debris is the key objective of the Central nucleus of the system. The decision of conducting an avoidance maneuver of operated space vehicles is made depending on the collision probability. On the basis of the certain geometrical dimension of relative position of risk space objects and spacecraft we consider the sphere with radius R with an origin at the centre of mass of the controlled spacecraft. The geometric interpretation of the event of hazardous approach will consist in the fact that the distance between the mass centres of two objects will be less than the radius R. Though the forecast of mutual distance between the risk space objects and the operated spacecraft may exceed the specified threshold value, taking into account the possible scatter (inaccuracy of evaluation) of position of both objects, there is probability of such an event when the relative distance of these objects will be less than R. Thus the task of approach control of space debris fragments comes to calculation of event rate when the relative distance of risk space object and operated space vehicle will be less than the threshold value. [3].

The initial conditions (state vectors) and matrixes of their errors are determined as the research results for the operated spacecraft and risk space objects, which pose potential hazard for space vehicles flight. Taking into account the calculated value of miss distance $d\bar{r}\ (t)_{min}$ and error matrix of a risk object’s movement relative to a space vehicle, the probability of their collision P_c is determined, the mathematical expectation and standard deviation for the vector of minimum distance and the relative velocity vector, as well as the table of relative movement parameters of an operated spacecraft and a risk space object in the vicinity of a hazardous approach.

It is considered that for the probability values $P_c < 10^{-5}$ the collision risk is so low that the avoidance maneuver of operated spacecraft from the risk space object is not provided. For the values P_c, in the range between 10^{-5} and 10^{-4} (the yellow threshold) the collision risk is rather high and an additional decision of avoidance maneuver is made on the basis of results of the revised forecasting of relative movement of a spacecraft and space object. For the values $P_c > 10^{-4}$ (the red threshold) the task of conducting an avoidance maneuver is considered. At that, several variants of spacecraft maneuvers realization are analyzed, which are in their turn checked up on the assumption of flight safety conditions of this space vehicle taking into account the whole catalogue of space debris fragments.

3 THE ANALYSIS OF HAZARDOUS APPROACHES OF SPACE VEHICLE WITH SPACE DEBRIS AND FALL OF RICK SPACE OBJECTS ON THE EARTH’S SURFACE

Currently the system provides detection and warning of dangerous encounters of space debris with more than sixty five space vehicles, such as: International Space Station (ISS),“Resurs-DK”, “Kanopus-V”, “Electro-L”, “Luch-5A”, 5B” satellites, GLONASS satellites, “Express”, “Yamal” and others. Supporting works are conducted on de-orbiting risk space objects with definition of time and area of their fall. More than two hundred dangerous approaches of operated space vehicles with space debris and up to five falls of risk space objects on the Earth's surface are registered every month.

The analysis of hazardous approaches of space vehicles with space debris in 2009-2013 showed that depending on altitude ranges of near-earth environment, space debris objects approach space vehicles less than 6 kilometers from 6 up to 20 times a month. Thus, about 6-10 approaches of space objects to ISS were detected and 8-15 – to "Resurs-DK" and "Kanopus-V" satellites. The number of approaches in the medium-altitude and geostationary area is considerably less: up to 2-3 approaches a month of space objects to GLONASS satellites, "Express", "Yamal", "Luch" and "Electro-L" satellites.

The estimated probability of space vehicles collisions with space objects (P_c) is given. It's specified that at average every tenth space object approaching the space vehicle at a distance of less than 6 km (10^{-4}>P_c >10^{-5}) reaches "the yellow threshold" and every twenty–fifth space vehicle reaches "the red threshold" (Pc > 10^{-4}). From 6-10 approaches of space objects to the ISS every month , only twenty four safety zone violations ("the red threshold") were noted during four years, nine avoidance maneuvers were conducted. Thirty-two cases of "the red threshold" violations were detected during the control of "Resurs-DK" satellite.

As an example, Table 1 presents the data on dangerous approaches of ISS, maintained at an orbital altitude of between 370 and 420 km, to space debris fragments in March 2013. Seven dangerous approaches were noted during the period under review, at that no violations of safety zones of ISS were showed.

Table 1

Date	Time	Space debris name	Minimum distance, km	Collision probability
04.03	00:31:04	DRAGON CRS-2 USA	3.650	2.7_{10}-6
09.03	04:27:46	MINOTAUR R/B USA	2.851	2.1_{10}-5
11.03	08:24:33	PSLV India	3.587	2.9_{10}-6
13.03	17:38:43	COSMOS 1174 Russia	4.321	1.6_{10}-6
14.03	15:52:02	FENGYUN 1C China	5.724	8.9_{10}-7
24.03	17:06:35	SL-8 R/B Russia	1.774	1.9_{10}-5
28.03	17:29:24	BREEZE-M Russia	3.434	2.8_{10}-6

Table 2 presents the approach results of "Resurs-DK1" satellite, maintained at altitudes of h ≈ 450-630 km, with space debris objects in March 2013. Eight approaches of the space vehicle with space debris were detected. In this case the absence of the space vehicle safety zone violations was also determined: the maximum value of collision probability doesn't exceed 3.9_{10}-5.

Table 2

Date	Time	Space debris name	Minimum distance, km	Collision probability
08.03	08:02:06	COSMOS 2251 Russia	1.282	3.9_{10}-5
11.03	12:09:23	COSMOS 2251 Russia	1.477	3.1_{10}-5
13.03	17:26:59	CZ-4 China	3.828	2.7_{10}-6
15.03	07:05:19	PSLV India	3.610	3.7_{10}-6
19.03	01:12:11	USA 55 USA	3.193	5.1_{10}-6
22.03	17:13:34	SL-16 Russia	2.773	8.2_{10}-6
27.03	05:07:39	FENGYUN 1C China	1.773	1.9_{10}-5
30.03	14:40:58	COSMOS 2251 Russia	2.421	5.4_{10}-6

The analysis of evolution of space objects' motion in the GEO area allows identifying the following features of orbital parameters changes with respect to time. As the geostationary plane doesn't coincide with the Earth and Moon orbit planes, the gravitational forces of these bodies have such an effect that moves the space objects from their equatorial orbits, gradually increasing the orbital inclination of the objects. Besides, because of a non-circular shape of the terrestrial equator, the part of uncontrolled space objects is slowly moving to one of the two points of the stable equilibrium along the equator. As a result, the east-west libration of the space object is carried out (drift forward and backwards) relative to these points and there is the danger of their collision with the other geostationary satellites.

As examples, the values of libration periods are presented in the table 3 on the basis of the methodology [4], minimum and maximum longitudes of subsatellite points of geostationary space objects. The dates of maximum approaches of "Electro-L" satellite with a space objects are given as well as the minimum distances between them, calculated in the period from March 2013. The names of this space debris objects are given as well. The data is given for different space objects drifting relative to the libration point of 75° east longitude. The data presented in Table 3 allows the preliminary forecasting of approach dates and distances of "Electro-L" satellite with the indicated space objects for a further period.

Table 3

№	Space object name	Libra-tion peri-od, days	λmin, deg/ time	λmax, deg/ time	Approach date/ distance to spacecraft, km
1	STTW-1 (China)	834	46.414 23.10.13	103.775 02.09.12	28.03.13 24
2	EKRAN 9 (Russia)	836	44.583 27.10.13	105.870 04.09.12	25.03.13 38
3	GALS 1	894	34.334 12.11.13	116.109 22.08.12	25.03.13 44
4	RADUGA 1-7 (Russia)	1056	15.974 20.06.12	130.624 30.11.13	27.03.13 74
5	INDOSTAR 1 (Indonesia)	904	30.633 20.11.13	118.104 25.08.12	28.03.13 52
6	RADUGA 27 (Russia)	1066	17.180 10.01.14	130.090 25.07.12	03.04.13 50

It is shown, that the libration period values of these space objects can be from ~ 2 - 2,5 years (space objects STTW-1, EKRAN 9, GALS 1, INDOSTAR 1) up to ~ 3 years (space objects RADUGA 1-7, RADUGA 27). For the space objects with longer periods the values of λmin are ~ 16-17° east longitude, and for space objects with shorter periods λmin are 44-46° east longitude. The applicable values λmax are in the range from ~ 103° up to ~ 130° east longitude.

The monitoring of falling objects on the Earth was performed using the facilities of hazardous forecasting system. The analysis of movement evolution of space objects shown, that from 3 up 7 large objects enter the atmosphere and fall on the ground every month.

The data on the falling objects during March, 2013 is presented in the table 4.

Table 4

Name of space object	Date and time of space object's deorbit		Deorbit coordinates of space object Latitude (deg)	Longitude (deg)
FALCON 9 R/B (USA)	11.03	03:04	- 46	249
WE-WISH (Japan)	11.03	02:59	48.5	118.7
SL-04 R/B (Russia)	31.03	03:08	44	308

The satisfactory high accuracy of time and coordinates determination of deorbiting risk space objects is shown, which is provided by the results of international testing campaigns, where calculation results received from the Russian system facilities are the most accurate among all the campaign participants.

Besides, the most significant operating results of automated hazard alarm system within the framework of international cooperation are as follows:

- ballistic and navigation support of the "Phobos-Grunt" final flight phase;
- deorbiting of telecommunication satellite "Express-AM4" and its submersion in the Pacific Ocean;
- detection and identification of space debris fragments generated after "Briz-M" upper stage destruction and others.

4 THE GROWING INTENSITY FORECAST OF HAZARDOUS APPROACHES DURING THE SPACE VEHICLE CONSTELLATION DEVELOPMENT

The presented data shows the possibility of efficient support of hazardous approaches of up to 100 space vehicles with the space debris. In case of fifty low-orbiting space vehicles control the limit number of space objects approaching these space vehicles up to 6 km will not exceed 700 per month and the safety zone violations will not exceed 40 per month. In case of fifty space vehicles control in medium-high orbits and geostationary orbits no more than 10 hazardous approaches with space objects per month are predicted. As a result the successful task solution of flight safety of satellite constellation is determined in many ways by effective control of these space vehicles approach to 50 risk space objects per month which can be achieved by the system facilities.

The effectiveness increase of this problem solution can be connected with the use of optimal involvement scheme for the NES observation means. At the same time it is necessary to perform the similar estimations on conditions of increase of catalogued space vehicles amount including the identification of small-sized and medium-sized space debris.

5 DEVELOPMENT PROSPECTS OF THE HAZARDOUS SITUATIONS FORECASTING SYSTEM

The near-term perspective is the use of the system for decision of detection tasks of hazardous approaches of space debris with a large number of space vehicles including the space vehicles of foreign countries. At that the monitoring efficiency of the NES increases with the use of observation facilities owned by different countries and located all over the world and also space-based facilities.

The main prospective lines of system development are as follows:

– enhancement of international cooperation concerning spacecraft flight safety, information and ballistic support of operators of satellite payload data for the detection of hazardous approaches with space debris and avoidance maneuvers;

– situation analysis, coordination of activities and optimizing of the Russian and foreign NES observation stations;

– elaboration of auxiliary means for observation of space debris including the space-based ones;

– open access to the information of catalogued space objects system.

– development of proposals on the principles and organizational procedures of system's interaction with the international structures;

– elaboration of normative documents on reduction of space debris growth both at the development stage of space complexes and during their operation.

6 CONCLUSION

Thus the created and developing hazard alarm system allows the efficient solving the tasks of the NES space debris environment monitoring and contributes to the safety improving of space activities. The efficiency of the chosen system layout and the made decisions taken as its basis, is confirmed by the safety of manned and automated space vehicles and the results of international testing campaigns on the falling objects.

The possibilities of the system as applied to the international cooperation consist in the fulfillment of the following tasks:

- detection of space debris fragments which pose a collision threat with space vehicles in all the NES areas;
- issue of hazard warnings and forecasting of hazardous situations development;
- estimated probability of space objects collision with operated space vehicles;
- open access to the data of catalogued space objects system.

At present the forecasting and detection of hazardous approaches of space debris with practically all the space vehicles of the existing orbital constellations of the Russian Federation in different NES areas can be already provided by the system. With the further development of the system the number of supported space vehicles can grow and include also the space vehicles of the foreign countries.

7 REFERENCES

1. Orbital Debris Quarterly News, Volume 13, Issue 2, 2009.

2. Buslov E.P., Golovko A.V. and others. The space activities issues specified by the space debris environment, ionizing radiation of the near-earth space and danger of asteroid and comet impacts. Moscow, 2010.

3. Ivanov V.M., Raspopov V.N., Sokolov N.L., Bendyakov V.F. Place and role of automated hazard alarm system of the near – earth space environment in the operation of manned and automated space vehicles. 2 – nd International Symposium «Space and Global Security of Humanity». Riga, Latvia, 5-9 July 2010.

4. Ivanov V.M., Sokolov N.L., Zakharov P.A. About the peculiarities of approach dynamics of space vehicles with the space debris fragments in the geostationary orbits area. 10-th International conference "Aviation and austraunatics – 2011". Moscow, 8-10 November 2011.