Method of safe descent in case of off-nominal onboard situation on Russian perspective manned spacecraft "Federation"

By Alexey Yu. Kutomanov[1], Maxim M. Matushin[1], Vladimir N. Pochukaev[1]

[1] *TSNIImash, Mission Control Centre*

The paper present basic results of developing method of safe descent in case of critical off-nominal onboard situation on every part of orbit. Questions of safety crew descent and landing in case of onboard off-nominal situation are considered. Nowadays method of providing safe descent of the modern Russian`s manned spacecraft "Soyuz MC" presupposes the possibility of landing in safety region only once per circle, for example time waiting of brake engine inclusion for safe descent can be 1.5 hours for ISS orbit. But due to the spaceflight a lot of critical off-nominal situations may occur. In case of impossibility to wait brake engine inclusion for safe descent, landing point would be in unfavorable land area. This scenario of descent and landing could contain high level of hazard for life and health of the crew. For decrease a possibility of landing to dangerous area, algorithm of safety deorbiting and landing scenario was developed. One of the main parts of this algorithm is digital map of all possible landing point.

Key Words: safety descent, high accuracy guidance system of descent, digital map

Nomenclature

φ	: latitude
λ	: longitude
ω_e	: angular velocity of rotation of the Earth
P(φ, λ)	: the function of the dependent classifier of the landing point from latitude and longitude

1. Introduction

Descent and landing are well known as most important and dangerous phases of every manned spacecraft flight. Nowadays regular dynamic operations of manned descent and landing are very good investigated. Only on ISS program was over 45 successful landings. But during of the spaceflight a lot of off-nominal situations can occur. In case of off-nominal situation on modern Russian`s manned spacecraft "Soyuz MC", safety descent and landing possible only in one point on orbit[1] (fig.1).

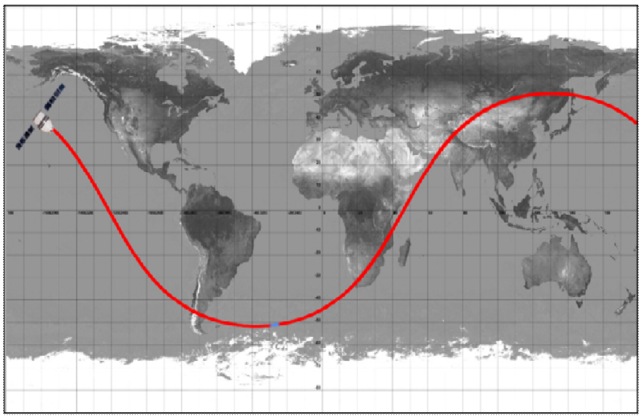

Fig.1. One point on orbit for safe descent.

For example time waiting of brake engine inclusion for safe descent can be 1.5 hours for ISS orbit. Moreover for providing safe descent and landing in case of off-nominal situations guidance system of descent is using ballistic trajectory. This trajectory is characterized by high levels of overload and uncertainty of landing points. In case of impossibility to wait brake engine inclusion for safe descent, landing point would be in unfavorable land area. These scenarios of descent and landing could contain high level of hazard for life and health of the crew. Thus it can be concluded, that presently we haven't got a method of safe descent in every parts of orbit.

2. Basic requirements for spacecraft "Federation" descent guidance system.

Modern stage of the space technology development can solve the task of providing safe descent and landing at every parts of the spacecraft orbit. But at first the following subtasks should be solved [2, 3]:

- on-boar digital map with characteristic of all possible landing areas should be developed;
- should be developed algorithm of searching safe variants of descent and landing;
- questions of possibility of using the algorithm of searching safe variants of descent and landing on board of the spacecraft "Federation" must be solved.

Following characteristics of the spacecraft "Federation" were used in development of the method of safe descent and landing:

- significant increase in accuracy of bringing recovery capsule to the parachute system inclusion point;
- guaranteed ability to use satellite navigation systems on every phases of descent and landing;
- possibility of a mathematical solution descent tasks with an on-board computer.

3. Digital map of all possible landing points

The main part of the method of "Federation" spacecraft safe descent is digital map of all possible landing point. Nowadays modern Russian manned spacecraft "Soyuz MC" in case of off-nominal situations for providing safe descent in the algorithm of searching nominal trajectory of descent use tables of depends longitudes of aiming landing points from longitudes of ascending node of orbit. In case of increasing accuracy of spacecraft “Federation” landing, number of safe landing point increase too. And it will be impossible to use spacecraft “Soyuz MC” tables of depends and algorithms of searching nominal trajectory of safe descent, because it will lead to uncertainty in the solution of the task of choosing the aiming point. On this basis, there was a need to develop new data structure with information of possible landing points safety and the algorithm of searching aiming point through this structure. After many studies, it was suggested to use principle of digital map construction in developing of new on board data structure with information about quality of possible landing points. This principle is based on the use of dependencies of various safety landing points characteristics, which are considered in a manned descent, from latitude and longitude. Basic requirements for the digital map are as follows: [4)]

- the classification of all possible landing points:
- the step of changing the classifier must be equal to accuracy of landing in case of off-nominal situation;
- the neighboring values of the classifiers must not differ by more than one unit;
- size of digital map must be smaller as it possible.

The digital map itself is a database, which have classification of all possible landing points. When it was build, different maps were used. It was a general physical map of the world, a population density map, a climate map, a political map and data from Earth remote sensing satellites. At fig. 2, digital map for ISS orbit. It have data about all possible landing points in area from -52° to +52° at latitude, and form -180° to 180° at longitude. All possible landing points are classified from 1 to 10 (colors from red to blue). Where 1 is the most disadvantaged areas and 10 is the regular areas of landing.

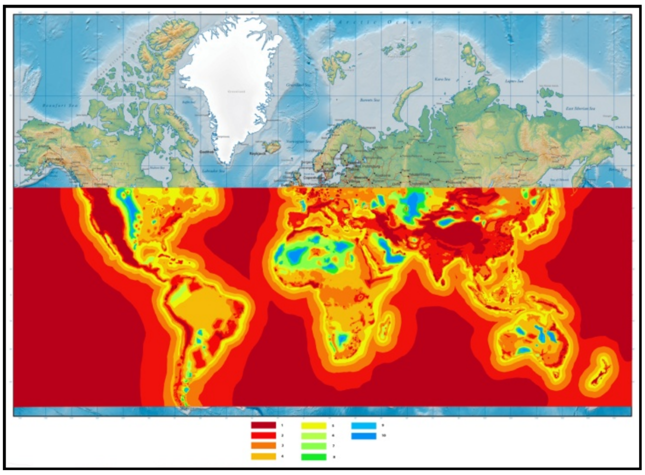

Fig.2. Digital map for ISS orbit.

When providing descent of modern Russians spacecraft “Soyuz MC”, the following criteria of safety possible landing points are taken into account:

- general characteristic of area (plane, or mountain);
- angle of the slope of the terrain to the horizontal;
- the presence of solid forest tracts;
- the presence of rivers, and lakes;
- the presence of electrical lines;
- remoteness from large cities and ect.

So if value of classifier of safety landing point will be between 1 and 2, descent and landing will be realized to disadvantage areas in mountains, or to far areas of the World Ocean, or to the large cities. If value of classifier will be between 3 and 5, descent and landing will be realized to more favorable areas in solid forest tracts. If value of classifier will be between 6 and 8, descent and landing will be realized to favorable areas which can have some trees, rivers, lakes and electric lines on the periphery.

One of the basic requirements for the method of safety descent in case of off-nominal situation is increasing as it possible time of algorithm of searching safe descent trajectory working. To satisfy the requirements instead of database view was developed matrix view of digital map (table 1). Step of classifier changing was suggested equal to 0.1° at latitude and longitude.

In case of increasing the accuracy of landing, step of classifier changing can be smaller, but at the same time it will increase size of digital map and will be larger and time of searching safe descent trajectory.

Table 1. Matrix view of digital map

φ	Classification of possible landing points						
	λ=0	λ=0.1	λ=0.2	λ=0.3	λ=0.4	...	λ=359.9
52	6	6	5	5	5	...	6
51.9	6	6	6	4	6	...	6
51.8	5	6	5	6	6	...	5
51.7	5	5	6	5	6	...	6
...	...	...	...	...	...	...	...
-51.9	4	4	4	4	4	4	4

The next base requirement for method of safe descent and landing is possibility of a mathematical solution descent tasks with an on-board computer. This problem can be solved by using the newest high-performance on board computers, which can produce a large number of computations in an acceptable time. Thus it will be possible to model many possible variants of descent and landing and choose the best from them. And this task will be solving on board of the spacecraft “Federation”.

4. Description of the algorithm of searching a safe descent trajectory in case of off-nominal situation

After occurrence of an off-nominal situation and decision to descent, the crew must initiate program of safe descent variant searching. For searching safe descent trajectory algorithm at fig. 3 was developed.

In this algorithm *P (φ, λ)* is function of depends classifier of landing point safety from latitude and longitude.

At the first stage of algorithm working with prediction of the spacecraft motion if first iteration determine coordinates of aiming landing point in admission that this point is on trace of spacecraft orbit. On the next step of the algorithm working, time of engine inclusion for descent to determined landing point is calculating. Because all previous steps of algorithm don't consider maneuver possibility of the spacecraft "Federation" recovery capsule, on the next step of algorithm working parameters of maneuver zone at entrance on the atmosphere time are calculating. This time was chosen because maneuver zone have maximum sizes exactly on this stage of descent.

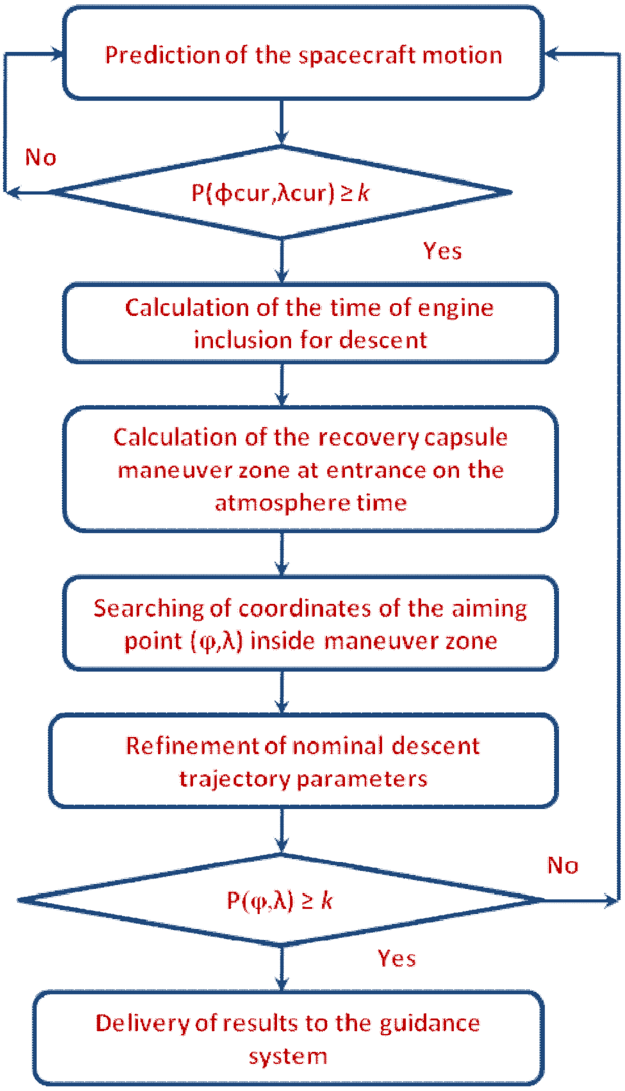

Fig. 3. The algorithm of searching safe descent trajectory

For zone maneuver determination on board computer must solve the task of prediction two landing points in descent mode with constantly bang angles 180° and 60°. This task can solve by integration of differential equations (Eq.1) [5-8]. Step for integration must be selected taking into account the necessity of providing guarantee accuracy of integration on one side and providing high speed of solving this task from the other side. Taking into account the discreteness of descent guidance system, the integration step is usually taken to be equal to the step of the descent guidance system works.

$$\begin{cases} \dot{\bar{r}} = \bar{V}; \\ \dot{\bar{V}} = \rho \bar{V}_{в}^{2}\left[-S_x \dfrac{\bar{V}_{вx}}{|\bar{V}_{в}|} + S_y\left(b\cos\gamma + d'\sin\gamma\right)\right] + 2\omega_e \times \bar{V} + \omega_e \times \\ (\omega_e \times \bar{r}) - \mu_e \dfrac{\bar{r}}{|\bar{r}|^3} + \dfrac{\partial R}{\partial \bar{r}} \\ \gamma = const \end{cases} \qquad (1)$$

where

$$v_{в} = \sqrt{v_{xв}^2 + v_{yв}^2 + v_{zв}^2} \ \text{– air speed.}$$

$$\vec{b} = \frac{\Pi \vec{d} \times \vec{c}}{|\Pi \vec{d} \times \vec{c}|} \ \text{– vector in the local vertical.}$$

$$\vec{d}\,' = \vec{c} \times \vec{b} \ \text{– vector in the local lateral plane.}$$

$$\vec{c} = \frac{\vec{v}_{в}}{v_{в}}.$$

$$\vec{v} = \begin{vmatrix} v_x - \omega_e y \\ v_y + \omega_e x \\ v_z \end{vmatrix} \ \text{– absolute velosity.}$$

$$\Pi = \begin{vmatrix} \cos\alpha & \sin\alpha & 0 \\ -\sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{vmatrix} \ \text{– transition matrix.}$$

For providing high speed of solving the task of integration, on board mathematical models are using simplified functions of accounting for the influence of the no centrality of the gravitational field of the Earth and function of calculating the density of the atmosphere.

Maneuver zone is approximating by ellipse, and these points are situated along the edges of big and small half axes of this ellipse. After that by mathematical method of gradient steepest descent the task of searching safe landing point inside of the maneuver zone are solving. On the next step of the algorithm working nominal descent trajectory parameters refined. This step is necessary because due to features of the descent guidance system, a situation may occur in which the control system will not be able to bring the spacecraft to the selected point. If this situation occurs, the algorithm produces coordinates of nearest possible landing point, and after that this landing point is once again checked for safety. If everything is ok, the results of refinement of descent trajectory parameters are delivered to the guidance system for realization. If checking of landing point is failed the algorithm goes to the first step. On board algorithm of safe descent scenario searching have constraint of maximum 10 iterations for solving the task of calculation parameters of guidance for bringing the spacecraft to aiming point.

At fig.4 results of working of the algorithm of searching safe variants of descent are presented. Figure illustrated maneuver zone of the spacecraft “Federation” and the process of searching safety landing point inside of this zone. In this example find safe scenario of descent and landing to the South America region was presented. This figure perfectly illustrated practically all kinds of classifier values for possible landing points.

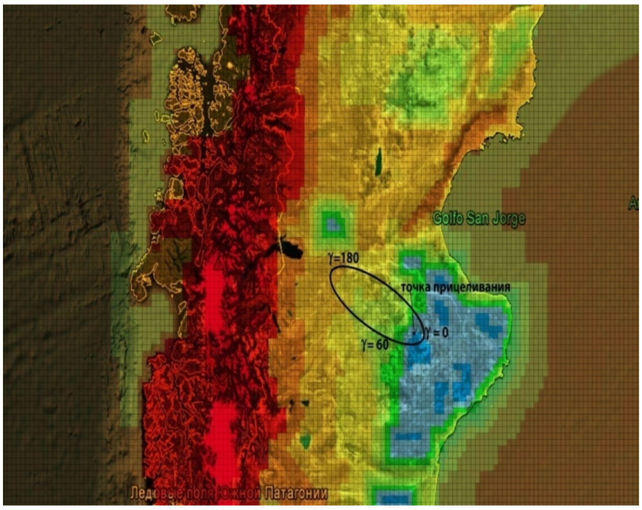

Fig. 4. Result of the algorithm of searching safe descent trajectory work

5. Timeline of working of the method of safe descent in case of off-nominal situation.

Because of the fact that the descent and landing are most dangerous phases of every manned spacecraft flight, after decision to descent and before engine inclusion, the crew must make several necessary preparatory operations. There are: closing of the transition hatch, the dressing of spacesuits, and checking the air tightness of the hatches. In case of off-nominal situation, time for doing these preparatory operations is very limited. At tab.1 and at fig. 5 all basic preparatory operations for providing safety descent are presented. All of these operations have limitations and particularities, which can affect the operation of the guidance system of descent. Moreover one of the most important requirements for providing high accuracy descent is availability of satellite GPS or GLONASS navigation at all stages of descent and landing. According this fact the task of searching safe scenario of descent and landing must solve in automatically mode at preparation stage of the descent. This is explained by two facts:

1) preparation stage of the descent require a lot of time, because all the necessity operations are performed by the crew in manual mode. Moreover this is the longest stage of the descent, therefore crew still has time to analyze onboard situation for the final selection of the descent scenario.

2) necessity of having information about chosen variant of safety descent to the moment of undocking for refinement the computed descent trajectory control parameters for providing high accuracy landing.

Thus, by the time of undocking, the crew must have an initial version of scenario of descent and landing. And after refinement of the trajectory parameters after undocking and withdrawal, the crew must have the final version of safety scenario of descent and landing.

Table 2. Cyclorama of preparation and carrying out of descent

№	The name of the operation	Approximate time for the operation
1.	Closing of the transition hatch, the dressing of spacesuits, and checking the air tightness of the hatches	≈ 20-40 min
2.	Choosing safety scenario of descent and landing	≈ 1 min
3.	Undocking and withdrawal of the spacecraft from the station	≈ 5 min
4.	Orientation building	≈ 15 min
5.	Waiting for engine inclusion time	depend of current position of the spacecraft on orbit
6.	Braking pulse	≈ 4 min
7.	Flight before entering the atmosphere and starting guidance	≈ 25 min
8.	Flight in the absence of radio communication	≈ 3- 5 min
9.	Flight by the algorithms of terminal guidance	≈ 10 min
10.	Parachute stage of descent	≈ 5 – 7 min

After withdrawal of the spacecraft from the station, and before inclusion of the braking engine, the spacecraft must build orientation. For solving this task, an on-board instrument is used - the infrared vertical. The principle of its work is to find two consecutive vertical directions to the Earth. In the algorithm of searching safe descent trajectory considered maximal time for this operation.

Time of waiting for inclusion of the braking engine depend from two factors:

1) Current position of the spacecraft on orbit after undocking and withdrawal;

2) Selected variant of descent and landing.

At any parts of the space flight different off-nominal situations can occur. Depending on the type of off-nominal situation method of safe descent can offer to the crew different scenarios for providing descent and landing. There are two basic scenarios: fast and safe.

These scenarios depend from minimal and maximum values of classifier of landing point safety. These values can be predefined before spaceflight, or defined by the crew during to the spaceflight. After finished of the algorithm of searching safe descent trajectory work, the crew can get two variants of descent scenario. This is depending on current position of the spacecraft at the moment when the algorithm of searching safe descent trajectory was started. If occurred off-nominal situation is critical, the algorithm can find most fast descent scenario variant but this scenario can be dangerous.

But if character of occurred off-nominal situations provide to the crew time for waiting while the spacecraft reach the track point where it is possible to realize more safety scenario of descent, the algorithm can offer to the crew this scenario. Sometimes these two variants of descent and landing can be same (in case of lucky current position of the spacecraft), in this case the algorithm of searching safe descent trajectory offer to the crew one optimum scenario of safe descent and landing.

After selection final scenario of descent and landing by the crew all the next stages of descent will be conducted in automatically mode.

6. Visualization format developing.

Another basic requirement to the method of safe descent in case of off-nominal onboard situation on Russian perspective manned spacecraft "Federation" is providing possibility to control possible working of the algorithm of searching safe descent trajectory from mission control center in on-line mode on every orbit during of the spaceflight[9]. Because scenario of safe descent and landing suppose minimal time between decision to descent and the brake engine inclusion, the crew and specialists of the mission control center at every time of spaceflight constantly must have operative information about possible variants which the algorithm of searching safe descent trajectory can offer to the crew.

For solving this task visualization format of results of working the algorithm of searching safe descent trajectory was developed (fig. 5).

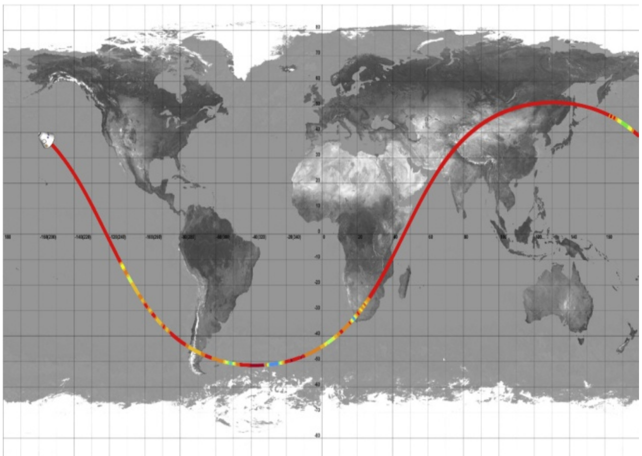

Fig. 5. Visualization format

This visualization format was developed for cosmonaut`s console at Russian perspective manned spacecraft "Federation", and the same format will in the control room at mission control center. The basic idea of this format is visualization of classifier values in case of braking engine inclusion at current position of the spacecraft. For convenient information perception at cosmonaut`s console, classifier values visualized only for one orbit. Periodically information at cosmonaut`s console automatically refresh, but it can be manual procedure.

To reduce required calculation resources of on board computer for getting necessity classifier values of possible landing points, the simplified equation for time of brake engine inclusion (2) was used. This equation is use on the algorithm of searching safe descent trajectory for calculation of brake engine inclusion at first iteration. For final descent trajectory parameters calculation this time could refine many times, but accuracy of Eq.(2) is enough for visualization format.

$$\Delta t_{inclusion} = -\frac{R_e \lambda \cos^2 \varphi}{|\vec{V}| \cos i}. \quad (2)$$

where

i – inclination of the spacecraft orbit,

$|\vec{V}|$ - module of the spacecraft velocity at the moment of brake engine inclusion.

With the Eq.(2) using, algorithm of visualization by mathematical simulation of descent and landing, solve the task of searching classifier landing point value. After that to the brake engine inclusion time added one second, and previous task are solving again. After several iterations all the finding values of classifier visuals on the map. Thus by this visualization format the crew and the specialists of mission control center can estimate the time reserve for the brake engine inclusion waiting for providing safe descent and landing in online mode.

7. Conclusion.

1) The method of safe descent and landing in case of off-nominal on board situation, which provide possibility of finding safe scenario of descent at every part of the spacecraft orbit, was developed.

2) The digital map with safety classification of all possible landing points was developed.

3) The visualization format of results of working the algorithm of searching safe descent trajectory was developed.

4) Simulation software for method of safe descent in case of off-nominal onboard situation on Russian perspective manned spacecraft "Federation" was developed.

5) Works to adapt the developed digital map and algorithm of searching safe descent trajectory for working at on board computer were carried out.

After completely realization developed method of safe descent at on board control loop of Russian spacecraft "Federation", the crew will have opportunity to find optimum safe scenario of descent and landing at every part of orbit, regardless of the time of off-nominal situation occurrence.

In the future researches will consider the questions of using developed method of safe descent and landing for different off-nominal situations that may affect for descent guidance system work.

References

1) Berenov N.K, Branets V.N, Evdokimov S.N. and others: *The guidance system of the descent of the Soyuz TMA spacecraft*, Gyroscopy and navigation, №3, Moscow, 2004.
2) Kutomanov A. Yu., Kutomanova T. V., Kudriavtsev S.I, .: *Algorithm of providing of safe descent in case of off-nominal situation*, Astronautics and rocket science №1(86), Korolev, 2016, pp. 12-20 (in Russian).
3) Kudriavtsev S.I.: *Complex ballistic analysis of problems of high accuracy descent guidance of perspective manned spacecraft at the Earth atmosphere*, Astronautics and rocket science №1(86), Korolev, 2016, pp. 5-13 (in Russian).
4) Kutomanov A. Yu.: Method of providing safe descent at all parts of orbit, Ph.D. Thesis, Moscow Aviation Institute (National Research University), 2005.
5) Ohotsimskiy D.E, Golubev Yu. F, Sicharulidze Yu.G. .: *Algorithms of spacecraft guidance at the Atmosphere entrance*, Moscow, 2016, 399 p (in Russian).
6) Ohotsimskiy D.E, Sicharulidze Yu.G. .: *Fundamentals of space flight mechanics,* , Moscow, 2016, 365 p (in Russian).
7) John Carl Adams: *Robust GPS ATTITUDE DETERMINATION FOR SPACECRAFT*, Ph.D. Thesis, 1999.
8) Kutomanov A. Yu., Kudriavtsev S.I, Kulyuka Yu. F.: *Flight dynamic's aspects of the communication satellite Express-AM4 flight termination from off-nominal orbit*, Collection of 23 ISFDS articles, http://issfd.org/ISSFD_2012/ISSFD23_CRSD2_2.pdf
9) Kutomanov A. Yu., Kudriavtsev S.I.: *Use in the operational control loop of the spacecraft of the perspective algorithm of choosing the safest version of descent in the event of an abnormal situation*, Engineering Journal: Science and Innovation №2(50), Moscow, 2016, http://engjournal.ru/catalog/arse/adb/1467.html (in Russian).