SOLVING THE INTERNATIONAL SPACE STATION (ISS) MOTION CONTROL LONG-TERM PLANNING PROBLEM

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Abstract: *Ballistic support of the orbital space stations long-term functioning at the altitudes up to 400 km provides not only for periodic altitude maintenance but also for the rather rigid orbital requirements fulfillment. Space station flight ballistic condition forming is caused by necessity of the optimal guidance conditions providing for the transport vehicles, approaching to the station, and Russian crew transport vehicles landing to the given regions. According to the international status of the ISS, the ballistic flight conditions for the international partners visiting vehicles must be taken into consideration when planning the orbit corrections. Research has shown that separate orbit forming (OF) for each ISS flight program operation results in higher fuel consumption for the station orbit maintenance, probable altitude constraints violation and visiting vehicles missions schedule violation. It causes the need in solving of the station motion control (SMC) long-term planning problem, which is characterized by the maneuver schedule time-span of several months and several ISS orbital requirements for different moments of time. The present paper is devoted to the method for solving the ISS motion control long-term planning multi-purpose problem.*

Keywords: *International Space Station, motion control planning, ballistics*

1. Introduction

The near-Earth space research using manned stations had begun in the seventies. In the same time transport vehicles (TV) needed for the crew and cargo delivery to the stations had been developed. Particular importance is given to the TV guidance optimal control methods developing. In regard to the long-term motion control of the station itself, the main research object is the atmospheric drag depending on the station orbit altitude and solar activity. However, the TV rendezvous duration depends on the start phase angle between the TV and the station. Moreover, the Russian crew TV landing to the appropriate region of the landing ground is also connected with the specified station location relative to the Earth ground on the landing date. Therefore, the manned station long-term flight program planning requires forming of defined ballistic parameters of its orbit.

The analysis of ballistic support of the Russian orbital stations “Salyut-6”, “Solyut-7” and “Mir” flight is shown that the principles used for planning and altitude maintenance of these stations are not sufficient for the ISS program. It became obvious that the complex approach to a problem of all requirements fulfillment is needed.

The new problem has been appeared – the SMC long-term schemes developing on basis of the optimization of the fuel consumption for the altitude maintenance and in consideration of orbital requirements and constraints caused by the TV flights. The features of such a problem are consideration of the time span for ISS maneuvering of several months and existence of polyterminal orbital requirements (requirements connected with the different time points).

Such a polyterminal character of the ISS OF conditions, an impact of stochastic atmosphere density variation and orbital perturbations on the orbital parameters during the process of the station functioning result in the need for taking into consideration all range of the possible task decisions for the purpose of later choice of robust decision.

The SMC planning for the certain flight stage must pursue two independent objects of ballistic support: altitude maintenance and forming the certain values of the orbital parameters satisfying the conditions of the TV flight program optimal fulfillment.

2. SMC long-term planning problem definition

There is reasonable to formulate SMC in the uncertain conditions as multistage stochastic programming problem, considering set of orbital corrections as stages. Taking into consideration the stochastic atmosphere density variation impact on the station motion, such successive correction of its orbit allows step-by-step approximation to the problem salvation.

The problem of choosing the ISS OF scheme reduces to definition the number of orbital correction ranges, theirs location relative to the operations dates and characteristic velocity distribution amongst these orbital correction ranges.

In the real-world problems of SMC the forming orbital parameters are semimajor axis (a) and longitude of ascending node (λ_{Ω}). It is these two parameters jointly or separately that characterized the ISS flights program requirements and orbital parameters constraints.

An input information consists of the following data:

- schedule of TV flights and crew landing;
- allowed values ranges of required ISS motion parameters;
- ISS flights altitude constraints;
- allowed ISS control range;
- predictable values of the solar activity index, geomagnetic disturbance index and ballistic coefficient for given control range.

Target parameters are:

- number and location of orbital correction ranges;
- orbit numbers of terminal requirements fulfillment;
- altitude maintenance characteristic velocity distribution amongst the maneuvering ranges.

3. Method

The fuel consumption for the TV rendezvous and landing regions of Russian manned TV is connected with longitude of ascending node of ISS orbit on the date of operation. Therefore, the

OF procedure before any TV operation consists in fulfillment the requirements of the ISS trace layout on the operational date. On the initial stage of SMC scheme developing it is permissible to consider that the trace shift is in proportion to the product $\Delta V_T \cdot \Delta D$, i. e. depends on the value of transversal component of the impulse and it’s distance to the given date. Since the station accomplishes about 15 circuits per day on the altitudes of 350-400 km, there is the same number of the trace shift options that is differ from each other in the orbit number of terminal requirements fulfillment. This is true for all operational dates that belong to the SMC scheme. Such variety of SMC results in the need for research all set of options in order to choose an option of the maneuvering scheme that fulfills the requirements in the best way, provides required accuracy of forming parameters, and is robust to orbit perturbation such as debris avoidance maneuvers. The significant characteristic of the given method of SMC control scheme developing is clearness of maneuvering schemes that allows to perform there’s comparative analysis, to reveal there’s features and connections, to assess the consequences of orbit perturbations, changes in flight program etc. This feature is provided by using graphical interpretation of SMC that is the basis of this method.

For imaging the ISS control motion there uses the rectangular coordinate system (D, $\Delta\lambda_\Omega$), where operations dates (D) place on the abscissa axis and desired shift values of longitude of ascending node ($\Delta\lambda_\Omega$) place on the ordinate axis. All requirements for operational dates concerning λ_Ω parameter can be presented in this coordinate system. The cross point of axes performs the reference point of SMC time span and of longitude shift of current values ($\lambda'_{\Omega\,\mathrm{cur}}$) from required ones ($\lambda'_{\Omega\,\mathrm{req}}$). Acceptable shift values of λ_Ω provided an opportunity for the flight trace to place within the certain longitude range. These shift ranges change discretely depending on orbit numbers of terminal requirements fulfillment:

$\Delta\lambda_\Omega = \lambda'_{\Omega\,\mathrm{cur}} - \lambda_{\Omega\,\mathrm{req}}$,

where $\lambda'_{\Omega\,\mathrm{cur}} = \lambda_{\Omega\,\mathrm{req}} + \Delta\lambda_{\Omega.\mathrm{orb}} \cdot n$;

$\lambda_{\Omega\,\mathrm{cur}}$ – closest value to $\lambda_{\Omega\,\mathrm{req}}$, $\lambda_{\Omega\,\mathrm{req}} \le \lambda_{\Omega\,\mathrm{cur}}$;

$\Delta\lambda_{\Omega\,\mathrm{orb}}$ – distance between adjacent orbits;

n – number of shifted orbits ($0 \le n \le 15$).

Every polyline that begins from D-axis and all its sections form an acute angle with D-axis reflects certain SMC program option. It is true only for the SMC schemes whose main purpose is connected with the altitude maintenance.

For example, fig. 1 presents in general 3-impulses SMC program.

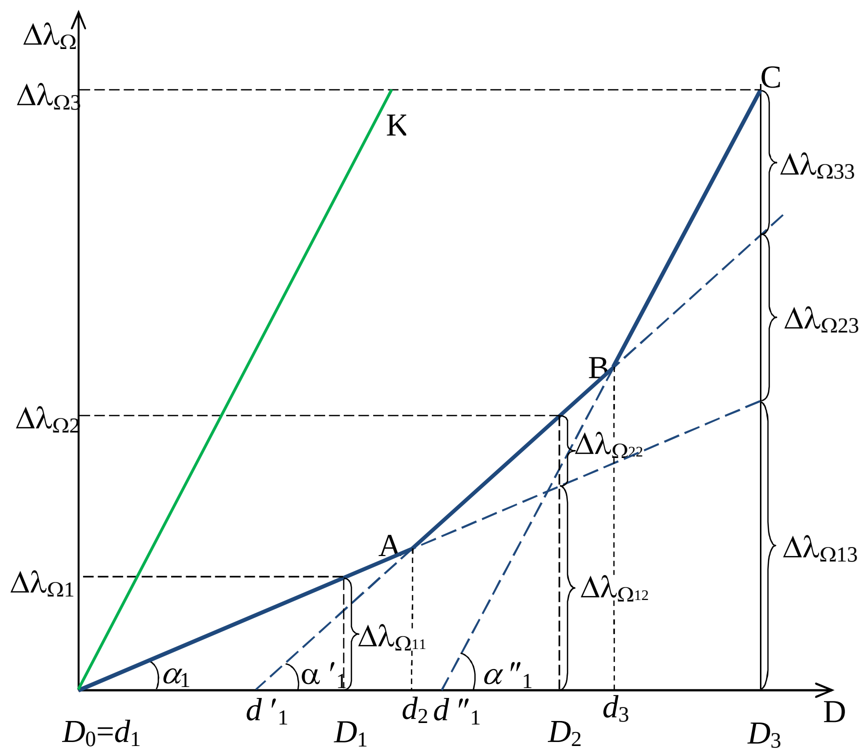

Figure 1. 3-impulses SMC program

Vertices of D_0ABC polyline represent moments of the station orbit corrections while exterior angles of vertices characterize corrective impulses values. Convex character of the line indicates the absence of retrograde impulses that means that the scheme fulfills the altitude maintenance requirement.

Thus, corrective impulses values can be found from the following formulas:

$$\begin{cases} \Delta V_1 = k \cdot \dfrac{\Delta\lambda_{\Omega 11}}{D_1 - d_1} \\ \Delta V_2 = k \cdot \dfrac{\Delta\lambda_{\Omega 22}}{D_2 - d_2} \\ \Delta V_3 = k \cdot \dfrac{\Delta\lambda_{\Omega 33}}{D_3 - d_3} \end{cases}, \quad (1)$$

where d_1, d_2, d_3 – dates of orbital corrections,

D_1, D_2, D_3 – dates of terminal requirements fulfillment,

$k \approx 7{,}353 \dfrac{\text{day} \cdot \text{meter}}{\text{deg} \cdot \text{sec}}$ – constant of proportionality.

If the flight trace needs to be shifted relative to the orbit without maneuvers by the value of $\Delta\lambda_{\Omega 1} = \Delta\lambda_{\Omega 11}$ on the date D_1, $\Delta\lambda_{\Omega 2} = \Delta\lambda_{\Omega 12} + \Delta\lambda_{\Omega 22}$ on the date D_2 and $\Delta\lambda_{\Omega 3} = \Delta\lambda_{\Omega 13} + \Delta\lambda_{\Omega 23} + \Delta\lambda_{\Omega 33}$ on the date D_3 for the purpose of providing the required λ_Ω terminal value, than D_0ABC polyline is interpretation of one of the possible SMC options.

Usually there is certain λ_Ω acceptable values range that fulfills operational requirements. In ($\Delta\lambda_\Omega$, D) coordinate system the ISS trace location requirements on the dates of operations images by segments that are perpendicular to D-axis.

For solving the complex problem of ISS altitude maintenance and orbit forming the polyline imaging it's motion control has to be convex and to intersect the ranges of allowable shifts. In some problems the characteristic velocity value (V_x) is limited: $\sum_{i=1}^{n} \Delta V_i \le V_{x\,\max}$.

The half-line K in ($\Delta\lambda_\Omega$, D) coordinate system imaging the limiting case $\Delta V_1 = V_{x\,\max}$ identifies allowable orbit numbers for fulfill the terminal requirements on the dates of operations.

In these cases the angles between every polyline segments and D-axis shouldn't be greater that angle between K half-line and D-axis.

4. Plotting the regions of the salvations

All set of allowable salvations of the ISS OF problem can be divided into the separate region depends on the orbits numbers of terminal requirements fulfillment, thus marking out those ones that solve the OF problem in the best way. The margins of these regions are segments of convex polylines that cross through the margins of the ranges of allowable λ_Ω values on the dates of operations and fulfill the last segment direction constraint. The number of these regions and there's forms depend on the ISS OF time-span length and characteristic velocity $V_{x\,\max}$ needed for altitude maintenance. Within each region of salvation there can be plotted the set of convex polylines that differ from each other by the number, the length and the direction of segments.

5. Choosing the SMC scheme

The ISS OF problem can be solved for different OF schemes. An opportunity of choosing command variables parameters results in the difference of quality and efficiency of orbital parameters requirements realization. As long as OF is connected with uncertainty, it is reasonable to prefer the schemes that provide an opportunity to parry orbit perturbation while coming closer to the dates of operations.

There are several efficiency criteria of motion control that must be taking into account while choosing the ISS OF scheme:

- energetic (minimization of fuel consumption relative to the altitude maintenance without additional requirements;
- robustness to orbital perturbation, including debris avoidance maneuvers;

- accuracy (quality of terminal requirements fulfillment).

Priority of mentioned ISS OF scheme requirements can differ depends on solar activity, ISS altitude, mass and its functioning conditions. Thus, during OF process in each case there must be used an individual approach to the SMC program choosing.

6. Example

The following example presents the real SMC scheme projecting in the first half-year of 2009.

6.1. Input data, constraints and plotting

The average ISS altitude on the 1st of January was 353.3 km. In the beginning of 2009 its flight program included the following TV operations:

- “Progress M-66” cargo TV launch (02/10/2009);
- “Shuttle STS-19” launch (02/12/2009);
- “Soyuz TMA-14” crew TV launch (03/25/2009);
- “Soyuz TMA-13” crew TV landing (04/05/2009);
- “Soyuz TMA-15” crew TV launch (05/27/2009).

Maximum allowable ISS altitude when STS-119 docking is 361.1 km, when STS-126 docking (planned on 08/08/2009) is 351.9 km.

ISS trace constraints when TV launching and Russian crew transport vehicle landing was following:

- for Russian vehicles 2-days rendezvous $22,5° \leq \lambda_{\Omega} \leq 31,5°$;
- for Russian cargo transport vehicles 3-days rendezvous $25,7° \leq \lambda_{\Omega} \leq 40,5°$;
- for Shuttle 2-days rendezvous $-7,5° \leq \lambda_{\Omega} \leq 9,4°$.

An opportunity of 2-days Shuttle rendezvous for the altitude range from 355 to 360 km can be provided continuously during 4-5 days when $6,4° \leq \lambda_{\Omega} \leq 9,4°$ or $5,0° \leq \lambda_{\Omega} \leq -1,0°$.

Solar activity was low during the year of 2009.

The long-term ISS orbit prediction is made with taking into consideration changing of the ballistic coefficient depending on Sun position relative to the ISS orbit plane and solar batteries orientation program.

According to the altitude constraint due to Shuttle docking the characteristic velocity value, acceptable for orbital correction, can’t be greater than 12.5 m/s before STS-126 launch, and 6.5 m/s of that can be realized before STS-119 launch.

Picture 2 presents an input data for ISS OF and possible SMC schemes before TV flights.

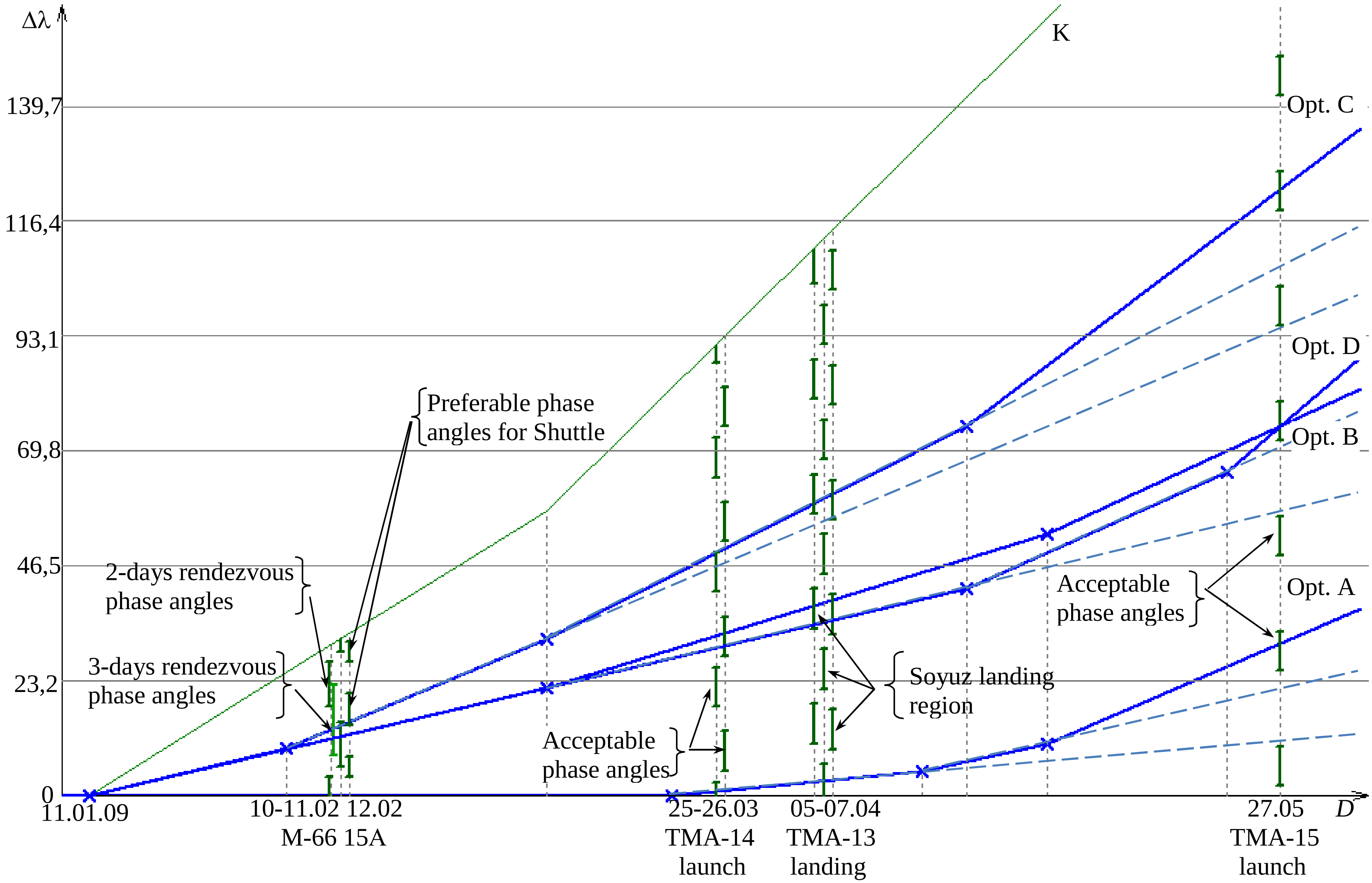

Figure 2. Graphical interpretation of input data and maneuvers options of SMC

6.2. ISS OF schemes analysis

6.2.1. ISS flight with low altitude (option A)

The first OF maneuver should be implemented 5-6 days before “Soyuz TMA-14” launch while the second and the third ones should before “Soyuz TMA-14” launch. The impulses values and corrections dates are:

$\Delta V_1 \approx 1.6$ m/s (03/20/2009);

$\Delta V_2 \approx 3.4$ m/s (04/15/2009);

$\Delta V_3 \approx 1.0$ m/s (05/22/2009).

The negative features of this OF scheme are:

- while 2-days rendezvous of “Progress M-66” was available for normal launch date, there wasn’t an opportunity of “Progress M-66” docking before Shuttle docking for backup launch date;
- the continuous range of available STS-119 launch dates begins only on the 13th of February;
- “Soyuz TMA-13” landing date has to be shifted by 1 day;
- ISS altitude has to be approximately 10 km lower than maximum available value till the end of May.

6.2.2. ISS flight with altitude maintenance (option B)

An orbital correction is planned before M-66 and STS-119 launched in order to fulfill the term of M-66 docking 1 day before STS-119 docking both for normal and backup M-66 launch dates. The impulses values and corrections dates are:

$\Delta V_1 \approx 3.05$ *m/s* (01/14/2009);

$\Delta V_2 \approx 1.16$ *m/s* (03/05/2009);

$\Delta V_3 \approx 1.85$ *m/s* (04/20/2009).

This OF scheme could be realized in case of TMA-14 launch 1-day shifting.

Option B provides better altitude maintenance than option A. But it still cannot provide an opportunity of STS-119 launch on the 12th of February.

6.2.3. ISS flight with the best altitude maintenance (option C)

According to this option, there should be two maneuvers before M-66 and STS-119 flights. It could provide both M-66 docking 1 day before STS-119 docking and necessary phase value for STS-119 launch. The impulses values and corrections dates are:

$\Delta V_1 \approx 3.05$ m/s (01/14/2009);

$\Delta V_2 \approx 1.45$ m/s (02/04/2009);

$\Delta V_3 \approx 3.30$ m/s (03/05/2009);

$\Delta V_4 \approx 1.20$ m/s (04/17/2009).

Option C provides the altitude of 10 km greater than options A and B and, fulfillment of TV launch and landing requirements according to the flight program and 5-days continuous time-span for STS-119 launch.

6.2.4. Further developments

On 14th of January during maneuver realization using two thrusters of Service Module (SM) with thrust of approximately 660 kilogram-force a hard vibration of the station occured. It results in a decision to stop the OF process for a while and consider an opportunity of OF before “Soyuz TMA-14” crew TV launch using two mid-ring thrusters of “Progress M-01M” cargo TV located on the nadir port with thrust of approximately 25 kilogram-force. Ballisticians had offered the new SMC scheme (option D) that didn’t require further OF, but require shifting of TMA-14 launch from the 25th to 26th of March and shifting of “Soyuz TMA-13” landing from 5th to 7th of April. The maneuver realized on the 14th of January had provided an opportunity of 3-days rendezvous for “Progress M-66” cargo TV for normal date of launch and 2-days rendezvous for backup date of launch (1 day later). Later the flight of STS-119 Shuttle was shifted at first to the end of February and then to the middle of March. The ballisticians offer had been accepted and successfully realized.

7. Conclusion

ISS OF is polyterminal problem with target functions and constraints that is allocated within a sizeable time-span.

An existence of a set of allowable solutions is the consequence of discreteness of target functions because of an opportunity of theirs fulfillment on the different orbit numbers.

For the first time the need in these problems has appeared when manned space stations came into existence. It is important to choose the best mode for altitude maintain along with fulfillment ballistic requirements connected with TV flights to a station, i. e. to find complex decision of the problem.

The described graphics-based method of polyterminal SMC planning problem allows getting the following results:

- imaging the set of allowable solution options with account taken of altitude constraints during given time-span;
- choosing station maneuvers regions and velocity values distribution options that allow to realize OF scheme provided altitude maintenance in the best way:
- clearly represent the SMC scheme in ($\Delta\lambda_{\Omega}$, D) coordinate system, allowing to implement an operational analysis of various situations connected with abnormal maneuvers realization, operational dates shifting, appearing an additional requirements to the ISS trace and so on.