CORONAS-F ORBIT MONITORING AND RE-ENTRY PREDICTION

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1. INTRODUCTION

Russian scientific satellite CORONAS-F was launched on July, 31, 2001. The object was inserted in near-circular orbit with the inclination 82.5° and a mean altitude ~ 520 *km*. Due to the upper atmosphere drag CORONAS-F was permanently descended and as a result on December, 6, 2005 it has finished the earth-orbital flight, having lifetime in space ~ 4.5 years. The satellite structural features and its flight attitude control led to the significant variations of its ballistic coefficient during the flight. It was a cause of some specific difficulties in the fulfillment of the ballistic and navigation support of this space vehicle flight.

Besides the main mission objective CORONAS-F also has been selected by the Inter-Agency Space Debris Coordination Committee (IADC) as a target object for the next regular international re-entry test campaign on a program of surveillance and re-entry prediction for the hazard space objects within their de-orbiting phases.

Spacecraft (S/C) CORONAS-F kept its working state right up to the end of the flight – down to the atmosphere entry. This fact enabled to realization of the additional research experiments, concerning with an estimation of the atmospheric density within the low earth orbits (LEO) of the artificial satellites, and made possible to continue track the S/C during final phase of its flight by means of Russian regular command & tracking system, used for it control.

Thus there appeared a unique possibility of using for tracking S/C at its de-orbiting phase not only passive radar facilities, belonging to the space surveillance systems and traditionally used for support of the IADC re-entry test campaigns, but also more precise active trajectory radio-tracking facilities from the ground control complex (GCC) applied for this object. Under the corresponding decision of the Russian side such capability of additional high-precise tracking control of the CORONAS-F flight in this period of time has been implemented.

The organizing of the CORONAS-F ballistic and navigational support (BNS) and solving its main tasks (such as S/C orbit determination (OD) and its motion prediction and connected with them) both for regular mission stage and for additional flight program were realized by the group of specialists from the Mission Control Center (MCC).

MCC was also assigned as a principal organization from the Russian side for participation in the 7-th IADC re-entry test campaign on CORONAS-F.

The CORONAS-F flight features and space environments circumstances during its flight as well as a methodology and technology of spacecraft ballistic and navigational support are given below. The BNS results for different phases of S/C flight, including the results of its re-entry predictions, obtained during the realization of the 7-th IADC test campaign are submitted.

The accuracy of space vehicle re-entry prediction and its dependence on various factors are analyzed in more details.

2. INFORMATION ABOUT S/C CORONAS-F AND SPACE ENVIRONMENTS DURING ITS FLIGHT

Spacecraft CORONAS-F related to a series of the scientific satellites launched within the frame of the project CORONAS. The purpose of a given international project is realization from an earth orbit of the complex investigations of the physical processes occurring both on a surface and in the bowels of the Sun. The project CORONAS presupposes the launches of the exploratory satellites in various periods of the solar activity cycle. Thus the predecessor of S/C CORONAS-F – the S/C CORONAS-I started working in its orbit in March 1994, i.e. in a period of a minimum of solar activity. The launch of the S/C CORONAS-F has been scheduled for the period near to a maximum of the 23-rd cycle of solar activity. According to the adopted schedule S/C CORONAS-F has been inserted in orbit on July, 31, 2001 by the rocket "Cyclone" from the launch site Plesetsk. Initial parameters of S/C orbit were such as:

- inclination – *82,5 deg.*;
- orbital period – *94,86 min.*;
- minimum distance from the Earth surface – *500.9 km*;
- maximum distance from the Earth surface – *548.5 km*.

This space vehicle has been appropriated with the International Designator: 2001-032A, and U.S. Satellite Number: 26873 in NORAD catalogue.

The set of scientific devices intended for examinations of high-power dynamic processes of the active Sun over the range from radio waves up to a gamma radiation, the study of the cosmic rays as well as the solar bowels and its corona has been established onboard of the S/C CORONAS-F. Besides, the S/C has been equipped with the onboard service systems necessary for the support of the S/C operating. For the control and navigational monitoring of S/C flight the usage of the regular control command tracking systems, which are included in the Russian ground control complex has been provided.

S/C CORONAS-F was a rather large space object: its dimensions (in a flight mode) were 2.3m×5m×12m, and the mass including the scientific equipment made ~ 2300 *kg*. The common of view of the space vehicle in operating mode in its orbit is shown on fig. 1.

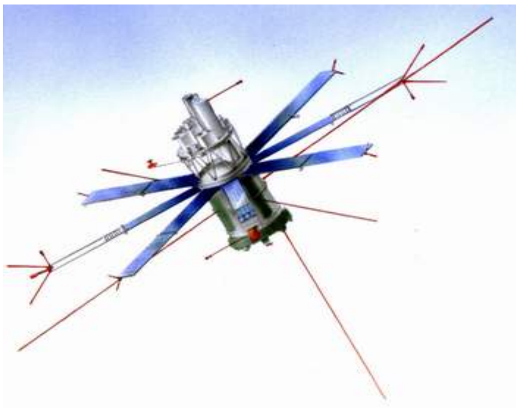

Fig. 1. CORONAS-F in flight mode.

The attitude of S/C was maintained so that the centerline of the vehicle kept the direction to the Sun, and the planes of S/C solar batteries (altogether 8 modules) were oriented orthogonal to the solar flux during all flight period.

To support the indicated mode of the flight the appropriate attitude control system and stabilization of the S/C was provided. The basis of this system was made with the help of accelerative means. At the same time for unloading hand-wheels in S/C real flight conditions the gas-jet engines were sometimes used as well.

S/C CORONAS-F was in its orbit starting the movement from a maximum of current 23-rd cycle of solar activity and continued flying, practically, up to the end of this cycle of solar activity in its decay phase. For 4.5 years S/C has been influenced by various helio-geophysical phenomena. The solar activity index variation within the period 2001 – 2005 is shown on fig. 2. Mid-annual value of a radio flux emission from the Sun for this period of time decreased from values $F_{10.7}$ ~ 181 (in 2001) down to values $F_{10.7}$ ~ 92 (in 2005).

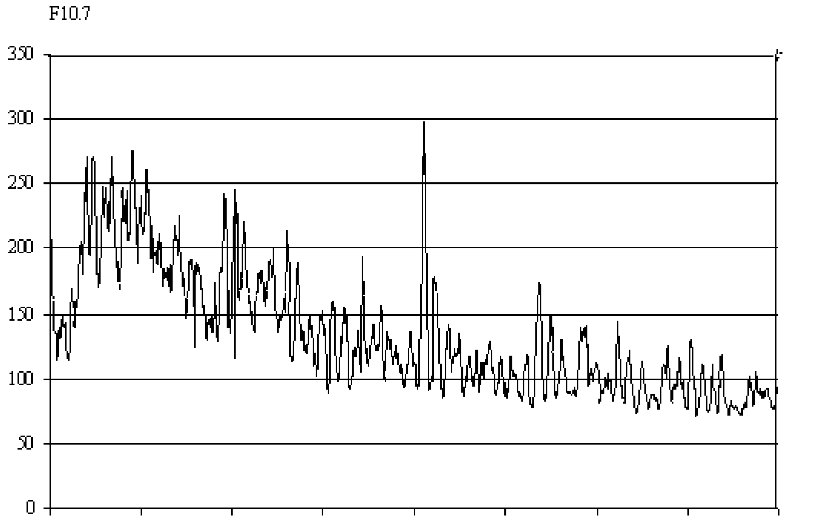

Fig. 2. The solar activity index variation during the period of CORONAS-F flight.

There was observed very high flash solar activity during all period of the CORONAS-F flight. Thus it is necessary to mark, that among the 5 largest x-ray flashes that were registered for all history of their observation there were 3 ones within this S/C flight time.

During the object's orbital life 209 magnetic storms have been registered. The mean diurnal Ap-indexes diagram for all flight time of S/C CORONAS-F is shown on fig. 3. At the top of this figure the moments of the outbreak of magnetic storms are indicated.

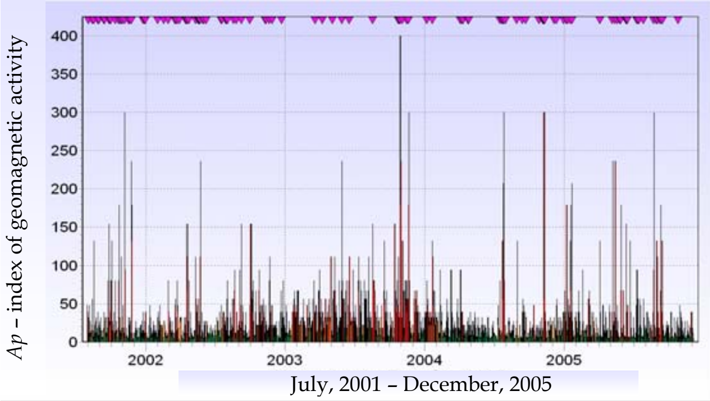

Fig. 3. Mean diurnal values of *Ap*-indexes of geomagnetic activity in lifetime of CORONAS-F.

The mean Ap-index for all lifetime of S/C CORONAS-F appeared to be equal to 15.39 ± 0.44, that noticeably is above the long-term average level of geomagnetic activity which makes the Ap = 14.6 ± 0.1 (during observation period 1932 - 2005).

During CORONAS-F flight time 180 quiet days, 612 minor perturbed, 403 perturbed and 395 days with a magnetic storm have been marked. The total amount of strong and severe storms (Ap≥180) was: 3 – in 2001, 1 – in 2002, 4 – in 2003, 3 – in 2004 and 8 – in 2005.

High solar and geomagnetic activity in the indicated period led to the increasing of the upper Earth's atmosphere density that affected acceleration of the descent rate of space objects that were orbiting the earth in LEO. It concerned S/C CORONAS-F as well. In the total, due to a natural atmosphere drag effect, the given vehicle could live in its orbit only ~ 4.5 years, much less, than its predecessor – spacecraft CORONAS-I.

3. BALLISTIC AND NAVIGATION SUPPORT ON THE MAIN PHASE OF S/C FLIGHT

3.1. *Main tasks and basic requirements for BNS*

The main tasks of the BNS of the spacecraft CORONAS-F flight consisted of:

1) Regular monitoring of the S/C flight and determination of its real orbit using the trajectory tracking data.
2) Prediction and analysis of S/C motion for the given time span. Accuracy estimation of the obtained prediction results.
3) Calculation of the navigational and astrodynamics parameters necessary for planning and realization of the ground control, and for solution of various target and service mission tasks.
4) Supply of the regular command & tracking systems and the ground facilities for the onboard data reception with the S/C motion parameters, that are necessary for pointing these facilities to the S/C and its tracking during a communication session.
5) Provision of the scientific organizations, participating in the project, with data about a real orbit of space vehicle for planning target measurements and experiments and space-time fixation of their results.

The basic requirements for BNS were defined as the following:

- Keep the approved schedule, discipline and technology of the work,
- Guarantee the necessary reliability and quality of the obtained results of the solved problems,
- Enough high operative efficiency of the obtaining and the following transmission of the output data.

Regarding the accuracy of navigation the following requirement was stated: the error in the spacecraft position, corresponding to the obtained solution of the OD task, did not have to exceed several tens kilometers within the adopted prediction time interval.

Besides for many reasons, it was required to achieve minimization of the number of the tracking sessions.

3.2. Methods and technology of the navigation support

To solve the problems of S/C CORONAS-F navigational support in the main phase of the S/C flight the usage of the trajectory measurement data obtained with the help of regular command tracking systems was provided. These data were radial velocities of S/C relative to a ground tracking station (based on the Doppler methods). The ground-based measurement facilities used for the navigation support of S/C CORONAS-F were located from west-to-east points within the Russia's territory so that they jointly could be able to ensure tracking the spacecraft in 5–6 adjacent orbits. It enabled to select enough effective and rational programs of the navigational measurements execution.

The propagation of the CORONAS-F motion in the BNS tasks was realized in a way that stipulated the obtaining the kinematics' state vectors of the S/C (its rectangular coordinates and velocities) at the given epoch by means of a numerical integration of the appropriate differential equations representing the mathematical model of motion of the S/C center of masses. At that for description of space vehicle's motion the rectangular geocentric inertial system of coordinates (reference frame – RF) relating to the reference epoch J2000 was used. The estimated calculations and tests carried out before the vehicle launch showed, that for support of S/C CORONAS-F flight control and fixation of target measurement and experimental data with required accuracy it is necessary in the S/C motion model to take into account the following forces:

- influence of non-central gravitational field of the Earth;
- aerodynamic drag of the Earth's atmosphere.

Thus the equation of S/C CORONAS-F motion in the geocentric inertial RF was represented as follows:

$$\ddot{\bar{r}} = -\mu \frac{\bar{r}}{r^3} + M \cdot gradU(\bar{r}') + \bar{F}_{atm} \qquad (1)$$

Here

μ– gravity constant of the Earth,

$\bar{r}, \ddot{\bar{r}}$ – geocentric radius-vector and acceleration vector of S/C,

$\bar{r}' = M^T \bar{r}$ – radius-vector of S/C in the rotated (Greenwich) RF,

M – transformation matrix from Greenwich RF to geocentric inertial RF (T - sign of a matrix' transposition),

$U(\bar{r}')$ – non-central part of a gravitational potential of the Earth, presented by expansion in the series of the spherical function (harmonics).

Influence of an atmospheric drag is submitted in the equations of space vehicle's motion by the acceleration:

$$\bar{F}_{atm} = \frac{1}{2} S_b \rho(h) V_{rel} \bar{V}_{rel} \,,$$

where $\rho(h)$ – atmospheric density corresponding to the adopted model,

h – altitude of space vehicle above the Earth' surface,

$\bar{V}_{rel}$ – S/C velocity vector relative to the atmosphere ($V_{rel} = |\bar{V}_{rel}|$),

S_b – the ballistic coefficient describing aerodynamic properties of the given space vehicle, so:

$$S_b = \frac{C_x S_м}{m},$$

C_x – coefficient of an aerodynamic drag,

$S_м$ – S/C cross-sectional area.

The Russian model of geopotential PZ-90 has submitted the gravitational field of the Earth in the mentioned model of S/C motion. At calculation of the effect of an atmosphere drag on S/C motion the Russian dynamic model atmosphere, appropriate to the GOST 25645.115-84 (in edition 1990г.) was used.

It is necessary to note, that the problem of the accurate calculation of atmospheric disturbances is one of the most difficult problems in the tasks associated with the propagation of the S/C motion in the range of the near earth orbits. One should take into account that the atmosphere's models now in use, are not fully adequate to its actual physical condition. This circumstance does not allow ensuring a high accuracy of density $\rho(h)$ calculation, and according to this, to ensure the desirable accuracy of orbit prediction for low-altitude space vehicles. The strongest effect of inaccuracy of atmosphere models adversely affects the S/C motion prediction along its track direction.

For obtaining the calculated values of the CORONAS-F motion parameters at the given epoch at the solution of all BNS tasks the software for numerical propagation, based on a special method of a numerical integration of the differential equations (1) was used. This method is the original MCC development [1]. It concerns methods of the high order and possesses high computing efficiency (in a sense of accuracy and speed). The method has been validated against the different space orbits and models of acting forces and now is successfully applied in MCC for solving various research and applied problems of the celestial mechanics and space navigation.

The task of the S/C CORONAS-F motion parameters determination in the majority cases provided the improvement by means of the measurements treatment not only the S/C kinematic parameters – the six-dimension state vector $\{\bar{r}_0, \bar{V}_0\}$, but also a ballistic coefficient – S_b in addition. It is necessary to point out, that in many of these cases S_b was considered as a fitting parameter which specified, in particular, inaccuracy of the used atmosphere model. The improvement of the S/C motion parameters was performed by fitting the measured observations under least squares method (LSM). The used procedure of the S/C motion parameters determination provided combining all available tracking data over a selected measured span. Besides sometimes the a-priory S/C orbital parameters were used as additional navigational measurements. The quality of the obtained LSM solution was characterized by a standard root mean square error σ_0, defined as:

$$\sigma_0 = \sqrt{\frac{\sum_k \sum_{i=1}^{M_k} P_i^k \left[\Psi_{i_{obc}}^k - \Psi_{i_{calk}}^k(\bar{q})\right]^2}{N - m}} \qquad (2)$$

In formula (2): $\Psi_{i_{obs}}^k$ – measured value of *i-th* observation of type *k*, $\Psi_{i_{calk}}^k(\bar{q})$ – the computed analog of this observation value corresponding to the improved vector of the determined parameters $\bar{q}$ by dimension *m* (in this case $\bar{q} = \{\bar{r}_0, \bar{V}_0, S_b\}$, $m = 7$), P_i^k - a weight of *i-th* observation, M_k – total number of fitted measurements of *k-th* type, $N = \sum_k M_k$. At a normal fitting of used measurements and the adequate definition of their weights the value σ_0 should be close to the quantity 1, or not much differ from it.

It is known, that the accuracy of the S/C orbit determination depends on an accuracy and a composition of the used trajectory measurements. At the absence of variety of available observations (we shall remind, that in our case were used one-type measurements of radial velocity) and demanded limitations on the total number of the tracking sessions the selection of the rational schemes of arrangement of these sessions was important. According to the adopted technology of BNS for the given S/C, the measurements of the current navigation parameters (MCNP) were carried out by the cycles – once a week during one day with the help of the used trajectory tracking facilities. The elaboration of the concrete MCNP programs within a navigational cycle was carried out by means of simulation of real S/C tracking conditions for the disposable ground stations and subsequent usage of the modeling measurements for S/C orbit determination and estimation of the OD accuracy. As a result of such a kind of investigations the following scheme of trajectory tracking within a navigational cycle has been recommended:

- the measuring cycle is fulfilled during a day on two–three orbits by means of three or two tracking stations in each orbit;
- measuring sessions in a cycle should cover as much as possible extended time interval;
- on each navigational orbit of a cycle the ground stations, maximal spread on a longitude (so-called, west and east measuring sites) should be used whenever possible for the S/C tracking.

According to the first mentioned recommendation it should be that the number of sessions in a cycle could be from 6 up to 9. The second and the third requirements allowed to increase the accuracy of the S/C motion parameters determination and, in particular, to improve a ballistic coefficient. At the same time, it was established, that in a case of absence of a capability of engaging several tracking stations to make the measurements in a certain orbit it was possible to transfer not implemented sessions in other orbits, admitting realization of one measuring session in an orbit. However the requirement of the second recommendation was valid.

Offered methods and technology have made the basis of the BNS fulfillment during the realization of a real flight of S/C CORONAS-F.

3.3. Results of the operative BNS

After the insertion of S/C CORONAS-F into its orbit the BNS of this vehicle was carried out in a regime of practical activities with an operating speed of fulfillment. This activity included:

- realization of cycles of the navigation measuring sessions under the coordinated program,
- treatment and the analysis of the observed data,
- improvement of a real orbit parameters and a ballistic coefficient,
- calculation on the base of the S/C improved motion parameters of the various stipulated ballistic and astrodynamic information within a future subsequent time span,
- performance of the improved orbit in the frame of the S/C motion models used in the corresponding software on the stations belonging to the regular control command & tracking system (RCCTS) and in the scientific organizations, participating in the project,
- formation and transmission of the navigational data on the communication lines,
- estimation of the OD and S/C motion prediction accuracy.

In the tasks, concerning the operative OD and motion prediction, at calculations of atmospheric density with the help of the used model the predicted values of the solar and geomagnetic activity indexes ($F_{10.7}$ and Ap), submitted by NOAA and Russian institute IZMIRAN were used. When an accuracy of the solution of the navigational task was analyzed the real (updated) values $F_{10.7}$ and Ap already available to that time were used.

At a phase of normal monitoring of S/C CORONAS-F at realization of the regular weekly navigational cycles the following scheme of the trajectory control was practically implemented:

a) The measuring cycle consists of 6-7 sessions, which are carried out in 4-5 measured orbits within a day;
b) The first 4 measuring sessions are carried out in three successive contiguous orbits, thus 2 sessions are carried out in the first orbit (by two spread tracking stations) and one by one session - in the second and third orbits;
c) Remaining 2-3 MCNP sessions are carried out on orbits, whenever possible, long distant in time during a day both from the first three measurement orbits and from each other.

For determination of current parameters of an actual orbit the measurements from the given navigational cycle were used, but at the same time for improvement of the ballistic coefficient S_b both the same navigational measurements and the discrepancy between the improved value of transit time of an ascending node corresponding to the S/C updated orbit – t_Ω^s and the predicted value t_Ω^{pr}, appropriate to orbit parameters and a ballistic coefficient, obtained in the previous navigational cycle were applied.

In total during the S/C CORONAS-F flight it has been performed over 260 cycles of navigational support, among them about 240 were fulfilled during the main phase of flight, i.e. prior to the beginning of the 7-th IADC test campaign on the re-entry control of this object.

4. BEHAVIOUR OF THE BALLISTIC COEFFICIENT OF S/C CORONAS-F DURING FLIGHT

According to the S/C CORONAS-F design structural data (the vehicle mass, assumed cross-sections area in flight and mean coefficient of its frontal aerodynamic drag) the nominal calculated value of a ballistic coefficient – S_b^0 has been defined.

As it was mentioned above, at orbital flight the attitude of S/C CORONAS-F was maintained so that the centerline of the vehicle kept the direction to the Sun, and the planes of S/C solar batteries in the greatest possible degree would be oriented orthogonal to the solar flux. To support the indicated mode of a flight the appropriate attitude control and stabilization system of the S/C was provided. During the S/C flight due to its orbit evolution and because of the Earth motion in its orbit around the Sun the direction to the Sun relative to the S/C was changed. It led in particular to a variation of an angle between the direction to the Sun and the orbital plane of S/C. The character of the angle φ (between vector S/C–Sun and the normal to the satellite orbital plane) changing during S/C flight is shown on fig. 4.

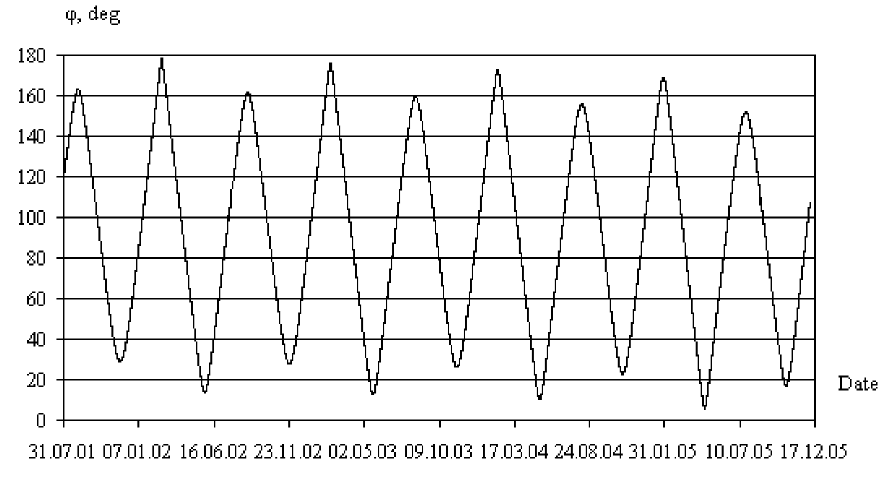

Fig.4. Variation of an angle between the direction to the Sun and the normal to the orbital plane of S/C CORONAS-F

Changing the direction of the S/C centerline relative to its orbital plane (in the requirements keeping the given orientation to the Sun) led to variation of the cross-section area of space vehicle that is a reason of the change of the S/C ballistic coefficient. Here it is necessary to indicate that value of S_b depends not only on the changeable S/C flight condition but also on the affecting the residual accelerations from activity of gas-jet system which was sometimes used (especially at the final phase of flight) for the support of the given attitude control mode and S/C stabilization, and these residual accelerations were not taken into account in the adopted S/C motion model. Besides, unknown modification of the atmosphere parameters and incorrectness of its used models influenced the value S_b as well. The behavior of the ballistic coefficient obtained as a result of the solution of the navigational task, for all period of flight of S/C CORONAS-F is shown on fig. 5. (Presented values correspond to the reduced ballistic coefficient S_b^*, defined as $S_b^* = \frac{S_b}{S_b^0}$).

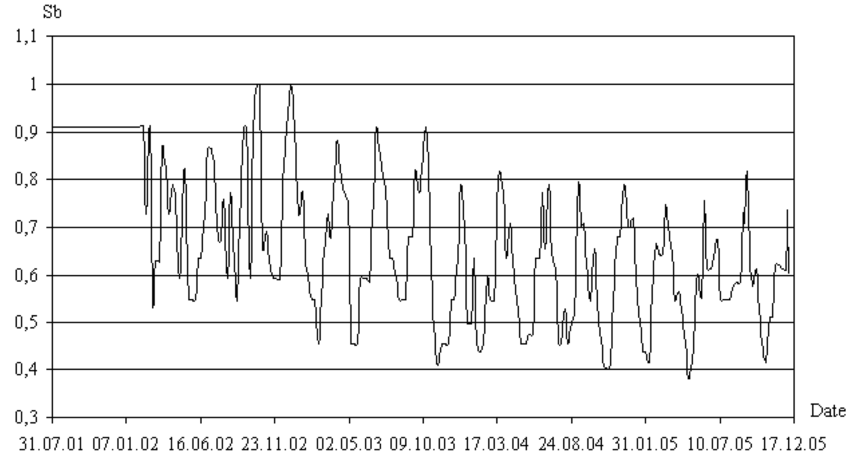

Fig. 5. Variation of the ballistic coefficient of S/C CORONAS-F during its flight

Comparing fig. 4 and fig. 5 it is possible to establish the character of correlation between variations of an angle φ and values S_b^*. So at φ tendency to values 0° or 180° the value S_b^* reached the minimum values. It corresponded to the situation that at the given period of flight the planes of the solar batteries of the S/C were practically parallel its orbital plane so these batteries were in a minimum degree influenced by the pressure of an approach air flow. On the other hand, in periods when the angle φ was close to 90°, S_b^* became nearer to the maximum values that can also have clear enough explanation.

5. THE ESTIMATION OF THE S/C CORONAS-F ORBITAL LIFETIME

During the execution of the CORONAS-F flight BNS the estimation of this object's orbital (ballistic) lifetime was periodically implemented. It was necessary for definition of the remaining flight time of S/C, distribution of the necessary resources for fulfillment of the mission tasks, planning and realization of some experiments, etc. Whereas the ballistic coefficient of S/C varied during flight, in correspondence to established relation of changing this parameter for estimation of S/C lifetime some average value S_b was chosen, and in the atmospheric model mean predicted indexes $F_{10.7}$ and Ap were used. Graphics of the S/C CORONAS-F predicted re-entry time as it was obtained on the base of the tracking data fulfilled during the last year of its flight is shown on fig. 6. Here on the abscise axis the date, when the certain prediction was calculated, and on the ordinate axis – the date of the S/C re-entry, corresponding to this prediction, are indicated. Taking into account, that CORONAS-F re-entered on 06.12.2005, it is possible to conclude, that in the time intervals remained before S/C re-entry, that was almost one year long, the predicted time of this event was precise enough. At the estimation of the remained lifetime of S/C the possible window of uncertainty in obtained results was calculated as well. This window of uncertainty in accordance with the reduction of the remained lifetime permanently decreased, and if in January 2005 it could reach 2-3 months then by November of the same year the window of uncertainty in the prediction of the S/C re-entry did not exceed several days any more.

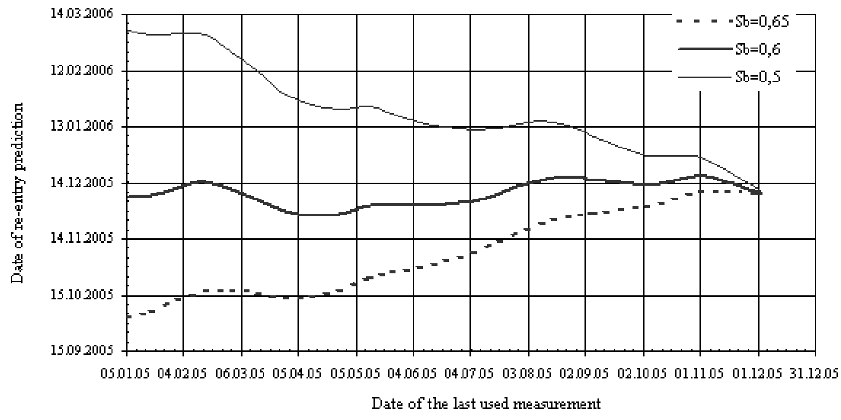

Fig. 6. The S/C CORONAS-F re-entry prediction during 2005 year

6. BNS AT THE FINAL PHASE OF S/C CORONAS-F FLIGHT AND CONTROL OF ITS DE-ORBITING WITHIN THE FRAME OF THE 7-TH IADC TEST CAMPAIGN

After selection of S/C CORONAS-F as the target object for the 7-th IADC re-entry test campaign the final stage of the S/C BNS began to be determined in many respects by the purposes and tasks of the given international experiment. The 7-th IADC test campaign began on 28.11.2005 and lasted up to S/C re-entering. 8 space agencies have taken part in this campaign.

6.1. CORONAS-F as the hazard object and the test article for the 7-th international campaign on control of re-entering objects

The space objects are considered as the hazard objects (HO) if they have a large mass, or if they incorporate the radioactive and other dangerous substances. Incontrollable re-enter, destruction in the atmosphere and an impact to the Earth survivable fragments of such objects can have the considerable negative aftereffects that cause particular worried attention for the government and the public of different countries. To support the adoption of the effective measures on reaction to crisis situations, connecting with HO re-enter, it is necessary to conduct the active information control of such events which is based on observations and the motion prediction of these dangerous HO. Taking into account the terrestrial significance, such task should be solved internationally. In this connection it has been decided in the framework of IADC regularly to conduct 1–2 times a year the international test campaigns on control of HO re-entering with the purposes:

1) Mobilization and consolidations of the efforts of different countries, which are carrying on space activity, on the solution of a problem of the flight monitoring and re-entry prediction for the de-orbiting space objects of the higher hazard,
2) Validation and optimizations of the re-entry target tasks solution techniques, the ways of the international cooperation and technology of the information exchanges.

The first test campaign under the IADC aegis was realized in 1998. CORONAS-F became the object of the 7-th test campaign. As it has already been said, the mass of S/C CORONAS-F in the flight was up to value ~ *2300 kg*. According to the information, provided by the relevant experts, during the atmosphere entering of S/C CORONAS-F and its break up in dense layers of atmosphere, the Earth's surface could be reach by 11 fragments of this vehicle in total mass ~ *440 kg*. Thus S/C CORONAS-F really represented the space object of a higher hazard. In the view of the spread of survival fragments' impact zones along the track and the inaccuracy of the re-entry predictions it was admitted, that these fragments can reach the surface of the Earth in a zone from ~ 82.5° N down to ~ 82.5° S.

Having the orbit with inclination i = 82.5°, S/C CORONAS-F was a convenient target for tracking by the ground facilities located in territories of Russia, CIS, US and other countries. Thus, the given object completely satisfied the purposes of the considered test campaign.

6.2. Organization of activity of the Russian tracking facilities for monitoring at the final phase of S/C CORONAS-F flight

6.2.1. Activity of the regular control command & tracking system (RCCTS)

According to the initial mission plan of S/C CORONAS-F the maintenance of activity with this object should be stopped after its orbit's lowering up to altitudes ~ 200÷150 km. Further any operations with the vehicle including realization of trajectory control were not provided. At the same time, taking into account a special case for S/C CORONAS-F as the test object for realization of the international campaign, and also a presented unique possibility of using additional, potentially more precise means of tracking for the flight control of S/C during this campaign, ROSCOSMOS admitted expedient to fulfill trajectory tracking with the help of nominal control command & tracking facilities which are included in the Russian ground stations network up to the end of the orbital flight of this S/C.

Simultaneously with this solution the Institute of Terrestrial Magnetism, Ionosphere and Radio wave Propagation of Russian Academy of Sciences (IZMIRAN), as a parent organization on the implementation of the scientific program of project CORONAS-F, also considered expedient to prolong the scientific mission plan, having expanded it at the expense of additional experiments on measurements performances of the lower layers characteristics of the upper aerosphere, down to S/C entering in dense layers of the atmosphere. In accordance with the adopted solutions a special program of trajectory monitoring of S/C at the final phase of its flight with the help of nominal means of RCCTS was elaborated and implemented.

The first series of the trajectory tracking data, used for the purposes of a test campaign, was made by means of RCCTS on 28.11.2005 in the regular cycle of trajectory control earlier foreseen for BNS of S/C CORONAS-F. Since December, 1, the MCNP sessions of S/C CORONAS-F by means of RCCTS were conducted daily. During the period 1–4 of December the sessions MCNP were conducted in four orbits, prolonged on a time in intervals from 5 o'clock till 18 o'clock (UTC) with usage of west and east tracking stations facilities.

On the 5-th of December measurements were carried out in ten orbits in the time interval from 2 o'clock till 19 o'clock. On the last day of S/C CORONAS-F life, on the 6-th of December, 2005 the program of realization of sessions MCNP on each visible orbit since 1 o'clock (UTC) was adopted. Thus the given program provided realization of measurements on an orbit by means of two tracking stations. The last trajectory data from RCCTS was obtained in an orbit of S/C re-entering at 17:06:50 UTC.

6.2.2. *Activity Russian space surveillance system*

Russian space surveillance system traditionally took part on the control of the de-orbiting object in the framework of IADC test campaign. S/C CORONAS-F during its final orbital flight stage was controlled by the permanent and addition engaged radars belonging to the Russian space surveillance system (RSSS). The S/C has been stable monitored by these facilities up to its last re-entry orbit. At that time the adequate accuracy for the fulfillment of the tasks in point of view of the S/C flight monitoring, tracking and determination of motion parameters of S/C, and the regular operative transmission of standard messages with the information on S/C orbit in MCC was ensured.

The delivery of the standard messages was produced on coordinated schedule. In accordance with this schedule during the period from 28.11.2005 till 03.12.2005 2 messages were delivered daily (in the morning and in the evening), on December, 4, 2005 the 6 messages were transmitted, on December, 5, 2005 – 7 messages and 06.12.2005 – again 6 standard messages were produced and delivered to MCC. On the last day before S/C re-entry standard messages were formed and delivered after the realization of a session of tracking on each information orbit in mode, approximate to a real time.

In total during the 7-th international test campaign on re-entry control of CORONAS-F 34 standard messages with orbit parameters of S/C CORONAS-F generated in the RSSS were produced. The last measured data of S/C CORONAS-F was fulfilled by the Russian radar when the object was at the altitude ~ *115km* above the Earth surface, less than 0.5 hours prior to its atmospheric entry.

6.3. The solution of the tasks of the S/C CORONAS-F motion parameters determination and its re-entry prediction in Mission Control Center

The procedure of determination and prediction of S/C CORONAS-F motion at the final phase of its flight including period of the IADC test campaign in main was the same that was described above. However the structure of the measuring information used at this phase was much wider: besides the trajectory tracking data from RCCTS for determination of S/C motion parameters were engaged also:

- orbital data, obtained by the Russian space surveillance system on the basis of radar data, presented as rectangular state vectors or osculating elements of an orbit, referred to identify epoch;
- orbital data as two-line elements (TLE) from the US space surveillance system (US SSS);
- orbital data in TLE format from other foreign participants of the test campaign (in particular, obtained on the basis of the FGAN radar data).

Data in TLE format from the US SSS and other foreign participants were available through the database REDB, operating in structure of IADC.

Activity on the determination and prediction of S/C CORONAS-F motion, including its re-entry prediction, was carried out in MCC in an operative (and on-line) mode. Observation data coming from all feasible sources were treated and analyzed. On the basis of these tracking data the tasks of the orbit determination of the descending spacecraft and the prediction of a time and a place of its re-entry were solved. The OD task was solved in the alternate statement providing implementation of various versions with the usage of different inputting measuring data. The selection of the most reliable OD results was produced after a detailed analysis of the obtained solution variants.

For obtaining higher accuracy of the re-entry prediction results the data about current helio-geophysical conditions, available from different independent sources were daily carefully analyzed. The preference at the solution of the prediction task was given to those values of indexes $F_{10.7}$ and A_p, which had large scientific and practical justification and allowed to obtain consistent results in a prediction of re-entry time of S/C.

In total during the 7-th IADC test campaign 25 official solutions of the OD and the re-entry predictions of S/C CORONAS-F were obtained in MCC, among them – 14 were obtained on the basis of fitting trajectory tracking data from RCCTS. The main characteristics concerning computation of these solutions are resulted in tab. 1.

Table 1

The main characteristics of the OD solutions at the final phase of S/C CORONAS-F flight, obtained in MCC

№ of the solution	Measured time interval (UTC)	Used measurements basis	RMS σ_0	Value S_b^*
1	28.11.05 03:11÷28.11.05 18:00	6 sessions of MCNP (RCCTS)	0.64	0.609
2	28.11.05 04:30÷29.11.05 12:00	3 TLE (NASA)+4 orbits (RSSS)	0.68	0.715
3	29.11.05 04:33÷30.11.05 04:19	4 TLE (NASA)+3 orbits (RSSS)	0.97	0.687
4	01.12.05 05:33÷01.12.05 10:04	4 sessions of MCNP (RCCTS)	0.69	0.736
5	30.11.05 21:55÷01.12.05 11:35	3 TLE (NASA)+2 orbits (RSSS)	0.67	0.755
6	01.12.05 11:35÷02.12.05 12:28	4 TLE (NASA)+3 orbits (RSSS)	1.30	0.735
7	02.12.05 08:18÷02.12.05 17:26	4 sessions of MCNP (RCCTS)	0.62	0.728
8	02.12.05 21:20÷03.12.05 10:57	2 TLE (NASA)+2 orbits (RSSS)	0.48	0.694
9	03.12.05 07:57÷03.12.05 17:08	4 sessions of MCNP (RCCTS)	0.62	0.668
10	03.12.05 10:57÷04.12.05 05:33	3 TLE (NASA)+2 orbits (RSSS)	0.37	0.676
11	04.12.05 07:35÷04.12.05 15:16	4 sessions of MCNP (RCCTS)	1.37	0.695
12	05.12.05 04:08÷05.12.05 08:40	5 sessions of MCNP (RCCTS)	1.02	0.645
13	04.12.05 19:34÷05.12.05 10:08	6 orbits (RSSS)	1.80	0.659
14	05.12.05 07:08÷05.12.05 14:50	5 sessions of MCNP (RCCTS)	0.81	0.636
15	05.12.05 08:41÷05.12.05 19:12	1 TLE (NASA)+5 orbits (RSSS) +1 TLE (FGAN)	0.64	0.579
16	05.12.05 14:50÷05.12.05 18:50	4 sessions of MCNP (RCCTS)	0.90	0.591
17	06.12.05 01:56÷06.12.05 05:12	3 sessions of MCNP (RCCTS)	1.10	0.636
18	05.12.05 22:04÷06.12.05 08:06	3 TLE (NASA)+2 orbits (RSSS) +1 TLE (FGAN)	0.76	0.600
19	06.12.05 01:56÷06.12.05 08:11	4 sessions of MCNP (RCCTS)	1.44	0.618
20	06.12.05 03:23÷06.12.05 09:34	4 sessions of MCNP (RCCTS)	1.43	0.614
21	06.12.05 00:31÷06.12.05 09:35	3 TLE (NASA)+3 orbits (RSSS)	0.52	0.609
22	06.12.05 08:11÷06.12.05 14:13	3 sessions of MCNP (RCCTS)	0.72	0.609
23	06.12.05 09:30÷06.12.05 15:39	3 sessions of MCNP (RCCTS)	0.94	0.600
24	06.12.05 14:12÷06.12.05 17:06	5 sessions of MCNP (RCCTS)	0.98	0.600
25	06.12.05 07:50÷06.12.05 17:08	1 TLE (NASA)+6 orbits (RSSS) +1 TLE (FGAN)	1.06	0.571

Here for each solution (with appropriate number) sequentially the following information is listed:

- measured time interval within which the tracking data were produced;
- measured basis for the OD: used RSSS orbital data; numbers of used tracking Doppler sessions, produced by the RCCTS; used data in TLE format from the US SSS and ESA;
- root mean square error σ_0 as a result of the fitting the used measurements under LSM;
- value of reduced ballistic coefficient S_b^*, as a result (solved-for parameter) of the CORONAS-F OD;

On the base of these solutions the re-entry time predictions of S/C CORONAS-F were implemented. The obtained data were put in the IADC database as the official results of the Russian side as the participant of the 7-th test campaign. Dynamics of the S/C re-entry time prediction, corresponding to the results of OD, is presented in a graphic form on fig. 7. On this figure for each of the solutions placed in tab. 1 the left and right borders of impact window are presented as well.

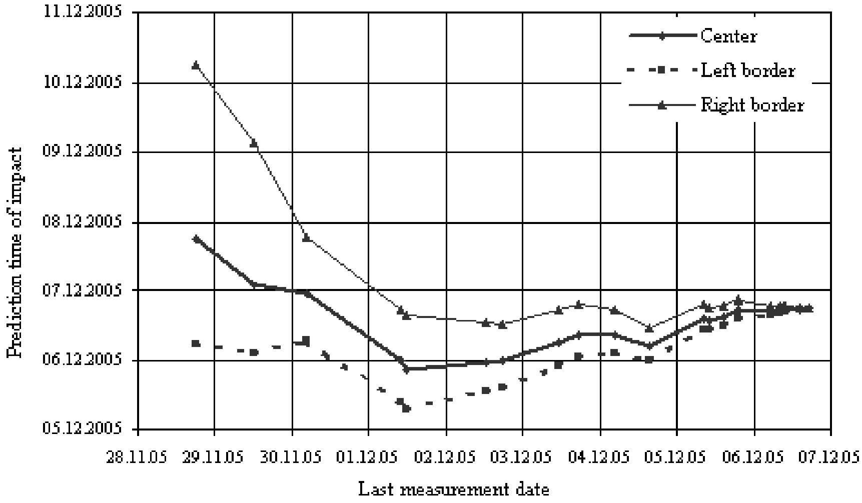

Fig. 7. Dynamics of the S/C CORONAS-F re-entry time prediction according to the MCC solutions

The final results of the S/C CORONAS-F re-entry time prediction correspond to two last solutions of OD presented in tab. 1 that were obtained in MCC by using the latest measuring data produced by the RCCST and RSSS, approximately for half an hour before the object re-entering when it was at altitudes ~ 120 - 115 *km*, are presented in tab. 2.

Table 2

Final results of the S/C CORONAS-F re-entry prediction, obtained in MCC

Used measurements	Epoch of the last used measurement	S/C re-entry epoch prediction	Zone of re-entry	
			Latitude	Longitude
MCNP (RCCTS)	06.12.05 17:06	06.12.05 17:34	40.8 S	84.8 E
Orbital data (RSSS, NASA, FGAN)	06.12.05 17:08	06.12.05 17:35	42.6 S	85.2 E

Both results of the re-entry prediction are in the close agreement with each other though they have been obtained under different observation data. These results are also well agreed with data of US Strategic command according to which atmospheric entry of the satellite number 26873 in NORAD catalogue (S/C CORONAS-F) has taken place at 17:24 UTC above the Indian Ocean near to the site 27° S, 83° E.

In accordance with methodology of the accuracy estimation of the uncontrollable HO re-entry prediction adopted in MCC, the window of uncertainty for an impact point of S/C CORONAS-F corresponding to the final solution has been calculated. This window, i.e. the area of probable impact zone on the Earth surface, including the beginning, the central point and the end of a possible re-entry time, is shown on fig. 8.

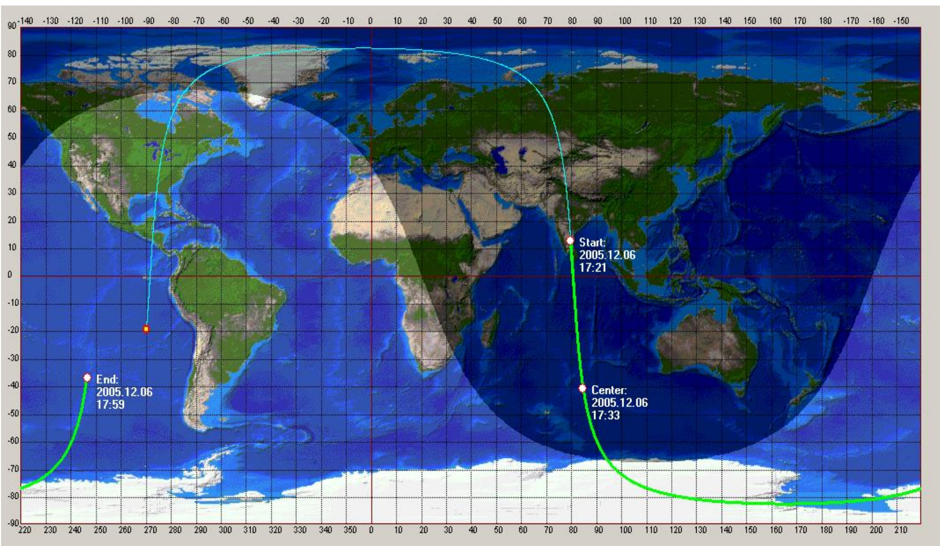

Fig. 8. CORONAS-F re-entry according to the last MCC solutions with the window of uncertainty

7. THE ANALYSIS OF THE S/C CORONAS-F RE-ENTRY PREDICTION ACCURACY

To get the finally estimation of the 7-th test campaign results on the S/C CORONAS-F re-entry control more detailed study of the accuracy of the solutions obtained during exercises on orbit tracking, OD and it prolongation has been made in MCC. This analysis was also useful from the point of view of obtaining the answer to a problem on possible accuracy of a prediction of the time and the impact area for the re-entered hazard space object, de-orbiting in an uncontrollable mode, if the necessary condition on organizing their active monitoring with producing the required measurements and on the effective information support of these events will be ensured. The difficulty of obtaining the precise re-entry prediction for such objects generally can depend on the following reasons:

- insufficient accuracy of used methods of a S/C motion prediction, when various complex perturbing forces influence a space object;
- errors of determination of the S/C motion parameters on the basis of which the subsequent task of prediction is solved,
- inadequacy of the used model of the S/C motion to the real character of the acting forces, in particular:
  - inadequate performance of real atmospheric density within the framework of the used atmosphere models,
  - not fully and / or insufficiently precise performance of the space object aerodynamic characteristics, used in the object motion model especially when they are changed during the flight,
  - residual accelerations created by different systems of S/C (in case of their functioning), or leakages of fluid or air from the spacecraft.

In addition, it is necessary to emphasize, that in many cases, when the descending S/C has enough complex construction and shape and conditions of its entry in denser atmospheric layers are not simple, the correct description and calculation of real motion of such S/C essentially represents the difficult physical and mathematical task.

In a case concerning the S/C CORONAS-F for prediction of its motion for a final flight and de-orbit phases as well as earlier, the mentioned above high-effective method of numerical integration [1,2] was used. This method allows to obtain the solution of differential equations with the arbitrary (on complexity) right parts with very high accuracy.

As the special estimations showed, the formal accuracy of the S/C motion parameters determination when enough precise measuring data from different sources having a good time spreading are used, also will be enough high. If the model of motion of the given S/C used on a prediction time interval fully corresponded to the real conditions of the S/C flight and the forces acting on it, the occurring errors of the orbit determination would not lead in most cases to the considerable errors in the prediction of S/C re-entry.

Therefore the main error source in the S/C CORONAS-F re-entry prediction is the insufficient correctness of used motion model of this object. The carried out estimations testified, that for the considered practical purposes it was enough to take into account in the model of the S/C motion only the effects of influence of a gravitational field of the Earth and an atmosphere drag both for the basic, and the final phase of the flight. While in this case the Earth gravity effect was taken into account with a high degree of accuracy, so from this side some noticeable (in the considered sense) errors in the calculated prediction result have been eliminated. Thus the accuracy of the S/C CORONAS-F re-entry prediction calculated during the test campaign depended, mainly, on the used model of atmosphere and the aerodynamic characteristics of this vehicle, reflected in the value of its ballistic coefficient. As it was already said, the ballistic coefficient was, in the particular sense, solved-for parameter, accumulating itself all incorrectness of used S/C motion model, including not simulated residual accelerations from the activity of gas-jet systems of a space vehicle.

The effect of influence of the used model of atmosphere and the ballistic coefficient on the S/C re-entry predictions was estimated for cases when the remaining lifetime of the vehicle t_{life} was in limits from three day till several hours, and the mean altitude of its orbit H made 230–150 *km*. Particularly these cases were characterized by the data which are listed in tab. 3.

Table 3

Initial altitude and time data for the S/C CORONAS-F re-entry prediction

Variant	1	2	3	4	5
$t_{life,}$, hours	71.5	49.4	21.4	6.8	2.4
H, km	230	220	200	165	150

Presented in tab. 3 variants corresponded to the solutions 9, 11, 16, 20 and 22 are placed in tab. 1.

For estimation of dependence of the prediction results on usage of some kinds of atmospheric models for each of considered cases it was realized on 4 versions of prediction of S/C re-entry time with consequent application in this task of the following models of atmosphere: a) GOST 25645.115-84 in edition 1990 (GOST), b) NRLMSISE-00, c) JACCHIA, d) GOST 4401-81 (STATIC). First three of these models are dynamic models of atmosphere, and the model of GOST 4401-81 is a static model. The S/C re-entry prediction in each case implemented with usage of the parameters of the orbits being results of chosen solutions, but the ballistic coefficient for all variants of the prediction was considered the constant. It corresponded to some average value S_b^*=0,636 (see the last column of tab. 1). Obtained for all considered variants of the prediction residuals Δt_{pr} in times of S/C re-entry between predicted values t_{pr} and a certain conventional "true" re-entry time t^* ($\Delta t_{pr}=t_{pr} - t^*$) are submitted in tab. 4. For realization of the comparative analysis the time appropriate to the final solution, obtained in MCC during a test campaign, i.e. t^* = 2005.12.06, 17:34 UTC, was accepted as the "true" value of re-entry time of S/C CORONAS-F.

Table 4

Residuals in predicted times of S/C CORONAS-F re-entry at usage different models of atmosphere

Variant	Δt_{pr}, hours			
	GOST 25645.115	MSISE 2000	JACCHIA	STATIC
1	-1.35	8.53	-1.47	-6.97
2	-6.97	-1.77	-7.17	-11.46
3	-1.12	0.83	-1.62	-3.56
4	-0.50	0.05	-0.57	-0.90
5	-0.08	0.10	-0.13	-0.18

As follows from the table, all surveyed models of atmosphere can be used for calculation of S/C re-entry on selected periods of the remaining lifetime. The similar results of the prediction give the dynamic models GOST and JACCHIA. Some systematic shift in the prediction is given by static model, but this shift, for example when comparing with GOST, does not exceed 4-11 % relative to the appropriate remaining lifetime t_{life}. On the other hand, comparing the results of the applied dynamic models obtained world wide recognition, it is possible to establish, that for the performed examples uncertainty in predictions of S/C re-entry times appropriate to these models, makes ~ 9-14 % from the S/C remaining lifetime.

For the estimation of effect of a possible error in value of ballistic coefficient on the results of the S/C re-entry prediction the variants of computation of re-entering for 5 considered initial orbits with variations in each case the initial nominal values of a ballistic coefficient on ±5%, ±10%, ±15% and ±20% have been implemented. In all of these variants of re-entry prediction the dynamic models of atmosphere GOST 25645.115-84 was applied, and the ballistic coefficient calculated to the mentioned above average value S_b^* as the nominal one was considered.

The differences of a predicted S/C re-entry times obtained in these variants from the "true" one, i.e. Δt_{pr} in days, are shown on fig. 9. This figure gives also graphically performance about the character of the effect of an error in value of ballistic coefficient on an error of the re-entry time prediction depending on value of relative error ΔS_b and the remaining lifetime of S/C in its orbit.

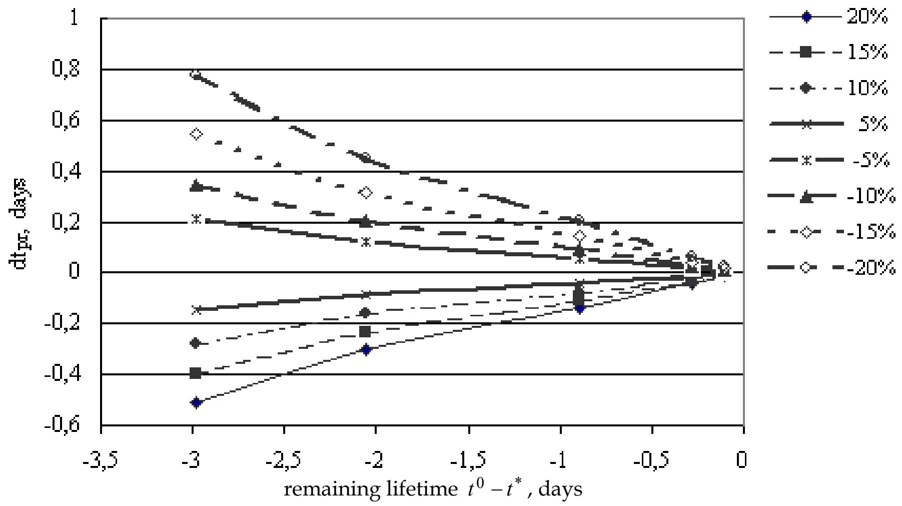

Fig. 9. Dependence of an error of S/C re-entry time prediction to an error of a ballistic coefficient

The obtained data testify that as a whole an error of S/C re-entry time prediction, in percentage of the remaining lifetime, corresponds in percents, to an error of value of a ballistic coefficient. In this case it can be marked, that a decreasing of a ballistic coefficient on some value ΔS_b leads to an error in the re-entry time prediction which exceeds a little (up to 1.5 times) the analogous error that appropriate to an increasing of S_b on the same value.

8. CONCLUSION

Scientific Russian satellite CORONAS-F has completely fulfilled the program of explorations assigned to it and even has expanded this program, carried out unique studies in the field of low-altitude orbits, in immediate proximity to the completion of flight. The success of the given program of explorations was promoted to no small degree by an effective ballistic and navigational support of this vehicle flight.

The test campai gn on the S/C re-entry control carried out in the IADC frames also was, in a particular sense, unique as during all orbital flight the object remained able to work and was observed by ground means of tracking up to 30 minutes before its entry in dense layers of the Earth atmosphere. At that not only means of monitoring of the space, traditionally used for realization of similar experiments, but also the means of the active trajectory tracking and flight control of the given S/C belonging to the regular ground command & tracking system network, were involved in the experiment process.

The test campaign and the analysis of the results, made during its period, have confirmed, that a problem of precise prediction of a time and an impact area of the hazard S/C re-entering in the incontrollable mode, being rather actual by supporting well-timed adoption of measures of protection and reaction to negative fatal consequences of re-entering such kinds of objects, remains difficult in the solution and to these days. Only due to inadequacy of used state-of-the-art models of atmosphere and really possible errors in a ballistic coefficient of the space object the error in the re-entry time predictions of space objects can reach 15-20% from the remaining lifetime in its orbit. Effective method of minimization of hazard of damage increase after non-acceptance of appropriate measures, or decreasing of volumes of unscheduled costs, is the careful navigational control for similar space objects on the final phase of their orbit flight which is desirable for performing up to the end of their flight by world wide network of tracking stations.

9. REFERENCES

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