ARRANGEMENT AND RESULTS OF THE PHOBOS-GRUNT EMERGENCY FLIGHT MONITORING AND ITS RE-ENTRY IMPACT WINDOW ESTIMATION IN RUSSIAN MISSION CONROL CENTER

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Abstract: *The results of works on the flight monitoring and re-entry prediction of the emergency spacecraft Phobos-Grunt fulfilled in Russian Mission Control Center within the range of the Roscosmos activity as well as within the framework of the IADC test campaign are presented. Information about the organization of these works and the methodic used for the solution of considered problems are given. For obtaining the most reliable data on the Phobos-Grunt' re-entry a special post-flight analysis on the base of realization of a great number of variants of its orbit determination at different input data – measurements and applied models was carried out. The results of determination of the most probable re-entry time and impact window for survived fragments of Phobos-Grunt are represented. The re-entry prediction data for the Phobos-Grunt, obtained by other participants of the international test campaign IADC are shown.*

Keywords: *SC Phobos-Grunt, SC Motion Monitoring, Re-entry Prediction, International Test Campaign, Atmospheric Models.*

1. Introduction

Intended for exploration of the Mars' moon Phobos interplanetary spacecraft (SC) Phobos-Grunt was launched from the spaceport Baikonur on November, 8th, 2011 at 20:16 UTC. With help of the launch vehicle «Zenith-2SB41» this SC was put into reference near-earth orbit.

Because of a mid-flight engine failure SC Phobos-Grunt was unable to insert in an interplanetary flight trajectory to Mars, and was left in a reference low earth orbit. Despite all attempts to restore its functionality the Phobos-Grunt remained to be an uncontrollable object which orbit constantly became lower due to perturbing forces. The lifetime of the Phobos-Grunt was reducing and after a while this SC had to re-enter. Having a total weight (together with fuel) ~ 13.5 tons, the Phobos-Grunt could create a real risk situation at destruction in the dense layers of atmosphere and falling of its survived fragments to the Earth. Whereas the SC theoretically could de-orbit over any point of the Earth' surface in a range of latitudes ±51.4º, the forthcoming re-entry event of this space vehicle drew a wide response all over the world.

For implementation of more accurate operative maintenance of the Phobos-Grunt flight and it de-orbit monitoring the special operative group (OG) was formed by Roscosmos. The flight dynamics experts from the Mission Control Center of the Central Research Institute of Machine Building (TsUP TsNIImash in Russian abbreviation) constituted the backbone of this OG. The designers of the Phobos-Grunt and other experts from different organizations competent of problems of a SC flight control were involved in the activity of OG as well. The procedure of the operations' sequence and informing of the interested state structures on SC flight conditions and a predicted of its re-entry impact window were determined.

In addition to that the Inter-Agency Space Debris Coordination Committee (IADC) initiated carrying out the international test campaign for the control of the Phobos-Grunt re-entry (IADC test campaign 2012\1). Roscosmos takes an active part in similar international experiments on the re-entering space objects that are directed on integration of capabilities of different countries under the control over the dangerous situations created by the risk space objects, and in the case of Phobos-Grunt Roscosmos was agreed with the IADC proposal and executed all the necessary procedures connected with the announced relevant test campaign.

The Russian Mission Control Center (TsUP TsNIImash) on behalf of Roscosmos always was a principal executor and coordinator of works on flight dynamics monitoring of the de-orbiting space objects within framework of IADC re-entry test campaigns. This role was given to TsUP in the Phobos-Grunt re-entry test campaign as well.

The results of the works on the Phobos-Grunt orbit determination (OD) and re-entry prediction executed by the Russian MCC experts within the range of the Roscosmos OG activities as well as within the framework of the IADC test campaign are presented below.

To estimate the most probable time of the Phobos-Grunt re-entry and impact area for its survived fragments a special post-flight analysis on the basis of realization of a great number of the OD variants at using of varied set of measurement data representing various tracking sensors and applying the different atmospheric models was fulfilled in TsUP. The final results of the estimation of the re-entry time and a possible impact area of the Phobos-Grunt obtained in TsUP as well as the similar results obtained by other participants of the IADC test campaign 2012/1 allowing compare them to each other are represented.

2. Common information on the space vehicle Phobos-Grunt

Interplanetary space vehicle Phobos-Grunt was intended for exploration of the Mars and its moon Phobos. Delivered to the Phobos' surface landing module was to take a sample of soil of this body and after opening a launch window for the flight from the Mars to the Earth SC Phobos-Grunt was to depart to the Earth. As a part of the space vehicle Phobos-Grunt there was also a small Chinese spacecraft which was to be put into an areocentric orbit.

The common view of the space vehicle Phobos-Grunt in the assembled mode and its main components are shown in a figure 1. The total weight of the Phobos-Grunt with the propellant was ~13 535 kg and its overall dimensions were: 3.8 m×8.0 m×6.3 m.

The launch vehicle Zenith-2SB41 with Phobos-Grunt started on November, 8th, 2011 at 20:16 UTC from the spaceport Baikonur and inserted the spacecraft into a reference near-earth orbit with parameters: an inclination $i \approx 51.40°$, the minimum altitude $H_\pi \approx 207$km, the maximum altitude $H_\alpha \approx 348$km that was close to the nominal one.

After flying on this initial orbit during about 11.5 minutes space vehicle was to be transferred into an intermediate orbit with parameters: i ~51,44°, H_π ~244.35 km, H_α ~4162.02 km. Further, in ~2.4 hours by means of executed of a corresponding accelerating burn SC Phobos-Grunt was to be transferred into an interplanetary trajectory to the Mars.

But because of the cruise engine failure the interplanetary spacecraft Phobos-Grunt remained in an initial near-earth orbit. This space object (SO) making flight in a near space was assigned by the international designation 2011-065A and by the number 37872 in NORAD catalogue.

Many attempts to establish a contact with the Phobos-Grunt and to recover its control were made. However the hopes of its reanimation were gradually fading. At the end of December, 2011 the Phobos-Grunt was definitely recognized as a lost one.

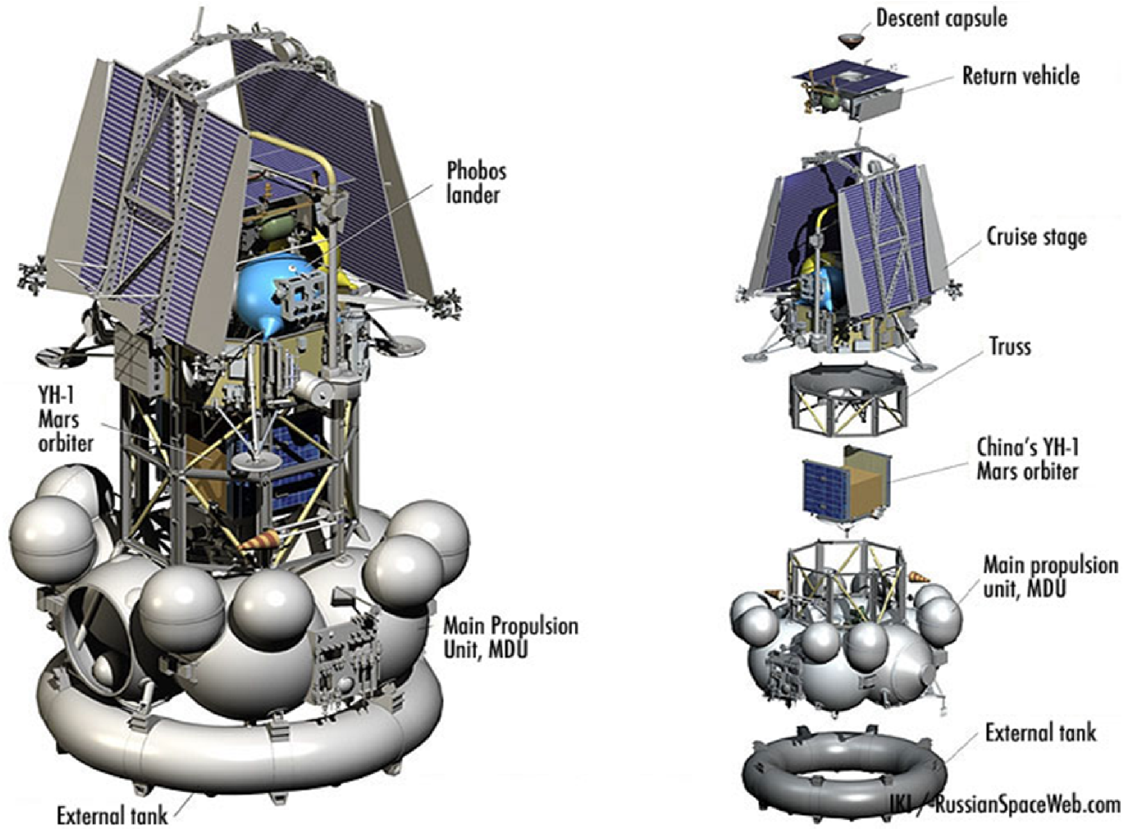

Figure 1. The common view and components of the space vehicle Phobos-Grunt

3. Navigation and information support of the emergency Phobos-Grunt' flight monitoring

After the Phobos-Grunt was not inserted into an interplanetary trajectory to the Mars, the regular activity on the monitoring of its motion was organized in Russian MCC (TsUP TsNIImash). As the onboard equipment of the regular command & tracking system also was unable to work, the tracking of the SC Phobos-Grunt was mainly implemented by means of the Russian space surveillance system (RSSS) and the USA space surveillance network (US SSN). The permitted relevant data from these systems were used in TsUP for monitoring of SC' orbit

The results of the Phobos-Grunt orbit determination obtained in TsUP were applied for the support of the attempts to establish a contact with this object and to estimate its flying state under indirect data. The data on a SC' actual orbit and its remaining lifetime were transmitted to the Roscosmos for an estimation of a real flight situation and acceptance of subsequent decisions.

After recognizing the fact that the Phobos-Grunt is lost, a decision on the organization of activities on the monitoring of the Phobos-Grunt de-orbit was accepted by the management of Roscosmos. A special operative group (OG) for realization of the given activities was formed. The space flight dynamics experts from the TsUP were a backbone of this OG.

Since that time the activity on determination of an actual orbit of the Phobos-Grunt and its re-entry prediction as well as on-line information of the Roscosmos and other interested entities about obtained results, has gained a continuous operative character in TsUP. The intensity and productivity of the given works increased here from the beginning of the IADC test campaign during which TsUP on behalf of Roskosmos was one of the most active participants.

3.1. Methodic of the Phobos-Grunt orbit determination and its motion prediction

At the solution of the tasks of the Phobos-Grunt orbit determination and its motion parameters prediction the methodic which main theoretical positions are given in [1] was used.
For the description of a SC motion in a low earth orbit the following model of acting forces was applied, where a gravitation field of the nonspherical Earth, an atmospheric drag and gravitational attraction of third body – the moon and the Sun were taken into account.
Thus the gravitational potential of the Earth was performed by the Russian model PZ-90 in which harmonics up to degree and order (16×16) were considered. The atmospheric density was calculated according to the Russian dynamic model GOST-2004. At calculation of disturbances from the moon and the Sun ephemerides DE403 were used.
For description of space vehicle's motion the rectangular geocentric inertial system of coordinates (reference frame – RF) referred to the mean equinox and equator of the standard epoch J2000 was used. The equations of motion in given RF had the following form:

$$\ddot{\bar{r}} = -\mu\frac{\bar{r}}{r^3} + M\cdot \operatorname{grad}U(\bar{r}') + \bar{F}_{atm}(\bar{r},\dot{\bar{r}}) + \sum_{\alpha=L,S}\mu_\alpha\left[\frac{\bar{r}_\alpha-\bar{r}}{|\bar{r}_\alpha-\bar{r}|^3} - \frac{\bar{r}_\alpha}{r_\alpha^3}\right] \qquad (1)$$

In the right hand part of "Eq. 1" the first summand corresponds to an acceleration due to the central force of the Earth gravitational potential, the second one takes into account influence of the non-central part of a gravitational potential, the third one presents an acceleration due to an atmospheric drag and the fourth summand characterizes the perturbation due to a gravitational attraction of the moon (L) and the Sun (S).
The non-central part of the Earth gravity field $U(\bar{r}')$, is represented in decomposition to a series by spherical functions (harmonics); (here $\bar{r}' = M^T\bar{r}$ — a SC' position vector referred to the geocentric Earth-fixed rotating coordinate system, M — a matrix of transformation from the rotating to the inertial co-ordinate system defined on the known formula).
The acceleration due to an atmospheric drag is defined by the expression:

$$\bar{F}_{atm} = -\frac{1}{2}S_b\rho V_{rel}\bar{V}_{rel} \quad . \qquad (2)$$

Here $\rho(h)$ — an atmospheric density in the given point of space according to the appropriated model, $\bar{V}_{rel}$ — velocity vector of a space vehicle concerning atmosphere ($V_{rel} = |\bar{V}_{rel}|$), S_b — the ballistic coefficient characterizing aerodynamic properties of a given space vehicle and defined by the relation:

$$S_b = \frac{C_x S_м}{m},$$

where C_x — a coefficient of an aerodynamic drag, S_M — a cross section area of a space vehicle, *m* — mass of a space vehicle.

Integration of the differential equations "Eq. 1" implemented by means of a numerical method of the high order which is original development of TsUP [2]. The method has been validated against different space orbits and models of acting forces, and allows to guarantee a high computing efficiency (in sense of accuracy and speed) for the long-term predictions [3].

The task of the SC' orbit parameters determination in the majority cases provided the improvement of the SC' six-dimension state vector $\{\bar{r}_0, \bar{V}_0\}$ referred to a given epoch t_0 and, as a rule, its ballistic coefficient – S_b in addition. The improvement of the SC motion parameters was performed by means of the selected measurements treatment under least squares method (LSM).

As the original measuring information data on the SC in given case the orbital parameters, performed in space surveillance systems of the Russia and the USA were used. These data are presented in a form of state vectors $\{\bar{r}, \bar{V}\}$, or in a form of TLE referred to some epoch. In both cases of the original data the SC' co-ordinates X, Y and Z (corresponding to the indicated data) with the assigned errors σ ~1 km were treated under LSM.

Quality of the obtained LSM solution was characterized by a standard root mean square error σ_0, defined as:

$$\sigma_0 = \sqrt{\frac{\sum_{k}\sum_{i=1}^{M_k} P_i^k \left[\Psi_{i_{obs}}^k - \Psi_{i_{calk}}^k(\bar{q})\right]^2}{N-m}} \tag{3}$$

In the formula "Eq. 3" the following denotations are used:

$\Psi_{i_{obs}}^k$ — the measured value of *i-th* observation of type *k* (i.e. X_i, Y_i or Z_i),

$\Psi_{i_{calk}}^k(\bar{q})$ — the calculated analog of this observation value corresponding to the improved vector of the determined parameters $\bar{q}$ having dimension *m*, (in our case $\bar{q} = \{\bar{r}_0, \bar{V}_0, S_b\},\ m = 7$),

$P_i^k = \dfrac{1}{\sigma_i^k}$ — a weight of *i-th* observation (σ_i^k − a mean-square measurement error),

M_k — total number of fitted measurements of *k-th* type, $N = \sum_k M_k$.

At a good fitting of the used measurements and the adequate definition of their weights the value σ_0 should be close to 1, or the requirement $\sigma_0 \le 1$ should be satisfied.

3.2. Information support of the Phobos-Grunt' flight in an near-earth orbit

The information support of the Phobos-Grunt' motion monitoring during its flight in a near-earth orbit, provided by the TsUP, consisted in the following activities:

- receiving different source' original data demanded for the solution of the problem of the SC'orbit determination,
- calculation and formation of the SC' motion information necessary for various users,
- informational interaction and data exchange with other participants in activities on surveying, tracking and the orbit monitoring of this space vehicle,
- on-line informing of the leadership of the Roscosmos and other interested governmental organizations about the actual orbit, remained lifetime and predictions of the expected re-entry of this uncontrolled SO.

As the original measuring information were used:

a) the orbital data performed by the Russian space surveillance center on the basis of its sensors measurements. These data were operatively transmitted to the MCC by means of the direct communication lines according to the adopted interchanging formats,

b) TLE performed by NORAD and accessible from the public sources,

c) TLE and state vectors (S/V) prepared by NASA and by other space agencies (DLR, ESA, CNES) which were put into the database REDB IADC during the test campaign,

d) data formed be some other surveying and tracking sensors (for example, observatories of the Russian Academy of Sciences).

The measured and forecasted values of indexes of the solar and geomagnetic activity ($F_{10.7}$ and A_p) submitted by both NOAA and the Institute of a terrestrial magnetism, an ionosphere and distribution of the radio waves of the Russian Academy of Sciences (IZMIRAN) were used for support of the SC' operative orbit determination and prolongation at atmospheric density calculations in applied model.

The results of the Phobos-Grunt' orbit determination and its re-entry prediction, obtained in TsUP, were compared to the similar results obtained at other ballistic centers of Academy of sciences and the Ministry of Defense of the Russian Federation.

Besides, during the international test campaign the operative interchange of information about SC measurements and its re-entry prediction between the TsUP and other participants through the database REDB IADC was implemented.

In TsUP it was calculated and operatively transmitted to the organizations that were responsible for the designing the Phobos-Grunt and its flight control the unconventional information about actual motion parameters of SC demanded for the analysis of the object state and for the support of attempts to establish a contact with it.

The ballistic information on the SC' flight and its re-entry prediction calculated in TsUP operatively transmitted to the Roscosmos, from where it was transmitted further to the Ministry of Emergency and to the Ministry of Foreign Affairs of the Russian Federation to support of acceptance of appropriate measure, in particular, to inform of the world community on the forthcoming event of a large space object re-entry.

3.3 Monitoring of the Phobos-Grunt motion in different phases of its orbital flight

Practically right after the Phobos-Grunt insertions into an initial near-earth orbit the monitoring of the SC' orbital flight was initiated in Russian MCC. This monitoring was fulfilled on the basis of the orbital data which were prepared by the space surveillance systems of the Russia and the USA. These data were essentially the integrated results of the original measurements executed by different sensors of these systems.

The first confident orbit determination of an uncontrollable SC Phobos-Grunt was obtained in the Russian MCC within the first day of an orbital flight of this object. The parameters of this actual orbit appeared close to the nominal one. It was estimated a remained lifetime of the given SO. According to the TsUP prediction the Phobos-Grunt was to be re-entered on January, 9th, 2012.

Further during the whole flight of the Phobos-Grunt in a near-earth orbit the parameters of its motion and its re-entry prediction were regularly updated in TsUP.

In figure 2 the data on changing of the SC' orbit parameters – maximal (in an apogee H_a) and minimal (in a perigee H_p) altitudes, and a nodical period (P_{nod}) that was regularly determined in TsUP during the period since 09.11.2012 till 03.12.2012 are represented.

Changing of the Phobos-Grunt' ballistic coefficient – S_b, as a solved for parameter in the OD task solution, and the re-entry time predictions corresponding to these solutions, are shown in figure 3.

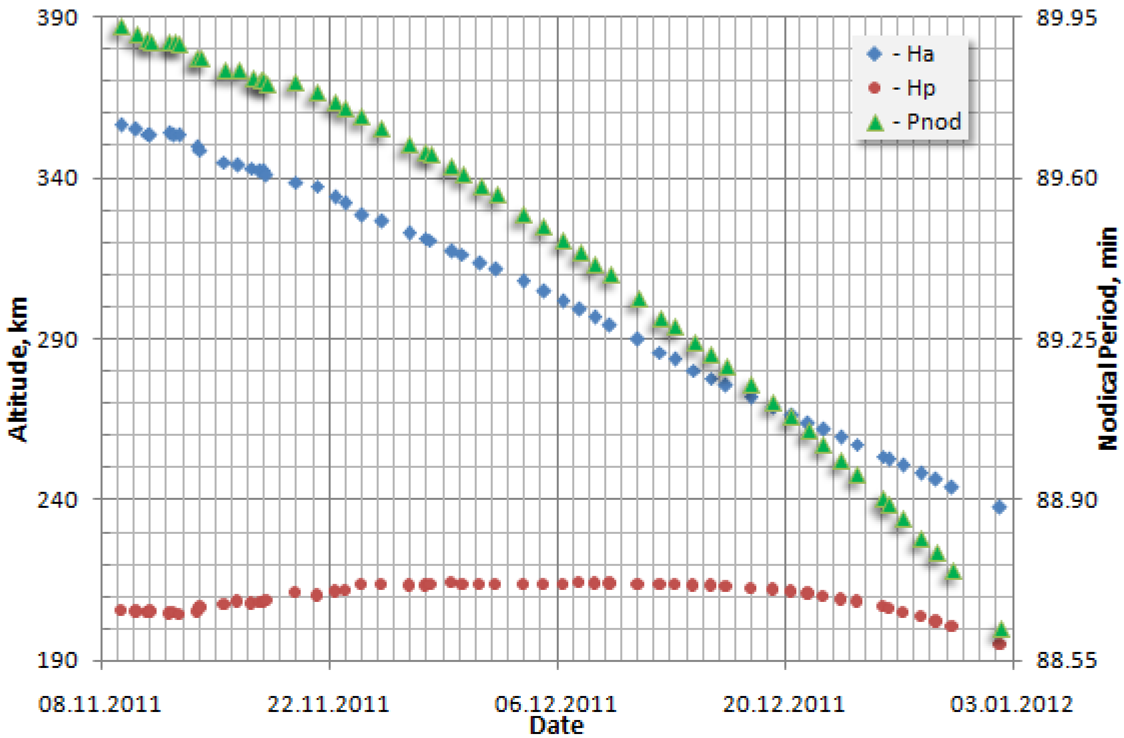

Figure 2. Changing the minimal and maximal altitudes and nodal period of the Phobos-Grunt orbit according to the Russian MCC solutions

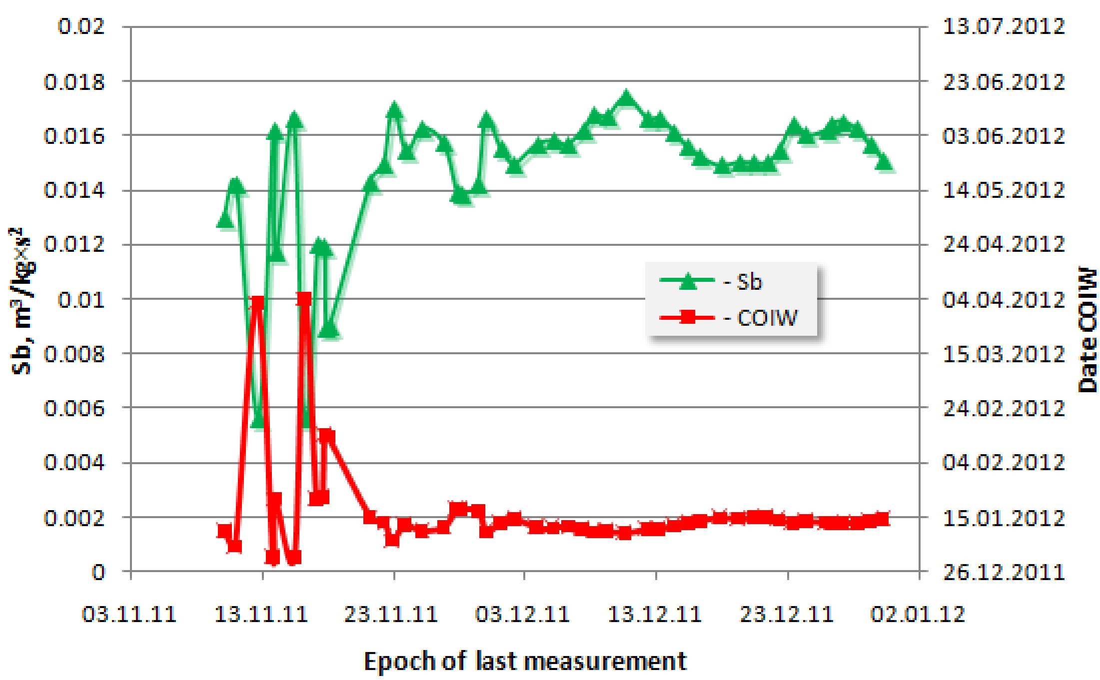

Figure 3. Values of the Phobos-Grunt' ballistic coefficient and the predicted re-entry time according to the TsUP' orbit determination task solutions

Within an initial phase of the Phobos-Grunt orbital flight - since 10th till ~ 23rd of November, 2011 – the determination of its motion parameters (orbital parameters and ballistic coefficient) was implemented on the basis of measurements distributed within the measured intervals of duration from 1 to ~ 1.5 days. There were certain problems in obtaining of the OD solutions during this period of flight. It concerned a level of measurements fitting (the parameter σ_0 often was more than 1). The defined at that period ballistic coefficient was varied significantly. Together with variations of S_b the predicted re-entry time of space vehicle varied in enough wide limits as well.

Not so good RMS fitting of used measurement and the considerable scatter of the defined values of the ballistic coefficient in the solutions obtained during the mentioned period, when the solar and geomagnetic activity was rather quiet, could be explained inadequacy of the SC motion model, applied in the navigation task, to the real forces acting on the object.

Really, in case when in the applied model it is not taken into account a certain perturbing force having a nonzero projection to a direction along track of the SC' motion, the unsuspected force influencing measured parameters can be cancelled in a certain degree by respective alteration of the force of an atmospheric resistance completely projected in the same direction. Demanded for such indemnification changing of an atmospheric drag' force and created by it acceleration $\overline{F}_{atm}$ according to the equations "Eq. 1" can be reached at the expense of respective alteration of the ballistic coefficient' value - S_b associated with $\overline{F}_{atm}$ by relation "Eq. 2". So, if the projection of perturbing force directed along track of the SC' motion, its influence on moving SO on some time interval can be considered within the limits of the used model appropriate decreasing of a value of $\overline{F}_{atm}$, and together with it - and decreasing of a value of S_b. On the contrary, if the projection of not considered perturbing force is directed against the SO' motion, the effect of its influence on moving object within the limits of the used model can be in a sense considered at the expense of appropriate increasing of the value S_b.

During the indicated initial phase of the Phobos-Grunt flight the attempts to recover its serviceability were undertaken. It was appeared, in particular, in the attempts to start a propulsion system for acceleration. The executed by onboard software or spontaneous activations of onboard devices capable to create a certain thrust. The facts of short-term activation of propulsion systems on the Phobos-Grunt were confirmed by the optical observation of this object made, in particular in the Russian observatory in the Sayan Mountains.

The described circumstances could become the reason of sharp changing of the determined (on the base of trajectory measurements) value of the Phobos-Grunt' ballistic coefficient on an initial phase of its flight. Less significant changes of S_b could be called by a variation of a cross-section area of the vehicle at the expense of its attitude changing in the course of flight.

At the following phase of flight, since November, 23rd till December, 20th, 2012, the Phobos-Grunt' orbit was characterized by enough stable altitude of a pericenter H_p~215 km though the altitude in an apocenter was permanently decreased from H_a~330 km to H_a~270 km. At determination of the SC' motion parameters during this phase the measured intervals, that mainly had a duration from 1.5 till 2 days, were used. These measured intervals involved great enough amount of the measuring information. The RMS error σ_0 (parameter of measurements fitting) in all solutions was good enough and it was not outside the limits $0.15 \le \sigma_0 \le 0.5$. The determined values of the SC' ballistic coefficient had uncertainty ±11% of around of the average value S_b≈0.0156. The predicted re-entry times of the space vehicle in obtained at the given stage of activities solutions were within a window: from January, 9 till January, 17th, 2012.

During the Phobos-Grunt' flight period from 21.12.2011 to 02.01.2012, i.e. up to opening of the IADC test campaign, the task of a SC OD was solved on the basis of measurements distributed on enough long arcs of trajectory, that had duration of 2.8 - 3.3 days. On this phase of flight the altitudes H_p and H_a were permanently decreasing and reached at its end the values: H_p~195 km, H_a~240 km. The predicted impact window, according to obtained solutions was narrowed to a three-day interval: from 12 up to 15 January 2012. It is necessary to mark, that heliogeophysical conditions in this period was enough stable: the solar activity index slightly fluctuated concerning value $F_{10.7} \approx 140$ and the geomagnetic activity index varied within $2 \leq A_p \leq 7$.

4. Monitoring of the Phobos-Grunt de-orbit and its re-entry prediction during the international test campaign

The activity in the Phobos-Grunt flight monitoring increased from the opening of the IADC test campaign which was opened on January, 2nd 2012г. In total 11 space agencies that are the IADC members took part in the given international experiment.

The participation of the Russian MCC as an affiliated organization of Roscosmos in a parallel activities on the monitoring of the Phobos-Grunt de-orbit within the framework of the IADC test campaign gave the chance to use official orbital data on this object from NASA, and from other sources of the additional measuring information, including CNES (France), DLR (Germany) and ESA. Besides there was a capability to compare the SC' re-entry predictions results obtained in TsUP with the similar data obtained by other participants of this campaign.

In this period in TsUP it was daily obtained from one to several solutions of the OD and re-entry prediction task. In total from 02.01.2012 till 15.01.2012 in TsUP were obtained 30 official solutions of the OD and re-entry predictions of the Phobos-Grunt. The obtained results of the monitoring of the descending space vehicle motion were used for information support of the Roscosmos and other interested organizations. The obtaining Phobos-Grunr re-entry prediction results were also put into the database REDB IADC according to existing rules.

In figure 4 the results of the Phobos-Grunt re-entry time predictions, obtained in Russian MCC during the IADC test campaign are shown in a graphical form. A red color line corresponds to the points of the center of impact window (COIW), blue and green – to the left and the right borders of these windows respectively.

It is apparent that during the whole period of the test campaign the results of the Phobos-Grunt re-entry time predictions obtained in TsUP practically in all solutions gave the date 15.01.2012 which appeared to be a real date of the SC' re-entry.

Especially strained activity on the monitoring of the descending space vehicle de-orbit was the last day of the Phobos-Grunt orbital flight before its re-entry. On that day TsUP received the measuring information from the RSSS, NASA, CNES, DLR and ESA. At an estimation of the possible scatter in the re-entry time impact window the analogous information from the appropriated organizations of the Ministry of Defence and Academy of sciences of Russia, also sharing in the monitoring of this descending object was used. Obtained on this day results of 8 official solutions on the Phobos-Grunt re-entry predictions that was transmitted to the IADC REDB are presented in table 1. Here are given the most probable time when descending SC reached the altitude H = 10 km with an estimation of a possible uncertainty window of this impact time. In table for each solution are given as well: a measured arc within which the used orbital data was spread, the total number of used sets of data and their sources, the epoch of the last used measurement data and its producer, the value of RMS error σ_0.

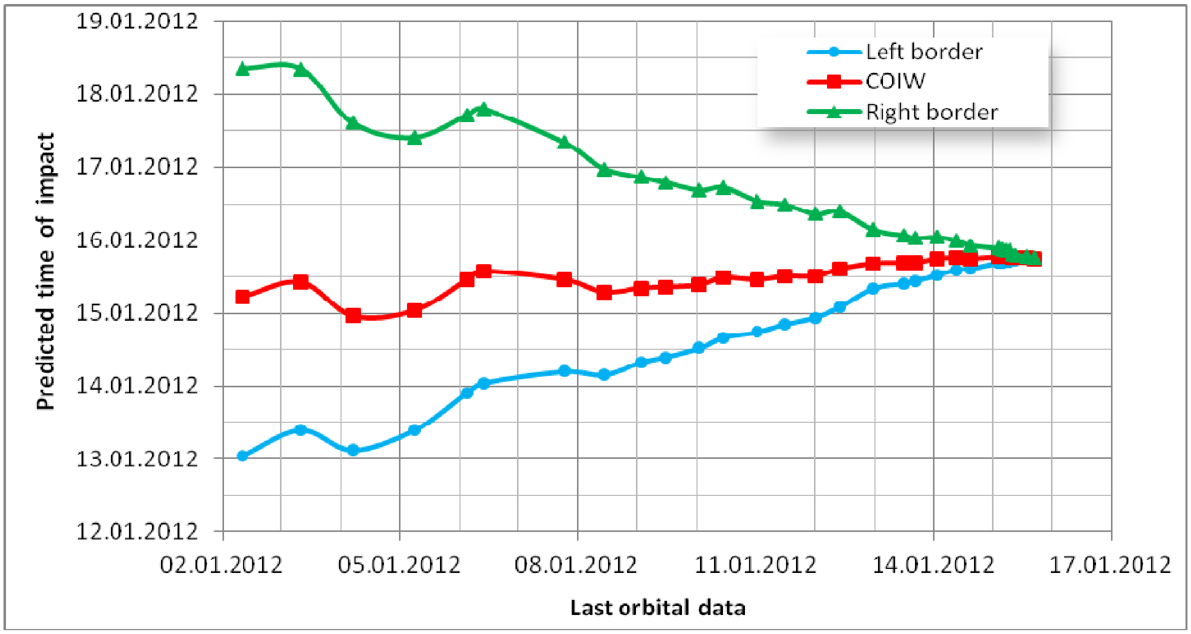

Figure 4. Phobos-Grunt re-entry time predictions according to the TsUP TsNIImash data

As it follows from table 1, on the last day before the impact of the Phobos-Grunt the predicted re-entry time monotonically restricted, in a whole on ~36 minutes. The last prediction of the Phobos-Grunt re-entry time, obtained approximately 1 hour before its re-entry, gave an epoch of re-entry referred to *15.01.2012, 17:59* UTC. The impact area of the space vehicle corresponding to this epoch fell above Brazil. This solution was put into the database REDB IADC as the last official solution obtained by the Russian side in the given test campaign.

Table 1. Results of the last 8 official predictions of the Phobos-Grunt re-entry, obtained in Russian MCC on 15.01.2012

Measured arc (hours)	Total number and source of data	Epoch of last data (UTC)	σ_0	Re-entry time (UTC)	Uncertainty window	
					Left border	Right border
25	21 (RSSS+NASA+CNES+DLR+ESA)	2012.01.15/02:05 USA	0.58	2012.01.15/ 18:35	2012.01.15/ 16:32	2012.01.15/ 21:20
22	21 (RSSS+NASA+CNES+DLR+ESA)	2012.01.15/03:32 Russia	0.58	2012.01.15/ 18:34	2012.01.15/ 16:41	2012.01.15/ 21:04
24	22 (RSSS +NASA+CNES+DLR+ESA)	2012.01.15/04:59 USA	0.60	2012.01.15/ 18:29	2012.01.15/ 16:48	2012.01.15/ 20:45
25	23 (RSSS +NASA+CNES+DLR+ESA)	2012.01.15/06:27 USA	0.59	2012.01.15/ 18:26	2012.01.15/ 16:57	2012.01.15/ 20:29
23	24 (RSSS+NASA+CNES+DLR+ESA)	2012.01.15/07:54 USA	0.55	2012.01.15/ 18:18	2012.01.15/ 17:24	2012.01.15/ 19:26
24	27 (RSSS+NASA+CNES+DLR+ESA)	2012.01.15/09:21 USA	0.50	2012.01.15/ 18:16	2012.01.15/ 17:30	2012.01.15/ 19:12
15	15 (RSSS+NASA+CNES+DLR+ESA)	2012.01.15/14:04 Russia	0.35	2012.01.15/ 18:04	2012.01.15/ 17:46	2012.01.15/ 18:28
13	14 (RSSS+NASA)	2012.01.15/16:54 Russia	0.44	2012.01.15/ 17:59	2012.01.15/ 17:40	2012.01.15/ 18:20

The information corresponding to the last predictions of the Phobos-Grunt re-entry (on reaching by it of a given altitude), obtained by other participants of this test campaign and put into the database REDB IADC, are presented in table 2.

Table 2. Last official predictions of the Phobos-Grunt re-entry obtained and inserted into REDB by the participants of the IADC test campaign 2012/1

Participant (country)	Epoch of last data (UTC)	Re-entry time (UTC)	Uncertainty window		COIW		
			Left border	Right border	H (km)	φ (deg)	λ (deg)
JAXA (Japan)	2012.01.15/09:21	2012.01.15/16:30	-1.10 (h)	+1.60 (h)	10	-	-
CNES (France)	2012.01.14/09:10	2012.01.15/17:10	-36 (m)	+57 (m)	10	+33.0	127.1 E
NASA (USA)	2012.01.15/09:21	2012.01.15/17:23	-24 (m)	+24 (m)	10	-7.6	161.1 E
NSAU (Ukrain)	2012.01.15/06:27	2012.01.15/17:26	-2.10 (h)	+2.65 (h)	10	-12.5	164.4 E
CNSA (China)	2012.01.15/12:30	2012.01.15/17:27	-30 (m)	+30 (m)	10	-	-
UKSA (UK)	2012.01.15/09:21	2012.01.15/17:36	-3.15 (h)	+3.13 (h)	-	-	-
ISRO (India)	2012.01.15/09:21	2012.01.15/17:37	-42 (m)	+1.57 (h)	10	-48.5	145.0 W
DLR (German)	2012.01.15/15:33	2012.01.15/17:43	-25 (m)	+24 (m)	10	-51.0	108.0 W
ESA (EU)	2012.01.15/17:03	2012.01.15/17:45	-9 (m)	+8 (m)	10	-51.4	113.9 W
ASI (Italy)	2012.01.15/17:03	2012.01.15/17:50	-12 (m)	+11 (m)	10	-	-
Roscosmos (Russia)	2012.01.15/16:54	2012.01.15/17:59	-19 (m)	+21 (m)	10	-18.2	49.3 W

The data listed in table 2 are given in the increasing order of the SC re-entry time obtained by the participants of the IADC test campaign. The uncertainty window is presented by its borders that are calculated from a point corresponding to the center of impact window to the left and to the right on the indicated value in hours (h) or minutes (m). The location of a COIW is determined by co-ordinates – latitude (φ) and longitude (λ) - at the indicated altitude (H). Absence of the SC re-entry parameters in table 2 means, that these data was not put into the database REDB by the corresponding participant of the IADC test campaign.

As a rule, in the IADC test campaigns on de-orbiting space objects as a final official result on determination of the SO re-entry parameters data (on reaching by SO of altitude H~80 km) submitted by the USA Strategic Command are adopted. Usually these data are transmitted in the IADC headquarter quickly enough, frequently - in limits from one till some hours. However in a case of the Phobos-Grunt a prompt reply from US STRATCOM on re-entry parameters has not happened. Only in 10 days after the SC re-entered − on January, 25th, 2012, US STRATCOM submitted data on a final determination of the Phobos-Grunt' re-entry, according to which the 80 km atmospheric interface pass of the SC led to 15-January-2012 17:46 UTC at about 87.0°W and 46.0°S. On the basis of this data the 10 km atmospheric interface pass of the SC was determined. This time threshold corresponded to the epoch *t = 15.01.2012, 17:53 UTC*. These data was serve as reference during the subsequent prediction assessments.

5. The post-flight analysis of the Phobos-Grunt orbit determination and impact area estimation

For the purpose of obtaining the most reliable parameters of the Phobos-Grunt re-entry and finding a center of impact window for the spacecraft survived fragments the special post-flight analysis of the orbit determination and re-entry prediction for the final phase of its flight was fulfilled. Different models of the SC motion and varied sets of the measurement data representing various tracking sensors were used in this analysis.

Source data for this analysis were:

- an available orbital data from different sensors,
- 3 models of a gravitational field of the Earth,
- 4 models of an Earth's atmosphere.

As it was mentioned above, as the measurements the packages of orbital data referred to the appropriated epoch were used. This orbital data was received either in a format of two-line elements (TLE) or in the form of rectangular state vectors (S/V) of the SC. In analysis mainly the orbital data received during the day before the SC re-entry were used.

At the post-flight analysis in the Phobos-Grunt' motion model the same forces which have already been described in 3.1 were considered. The carried out estimates showed, that at the solving of the given problem the influence of other natural perturbing forces can be neglected. Some onboard processes could produce a certain perturbation on the SC' motion but there were no reliable data about this.

For the estimation of the influence of one or another model of a gravitational field of the Earth on the results of a navigation task solution the corresponding calculated parameters of SC' motion were compared. For this purpose the Russian model PZ-90, the American model JGM-3 and the European model GEM-T3 were chosen. The comparison of the calculated parameters of SC' motion when different numbers of harmonics of the selected geopotential models were used was done as well.

For the estimation of a dependence of the predicted re-entry time on the chosen atmospheric model the variants of a problem' solution at using of the dynamic models of the Earth atmosphere GOST-2004, NRL MSISE-2000, Jacchia and the static model of atmosphere SMA-62 were realized. At carrying out the estimating calculations in the indicated dynamic models of the atmosphere the actual (i.e. updated on the real measurements) indexes of solar ($F_{10.7}$) and geomagnetic (A_p) activity were used.

At the calculation of parameters of SC' motion implemented by means of numerical integration of the equations "Eq. 1" the parameters of the applied high-performance method allowing to reach any given precision was set up in such a way that the methodic error in the numerical prediction of the SC' trajectory was negligibly small.

The usage of different models of a gravitational field of the Earth at the final phase of the SC' flight led to the residuals (in calculated positions of a space vehicle on a prolongation interval of one day) having the values of no more than 850 meters (for the same number of taken into account harmonics). The difference in the calculated SC' positions on the given interval of prediction at taking into account the restricted and full number of harmonics in the used model of a geopotential could be already more considerable. So, for the case of usage of the model PZ-90 the results obtained on the base of restricted number of harmonics up to (16×16) and on the base of full number of harmonics for the given model differed on the value reaching ~4.5 km.

In table 3 the common set of the orbital data received in TsUP during the last day of the SC' flight and being used at the post-flight analysis is presented. Here sequentially are given: an ordinal number of measurement data; epoch of this orbital data; a remaining number of orbits (before re-entry) to which the data corresponds; the source of measurement; a format of data. Thus, the data on the Phobos-Grunt orbit during the last day of its flight was performed by 5 sources (Russian space surveillance system - RSSS, US space surveillance network - NASA, German tracking sensors - DLR, France tracking sensors - CNES, ESA tracking sensors - ESA). It is seen that in the final phase of SC' flight beginning with the forth orbit before re-entry the measurement information was mainly gained (except for one set of measuring data) from the Russian space surveillance system.

Table 3. The orbital data received in MCC during the last day of the Phobos-Grunt flight

N	Epoch of data (UTC)	Remaining orbits	Source	Format	N	Epoch of data (UTC)	Remaining orbits	Source	Format
1	2012.01.14/17:49	17	RSSS	S/V	18	2012.01.15/04:59	8	NASA	TLE
2	2012.01.14/19:02	16	DLR	TLE	19	2012.01.15/06:27	7	NASA	TLE
3	2012.01.14/19:16	16	RSSS	S/V	20	2012.01.15/07:54	6	NASA	TLE
4	2012.01.14/20:15	16	NASA	TLE	21	2012.01.15/07:54	6	NASA	TLE
5	2012.01.14/20:32	15	DLR	TLE	22	2012.01.15/09:21	5	NASA	TLE
6	2012.01.14/20:48	15	RSSS	S/V	23	2012.01.15/09:21	5	RSSS	S/V
7	2012.01.14/21:24	14	ESA	TLE	24	2012.01.15/12:31	4	RSSS	S/V
8	2012.01.14/22:03	13	DLR	TLE	25	2012.01.15/12:34	4	RSSS	S/V
9	2012.01.14/22:11	13	RSSS	S/V	26	2012.01.15/13:59	3	RSSS	S/V
10	2012.01.14/22:30	13	ESA	TLE	27	2012.01.15/14:03	3	RSSS	S/V
11	2012.01.14/23:10	12	NASA	TLE	28	2012.01.15/14:04	3	RSSS	S/V
12	2012.01.14/23:34	12	DLR	TLE	29	2012.01.15/15:21	2	RSSS	S/V
13	2012.01.14/23:42	12	ESA	TLE	30	2012.01.15/15:33	2	RSSS	S/V
14	2012.01.15/01:40	11	CNES	S/V	31	2012.01.15/16:36	1	NASA	TLE
15	2012.01.15/02:05	10	NASA	TLE	32	2012.01.15/16:54	0	RSSS	S/V
16	2012.01.15/03:32	9	NASA	TLE	33	2012.01.15/17:02	0	RSSS	S/V
17	2012.01.15/03:32	9	RSSS	S/V	34	2012.01.15/17:03	0	RSSS	S/V

For the definition of the best combination of the measurements for the solved problem from those received during the last day of SC' flight various samplings of this information were analyzed. In each variant corresponding to the made sampling the task of the SC OD improving the six-measured state vector and ballistic coefficient of the object was solved. Further on the basis of the improved parameters the SC' orbital motion the prolongation of its motion up to the restricted epoch T_f corresponding to the orbital altitude H ~100km was implemented.

On the basis of estimation of the fitting value σ_0 and the formal errors of the orbital parameters determination at the applying the LSM the navigation efficiency of the selected combination of the measurements, its capability on reaching (in an ideal case) of a certain precision of the predicted lifetime of the Phobos-Grunt was estimated. Such a kind of calculations were carried out at using of the Earth gravitational potential model PZ-90 where was taken into account a full number of harmonics, and dynamic model of the Earth' atmosphere GOST-2004 [4].

In table 4 the results of the measurements fitting and the formal estimations of the improved parameters' precision for different variants of the OD task solutions on the base of measurements spread within orbital arcs of different duration - from ~4.3 hours up to ~1 day are given.. In table are given as well: the beginning and the end of a measured interval, its duration; total number of the used sets of original orbital data and their distribution on sources; the RMS error σ_0; the value of a ballistic coefficient S_b obtained in the corresponding solution with its formal error (3σ); the formal errors of the SC' position (3σ) referred to the moment T_f in the orbital co-ordinate system RNB (the centre of the given system of coordinates coincides with the centre of SC' mass, the axis R is directed from the Earth' centre towards the space vehicle, the axis N is orthogonal to the R, it lies in the orbital plane and directed towards a space vehicle movement, the axis B supplements the right handed system). At treatment of the measurements under the least squares method it was supposed that all data from different sources have the same precision, which was determined by the root-mean-square errors of the object position (after transformation of the original data to the form of SC' state vectors): σX = σY = σZ = 1 km.

The last two of the presented in the table 4 solutions (variants 11 and 12) were obtained on the basis of measurements only from one principal source of information: in the first case - from RSSS, in the other - from NASA. Thus, in each case all the measurements from the appropriate source performed during the last day of SC' flight were used.

At selection of the best variants of the OD solutions for the concerned purposes there were taking into account the following arguments: the used combination of measurements, the value of RMS error σ_0, the obtained value of a ballistic coefficient S_b and its error, the values of prediction errors at the epoch T_f. Thus the prediction errors were determinant.

Table 4. The main characteristics of the solution of a problem of the SC orbit determination on the base of various combinations of the measurements.

Var. #	Measured interval		Total number, Source of data	RMS σ_0	Obtained value of S_b	Prediction errors at T_f		
	Begin – end, (UTC)	Duration, hours				3σR, km	3σN, km	3σB, km
1.	2012.01.14/17:49 – 2012.01.15/02:05	8.25	15 –RSSS(4), NASA(3), ESA(3), DLR(4), CNES(1)	0.427	0.0135±0.00026	0.260	10.818	0.522
2.	2012.01.15/02:05 - 2012.01.15/07:54	5.83	7 –NASA(6), RSSS(1)	0.553	0.0120±0.00063	0.659	29.226	0.633
3.	2012.01.15/07:54 - 2012.01.15/13:59	6.08	7 –NASA(3), RSSS(4)	0.605	0.0138±0.00042	0.978	10.941	0.897
4.	2012.01.15/12:31 - 2012.01.15/17:03	4.30	11 –RSSS(10), NASA(1)	0.310	0.0141±0.00012	0.474	2.676	0.630
5.	2012.01.14/17:49 – 2012.01.15/06:27	12.62	19 –RSSS(5), NASA(6), ESA(3), DLR(4), CNES(1)	0.449	0.0133±0.00011	0.228	6.852	0.423
6.	2012.01.15/02:05 – 2012.01.15/13:59	11.90	12 –NASA(7), RSSS(5)	0.574	0.0136±0.00012	0.552	7.893	0.570
7.	2012.01.15/04:59 – 2012.01.15/17:03	12.07	17 –NASA(6), RSSS(11)	0.470	0.0138±0.00004	0.447	3.492	0.492
8.	2012.01.14/17:49 – 2012.01.15/12:34	18.73	25 –RSSS(8), NASA(9), ESA(3), DLR(4), CNES(1)	0.566	0.0134±0.00005	0.263	5.109	0.447
9.	2012.01.14/23:10 – 2012.01.15/17:03	17.88	24 –RSSS(12), NASA(9), ESA(1), DLR(1), CNES(1)	0.562	0.0137±0.00003	0.324	3.396	0.471
10.	2012.01.14/17:49 – 2012.01.15/17:03	23.23	34 –RSSS(16), NASA(10), ESA(3), DLR(4), CNES(1)	0.759	0.0136±0.00003	0.314	4.137	0.561
11.	2012.01.14/17:49 – 2012.01.15/17:03	23.23	16 –RSSS	0.526	0.0138±0.00003	0.498	4.665	0.687
12.	2012.01.14/20:15 – 2012.01.15/16:36	20.35	10 –NASA	0.377	0.0135±0.00002	0.373	12.875	0.375

As a result of the fulfilled analysis the variants 4, 7 and 9 were selected. In all these variants the latest measuring data on the Phobos-Grunt' orbit was used. This measurement was performed in a set of orbital parameters referred to 2012.01.15, 17:03 (UTC) by RSSS.

Formally the best value σ_0 of the LMS fitting and the best precision of the SC' trajectory prolongation at T_f were in variant 4. However it was obtained on the base of enough short measured arc (duration of this arc ~4.3 hours) having, mainly, data from one source (RSSS).

Variants 7 and 9 yielded comparable results on precision of the trajectory prolongation at T_f.

Thus the variant 7 (with estimation RMS error σ_0 = 0.470) was obtained on the base of 17 sets of orbital data that was received from two sources (RSSS and NASA) and spread within ~ 12 hour interval. Formally, the estimation of RMS error in the variant 9, obtained on the base of 24 measurements distributed over ~18 hours interval was a little bit worse (σ_0 = 0.562) than in the solution 7. However in variant 9 both the number of the treated orbital data and the number of sources (5) were greater that made more random a scatter of possible errors of measurements.

The SC impact time (the time when SC reached an altitude H = 10 km at using the atmospheric model GOST 2004) − t^{10}_{GOST} in the indicated variants was determined as the following:

- for variant 4: t^{10}_{GOST} = 2012.01.15, 17:55 (UTC),
- for variant 7: t^{10}_{GOST} = 2012.01.15, 17:57 (UTC),
- for variant 9: t^{10}_{GOST} = 2012.01.15, 17:59 (UTC).

Apparently, a difference in the Phobos-Grunt' re-entry time predictions at usage of the atmospheric model GOST-2004 for the selected variants makes 2-4 minutes.

A dependence of the precision of the obtained results at solving the tasks on the Phobos-Grunt orbit determination and re-entry prediction on the chosen atmospheric model at the final phase of SC flight was estimated. For this purpose the solutions of the OD and re-entry prediction tasks on the base of the same combination of the measuring information as in variants 4, 7 and 9, but at using in the SC' motion model of other atmospheric models, namely: NRL MSISE-2000 [5], Jacchia [6] and Russian static model MSA-62 [7], were fulfilled.

In table 5 the values of RMS errors σ_0 obtained in the indicated variants of the OD task solutions, and a difference in the SC' impact time determined in these variants and predicted in similar variants at usage of the GOST-2004 model are presented. The given difference is determined as $\Delta t^{10}_{other} = t^{10}_{other} - t^{10}_{GOST}$, where a bottom index «other» takes on the values: MSISE, Jacchia or MSA-62 and means that the given difference is obtained at usage of the appropriate model of atmosphere. The superscript «10» indicates, that the calculated re-entry time corresponds to the time when SC reaches the altitude H=10 km.

Table 5. Quality of the obtained OD solutions and differences in a predicted impact time at using of different atmospheric models.

Variant #	NRL MSISE-2000		Jacchia		MSA-62	
	σ_0	Δt^{10}_{MSISE}, min	σ_0	$\Delta t^{10}_{Jacchia}$, min	σ_0	Δt^{10}_{MSA}, min
4	0.364	-11	0.325	-10	0.312	-7
7	0.668	-17	1.111	-20	0.973	-17
9	0.695	-19	1.367	-25	0.898	-19

The calculated model force of an atmospheric drag is defined by the used model of the atmosphere density and the ballistic coefficient of SC. On the other hand a ballistic coefficient of SC is correlated with an atmosphere density and is in some sense a solved for parameter flattening errors of an atmospheric model at fitting of the trajectory measurements. Thereby an inaccuracy in the atmospheric model will be revealed in the calculated atmospheric drag force and therefore in the calculated parameters of a SC motion and further in the calculated values of the observed parameters (C), and as a result it will be appeared in appropriate residuals (O-C).

For estimation of the considered atmospheric models validity the following comparative analysis have been carried out. Two sets of the measurements based on the orbital data used earlier in the considered variants 7 and 9 of the OD solution but which did not include three last measurement sets performed be the RSSS were selected. In other words, the last used measurement in these sets, was NASA' TLE referred to the epoch t_{obs} = 2012.01.15/16:36 (UTC). The solution of the OD task on the base of these sets of measurements with the use of different atmospheric models (from among indicated above) was fulfilled. On the base of the obtained in each variant improved orbital parameters the prolongation of the SC motion on the epochs to that the 3 last untreated measurements were referred was implemented. Further the comparison of the observed (O) and calculated (C) of the SC position at measurements' epochs was implemented.

In table 6 for the considered variants of the OD task solutions and the subsequent prolongation of the SC' movement the following information is placed: the value of RMS error σ_0 of the used measurement data fitting, the residuals of the measured and the calculated values of the SC state vectors for the appropriated epochs corresponding to the untreated measurements. This residual was transformed into the form:

$$\Delta r = \sqrt{\left\{(x_{obs} - x_{cal})^2 + (y_{obs} - y_{cal})^2 + (z_{obs} - z_{cal})^2\right\}} \ .$$

Table 6. Characteristics of the solution of the SC orbit determination task at measurements treatment with using of different atmospheric models.

Measured interval	Atmospheric model	σ_0	Residual Δr (km) at t_{obs} (UTC)		
			t_{obs}=2012.01.15, 16:54	t_{obs}=2012.01.15, 17:02	t_{obs}=2012.01.15, 17:03
2012.01.15/04:59 – 2012.01.15/16:36 (11.6 hours)	GOST-2004	0.470	1.779	2.522	2.702
	NRLMSISE-2000	0.516	3.617	6.177	6.249
	Jacchia	0.920	6.938	10.841	11.176
	SMA-62	0.733	7.646	10.126	10.415
2012.01.14/23:10 – 2012.01.15/16:36 (17.4 hours)	GOST-2004	0.494	3.064	4.048	4.303
	NRLMSISE-2000	0.551	2.633	4.850	4.827
	Jacchia	1.069	9.022	13.411	13.837
	SMA-62	0.777	3.634	6.342	6.440

On the basis of the data given in the table 6 it is possible to draw a conclusion, that old enough models of atmosphere Jacchia and MSA-62 considerably yield on precision of representation of a real atmospheric density to the more resent dynamic models of GOST-2004 and NRL MSISE-2000. It confirms both by the measurements fitting parameter (σ_0) and the residuals Δr between measured and calculated values of the orbital parameters on the prediction arcs, received with using of the given models. It is possible to suggest with a high confidence, that the prediction of the SC' re-entry time and an impact area with usage of these old models will have also the considerable error.

Usage of GOST-2004 and NRL MSISE-2000 models in the considered variants of the OD task solutions allow to reach much better level of the measurements fitting. Thus, at usage of these models it is possible to consider that the results of the measurements fitting by criterion σ_0 are quite comparable in a whole though formal the result of data treatment at usage of GOST-2004 model was a little bit best. Within the prolongation arcs a precision of the calculated position of the SC (at comparison with the untreated measurements) depended on the variant of the OD solution. So, as it follows from table 6, for the solutions, obtained on the basis of greater number of measurements fulfilled on the longer measured interval, the measurement fitting parameter σ_0 and a prediction error are comparable at usage of both GOST-2004 and NRL MSISE-2000 models. At the same time, in case of the navigation task' solution on the base of shorter measured interval, despite comparable results of the same combination of measurements fitting (by measure σ_0), the prolongation of the space vehicle motion with usage of GOST-2004 model was much more exact, than at usage of NRL MSISE-2000 model.

Thus, the fulfilled analysis allows preferring GOST-2004 model, as the most adequate on representation of the real atmospheric density in the space areas where the Phobos-Grunt was in orbit during the last day of its flight.

At the same time, there was opened a question why at the relative proximity of the results of the Phobos-Grunt orbital motion at final phase of its flight, the re-entry prediction of this object at usage of GOST-2004 and NRL MSISE-2000 models enough strongly differed. The answer to this question was found on the basis of comparing the atmospheric densities produced by these models in the areas of space through which the Phobos-Grunt passed at the final phase of its flight up to the entry into dense layers of the Earth' atmosphere.

In figure 5 the behavior of the ratio of densities ρ_{MSISE}/ρ_{GOST}, calculated at using NRL MSISE-2000 and GOST-2004 models accordingly, in space points through which the Phobos-Grunt flew during the remained lifetime, starting approximately at 12 hours before the time t^{80} when the descending object has reached the altitude H=80 km is shown. In the same figure the curve of an altitude changing for the indicated points of space over the Earth' surface is given.

As one can see from a figure, the ratio of densities ρ_{MSISE}/ρ_{GOST} on a flight arc from 12 o'clock till approximately 1 hour before the SC entry into the atmosphere dense layers had the oscillating character correlated with the varying profile of the SC' altitude in appropriate points of space. The amplitude of oscillation of the ratio ρ_{MSISE}/ρ_{GOST} on this flight arc was negligible, and its average value gradually decreased at reduction of the remained lifetime of the object from the value ~1 at the beginning of a considered interval (~12 hours before to t^{80}) to approximately 0.8 at the end of this interval (1 hour before to t^{80}). However at descending of the SC, since an altitude band of 120-110 km, the character of changing of the ratio ρ_{MSISE}/ρ_{GOST} became sharp. The value of this ratio fast increased during a process of the altitude decreasing, having reached the value ρ_{MSISE}/ρ_{GOST} ~1.7 at H ~ 100 km. After that the ratio of densities also promptly began to decrease, having reduced to the value ~ 1.1 at the altitude H ~ 80 km.

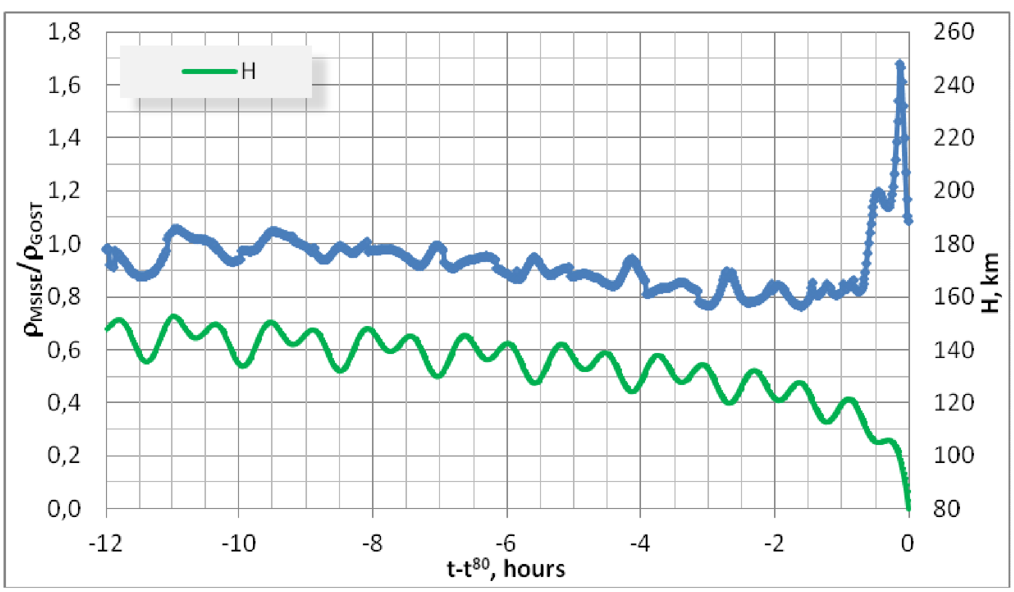

Figure 5. Dynamics of changing the ratio of atmospheric densities ρ_{MSISE}/ρ_{GOST} and the altitudes of the Phobos-Grunt orbit during the final phase of its flight

The revealed fact of the essential distinction in the atmospheric densities produced by models NRL MSISE-2000 and GOST-2004 during the Phobos-Grunt' descending in an altitude band of 110-80 km was, most likely, the reason of the considerable divergence in an impact time of the space vehicle predicted at usage of one and other model, even when both these models supplied the similar results of the space vehicle motion in its orbit.

Returning to a problem on determination of the most probable re-entry time and impact area of the Phobos-Grunt it is necessary to make a following conclusion. As a result of the investigations fulfilled on the basis of implementation of a great number of various calculations and a detailed study, the preference in the solution of the task of the Phobos-Grunt' OD and its re-entry time and location prediction at the final phase of its flight has been given to the variant 7 from among the considered above ones. In this variant the SC' motion model, considering the influence of the Russian complete model of gravitational potential PZ-90 and the atmospheric drag introduced by the Russian model GOST-2004 was used. The measuring basis of the given variant was the Russian and American orbital data received in the last day of the Phobos-Grunt ballistic lifetime including the latest data from the Russian space surveillance system produced less than 1 hour before the SC' re-entry at extremely low altitudes of its flight.

According to the selected variant of the navigation task solution the Phobos-Grunt entered into the dense layers of the Earth' atmosphere at the altitude H=80 km on January, 15th, 2012 at 17:51 UTC at the point with co-ordinates: 36.9°South and 291.0°East. The survived fragments of this space vehicle reached the altitude H=10 km at 17:57 UTC with a grouping centre over the point with co-ordinates: 24.8°South and 305.0°East.

The possible scattering of parameters of a re-entry point was estimated by the uncertainty window which left border (start) was determined by the epoch t_s = 2012.01.15/17:53 UTC and the point with co-ordinates 35.1°South and 293.4°East and the right border (end) was determined by the epoch t_e = 2012.01.15/18:02 UTC and the point with co-ordinates 10.0°South and 317.2°East.

The possible scattering of the Phobos-Grunt' re-entry points according to the selected variant is shown by a solid line against a card of the Earth in figure 6. Here the left border, the center and the right border of an impact window are shown. In figure 6 a point indicated as *ROSCOSMOS* is the center of an impact window corresponding to the last official solution, obtained in the Russian MCC and inserted into the REDB IADC during the test campaign.

The point corresponding to the center of an impact window officially adopted by IADC is shown in this figure as well. This point referred to the epoch t_c = 2012.01.15/17:53 UTC which is the time when the descending SC Phobos-Grunt passed the altitude level H=10 km. The given official IADC data was obtained on the base of the SC Phobos-Grunt re-entry parameters that was determined by the Joint space operations centre (JSoC) of the USA Strategic Command.

According to the US STRATCOM' data the Phobos-Grunt intersected the altitude H = 80 km at the epoch t^{80} = 2012.01.15, 17:46 UTC ± 1 minutes. It happened over a point of the Earth' surface with co-ordinates: ≈ 46°South and ≈ 273°East.

It is possible to notice, that the IADC' official Phobos-Grunt re-entry data practically coincides with the left border of the impact window determined for the best selected solution, obtained in TsUP TsNIImash.

In figure 6 the points corresponding to the center of an impact window, obtained and inserted into the REDB IADC by some other participants of the test campaign, are shown as well.

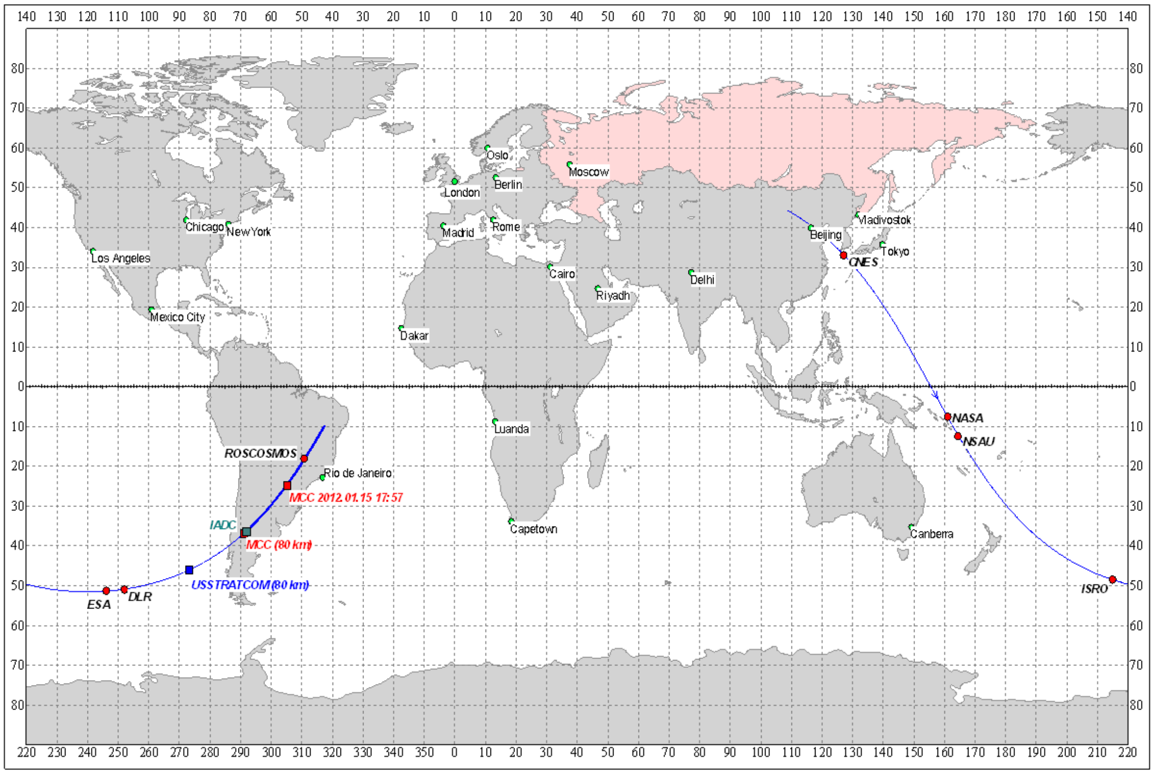

Figure 6. The Phobos-Grunt impact window corresponding to the Russian MCC results, official IADC and US STRATCOM data and results of some other participants of the international test campaign

6. Conclusion

The Russian MCC (TsUP TsNIImash) began monitoring the Phobos-Grunt' flight practically right after it was not inserted into an interplanetary trajectory to the Mars because of a failure of a SC mid-flight propulsion system and it remained in an initial supported near-earth orbit.

Because of the loss of serviceability of this SC and impossibility of its regular trajectory tracking the activity on an actual SC' orbit determination on the base of an alternating measurements from other sources, first of all, from the space surveillance systems of the Russia (RSSS) and the USA (US SSN) was fast organized in TsUP.

The principal executor of activities within a special operative group formed by the Roscosmos for the monitoring of Phobos-Grunt de-orbiting after recognizing its full uselessness, was a ballistic & navigation division of TsUP. From that time the regular operative maintenance of the Phobos-Grunt flight including its OD and a re-entry prediction with on-line information support of the Roscosmos and other interested entities was fulfilled in TsUP.

The intensity of the works on monitoring SC de-orbit increased here from the opening by IADC the international test campaign on the Phobos-Grunt during which TsUP on behalf of Roskosmos was one of the most active participants. In total 11 space agencies that are the IADC members took part in the given experiment. During the test campaign 30 official solutions of the Phobos-Grunt re-entry prediction were obtained in TsUP and transmitted to the REDB IADC. Practically in all these solutions an epoch of the SC re-entry was stably predicted on January, 15th, 2012. The last solution obtained in TsUP approximately one hour before the termination of SC flight, determined an epoch of its impact as *15.01.2012, 17:59* UTC.

The fulfilled post-flight analysis, in which different variants of the orbit determination task were considered and all circumstances influencing on a precision of the SC re-entry parameters were in details examined allowed to update a time and an impact area of the Phobos-Grunt' re-entry. According to the best solution, obtained by using of the TsUP methodic, the Phobos-Grunt entered atmospheric dense layers at the altitude H=80 km on 15.01.2012 at 17:51 UTC and passed the altitude H=10 km at 17:57 UTC with the centre of grouping of its survived fragments over the point with co-ordinates: 24.8°South and 305.0°East. The possible uncertainty in the SC impact time was estimated by a value ~ ± 4 minutes. The official impact time of the Phobos-Grunt, adopted for IADC test campaign corresponded to an epoch 15.01.2012, 17:53UTC, i.e. differed from the TsUP updated data on 4 minutes and, thereby, was within admissible scattering for this data.

The post-flight analysis revealed an essential divergence in atmospheric density representation within a descent arc of the Phobos-Grunt flight at the altitude range 110-80 km at it producing by the dynamic models of atmosphere GOST-2004 and NRL MSISE-2000. That can be a subject of investigation for developers of the given models.

7. References

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