BALLISTICKS, NAVIGATION AND MOTION CONTROL OF THE SC ON STAGES OF THE PHOBOS SURFACE APPROACHING AND LANDING

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ABSTRACT

The main purpose of the Federal space program «Phobos-grunt» project is to deliver samples of a ground of Mars's natural satellite Phobos on Earth. Mission is planned to begin at the start window of 2009 year and to finish at 2011 year. The work is devoted to problems connected with development of the Phobos landing scheme. The major factors, the landing strategy is formed on, are the tasks connected with orbital mechanics, restrictions obliged by the space craft (SC) onboard systems, inexact knowledge of the Phobos's kinematics parameters, its hypsometry and gravity field.

INTRODUCTION

The main purpose of the project of the Federal space program "Phobos-grunt" is to deliver samples of a ground of the minor celestial body — Natural Mars's satellite Phobos on Earth. According to modern propositions the Phobos's substance, as well as of other bodies of Solar system, can save an initial primary material of a protoplanet cloud (relict substance), from which the planets of Solar system have arisen. The delivery of this substance to Earth with the purpose of detail researches of its structure in laboratory conditions has essence significance for a solution of one of fundamental problems of natural sciences — problem of an origin and evolution of Solar system.

The mission is planned to begin in the window of 2009 starts and to finish at 2011. It consists of four sequential stages [1,3] (Fig. 1):

- Inserting of the SC on the departure from Earth trajectory;
- Passage from Earth to Mars finished by the transition on the artificial satellite of Mars (ASM);
- Orbital motion of the SC along the orb in the Mars's influence sphere and maneuvering to maintain a close nearness of the SC with Phobos, landing of the SC on its surface, taking of rock sample, the returned craft lift-off and its flight around Mars along the wait orbit;
- Start from the wait orbit of the returned SC and passage to Earth finished by re-entry in its atmosphere and landing in the specific region of our country.

The present work is devoted to problems of flight dynamics connected with development of the landing scheme. The development of the strategy landing includes a research of possible problems originating in unknown relevant conditions. To major factors, the strategy of landing is formed of, can be referred ones connected with orbital mechanics, restrictions obliged by the SC onboard systems, inexact knowledge of the Phobos's kinematics parameters, its surface and gravitational field as well.

The landing on Phobos assumes fulfillment of the following main operations:

- Choice of the quasi-synchronous orbit (QSO), satisfying to the landing conditions;
- Calculation of the maneuver for the transition from observation orbit on selected QSO;
- Transition on QSO;
- Getting of the image of landing region;
- Analysis of the hypsometry and clarification of the landing point;
- Calculation of the departure from QSO maneuver;
- Departure from QSO and landing.

APPROACHING WITH PHOBOS

The approaching with Phobos scheme should provide:

- Bringing of the SC in the region located at 40-60 km height above specific landing point ;
- Making up of lightning conditions under landing (20°< Angle SUN-PHOBOS-SC <70°);
- Fulfillment of conditions on radio visibility from tracking stations in Evpatoria, Ussurysk and Bear Lakes;

- Forecasting of the SC and Phobos relative movement on a moment of the landing beginning with accuracy not worse than 3 km per a position and 1 m/sec per a velocity;
- Possibility of checking of on-board systems serviceability prior to the departure from QSO;
- Possibility of the creation of conditions for the landing beginning under the repeated coming on the landing session;
- Getting of the landing region image.

After transition into orbit of observation the following

operations are executed:

- Realization of research experiments. Fulfillment of maneuvers of phasing;
- There are measurements during one month prior to the transition on QSO, which provide high-precision prediction of the SC motion relatively Phobos;
- The 2 pulses maneuver for transition from observation orbit on QSO;
- The 4 measurement days for prediction of the relative motion on a moment of the beginning of landing session;
- The 1 day preparation for a landing session;
- The landing session or a maneuver in not-nominal situation;
- Repeated session of landing.

The problems of the observation orbit choice are considered explicitly in the work [1]. There is selected as one with the following parameters.

	Meaning
Revolution period, hours	8.32333
Pericentre distance from Mars,km	9905
Inclination to the Phobos's orbit plane, deg.	0
Repetition of closeness with Phobos, days	4
Repetition of closeness with Phobos, ensuring a possibility of autonomous navigation measurements ,days	8
Minimal time span during one the mutual distance the SC-Phobos is less than 1000 km, hours	1.6667

CHOICE OF QSO

The problems arisen in choosing of QSO are explicitly considered in the work [2]. There have been formed the base of quasi-synchronous orbits as a result of carried investigations. The researches of classes of orbits for stability because of perturbations caused by non-centrality of the Phobos's gravity field have been conducted. The algorithms and programs of the orbit choosing from a specific class and time spans have been developed, on which the conditions, necessary for making of an autonomous system of landing, are executed.

QSO are classified by following parameters: a distance between the SC and Phobos and a number of the SC's revolutions around Phobos over specific number of Phobos's revolutions around Mars. The distance is considered in two directions: in a direction of a line-of-sight Mars-Phobos (axes ξ) and in a direction of Phobos's movement around Mars (axes η).

For landing on Phobos there has been selected QSO 50x100 (ξ = 50, η = 100). The transition into this orbit is made immediately from orbit of observation. Orbit, coming Phobos nearer, on a closer distance, is used in case if the transition on QSO has taken place with large errors and the conditions necessary for successful work of an autonomous system of landing are defaulted. As a more close orbit can be used QSO 41x77, which is stable against perturbations caused by the non-centrality of the Phobos's gravity field. The orbits closer to Phobos have not this property. The SC motion on such orbits can reduce in collision with Phobos.

The direct transition from orbit of observation on this QSO is impossible because of errors of performance. The transition into this orbit is possible, for example, from QSO 50x100 by two impulses. The total characteristic velocity ~7 m/sec, the accuracy of bringing in region of prospective landing is not worse 7 km per a position and 1.6 m/sec per a velocity.

The difference of the rendezvous with Phobos scheme in the project "Phobos-grunt" from the rendezvous one in the project of flight to Phobos in 1988-1989 years is, that in the old project the two QSO was always planned to use for approaching with Phobos. The first QSO had parameters 200x400. The SC "Phobos-2" was on this QSO (Fig. 2) at the moment of loss of communication with it.

TRANSITION FROM OBSERVATION ORBIT ON QSO

Generally, the transition from observation orbit on QSO can be made by three maneuvers. The total characteristic velocity of maneuvers of the SC transferring from initial orbit of observation on QSO does not exceed 150 m/sec. At that a sum of modules of two final impulses consists of ~70 m/sec. The transition from the observation orbit on QSO 50x100 is shown in Fig. 3. The magnitude of the first impulse of final pair has made 41.7 m/sec. This impulse is performed under transition from observation orbit on the overflight path. The final stage of the flight trajectory is shown by a dotted line. The SC flies

around Phobos and performs the second impulse: 23.0 m/sec. It should be noted that the transitional trajectories without flight-around Phobos allow to reduce total characteristic velocity of two impulses, however errors of performance can lead to the large distortions of the nominal QSO.

LANDING ON PHOBOS

The scheme of landing on Phobos assumes using of a trajectory consisting of three sites:

- Site of flight from QSO in the point, located above region of landing;
- Site of vertical descent;
- Site of precision braking.

The overflight site from QSO to the point located above the region of landing begins with a maneuver of departure from QSO and is finished at the moment of hitting in the particular point. During of flight the trajectory corrections are foreseen.

Under the SC motion on the site of vertical descent a horizontal velocity component is compensated. If horizontal velocity component is exceeded a threshold significance, the engine compensating horizontal component is switched on. At that the error in a horizontal plane can be accumulated due to rested velocity. Therefore the descent velocity should be sufficient the error would not be stored during the descent time. There is ensured orientation of the SC longitudinal axes along the measured instant normal at the Phobos underneath surface, that has the large curvature. At the end of descent site the autonomous system should, using the television camera, to select landing area maximum convenient by surface.

On the precision braking site there is diminished gradually vertical and horizontal velocity components up to magnitudes suitable for touching with surface. There is made lateral maneuver of apparatus to shift on the elected for landing surface site. There is realized oriented soft-landing on the Phobos's surface. There is produced a press to the surface.

For a motion control at landing the following measuring means are used:

- Gyro-inertial system;
- Laser altimeter;
- Doppler measuring instrument of velocity vector and height above a surface and of normal to the underneath surface;
- Television system of the landing site choice.

The laser altimeter ensures measurements of a distance up to a surface and determines a direction of a perpendicular to an underneath surface. It performs navigational measurements on the site from the moment of departure from QSO down to height of 2 km, on which the Doppler system begins to work.
The Doppler-measuring instrument of a vector of a velocity executes measurements of the SC velocity vector relatively surface, and also the SC height above a Phobos's surface and a normal to it.

A main task of the television camera is to determine a region in neighborhood of nominal landing point, where a surface in maximum fits for landing. The television camera allows to receive some navigational measurements. These measurements are reserve in case of failure situation.

Main restrictions:

- On maximum magnitudes of the rested values of vertical and horizontal velocity components at the moment of landing (some units of m/sec);
- On the maximum deviation of the longitudinal axes from the normal to the landing site;
- On permissible spending of energy for landing;
- On scattering of landing point coordinates relatively assign point coordinates;
- On duration of whole landing operation;
- On height, since which it is impossible the vertical engine to switch on braking not to damage optical conditions for surface observing.

The development of the landing on Phobos scheme puts a number of problems in the field of a flight dynamics. These problems concern:

- Choice of a overflight trajectory from QSO in a point located above landing point;
- Analysis of movement on the site of vertical descent;
- Estimation of forecasting and brining errors.

From point of view of on-board equipment developers the shorter session of landing the better, because there are used large number of hardware and reliability of whole system drops with increasing of time. The main span of time of the landing session is allotted for the overflight from QSO in the point located above selected region. For the costs of characteristic velocity the more this time the less total costs of impulse for departure from QSO and of impulse for elimination of longitudinal velocity component at the moment of transition in particular point.

The following algorithm makes the computation of the departure from QSO maneuver. There is selected the point located at height h, $h \sim 10 - 12$ km above Phobos's surface. The transition paths in this point from QSO are considered at the moment of passing a

longitude 270º. A free parameter is the time of transition. Four variants of transition are shown in the following table.

Transition time , min	Module of the departure impulse, m/sec	Module of the impulse for eliminating of horizontal component of the velocity, m/sec	Vertical velocity value, m/sec
37	21.6	22.0	14.3
68	7.2	9.4	11.3
97	3.8	12.7	9.7
105	4.1	12.1	9.3

The transition path is shown in Fig. 4. There is Phobos at center of frame. The abscissa axes is directed from the Phobos's center along a ray going from the Mars's center to the Phobos's center. The ordinate axis is directed so that its positive direction corresponds to a direction of the Phobos's motion on orbit. The dependence of flight height above Phobos from time is shown in a Fig. 5 for the first variant of transition on the interval from the departure from QSO up to the 1-km reaching. Heights are laid down the ordinate axis in km. Times are laid down on the abscissas axes in sec from the moment of departure from QSO.

The essential peculiarity of the Phobos's landing consists in the necessity to take into account the Phobos's rotation around its axes in the control algorithms. The slower a descent is going on the more arc a surface point interested us is going on, thus the more characteristic velocity is needed for compensation of this rotation. In the next table there are characteristics of the vertical descent site for the three values of the descent velocity: attained at the end of the transition site (14 m/sec), enlarged up to 20 and 30 m/sec.

Descent velocity, m/sec	Descent time down to 1 km, min.	Evaluation of the number of adjusting impulses, m/sec	Total characteristic velocity of adjusting impulses, m/sec	Error of the longitude brining, the Phobos rotation not taking into account, deg.
14	13	25	18	10
20	10	20	14	7.5
30	7	16	11	6

Evaluation of the number of adjusting impulses have been carried out under assuming that an adjusting impulse is performing, if a lateral velocity exceeds a threshold 0.7 m/sec, but no quicker then one time per 30 sec. Such manner of movement under ideal performance of adjusting impulses provides a descent down vertical above the assigned point with accuracy not worse 0.1º on latitude and longitude.

CONCLUSIONS

1. There are offered the scheme of the SC and Phobos rendezvous and of landing on its surface. The dynamic operations beginning with the SC observation orbit motion and finishing landing moment are considered.
2. From the flight dynamic point of view the basic elements of the approaching scheme are: choice of QSO, choice of the maneuver scheme for transition from observation orbit to QSO, choice of the landing path and the maneuver scheme for transition on it from QSO, accuracy estimation of the suitable maneuver performance.
3. The offered scheme ensures approaching and landing on Phobos in nominal case and has sufficient flexibility for escaping from possible emergencies.

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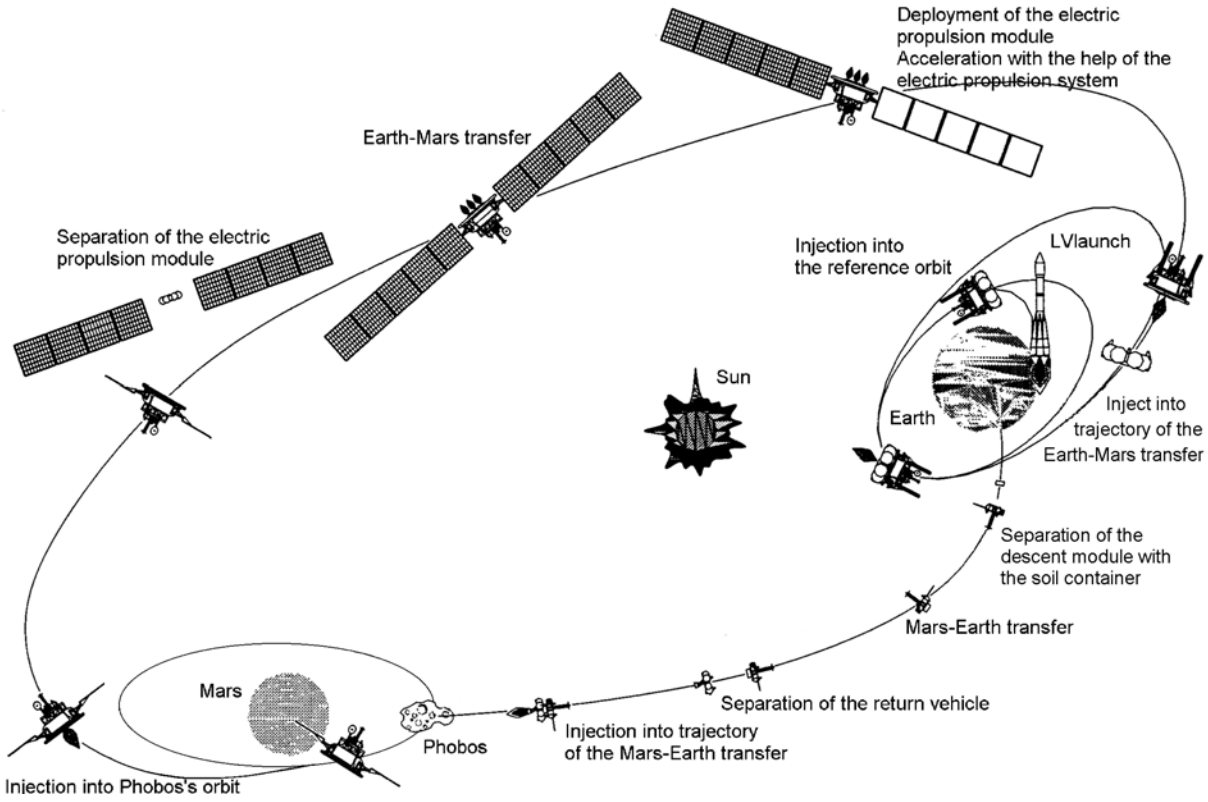

Fig. 1. Mission scheme

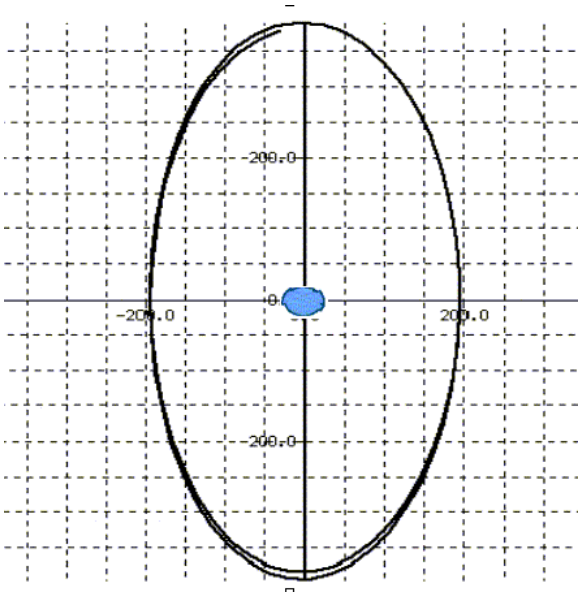

Fig. 2. The SC "Phobos-2"quasi-synchronous orbit in 1989 yr.

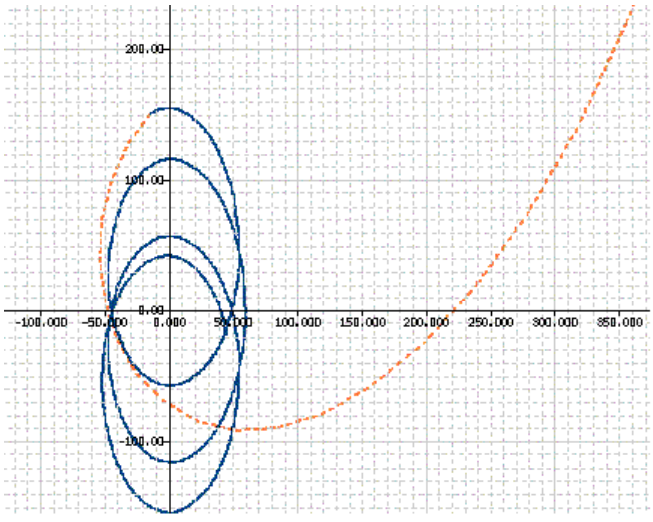

Fig. 3. Transition from observation orbit on QSO

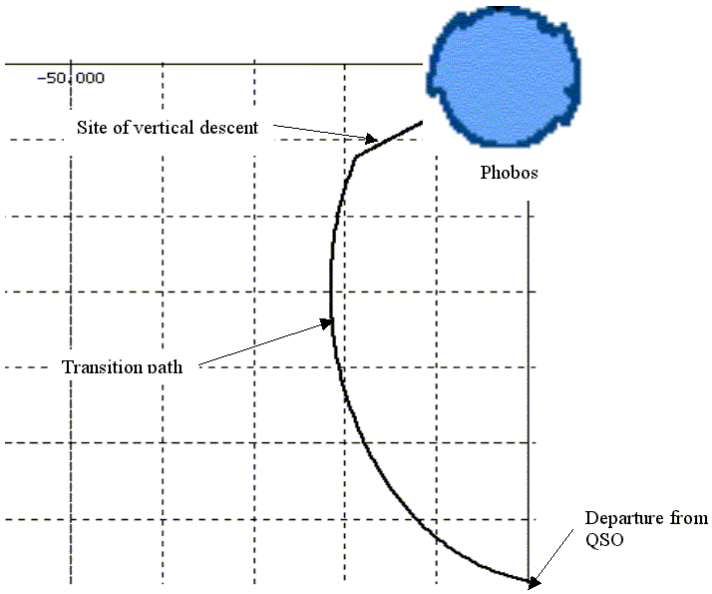

Fig. 4. Transition path from QSO to a point located up the height 1 km above the assigned point of landing

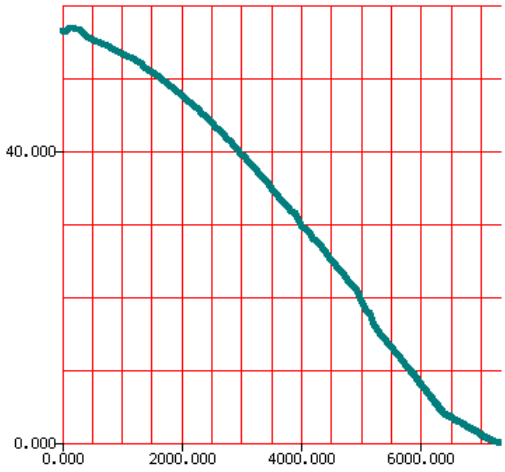

Fig. 5. Dependence of the flight height from the time above Phobos on the span from the departure from QSO up to reaching height of 1 km