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ANALYSIS FOR POSSIBILITY TO USE SPACE PLATFORM WITH ELECTRIC PROPULSION SYSTEM IN COMBINATION WITH THE LAUNCH VEHICLE FOR AIR LAUNCH

G.A. Popov, V.M. Kulkov, V.G. Petukhov
Research Institute of Applied Mechanics and Electrodynamics of MAI, Russia

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Abstract

Justification of a possibility to use Air Launch Aerospace System (ALAS) for insertion of spacecraft (SC) with sustainer electric propulsion system (EPS) into a high operating orbit is given. The results of mission analysis for the combined flight profile of space platform with electric propulsion system insertion into a geostationary Earth orbit (GEO) are presented. The solutions of the optimization problem for the trajectory spacecraft insertion into high target orbit are presented. The possibility of increasing the mass of the spacecraft delivered to geostationary orbit by means of ALAS " Air Launch ", " Svitiaz " and MAKS-T using the spacecraft electric propulsion system is considered . The proposals on concept design of a space platform with the sustainer electric propulsion system are developed for the solution of a problem of the spacecraft delivering into high target orbits (including GEO). Feasibility study showed possibility of essential increase in mass of SC in GEO at spacecraft insertion with the use of the electric propulsion system.

1 Introduction

One of the directions of increase of efficiency of transport operations of insertion of spacecraft (SC) into high-energy orbits, including a geostationary Earth orbit (GEO), is the use of air launch. Air start of launch vehicle (LV) from a board of the carrier aircraft (CA) in comparison with its land-based launch allows to increase the payload capabilities of launch vehicles, to lower economic costs of insertion of satellites in space, to expand the range of realized inclinations of orbits, to take out to safe places the route of flight and areas of falling of separated elements of launch vehicle (spent stages and a fairings). Thanks to start from the CA which imparts an additional gain in speed, the increase in power opportunities of basic LV is reached. Start is carried out at altitudes, in less dense layers of the atmosphere that reduces aerodynamic losses. There is a possibility of installation at the first stage of a rocket engine with high-altitude nozzle. Also, in most cases, starts of LV are offered to be made from the near-equator regions that increases payload possibilities of LV thanks to low latitude of start.

Realization of an optimum trajectory of flight because of the exclusion of a vertical initial leg of flight necessary at land-based launch, optimization of an arrangement of the route of flight and areas of falling of separated elements of the LV allow to reduce losses of a payload. As a whole the total payload capacity of the LV with air launch significantly increases in comparison with land-based launch vehicles of a similar class.

One of the ways of increase of efficiency of systems of air launch is the application as a part of launch vehicles, along with chemical upper stage (US), of electric propulsions. Efficiency of air launch can be significantly raised due to its use in combination with application of a space platform with the electric propulsion system (EPS). The main advantage of use of EPS in comparison with traditional chemical propulsion unit (PU) is the possibility of essential increase in mass of SC in a final orbit at the expense of a high specific impulse of electric propulsion thrusters (EPT).

The price of increase of final mass of SC is the increase in transfer time as the thrust of EPT is low in comparison with traditional rocket engines is, and its value is limited by the electric power available on board SC.

The additional increase in mass of SC in a target orbit at acceptable insertion time is reached when using the combined scheme of insertion by means of a combination of the US with chemical PU and a space platform with the electric propulsion system.

According to the initial concept, for the achievement of a goal the following problems are solved:

– the design-ballistic analysis of the combined scheme of insertion of a space platform with the electric propulsion system into high target orbits (including GEO) when using ALAS of air launch;

– development of method for solving the low-thrust trajectory optimization problem;

– formation of concept design of a space platform with the sustainer electric propulsion system for injection of the spacecraft into high target orbits.

2 Conceptual projects of air launch

Now design studies of options of increase in payload capabilities of domestic launch vehicles are intensively carried out. The analysis of projects of aerospace systems belonging to the light and medium classes offered for development, allows to conclude that realization of air launch will help to improve payload capabilities of domestic space launch vehicles.

So far in our country the considerable volume of researches and design studies on creation of aviation and rocket complexes for space is executed. As carrier aircrafts, subsonic and supersonic planes of various classes of loading capacity (MiG-31, Tu-160, Tu-22M, M-55, An-124, etc. [1 - 3]) are considered. Aviation and space-rocket complexes on their bases can put to low orbit a payload from several tens kilograms to several tons.

By the leading aerospace enterprises by request of Air Launch Aerospace Corporation it was developed a unique Air Launch System [1]. The two-stage launch vehicle "Polyot" with a starting weight of 100 t is started (Fig. 1) from the transport and starting container of the plane AN-124-100 carrier aircraft (Fig. 2).

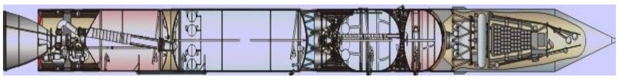

Fig. 1. Launch vehicle of air launch airspace system "Air Launch"

Fig. 2. AN-124-100 plane

The choice of such technical solution allows providing satellites delivery in the wide range of altitudes and inclinations of orbits with the payload mass 30-40% more, than by means land-based launch. The SC with a weight of up to 3900 kg is capable to put by ALAS to 200 km orbit. When using the US the complex puts to geotransfer orbit (GTO) a payload weighing 1500 kg, to GEO - 650 kg.

Significantly greater payload capabilities has the reusable aerospace MAKS system offered for development by NPO “Molniya”. Reusable aerospace MAKS system is the two-stage complex consisting of the carrier aircraft (as CA in the project the super-heavy cargo class "Mriya" An-225 plane is used), to which the second stage is mounted [2]. Cargo modification of system (MAKS-T), by estimates of developers, is capable to insert into a low Earth orbit payload weighing up to 20 tons (Fig. 3).

Fig. 3. Cargo modification of aerospace system MAKS-T

It should be noted that design studies on MAKS system are conducted during more than 20 years, however they didn't pass into the category full-scale project because so far there are no clear prospects of its target application, and also because of high complexity of problems of creation and high expenses of development [3].

The "Svityaz" Air launch airspace system (Fig. 4) is intended for insertion of spacecrafts of different function into circular, elliptic and high circular orbits, including a geostationary orbit [3].

Fig. 4. Air launch airspace system "Svityaz"

The project of launch vehicle "Svityaz" was developed on the basis of units and systems of launch vehicle "Zenith". It is under construction according to the three-stage scheme and uses nontoxical components of propellant – liquid oxygen and kerosene.

3 Standard flight profile of insertion of SC with EPS into high target orbits

The flight profile of Air launch system (Fig. 5) provides delivering of satellites to Earth orbits practically with any inclination [1]. Such opportunity is realized due to carrier aircraft flight with the fuelled launch vehicle and the satellite to the zone of start-up located at certain distance from airfield.

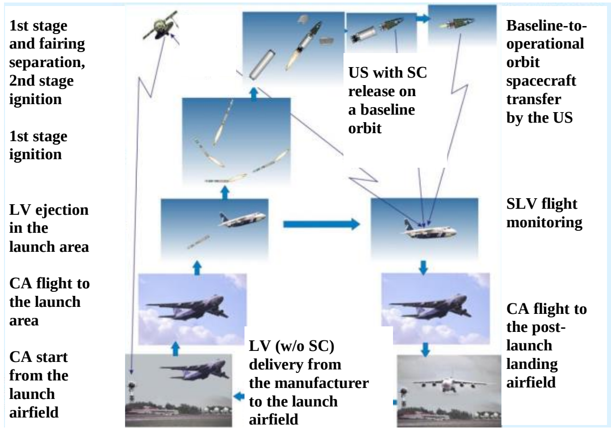

Fig. 5. Standard flight profile of Air Launch Aerospace System

Possibility of increase in mass of the payload delivered to GEO, due to the use in combination with the upper stage (the US with the propulsion system on the basis of the chemical rocket engine) a space platform with EPS is analyzed. Within the combined scheme the US delivers SC to some intermediate orbit, transfer from which to GEO is carried out by means of EPS.

The main disadvantage of use of EPS is the long time of flight caused by a low thrust-to-weight ratio of SC with EPS. Therefore for insertion of SC with EPS into high target orbits (for example, GEO) usually there considered the use of the combined scheme of the insertion which is a compromise in relation to requirements of achievement of the maximum mass of SC in a final orbit and implementation of interorbital transfer with minimum possible duration.

The combined scheme of insertion of SC into a working orbit includes stages of transfer to a low Earth (parking) orbit by means of LV and, probably, the first burn of the US propulsion unit, formation of some intermediate orbit (IO) by means of PU of US (or "apogee" chemical PU of SC) and transfer from IO into a target orbit by means of sustainer EPS of SC. Within this flight profile the possibility of use of an elliptic intermediate orbit is considered. The carried out study shows that the use of an elliptic intermediate orbit for many projects of insertion of SC on GEO is much more effective, than the use of circular intermediate orbits. The standard scheme of insertion of SC with sustainer EPS on GEO is given in figure 6.

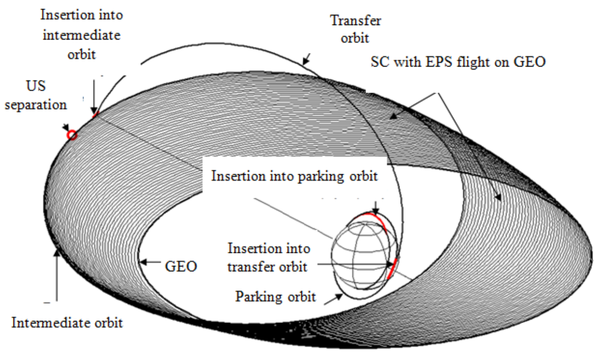

Fig. 6. The standard scheme of insertion of SC with sustainer EPS into GEO

In the standard scheme, flight between parking and intermediate orbits is carried out according to the two-impulse scheme: the first impulse near the node of a parking orbit forms a transfer orbit with the apogee altitude, equal to the altitude of apogee of an intermediate orbit, and the second impulse – in the apogee of a transfer orbit – increases the perigee altitude. Change of an inclination is made when carrying out both impulses for the purpose of minimization of expenses of characteristic velocity. The main share of change of an inclination is the share of the second impulse.

When using the scheme of air launch, the flight of SC can be carried out from a low Earth equatorial orbit and there is no need to change its inclination.

After the US separation, the spacecraft by means of sustainer EPS is transferred to a geostationary orbit. Level of a thrust acceleration which is provided by the electric propulsion thruster is very small, therefore duration of an EPS operation is long, and a transfer trajectory has a spiral form with slowly changing osculating elements.

4 Design-ballistic analysis of the combined flight profile

For achievement of the best results in case of use of LV of air start, parameters of an intermediate orbit have to be optimized along with optimization of a trajectory of flight with EPS. The optimum intermediate orbit is elliptic, and its inclination, altitude of a perigee and altitude of apogee have to be chosen from delivery terms to GEO of the maximum mass of payload during the given duration of flight. At insertion into the equatorial orbit, altitudes of a perigee and apogee of an intermediate orbit have to be optimized only.

Within offered approach [4,5], the inclination, altitudes of a perigee and apogee of IO are considered as the external parameters which are to be optimized. For each set of these parameters the mass of the SC delivered by means of the US to IO is calculated, and then the trajectory of flight of SC with EPS from IO to GEO for the purpose of definition of the trajectory delivering SC to GEO during the minimum time is optimized. For carrying out optimization of the combined scheme of insertion in advance counted values of characteristic velocity for optimum trajectories of transfer from the inclined elliptic orbits to GEO on a three-dimensional grid of values of altitude of a perigee, apogee and inclination IO – $V_{EPT}(i, h_p, h_a)$ were used. It is possible as at rather low thrust acceleration of SC (less than 2-4 mm/c^2), the considered optimum multi-revolutional trajectories of flight possess property of asymptoticity – in such trajectories the characteristic velocity of flight practically doesn't depend on level of thrust acceleration therefore the problem of determination of mass of SC (a parametrical problem) can be solved after the solution of a problem of a trajectory computation (a dynamic problem). Taking into account the possibility of scaling of values of characteristic velocity to various final circular orbits and the noted asymptoticity, it is possible to call three-dimensional tables of characteristic velocity as universal [6,7].

As a result, the problem of an assessment of characteristics of the optimum combined scheme of insertion at the set IO parameters is reduced to the following:

1) Calculation of characteristic velocity of flight from a basic orbit to IO by means of US for the purpose of determination of mass of SC in IO M_{SC}^{IO} (i, h_p, h_a). In the course of calculation the change of an inclination in impulses is optimized, and losses of velocity are either set by a constant relative value, or calculated by approximating dependences.

2) Interpolation of characteristic velocity at a low-thrust phase on a three-dimensional grid of altitude of a perigee, altitude of apogee and an inclination of an intermediate orbit of V_{EPT} (i, h_p, h_a). For carrying out optimization of the combined scheme of insertion, the in-advance computed values of characteristic velocity for optimum trajectories of transfer from the inclined elliptic orbits to GEO on a three-dimensional grid of values of altitude of a perigee, apogee and inclination IO – V_{EPT} (i, h_p, h_a) were used.

3) Calculation of final mass of SC in GEO:

$$M_{SC}^{GEO} (i, h_p, h_a) = M_{SC}^{IO} (i, h_p, h_a) \cdot exp\,[-V_{EPT} (i, h_p, h_a) / I_{s\,EPT}]$$

and flight duration:

$$T_a (i, h_p, h_a) = [M_{SC}^{IO} (i, h_p, h_a) - M_{SC}^{GEO} (i, h_p, h_a)] / (R_{EPT}/ I_{s\,EPT}),$$

where $I_{s\,EPT}$ – a specific impulse of EPT, R_{EPT} – thrust of EPT.

Optimization of the combined scheme is reduced to a problem of determination of such IO parameters i, h_p, h_a which would provide M_{SC}^{GEO} maximum at given T_a, and both functions - M_{SC}^{GEO} and T_a – are calculated by simple high-speed algorithms. Such method of optimization of the combined schemes of flight was offered in [4, 5], was reused and showed the reliability and efficiency.

The results received by stated way have small methodical errors connected with ignoring of perturbations, inaccuracy of computing of losses of characteristic velocity on a phase of work of US, errors of three-dimensional interpolation, ignoring of features of the operating lifetime of work of SC on various phases of flight. Therefore, the key trajectory parameters need to be clarified further with the use of more adequate mathematical models for both phases of flight – with high and with low thrust.

The mass of the SC delivered to GEO, is considered as criterion of optimization: such scheme of flight and its characteristic are chosen which maximize the mass of SC in a working orbit. Thus, the problem of a choice of optimum parameters of an intermediate orbit which provide insertion of SC of the maximum mass for fixed time at the given electrical power of EPS [5] is considered. Having defined dependence of mass and power characteristics on parameters of an intermediate orbit, it is possible to find out the mass of the SC delivered to GEO, as a function of time of flight. In figures 7-9 dependence on transfer time of mass of the SC delivered to a geostationary orbit by means of ALAS "Air start", "Svityaz" and MAKS-T is presented when using the electric propulsion system.

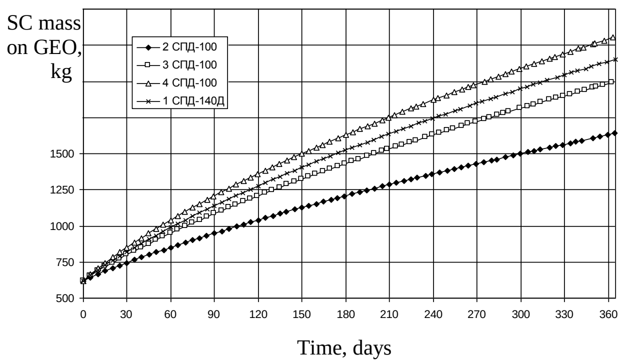

Fig. 7. Dependence of mass of SC in GEO from transfer time for various options of EPS SC (ALAS "Air Launch")

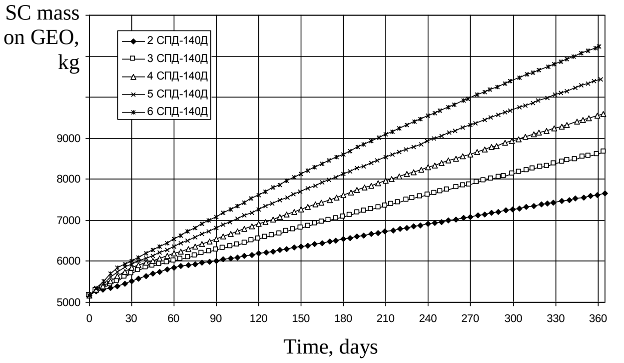

Fig. 8. Dependence of mass of SC in GEO from transfer time for various options of EPS SC (ALAS MAKS-T)

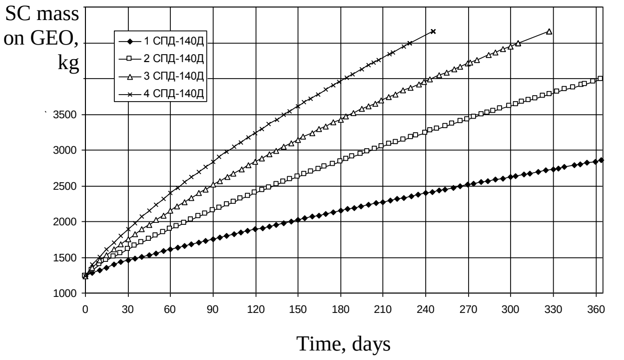

Fig. 9. Dependence of mass of SC in GEO from transfer time for various options of EPS SC (ALAS "Svityaz")

5 Concept design of SC with EPS

Proposals on concept design of a space platform with the sustainer electric propulsion system for the solution of a problem of a injection of the spacecraft into high target orbits (including GEO) are given.

For insertion of SC into high orbits as a part of ALAS the two-stage system is used: the US with the chemical rocket engine and the space platform (SP) - the electric propulsion transport module (EPTM) with the EPS [8].

SP design with EPS has to provide placement of devices and systems inside and outside of the SC and their functioning at all stages of flight. In figure 10 the standard option of concept design of a space platform with EPS is given in transport position [9].

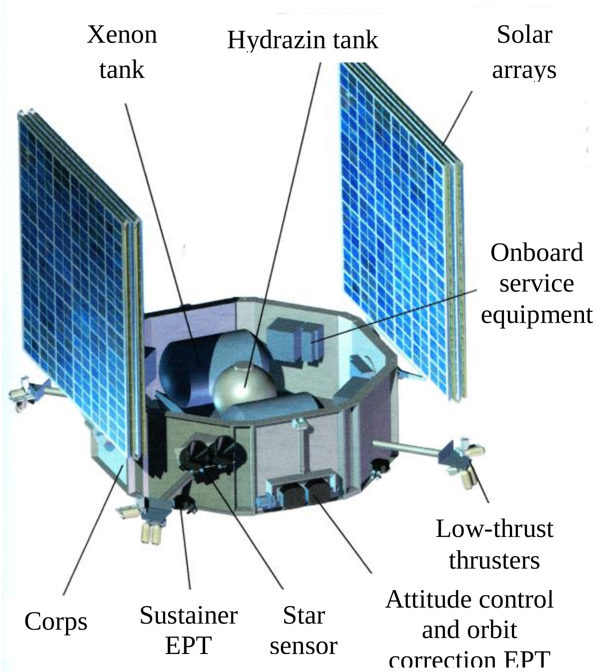

Fig. 10. Concept design of space platform with EPS in transport position

The concept design of SP with EPS together with the US is presented in the transport provision in figure 11 [9].

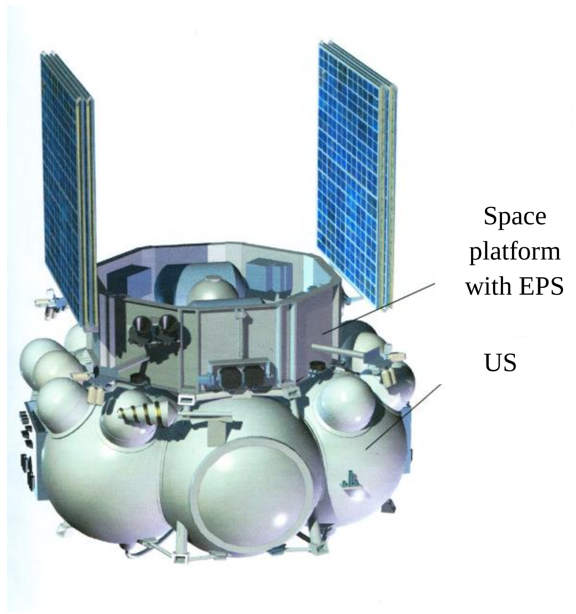

Fig. 11. Space platform with EPS together with the upper stage

6 Conclusions

Radical way to solve the efficiency increase problem for air launch airspace systems is the application of a space platform with the electric propulsion system, allowing to deliver of SC into a working orbit and ensuring its long operation.

Application of a space platform with the electric propulsion system can provide increase of payload of LV of air launch in comparison to delivery of SC into high orbits with use of traditional upper stages using chemical propellant. This way of payload increasing can be fully realized using the LV "Polyot", LV of the second stage of MAKS-T system and LV of the second stage the ALAS "Svityaz".

The description of the standard flight profile is presented. Possibility of essential increase in mass of the SC delivered by listed ALAS to GEO at use of EPS SC for its delivering from IO to GEO is shown.

The design-ballistic analysis of the combined scheme of insertion of a space platform with the electric propulsion system into GEO is carried out when using ALAS of light ("Air Launch"), medium ("Svityaz ") and heavy (MAKS-T) classes using as carrier aircraft the “Ruslan” AH-124 or “Mriya” AH-225 planes.

Results of the design-ballistic analysis of SC insertion in GEO when using ALAS "Air Launch", "Svityaz" and MAKS-T are given. Design-ballistic researches of characteristics of insertion of SC into GEO in structure of ALAS are based on the combined system: the upper stage with the chemical rocket engine and the electric propulsion transport module with the electric propulsion system. The design-ballistic analysis showed efficiency of the use of the combined propulsion system in combination with air launch for delivery of payload to GEO.

In the paper the results of the solution of a problem of optimization of a trajectory of transfer of the spacecraft with the electric propulsion system into high target orbits are given.

Expediency of use of the electric propulsion system is defined by significant increase in mass of the SC delivered to GEO. EPS application in addition to the upper stage allows to deliver to GEO a SC with a mass of 1 – 1.5 t for the ALAS of "Air Launch", 6-9 t for the ALAS of MAKS-T, 1.5-3 t for the ALAS of "Svityaz" that considerably expands transport opportunities of a complex of air launch.

Results of study of concept design of a space platform with the sustainer electric propulsion system for the solution of a problem of a delivery of the spacecraft into high target orbits (including GEO) are presented.

Acknowledgments

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Contact Author Email Address

riame@sokol.ru

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