Application of stationary plasma thrusters for spacecraft insertion into the geostationary orbit

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Abstract

Application of electric propulsions (EP) allows increase for the efficiency of solving a number of transportation problems in space. Such problems include the problem of spacecraft insertion into high operational orbits. Multiple studies are devoted to proving the efficiency of EP use for solving such transportation problems. Characteristics of spacecraft (SC) insertion into the geostationary orbit by the transport space system based on the "Soyuz-2-1B" launch vehicle, sustainer chemical engine of "Fregat" booster (thrust 19.7 kN, specific impulse 331 s) and solar electric propulsion system are under description for "Baikonur" and "Kourou" space centers. The analysis is limited by the following two parameters: time of transportation task execution (is parametrized), and SC mass at the moment of insertion as an optimization criterion for the given insertion times. Depending on the time of SC transfer from reference orbit to GEO, the orbit inclination is secured mainly by the operation of CPS (relatively short time) or EPS (relatively long time). At the leg of EP operation, control is optimized in accordance with statement, in which Pontryagin's principle of the maximum is used as the basic method. According to the analysis made, application of electric propulsion system based on the stationary plasma thrusters produced by EDB "Fakel" makes it possible to secure insertion into GEO of a spacecraft with higher mass than in the case of common method of spacecraft delivery to GEO. So, in the case of launch from "Baikonur" Space Center and payload insertion time of 60…190 days, the considered space transport system secures delivery of a satellite with the mass of 1660…2350 kg to GEO. If "Kourou" Space Center is used, the space transport system can secure delivery of a satellite with the mass of 2520…3000 kg during the spacecraft insertion time of 94…180 days.

1. Analysis for the Characteristics of Spacecraft Insertion with the Use of "Soyuz-2-1B" Launch Vehicle, Cruise Chemical Propulsion System and Electric Propulsion System

Application of electric propulsions (EP) allows increase for the efficiency of solving a number of transportation problems in space. Such problems include the problem of spacecraft insertion into high operational orbits. Multiple studies, [1…8] in particular, are devoted to proving the efficiency of EP use for solving such transportation problems. Characteristics of spacecraft (SC) insertion into geostationary orbit by the transport space system based on the "Soyuz-2-1B" launch vehicle, cruise chemical propulsion system of "Fregat" booster and solar electric propulsion system are discussed in this report.

Basic design and ballistic parameters of the space system elements, which are accepted for consideration, are presented hereinafter.

1.1 Characteristics of the space system elements

"Soyuz-2-1B" Launch Vehicle

Mass inserted into the reference orbit: – 8080 kg, when launched from "Baikonur" Space Center, – 9000 kg, when launched from "Kourou" Space Center;

Circular reference orbit altitude: – 200 km, when launched from "Baikonur" Space Center, – 200 km, when launched from "Kourou" Space Center;

Reference orbit inclination: – 51.6°, when launched from "Baikonur" Space Center, – 5.22°, when launched from "Kourou" Space Center.

Chemical Propulsion System (CPS)

Maximum operating fuel capacity – 5600 kg;
Total fuel capacity (it includes warranted capacity and non-consumable remainder) – 5700 kg;
Cruise engine thrust – 2000 kgF;
Engine specific thrust – 331 s;
CPS dry mass – 650 kg;
Mass of CPS with fuel – 6350 kg;
Final CPS mass taking into account warranted fuel capacity and non-consumable remainder –750 kg.

Propulsion Unit Configuration for the Cruise Electric Propulsion System (EPS)

Propulsion module (PM) type – SPT-140;
Total amount of PM – 4 (n_{total} = 4), including: primary modules operating simultaneously – 2; reserve – 2.

SPT-140 Based Sustainer Propulsion System

Thruster: SPT-140;
Anode voltage – 350 V;
Thrust – 0.210 $N \times 2$ = 0.42 N;
Specific impulse – 19.00 km/s;
Input electric power of the module – 3650 W;
Power to thrust ratio – 18.25 kW/N;
Module mass with two gas distribution units BGR-140 – M_{PM} = 10 kg.
Power processing unit mass – 40 kg;
Mass of other propulsion system units and design load-bearing elements ~60 kg.

Configuration of the auxiliary electric propulsion system (AEPS) at its use in GEO

Type of the propulsion modules (PM) used – SPT-100;
AEPS is used for SC keeping in the operational orbit during the entire period of the launched satellite operation;
AEPS dry mass is assumed to be 60 kg;
Propellant (xenon) store for SC keeping in the operational orbit is ~ 120 kg (it depends on the SC mass and its powered period).

Power Supply System for the Electric Propulsion System

Power supply for the electric propulsion system is provided by solar power plant (SPP);
SPP power for the entire space system – 10 kW;
Power supplied to the propulsion unit at the operation start – 7.7 kW;
It was assumed for the payload mass calculation that the mass of service module with service systems is ≈ 570 kg;
Payload mass (Mpl) was calculated as mass difference between SC mass delivered to the operational point of final orbit and mass of the service platform and inseparable cruise EPS.

1.2 Characteristics of the space system elements

Several parameters are considered while analyzing projects of insertion into the operational orbits, into GEO in particular, with the use of electric propulsion systems. Electric power, time of transportation task execution, total SC mass and mass of payload delivered to operational orbits are the main of them.
Electric power is one of the basic parameters. In view of constraints imposed on volume assigned to SPP, let's consider that electric power of onboard power plant is fixed. So, our analysis is limited by the following two parameters (two criteria):

- time of transportation task execution (for the task under consideration it is the time of SC insertion into the designation orbit);
- SC mass parameter (for the considered task statement, when SC mass in the initial orbit is assumed to be known, it is the mass of spacecraft and payload (PL) inserted into the designation orbit).

In this work we parametrized (searched within some range) the first of the above parameters, i.e. the time of SC insertion into the designation orbit. In other words, rather wide range of insertion time, which is realizable and interesting from our point of view, is considered.
The second parameter (SC and payload mass inserted into the operational orbit) is considered in this study as some optimization criterion for the given insertion times. We select such mission pattern and its characteristics, which would maximize SC mass (and actually that of the payload) in the operational orbit.

We consider the problem of choosing an optimum pattern of SC insertion into GEO and optimum parameters of space system (including CPS fuel mass and optimum EPS xenon mass), which secure insertion of maximum mass during the fixed time period.

2. The Pattern of SC Insertion into GEO with the Use of Electric Transport Module

The following pattern of SC insertion into GEO is considered.
It is assumed that the launcher delivers SC into the low Earth (reference) orbit.
The spacecraft is launched from the low reference orbit and transferred to some intermediate orbit by the cruise chemical propulsion system. Several starts (2 or 3) of the cruise CPS are possible in this case.
In general case, major semiaxis, eccentricity (apogee and perigee altitudes), inclination, perigee argument and ascending node longitude of the intermediate orbit are the parameters, which are selected during the process of the transfer pattern optimization.
After the cruise propulsion system separation, the booster is transferred to the geostationary orbit by the SC electric transport module. The level of overload secured by electric propulsion is rather low, so the duration of powered leg is rather long, while the flight trajectory is a multiturn helix with slowly varying osculating elements. The trajectory of SC with EP is in many respects defined by the elements of intermediate orbit and, in particular, its eccentricity.
Depending on the time of SC transfer from reference orbit to GEO, the orbit inclination is secured mainly by the operation of CPS (relatively short time) or EPS (relatively long time).
At the leg of EP operation, control is optimized in accordance with statement, in which Pontryagin's principle of the maximum is used as the basic method. Description of methodic approach can be found in [9…11].
Basic results of calculation made during the analysis of space insertion system under consideration are presented hereinafter.

3. Space System Characteristics as Insertion Time Functions at the Lunch from "Baikonur" Space Center

Figure 1 shows the mass of satellite inserted into GEO as a function of insertion time.

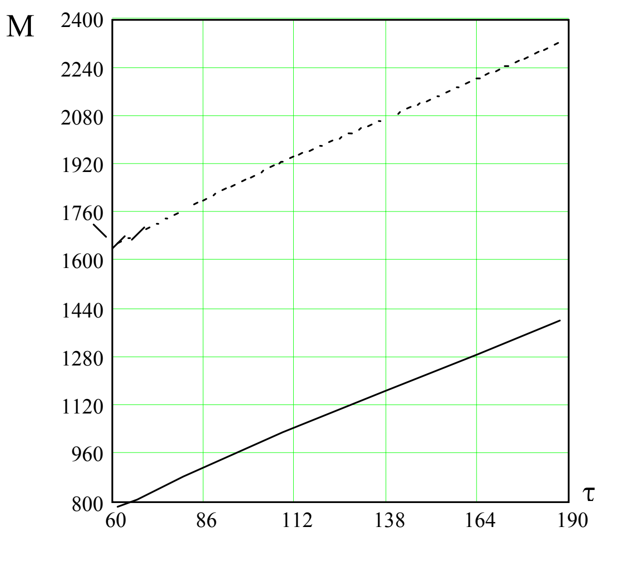

Figure 1: Mass inserted into GEO [kg] as a function of insertion time [day]

Upper curve shows SC mass at the moment of insertion into operational orbit. Lower curve shows assumed payload mass for a SC inserted into the operational orbit

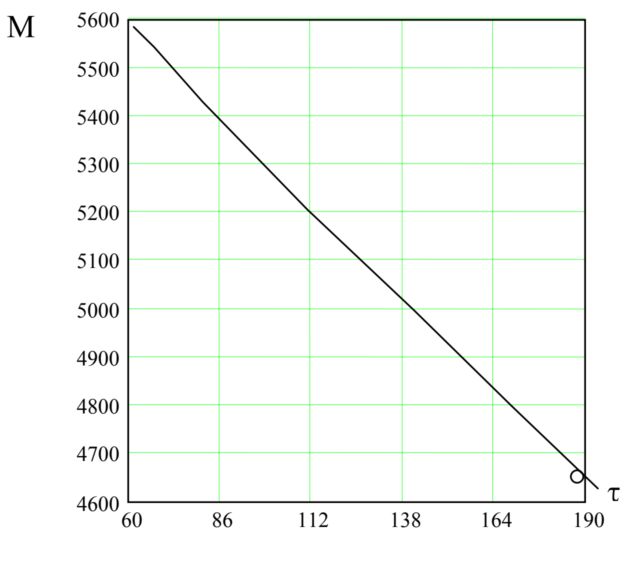

Figure 2: Mass of chemical booster fuel [kg] as a function of SC insertion into GEO [day]

According to the analysis of above dependence, at the insertion time increase (from 60 to 190 days) the mass of SC inserted into GEO grows monotonically (from 1600 kg up to 2350 kg). The presented dependence is close to linear, and mission duration increase by 10 days results, on average, in the inserted mass increase by about 50 kg. It should be noted that in spite of the low thrust level of the thruster the insertion time is relatively short and mass efficiency of the project is high. So, during the maximum considered time (190 days) it is possible to insert a satellite with the payload mass of about 1440 kg at the total SC mass of about 2350 kg. The latter is close to the SC mass in GEO in the case of SC launch from "Baikonur" Space Center by a space system based on the modern "Proton" launcher with "DM" or "Briz" booster.

The apogee altitude changes with the first CPS start. Depending on the transfer duration the second start is realized either at apogee or at perigee. An apogee altitude and orbit inclination or a perigee altitude change with this, correspondingly.

In all considered variants the optimum insertion pattern is characterized by the fact that the cruise chemical engine is operated for the third time at the apogee of the transfer orbit. In the case of fast transfers the intermediate orbit perigee altitude is slightly increased due to this operation. For example, at the insertion time of 60 days the optimum perigee altitude is a little bit more than 12 000 km, while at the insertion time of 80 days the optimum perigee altitude of the intermediate orbit is nearly 8000 km. In the case of fast insertion the second operation of the booster engine results in considerable variation of orbit inclination. So, at the duration of 60 days the optimum inclination of intermediate orbit is a little bit less than 9.5o, and at the duration of 108 days the optimum inclination of intermediate orbit is 22.5°.

Figure 2 shows optimum fuel mass of "Fregat" booster cruise propulsion system as a function of time of insertion into the operational orbit. It is obvious that this dependence is monotonely decreasing. At the transfer of 60 days in duration the optimum mass of fuel required for the chemical propulsion system is practically equal to the maximum possible of about 5 600 kg. At the transfer of 108 days in duration the optimum mass of fuel required for the chemical propulsion system is about 5 220 kg. At the transfer during 187 days the optimum mass of fuel is 4650 kg.

In this work we consider CPS similar to the CPS of "Fregat" booster as the cruise chemical propulsion system. It is necessary to note that the optimum mass of CPS fuel does not differ substantially from the maximum one for the cruise propulsion system of "Fregat" booster.

Figure 3 shows optimum mass of xenon required for the electric propulsion system of transport platform as a function of time of insertion into the operational orbit. It is obvious that this dependence is monotonely increasing and very close to the linear one. At the transfer of 60 days in duration the optimum xenon mass is about 127 kg. At the transfer during 108 days the optimum xenon mass is about 226 kg. At the transfer during 187 days the xenon mass is about 393 kg.

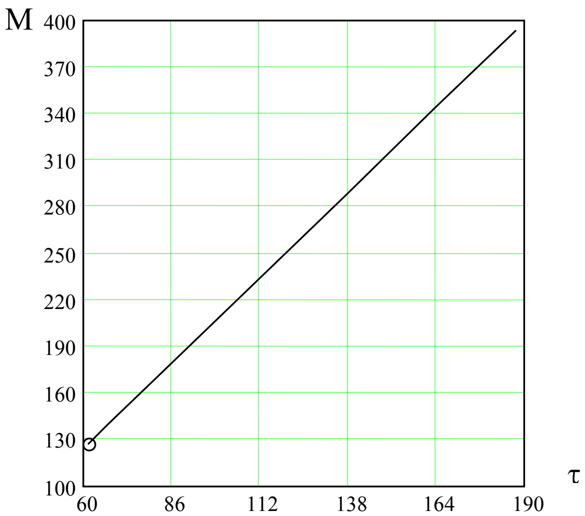

Figure 3: Optimum EPS xenon mass [kg] as a function of insertion time [day]

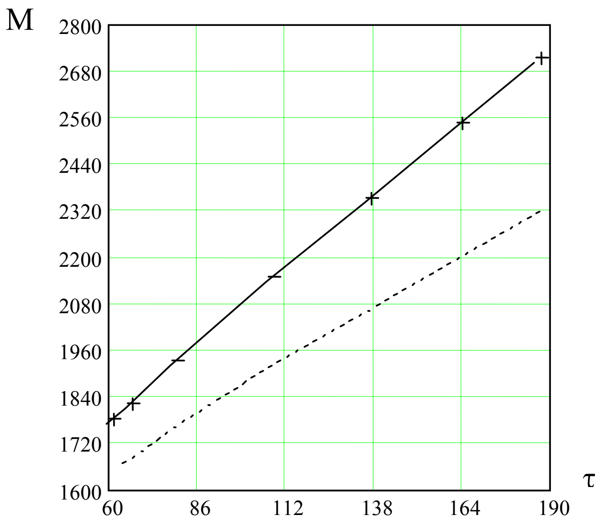

Figure 4: Initial (upper curve) and final mass of SC with EPS [kg] as a function of time of SC insertion into GEO [day]

Figure 4 shows dependences for the SC mass after the separation of the booster cruise chemical propulsion system (initial mass of SC with EPS) and SC mass at the moment of its insertion into the operational orbit (final mass of SC with EPS) on the time of insertion into the operational orbit. It is obvious that these dependences are monotonely increasing. At the transfer of 60 days in duration the initial mass of SC with EPS is about 1780 kg, final mass – 1660 kg. At the transfer of 108 days in duration the initial mass of SC with EPS is about 2150 kg, final mass – 1925 kg. At the transfer of 190 days in duration the initial mass of SC with EPS is about 2710 kg, final mass – 2320 kg.

4. Space System Characteristics as Insertion Time Functions at the Launch from "Kourou" Space Center

Mass of satellite inserted into GEO as a function of insertion time is shown in Figure 5.

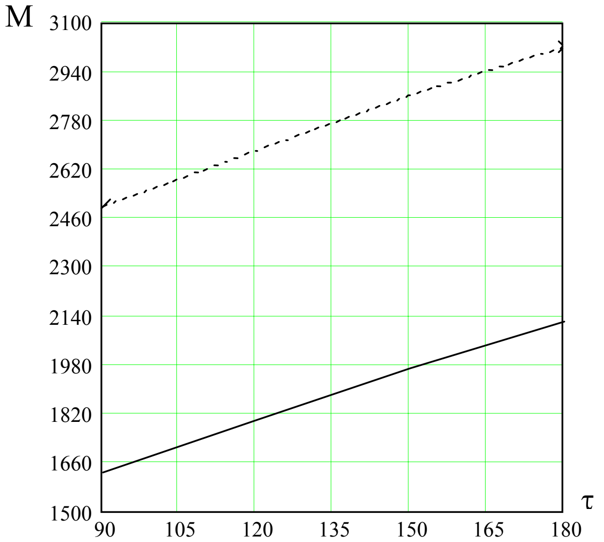

Figure 5: Mass inserted into GEO [kg] as a function of insertion time [day]

Upper curve shows SC mass at the moment of insertion into operational orbit. Lower curve shows payload mass for a SC inserted into the operational orbit

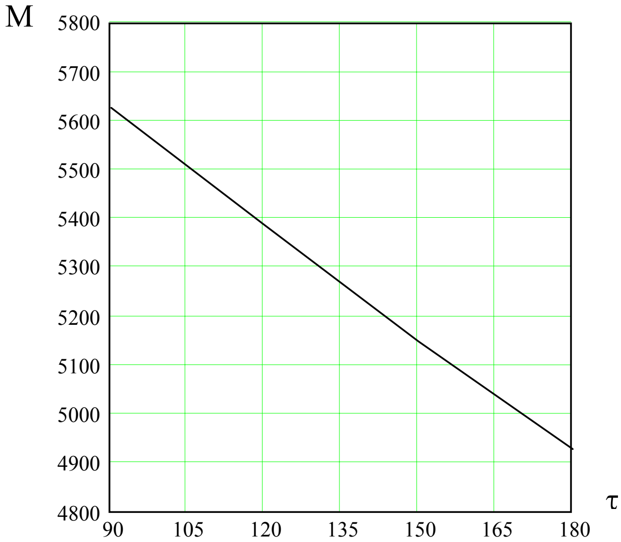

Figure 6: Mass of chemical booster fuel [kg] as a function of time of SC insertion into GEO [day]

Minimum insertion time defined by the maximum store of fuel of the chemical booster (~ 5 600 kg) appears to be 94 days.

According to the analysis of the presented dependence, the mass of SC inserted into GEO grows monotonically (from 2520 kg to 3000 kg) with the insertion time increase (from the minimum of 94 days to 180 days). This dependence is close to a linear, and mission time increase by 10 days results, in general, in the inserted mass growth by about 53 kg. It should be noted that in spite of the low thrust level of the thruster the insertion time is relatively short and mass efficiency of the project is high. So, during the maximum considered time (180 days) it is possible to insert a satellite, payload mass of which is over 2100 kg.

Figure 6 shows optimum fuel mass for the cruise chemical propulsion system (CPS of "Fregat" booster actually) as a function of time of insertion into the operational orbit. It is obvious that this dependence is monotonely decreasing. At the transfer of 94 days in duration the optimum mass of fuel required for the chemical propulsion system is practically equal to the maximum possible (about 5600 kg). At the transfer of 120 days in duration the optimum mass of fuel required for the chemical propulsion system is about 5 390 kg. At the transfer of 150 days in duration the optimum mass of fuel required for the chemical propulsion system is about 5150 kg. At the transfer during 180 days the optimum mass of "Fregat" fuel is about 4930 kg. It is necessary to note that, similarly to the launch from "Baikonur" Space Center, it generally appears that the optimum mass of cruise CPS fuel does not differ substantially from the optimum one for the cruise propulsion system of "Fregat" booster.

The use of cruise propulsion system that is similar to the propulsion system of "Fregat" booster makes it possible to develop promising transport system within a rather short period of time.

Figure 7 shows optimum mass of xenon of the transport platform EPS as a function of time of insertion into the operational orbit. It is obvious that this dependence is monotonely increasing and very close to the linear. At the transfer of ~ 94 days in duration the optimum xenon mass is about 185 kg. At the transfer of 120 days in duration the

optimum xenon mass is about 240 kg. At the transfer of 150 days in duration the optimum xenon mass is about 300 kg. At the transfer of 180 days in duration the xenon mass is about 360 kg.
In order to compare efficiencies of the use of combined propulsion system based on CPS and EPS for the delivery of SC and their payloads to GEO and ordinary methods of SC delivery to GEO with the use of chemical engines only, let's consider mass parameters of both variants. For this we use the same "Soyuz2-1B" launcher for both variants; for the currently used method supposing application of cruise propulsions only we consider additional use of "Fregat" booster, and for the combined variant – cruise chemical propulsion system similar to the propulsion system of "Fregat" booster and SPT-140 based EPS.

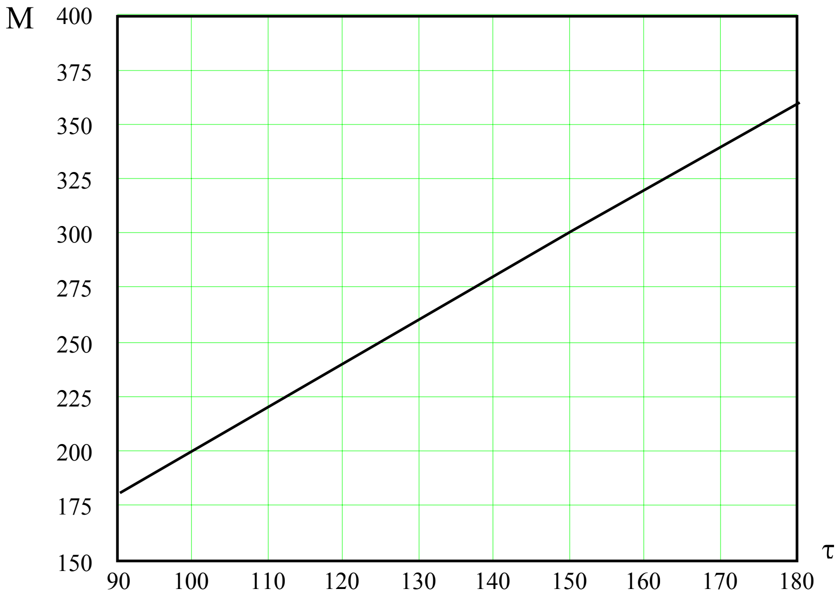

Figure 7: Optimum EPS xenon mass [kg] as a function of insertion time [day]

Calculation results for "Baikonur" Space Center are presented in Table 1, and results for "Kourou" Space Center are presented in Table 2. At that, the cases of direct 2-impulse and 3-impulse delivery and delivery with the realization of maneuver near Moon are considered for purely chemical variant. Comparison of two variants (with CPS only and with CPS and EPS) reveals considerable advantage of the variant with the use of EPS. Depending on the transfer time, the SC mass delivered to GEO in the case of combined propulsion system use is 2-2.5 times for "Baikonur" Space Center and 1.5 – 2 times for "Kourou" Space Center higher than the SC mass in GEO for the purely chemical variant. Similar conclusion can be made for the payload mass.

Table 1: Performance capabilities for the SC insertion into GEO from "Baikonur" Space Center

Launch services	SC mass delivered to GEO, kg	Comment
"Soyuz2-1B" launcher + "Fregat" booster	~ 800 - 1000	Application of 2- or 3-impulse insertion pattern and modifications of "Fregat" booster
"Soyuz2-1B" launcher + "Fregat" booster + gravity-assist maneuver near Moon	~ 1150	
"Soyuz2-1B" launcher + "Fregat" booster + apogeum engine	~ 1200-1400	
"Soyuz2-1B" launcher + ETM (10 kW) 120 days/140 days/180 days	1980/2080/2280	

Table 2: Performance capabilities for the SC insertion into GEO from "Kourou" Space Center

Launch services	SC mass delivered into GEO, kg	Comment
"Soyuz2-1B" launcher + "Fregat" booster	~ 1400-1450	Application of 2-impulse injection pattern is the best option
"Soyuz2-1B" launcher + ETM (*N* = 10 kW) 95 days/120 days/150 days/180 days	2520/2690/2860/3020	

Conclusion

According to the analysis made, application of electric propulsion system based on the stationary plasma thrusters produced by "Fakel" Experimental Design Bureau makes it possible to secure insertion into GEO of a spacecraft with higher mass than in the case of common method of spacecraft delivery to GEO. So, in the case of launch from "Baikonur" Space Center and payload insertion time of 60…190 days, the space transport system comprising middle-class launcher of "Soyuz2-1B" type, cruise chemical propulsion system similar to the CPS of "Fregat" booster, and solar electric propulsion system secures delivery of a satellite with the mass of 1660…2350 kg (with this the payload mass is about 800 – 1440 kg, respectively) to GEO.

If "Kourou" Space Center is used, the considered space transport system can secure delivery to GEO of a satellite with the mass of 2520…3000 kg during the spacecraft insertion time of 94…180 days. Expected payload mass will be about 1650 - 2130 kg, respectively.

In general, mass efficiency of the use of combined system (CPS and EPS) is 1.5 – 2.5 times higher than in the case of SC delivery to GEO with the use of propulsion systems comprising chemical engines only.

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