ELECTRIC PROPULSION MISSION TO GEO USING *SOYUZ/FREGAT* LAUNCH VEHICLE

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ABSTRACT

There are analyzed solar electric propulsion missions to geostationary orbit (GEO) using *Soyuz* launch vehicle and *Fregat* upper stage. The considered combined flight profile includes insertion into the low Earth orbit (LEO) using *Soyuz/Fregat* launch vehicle, transfer into an intermediate orbit providing by *Fregat* upper stage, and electric propulsion transfer into GEO. The purpose of study is search for commercially available space platform, which could be adopted to realize electric propulsion transfer into GEO using *Soyuz* launch vehicle. The transfer duration was considered as criteria of the mission commercial viability. Eighteen commercially available space platforms were analyzed. There were considered upgraded (electric propulsion) versions of these platforms: the conventional apogee propulsion system was considered to be replaced by electric propulsion unit. The *SPT-100/140* and *XIPS-13/25* thrusters were considered for the electric propulsion unit. The carried out analysis shows that the transfer duration is less then 3 months for 4 space platforms (*STAR 1*, *STAR 2*, *HS 376HP*, *Spacebus 1000*) and within 3-4 months for 6 space platforms (*FS 1300HP, A2100, A2100AX, Eurostar 2000, Spacebus 2000, Spacebus 3000*).

INTRODUCTION

Soyuz/Fregat launch vehicle (LV) cannot insert into GTO or GEO commercial communication spacecraft using conventional (direct or supersynchronous) flight profiles. The main reason is disadvantageous geographical placement of *Baikonur* launch site and corresponding high inclination of the parking orbit (51.8°). For example, *Soyuz* LV with upgraded *Fregat* upper stage (ChUS) delivers payload up to 400 kg (450 kg) into GEO using direct 7-hours (supersynchronous 24-hours) insertion. The dry mass of corresponding spacecraft (SC) equals to 283 kg (318 kg) in case of conventional spacecraft propulsion using. Payload, delivering by *Soyuz/Fregat* LV in the *Ariane's* GTO, equals to ~1150 kg. Conventional spacecraft propulsion (specific impulse 308 sec) provides insertion into GEO ~700 kg in this case. Corresponding SC dry mass equals to ~490 kg. But real dry mass of commercial communication satellites is varying within the range 600-3000 kg and more.

One way to enhance launch vehicle performance for GEO missions is using of spacecraft with electric propulsion[1 - 8]. High specific impulse of electric propulsion leads to increasing payload, but transfer duration increases too due to low thrust magnitude. The combined mission profile realizes the compromise between payload and time constraints. *Soyuz/Fregat* LV inserts SC into an intermediate orbit. Then SC delivers itself into GEO using onboard electric propulsion unit. Varying the intermediate orbit parameters, we can vary the payload and the transfer duration. The transfer duration 3-4 months seems to be a most attractive from the point of view the "transfer duration – payload" compromise.

The purpose of study is search of commercially available space platform, which could be adopted to realize electric propulsion transfer into GEO using *Soyuz*/*Fregat* LV. The transfer duration was considered as criteria of the mission commercial viability (the maximum transfer duration should not exceed 3-4 months).

So, the trajectory optimization problem becomes the problem of top priority. 3-4 optimization problems were solved for each space platform: optimization electric propulsion transfer from intermediate orbit into GEO, optimization *Fregat* upper stage maneuvers to insert spacecraft from initial orbit to intermediate orbit, optimization of insertion into LEO using *Fregat* (optionally), and intermediate orbit optimization. The non-linear programming methods were used to optimize finite-thrust maneuvers of *Fregat* upper stage and parameters of intermediate orbit. The electric propulsion transfer was optimized in the sense of maximum principle.

Eighteen commercially available space platforms were analyzed. There were considered upgraded (electric propulsion) versions of these platforms. Namely the conventional apogee propulsion system was considered to be replaced by electric propulsion unit.

The SPT-100/140 and XIPS-13/25 thrusters were considered for the electric propulsion unit. Comparison of *Soyuz*/FG and Soyus/ST LV using was conducted.

MISSION PROFILE

Considered space transportation system consists of *Soyuz* LV, *Fregat* ChUS, and SC equipping by electric propulsion unit.

The considered mission profile consists of following phases:

1. Insertion into the circular parking LEO. The *Soyuz* LV launches from the Baikonur launch site and inserts payload either into circular LEO (altitude 200 km, inclination 51.8°) either into a sub-orbital trajectory. In the last case, the 1^{st} burn of *Fregat* is used to place upper composition (*Fregat* + adapter + SC) into the parking orbit.
2. Insertion into the intermediate orbit providing by *Fregat* ChUS. SC separation (Fig. 1).
3. Transfer from the intermediate orbit into the GEO using electric propulsion (Fig. 2).

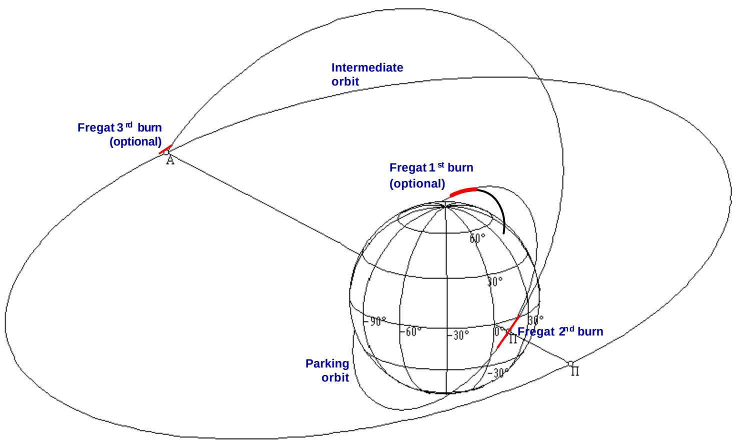

Fig. 1. Fregat maneuvers

LAUNCH VEHICLE AND UPPER STAGE

Two versions of *Soyuz* LV were considered: *Soyuz*/FG and *Soyuz*/ST. Both launch vehicles can insert payload either into LEO either into sub-orbital trajectory. *Soyuz*/FG is flight-proven commercial available LV. *Soyuz*/ST is its upgrade version using enlarged fairing and providing extended range of sub-orbital trajectories.

There were assumed following performance of launch vehicles:

- Mass of upper composition (*Fregat* + adapter + payload) in LEO
  - *Soyuz*/FG: 6840 kg,
  - *Soyuz*/ST: 6800 kg.
- Altitude of circular LEO: 200 km,
- LEO inclination: 51.8°.

It was considered the upgraded version of *Fregat* ChUS having follows specification:

- final ChUS mass: 1000 kg;
- thrust: 2000 kgf;
- specific impulse: 330 sec;
- active fuel: up to 5350 kg;
- operational on-orbit time: up to 24 hours;
- payload adapter: 100 kg.

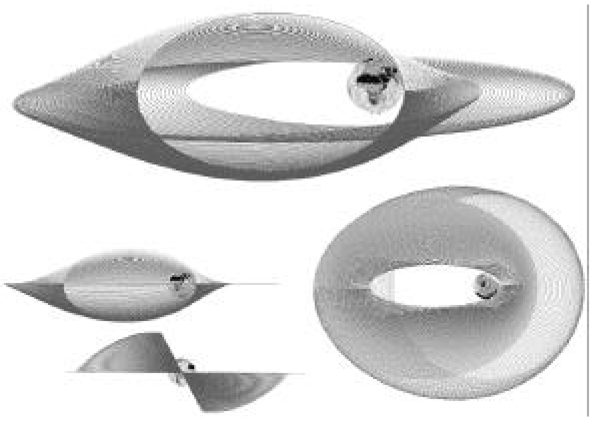

Fig. 2. Low-thrust trajectory to GEO

Soyuz/*Fregat* LV payload on LEO can be increased using insertion via sub-orbital trajectory. In this case, 3rd stage of *Soyuz* LV inserts the upper composition into an sub-orbital trajectory and the *Fregat* 1st burn realizes the final insertion into the parking LEO. Dependency of payload mass in the LEO versus *Fregat* propellant consumption during this 1st burn is presented in the Fig. 3.

SPACECRAFT AND PROPULSION SYSTEM

The simple mathematical model of SC was applied to the list of 18 space platforms having conventional apogee

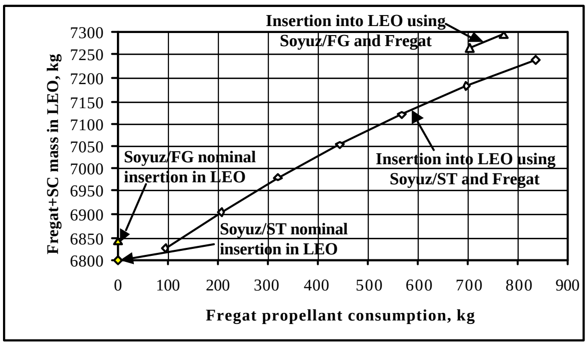

Fig. 3. Insertion into LEO using Fregat US

propulsion systems. The launch (m_o) and dry (m_{dry}) mass of each platform is known. So, we can estimate mass of chemical apogee propulsion system m_{aps}. It was assumed that its mass is proportional to propellant mass $m_p=(m_o-m_{dry})$: $m_{aps}=0.1125m_p$.

For the purpose of providing combined flight profile, the conventional chemical apogee propulsion system was replaced by electric propulsion unit having follows mass:

$$m_{epu}=(n_b+n_s)m_{thruster}+n_b m_{control}+m_{ppu}+$$
$$+m_{xe}(1+k)(1+a_{tank}),$$

where n_b - number of simultoneusly running thrusters,

- n_s - number of spare thrusters,
- $m_{control}$ - mass of control unit for 1 running thruster,
- m_{ppu} - mass of power processing unit,
- $m_{ppu}=\gamma N_{el}$,
- γ=5 kg/kW - specific mass of PPU,
- N_{el} - input PPU electrical power,
- k=0.05 – propellant (xenon) margin,
- a_{tank}=0.13 - tank-to-xenon mass ratio.

So, electric propulsion version of SC has follows dry mass:

$$m_{dry}^{EP}=m_{dry}-m_{aps}+m_{epu}.$$

The number of simultaneously running thrusters during transfer to GEO and input PPU electrical power N_{el} is defined by given electrical power of the solar arrays ($N_{el}=N_{sa}-N_{ss}$, where N_{sa} – solar arrays power, N_{ss}=200 W – consumed electrical power of other SC systems) and thrusters performance (see Tables 1, 2).

Table 1

Thrusters performance

	Hall thrusters/ SPT		Ion thrusters/ XIPS	
	SPT-100	SPT-140	13 cm	25 cm
Thrust [mN]	80	200	18	165
Consumed power [W]	1350	3000	500	4500
Specific Impulse [s]	1630	1630	2568	3800

Table 2

Mass of EPU components

	SPT-100	SPT-140
$m_{thruster}$ [kg]	3	7
$m_{control}$ [kg]	2	6

Required xenon consists of two parts. The first part is xenon, which is required to deliver SC into GEO. Trajectory optimization problem should be solved to find this xenon consumption. The second xenon part is xenon, which is required for SC station-keeping. This xenon consumption provides velocity increment 70 m/s per year for a 15-years lifetime (total 1050 m/s).

TRAJECTORY OPTIMIZATION

Ascent trajectory.

The ascent trajectory of launch vehicle is supposed to be given and it is not optimized. If insertion via the sub-orbital trajectory is used, then the 1st burn of *Fregat* ChUS provides the final insertion into the parking orbit. This maneuver was optimized. Another 1-2 *Fregat* burns form intermediate orbit.

Fregat maneuvers.

All *Fregat* maneuvers (Fig. 1) were optimized. The final goal of *Fregat* maneuvers is insertion of maximal payload into the given intermediate orbit. The *Fregat* thrust steering is supposed to be linear function with respect to time. The control parameters, which are associated with each *Fregat* burn, are following: start time of burn, burn duration, initial pitch/yaw angles, and pitch/yaw angular rates. These control parameters where optimized taking into account pitch/yaw angular rate constraints and desired time delay between 3rd *Soyuz* stage separation and first ignition of *Fregat*. The two-phase non-linear programming method was used to maximize payload in the given intermediate orbit. At the first, the impulsive transfer was optimized. Then obtained optimal impulsive solution was used to generate guess values of control parameters for solver of optimal finite-thrust problem.

Electric propulsion transfer from given intermediate orbit into the GEO.

The optimal control problem in the sense of Pontryagin's maximum principle was solved. The performance index was minimum transfer time. The thrust value was assumed to be unregulated during the burns. According to maximum principle, the thrust should acts continuously during the transfer in case of minimum-time problem. The transfer duration, optimal thrust steering, and orbital parameters evolution was obtained as solution of corresponding two-points boundary value problem. The continuation method and averaging techniques was used to solve the boundary value problem.

MISSION ANALYSIS

Eighteen space platforms were reviewed for realization considered mission. Main study results are presented in the Table 3 (the minimal transfer duration is presented in the last column) and Fig. 4.

Below there are presented the detailed results for electric propulsion versions of several space platforms.

Spacebus 3000 space platform

Launch vehicle

LV version — *Soyuz*/FG

Insertion using *Fregat* first burn

(*Fregat* separation velocity 7475 m/s)

Electric propulsion unit

Number of thrusters	4 SPT-140 (+4 spare)
Consumed electric power	12800 W

Intermediate orbit

Apogee altitude	45500 km
Perigee altitude	290 km
Inclination	51.8°
Initial spacecraft mass (in the intermediate orbit)	2141 kg
Fregat ChUS flight duration	< 2 hours

Table 4

Fregat burn No.	Fuel consumption
1	775 kg
2	4052 kg
Total	4827 kg

Electric propulsion phase

Transfer duration	90 days
Spacecraft mass in the GEO	
nominal	1764 kg
taking into account 5% margin of xenon	1745 kg
Dry mass	1634 kg

Required dry mass is 1674 kg. The 40 kg dry mass shortage can be compensated by communication payload reduction. From other hand, the dry mass can be increased up to required 1674 kg by means of increasing transfer duration up to 99 days.

Table 3

Mission analysis results

Platform	Power [W]	100% chemical propulsion spacecraft: Launch mass [kg]	Dry mass [kg]	Dry mass of prop. unit [kg]	Dry mass w/o prop. unit [kg]	100% electric propulsion spacecraft: Thruster	N of thrusters (main+spare)	Xenon for transfer [kg]	Xe for station-keeping [kg]	Dry mass [kg]	Final mass (GEO, BOL)	Min. transfer time [d]
STAR 1	1700	1600	688	103	585	SPT-100	1+1	41	42	612	653	57
STAR 2	5000	2300	989	147	842	SPT-140	2+2	145	63	933	996	66
HS 376HP	1400	1600	688	103	585	SPT-100	1+1	32	41	609	650	67
HS 601	3000	2800	1204	180	1024	SPT-140	1+1	174	74	1091	1165	175
HS 601HP	5800	3600	1548	231	1317	SPT-140	2+2	328	98	1441	1538	174
HS 702	14000	5200	2236	333	1903	SPT-140	4+4	925	149	2191	2340	195
FS 1300	4800	3100	1333	199	1134	SPT-140	2+2	230	84	1238	1322	145
FS 1300HP	7600	3600	1548	231	1317	SPT-140	2+2	305	98	1447	1545	115
A2100	4500	2750	1182	176	1006	SPT-140	2+2	178	75	1100	1175	120
A2100AX	8500	3750	1612	241	1371	SPT-140	3+3	340	104	1531	1635	118
Eurostar 1000	1200	1900	817	122	695	SPT-100	1+1	50	49	721	770	143
Eurostar 2000	6500	3200	1376	205	1171	SPT-140	2+2	217	87	1282	1369	100
Eurostar 3000	8000	5000	2150	321	1829	SPT-140	3+3	402	136	1998	2134	150
Spacebus 1000	1500	1500	645	96	549	SPT-100	1+1	36	39	573	612	43
Spacebus 2000	3500	2500	1075	160	915	SPT-140	1+1	126	66	976	1042	110
Spacebus 3000	13000	4000	1720	257	1464	SPT-140	4+4	396	114	1674	1787	99
Spacebus 4000	20000	6000	2580	385	2195	SPT-140	6+6	1366	178	2615	2792	210
BCP 4000	1500	2100	903	135	768	SPT-100	1+1	71	54	799	853	177

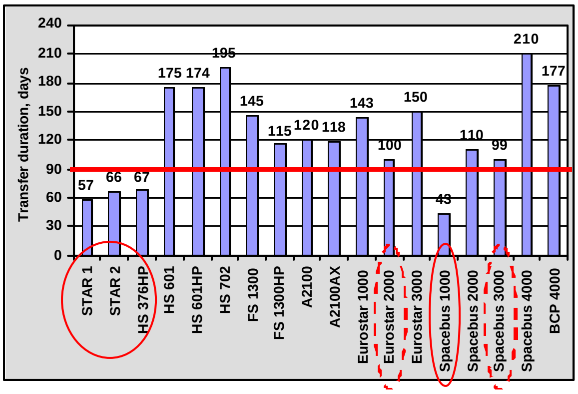

Fig. 4. Duration transfers to GEO

SC mass, delivering in GEO, versus transfer duration is presented in the Fig. 5 (*Soyuz*/FG LV, *SPT-140* option).

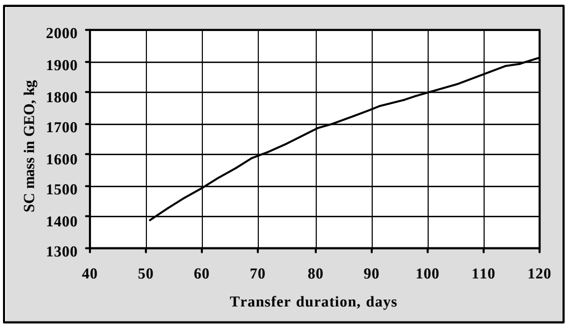

Fig. 5. *Spacebus 3000* performance

SC trajectory to GEO, orbital parameter evolution during the transfer, and thrust steering is shown in the Figs. 6-8.

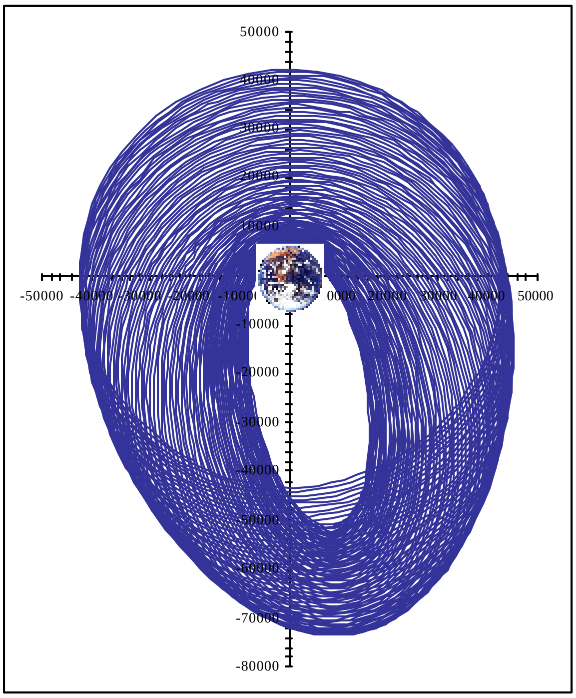

Fig. 6. *Spacebus 3000*: trajectory to GEO

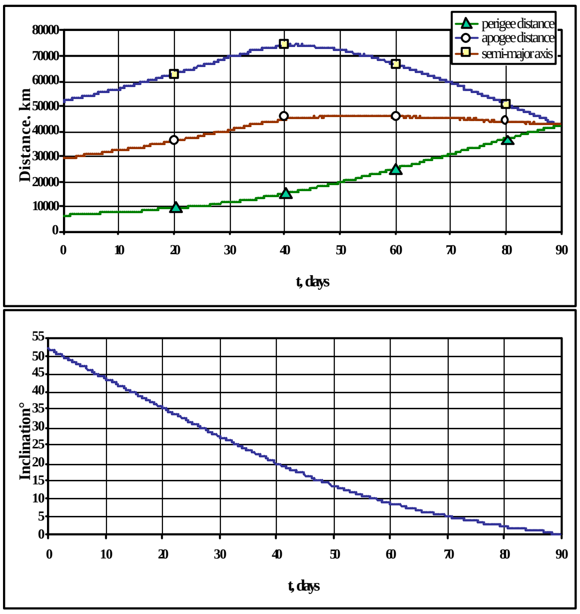

Fig. 7. *Spacebus 3000*: orbital parameters evolution during transfer to GEO

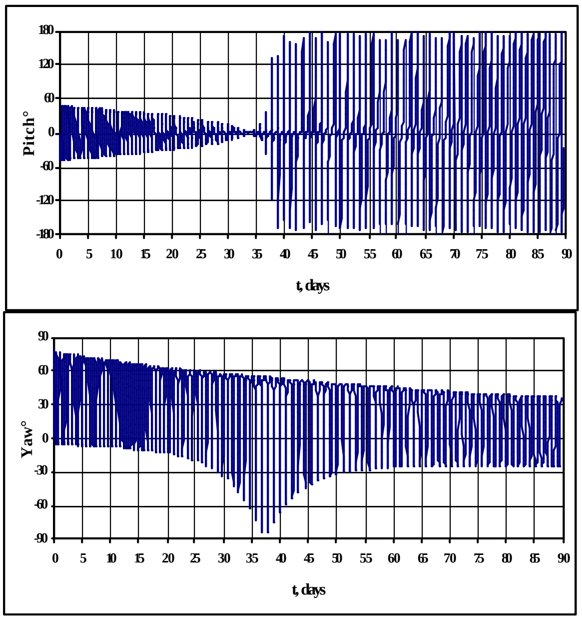

Fig. 8. *Spacebus 3000*: optimal thrust steering

Eurostar 2000 space platform

Launch vehicle

LV version *Soyuz*/FG
Insertion using *Fregat* first burn
(*Fregat* separation velocity 7500 m/s)

Electric propulsion unit

Number of thrusters	2 SPT-140 (+2 spare)
Consumed electric power	6300 W

Intermediate orbit

Apogee altitude	78500 km
Perigee altitude	2488 km
Inclination	29.785°
Initial spacecraft mass (in the intermediate orbit)	1588 kg
Fregat ChUS flight duration	15 hours

Table 5

***Fregat* burn No.**	**Fuel consumption**
1	707 kg
2	4282 kg
3	295 kg
Total	5284 kg

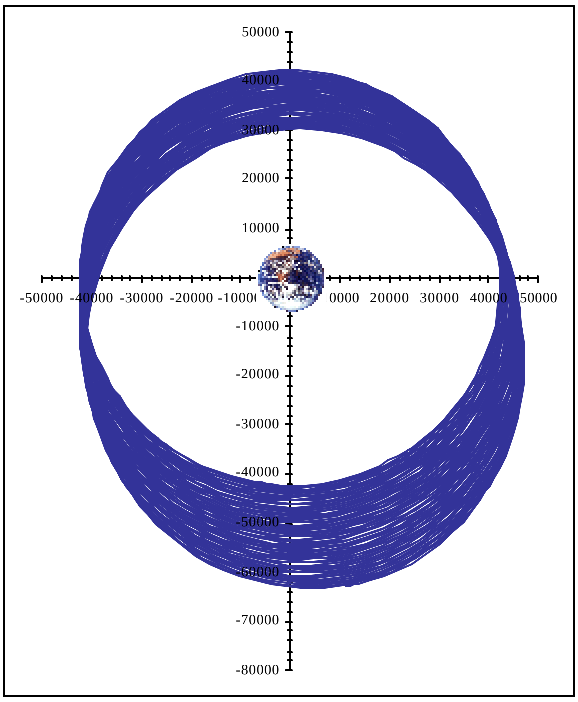

Fig. 9. *Spacebus 1000*: trajectory to GEO

Electric propulsion phase

Transfer duration 99.14 days

Spacecraft mass in the GEO

nominal 1383 kg

taking into account

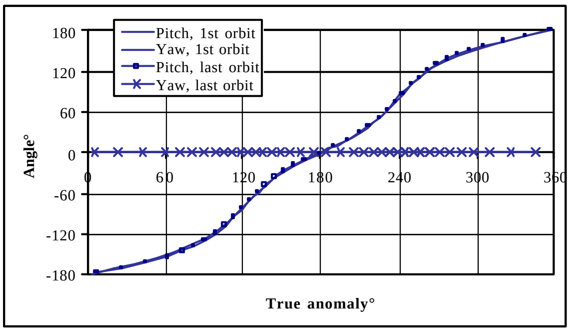

Fig. 10. *Spacebus 1000*: optimal thrust steering

5% margin of xenon 1373 kg

Dry mass 1285 kg

Required dry mass is 1283 kg. So the space platform *Eurostar 2000* can be inserted into GEO by the use of the considered transport space system for 99 days.

<u>*Spacebus 1000* space platform</u>

Launch vehicle

LV version *Soyuz*/FG

Direct insertion into the parking orbit

Electric propulsion unit

Number of thrusters	1 SPT-100 (+1 spare)
Consumed electric power	1300 W

Intermediate orbit

Apogee altitude	57500 km
Perigee altitude	23744 km
Inclination	0°
Initial spacecraft mass (in the intermediate orbit)	711 kg
Fregat ChUS flight duration	11 hours

Table 6

***Fregat* burn No.**	**Fuel consumption**
1	3916 kg
2	1113 kg
Total	5029 kg

Electric propulsion phase

Transfer duration 86 days

Spacecraft mass in the GEO

nominal	678 kg
taking into account	
5% margin of xenon	676 kg
Dry mass	633 kg

Required dry mass is 573 kg. Therefore the communicational payload of this space platform can be increased by 60 kg.

Optimal low-thrust trajectory and corresponding thrust steering are shown in the Figs. 9-10. In this case deviation of optimal thrust direction does not exceed 30° with respect to the fixed averaged vector.

STAR 2 space platform

Launch vehicle

LV version	*Soyuz*/FG
Direct insertion into the parking orbit	

Electric propulsion unit

Number of thrusters	2 SPT-140 (+2 spare)
Consumed electric power	4800 W

Intermediate orbit

Apogee altitude	74000 km
Perigee altitude	5844 km
Inclination	16.835°
Initial spacecraft mass (in the intermediate orbit)	1223 kg
Fregat ChUS flight duration	14 hours

Table 7

Fregat burn No.	Fuel consumption
1	4011 kg
2	506 kg
Total	4517 kg

Electric propulsion phase

Transfer duration	83 days
Spacecraft mass in the GEO	
nominal	1092 kg
taking into account	
5% margin of xenon	1085 kg
Dry mass	1016 kg

Required dry mass is 933 kg, so communication payload can be increased by 83 kg.

SPT and *XIPS* comparison

In a Fig. 11 and 12 the results of the comparative analysis of possibility of using of Hall thrusters (*SPT*) and ion thrusters (*XIPS*) for investigated transportation are submitted. As a rule, at the use of *XIPS* (with more higher specific impulse, but smaller thrust) the optimal parameters of insertion into geostationary orbit change as follows:

- The optimal fueling of the chemical ChUS is augmented; the demanded mass of a xenon is decreased;
- The characteristics of an optimal intermediate orbit become more close to the characteristics of geostationary orbit. In particular, its inclination is being decreased.

For all considered transport maneuvers of the ascent of space vehicle into geostationary orbit the stiff (high) price of thrust of ionic engines results in deterioration of efficiency (basic indexes of the insertion) at their usage. Moreover, the optimum value of specific impulse of fixed plasma jets for many transfers into geostationary orbit is much less maximal acceptable values and seldom exceeds 20 km/sec.

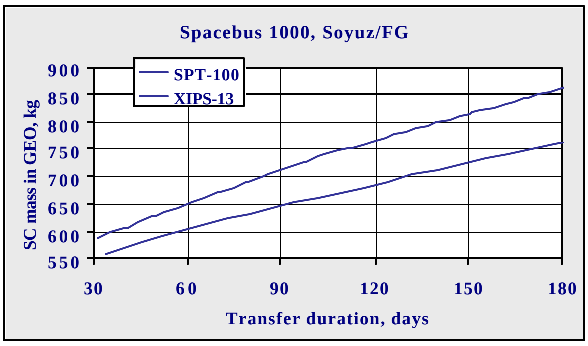

Fig. 11. *SPT-100* and *XIPS-13* comparison

In a Fig. 11 mass injected into geostationary orbit as a function of insertion duration of a space platform *Spacebus 1000* is presented. The upper curve corresponds to a case of *SPT-100* using, the lower curve corresponds to *XIPS-13*. It is visible, that at the use of *XIPS-13* injected mass is much less than injected mass at *SPT-100* using. For example, at insertion duration 120 day the use of *XIPS-13* allows to insert a space vehicle of mass 685 kg. The use of *SPT-100* increases this mass up to 765 kg (approximately on 80 kg).

In Fig. 12 mass injected into geostationary orbit as a function of insertion duration of a space platform *Spacebus 3000* is presented. The upper curve corresponds to case of *SPT-140* using, the lower curve corresponds to *XIPS-25* using. It is visible, that at the use of *XIPS-25* injected mass is

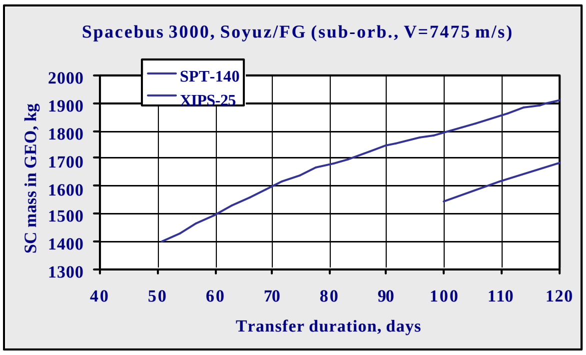

Fig. 12. *SPT-140* and *XIPS-25* comparison

much less than injected mass at *SPT-140* using. For example, at insertion duration 100 day the use of *XIPS-25* allows to insert a space vehicle of mass 1550 kg. The use of *SPT-140* increases this mass up to 1800 kg (approximately on 250 kg).

CONCLUSION

- *Soyuz*/*Fregat* launch vehicle provides the insertion of satellite into GEO using solar electric propulsion. The transfer duration of some commercial available space platforms is small enough. For example, the transfer duration of space platform STAR1 is equal to 57 days; STAR2 - 66 days: HS 386HP - 67 days; Eurostar-2000 - 100 days; Spacebus-1000 - 43 days; Spacebus-3000 - 99 days.
- The using of highly elliptical intermediate orbit, which apogee altitude exceeds the GEO altitude, is optimal for many space platforms.
- The *Soyuz*/FG LV using is more preferential. But if the fairing of the *Soyuz*/ST LV is required, then this version of launcher can be used too. The increase of the transfer duration will be small enough. For example, the duration of the STAR 1 transfer will be increased from 57 days up to ~60 days; the duration of the Spacebus-3000 insertion will be increased from 99 days up to ~104 days.
- The using of a sub-orbital trajectory is expedient in some versions of the insertion into GEO, especially for large SC. The using of a nominal mission profile, provided by *Soyuz* 3rd stage, is rational for small space platforms.
- The optimal *Fregat* ChUS fueling is equal to 4500.. 5350 kg. This value is very close to maximal mass of the active fuel of "*Fregat*". Therefore usage of a

space system *Soyuz*/*Fregat*/SC's solar electric propulsion is effective for considered space maneuvers.

- The using of SPT is preferential for all reviewed space platforms. The using of XIPS results in increase of the transfer duration. For example, for Spacebus-1000 the transition from SPT-100 to the XIPS-13 increases the transfer duration from 43 days up to about 65 days.

REFERENCES

1. Olesen S.R., Myers R.M., Kluever C.A., Riehl J.P., Curran F.M. *Advance Propulsion for Geostationary Orbit Insertion and North-South Station Keeping.* Journal of Spacecraft and Rockets, Vol. 34, No. 1, January-February 1997.
2. Schwer A.G., Schottle U.M., Messerschmid E., *Operational Impacts and Environmental Effects on Low-Thrust Transfer-Missions of Telecommunication Satellites.* 46th International Astronautical Congress. IAF-95-S.3.10. Oslo, Norway, 1995.
3. Spitzer, A., *Novel Orbit Raising Strategy Makes Low Thrust Commercially Viable.* 24th International Electric Propulsion Conference, IEPC 95-212, Moscow, Russia, 1995.
4. Saccoccia G., Gonzalez J. *Electric Propulsion Technologies Comparative Analysis: Application to Current and Future Space Mission.* 30th AIAA/ASME/SAE/ASEE Joint Propulsion Conference. AIAA-94-2860, Indianapolis, June 1994.
5. Fedotov G., Kim V. Konstantinov M., Petukhov V., Popov G. *Estimation of optimal combination of chemical upper stage and solar stationary plasma propulsion for the geostationary transfer.* 47th International Astronautical Congress. IAF-96-S.3.09. Begin, China, 1995.
6. Konstantinov M., Kim V., Scortecci F. *Investigation of a Fully Integrated Solar Stationary Plasma Propulsion System for Geostationary Orbit Insertion,* IEPC-97-157, Cleveland, Ohio, USA, 1997.
7. Konstantinov M., Popov G., Fedotov G. *Estimation of possibility of using of stationary plasma thrusters M100…M200 for insert into working earth orbits.* 49th International Astronautical Congress. IAF-98-S.4.06. Melbourne, Australia, 1998.
8. Medvedev A., Khatulev V., Yuriev V., Petukhov V., Konstantinov M.S. *Combined flight profile to insert telecommunication satellite into geostationary orbit using "Rockot" light-weight class launch vehicle.* 51st International Astronautical Congress. IAF-00-V.2.09, Rio-de-Janeiro, Brasilia, October 2-6, 2000.