Pulsed Plasma Thruster Propulsion Technology for Small Satellite

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Abstract

Ablative Pulsed Plasma Thrusters (APPT) is attractive electric propulsion device for Small Spacecrafts (SSC) due to its simplicity, low mass, appropriate power level, high I_{sp} and low cost. Paper presents the results of estimates of APPT propulsion system application for Earth observing (EO) constellation based on eight 350 kg in mass satellites with orbit range 500-900 km. PPT technology shows the high competitiveness among another small propulsion systems developed for SSC orbit control (translational maneuvers, orbit maintenance and positioning). Estimated total impulse for producing all types of orbit maneuvers for SSC having 7- years service life is 77 kNs. For precision orbit correction necessary thrust impulse has appeared at the level of 0,1 Ns. Estimated propulsion system dry mass containing 2 APPT-150 and 2 APPT-70 is approximately 17 kg. The total propellant consumption is 4,3 kg. The danger of contamination of SSC and it functional instrumentation is tested for APPT-150. It is observed decreasing of an integral transparency of optical devices in visible area of a spectrum during APPT-150 service life will not exceed 2,5 % that much lower than effect of space factors. Inductive electromagnetic disturbances created by APPT-150 firings, have not dangerous value.

Introduction

Last years, SSC constellations exhibit great interest due to rather low cost their development and manufacturing, as well as price reduction of orbital injection [1-3]. Quite a number of small satellite LEO constellations (e.g. Globalstar, 48 satellites, 500 kg in mass; Vulkan, 24 satellites, 250 kg in mass; Gonets-2, 24 satellites, 350 kg in mass etc) are now under development or have reached an advanced stage of mission definition. Application field of small satellites is wide enough and includes communication, navigation, meteorology, Earth observing and environmental control etc. Now, the concept also arisen to supplement available terrestrial means of the prevention of natural and technical catastrophes by space monitoring and near-term forecast. The selection of APPT for SSC orbital control became possible due to considerable progress reached in Russia in researches and development of the competitive APPT [4 - 6]. High efficient APPT has number modifications in range of stored energy from 30 J up to 150 J. It is capable to produce translational maneuvers, orbit maintenance and positioning LEO and GEO small satellites (50-500) kg in mass [7, 8]. Now in Russia the decision about manufacture PPT propulsion system at energy level $(100 \div 150)$ J is made. Paper presents mission description, choice of propulsion system and results of estimates of PPT propulsion system usage for Russian SSC constellation having orbits 500 km and 900 km with 350 kg of spacecraft mass.

Mission Description

Considered SSC constellation is aimed to Earth observing and space monitoring as well as near-term forecast of any large-scale catastrophes. Some possible versions of the SSC constellation creation were considered. The preliminary analysis has shown, that this constellation should be sun – synchronous, stacked, and multi-planar with orbits having stable routes, with latitudinal stability of an altitude. Also it is assumed, the constellation should have minimal number of satellites with mass minimized for low cost launchers. As a result, the version with two SSC placed in Russian launcher STRELA is accepted. In considered version four SSC 350 kg in mass each should be injected into SSO orbits, with altitudes 500 (2 SSC) and 900 km (2 SSC) by the launcher STRELA. SSC constellation represents 2-altitude 8-planar structure containing 4 SSC in each altitude (SSO, 500 and ~ 900 km). Considered orbits have, latitudinal stability of an altitude with an effective range of its change relating to the ascending node of $\Delta H = H_{\Omega\,-2}^{\;+25}$ km.

The launcher STRELA has injection accuracy for the cycle time up to ±4 s, for the altitude ±7 km and for the inclination ±2'. Initial correction for an altitude and inclination is not required. The main mission requirements are given in Table 1.

Table 1. Mission requirements.

Mission duration	7 years
Orbit	LEO circular sun-synchronous
Orbit altitudes	500 km, 900 km
Orbit plane inclination	97 deg for 500 km, 99 deg for 900 km
Maximal orbit injection errors (due to launch)	±7 km on nominal altitude ±0.1 deg on nominal inclination
Number of satellites	8 (4+4)

Power capabilities of Russian launcher STRELA allow to launch spacecraft of 1030 kg in mass on an altitude of 500 km, spacecraft of 780 kg in mass on an altitude of 900 km. Taking into account mass of the connector block of 2 SSC at batch launch, output mass of each SSC in this case makes 365 kg. In each altitude the orbital planes of four SSC are uniformly spaced apart with a step of 45°. The scheme of arrangement of routes of a 2-altitude 8-planar constellation, having 4 SSC in each altitude is shown in Figure 1.

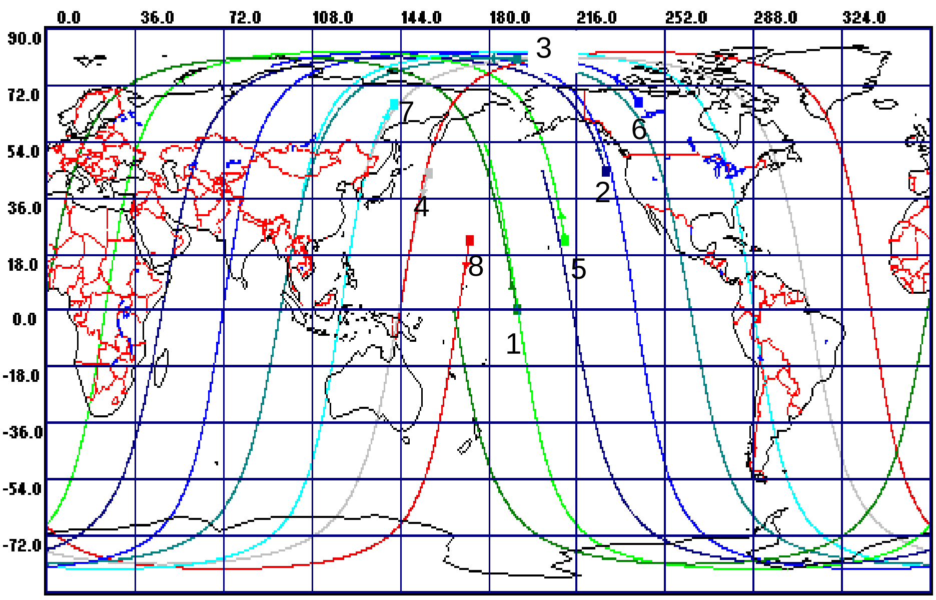


Figure 1. SSC Routes; 1-4 correspond the altitude of 900 km,. 5-8 correspond the altitude of 500 km.

The required power, times for correction of centers of SSC mass, included in a system structure were determined outgoing from the given version of SSC constellation. The basic SSC characteristics are listed in Table 2.

Table 2. Spacecraft characteristics

Mass	350 kg
Payload	130 – 150 kg
Length L (velocity direction)	1200 mm
Width W Height	1200 mm 980 mm
Solar array surface Average power	➢ 7.5 m2 ➢ 490 W
Ballistic coeff.	0.05 $m^3 kg^{-1} c^{-2}$
Injection to working orbit	Batch, 2 SSC, Launcher STRELA

The SSC appearance scheme with propulsion system is shown in Figure 2.

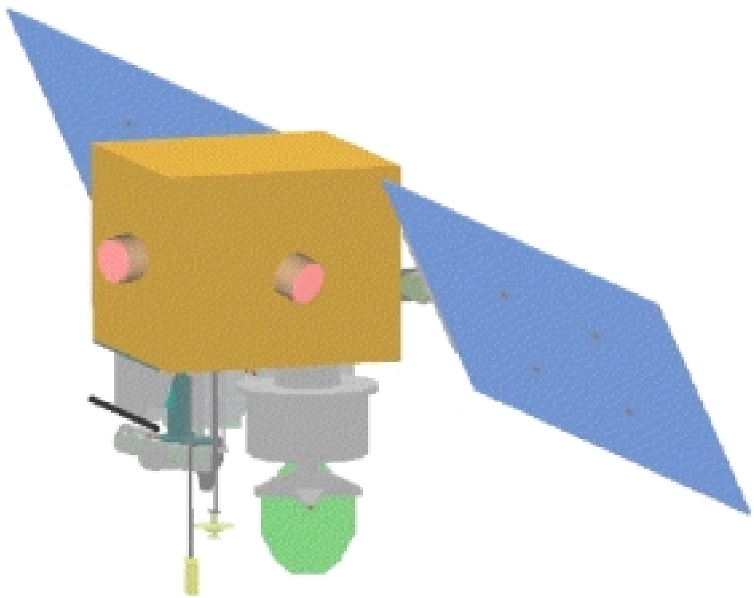


Figure 2. Drawing of spacecraft. 2 thrusters of 4-th are visible.

Constellation orbit control requirements

The total thrust impulse I_Σ =77 кNs is necessary for SSC orbit control during 7 years service life. According to Table 3 the following control tasks for SSC constellation to be solved: initial correction, phase equalization, orbit inclination and altitude maintenance for SSC constellation.

Table 3. Orbit control tasks

Orbit altitude	Total thrust impulse, kNs				
	Initial correction			Maintenance during 7 years	
	Δ H	Δi	Δφ	ΔH	Δi
H = 500 км	–	–	3,2	53,3	20,2
H = 900 км	–	–	3,2	1,14	20,2

The correcting maneuvers for altitude, inclination, and phase are calculated under following conditions: the correction schedule of altitude was calculated for an index of solar activity $F_{10,7}$ = 200 $10^{-22} W\ m^{-2} Hz^{-1}$; the correction of inclination is produced for maximum change of inclination equal 3′ annually on two symmetrical segments in range ±60° in a neighborhood of ascending and descending nodes. The phase equalization is produced with the help of misalignment of periods from nominal on 10 s with the subsequent tuning of a phase to 90° for each SSC. In Table 4 the expected schedule of corrections during SSC service life and value of firing time are shown.

Table 4. Schedule of orbit corrections, value of firing time

Corrections	Initial $\Delta\varphi$	Maintenance		
		ΔH		Δi
Number of corrections	Up to 10 days	H= 500 km One correction per day	H= 500 km One correction per month	Two correction per month
Firing time		1.7 hour	One hour	10 hours.

Orbit Correction Propulsion System (OCPS)

A number of serious limitations are implied on OCPS parameters by features of the considering SSC design, conditions of it operation and solving tasks:

- Limitation on power consumption (100 W);
- Limitation on mass (25 kg);
- Limitation on a minimum impulse bit, which is capable to supply given accuracy of orbit maintenance (0,1 Ns).

SSC small sizes and mass and, therefore, capabilities of power supply and arrangement of on-board equipment stipulate the first two limitations. The limitation on an impulse bit is called by high accuracy requirements to maintenance of cycle time of each SSC, which should be supported to within 0,001 s.
The total calculated impulse necessary for SSC initial correction, constellation formation and orbit maintenance is equal $P_{\Sigma}\approx 77$ kNs. The total impulse needed for maintenance of an SSC orbital altitude is 53,3 kNs. High value of characteristic velocity of the SSC ($\Delta V \sim 220$ m/s), causes to prefer thrusters with high specific impulse (not less than 1000 s), that allows to reduce noticeably propellant mass and mass of whole propulsion system.
Comparative analysis for different OCPS options was made with account of given limitations.

In Table 5 the parameter of thrusters, which possibilities were analyzed are shown.

Table 5. Thruster parameters

#	Thruster	Impulse bit, Ns	Specific impulse, s	Propellant mass, kg
1	Hydrazine thermo-catalytic thruster	5	220	35
2	Two-component small–size thruster	1	280	27
3	BHT-200 (100 W operating power)	$4{,}0\cdot10^{-3}$	800	9,6
4	High eff. APPT - 150 J (100 W operating power)	$3{,}5\cdot10^{-3}$	1900	4,3

It is seen from the Table 5 that first two from considered thrusters have a too high impulse bit and consequently do not meet the requirements to the orbit correction PS on accuracy of cycle time maintenance. Besides, these thrusters exhibit too low specific impulse and, accordingly, excessive propellant flow rate. This does not allow examine them as perspective thrusters for usage in considered SSC. Advantages of high performance electric propulsion systems are now recognized and these new technologies have been accepted for development of new devices.

The Hall thruster BHT-200 [8], developed by Busek Co. Inc. (USA) has parameters permitting to utilize it for considered SSC. However BHT -200 at power consumption of 100 W has insufficiently high average exhaust velocity of plasma that results in necessity to store up to 10 kg of a propellant. Evidently, that mass of a propulsion system on the basis of 4 x BHT -200 will exceed an established limit in 25 kg.
As to modification of BHT -200 operation in pulse mode [9], at duration of an impulse up to 50 ms (case estimated in [9]) the thruster has a low specific impulse (~ 0,5 mNs). Accordingly, it will be required up to 10^8 firing for SSC orbit maintenance. It does not allow to provide proper reliability of the OCPS. Problem could be decided with considerable increasing of discharge duration. However a number of other problems occurs, connected with such kind performance of BHT –200 modification. One of them is increasing of the propellant flow rate in Pulsed BHT compare with stationary one. It leads to operating inefficiency of the OCPS based on this thruster.
Developed in Russia and existing in different modifications APPT allows to realize orbit control tasks for considered SSC constellation.
Last years a considerable progress in development of the competitive Ablative Pulse Plasma Thrusters (APPT) with side feed of a propellant was reached [4]. APPT is able to decide the majority of the orbit control tasks with SSC (50 - 500) kg in mass [7]. Progress in APPT performance is illustrated in Figure 3, where dynamics of thrust efficiency and specific impulse increase for last 5 years are shown.

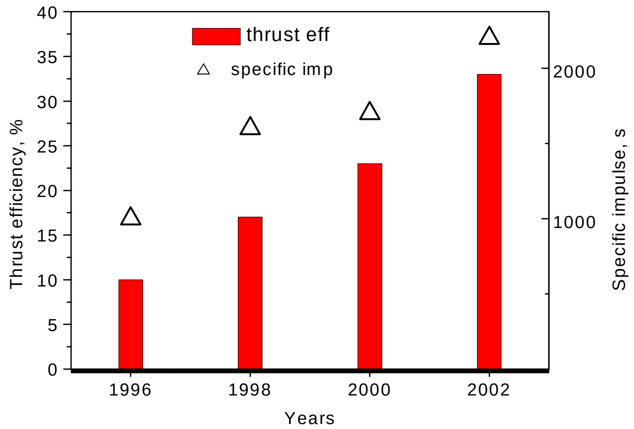


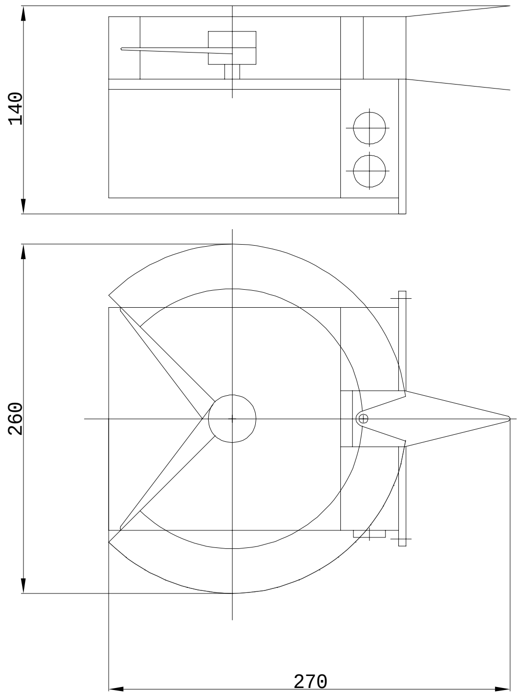
Figure 4. Progress in development of APPT with side-feed propellant for the last 5 years. Parameters of APPT, with bank energy equal 150 J.

The obtained results allow APPT to be used in orbit correcting propulsion systems (OCPS) for different LEO and GEO SSCs.
In [10] a number of small thrust OCPS used for constellation orbit formation and maintenance were analyzed. It is shown that APPT is mostly effective for 250 kg EO SSC constellation deployment and long-term orbit maintenance on 500 km orbit. Moreover APPT is generally robust device, having most low cost among another thrusters. High efficiency and the service performance, as well as low cost of APPT attract the interest of a number of Russian corporations - developers SSC. It concerns, in particular, considered below LEO EO SSC constellation, because such king of systems often require high accuracy for their orbit control.
For the solution of the most power consumable tasks of orbit altitude maintenance the APPTs with 150 J bank energy can be successfully used. For the task of orbits correction (inclination and phase) thrusters with bank energy 70 J (APPT-70) are planned. A feature of considered propulsion system based on four APPTs is only two capacitors will feed four APPTs. One capacitor is used for a feed of two APPT-150, other for a feed of two APPT-70. The total quantity of firings per each capacitor will make $(1 – 1,2)\cdot 10^7$ that satisfy the requirements on reliability.
As the thrusters should mutually place on the counter SSC walls, the layout of SSC will be utilized, at which pair thrusters directly connected with capacitor. One is placed near capacitor, the second discharge channel established apart, up to one meter from first with usage of the low-impedance floppy current bus. The bench test of such scheme of discharge channels layout has shown, that at length of the current bus from 0,5 m up to 1 m, losses of thrust efficiency of the thruster do not exceed (5 - 10) %. Parameters of APPTs with stored energy 150 J and 70 J are given in Table 6.

For APPT-150 the maximal value of propellant mass necessary for the SSC orbit altitude maintenance is shown. For the thruster performing mutual phase correction, the consumption of a propellant will not exceed 0,15 kg.

Table 6. APPT-150 and APPT-70 parameters.

Thruster	Bank energy, J	Impulse bit, 10^{-3}, Ns	Specific impulse, s	Thrust efficiency	Capacitor mass, kg	Thruster dry mass, kg	Propellant mass per thruster, kg	Number of firings
APPT-150	150	4,5	2000	0,30	5	7,5	2,8	$1{,}1\cdot10^7$
APPT-70	70	2,2	1500	0,23	2,8	4,85	0,75	$0{,}45\cdot10^7$



The OCPS consisting of 4 thrusters will have mass close on 21 kg at dry mass near 17 kg.
In Figure 4 the dimensional scheme of APPT-150 for SSC orbit maintenance is presented.

Figure 4. Dimensional scheme of APPT-150 with single-block energy storage

APPT-150 propellant is placed and moves to a discharge channel by a conventional way for side – feed thrusters. Two Teflon bars are moved to a channel by a spring. At selected geometry of discharge channels the diameter of Teflon propellant bars for APPT-150 and APPT-70 will make accordingly 260 mm and 180 mm that is represented by reasonable values.

In Figure 5, APPT-150 protoflight model with a single-block energy storage intended for phase equalization is shown. APPT-70 is made under the similar scheme, however its energy storage consists of 4 capacitors.

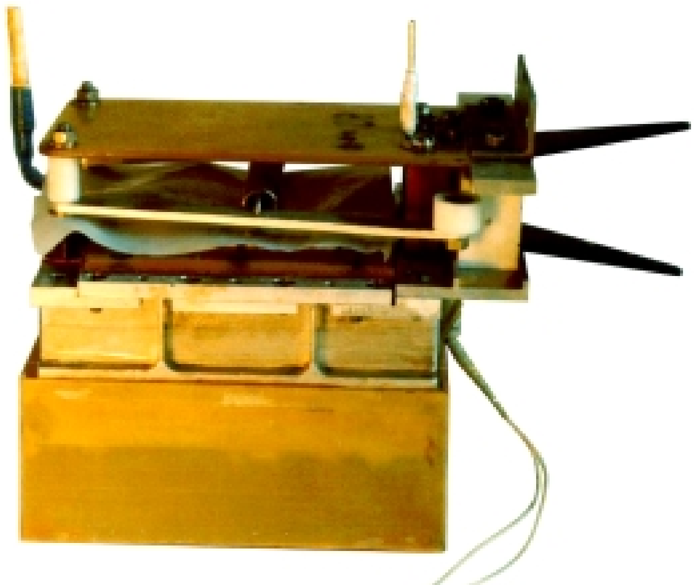


Figure 5. APPT-150 protoflight model

APPT-150 bench tests

PS layout versions considers arrangement of APPT-150 in immediate proximity from solar array, that can results in gradual lowering of their efficiency because of a deposition of carbon onto protective coatings and decreasing of their transparency. Though high efficiency APPT has a very good focusing of a plasma jet (total angle of a plasma jet expansion does not exceed 30°), nevertheless insignificant part of propellant flow after of the electrical discharge termination leaves an accelerating channel with thermal velocities, thus the angle of expansion of a jet makes more than 180°. This part of a flow can pollute neighboring surfaces of SSC, including surfaces of solar batteries.

The danger of contaminating of SSC and its functional instrumentation is mostly real. For this reason a bench tests of APPT-150 have been produced to study contamination of an optical instruments and protective coatings of solar batteries.During tests APPT was placed in vacuum chamber. The quartz glass plates were placed around, their transparency was determined prior to the experiment. A screen receiving a considerable amount of carbon environs the discharge channel of APPT. This screen protects construction items and instrumentation, located near the thruster. The similar screen will be used in the space conditions.Loss of quartz transparency after several thousand of firings was determined by the spectrometer.

The carbon fluxes in neighborhoods of the thruster were estimated with usage of a computational model [11]. The model allows estimating flows of any substance (in this case carbon) on any place, arbitrary oriented relating to discharge channel and change of optical behavior of coatings for any firings. It is established, that the contaminating of optical coatings located parallel plasma flow in a distance of 0,5 m from a channel, for $\sim 1{,}1 \cdot 10^{7}$ firings (full operating time of APPT-150, located near to a solar battery) does not exceed $2{,}5 \cdot 10^{-6}$ g/cm^2. The decreasing of an integral transparency of optical devices in visible area of a spectrum during operation APPT-150 will not exceed 2,5 %. Apparently, that for 7 years of SSC operation, the degradation of a solar battery protective coating will appear much greater under the effect of space factors.

In the same series of experiments the problems, connected with APPT electromagnetic compatibility with SSC sensing instrumentation were studied. It was established, that the electromagnetic radiation from plasma in the gigahertz and megahertz frequencies range have low intensity and do not introduce a danger to the relevant instrumentation. The most intensive oscillations in APPT plasma are the oscillations of magnetic field, and their maximum amplitude is low and does not exceed (1 - 3) A/m. Such oscillations do not introduce severe danger to reference instrumentation of SSC.

Conclusion

Earth observing (EO) constellation based on eight 350 kg in mass satellites with orbit range 500-900 km have been described. SSCs will be injected into SSO orbits by the launcher STRELA. The following tasks for SSC constellation to be solved: initial correction, phase equalization, orbit inclination and altitude maintenance. The total thrust impulse I_{Σ} =77 κNs is necessary for SSC orbit control during its service life.

The possibilities of a different types thrusters for the orbital control LEO SSC constellation with spacecraft mass equal 350 kg have been analyzed. It is shown, that due to last years APPT R&D rational characteristics for single SSC orbit maintenance and SSC constellation formation have been obtained. Mass of propulsion system based on 2APPT-150 and 2APPT-70 will be of 21 kg. APPT has inherent to it robust design, low cost, that should essentially increase thruster competitiveness among other electric thrusters, considered, for orbit control of SSC.

The bench tests of APPT-150 have shown the possibilities of its space applications. During bench testing a number of problems of APPT integrating with SSC were studied:

- The possibility of APPT discharge channel mounting separately from capacitor without serious energy losses;
- Very good focusing of the high efficient APPT plasma jet (no more than 30^{o});
- The decreasing of an integral transparency of optical devices in visible area of a spectrum during APPT-150 service life will not exceed 2,5 % that much lower than effect of space factors.
- The inductive electromagnetic disturbances created operating APPT-150 are low-frequency ones. Only magnetic field component has noticeable, but not dangerous value, (no more than 3 A/m).

References

1. S. R. Oleson, Electric Propulsion For Low Earth Orbit Communication Satellites IEPC-97-148 914-921.
2. Electric Propulsion Activity in Russia, V. Kim, G. Popov, B. Arkhipov, V. Murashko, O. Gorshkov, A. Koroteyev, V. Garkusha, A. Semenkin, S.Tverdokhlebov, 27th International Electric Propulsion Conference, , IEPC-01-05, Pasadena, CA, USA, 2001.
3. V.P Khodnenko. Electric propulsion systems for spacecraft application and the methods of improving their effectiveness, Proc.Second European Spacecraft Propulsion Conference, 27-29 May, 1997, pp 321-325 (ESA SP-398, Aug. 1997)
4. N. Antropov, G. Diakonov, M. Orlov, G.Popov, V.Tyutin, V.Jakovlev, Yu. Alexeev, M.Kazeev, F.Darnon "High Efficiency Ablative Pulsed Plasma Thruster Characteristics", 3 rd International Conference on Space Propulsion, Cannes, France, 2000.
5.Garry Popov, Nikolay Antropov et al " Experimental Study of Plasma Parameters in High–Efficiency Pulsed Plasma Thrusters", 27-th IEPC, Pasadena, USA, 2001.
6. M.N. Kazeev, G.A. Popov, et al "Dynamics and Distribution of Electron Density in the Channel of Pulsed Plasma Thruster", 38-th JPC, Indianapolis, USA, 2002.
7. N.N. Antropov, G.A. Diakonov, A.I. Pokryshkin, G.A. Popov, M.N. Kazeev, V.P. Hodnenko "Pulsed Plasma Thrusters for Spacecraft Attitude and Orbit Control System", Applied Physics, № 1, 2002.
8. Jeff Monheizer, Viad Hruby et al "Development and Testing of a Low-Power Hall Thruster System", Micropropulsion for Small Spacecraft, Progress in Astronautics and Aeronautics, Vol. 187, p.p. 255-270, 2000.
9. Vlad Hruby, Bruce Pote, et al "Hall Thrusters Operation in Pulsed Mode", 27 th IEPC, Pasadena, USA, 2001.
10.G.A. Avatinyan, N.P. Shelkov, N.N. Antropov, G.A.Diakonov, V.N. Jakovlev "Orbit Correction Propulsion System Alternative for "Vulkan" Small Spacecraft", 3 rd International Conference and Exhibition Small Sattelites: New Technologies, Miniaturization Efficient Applications in the 21 th Century, Korolev, Moscow Region, Russia, 2002.
11. K.P. Kozubsky, V.I. Murashko et al “SPT operates in Space”, Physics of Plasma, V.29, №3, 2003.