

APPT Propulsion System for Small Satellites

IEPC-2005-111

*Presented at the 29th International Electric Propulsion Conference, Princeton University,
October 31 – November 4, 2005*

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Abstract: Paper presents data of EPS based on APPT with bank energy 30 J- 150 J. Main application considered for APPT based EPS are connected with LEO. Several LEO Missions using APPT based EPS as main spacecraft EPS for small satellites with mass at the level of 100 kg – 400 kg evaluated. Developed thrusters provide total impulse up to 50 kNs with specific impulse up to 2500 s. Analysis of some LEO Missions allows to outline the application area of EPS based on developed models and to select more adoptable ones for a number of applications. Developed in Russia APPT – 50 flight prototype allows to realize orbit control tasks for a number of SSC LEO missions. This thruster seems most universal for reviewed applications. Total impulse up to 50 kNs is achievable with use of high power APPT - 150 working in electrodynamic mode of operation. In this case propellant consumption will be at the level of 2 kg. Analysis shows that initial correction, phase equalization, orbit inclination, and altitude maintenance can be solved with APPT based EPS with significant mass saving.

Nomenclature

<i>EP</i>	=	electric propulsion
<i>EPS</i>	=	electric propulsion system
<i>APPT</i>	=	ablative pulsed plasma thruster
<i>LEO</i>	=	low Earth orbit
<i>SSC</i>	=	small spacecraft
<i>EO</i>	=	Earth observation

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SSO = Sun-synchronous orbit
 USP = universal space platform
 I_{total} = total impulse

I. Introduction

Pulsed Plasma thruster has more than 40-year history of the development and application. Ablative Pulsed Plasma Thrusters (APPT) were the first application of electric propulsion in space 40 years ago¹.

Last decade developments of APPT have resulted to appearance of high efficiency thrusters in energy range 30 J -150 J. These have different characteristics in total impulse, specific impulse, etc. Developed thrusters provide total

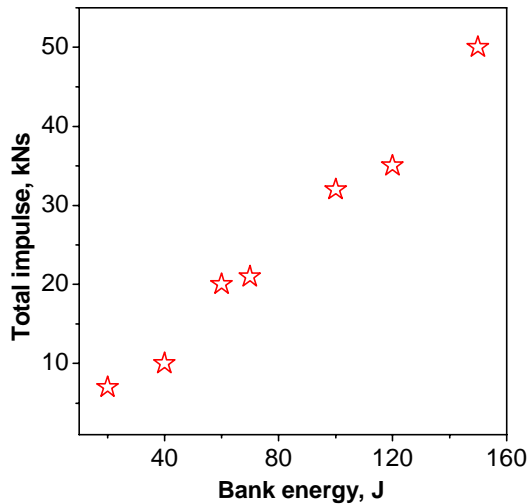


Figure 1. Total impulse – bank energy diagram (with reference to 10^7 firings). RIAME developed APPTs.

impulse up to 50 kNs with specific impulse up to 2500 s. Total impulse – bank energy diagram is shown in Figure 1. The fundamental operation of the APPT consists of repeated discharge pulses across a solid propellant surface. Useful thrust is produced by gas-dynamic and electromagnetic acceleration of the ablated mass that has been ionized. The applications ranged from control propulsion for larger satellites to primary propulsion for small satellites^{2,3,4,5}. Currently, APPTs are considered as an attractive propulsion option for stationkeeping and drag makeup purposes of mass and power limited satellites. High efficient APPT has number modifications in range of bank energy from 30 J up to 150 J with thrust efficiency from 15 to 40%. Total impulse of thruster reaches 50 kNs, thrust 0.9–4.5 mN, specific impulse (1-2.7) 10^3 s. It is capable to produce translation maneuvers, orbit maintenance and positioning LEO and GEO small satellites (50-500) kg in mass. SSC constellations exhibit great interest due to rather low cost their development and manufacturing, as well as price reduction of orbital injection. Quite a number of small satellite LEO constellations (Volcano 1” and “Volcano 2, Compass etc.) having SSC mass from 70 to 500 kg are now under consideration and

development in Russia. The selection of APPT for SSC orbital control became possible due to considerable progress reached in researches and development of the competitive APPT^{6,7,8}. Application field of SSC 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.

Paper presents data of EPS based on APPT with bank energy 30 J- 100 J. Several LEO Missions using APPT based EPS as main spacecraft EPS for SSC with mass at the level of 80 kg – 400 kg. evaluated. Analysis of some LEO Missions allows to outline the application area of EPS based on developed APPT models and to select more adoptable ones for a number of applications.

II. Missions

There are four programs in Russia aimed to the creation of SSC having on-board EPS at the level of 100 W. At present the decision is already accepted, that two SSC (“Volcano 1” and “Volcano 2”) will use EPS on the base APPT. SSC constellations “Volcano 1” and “Volcano 2” are developed on the base of small space platform having dry mass at the level of 150 kg – 180 kg. Estimated mass values of SSCs “Volcano 1” and “Volcano 2” make ~ 300 kg and 400 kg accordingly.

Table 1. Mission requirements

Mission	Volcano 1	Volcano 2	Compass	NPO Mash
Mission duration	5- 7 years	5- 7 years	5- 7 years (120 days)	5- 7 years
SSC mass, kg	300	400	85	170
Maximal/ mean power, W	100/20	100/20	55/10	-
Total impulse, kNs	22	22	16,7	10
Orbit	500 km, 900 km	500 km, 650 km	500>>800- 900km	500 km
Thruster	APPT-50	APPT-50	APPT-35	APPT-35
EPS weight, kg, dry/full	7/8.3	7/8.3	5/4	-

On-board EPS is required to perform initial correction of SSC orbits in an inclination and altitude, maintenance of SSC constellations within 5-7 years.

Maximum power allocated to EPS for the solution of the first problem is 100 W. The mean power ~ 20 W suffices for the solution of the second problem. Total impulse of a thrust needed for SSC is 22 kNs. Initial correction of SSC requires - 1,3 kNs during 45 day. Mission requirements for these application are shown in Table 1. Besides there are two projects of SSC development,

which developers have not accepted the final solution of SSC EPS type. At the preliminary stage they are seduced to APPT usage. These are: SSC development of NPO Mash and SSC development under "Compass" project of Makeev Design Office. Last project is aimed for SSC orbit transfer from 500 km to (800-900) km. APPT-35 developed in RIAME MAI is the promised candidate for the completing of last both projects.

Table 2. APPTs with stored energy 35 J, 50 J and 100 J

Bank energy, J	35	50	100
Working frequency	3	3	2
Thrust, mN	3	4.5	6
Total impulse, kNs max (1,5 10^7)	15	21.3	45
Propellant (Teflon) mass per thruster, kg	1	1.5	2
Impulse bit, mNs	1.3	1.7	2.7
Specific impulse, s	1300	1700	2200
Propulsion system dry mass, kg	4	6.5	9

50 J and 100 J are given in Table 2.

For the solution of the most power consumable tasks of orbit altitude maintenance the APPTs with 150 J bank energy can be successfully used. Total impulse up to 50 kNs is achievable with use of high power APPT -150 working in electrodynamic mode of operation. Operation frequency is 1 Hz.

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 to 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.

In⁹ 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 mostly 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 kind of systems often require high accuracy for their orbit control.

Parameters of APPTs with stored energy 35 J,

III. APPT Based EPS Applications

APPT with side feed of a propellant obtain a considerable progress in development of the competitive models¹³. Such APPT is able to decide the majority of the orbit control tasks with SSC (50 - 500) kg in mass. Analysis for the efficiency of pulsed plasma thrusters application as a part of SSC control system comparing to alternative EPS variants allows to highlight a total pulse range within which APPT secures the lowest mass loss for EPS. This exactly is one of the factors stipulating the limitation of the field of efficient APPT application as a part of a SSC control system from the mass criterion point of view.

Low thrust level is critical while selecting the electric propulsion for a number of tasks having limitations in the duration of maneuvers, providing final satellite injection into the operating orbit with the minimization of transfer time in particular. The period of final satellite injection into the orbit with the use of complete resource of one APPT module characterized by the number of operating cycles of up to $2 \cdot 10^7$ and pulse repetition frequency $f = 2$ Hz will be no shorter than months, and more than a year in the case of thruster operation with the frequency of 0.5 Hz.

EPS with the total pulse of up to $I_{total} = 100$ kNs – 200 kNs producing high characteristic velocity $V_{char} = 200$ m/s – 2000 m/s for SSC of 100 kg – 500 kg in mass allows to secure the solving of a rather broad range of SSC tasks with the execution of the following maneuvers:

- final injection of a small satellite into the operating orbit and its removal from the orbit in the end of the life-time;
- stationkeeping and keeping of structure for the constellations of low-orbit small satellites;
- correction for the geostationary small satellite keep point;
- aerodynamic drag compensation for the low-orbit Earth observation SSC;
- SSC attitude control.

Comparative analysis for the mass characteristics of propulsion systems on the basis of different EPS showed

that the APPT application with Teflon as propellant and modern level of EPS mass perfection allows to reduce the mass loss for propulsion system comparing to SPT and ion thrusters within the range of total pulses of up to $I_{total} < 100$ kNs – 200 kNs¹⁰.

As it was shown^{11,12,3} even a low effective APPT can be successfully used in a number orbital spacecraft mission applications. APPT use for final insertion of an Earth observing with the mass of 60 kg – 100 kg at the available power of 50 W – 300 W to increase the number of satellites launched by one firing. Effective APPT application may be expected in the tasks of prolonging the period of active life for the small satellites by compensating the aerodynamic drag and increasing the height of their operation using the pulsed

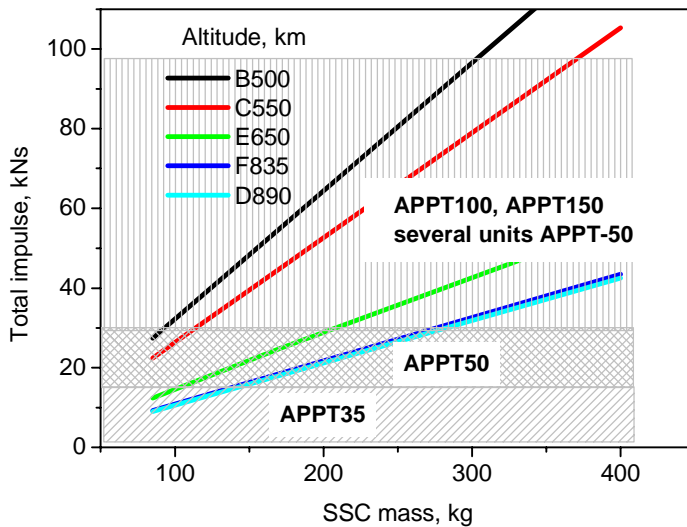


Figure 2. SSC Orbit maintenance using APPT based EPS (per one thruster)

plasma thrusters. For the precision keeping of relative distance (~1 cm for the distance of 10 km – 100 km) and attitude of three satellites with the mass of about 120 kg being the parts of constellation (Deep Space 3), it was proposed to use APPTs securing the required level of minimum pulses at high enough required total pulse ($I_{total} = 120$ kNs)³. The possibilities of APPT usage for orbit maintenance for different mass SSC are shown in Figure 2, presenting total impulse costs for different altitudes and SSC masses. Seems the limit of this application is near 500 km for SSO and 500 kg for more higher orbits.

IV. EPS Based on APPT-50

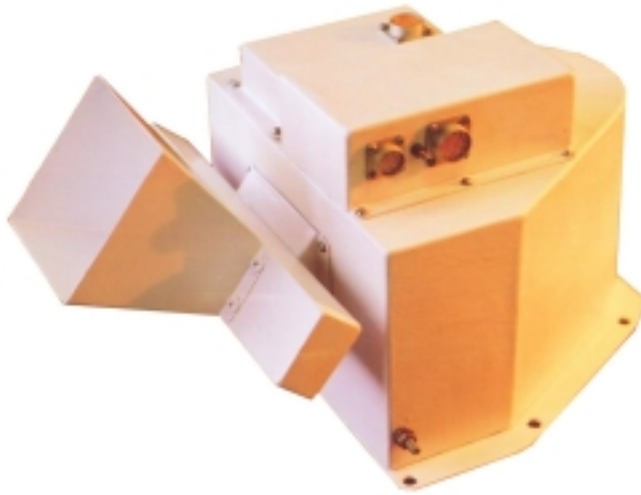


Figure 3. Mass-dimensional APPT-50 mock-up

should be supported to within 0,001 s. In¹⁰ a number of small thrust OCPS used for constellation orbit formation and maintenance were analyzed. It is shown that APPT is mostly effective for EO SSC constellation deployment and long-term orbit maintenance on 500 km level orbits. Moreover APPT is generally robust device, having mostly low cost among another thrusters. Developed in Russia¹³ APPT –50 flight prototype allows to realize orbit control tasks

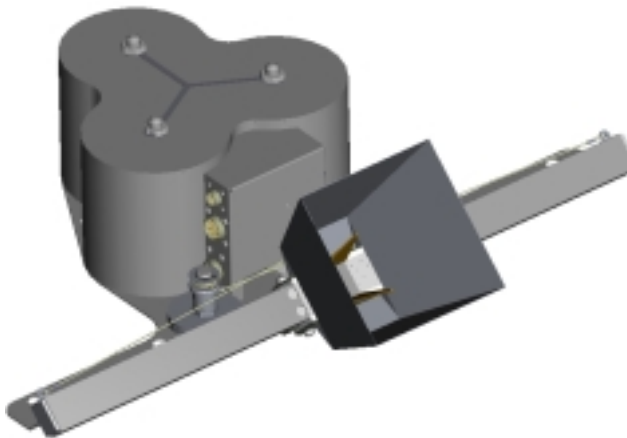


Figure 4. APPT-50 flight prototype

propellant consumption will be at the level of 4 kg. Operation frequency is 1 Hz thrust efficiency is 40%.

Table 5. APPT-50 characteristics

Bank energy, J	50
Power consumption, W	10- 110
Working frequency	0.2 -2
Thrust, mN	0.3 - 3
Thrust efficiency	25%
Total impulse, kNs max	21.3
Propellant mass per thruster, kg	1.5
Impulse bit, 10 ⁻³ , mNs	1.5
Specific impulse, s	1700
Propulsion system dry mass, kg	6.5

A number of serious limitations are implied on propulsion system by features of the SSC design, conditions of it operation and solving tasks: limitation on power consumption, limitation in mass, and limitation in a minimum impulse bit. 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 determined by high accuracy requirements to maintenance of cycle time of each SSC, which can be used for the solution of the more power consumable tasks of orbit altitude maintenance due to possibility of 2-3 Hz operation. The total quantity of firings per each capacitor will make (1–1,2) 10⁷ that satisfy the requirements on reliability. APPT-50 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. APPT-50 designed by RIAME for USP “Volcano 1” Parameters of APPT-50 are given in Table 5. Mass-dimensional mock-up and APPT-50 flight prototype developed in RIAME are shown in Figures 3, 4. USP platform “Volcano 1” is shown in Figure 5.

Total impulse up to 50 kNs is achievable with use of high power APPT -150 working in electrodynamic mode of operation. In this case

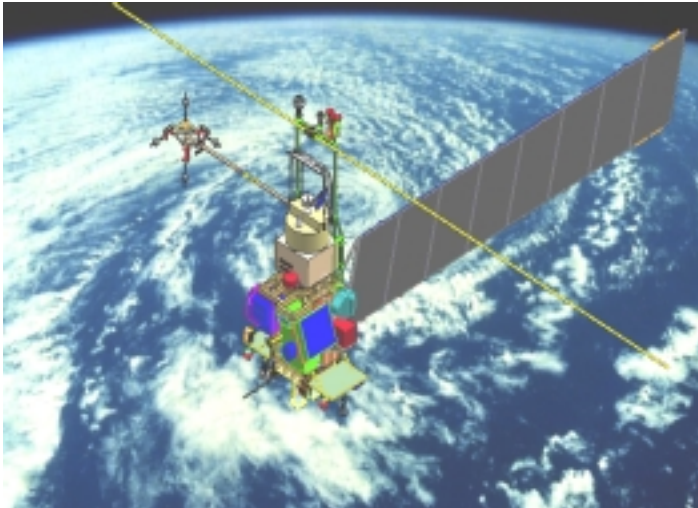


Figure 5. SSC “Volcano”

V. Conclusion

Last years a considerable progress in development of the competitive Ablative Pulse Plasma Thrusters (APPT) with side feed of a propellant was reached. APPT is able to decide the majority of the orbit control tasks with SSC (50 - 500) kg in mass. There are a few projects in Russia to apply APPT EPS in space. It is shown that EPS based APPT are capable to maintain SSC with orbits higher than 500 km and SSC mass up to 500 kg.

Modern APPTs are capable to provide total impulse at the level of tens kNs with thrust efficiency up to 40%. Three LEO Earth observing missions with SSO, covering 500 km – 900 km altitude were considered with SSC mass from 100 kg to 350 kg. APPT-50 based EPS is in the way to space tests.

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