PRESENT AND NEAR FUTURE APPLICATIONS OF SPT M 2 THRUSTERS

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Abstract

The SPT 100 and SPT M 2 are presently qualified and developed mainly for the orbit control of geostationary spacecraft. They offer new opportunities for several low cost space exploration programmes, while more powerful SPT offer the opportunity to develop large solar electric platforms. In low earth orbit, SPT offer a number of interesting applications: low power SPTs can be used for the automatic orbit maintenance of small satellites constellations, standard SPT for the drag compensations of earth resource spacecrafts and high power SPT for the drag compensation of manned space stations.

It is shown that the standard (80 mN) SPT can cover a wide range of applications and that three power levels are sufficient to cover most cases.

1. INTRODUCTION

Most of the ISTI effort is devoted to the development and qualification of a 80 mN class SPT subsystem for geostationary spacecrafts.

SPT 100 has been already life tested with great success showing an ability to deliver twice the required total impulse, the PPU is under qualification while SPT M 2 is under development at SEP and FAKEL for a first flight foreseen on STENTOR spacecraft in 1999.

It is worth remembering that the main reason for the introduction of SPT on geostationary spacecrafts is an economical one: the important weight gain allowed by SPT translates into large launch cost gains or, at equal launch weight, by more numerous repeaters, leading for much higher revenues.

This paper intends to show that this is true not only for geostationary spacecrafts but also for scientific missions and for low earth spacecrafts.

On the other hand, large SPT can deliver higher specific impulses than the 80 mN ones, it is then possible to devise very high energy missions with solar electric platforms simpler than the ones propelled by other types of ion thrusters.

In the field of low earth orbit spacecrafts, the recent trend toward constellations lead to a new problem: it is very difficult (and costly) to control numerous spacecrafts simultaneously. The use of SPT (and generally electric propulsion) owing to the low acceleration induced, allow to perform automatic and autonomous orbit control of each spacecraft, thus simplifying considerably the constellation control. For these constellations, cost is an obvious issue. Some redundancies can be traded off considering the overall constellation reliability. This lead to an extremely simplified SPT / PPU concept. On the other end of the mass scale, the space station drag compensation by SPT will allow to divide by a factor five the propellant mass needed and will not induce micro gravity disturbance during the propulsion phase.

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2. SMALL SCIENTIFIC MISSIONS APPLICATIONS

Many planetary missions or astrophysics missions require very high speed increment thus needing powerful launchers and dedicated launches, as far as chemical propulsion is concerned. This in turn induces a high cost; this is why scientific missions are not numerous.

It is of course possible to design a SPT based platform with a propulsive power of 5 to 10 kW (300 mN to 600 mN class), thus leading to exciting major scientific missions (Asteroid multiple rendez-vous, etc.), but, due to the high cost of such spacecrafts, it is felt that more affordable small platforms should be proven as a first step.

2.1. Missions identification

The use of electric propulsion has been proposed in the 70's and 80's essentially on performance grounds [1], [2], like Tempel comet rendez-vous or out of ecliptic asteroid encounter. The spacecrafts studied at that time were large (2 to 5 tons at launch), powerful (20 kW at least) and needed a dedicated launch. More recently, NASA studied a much smaller ion thruster propelled spacecraft, N_STAR, [3] [4] with much lower power (2.3 kW) and mass budget. This reflects the miniaturisation possibilities pioneered by the Fast Pluto Fly By project [6]. A small electrically propelled spacecraft has been also studied in Japan [7].

This means that it is possible to design a useful scientific spacecraft using electric propulsion with an much less power and mass than 20 years ago. This offer the opportunity (due to the small spacecraft mass) to perform a piggy back launch, thus leading to a fairly modest launch cost and frequent launch opportunities.

Analysing what can be made with SPT on this field, one can reach a striking conclusion.

For spacecrafts or probes using less than 2 kW of power, the SPT 100 (or SPT M 2) is an obvious choice with a nominal thrust of 83 mN (throttletable from 50 to 92 mN) and a nominal PPU input power of 1.5 kW. In addition, using the latest results of life tests (2 MN.s), a useful total impulse of 1.33 MN.s can be reasonably expected.

The table 2.1 shows what speed increment can be reached with SPT operated at specific impulse of 15205 or 17658 Ns / kg, and with spacecraft dry mass of 100, 150 and 200 kg. It can be seen that the speed increments can reach almost 10 km/s, which allow to perform a large number of interesting missions. For example, a continuous thrust duration of only 190 days can produce a 10 km/s speed increment.

Table 2.1: Speed increment versus specific impulse and spacecraft dry mass

<table>
<thead>
<tr>
<th>Specific impulse</th>
<th>15 206</th>
<th>17 658</th>
<th>Ns/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total impulse</td>
<td>1.33E+06</td>
<td>1.33E+06</td>
<td>N.s</td>
</tr>
<tr>
<td>Dry mass</td>
<td>100</td>
<td>150</td>
<td>200</td>
</tr>
<tr>
<td>Speed increment</td>
<td>9 556</td>
<td>6 985</td>
<td>5 516</td>
</tr>
<tr>
<td>Xenon mass</td>
<td>87.5</td>
<td>87.5</td>
<td>87.5</td>
</tr>
</tbody>
</table>

In other words, a thruster initially designed for NSSK can be also used for the primary propulsion of small probes, thus avoiding the costly development of a dedicated thruster.

As a purpose of comparison, the speed increments associated with some typical missions are listed in table 2.2. It can be seen that, with the exception of very high energy direct missions (out of ecliptic direct, high energy comet rendez-vous), all foreseeable
science and planetary missions requiring high speed increments could be accomplished with SPT.

### Table 2.2: Typical mission requirements (km/s)

<table>
<thead>
<tr>
<th>Mission</th>
<th>Optimum transfer with high thrust</th>
<th>Low thrust transfer</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>From GTO (Ariane 5)</td>
<td>From parabolic branch (beyond earth escape)</td>
<td>From GTO (Ariane 5)</td>
</tr>
<tr>
<td>Escape</td>
<td>0.8</td>
<td>-</td>
<td>1.8</td>
</tr>
<tr>
<td>Moon orbit</td>
<td>1.5</td>
<td>-</td>
<td>3.2</td>
</tr>
<tr>
<td>120° phase, 1 AU orbit (with time constraint)</td>
<td>3.5</td>
<td>4.8</td>
<td>5.3</td>
</tr>
<tr>
<td>180° phase, 1 AU orbit (with time constraint)</td>
<td>4.5</td>
<td>6.5</td>
<td>7.2</td>
</tr>
<tr>
<td>Mars orbit</td>
<td>3.3</td>
<td>7.0</td>
<td>7.2</td>
</tr>
<tr>
<td>Venus orbit</td>
<td>4.4</td>
<td>8.2</td>
<td>9</td>
</tr>
<tr>
<td>Jupiter fly-by</td>
<td>3.9</td>
<td>8.8</td>
<td>10.3***</td>
</tr>
<tr>
<td>ATEN asteroid rendezvous</td>
<td>7.6</td>
<td>11.9</td>
<td>13.1</td>
</tr>
</tbody>
</table>

**notes:**
* Those speed increments are provided far from the perigee of the orbit, so that they are more expensive than those "from GTO" (with part of the speed increment provided at perigee of GTO).
** Speed increment are estimated with the following hypothesis: 295 kg initial mass, 80 mN thrust and 16000 Ns/kg specific impulse.
*** For Jupiter fly-by, two perigee burns reduce the penalty due to the low thrust.

All examples selected in table 2.2 require only solar electric propulsion (SEP). In the case of Jupiter fly-by (or Pluto fly by), the solar electric propulsion stage will be used as a tug for a probe supplied by a RTG.

The 120° phase, one A.U. mission deserves special explanations. Three small probes located at one A.U. equally spaced at 120° (one within earth vicinity and two 120° apart) will give a total and real time coverage of sun photosphere and Corona (figure 2.1). From earth, it is possible to have only a partial coverage due to the mean photosphere rotation of 30 days. The Corona is only viewed as a two dimensional picture, while the understanding of plasma phenomena will require 3 Dimensional data.

Such a global solar observatory will normally contribute to a better solar physics understanding. To install such a small constellation in a reasonable time (e.g. 20 months), it is not sufficient to allow a slow drift of the spacecrafts along earth orbit, one shall use an intermediate elliptical transfer orbit with an acceleration phase, a cruise phase and a slow down phase (figure 2.2). The speed increment associated to these manoeuvres is quite large, which justifies the use of electric propulsion (in addition, the GTO to escape velocity transfer can be performed also using E.P. at least in part, thus improving the mass gain).

The missions to the Moon or to the Lagrangian points of the earth - Moon system have been extensively studied [8]. The reference [8] illustrates the possible design of a small spacecraft using a T5 thruster, while the reference [10] describes a small spacecraft using an SPT 100.
2.2. Small spacecraft possible design

To reach a small overall mass, an integrated design is necessary, i.e. some functions should be merged together like structure and xenon tank by attaching the p.c.b. of the electronics directly to the structure (deletion of the electronics boxes weight.). Titanium tanks and especially cylindro-spherical ones offer a good compromise between tank mass and the use of tank as an integrated structure. The xenon tank will be the core of the small spacecraft (figure 2.3).

For most planetary missions (when no spiral up or spiral down is required), the angle between thrust vector and sun direction varies less than +30°. This means that the solar panels can be directly deployed from the spacecraft structure, thus leading to a very low weight. For the required power, a solar panel mass of slightly less than 20 kg could be foreseen (2 kW).

The attitude control could be performed by cold gas thrusters (using xenon) in the acquisition mode and solar radiation pressure in the normal mode.

The small axial torque generated by the operating SPT could be countered by a movable solar sail. If a fine attitude control is required, reaction wheels will be added. The table 2.3 provides a tentative mass budget for a typical probe.
Table 2.3: Typical small probe mass budget (in kg)

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure (including tank)</td>
<td>25</td>
</tr>
<tr>
<td>Solar panel</td>
<td>20</td>
</tr>
<tr>
<td>PPU</td>
<td>8</td>
</tr>
<tr>
<td>Thruster unit (including PMA)</td>
<td>7</td>
</tr>
<tr>
<td>Integrated control / TM / TC</td>
<td>10</td>
</tr>
<tr>
<td>Antenna</td>
<td>3</td>
</tr>
<tr>
<td>Harness</td>
<td>4</td>
</tr>
<tr>
<td>Thermal control</td>
<td>6</td>
</tr>
<tr>
<td>Payload (minimum)</td>
<td>17</td>
</tr>
<tr>
<td>Total (dry)</td>
<td>100</td>
</tr>
<tr>
<td>Xenon (maximum)</td>
<td>87.7</td>
</tr>
<tr>
<td>Total (loaded)</td>
<td>187.7</td>
</tr>
</tbody>
</table>

Such a small spacecraft could be piggyback launched on - e.g. ARIANE - into GTO or 8000 km circular orbit during any commercial launch. Owing to the orbit constraints thus induced, a small perigee kick stage could be used in the GTO case to provide the most favourable velocity vector (generally, in the ecliptic plane) for electric propulsion phase.

The big advantage of a commercial launch is related to the moderate cost and to the large number of flight opportunities offered. Therefore, the combination of electric propulsion and piggy back launch may well lead to a new family of low cost scientific missions.

The specific advantage of SPT 100 / SPT M 2 is related to its very high thrust to mass ratio associated to a sufficiently high specific impulse. In solar orbit, the propulsive phase duration is generally small when compared to the orbital period, thus leading to a small loss w.r.t. the Hohmann transfer speed increment. For example, a 100 kg dry mass spacecraft will need only 60 days to reach a speed increment of 3900 m/s. Therefore the lower specific impulse of SPT versus ion thrusters is at least partly compensated by a lower total impulse requirement.

3. LOW EARTH ORBIT APPLICATIONS

3.1. Satellites constellations

The small satellites constellations are characterised by a new satellite design approach. For example, the system reliability shall be determined at the constellation level. This may allow to eliminate some redundancies at spacecraft level.

In order to lower cost, the spacecrafts must be autonomous and the launch preparation operation simplified.

The present generation of constellations (e.g. IRIDIUM (R) ) use hydrazine thrusters for propulsion purposes. It has been proposed to use small pulsed plasma thrusters (PPT) instead in order to eliminate the hydrazine loading operation before launch.

The use of electric propulsion offer two other advantages:
- due to the low thrust, the on board computer can detect a propulsion system malfunction and stop the faulty thruster before the spacecraft control could be jeopardised,
- the higher specific impulse of electric propulsion allows to perform an orbit transfer from say 300 to 700 km, thus putting less requirements on the launcher (and then, orbit maintenance and de-orbit manoeuvre).

For 600 to 800 kg spacecrafts, a 40 mN SPT is well adapted. Four to six thrusters will be sufficient. In the perspective of spacecraft redundancy deletion, the thruster and PPU designs could be drastically simplified:
- single cathode,
- single xenon flow control valve,
- single 600 W discharge supply module.

By this way, the weight and the cost of the propulsion subsystem will be considerably reduced.

3.2. Earth observation

As underlined in ref. [9], earth observation satellites will benefit from electric propulsion...
for fast orbit change. This is needed not only for military spacecrafts but also for new commercial earth resource spacecrafts required to observe the same point with a short repetition time.

Electric propulsion is also very useful for SAR (Synthetic Aperture Radar) orbit maintenance. Interferometric images from SAR require an extremely precise orbit control.

The most important issue is drag compensation. This could be accomplished in real time and without attitude disturbance using SPT, preferably in a variable thrust mode (either variation of a continuous thrust (thrust range: 30 to 120 %) or pulse width modulation (thrust range: 1 to 100 %)).

LEO scientific missions benefit also from electric propulsion drag compensation, such as gravimetric mission [11].

3.3. Space station

The space station drag make up requires typically 10 tons of bi-propellant per year (c.a. 30 MN.s per year). This lead to at least one dedicated launch per year.

In addition, when the chemical thrusters are fired, the micro gravity requirements (less than 10^{-5} g steady state acceleration, i.e. 10 N for a 100 000 kg platform) are not fulfilled. Many sensitive micro gravity experiments will require more stringent micro gravity levels (10^{-6} g, i.e. less than the actual drag induced acceleration) during extended periods of time. The big advantage of SPT drag make up is that it produces not only no adverse g jitters, but also an improved quality of micro gravity by cancelling the atmospheric drag.

The propellant mass gain is very important too: only two tons of xenon are needed per year instead of 10 tons of bi-propellant.

For a firing duration of 4400 hours per year, taking into account the requirements of thrust strategy and of mission, a mean thrust of 2 N will be needed, this could be delivered by a single 30 kW SPT or by several lower power SPT (e.g. four 7.5 kW SPT 200).

The advantage of the multi-SPT layout is that they can compensate for the drag vector excursion by differential throttling, in addition, they can be fired individually when the drag is lower. On the thruster designer side, the development of 5 to 7.5 kW subsystems could be justified for several missions (orbit raising, large planetary missions), while the 30 kW subsystem class will find much less applications, until affordable high power energy sources become available for space use.

4. ORBIT RAISING

4.1. Interest of electric propulsion for orbit raising

The orbit transfer by electric propulsion has been studied since many years. However the commercial users object that the transfer time is too long. The early studies of LEO / GEO orbit transfer were motivated - especially in Europe - by the small capacity of the launchers available at that time. Now the launcher capacity is no more a limitation.

The ultimate interest of GTO - GEO transfer (or intermediate circular orbit allowed by ARIANE V to GEO) is that it allows to use an unified SPT propulsion system, thus eliminating the need of the sometimes called hazardous chemical propellant on board. The integration and preparation sequence of the spacecraft will be greatly simplified.

The other interest is obviously economic:

- the launch mass being smaller, the launch cost is reduced,
- the deletion of a bi-propellant propulsion subsystem will generate a substantial spacecraft cost reduction, directly (hardware cost) and indirectly (simplification of the spacecraft architecture) as well as a reduction in manufacturing time.

Of course, less revolutionary solutions, using in part a chemical ABM, will be probably operated in a first time.

4.2. Examples of orbit raising operations

The near future telecommunication spacecrafts will offer solar panel power (BOL) in excess of 8 kW. Even if one consider that only a part of this power could be used for propulsion (e.g. 5.5 over 8 kW), the thrust to power ratio of SPT allows to
deliver a thrust of 320 mN.
In such a case, only 60 days are needed to communicate to a 1620 kg platform (1500 kg dry mass plus 120 kg of xenon for orbit control) a 1000 m/s speed increment. The table 4.1 gives some examples of orbit transfer capabilities.

<table>
<thead>
<tr>
<th>Launcher and satellite characteristics</th>
<th>BOLGEO Mass (kg)</th>
<th>Launch mass (kg)</th>
<th>Duration (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ariane 5 Launch GTO 620x36 000 km satellite with bi-propellant apogee system (as reference)</td>
<td>1 620</td>
<td>2 610</td>
<td>2</td>
</tr>
<tr>
<td>Ariane 5 Launch GTO 620x36 000 km satellite with plasma thrust (320 mN)</td>
<td>1 620</td>
<td>1 810</td>
<td>177 (5.9 months)</td>
</tr>
<tr>
<td>Ariane 5 Launch Super-geosynchronous TO 620x57 000 km satellite with plasma thrust (320 mN)</td>
<td>1 620</td>
<td>1 830</td>
<td>150 (5 months)</td>
</tr>
<tr>
<td>Ariane 5 Launch circular orbit 8 000 km satellite with plasma thrust (320 mN)</td>
<td>1 620</td>
<td>1 860</td>
<td>166 (5.5 months)</td>
</tr>
</tbody>
</table>

The saving masses at launch are almost the same for those different orbit raising scenarios (i.e. more than 750 kg w.r.t. bi-propellant apogee reference system). In fact, if we take into account the foreseen launcher performances, we have found that it is almost true to said that the saving masses are proportional to the duration of the orbit raising (almost 130 kg per month).

4.3. Possible unified SPT subsystem architectures

Starting from the present NSSK hardware (SPT 100 / SPT M 2 thrusters, SSL PPU and TSU), it is possible to devise an orbit transfer system using four standard thrusters (Figure 4.1). The advantages of this solution are related to the reuse of an existing and proven technology and the possibility to have a commonality between orbit raising and NSSK hardware especially PPU's.

On the other side, it could be beneficial to develop a more powerful thruster, as larger thrusters provide a higher efficiency (for a similar technology) than the 80 mN class thruster. This means that more mN will be available per kilowatt, yielding a shorter trip time.

The drawbacks of this solution is that a separate development is needed for the 5 kW thruster and PPU and that there is no commonality between orbit raising and NSSK PPU's.

5. CONCLUSION:

It is possible to cover a wide area of applications with the 80 mN SPT's: NSSK of course, but also geostationary spacecrafts orbit raising, small interplanetary spacecrafts and drag compensation.

The emergence of new spacecraft families:
LEO constellations and small LEO spacecrafts could justify the development of a new simplified 40 mN subsystem extrapolated from the SPT 70.

On the other end of the power scale, several applications:
- geostationary spacecrafts orbit raising,
- large interplanetary platforms and
- Space Station drag compensation, may justify to develop a large power subsystem in the 5 to 7.5 kW power range.

Three power levels seem a reasonable compromise between the need to skip to many applications with many different thrusters and the substantial effort required by each development.

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