

Next Generation of Thruster Module Assembly (TMA-NG)

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Anthony LORAND¹, Olivier DUCHEMIN² and Nicolas CORNU³
SNECMA Division Moteurs Spatiaux, Vernon, 27200, France

Abstract: SNECMA has acquired an expertise in the field of the Electrical Propulsion System for almost 40 years. Taking benefit from electric Hall Effect Thruster (HET) to mainly perform satellite North/South station keeping, the Thruster Module Assembly (TMA) has been designed, assembled and qualified by SNECMA in the frame of the STENTOR project initiated by CNES 11 years ago.

Since 2001, SNECMA has become the European leader for the supply of electric propulsion thrusters modules, with a successful In flight heritage on Intelsat 10-02, Inmarsat4-F1, Inmarsat4-F2, Inmarsat4-F3, KaSat, YahSat 1A and by the end of 2011 on and YahSat 1B.

The constant increase of larger satellite mass will require in the next years for HET propulsion, a total impulse over 2,6 MN.s up to 3,3 MN.s by 2020 (including coefficient margin). In addition, the future satellites face to higher position of center of gravity, launch constraint evolution, and EMC/Plasma noise compatibility will impose a new HET propulsion system with increased performances and functions.

In front of those evolutions, Snecma is developing the Next Generation of Thruster Module Assembly (TMA-NG). Besides performances and function improvement, one main driver of this evolution is to reduce recurring cost without impact on reliability by using fully qualified and flight proven hardware.

Nomenclature

<i>HET</i>	=	Hall Effect Thruster
<i>TMA</i>	=	Thruster Module Assembly
<i>XFC</i>	=	Xenon Feed Controller
<i>FU</i>	=	Filter Unit
<i>PPU</i>	=	Power Processing Unit
<i>F</i>	=	Thrust
<i>Isp</i>	=	Specific Impulse
<i>EMC</i>	=	ElectroMagnetic Compatibility
<i>BPRU</i>	=	Bang-bang Presion Regulation Unit
<i>HIB</i>	=	Hot Interconnection Box
<i>O.T</i>	=	Orbit Topping
<i>M_L</i>	=	Launch Mass
<i>M_D</i>	=	Dry Mass

¹ Thruster Module technical authority, Space Engine Department, anthony.lorand@sneema.fr.

² Plasma propulsion senior engineer, Space Engine Department, olivier.duchemin@sneema.fr.

³ Head of plasma propulsion team, Space Engine Department, nicolas.cornu@sneema.fr.

I. Introduction

A typical Electric Propulsion Sub-System (EPS) main features are roughly described here after.

Beside the thrusters, the whole EPS^{1,2,3,4}, fig. 1 & 2, includes for the four following main functions:

- Xenon supply system
- Electrical power supply
- Digital interface and communication system
- Thrusters and/or Thrusters Module Assembly

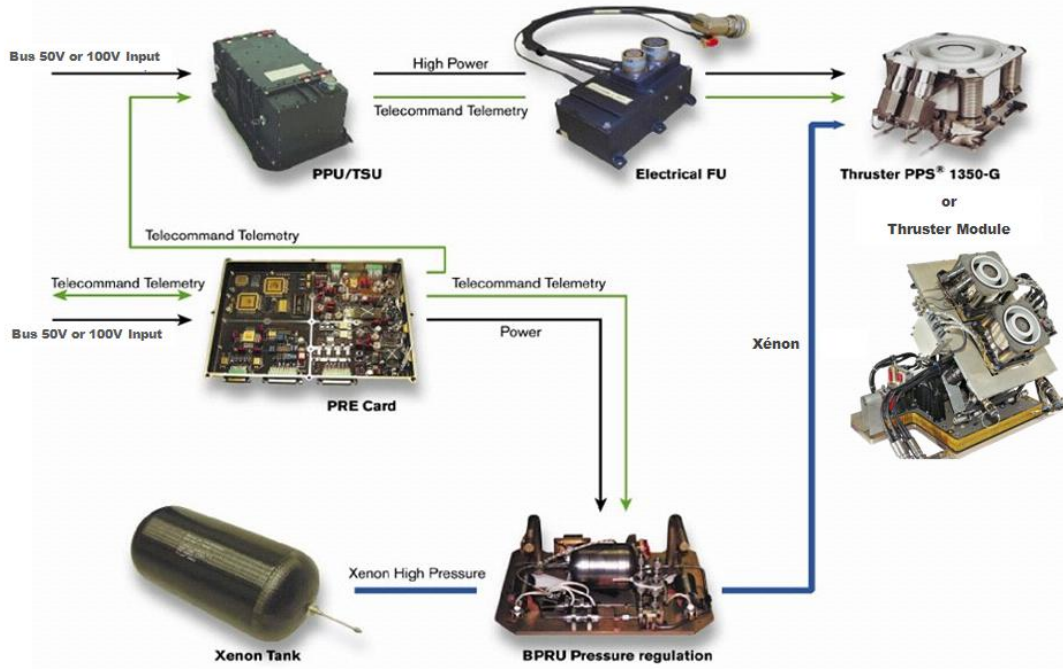


Figure 1. Typical Electric Propulsion SubSystem.

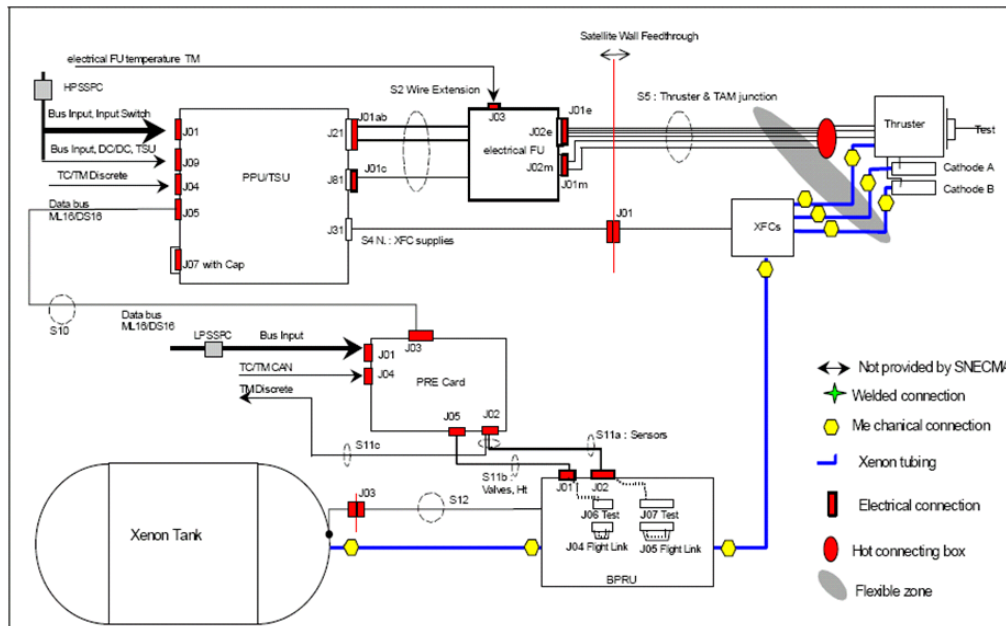


Figure 2. EPS functional diagram.

A. Xenon Supply System

The xenon is stored in the main Xenon Tank under high pressure (up to 150bars). A pressure regulator called the Bang-Bang Pressure Regulation Unit⁵ (BPRU) regulates the xenon down to a constant low pressure (around 2.6 bars). The low-pressure xenon is then fed into the adjustable flow regulator, called the Xenon Flow Controller (XFC). A simple and robust control loop algorithm, located in the Pressure Regulation Electronic Card (PRE Card), controls the constant pressure delivered by the BPRU. The XFC then provides fine control of xenon mass flow rate to the thruster anode and cathode.

The intrinsic concept of Bang-Bang regulator introduce a very regular fluctuation of the “constant regulated pressure”: each time the measured pressure become lower than the target pressure, the bang-bang valves are activated and a small positive step in the pressure of the plenum volume occurs. This characteristic, as the heart of the system, is visible on about all the measured functional parameters of the EPS. The flight hardware is shown in Figure 3.

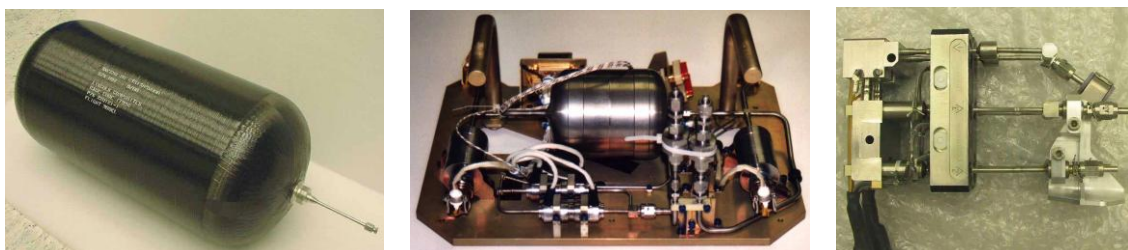


Figure 3. Flight model hardware: Xe Tank, BPRU and XFC.

B. Electrical power supply and Digital interface

The electrical power supply and thrusters is composed of a main power transformer called Power Processing Unit (PPU) which transform the electrical voltage delivered by the satellite, 50 or 100 Volts DC, into the voltage required by the thruster (from 220 up to 350 Volt DC).

All Telemetry (TM) and Telecommands (TC) are interfaced to the EPS through the PRE Card. Commands reaching the PRE Card are either executed by the PRE Card (if relating to the BPRU control) or passed to the PPU. An electric filter called the Filter Unit (FU), is included to reduce propagation of the electrical thruster oscillations and to protect the PPU electronics. Both the PRE Card and PPU contain software with “automatic mode” subroutines. These routines reduce the number of commands that need to be routinely sent to the EPS.

In routine operation the EPS has two automatic loops running. One software loop, contained in the PRE Card, regulates the xenon pressure, in the low-pressure tank feeding the XFC. In order to deliver a constant thrust while the thrusters is firing an other algorithm loop is integrated into the PPU/TSU and generate the analogical control signal to the XFC.



Figure 4. Flight model hardware: PPU, FU and PRE Card.

II. TMA Description

Based on Hall Effect Thruster (HET), the Thruster Module Assembly⁶ (TMA) has been designed, assembled and qualified by SNECMA in the frame of the STENTOR project initiated by CNES 12 years ago.

Since 2001, SNECMA has become the European leader for the supply of electric propulsion thrusters modules, with a successful In flight heritage on :

- Intelsat 10-02⁷
- Inmarsat4-F1⁸, Inmarsat4-F2, Inmarsat4-F3
- KaSat (Eutelsat)
- YahSat 1A and by the end of 2011 on YahSat 1B

A total of sixteen TMA has already been produced by SNECMA, with at this time, more than 47 years on flight⁹ cumulated experience (2004 → 2011) and more than 14 000h cumulated firing duration (~3400h per year). The two TMA per satellite, located near the anti-earth wall, main mission is to ensure the inclination and eccentricity orbit control (NSSK) and momentum wheels dumping.

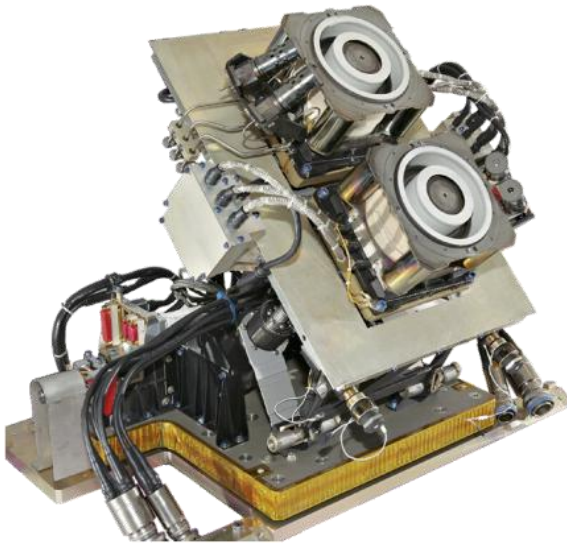


Figure 5. TMA Flight model. (FM15)



Figure 6. TMA on Inmarsat-4.

Current TMA is mainly composed of :

- ✓ Two SPT-100 thrusters (Thrust : 81,5mN, Isp : 1510s and total impulse : $2,6.10^6$ N.s, Input power: 1,35kW) delivered in the frame of ISTI (joint venture between SNECMA\EDB Fake\SSL)
- ✓ A Thruster Orientation Mechanism (TOM) provided by THALES ALENIA SPACE (Angular range +/-12°, Resolution step < 0.005°)
- ✓ Two filter Unit (FU) provided by EREMS, (mainly composed of low pass filter and discharge current oscillation probe)
- ✓ A honey comb baseplate to enable structural integrity of the TMA
- ✓ Redounded active thermal control hardware (heaters, thermistors, and thermostats) for thermal regulation of thrusters mobile plate and XFCs
- ✓ ElectroMagnetic Compatibility/ElectroStatic Discharge/Plasma protection devices for electrical components (including 360° overshielded harnesses and specific grounding mapping)

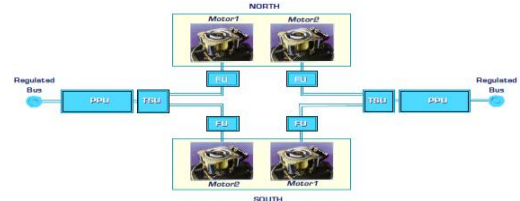


Figure 7. EPS configuration

A. TMA Design

The most impressive design specificities of the TMA are:

- Modularity: the final assembly of the TMA requires only screwing and no gluing or welding. Each major component (thrusters, Filter Units, XFC module, TOM) can be mounted or dismounted in few minutes or hours thanks to the fluidic screwed connections downstream XFC module and thanks to HIB (Hot Interconnexion Box) which includes high performance and reliable electric connections without potting.
- Particular and chemical cleanliness of the fluidic system, which requires numerous processes and care along all the TMA manufacturing, assembly and tests.
- EMC/ESD/plasma media compatibility design solution for electrical components. All electrical harnesses (power and measurement of thruster, XFC, TOM actuators and optical switches, thermal control) are shielded or overshielded for EMC/ESD protection and to avoid plasma noise to be picked up and propagated upstream, toward satellite electric system. Electric components are protected by metallic caps, with specific devices enabling depressurization but preventing from plasma media entering. The Hot Interconnection Box has been designed in the same way, but with high voltage (500V), high current (14A) and important cycled temperature range (-25°C/+130°C).
- Thermal design of TMA shall allow a firing thruster to evacuate approximately 20W by conductive link. The Thermal control hardware allows, to maintain the temperature around +10°C for the three independent areas of the TMA (TOM mobile plate, XFCs of first and second thrusters), and to bear thermal environment up to -41°C / +69°C at satellite interface.



Figure 8. TMA FM16 integrated in Snecma LIA Vacuum test bench.

LIA is a dedicated test bench for TMA thermal vacuum and firing acceptance tests.

B. TMA qualification logic

Under SNECMA responsibility, the TMA and electrical module initial development and qualification has been realized in the frame of the STENTOR program initiated by the CNES in 2000. The 15 years In Orbit Lifetime qualification logic was the following one:

All sub-equipments have been first qualified separately:

Table 1. TMA sub-equipments qualification logic.

	Bread Board (BB)	Electrical model (EM)	Structural Model (StM)	Qualification Model (QM)
Thruster		X	X	X
TOM			X	X
Filter unit	X	X		X
PPU	X	X		X

In addition, at TMA level with a Thermal representative Model, thruster firing was performed under vacuum and sun simulation with Xenon lamps.

The most impressive SNECMA campaign was the combined test: TMA firing during TOM mobility in thermal vacuum conditions (hot, cold or worst gradient conditions for satellite I/F, space simulated by a liquid nitrogen cooled screen and sun power simulated by electrical heater at mobile plate level).

Several separated and End to End test campaign for Thruster / FU / PPU development and qualification including ESD and EMC matters were performed.

For commercial satellite applications, financed by various customers, under the SNECMA responsibility in its test benches, a full qualification campaign with enhanced environment (thermal cycling, vibrations, satellite and TOM release successive shocks) and a lifetime of 8990 h and 5707 cycles, mainly with flight hardwares PPU and FU, and Gas Module Xenon supply, has been realized. (Figure 9)

An ElectroMagnetic Interferences measurement campaign has been performed in a dedicated firing test bench to characterize thrusters (various aging) connected to a HIB, a representative harness and a Filter Unit.

Series of Pyroshock have been performed on thrusters and structural model including sensitive parts. A satellite shock has been performed on a TMA composed of a flight standard baseplate with the TOM QM and thruster dummies mounted on. Finally, three Proto Flight Model (PFM1, PFM7 and PFM14) have been done for obsolescence validations or satellite specification evolutions (Ex : Generic Geostationary family → Geomobile family)

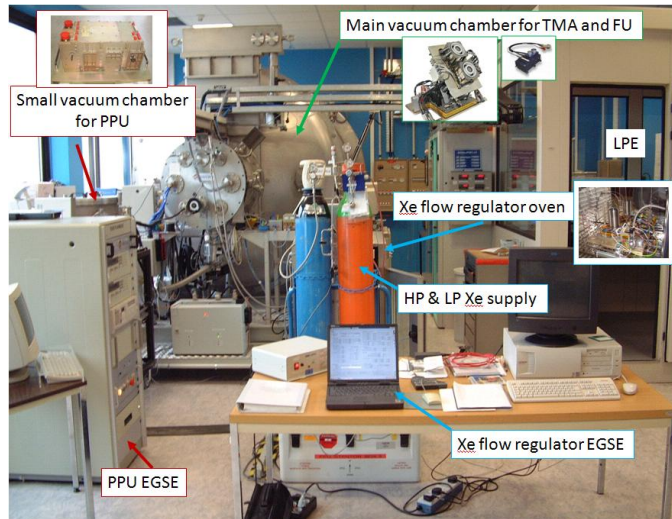


Figure 9. End to End EPS test in SNECMA Vacuum test benches. (2002)

III. TMA-NG Description and performances improvement

A. Market trend

For 30 years, based on the five satellite prime contractor world leaders, the market trends indicate a constant increase of the maximum mass of geostationary telecommunications satellites (Comsats). Since 2004, the rise of the electric propulsion to ensure satellites North/South Station Keeping (NSSK), has nevertheless limited the exponential effect of the mass growth rate²³. If this trend continues in the next years, larger satellites will require for NSSK propulsion, a total impulse over 2,6 MN.s up to 3,3 MN.s by 2020 (including coefficient margin). In addition, the future satellites face to higher position of center of gravity, N/S nodes firing duration and efficiency, launch constraints evolution, in-orbit radiations and EMC/Plasma noise compatibility will impose increased performances for electrical thruster module.

Moreover, the emergence of new attractive medium size launchers and the limited mass capacity of Heavy launchers, *versus* bigger and powerful payload demand, lead to develop New-Generation electric propulsion system that could permit satellites to become lighter. As HET Isp is 5 times higher than chemical propulsion one, an improved Electric Propulsion implement for NSSK could also be used for additional sub-function, (like orbit topping, partial orbit raising, repositioning, de-orbit), without a dedicated EPS.

Anticipating those evolutions, SNECMA is proposing the Next Generation of Thruster Module Assembly (TMA-NG). Besides performances improvement and functions extension, the drivers of this development are reduced recurring cost, increased reliability and quick availability by using fully qualified and flight proven hardwares.

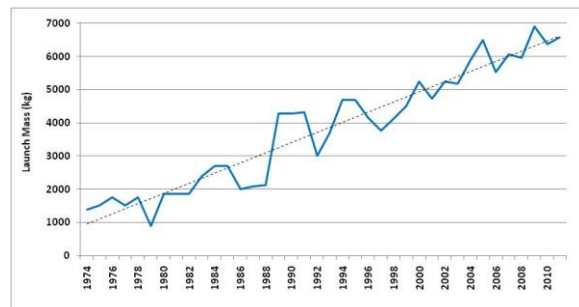


Figure 10. Comsats maximum launch mass. (SNECMA database)

B. TMA Next Generation (TMA-NG) delta design and performances

The TMA-NG is mainly composed of :

- ✓ Two PPS®1350 thrusters provided by SNECMA, flight proven on SMART-1 (5000h) and fully qualified in the frame of ESA/CNES *AlphaBus* Program
- ✓ A Thruster Orientation Mechanism (@Bus TOM) provided by THALES ALENIA SPACE which main sub-components (linear actuator, gimbal) are re-used from flight proven TOM on current TMA, and fully qualified in the frame of ESA *AlphaBus* Program.
- ✓ Two filter Unit (FU) provided by EREMS flight proven on current TMA
- ✓ Simplified but redunded active thermal control hardwares (heaters, thermistors, and thermostats) for thermal regulation of thrusters. (EEE components re-used from current TMA)
- ✓ ElectroMagnetic Compatibility/ElectroStatic Discharge/Plasma protection devices for electrical components

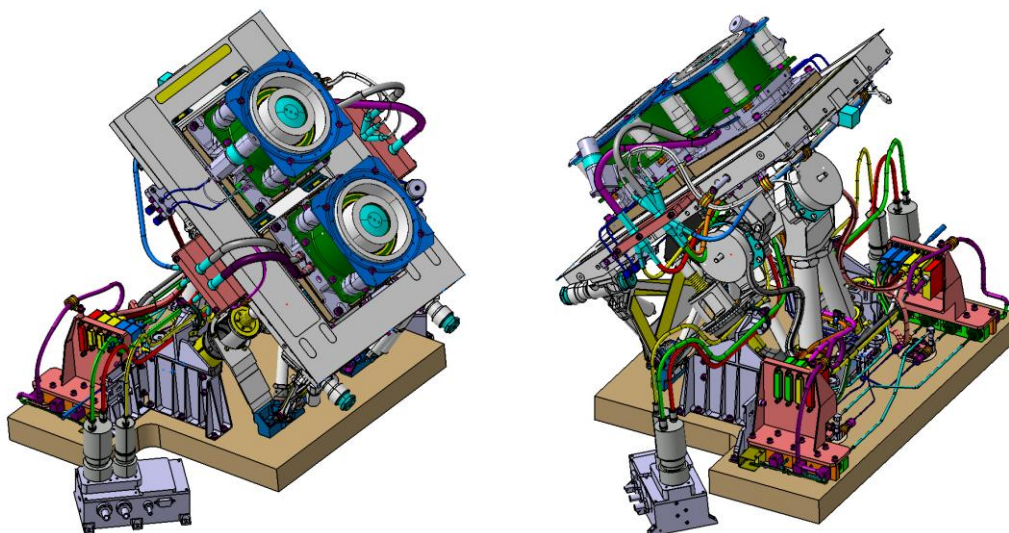


Figure 11. 3D-drawing views of TMA-NG

Compared to TMA, the TMA-NG increase total impulse by + 30% and thrust by +10% by using PPS®1350

The PPS®1350 Hall Effect Thruster is a 1.5-kW class stationary plasma thruster specifically designed and qualified by SNECMA to meet the needs of the larger, commercial GEO satellites by increasing the robustness of the thruster to ensure compatibility with more stringent environment requirements and with the increased lifetime demanded with 15-yr operational service life. This was demonstrated by the PPS®1350-G qualification campaign, which included a record-duration life demonstration test for Hall thrusters of 10,532 hrs and 7,309 on/off cycles. During this test, the PPS®1350-G QM processed a total xenon mass of 210 kg and a total energy of 57 GJ to deliver a total impulse of 3.4 MN.s.^{10,11,12}

PPS®1350-G Nominal performance	
Thruster input power :	1.5 kW
Thrust :	89 mN
Specific impulse :	1650 s
Total impulse :	3,4 MN.s
Total efficiency ** :	50%
** Includes hollow cathode flow and electromagnet coils power	



Four PPS®1350-G flight units have been delivered in 2010 to fly in 2012 on the joint ESA/CNES *Alphasat* spacecraft, within the frame of the *Alphasat* large commercial geostationary platform development program.

The flight experience of the PPS®1350-G on board the small ESA *Smart-1* lunar mission demonstrated the capability of the thruster to operate under stringent low-power limitations^{10,11,13}. With the nearly 5,000 hrs of thruster operation cumulated throughout the mission, the *Smart-1* experience is therefore very relevant to future applications of the PPS®1350-G.

Table 2. PPS®1350 qualification and flight program heritage.

Qualification programs	Flight heritage (year of launch) – FM units produced
- <i>Stentor</i> : 2,400 hrs; 2,026 cycles	- <i>Stentor</i> (2002) – 2 units
- <i>Alphabus</i> : 10,532 hrs; 7,309 cycles	- <i>Smart-1</i> (2003) – 1 unit
- Foreign qualification: 7,180 hrs; 8,499 cycles	- <i>Alphasat</i> (2012) – 4 units
	- Additional FM produced (1999 – 2008) : 5 units (incl. QMs)

Using the TMA-NG for a NSSK mission, the 10% increased thrust allows reducing N/S nodes firing duration and thereby improves thrust efficiency and xenon mass saving. This increased thrust efficiency combined with the 30% increased total impulse allows the use of TMA-NG, *i.e.* 1,5 kW class thruster, for comsats as large as 8000kg. (Current TMA limitation is around a 6300kg satellite launch mass / 15 yr life time). As detailed in Chapter D, the total impulse of PPS®1350 combined with the TOM extended angular range can also be exploited to make enhanced function like orbit raising or orbit topping.

Compared to TMA, the TMA-NG increase angular range by +10% by using Alphabus TOM

The TOM is manufactured by Thales Alenia Space - France in Cannes and is already qualified and flown on TMA on spacecrafts listed in Chapter II and Table 3.¹⁵

The adaptation of the Mechanism to the PPS®1350 (TOM @Bus) has been performed and validated through a Delta Design Review, which has been held and closed in the frame of *Alphabus* Program. A qualification model DQM has been built in order to perform a delta qualification test sequence.

Two complementary life tests have been performed:

- The first one in ambient pressure and thermal conditions.
- The second one, with a small motion profile: in vacuum and ambient temperature.

Considering:

- TOM @BUS need for mechanical life cycles
- Test qualification performed (no wear out failure appears on TOM, comfortable motorisation margin all along life tests)
- Analysis of lubrication behavior (thermal and vacuum influence),
- Oil loss calculation

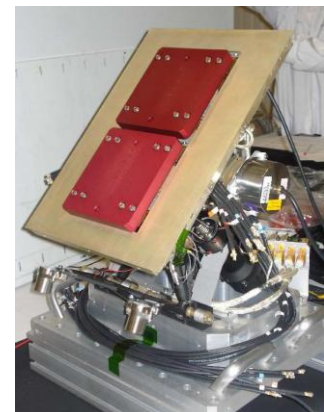


Figure 12. TAS @Bus TOM

Thales Alenia Space has demonstrated that qualification heritage performed in the frame of STENTOR covers @BUS need.

Table 3. TOM qualification and flight program heritage.

Qualification programs	Flight heritage (year of launch) – FM units produced
- Stentor	- Stentor (2002) – 2 units
- Astra 1K	- Astra 1K (2002) – 2 units
- Intelsat 10-02 (Delta Qual)	- Intelsat 10-02 (2004) – 2 units
- Inmarsat-4 (Delta Qual)	- Inmarsat-4 (2005-2008) – 6 units
- Alphabus (Delta Qual)	- KaSat (2010) – 2 units
	- Yahsat (2011) – 4 units
	- Alphasat (2012) – 2 units (TOM @Bus)
	- Additional FM produced (1999 – 2011) : > 6 units (incl. QMs)

As qualified on STENTOR TOM QM, and contrary to current TMA limited to $\pm 12^\circ$, the TOM for TMA-NG has a two axis $\pm 16^\circ$ angular range with resolution step better than 0.005° . Depending on the satellite position of mid of life center of gravity (MOL CoG), additional thruster shims are implemented on TMA-NG; shim angular range possibility is $[-9.3^\circ; +9.3^\circ]$.

Typically, TMA are installed on North and South satellite walls. In order to limit solar array and thruster's plasma interaction, TMA in lock position are inclined at 44° to Z axis (apogee engine axis), i.e. 46° to solar arrays axis (Y axis). NSSK thrust vector angular range is lower than $\pm 8^\circ$ around this 44° . As illustrated on Figure 13, thanks to its $\pm 16^\circ$ angular range, the TMA-NG could be inclined of 8° toward Z axis while maintaining NSSK thrust vector need. In this configuration, with a 9.3° thruster shim, one of the two thruster dedicated for orbit raising or topping, could be at 10.7° to Z axis, i.e. with a thrust efficiency of 98% (cosines 10.7°) toward apogee engine axis. In this option, the two TMA-NG would be in simultaneous firing. The Chapter D will describe the mass benefit of such firing configuration for orbit raising and circularisation. For heavy satellites, thanks to the increased Isp, and the N/S node firing duration reduction, the higher position of center of gravity could be counteracted by the previous TMA-NG wall implantation.

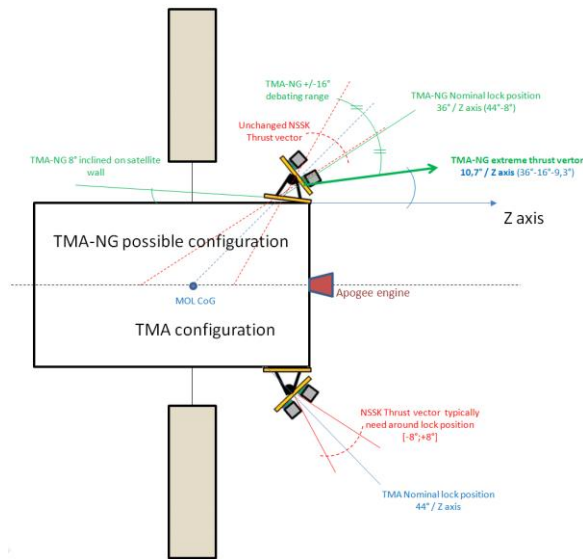


Figure 13. TMA-NG proposed implantation for a 98% firing efficiency regarding apogee engine axis

Compared to TMA, electrical architecture of TMA-NG is simplified but using flight proven hardware and process

As explained in Chapter I and illustrated in Figure 7 for In Flight TMA, the TMA-NG will be associated with its PPU. The main PPU functions are to supply the necessary discharge and auxiliary power inputs to the thruster, to regulate the discharge current via a closed-control loop acting on the xenon flow rate, and to ensure most of the Telemetry and Telecommand (TM/TC) interface between the satellite monitoring software and the Thruster Module. In addition to this, the PPU also has thruster selection and cathode/XFC branch selection functions. It also sequences all thruster operations such as, automatic startups and shutdowns. The PPU (Figure 14) is provided by Thales Alenia Space ETCA (Belgium). This Unit comprises five internal mechanical modules: the primary module, the anode module, the HIM (Heater

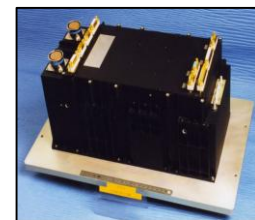


Figure 14. ETCA PPU

Ignitor Magnet) module, the upper module (sequencer and XFC drive), and the TSU (Thruster Selection Unit) module. The PPU to be used with TMA-NG, developed and first qualified under SNECMA specification and responsibility, enjoyed the extensive flight heritage already accumulated on this design^{7,8,9}, with already 33 flight models produced to date (Table 4).

Table 4. PPU/TSU qualification and flight program heritage.

Qualification programs	Flight heritage (year of launch) – FM units produced
- <i>Stentor</i> : 740 hrs and 840 cycles	- <i>Stentor</i> (2002) – 2 units
- <i>Astra-1K</i> : 10,474 hrs and 11,569 cycles	- <i>Astra-1K</i> (2002) – 2 units
- <i>Alphabus</i> : 6,320 hrs and 4,130 cycles	- <i>Smart-1</i> (2003) – 1 unit
	- <i>Intelsat 10-02, Inmarsat 4, Ka-Sat</i> (2004-10) – 10 units
	- <i>Yahsat</i> (2010-2011) – 4 units
	- <i>Alphasat</i> (2012) – 2 units
	- <i>Hispasat-AG1</i> (2013) – 2 units **
	- To be allocated – 10 units

** The HispaSat-AG1 PPU and FU units, in the Frame of EPS under Snecma responsibility for SmallGeo ESA Program, have started the acceptance test.¹⁴



Figure 15. EREMS FU

The PPU electronics is insulated from any conducted noise generated by the thruster by the electrical inductive-capacitive line Filter Unit (FU), placed between the PPU and the thruster, which other function is to facilitate plasma discharge ignition. It therefore filters out the perturbations and allows the thruster to be compliant with usual EMC requirements.

An important flight heritage also exists on the FU manufactured by EREMS, as shown in Table 5. To date, a total of 36 FMs have been produced, with another 8 currently in acceptance test **.

Table 5. FU qualification and flight program heritage.

Qualification programs	Flight heritage (year of launch) – FM units produced
- <i>Stentor</i> : 740 hrs and 840 cycles	- <i>Stentor</i> (2002) – 4 units
- <i>Astra-1K</i> : 7,309 hrs and 4,597 cycles	- <i>Astra-1K</i> (2002) – 4 units
	- <i>Smart-1</i> (2003) – 1 unit
	- <i>Intelsat X, Inmarsat 4, Ka-Sat, Yahsat</i> (2004 - 11) – 24 units
	- <i>Hispasat-AG1</i> (2013) – 8 units **
	- Additional FM (2010 - 11) – 3 units

Without modification at electrical module level (FU and PPU), the TMA-NG electrical architecture still has been simplified. First of all, XFC of PPS®1350 is qualified for -35°C while XFC-100B is qualified for -15°C. This step permits the suppression of thermal control hardware (redounded thermistances and heaters) on XFC module.

In addition, the PPS®1350 main power hot wires, ECSS qualified, that are flexible, and with shielding wrapping and, enable to simplify the harness and remove the current HIB assembly.

Finally, TMA-NG takes into account design to cost architecture. The baseline configuration is the use of PPS®1350 single cathode, with simplified power harnesses for thruster and XFC (-30%). This choice is justified and described hereafter.

C. TMA-NG design to cost consideration

Commercial communications satellites are drastically cost-constrained by international concurrence. As a short-term yet significant cost-reduction measure, on TMA-NG, the existing PPS®1350 design is proposed in baseline with a single cathode. This single-cathode version of the thruster unit, known as the PPS®1350-S, was first proposed and selected in 1999 for the *Skybridge* program, which was later stopped. Even with two cathodes, the life qualification requirements, including life duration and cycling, have always been met with single-cathode operations, whether for the foreign qualification of the PPS®1350,¹⁰ the PPS®1350-G qualification at Snecma,^{10,16} the European qualification of the SPT-100 at Snecma,¹⁷ or the US qualification of the SPT-100 at JPL/Fakel.¹⁸ Other, more recent Hall thruster designs now feature a single cathode.^{19,20} It should finally be pointed out that on TMA-NG, cold thruster redundancy is of course always in effect.

However, on TMA-NG, SNECMA offer to integrate a complementary hot redundancy, by enabling cathode cross firing (Figure 16). In such way, one thruster's anode can be firing with any of the two cathodes, *i.e.* including the cathode of the other thruster, and *vice versa*. With this redundancy, the reliability of TMA-NG thrust functions is almost multiplied by two in comparison of a basic single cathode thruster's module.

In order not to impact flight hardware and generate none recurring cost, the crossed redundancy technical design has been integrated on TMA-NG without modification on PPU and FU, *i.e.* on satellite monitoring interface. Each couple PPU/ FU is adapted for two firing configuration, a thruster anode with its nominal and redundant cathode. At satellite level, the two PPU with the eight FU, provide eight firing configurations. The two TMA-NG per satellite will also offer eight firing configurations. (Figure 17)

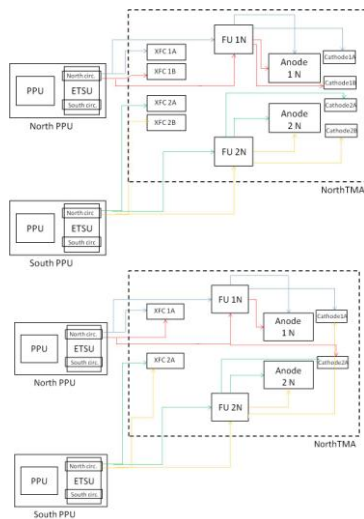


Figure 17. TMA and TMA-NG firing configurations

First improvements will be visible and measurable in 2011 in the frame of TMA *FM18* and SmallGeo Electrical Propulsion Thruster Assembly (EPTA)^{3,14} productions, and will be profitable for TMA-NG.



Figure 16. Nominal firing on first TMA-NG demonstrator.
(2011 in LIA Snecma vacuum test bench)
First cathode cross firing foreseen 3rd quarter 2011

Taking account previous considerations, it appears appropriate to propose a single-cathode thruster on TMA-NG, therefore and because a redundant XFC is associated with the redundant cathode on the PPS®1350-G, suppressing the redundant cathode also implies that a single XFC is used on the PPS®1350-S. The ensuing cost and price reductions for the thruster sub-equipments can then be significant and approach 25%.

For several years now, SNECMA Space Engines Division is engaged in a Six Sigma and Lean manufacturing approach on electric propulsion and module production. First analyses have enabled to identify manufacturing cycle optimizations and cost reductions with the adapted solutions, like:

- Extension of a clean room, for collocation of all thruster sub-assemblies production and vacuum leak test (2010)
- Modification of LIA test bench to enable a 100% automatic thermal and mobility vacuum test campaign (2011)

SNECMA being in charge of thruster manufacturing and module assembly, another interest of TMA-NG is the opportunity to realize a sharing of activity between sub-equipment and equipment, both in term of manufacturing that in term of acceptance tests. Thruster xenon tubing and power wire interfaces will be directly adapted to module needs, as a result the suppression of additional soldering and interconnection wiring activities usually realized at module level.

Moreover, currently, thruster acceptance test sequence (Figure 18) includes a first performance firing, vibrations, thermal vacuum cycles and a final firing test. Identical tests are renewed after module assembly. A better optimization is foreseen for TMA-NG acceptance tests logic, with the postponement of PPS® 1350 vibration, thermal vacuum cycles and last firing test until module acceptance tests. The extensive experience and manufacturing quantity of reliable sub-equipments, also allows a simplification of their own acceptance test sequences (e.g., no failure has been revealed during the 36 FU vibration tests ; FU dummies are added for thruster module vibration ; For TMA-NG, FU vibration test will be done at TMA level thanks to the replacement of the FU dummies by the flight model for TMA-NG vibration test).

The easy disassembly of the TMA-NG, associated with a full acceptance tested sub-equipments spare logic, make relevance the proposed cost optimization approach, with minimized program risk.

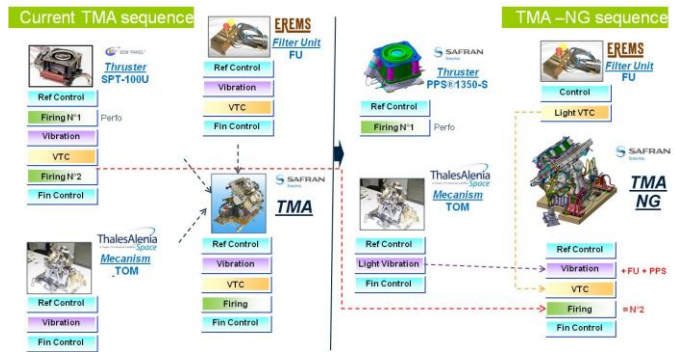


Figure 18. TMA and TMA-NG acceptance test logic evolution

D. TMA-NG performances' improvement

The TMA-NG main performances' improvement detailed in previous chapters could be resumed by:

Table 6. TMA-NG performances' improvement.

	Current TMA	TMA-NG	Step
Total Impulse	2,6 MN.s	3,4 MN.s	+30%
Nominal Thrust	81,5mN	89mN	+9%
Cycles	5682	7309	+28%
Nominal Isp	1510s	1650s	+9%
TOM Angular operating range	+/-12°	+/-16°	+33%
Mass	29,3 kg	32,1 kg	+9%

Some improvements could also generate simplification at satellite integration level, notably for environmental integration problematic or antenna localization aspects. Indeed, the TMA-NG, using PPS® 1350 enables to :

- reduce substantially the Electromagnetic emissions above 1GHz²¹
- authorize 38g Peak and 200°C at thruster interface, instead of 20g peak and 150°C on current TMA
- avoid export license control constraints

E. TMA-NG extra functions opportunities

The 3.4 MN.s total impulse offered by the PPS[®]1350-G allows to envisage orbit topping with electric propulsion.

As illustrated Figure 13, the extended angular range and the available total impulse of TMA-NG give the opportunity to meet NSSK future heavy comsats needs, and benefit of an extra in-orbit lifetime and/or an extra propellant mass saving thanks to orbit topping in addition of NSSK²² without transfer dedicated EPS over cost. The Figure 19 presents the TMA-NG orbit topping contribution capacity and the resulting mass saving in function of satellite dry mass.

In this study, during transfer, one thruster on both TMA-NG fire simultaneously with Z-axis thrust efficiency of 98%. (Case A - Figure 22) The second thrusters are considered as cold redundancy, i.e., each

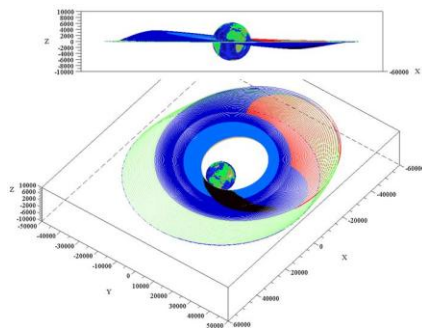


Figure 20. Electric propulsion orbit raising from standard GTO initial orbit (Snecma Software)

thruster is able to cover orbit transfer and NSSK total impulse needs, including margin coefficient. A limitation at 90 days for orbit topping duration has been applied. For station keeping, the results take into account a 15-year service life satellite.

Spacecraft trajectory with electrical/chemical hybrid propulsion system has been established with a SNECMA software (Figure 20.), taking into account exposure to proton flux in the Van Allen radiation environment and earth shadow periods.²³ Our case of study considers a satellite launch injection at a standard GTO (200 x 35,786 km, $i=7$ deg.), i.e. with a remaining 1500m/s GTO→GEO ΔV in classical chemical propulsion. With this injection option and an hybrid transfer, the best optimization is to perform the first corrections with chemical propulsion, in order to : 1) correct the 7° of inclination; 2) reduce eccentricity while the perigee altitude increases. Then, GEO orbit is reached with continuous electrical thrusting, mainly oriented in the direction perpendicular to the vector radius to zero out the eccentricity. It should be noted that beyond a 50% GTO→GEO chemical transfer, all the electrical thrusting is performed outside the Van Allen belts.

Highlighted conclusions of TMA-NG NSSK and orbit topping dual configuration, and detailed in Figures 19 & 21, are:

- Below a dry Mass (M_D) of 1500kg, excepted for limited bi-propellant size tanks reason, alone EP NSSK is not profitable, but it becomes with combined EP NSSK and Orbit Topping (O.T) (Between 40% & 25% of GTO/GEO transfer)

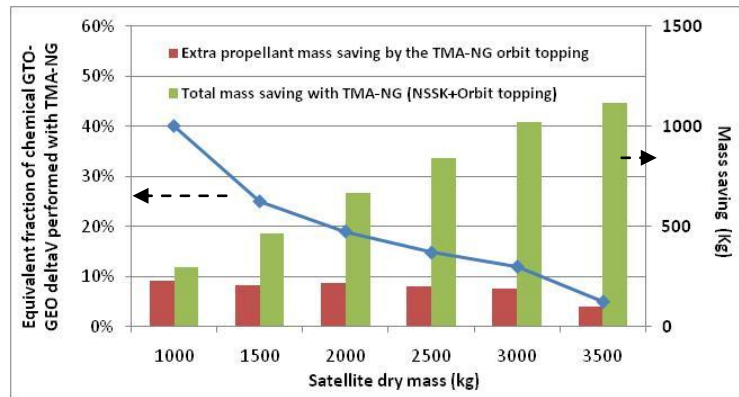


Figure 19. In addition to NSSK, TMA-NG orbit topping capacity and associated mass saving

e.g. for a 3000kg satellite dry mass, around 10% of the GTO→GEO orbit transfer can be performed by TMA-NG thrusters, i.e. a ΔV of 1350m/s (90% of 1500m/s) with chemical propulsion and the last 10% with electric propulsion, corresponding to a ΔV of 315m/s. TMA-NG orbit topping generates an additional propellant mass saving of 190kg and including NSSK benefits, a total satellite mass saving of around 1000kg

thruster is able to cover orbit transfer and NSSK total impulse needs, including margin coefficient. A limitation at 90 days for orbit topping duration has been applied. For station keeping, the results take into account a 15-year service life satellite.

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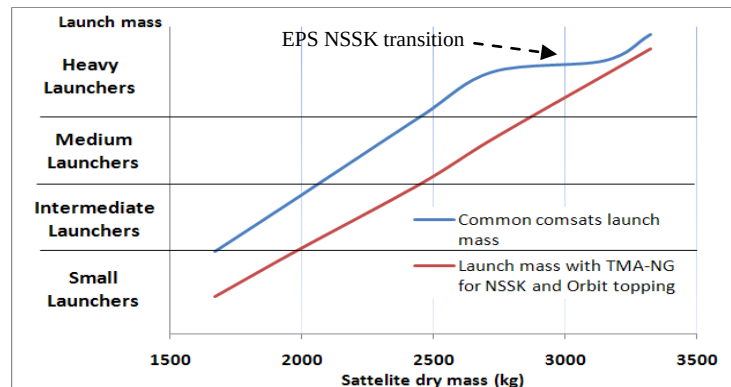


Figure 21. TMA-NG satellite launch mass saving versus launchers families' availability

- Beyond M_D of 3000kg, EP $O.T$ contribution is limited by NSSK total impulse need complementary to the $O.T$ one. Below, limitation is attributable to the 90 days born.

- Between M_D of 1600kg and 2800kg, i.e a common launch mass (M_L) range of 3500-6000kg, with dual EP functions of TMA-NG, launchers class switching becomes visible.

(e.g., a M_L which fell from 6000kg to 5100kg, or 5400kg to 4500kg or 4300kg to 3600kg)

In addition, SNECMA is studying TMA-NG compatibility and/or necessary adaptations to a dual thruster firing (Case B on Figure 22). Cold redundancy will not be 100% conserved; each PPS[®]1350 would be still able to performed NSSK and $O.T$, but in case of one thruster failure during $O.T$, transfer duration would be over 90 days. This configuration requires two additional PPU, but, by faster EP transfer duration, enables for specific M_D to switch two launchers classes. (Figure 23)

(e.g., for a M_D around 2500kg and 2000kg, i.e M_L around 4500kg and 3600kg)

Finally, in the next 5 years, two others configurations (Case C and D on Figure 22), could be considered. Case A

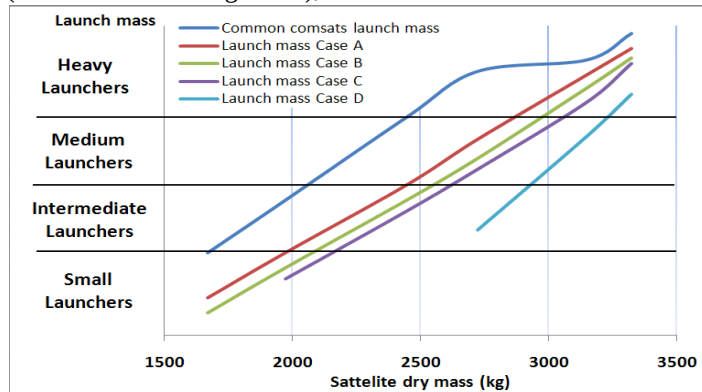


Figure 23. TMA-NG combined with PPS[®]NG satellite launch mass saving versus launchers families' availability

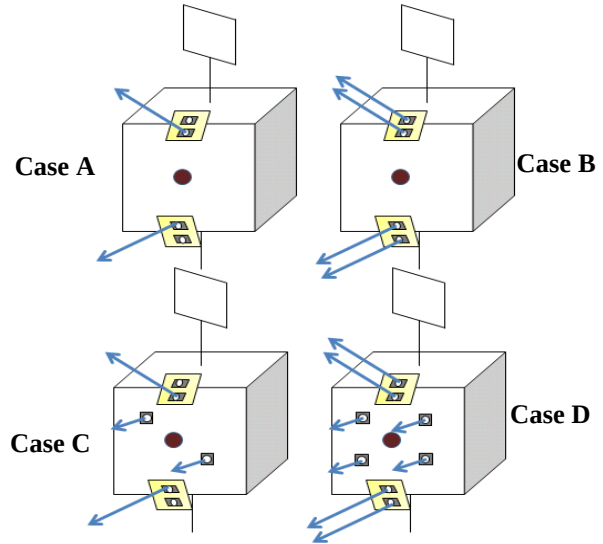


Figure 22. TMA-NG and PPS[®] Firing configuration.

Case A : 2 PPS[®]1350 simultaneously in firing

Case B : 4 PPS[®]1350 simultaneously in firing

Case C : 2 PPS[®]1350 and 2 PPS[®]NG simultaneously in firing

Case D : 4 PPS[®]1350 and 4 PPS[®]NG simultaneously in firing
(Case D' : Case D with 4 PPS[®]1350 instead of the 4 PPS[®]NG)

and Case B respectively combined with 2 or 4 PPS[®]NG²⁴ located near apogee engine and specifically dedicated for $O.T$. These two configurations, although generating additional-costs for the dedicated $O.T$ thrusters and PPU/FU, also enable for specific but larger M_D to switch two launchers classes.

(e.g. Case D, for a M_D around 2700kg, the common M_L around 6000kg should be reduced to around 4000kg; In Case D', i.e 4 on the shelf PPS[®]1350 instead of the 4 PPS[®]NG, the 6000kg M_L should be reduced under 4500kg, with a 90 days $O.T$, corresponding to 60% of GTO/GEO transfer (equivalent to 1535 m/s in EP $O.T$)).

IV. Conclusion

Electric propulsion is now widely used on heavy commercial satellites, and the prospects of all-electric satellites may be considered for mid-term comsats and on an extended range of mass. At short-term, the emergence of new attractive medium size launchers should also increase a democratized use of electric propulsion for NSSK and involve additional functions like orbit topping. Derived from the TMA and its extensive flight heritage, the TMA-NG should provide an adapted solution to the short term market need. With an increased total impulse, specific impulse and thrust, the TMA-NG addressed the NSSK need of the incoming heavy comsats and for the next decade, researching a growth of total impulse and thrust efficiency. With an increased angular range and total impulse, the TMA-NG orbit topping capability would enable for satellite dry mass less than 3000kg, to skip one or two launcher size classes.

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