The Thruster Module Assembly (Hall Effect Thruster) design, qualification and flight

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Abstract: Using electric Hall Effect Thrusters to perform satellite North/South Station Keeping, the Thruster Module Assembly (TMA) has been designed, assembled and qualified by SNECMA with ASTRIUM as customer, to equip their EUROSTAR 3000 satellite family.

The TMA is composed of :

- **two SPT100 thrusters manufactured by EDB FAKEL in Russia (thrust: 83mN, specific impulse : 1600s, power : 1350W),**
- **a Thruster Orientation Mechanism provided by ALCATEL ALENIA SPACE (+/-8° or +/-12°, 2 axes, pyro release),**
- **two Filter Units provided by EREMS,**
- **a structural honey comb baseplate,**
- **modular piping, harnesses and Hot Interconnection Boxes,**
- **active and passive thermal control elements.**

The large heritage, in design and qualification status, issued from the Thruster Module developed in close relation with the Electric Module in the frame of the STENTOR program (launch failure in Dec. 2002), is described. The design modifications, having led to the TMA are presented.

Four TMA are satisfactory used on orbit on two large geostationary satellites for several months. Eight others are waiting for launch or in delivery phase.

I. Introduction

Electric propulsion based on Hall Effect Thrusters (HET) are now operating on geostationary telecommunication satellites, to provide inclination and eccentricity control for North/South Station Keeping and momentum wheels dumping. The Plasma Propulsion System used on the ASTRIUM EUROSTAR 3000 platform is composed of a Gas Module with its Xenon tank, two electric Power Processing Units for redundancy matters and of two Thruster Module Assemblies (TMA). The two TMA are located near the Anti-Earth wall. The North TMA (South respectively) is firing approximately along the bisecting line " North axis (South axis respectively) / normal axis to Anti-Earth panel" to avoid plume damage on solar arrays. The large fuel saving provided by the Plasma Propulsion (Specific Impulse of 1600s instead of 300s for bipropellant chemical propulsion) authorizes a satellite total mass saving of near 20% enabling important launch cost saving, or payload increase or longer satellite lifetime (e.g. 15 years instead of 10).

II. TMA origin

Plasma Propulsion has been developed, since 70's, by Russian industrials and research laboratories. The Stationary Plasma Thruster (SPT) family, originated with the 50 series and leading to the 140 series, has been intensively flying on Russian satellites (Kosmos, Luch, Meteor, GALS, Express, …). The most promising and mature thruster, is the SPT100, manufactured by EDB FAKEL in Russia and sold in Europe by SNECMA. It has been mounted, with an other HET thruster, on the original TMA, developed and qualified with its Electric Module by SNECMA, in the frame of the STENTOR satellite program of CNES French space agency. Despite the lack of flight experience (STENTOR launcher failure in Dec. 2002), the TMA has been slightly modified and adapted to the ASTRIUM EUROSTAR 3000 platform, in two versions (Generic Family and Geomobile Family). It benefited from additional and enhanced qualification efforts.

III. TMA description

The TMA is composed of :

-two SPT100 thrusters (one nominal, one redundant) with their associated Xenon Flow Controllers (XFC), (thrust : 83 mN, specific impulse : 1600s, power : 1350W, discharge voltage : 300V, discharge current : 4.5A). Each thruster, manufactured and acceptance tested by EDB FAKEL in Russia, is equipped with two cathodes (and associated XFC parts) for additional redundancy,

-a Thruster Orientation Mechanism[4] provided by ALCATEL ALENIA SPACE in Cannes, France (+/-8° for Generic Family or +/-12° for Geomobile Family, 2 axes). This mechanism, also developed for STENTOR, comprises a multi-tubular structure with dampers, a cardan, a mobile plate, two actuators based on roller screws and stepper motors, two optical switches and a pyro release blade. Ball bearings are lubricated with fluid oil. The TOM mass is 11.3 kg.

-a Honey Comb baseplate to enable structural integrity of the TMA and global shimming at I/F on the satellite wall,

-two Filter Units, to filter thruster discharge current oscillations with regard to PPU outputs, to fix electric potentials (as Cathode Reference Potential,…) and to flow out charging. They are low pass filters and are mainly composed of passive components and include a discharge current oscillation probe. For memory, the PPU manages the outgassing and prestart operations and control and monitor the thruster and its XFC. The XFC flowrate is controlled to obtain a 4.5A discharge current.

-two S5 flexible harnesses to supply thruster and passing through TOM cardan,

-two Hot Interconnection Boxes (HIB), located on the TOM mobile plate, to connect thruster to S5 harness and some thermal control lines,

-a XFC fluidic module, located on the baseplate, including XFC and piping (welded connections upstream XFC and screwed connections downstream) (see TMA fluidic diagram on Figure 3.),

-6 titanium flexible tubing, passing through TOM cardan,

-redunded active thermal control hardware (heaters with a global power of 62W per TMA which are ON/OFF cycled, safety thermoswitches and thermistors to enable the satellite computer to control the temperature around +10°C for the three independent areas of the TMA (TOM mobile plate, XFC of first thruster, XFC of second thruster)),

-ElectroMagnetic Compatibility/ElectroStatic Discharge/Plasma protection devices for electric hardware,

-individual shim under each thruster, to be determined and machined before TMA assembly.

The TMA mass is 28.7 kg.

See Figures 1.,2. and 4. for TMA views.

The external MLI, to be compatible with TMA mobility and with thruster firing plasma, is under the satellite responsability.

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 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 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 approximatively 20W by conductive link (lower, the thruster low part would be at temperatures near 250°C which is not acceptable, higher, the flux rejected towards satellite wall would be too important).

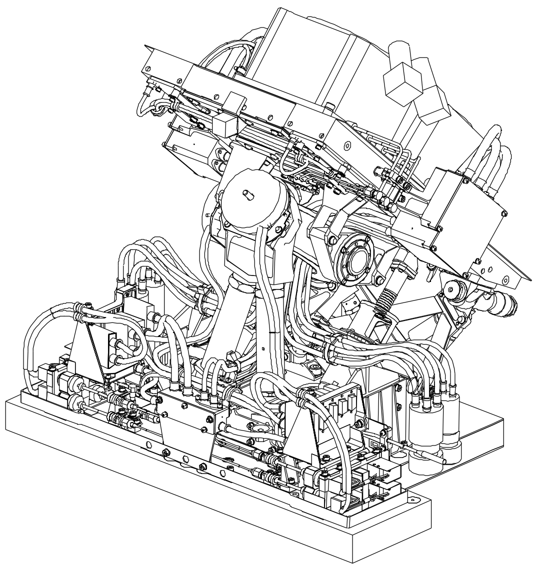

Figure 1. TMA without FU & MLI (back view)

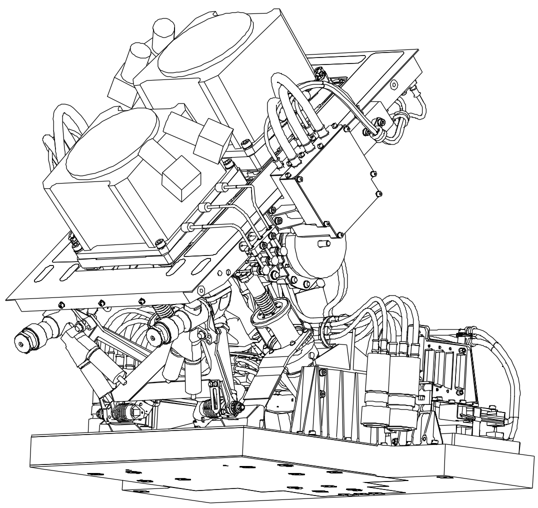

Figure 2. TMA without FU & MLI (front view)

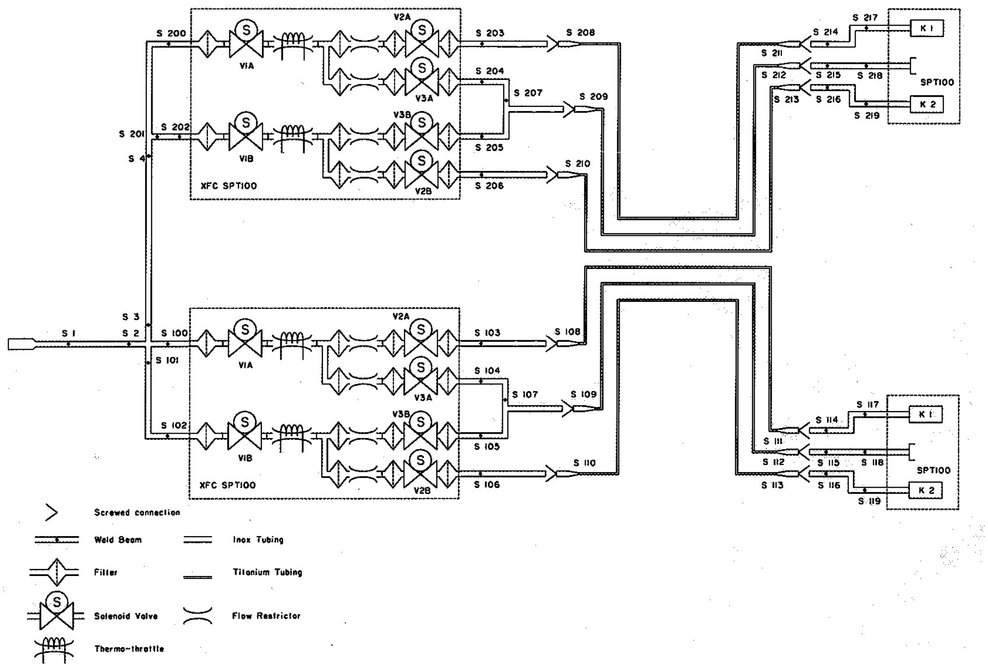

Figure 3. TMA fluidic diagram

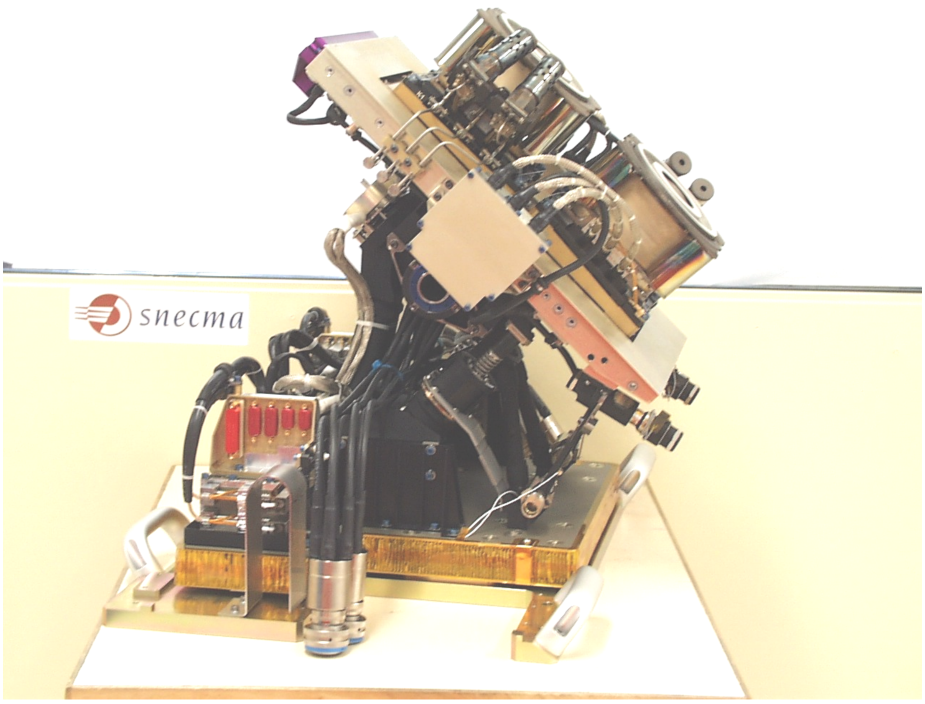

Figure 4. TMA

IV. HET thruster description

The Stationary Plasma Thrusters are gridless ion thrusters using Xenon as a propellant.

Xenon gas is routed through the anode gas distributor into the discharge chamber (see Figure 5.).

An essentially radial magnetic field is produced by outer and inner solenoids (electrically fed in series with the discharge), and concentrated by outer and inner pole pieces forming a magnetic lens at the outlet of the discharge chamber.

Electrons emitted from one of two redundant hollow cathodes are hindered in their motion to the anode by the transverse magnetic field thereby establishing an electrical field and colliding with xenon atoms to form ions.

A part of the electrons emitted by the cathode also acts to neutralize the ions exhaust beam.

The anode-gas distributor and the propellant feeding line are electrically at a potential of + 300 V or 350 V during the discharge and therefore are isolated from the inlet gas supply line through two redundant electrical isolators.

The discharge chamber is an annular U shaped unit composed of a ceramic BN SiO_2 which insulates the thruster body from the thruster plasma.

Each hollow cathode contains:

-a LaB6 thermal emitter which, heated to a high temperature, ensures emission of electrons,

-a heating coil which is used during start up phase to bring the device to the necessary temperature,

-a getter composed with tantale sheets which traps all the oxygen trace in the xenon before feeding the hot temperature core,

-an igniter.

The XFC consists of series redundant isolation valves, thermally constricting capillary tubes (thermothrottles), flow restrictors to control the Xenon flow ratio between the operating cathode and the anode unit, and gas filters at the inlet of each valves.

The Power Processing Unit provides a closed loop Xenon flow regulation to the thruster : the thermothrottle current is adjusted by the PPU and thereby the temperature of the gas changed in order to keep the delivered mass flow rate and so, the discharge current at a nominal set value.

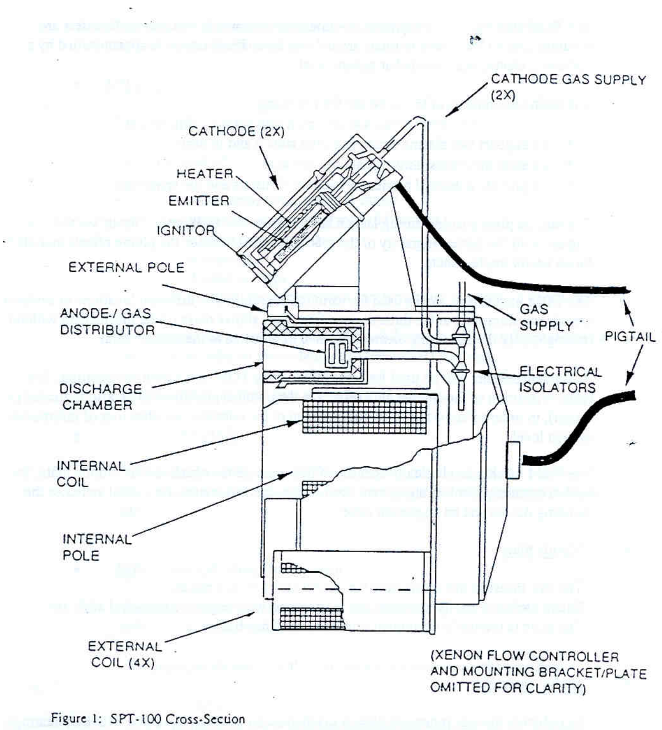

Figure 5. HET thruster functional elements

V. TMA initial development for STENTOR

Since the middle of 90's, SNECMA has developed and qualified, with the participation of EDB FAKEL, a thruster called PPS®1350 (thrust : 88 mN, specific impulse : 1650s, power : 1500W, discharge voltage : 350V, discharge current : 4.28A) belonging to the same class as SPT100 one. One of the goal of STENTOR satellite was the flight evaluation of both thrusters, so each of the two TMA comprises a SPT100 thruster and a PPS®1350 thruster. ALCATEL ALENIA SPACE was in charge of the Gas Module development/qualification and was the Plasma Propulsion Subsystem responsible. SNECMA was in charge of the TMA and of Electrical Module development/qualification and particularly of the coupled design/development/qualification of PPU/FU/thrusters. ALCATEL ETCA (Belgium) was selected for the PPU activities and EREMS (Toulouse, France) for the FU.

The TMA development/qualification logic was the following one:

- Thrusters: an Engineering Model (EM), Structural Model (StM) and two Qualification Models (QM) for PPS®1350 thruster, original qualification by EDB FAKEL for SPT100 thruster, plus a Flight Model tested in enhanced environment.

-TOM: an StM, a first QM for thermal, vibration and lifetime and additional vibration leading to failure, a New QM with modified design for series of manual and pyro releases, vibration, satellite shocks and new lifetime, and a PFM for additional vibrations.

- Filter Unit: a BreadBoard Model, EMs and a QM.

- Several separated and End to End test campaign for thruster /FU/PPU development and qualification including ESD and EMC matters.

-For TMA, Thermal Mock-up with firing thruster or sun simulation with Xenon lamps under vacuum, HIB temperature and current cycles under vacuum was performed with CNES assistance. Confidence Mock-Up (hundreds of lifetimes without failure at ambient pressure and temperature) for S5 flexible harness and only a ProtoFlight Model for TMA. The most impressive 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).

VI. TMA design evolutions for EUROSTAR 3000 platform

Satellite operators and ASTRIUM have selected the SPT100 for the two thrusters of each TMA. The honey comb baseplate has been added. The TOM and TMA angular range has been kept at -/+ 8° for EUROSTAR 3000 Generic Family and set to +/- 12° for Geomobile Family (note : TOM QM has been designed and qualified up to +/-16°). The TMA thermal control heater power has also been kept for Generic Family and increased to 6W twice for XFC to bear thermal environment up to (qualification temperature) –41°C / +69°C at satellite I/F and +5°C/+89°C at TMA mobile plate levels, for Geomobile Family. The radiator function of the TOM mobile plate, covered by Optical Solar Reflector mirrors radiating towards space for STENTOR has been deleted for EUROSTAR (mobile plate being covered by the MLI) due to a better knowledge of the temperature margins after STENTOR and thermal tests and upgraded computerized thermal model. To follow the TOM mobile plate rotation, ASTRIUM selected a concertina concept for the TMA MLI instead of the "double stiff box with gap" concept of STENTOR.

VII. TMA additional qualification efforts for EUROSTAR 3000 platform

Financed by various customers, SPT100 thruster (#49) has been submitted under the SNECMA responsability in its test benches, to a full new qualification campaign with enhanced environment (thermal cycling, vibration, satellite and TOM release successive shocks) and a lifetime of 8990 h and 5707 cycles, in test bench supply mode but also mainly with flight hardware PPU and FU, and Gas Module Xenon supply.

The last part of the TOM qualification test campaign took into account the EUROSTAR 3000 additional requirements (vibration with two SPT100, manual and pyro releases, satellite shock test, new lifetime profile).

Some FU have been submitted to protoqualification tests.

An ElectroMagnetic Interferences campaign has been led in an U.S. firing test bench to characterize 4 SPT100 thrusters (various aging) connected to a HIB, a S5 harness and a Filter Unit.

Series of Pyroshock have been performed on SPT100 thrusters and mock-up including sensitive parts.

A satellite shock has been performed on a TMA mock-up composed of a flight standard baseplate with the TOM QM and thruster mock-up mounted on.

For each family (Generic and Geomobile), a TMA has been acceptance tested as a PFM with enhanced environments(vibration and thermal vacuum).

VIII. TMA flight experience

One Generic Family and one Geomobile Family EUROSTAR 3000 satellites (4 SPT100 on two TMA for each) have been launched in 2004 and 2005 with a maximum firing rate of 300 hours per year and per TMA . Two other Geomobile Family satellite are waiting for launch. Three other TMA are spare.

Concerning the 1500W thruster class :- an American satellite builder, using also 4 SPT100 per satellite, has launched, 3 satellites in 2004/2005 and is preparing for launch two other satellites. Concerning the Russian satellites (using 8 thrusters without alignment mechanism), near 32 SPT100 thrusters have been launched in 90's and near 64 SPT100 thrusters have been launched since 2000 and are still in operations. A PPS®1350 has been launched in September 2003 on the European probe SMART-ONE and successfully [1] led it around the Moon as main propulsion thruster (5000 hours of firing at various power levels). Currently, no in-flight failure of Electrical Propulsion System based on Hall Effect Thruster is reported. The analysis of the initial flight operations of the first E3000 satellites[2,3], shows a very efficient use and consistent with predictions, of Plasma Propulsion System.

IX. TMA development lessons learned

The development/qualification of the HET thruster with its Filter Unit and Electrical Module, is certainly the longest, expensive and difficult challenge. An other difficult point, not to be minimized in term of industrial risk is the coupled behaviour HET thruster / alignment mechanism, in thermal and vibration domains.

The TOM, too high (i.e. amplifying at thruster level, the satellite wall vibration by rotation of its basis), requested during development, the use of flexible blades at thruster I/F and of many silicone dampers to avoid to exceed 20g at thruster basis, despite notching down to 0.4g at TOM basis.

The use of TOM pyro release system requested additional shock qualification campaign (performed at ambient temperature) for several equipments and required to select the most appropriate time to release in orbit.

Optical switch system could be simplified. The current modularity of the TMA shall be kept or even increased in order to reduce the 24 month TMA manufacturing and test delay, which is time critical. In the same way, the PFM logic is time risky. For a new generation TMA, with the obtained thermal data, it should be possible to reduce the number of TMA internal parts requiring high emissivity surface treatment. Thruster with a single cathode and XFC could be an interesting way for cost and mass saving.

X. Outlook

A New Generation of TMA, compatible with SPT100 thrusters and other 1500W class HET thrusters, is envisaged. It would incorporate a less complex orientation mechanism.

At satellite level, a propulsion architecture with no chemical thrusters, based only on HET Electric Propulsion located on TMA and on fixed pods, is very promising. Nevertheless, a solution has to be found to reduce the orbit raising duration. HET thrusters, despite their moderate Specific Impulse (1600s to be compared to the 3000s of a grid ion thruster) appear to be the best candidates due to their high thrust level, compactness, moderate supply voltage and power, flight experience without noticed failures.

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