Plasma Propulsion on STENTOR Satellite: In Flight Acceptance Operations and Experimental Program*†

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STENTOR is a French technological telecommunication satellite, to be launched in December 2001 and equipped with 4 plasma thrusters (SPT100 and PPS1350) for performing its north/south station keeping. In this paper, are reported:

- **The STENTOR Plasma Propulsion System (PPS);**
- **The flight acceptance operations that will be performed after the orbit raising;**
- **The operational and experimental program of the Plasma Propulsion sub-System;**
- **The associated experimental program (mainly on plume effects).**

Introduction

STENTOR is a 2210 kg French geostationary telecommunication satellite.

Figure 1: STENTOR

Its purpose is to give flight opportunities to some strategic new equipments and sub-systems and to fully demonstrate and validate their performances in geostationary orbit. The Electric Propulsion (EP) is one of these new technologies. The program is managed by a governmental team (CNES, France Telecom and DGA). The Plasma Propulsion System (PPS) is developed by Alcatel Space. It is described in part I.

The STENTOR launch is scheduled for December 2001 on Ariane 5 launcher. After the launch and the orbit raising, some operations will be performed on the PPS (preparation for operation and acceptance tests). They are described in part II.

Then, the PPS will be used for the north south station keeping and excentricity control of the spacecraft (s/c). In parallel, the PPS will be used as a flight test bench to characterize and perform experiments on the thrusters.

This operational and experimental utilization of the thrusters is described in part III.

Other experiments dedicated to plume and to plume effect characterizations will be conducted. They are described in part IV.

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The STENTOR project is expected to result in consequent industrial fallouts (flight demonstration of the sub-system and of the thrusters) as well as scientific and technological ones (thruster and plume effects characterizations). This is done in close connection with the French program in EP [1].

I. STENTOR Plasma Propulsion System (PPS)

The STENTOR PPS is described in detail in [2]. The sub-system is represented figure 8 (end of the paper).

The PPS is composed by a gas module, two thruster modules (one north and one south, tilted by about 45° with the Y axis and located on the anti-earth wall as represented figure 2) and two electrical modules (one nominal and one redundant).

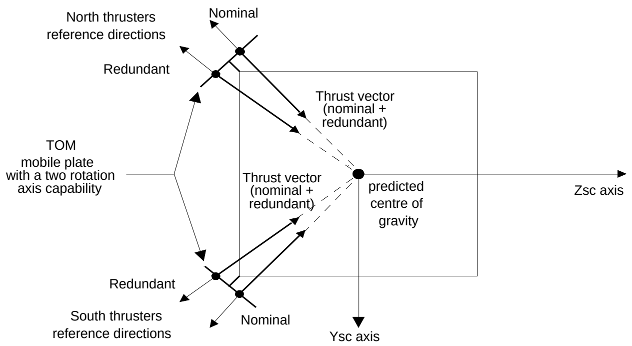

Figure 2: Schematic representation of the thruster (black arrows) module implementation on the s/c

The gas module

The gas module includes the following equipments:

- one 68 l Xenon tank allowing Xenon storage at an optimized pressure of 150 bar (but not fully filled for the STENTOR mission),
- a normally closed pyro valve isolating the storage volume during ground integration activities and launch,
- high pressure transducers for Xenon gauging,
- titanium feed lines
- fill and drain valves for on-ground operations,
- isolation valves,
- Xenon filter,
- a mechanical pressure regulator which is fully series redundant. Each stage is capable of delivering Xenon at the regulated pressure needed by the thruster modules and is providing leaktightness between two thruster operations,
- low pressure transducers used to tightly monitor the level of the regulated pressure.

The thruster modules

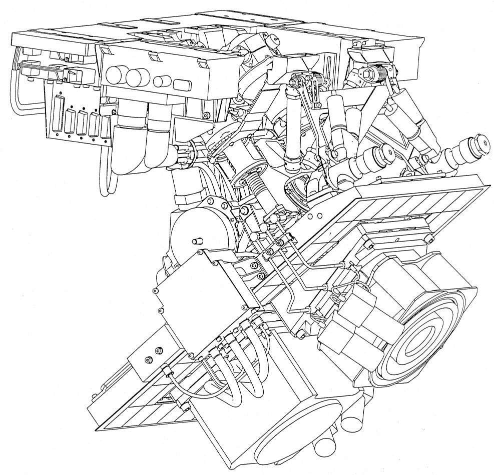

Figure 3 Thruster module

Each thruster module includes:

- Two Hall effect plasma thrusters: one SPT-100 (manufactured by FAKEL) and one PPS-1350 (manufactured by SNECMA), each thruster being equipped by two redundant cathodes.

Figure 4: The PPS-1350 flight model

- Two Xenon Flow Controllers (XFC) associated to each thruster. The XFC includes a thermothrottle which allows to control the Xenon mass flow in a closed loop based on the discharge current monitoring.
- A Thruster Orientation Mechanism (TOM) used to steer the plasma thrusters around two axes in a 8° half cone. The TOMs are stored in a locked position during launch and are released once in orbit using pyrotechnic devices.
- One set of Xenon feeding pipes and electrical harness to supply SPTs and XFCs. Routing toward the thrusters is arranged near the TOM rotation center in order to minimize resisting torques.
- One set of thermal control devices (temperature sensors, heaters, thermooptical tapes).

The mobile plate of this mechanism is also used as a radiative plate.

The electrical modules

The electrical modules manage and deliver to thrusters and XFC the required power for operation. Each electrical module (prime and redundant) is connected to two thrusters (one north and one south) but operates only one thruster at one time. On one hand, the SPT-100s are operated with the electrical module configured in 300 V; on the other hand, the PPS-1350s are operated with the electrical module configured in 350 V.

Each module is made of the following components:

- One Power Processing Unit (PPU) and its associated Thruster Selection Unit (TSU). The PPU controls the selected thruster and its associated XFC on the basis of programmed procedures and commands received from the on-board computer. In particular the PPU manages an automatic sequence for the thruster start-up and controls the discharge current closed loop. PPU also includes a remote control mode in order to provide tools for step by step control / diagnostic purposes. The PPU is connected to the 1553 Data Bus and to the 50 Volts power bus.
- Two electrical filters (one per thruster). The Filter Unit (FU) is located upstream each thruster in order to limit electromagnetic conduction from the thruster towards the PPU. For this reason the filters units are located as close as possible from the thrusters.
- The associated harness between PPU, FU and thruster modules.

II. In flight acceptance operations

After the orbit raising, the PPS will be initialized and tested by performing successively the following operations:

Thruster orientation mechanism unlocking

During launch, the mechanisms are stowed and maintained in a locked position. This operation consists in releasing the two mechanisms by firing pyro actuators. Optical switches that are integrated onto the thruster modules are then used to check the correct unlocking.

Venting of the Xenon gas lines

The isolation valves and the XFC valves are open successively for the four thrusters. The purpose is to vent the gas lines downstream the pyro-valve. Then, all the valves are switched to the off position.

Priming of the pyro-valve

The normally closed pyro-valve, isolating the high pressure part of the gas module is activated, which pressurizes the circuit upstream the isolation valves with Xenon. The pressure regulator reaches then its lock up pressure and the subsystem is ready for operation.

Thruster acceptance tests

Each thruster will be fired twice, one time with the nominal cathode and XFC and one time with the redundant branch. The thruster firing duration and scheduling depend on mission and system constraints. Basically each firing will last approximately 30 min and be performed when plume effects are minimum (roughly at 6 h and 18 h). During these firings, the AOCS will be operated in "Ion Station Keeping Mode", controlling in closed loop the thruster orientation mechanism. The AOCS is expected to converge during these preliminary firings, aligning the

resulting force produced by the thruster with the satellite center of mass.
The check of the proper PPS operation for each thruster and cathode will be made by a telemetry analysis (pressures, temperatures, electrical parameters, AOCS data). The thruster performances will be determined later as far as ceramics outgassing is expected to change a little the thruster characteristics during the first firings. Moreover, these preliminary tests will allow to determine the initial steering to apply on thruster orientation mechanisms for next firings.

Thruster orientation mechanisms acceptance tests

Out of any plasma thruster firing, the orientation mechanisms will be moved around their two axis (in open loop, using nominal and redundant actuators), in order to check their proper operations.

All these operations will be carried out in the 4 weeks after that the satellite will be on station.

III. Operational thruster utilization and experimental program

North-South Station Keeping and excentricity control

The orbit inclination control is realized by firing alternatively north and south thrusters when the spacecraft is respectively at the ascending and descending node. The firings are performed each 12 or 36 hours (i.e. ½ or 1½ orbit between a north and a south maneuver). The Firing duration is typically between a few tens of minutes up to two hours. The maneuver planning and duration is reoptimized during the spacecraft mission considering various aspects:
- space dynamics (N/S and excentricity control)
- mission constraints (incompatibility with some other s/c operations)
- power resources (battery depth of discharge, eclipse)
- thruster corrected performances (thruster aging, plume effects).

The ground uploads the firing date, its duration, the PPS configuration (nominal or redundant equipments) and the TOM initial position. Then the operations are realized fully automatically, managed by the on board computer, by the PPU (start-up sequence, thrust control and security checks) and by the AOCS (TOM position controlled in closed loop to minimize the s/c attitude perturbations).

Fine estimation of the thrust (magnitude, direction and perturbation)

One of the first experiment that will be carried out on STENTOR will be the fine evaluation of the thrust generated by each thruster (magnitude and triaxiality). Complementary to this experiment, the thrust loss and the torque due to the mechanical interaction between the plume and a solar array will be estimated. The purpose is firstly to provide a validation of ground measurements and secondly to initialize the models requiring as input the thruster performances and the plume effects (station keeping strategy i.e. s/c autonomy ; propellant gauging and energy management,…). The experimental methodology is described below:

During the first months, the drift of STENTOR orbit inclination will be authorized (as far as the s/c is still inside the orbital slot). As no north/south maneuvers will be realized during this period, plasma thrusters (and their firing strategy) will be optimized for the only purpose of this experiment. Each thruster will be typically fired successively several times for remarkable solar array positions (for example in order to have best and worst cases in term of plume effects):

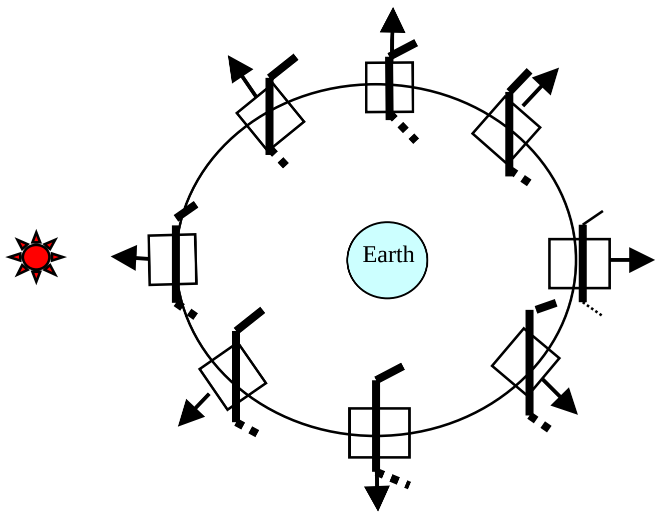

Figure 5: Relative thruster (arrow) / solar array (dark line) position during one day

Before and after each thruster firing, a very fine satellite ranging (using a channel of the KU payload and 3 ground stations) will be performed to determine the effective deltaV (magnitude and direction) for each maneuver. Knowing these data and the kinetic momentum accumulated on different axis, it will be possible to calculate precisely the thrust components and the plume effects. A very good precision is expected (for example 1 % on the thrust magnitude).

Complementary thruster characterization

Thruster aging: As it is well known, the thruster performances are slightly changing with the thruster aging. A drift of both the thrust and the specific impulse (Isp) is measured during ground lifetime tests, especially during the first 1000 operating hours. This drift in performances is mainly linked to the ceramics (discharge channel) erosion and it occurs with a rather good repetitiveness comparing one lifetime test to another.
The performance profile of the thruster as a function of the cumulated firing time will be evaluated. This will be realized by monitoring the thrust (through s/c ranging) and the Isp (through the mass flow rate consumption). If necessary, to refine the thrust determination, and to measure triaxiality and plume effects, the same experiment as the one described in the previous part will be reproduced.

Thruster operating domain: The STENTOR PPS can be tested at different operating points, by changing the discharge current (i.e. the mass flow rate) or the magnetic tuning (adding some current in the magnetic coils). This kind of thruster characterization are commonly performed during ground tests and it will be very interesting to have comparison point between ground and flight performances, for example in term of optimal magnetic tuning.

IV. Plume effect characterization

Due to the large thruster plume divergence, some interactions with the spacecraft may occur (plume effects listed in [3]). Up to now, these interactions are a concern as far as current plume models and interaction models are not properly validated. Indeed, the model validation is a big issue, due to the low representativity of ground tests in some cases (facility and pressure effects) and due to the lack of flight data (at least in Europe). Consequently, one major part of the STENTOR experimental program is dedicated to the study of these plume phenomena. Both the plume and the plume/spacecraft interactions will be characterized on STENTOR, in order to validate the models and to provide data that can be compared directly to ground measurements [3].

Plasma Diagnostic Package

The plume characteristics will be investigated on STENTOR using a Plasma Diagnostic Package (PDP), designed and manufactured by LABEN/Proel, with Alcatel Space as prime. The equipment is described in detail in [4].

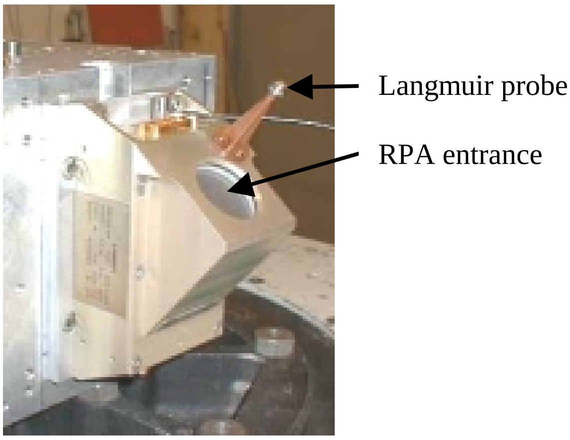

Figure 6: Flight model of the Plasma Diagnostic Package (Langmuir and RPA probes)

It is composed of a probe module constituted with one Retarding Potential Analyzer (RPA) and one Langmuir Probe (LP). These two probes will be used to measure the plasma beam characteristics (ion energy distribution function, plasma density, electron temperature, plasma potential and ion flux) for different locations in the plume. Indeed, the probe module is mounted on the north solar array yoke as indicated figure 7:

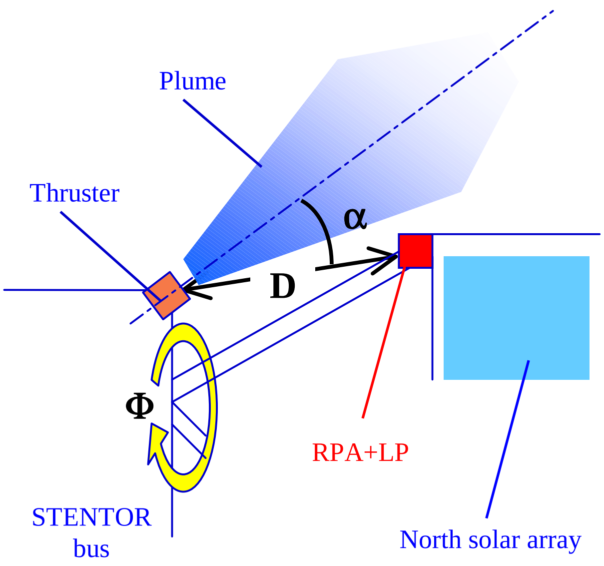

Figure 7: Location of the Plasma Diagnostic Package on board of STENTOR satellite

This arrangement allows to characterize a wide area of the plume, preventing the utilization of a complex deployable mechanism. Depending on the local time, the solar array (sun pointed) will have different orientation wrt the thrusters (on the anti-earth satellite side). This enables a characterization of the plume for divergence angles higher than 60° (α on figure 7) which is a region of interest concerning interactions with the s/c and moreover a region where ground data are strongly altered by facility effects. The probes have been optimized for plasma measurements in this low-density area.

On STENTOR, it is also proposed to use this diagnostic tool for determining the long term evolution of the plasma plume linked to thruster aging and for measuring the plume behavior when changing the thruster operating point.

The same diagnostics have been used in ground facilities to provide direct comparison points [3]. It has been especially highlighted the large proportion of low-energy charge exchange ions for a divergence higher than 60°. The charge exchange ion population is expected to be lower on geostationary orbit, because of the much lower residual pressure, as predicted by the plume models.

Solar array impingement

The north solar array is instrumented by two temperature compensated Quartz Crystal Micro-balances (QCMs) coated by two materials (Ag and SiO2). Depending on the relative thruster / solar array position, the QCMs will be submitted to an ion flux with different energy and incidence angle. Consequently, it is expected to determine the sputtering and the deposition rates onto these two materials (Ag and SiO2) due to xenon ion bombardment. This experiment will provide direct comparison points with predictions provided by plume interaction models [3].

Moreover, the north solar array is instrumented with solar cell samples with the purpose to determine their electrical performance evolution due to the thruster firings and plume impingement.

Conclusion

The technological satellite STENTOR offers a "flight test bench" to demonstrate and to experience new space technologies. Electric propulsion is one of these key technologies. A consequent experimental program (both on the thruster and on its interactions with the s/c) has been settled in complement to a "nominal" utilization of the thruster for performing the north/south and exentricity orbit control.

We expect from this flight program a very strong technological and scientific return, beneficial for the European space community.

References

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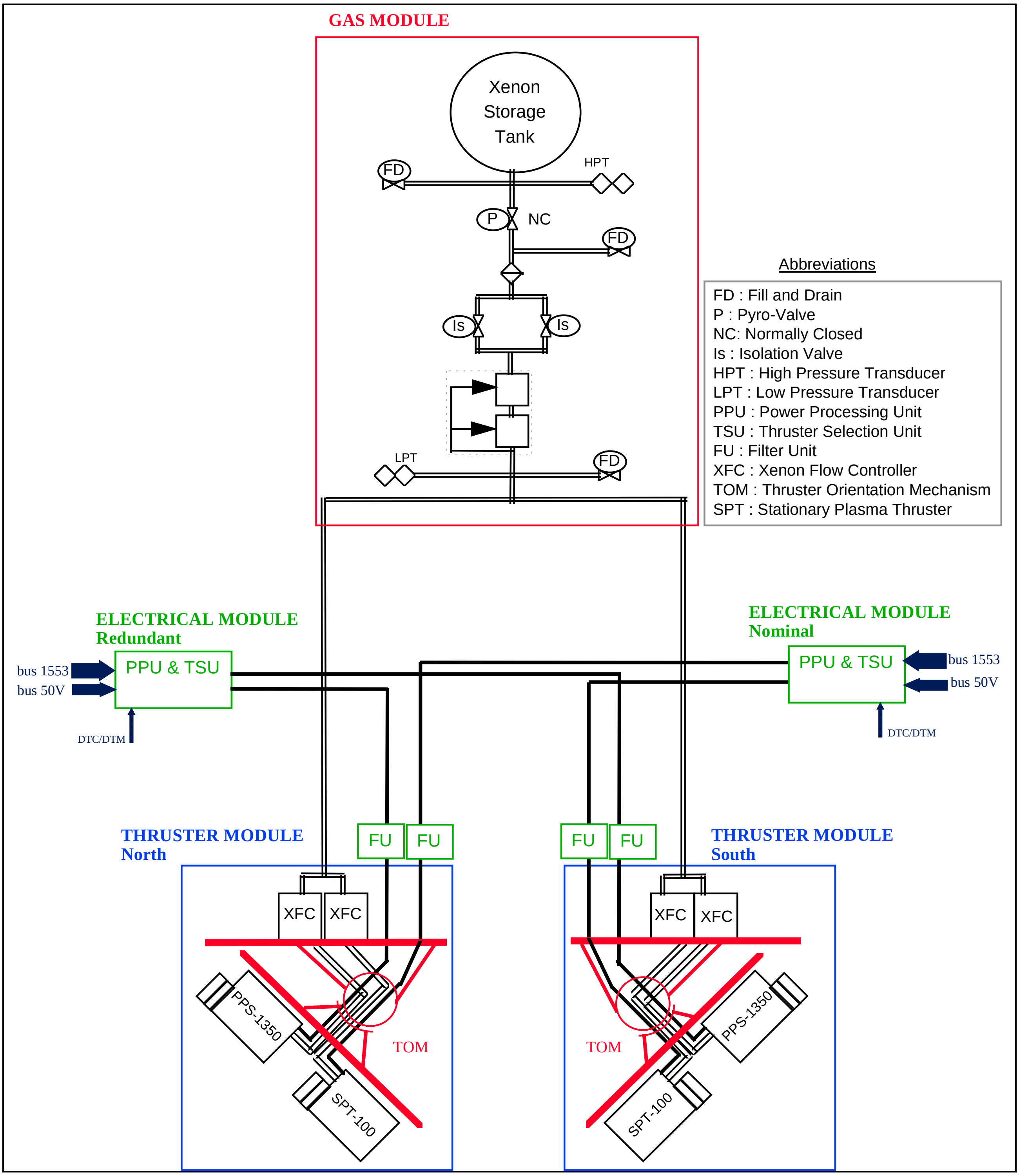

Figure 8: Plasma Propulsion System (PPS) synoptic