Power Processing Unit Activities at Thales Alenia Space ETCA

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Eric Bourguignon[1], Stéphane Fraselle[2] and Thierry Scalais[3]
Thales Alenia Space ETCA, B-6032 Mont-sur-Marchienne, Belgium

Abstract: Since 1996, Thales Alenia Space ETCA designs, develops and produces Power Processing Unit (PPU) to supply Hall Effect Thrusters: SPT-100 from Fakel and PPS-1350-G from Snecma. The first qualification model, developed for the 50V bus Stentor program, has supplied during 8900 hours an SPT-100 thruster in a vacuum chamber simulating space environment. Qualified for the Spacebus 4000 platform, with a 100V regulated bus, the SB4000 PPU and Filter Unit EQM have cumulated 6300 hours ground operation with a PPS-1350-G thruster. Nineteen PPU flight models were delivered for the Stentor, Astra-1K, Smart-1, Intelsat, Inmarsat, Eutelsat and Yahsat satellites. In October 2005, the Smart-1 spacecraft reached the Moon after 4958 hours of cumulated operation of the PPU and its PPS-1350-G thruster. In March 2011, the twelve PPU's currently performing North South Station Keeping with SPT-100 thrusters on six telecom satellites have cumulated more than 12 000 hours flight operation. Following the selection of the PPS-1350-G as baseline thruster for the AlphaBus platform, the Alphabus PPU was developed and two flight models were delivered for AlphaSat. On the SmallGEO platform, one EPTA branch has to drive one out of four SPT-100 thrusters. As the PPU drives one out of two thrusters, TAS-ETCA has developed an External Thruster Selection Unit (ETSU) to be associated to a PPU. Two flight sets (PPU+ETSU) are being manufactured. In order to propose a more competitive product, TAS-ETCA has started the design, development and qualification of the new generation of PPU, called PPU Mk2. In addition, a higher discharge power capability and an improved flexibility with respect to the thruster operating point have been considered as design targets. This article will present an overview of the Power Processing Unit activities in Thales Alenia Space ETCA, including flight heritage, lessons learnt and the development of the PPU Mk2.

Nomenclature

EPS	=	Electric Propulsion System
EPTA	=	Electric Propulsion Thruster Assembly
ETSU	=	External Thruster Selection Unit
HPPU	=	High Power Processing Unit
PHVC	=	Positive High Voltage Converter
PPU	=	Power Processing Unit
PSCU	=	Power Supply and Control Unit
SPT	=	Stationary Plasma Thruster
TSU	=	Thruter Selection Unit
XFC	=	Xenon Flow Controller

[1] PPU Product Manager, eric.bourguignon@thalesaleniaspace.com
[2] PPU Mk2 Technical Manager, stephane.fraselle@thalesaleniaspace.com
[3] PPU Small GEO Technical Manager, thierry.scalais@thalesaleniaspace.com

I. PPU main functions

PPU is composed of the following modules (see Fig. 1):

- Interface on the Primary input power bus, insures main bus protection, voltage level conversion and galvanic isolation required by the SPT supplies.
- SPT power supplies, the 4 types of electrodes of the Stationary Plasma Thruster (anode, magnet, heater, ignitor) are supplied according to their specific power profile.
- XFC power supplies, PPU supplies the Xenon Flow Controller: opens or closes the xenon valves and controls the discharge current by the regulation of the xenon flow via the thermothrottle power supply.
- Sequencer, insures the automatic control and the survey of the thruster operation: start-up, stop, regulated thrust, failure recovery, ...
- TC/TM interface with the satellite communication bus.

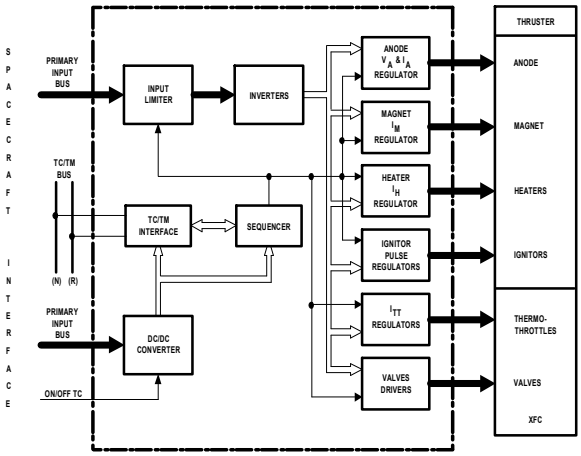

Figure 1. PPU functional block architecture

II. Current PPU Product

The main characteristics of the 1.5kW class PPU are summarised hereunder:

- Compatible with SPT-100 and PPS-1350-G Hall Effect Thruters.
- Includes SPT and XFC power supplies.
- Maximum Power in the thruster discharge circuit: 1500 W.
- Compatible with 50V or 100V regulated input power bus.
- TC/TM plug-in module available for MIL-STD-1553, ML16-DS16 and OBDH-RS485 (RUBI) communication busses.
- Can be equipped with or without a switching module (called TSU for Thruster Selection Unit) allowing to drive one out of two motors ; this module is typically used for North-South station keeping application on geo-synchronous satellite.
- Efficiency in nominal operating conditions:
  - 91.6 % for Vbus = 50V
  - 92.4% for Vbus = 100V.
- Mass for one PPU including TSU: 10.4 kg.
- Dimensions: 390mm x 190mm x 186 mm (LxWxH).

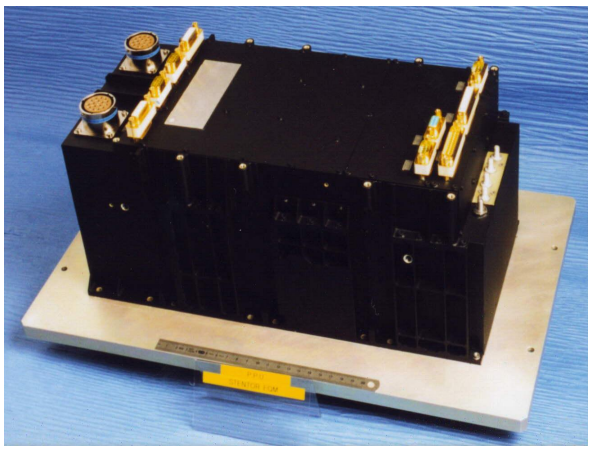

Figure 2. Stentor PPU EQM

- Fully qualified according to environment specifications of Europeans platforms Eurostar 3000, Spacebus 3000, Spacebus 4000 and AlphaBus.
- 8 900 hrs lifetime test in space vacuum conditions coupled with SPT-100 thruster.
- 4 958 hrs flight experience on Smart-1 launched in September 2003.
- Since July 2004, 12 000hrs cumulated flight operation on six geo-synchronous telecom satellites: Intelsat 10-02, Inmarsat 4-F1, 4-F2, 4-F4, Kasat, Yahsat-1A.
- Twenty-one flight models already delivered for the Stentor, Astra-1K, Smart-1, Intelsat 10-02, Inmarsat 4-F1, 4-F2, 4-F4, Kasat, Yahsat-1A, 1B, AlphaBus

III. Smart-1 PPU

A. Specific Features

On Smart-1 spacecraft, one PPU drives one PPS-1350-G Hall Effect Thruster with variable power from 300W up to 1.2kW according to an external telecommand. With this telecommand, the spacecraft adjusts the Electrical Propulsion sub-system demand with power available from the solar arrays during the different phases of the mission.

B. Variable Anode Voltage and Power

The anode output characteristic is adjustable from 175V/306W up to 350V / 1225W (see Fig. 3).

For each setting of anode output characteristic, the additional magnet current setting and the discharge current setting are automatically adjusted by the sequencer.

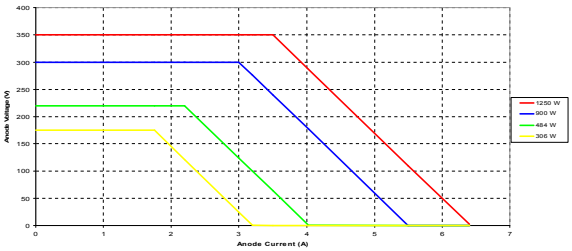

Figure 3. Anode output characteristic

C. Low Power Start-Up

To reduce power inrush demand on main bus, the thruster start-up is performed by PPU sequencer at 220V anode voltage and anode power limited to 484W. Cathode heater supply is switched off before the application of the ignitor pulses. This reduces the bus current inrush at thruster start-up below 20A. After start-up detection, the sequencer automatically increases anode power from 484W until nominal power requested by the spacecraft via external TC.

Figure 4 shows anode voltage increase from 220V at start-up up to 350V in 50s. Associated bus current is provided on Fig. 5 (5A/10mV), 10A after start-up increased up to 25A at nominal operating point.

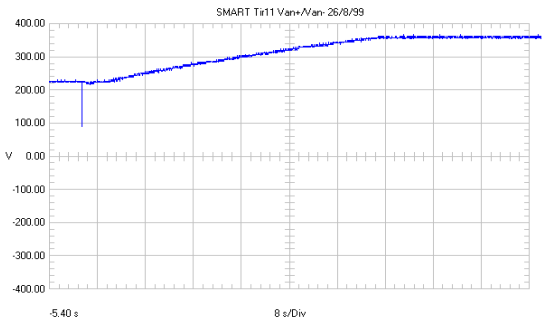

Figure 4. Anode voltage during start-up

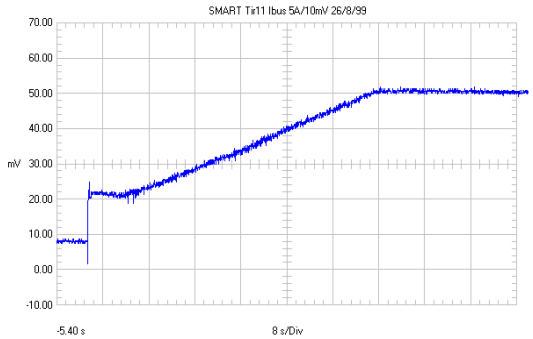

Figure 5. Bus current (5A/10mV) during start-up

D. Lessons Learned

No electrical nor thermal characteristic modification nor degradation were observed during the 4 958 hours flight operation.

1. Cathode Reference Point Voltage Range

The Cathode Reference Point voltage varied in flight between (–7 V, +13V), about 25 V higher than the measurement performed in vacuum chamber because the plasma in flight plays the same role as the electrical ground of the test facility. The range of the CRP telemetry range on SMART-1 (-50V, +10V) has been extended up to (-50V, + 100V) on current products.

2. Anode Supply SET Sensitivity

The anode voltage setting, specific to SMART-1, is transmitted by the sequencer to the anode module via a burst of pulses, through a fast optocoupler HCPL-5600 which has revealed sensitivity to radiation Single Event Transient. The energy left on the optocoupler by incident high energy particles, heavy ions, protons generates output glitch, around 100 ns width, without optocoupler degradation. This parasitic glitch is seen by the logic devices after

the optocoupler as a nominal pulse resetting the anode voltage setting value and leading to 0V output anode supply, switching the thruster OFF.

During the 4 958 hours operation, 38 opto SET have been observed and managed by the SMART-1 spacecraft S/W by sending a restart TC to PPU which performs the complete automatic thruster start-up (cathode heating, ignitor pulse application and anode power increase).

On current products, the anode setting transmission is improved to guarantee robustness to SET optocoupler

3. Efficiency and thermal measurements

During the 108 hours continuous thrust of the PPS-1350-G performed in November 2004, the efficiency in flight of the PPU operating at 330V/3.3A was correlated with the PPU baseplate temperature depending on the spacecraft orientation:

- 93.4% measured at 19°C baseplate
- 92.3% measured at 42°C baseplate

IV. HPPU

A. HPPU Development

In 2003, TAS-ETCA started the development of the High Power Processing Unit to drive high power Hall Effect Thrusters: Snecma PPS-5000, Fakel SPT-140, Astrium ROS-2000 and compatible with the current Snecma PPS-1350-G and Fakel SPT-100.

HPPU is constituted of several 2.5kW discharge supplies interconnected in parallel or series.

Each discharge supply interfaces the input power bus with the plasma discharge circuit. The topology selected resulting from the trade-off activities is based on the Stentor PPU heritage. Each module includes one input filter, input switch, inverter, power transformer and anode regulator including output voltage regulation and current limitation (see Fig. 6).

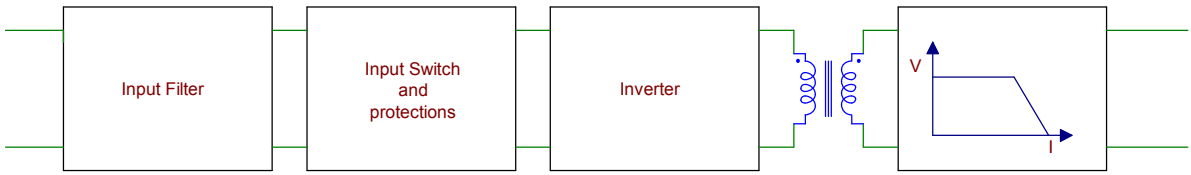

Figure 6. Discharge supply topology

The output voltage and the output short-circuit current of each module are adjustable by serial telecommand up to 400V and up to 12A (see Fig. 7). It is thus possible to adapt the anode voltage depending on the thruster type or the mission phase (orbit raising or attitude control). It also allows to limit the maximum input current to be compatible with the platform capability.

Two discharge supply modules of 2.5kW were manufactured and tested up to 3kW. Measured efficiency, including low level consumption, is 95.3% at 400V / 3kW and 95.1 % at 350V / 2.5kW. The modules were associated and tested:

- in parallel configuration: delivering up to 400V/ 5kW, 24A short-circuit.
- in series configuration: delivering up to 800V/ 5kW, 12A short-circuit.

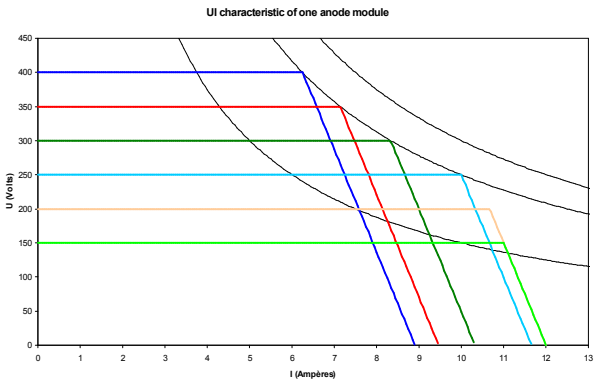

Figure 7. V – I discharge characteristic

B. Coupling Test with PPS-X000 Thruster

The HPPU discharge supply was successfully coupled during two weeks with the Snecma PPS-X000 thruster at QinetiQ facilities, in October 2004.

Three steady state configurations were fully characterised:

- 550V optimising thruster Isp. The two HPPU discharge modules are connected in series.
- 300V optimising thruster thrust. The two HPPU discharge modules are connected in parallel.
- 350V with single HPPU discharge module active.

For each configuration, the matching between the HPPU output impedance, the Filter Unit impedance and the thruster plasma has been validated. The HPPU bus current consumption, transients and ripple, the thruster anode voltage and current ripple before and after the Filter Unit have been monitored. The start-up procedure, system stability and the transient behaviour have been checked.

V. PSCU

A. PSCU Development

In the frame of AlphaBus predevelopment activities, TAS-ETCA developed power supplies for the Power Supply and Control Unit to drive Astrium-ST high power Gridded Ion Thruster RIT-22.

The Positive High Voltage Converter (PHVC), the most powerful supply, provides 4.5kW regulated positive high voltage commandable up to 2kV to the thruster screen grid with output current limitation commandable up to 2.6A. PHVC is constituted of two identical modules interconnected in series, each one delivering 1kV output voltage. Two PHVC modules were manufactured and electrically characterised up to 2 kV and 4.7kW.

- Measured efficiency is higher than 95%, in the range 1A - 2.5A
- at 1900V output voltage (see Fig. 8).
- Measured output voltage accuracy versus reference transmitted by telecommand is better than 0.4%.
- Measured output ripple is 1% at 1900V/2.5A.

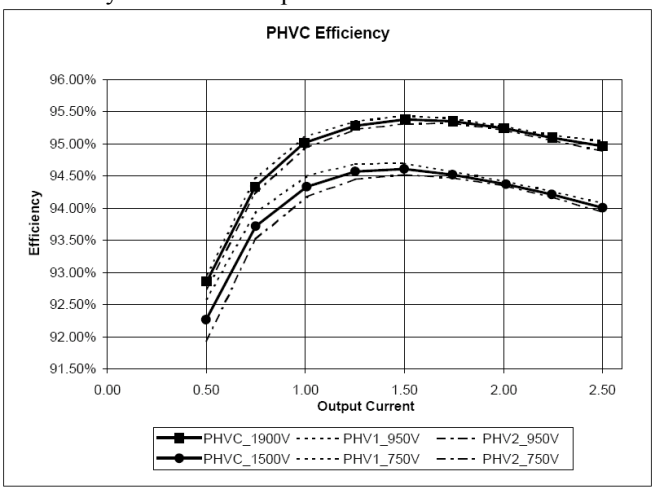

Figure 8. PHVC efficiency

B. Coupling Test with RIT-22 Thruster

The two PHVC modules were successfully coupled with the ASTRIUM-ST RIT-22 thruster at Giessen facilities, in October 2006. Steady state operation from 900V up to 2kV and from 750mA up to 2.4 A was validated with the thruster and characterised in term of PHVC efficiency, input and output ripple, thruster thrust and Isp. Various operating modes, thruster start-up and switch OFF were also characterised.

After this coupling test, PHVC modules have supplied RIT-22 thruster during its additional 500h life-test performed from October 2006 till December 2006.

C. Coupling Test with HEMP Thruster

In March 2007, one PHVC module (1kV / 2.5A) was successfully coupled during one week with the Thales TED HEMP-3050 thruster in Ulm facilities. Steady state operation in the range 500V – 1kV was characterized for different mass flow rates, in term of PHVC efficiency, input and output ripple, thruster thrust and Isp. Various thruster start-up and switch OFF modes were also validated.

VI. PPU SmallGEO

A. PPU SmallGEO Introduction

The Electric Propulsion System (EPS) of the new small geostationary satellite platform “SmallGEO” is based on two redundant Electric Propulsion Thruster Assembly (EPTA) branches (see Fig.9). Each EPTA branches includes one PPU driving one out of four thrusters. As the TAS-ETCA PPU includes one Thruster Selection Unit (TSU)

module performing 1:2 selection, a new equipment, the External Thruster Selection Unit (ETSU), is developed to be connected in series with PPU output terminals and to perform 2:4 selection. The configuration with 2 equipments (PPU + ETSU) was preferred to benefit from PPU flight heritage without major PPU mechanical modification to implement additional modules to perform the 2:4 selection.

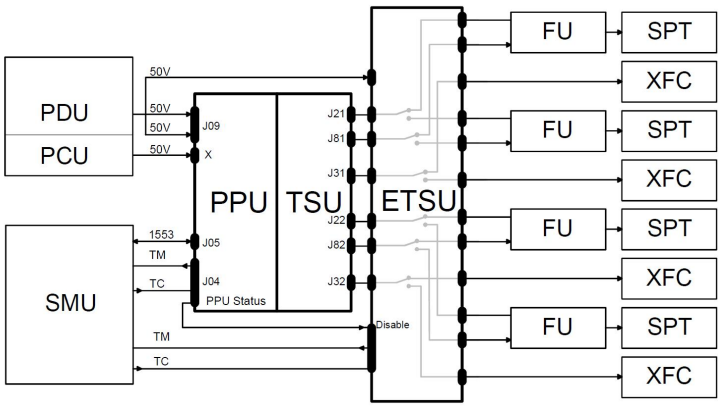

Figure 9. SmallGEO EPTA

ETSU qualification is on-going. Two flight sets (PPU +ETSU) are being manufactured in TAS-ETCA for SmallGEO

B. PPU SmallGEO Description

In order to insure compatibility with the requirement of 1.5kW maximum consumption on SmallGEO power bus, the following modifications are implemented on PPU SmallGEO:

- The ability to set the anode supply output voltage from 220V to 301V while the voltage was a fixed value on Stentor PPU. Anode voltage may be commanded via a serial data bus TC either in remote mode or in automatic mode.
- A new thruster start-up procedure in automatic mode. The differences could be summarised as follows:
  - The thruster is ignited with a low anode voltage setting.
  - A pre-defined delay (Tlow) after the ignition, the voltage increases to its nominal value (301V).
  - The Tlow as well as the low anode voltage and the anode nominal voltage may be modified by TC through the serial data bus.
  - The heater supply is turned OFF before the ignition to minimise PPU inrush current peak.
- On the anode supply, the output of the DAC opto-coupler is filtered to prevent the flame out due to a SET on this opto-coupler output observed on Smart-1 in orbit.

C. ETSU Description

The External Thruster Selection Unit is composed of 2 modules (see Fig.10). As the TSU module integrated in the PPU, each ETSU module includes electro-mechanical latching relays and their drivers to switch PPU SPT and XFC lines to one out of two thrusters and XFC. The ETSU also includes

- Auxiliary Power Supply to directly supply the relay drivers,
- TC/TM interface to activate ETSU and perform selection
- Discharge networks connecting floating electrodes of the thruster to ETSU structure. These resistances draw the electrons captured by the thruster electrodes (and their wiring harness) to the satellite electrical ground.

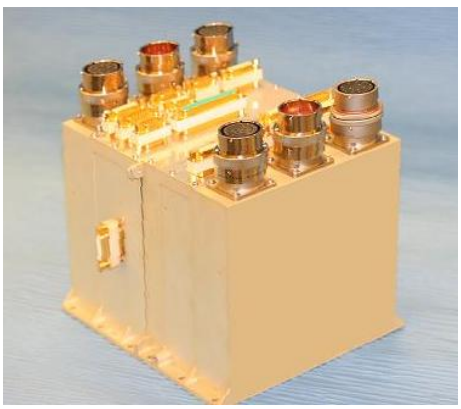

Figure 10. ETSU

VII. PPU Mk2

A. PPU Mk2 Development

In the frame of AlphaBus extension program and in partnership with the Primes, TAS-ETCA is now developing an optimized and more competitive product: the PPU Mk2. The PPU Mk2 addresses SPT-100, PPS-1350-G and Hall Effect Thrusters up to 2.5kW and is dedicated to AlphaBus, Eurostar 3000, SpaceBus 4000 and SmallGEO platforms. Taking benefit of flight experience and improvements developed for HPPU, PSCU and validated by successful integration tests, PPU Mk2 provides 1.6 more output power (1.5kW -> 2.5kW), more flexibility to thrusters and platforms, with reduced manufacturing cost.

B. PPU Mk2 Objectives

PPU Mk2 objectives are:

- More competitive product
- Replacement of obsolete parts
- Compliance to current Primes AD's and ECSS rules
- Dedicated to PPS-1350-G, SPT-100 and Hall Effect Thrusters up to 2.5kW. The selection of thruster type may be performed after assembly and test, by an external strap.
- Dedicated to AlphaBus, SB4000, E3000, SmallGEO platforms.
  - Bus voltage: 100V or 50V regulated versions
  - MIL-STD-1553B interface

C. PPU Mk2 Description

PPU Mk2 features are:

- Thruster type may be defined after PPU manufacturing, via external configuration straps
- Anode output characteristic is commandable in the range 220V – 350V, with short-circuit current commandable in the range 5A – 11A, see Fig 11 .
- Standard start-up or low power/low voltage start-up to reduce inrush current may be selected
- PPU is robust to abnormal pressure increased inside satellite up to 1Pa, by mechanical architecture
- Sequencer based on a FPGA provides more flexibility, the defaults values and major parameters are adjustable during flight by telecommand

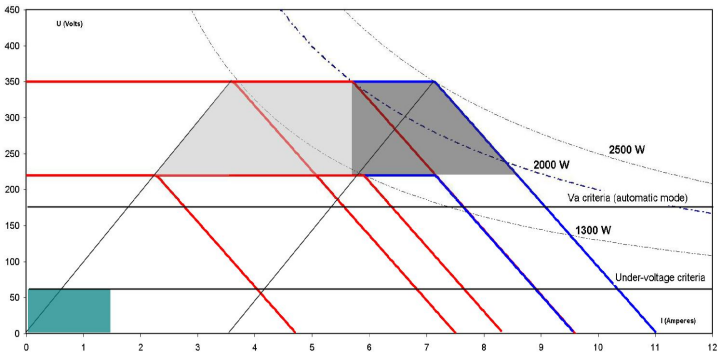

Figure 11. Anode output characteristic

- Removable magnet supply
- PPU Mk2 is composed of 6 modules which can be tested separately before integration:
  - Primary: input switch for bus protection and DC/DC to supply the low-level
  - Anode supply
  - Heater and Ignitor supplies
  - Thermothrottle and Magnet supplies
  - TSU and Valve Driver
  - Sequencer
- Same baseplate size (390mm x 190mm) and fixation holes as current PPU, to ease replacement with current PPU on platforms.

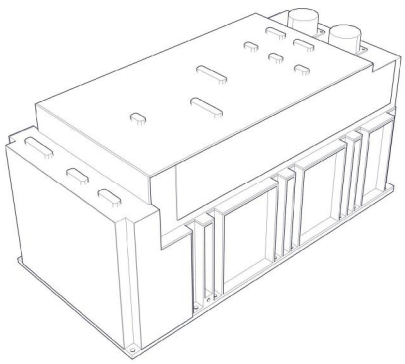

Figure 12. PPU Mk2

D. PPU Mk2 Status

A first phase, conducted with ESA, Astrium and TAS-F, was dedicated to specification and architecture definition. It was successfully concluded with the Baseline Design Review in December 2010. This review has released the development and manufacturing of the Demonstration Model. The two most powerful modules: primary and anode supply, are manufactured and under test. The test results will be presented at Preliminary Design Review, planned end 2011. The CDR presenting detailed design validated by tests on complete DM, is foreseen mid 2012 to release Qualification Model assembly. Qualification is planned begin 2013 in order to deliver first PPU Mk2 flight models in 2014.

VIII. Conclusion

Up to now 34 flight models of 1.5kW PPU have been ordered, 21 delivered and 12 are currently in flight:

Customer	Program	PPU Models	Status
CNES	Stentor	2 FM	Delivered, launch failure
Thales Alenia Space	Astra-1K	2 FM	Delivered, launch failure
	AlphaSat PFM for Inmarsat	2 FM	Delivered, to be launched in 2012
	To be allocated	6 FM	Manufacturing suspended
ESA	Smart-1	1 FM	In orbit since September 2003, mission completed after 4958 hrs PPU operation
Astrium	Intelsat 10-02	2 FM	In orbit since June 2004
	Inmarsat 4-F1	2 FM	In orbit since March 2005
	Inmarsat 4-F2	2 FM	In orbit since October 2005
	Inmarsat 4-F3	2 FM	In orbit since August 2008
	KaSat	2 FM	In orbit since December 2010
	Yahsat-1A	2 FM	In orbit since April 2011
	Yahsat-1B	2 FM	Delivered, to be launched in 2011
	To be allocated	5 FM	To be delivered in 2011-2012
OHB	SmallGEO	2 FM	To be delivered in 2011-2012
TOTAL		34 FM	

These orders demonstrate the confidence of Primes and customers in TAS-ETCA experience in Electric Propulsion, based on:

- 8 900 hrs ground coupling test with EQM Stentor
- 6 400 hrs ground coupling test with EQM SB4000
- 4 958 hrs flight operation of SMART-1
- 12 000 hrs in orbit on Sat Com

TAS-ETCA has acquired a solid experience and a very good knowledge of the electrical interfaces between thruster and PPU confirmed by the success of numerous integration tests with SPT-100, PPS-1350-G, PPS-X000, RIT-22, HEMP thrusters. These tests consolidate the concepts and the improvements that are implemented in the PPU Mk2.