Power Processing Unit Activities at Thales Alenia Space Belgium (ETCA)

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Abstract: Since 1996, Thales Alenia Space Belgium (ETCA) designs, develops and produces Power Processing Unit (PPU) to supply Hall Effect Thrusters: SPT-100 from Fakel and PPS1350-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 PPS1350-G thruster. Twenty three PPU flight models were delivered for the Stentor, Astra-1K, Smart-1, Intelsat, Inmarsat, Eutelsat, Yahsat satellites. In October 2005, the Smart-1 spacecraft reached the Moon after 4958 hours of cumulated operation of the PPU and its PPS1350-G thruster. Fourteen PPU's currently in flight for North South Station Keeping on seven telecom satellites have cumulated more than 20900 hours flight operation. Following the selection of the PPS1350-G as baseline thruster for the AlphaBus platform, the AlphaBus PPU was developed and two flight models were delivered for AlphaSat, launched in July 2013. The flight validation of the AlphaBus electrical propulsion has been performed successfully in August 2013. 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-B (ETCA) has developed and qualified an External Thruster Selection Unit (ETSU) to be associated to a PPU. Two flight sets (PPU+ETSU) were delivered for SmallGEO. In order to propose a more competitive product, TAS-B (ETCA) has developed the new generation of PPU, called PPU Mk2 dedicated to Hall Effect Thruster up to 2.5kW. Following the CDR concluded in November 2012, the PPU Mk2 qualification phase is on-going. Twelve PPU Mk2 flight models are already ordered by two different customers. In response the market demand of using Electrical Propulsion for Orbit Raising, TAS-B (ETCA) starts the development of the PPU Mk3 dedicated to 5kW Hall Effect Thrusters. This article presents an overview of the Power Processing Unit activities at Thales Alenia Space Belgium (ETCA), PPU Mk2 qualification status and the development of the PPU Mk3.

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

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PSCU = Power Supply and Control Unit
SPT = Stationary Plasma Thruster
TSU = Thruter Selection Unit
XFC = Xenon Flow Controller

I. PPU main functions

The 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.

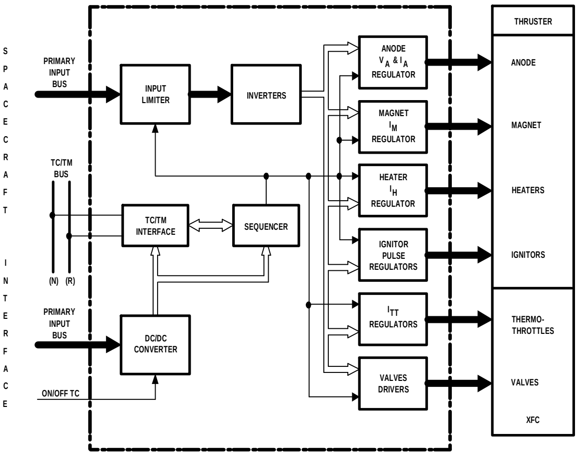

Figure 1. PPU functional block architecture

II. PPU Mk1

The main characteristics of our current PPU Mk1 product are summarised hereunder:

- ♦ Dedicated to SPT-100 and PPS1350-G Hall Effect Thruters.
- ♦ Compatible with 50V or 100V regulated input power bus.
- ♦ Maximum Anode Power : 1500 W.
- ♦ Includes SPT and XFC power supplies.
- ♦ 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 thrusters ; 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: 10.9 kg.
- ♦ Dimensions: 390mm x 190mm x 186 mm (LxWxH).
- ♦ 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 May 2013, 20900 hours cumulated flight operation on seven geo-synchronous telecom satellites: Intelsat 10-02, Inmarsat 4-F1, 4-F2, 4-F4, Kasat, Yahsat-1A, 1B.

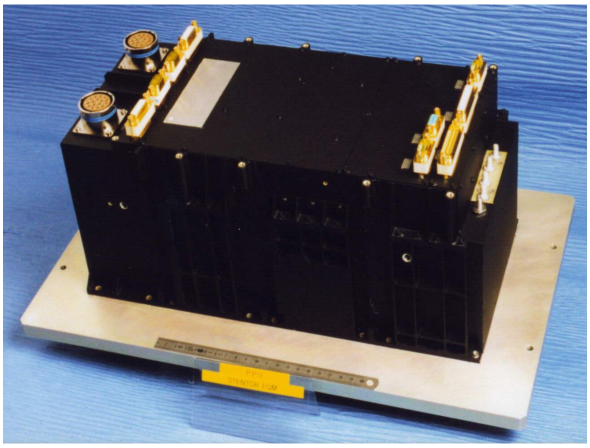

Figure 2. Stentor PPU EQM

- Twenty seven 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
- Components obsolescence has been handled to continue production of PPU Mk1 for 50Vbus; the 100Vbus version of PPU Mk1 is replaced by the PPU Mk2.

III. HPPU

A. HPPU Development

In 2003, TAS-B (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.

HPPU is constituted of several 2.5kW discharge supplies interconnected in parallel or in 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. 3).

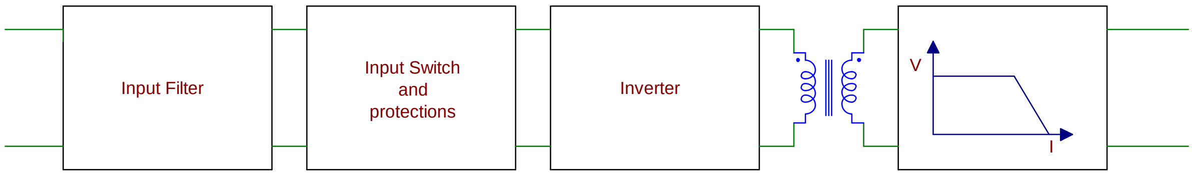

Figure 3. Discharge supply topology

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. 4). 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.

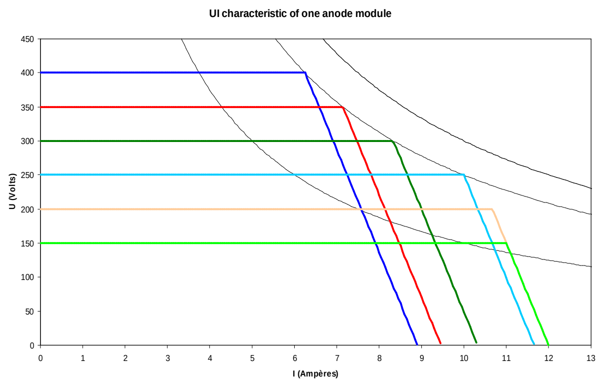

Figure 4. V – I discharge characteristic

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.

IV. PSCU

A. PSCU Development

In the frame of AlphaBus predevelopment activities, TAS-B (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. 5).
- Measured output voltage accuracy versus reference transmitted by telecommand is better than 0.4%.
- Measured output ripple is 1% at 1900V/2.5A.

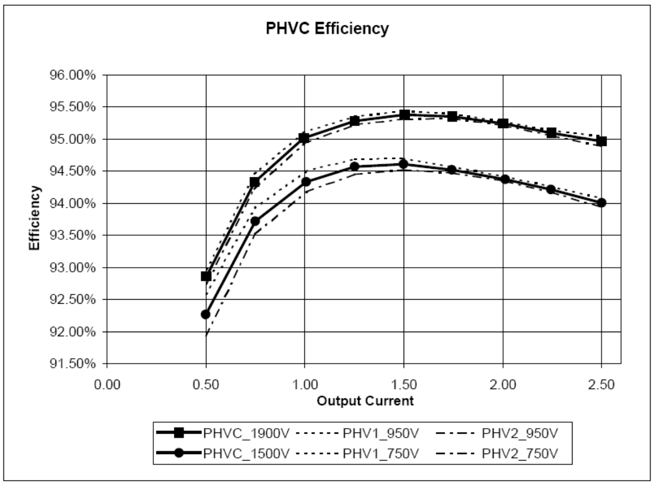

Figure 5. PHVC efficiency

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.

V. 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.6). Each EPTA branches includes one PPU driving one out of four thrusters. As the TAS-B (ETCA) PPU includes one Thruster Selection Unit (TSU) module performing a 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 a 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.

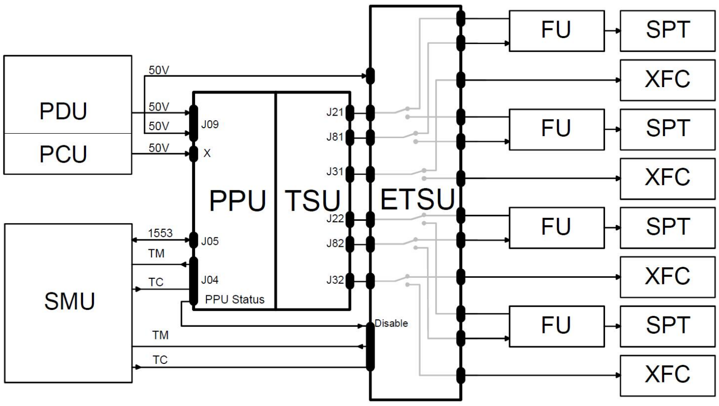

Figure 6. SmallGEO EPTA

ETSU equipment is qualified. Two flight sets (PPU +ETSU) have been delivered 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.

C. ETSU Description

The External Thruster Selection Unit is composed of 2 modules (see Fig.7). 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.

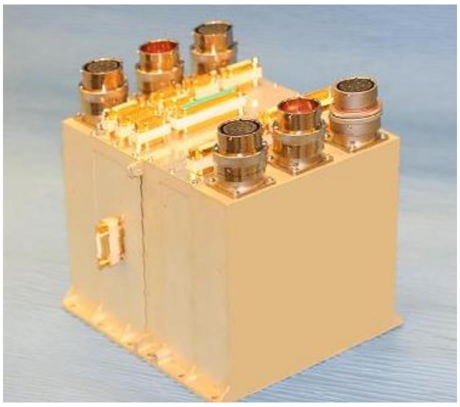

Figure 7. ETSU

VI. PPU Mk2

A. PPU Mk2 Development

In the frame of AlphaBus extension program and in partnership with the Primes, TAS-B (ETCA) has developped an optimized and more competitive product: the PPU Mk2. The PPU Mk2 addresses SPT-100, PPS1350-G and Hall Effect Thrusters up to 2.5kW and is dedicated to AlphaBus, Eurostar 3000, SpaceBus 4000 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 PPS1350-G, SPT-100 and Hall Effect Thrusters up to 2.5kW.
- ♦ Dedicated to AlphaBus, SpaceBus 4000, Eurostar 3000 platforms.
  - Bus voltage: 100V regulated
  - MIL-STD-1553B interface

C. PPU Mk2 Description

PPU Mk2 features are:

- ♦ Anode output characteristic is commandable in the range 220V – 350V, with short-circuit current commandable in the range 5A – 11A, see Fig 8 .
- ♦ Thruster type may be defined after PPU manufacturing, via external configuration straps
- ♦ 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. By telecommand, the defaults values and major parameters are adjustable, the protections may be inhibited.
- ♦ Optional magnet supply
- ♦ PPU Mk2 is composed of 6 modules:
  - 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 Mk1, see Fig.9.

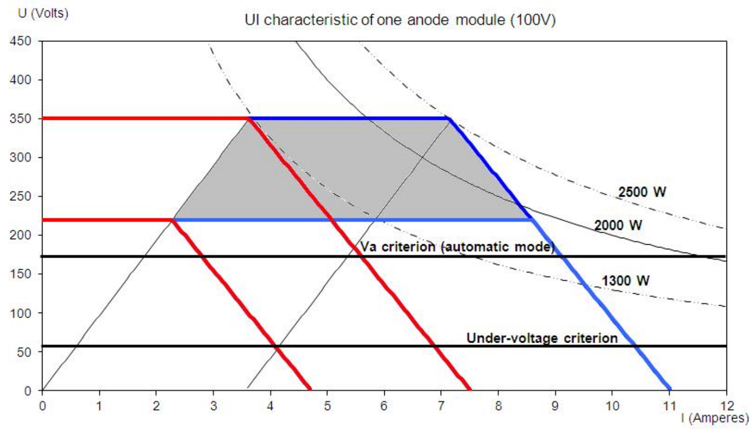

Figure 8. Anode output characteristic

Figure 9. PPU Mk2

D. PPU Mk2 Status

The 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. This review has released the development and manufacturing of the Demonstration Model. The test results, including temperature tests of all modules to validate the electrical behaviour and thermal handling, were presented at the Critical Design Review held in November 2012. The Qualification Model was then built and tested. Figure 10 shows the efficiency measurements obtained on the Qualification Model in function of the discharge supply output power at a voltage of 350V with the valve driver and the thermothrottle supply active: above 94.4% up to 2.68kW.

Just as the other TAS-B (ETCA) PPUs, the PPU Mk2 presents a defined voltage-current slope above the knee current to enable the thruster start-up without risking a locking point at low voltage due to the thruster characteristic. Figure 11 shows the voltage-current characteristic measured on the PPU Mk2 with the anode voltage set at 300V and the knee-current at 5A.

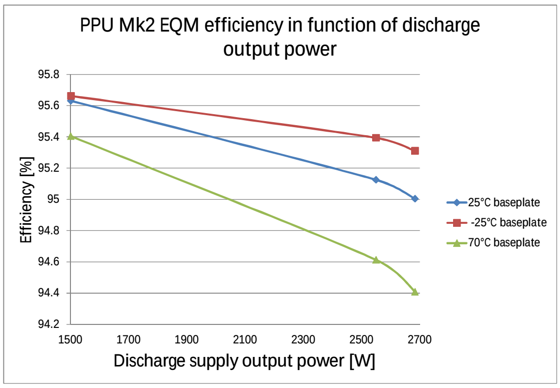

Figure 10 : EQM efficiency at 350V

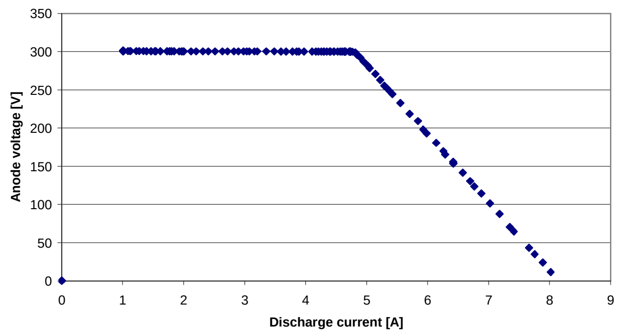

Figure 11 : Anode voltage-current characteristic
(with voltage setting at 300V and knee-current at 5A)

Thruster start-ups were recorded on the Demonstrator Model using a representative thruster simulator based on initially discharged capacitors. Figure 12 presents the output voltage, output and input current during a thruster start-up. During this test, the discharge voltage was set at 300V before the thruster start-up occurred and the knee-current was set at 5.5A. The thruster load after start-up is 5A imposed by a resistive load.

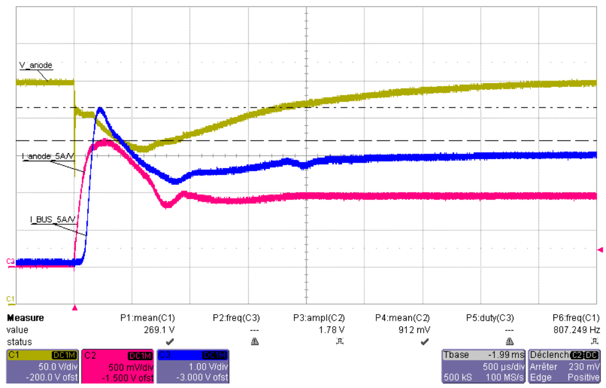

Figure 12 : Thruster start-up

It may be seen that during the thruster start-up test, the discharge voltage initially drops because the thruster consumption is higher than the knee-current. The discharge voltage then recovers its setting value as the discharge current diminishes after the start-up. The discharge current is reflected on the primary bus consumption through the PPU transformer scaling and its power filters. The knee-current setting enables to modify the peak input-current because it changes the peak power output of the PPU.

The PPU Mk2 provides a numerical proportional-integral regulation of the discharge current by acting on the thermothrottle current. This regulation enables to control the thrust despite the pressure perturbations upstream the thermothrottle. The effectiveness of the regulation has been validated with a worst-case simulator of the thermothrottle current to discharge current transfer-function. Figure 13 presents a step response recorded with the PPU Mk2 coupled to the transfer function simulator when the discharge current setting is changed from 5A to 4A.

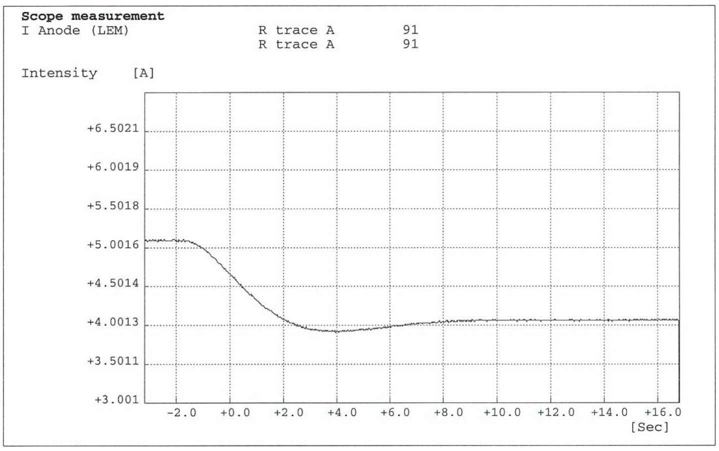

Figure 13 : Discharge current step change response

The PPU Mk2 mechanical qualification, including vibration and pyro-shock test is successfully completed. The thermal vacuum qualification tests are on-going. They will be followed by a complete EMC test campaign. After the PPU Mk2 Qualification Review, coupling tests with the PPS1350-G and the SPT-100 are foreseen.

VII. PPU Mk3

Recent studies from telecom satellites manufacturers and even from telecom operators have demonstrated that the use of Electric Propulsion not only for N-S and E-W Station Keeping but also for orbit raising will significantly reduce the costs of the couple satellite-launcher. This evolution to the Full Electric telecom satellites needs higher power thrusters, and so more powerful PPU, in order to reduce the orbit transfer duration at a value acceptable for the operators. In line with this evolution of the telecom satellites market, the satellite manufacturers foresee the use of Electric Propulsion to perform orbit raising with 5kW-class Hall Effect Thrusters. In response to this demand, TAS-B (ETCA) is starting the development of the PPU-Mk3 based on its significant heritage by a Study Phase with the following objectives:

- Issue a preliminary specification of the PPU Mk3 and review it with thruster manufacturers and primes.
- Analyse with the primes the different possible configurations of the full EP sub-system
- Define the PPU Mk3 architecture
- Issue the PPU Mk3 Technical Requirement Document to start the development and qualification phase of the PPU Mk3.

The meetings with the thruster manufacturers have identified the following differences between 5kW HET and the current 1.5kW HET:

- Anode power increased up to 5kW
- Thruster magnet coils independent from the discharge, requesting higher current
- Increased heater current
- Filter Unit to be adapted.

The main difference, providing up to 5kW anode power, may be covered by basically connecting two 2.5kW discharge supplies in parallel. This concept was already validated in the frame of HPPU project with 2 anode Demonstration Modules of 2.5kW coupled in parallel and confirmed by a coupling test with the PPS-X000 thruster up to 5kW. As the magnetic circuit is not in series with the discharge, the PPU Mk3 will thus feature a reviewed magnet supply design. The automatic thruster start-up sequence will be also adapted.

VIII. Conclusion

Up to now 41 flight models of PPU Mk1 have been ordered, 27 delivered and 16 are in flight:

Customer	Program	PPU Models	Status
Snecma	ESA-Stentor	2 FM	Delivered, launch failure
Thales Alenia Space	Astra-1K	2 FM	Delivered, launch failure
	AlphaSat PFM for Inmarsat	2 FM	In orbit since July 2013
	To be allocated	6 FM	Manufacturing suspended
Snecma	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	In orbit since April 2012
	To be allocated	4 FM	Delivered in 2012-2013
	To be allocated	6 FM	To be delivered in 2014-2015
Snecma	OHB-SmallGEO	2 FM	Delivered in 2011-2012
IAI	AMOS	2 FM	To be delivered in 2014
TOTAL		41 FM	

Twelve PPU Mk2 flight models are also already ordered by two different customers.

These orders demonstrate the confidence of Primes and customers in TAS-B (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
- 20 900 hrs in orbit on telecom satellites

TAS-B (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, PPS1350-G, PPS-X000, RIT-22, HEMP thrusters. These tests consolidate the concepts and the improvements that are implemented in the PPU Mk2 currently in qualification. In order to address 5kW thrusters, the PPU Mk3 definition is on-going.