

POWER PROCESSING UNIT ACTIVITIES AT THALES ALENIA SPACE BELGIUM (ETCA)

SPC-2014

Presented at the Space Propulsion 2014, 19 to 22 May 2014, Cologne, Germany

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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 and DirecTV satellites. In October 2005, the Smart-1 spacecraft reached the Moon after 4958 hours of cumulated operation of the PPU with PPS1350-G thruster. Fourteen PPU's currently in flight for North South Station Keeping on seven telecom satellites have cumulated more than 24100 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, they have cumulated 350 hours operation.

On the SmallGEO platform, one EPTA (Electric Propulsion Thruster Assembly) 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 Thrusters up to 2.5kW. The qualification phase is ending with the Qualification Test Review Board successfully hold in April 2014 and the final Qualification Review planned in June 2014. Twelve PPU Mk2 flight models are already ordered by two customers. In response to the market demand to use Electrical Propulsion for Orbit Raising, TAS-B (ETCA) has started the development of

the PPU Mk3 dedicated to 5kW Hall Effect Thrusters. This paper presents an overview of the Power Processing Unit activities at TAS-B (ETCA), including flight heritage, PPU Mk2 qualification and the development of PPU Mk3.

Nomenclature

<i>EPS</i>	=	Electric Propulsion System
<i>EPTA</i>	=	Electric Propulsion Thruster Assembly
<i>ETSU</i>	=	External Thruster Selection Unit
<i>FU</i>	=	Filter Unit
<i>HPPU</i>	=	High Power Processing Unit
<i>PHVC</i>	=	Positive High Voltage Converter
<i>PPU</i>	=	Power Processing Unit
<i>PSCU</i>	=	Power Supply and Control Unit
<i>SPT</i>	=	Stationary Plasma Thruster
<i>TSU</i>	=	Thruster Selection Unit
<i>TVAC</i>	=	Thermal Vacuum
<i>XFC</i>	=	Xenon Flow Controller

1. 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

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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.

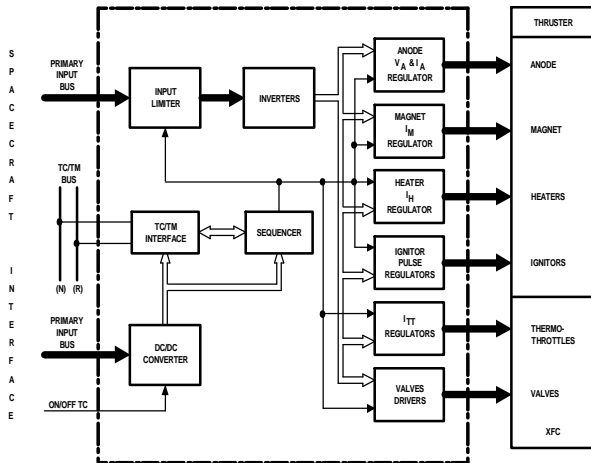


Figure 1. PPU functional block architecture

2. PPU Mk1

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

- ◆ Dedicated to SPT-100 and PPS1350-G Hall Effect Thrusters.
- ◆ 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 $V_{bus} = 50V$
 - 92.4% for $V_{bus} = 100V$.
- ◆ Mass for one PPU including TSU: 10.9 kg.
- ◆ Dimensions: 390mm x 190mm x 186 mm (LxWxH).
- ◆ Fully qualified according to environment specifications of European 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 March 2014, 24100 hours cumulated flight operation on seven geo-synchronous telecom satellites: Intelsat 10-02, Inmarsat 4-F1, 4-F2, 4-F4, Kasat, Yahsat-1A, 1B.
- ◆ 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, DirecTV15 and Sky-Brazil.
- ◆ 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.

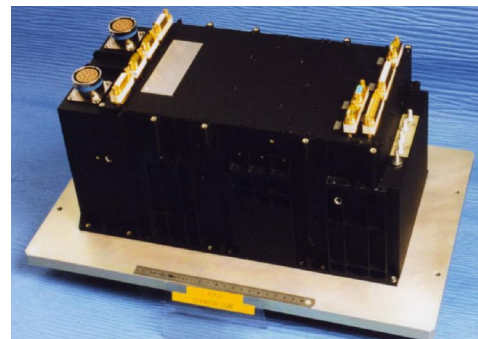


Figure 2. Stentor PPU EQM

3. FU

In a standard EPS configuration, a filter unit (FU) is used between the PPU and each thruster. The aim of the FU is to

- ◆ provide filtering on the thruster lines, the thrusters behaving as noise generators at high frequencies;
- ◆ provide stabilization of the anode discharge current in order to avoid degradation of thruster efficiency with quasi-periodic oscillations in the 10-50 kHz range;
- ◆ limit the radiated emission inside the spacecraft;
- ◆ limit the conducted susceptibility at PPU level.

To achieve these functions, a passive filtering unit has been designed.

The 1.5 kW version of the FU was fully qualified through an EQM programme followed by a PFM. It has been validated with PPU Mk1 and was used for coupling tests with SPT-100 and PPS1350-G thrusters.

TAS-B provided the FU's for ASTRA-1K, AlphaSat and is currently preparing deliveries for AMOS-6.



Figure 3. FU

4. PPU SmallGEO

4.1. 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. 4). 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.

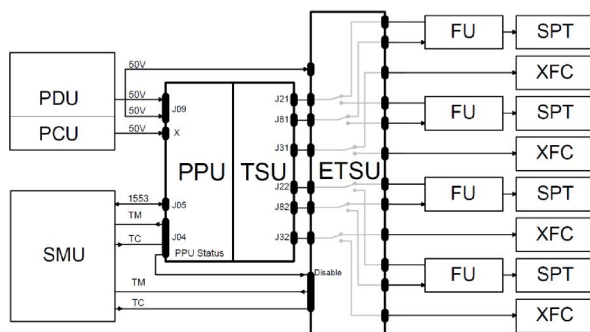


Figure 4. SmallGEO EPTA

The ETSU equipment has been qualified. Two flight sets (PPU +ETSU) were delivered for SmallGEO

4.2. PPU SmallGEO Description

The PPU SmallGEO is a modified PPU Mk1. 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.

4.3. ETSU Description

The External Thruster Selection Unit is composed of 2 modules (see Fig. 5). 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 ways. 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.

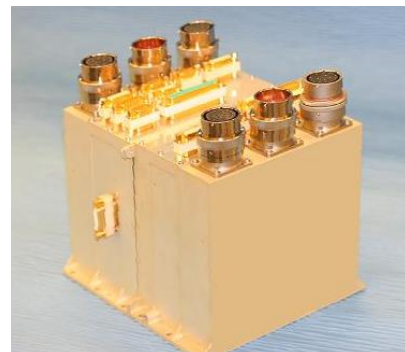


Figure 5. ETSU

5. PPU Mk2

5.1. PPU Mk2 Development

In the frame of AlphaBus extension program and in partnership with the Primes, TAS-B (ETCA) has developed 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, the PPU Mk2 provides 1.6 times more output power (1.5kW \rightarrow 2.5kW) and more flexibility to thrusters and platforms, with reduced manufacturing cost.

5.2. 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.
- ◆ Common design for AlphaBus, SpaceBus 4000, Eurostar 3000 platforms:
 - Bus voltage: 100V regulated
 - MIL-STD-1553B interface

5.3. 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 6 .
- ◆ 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.

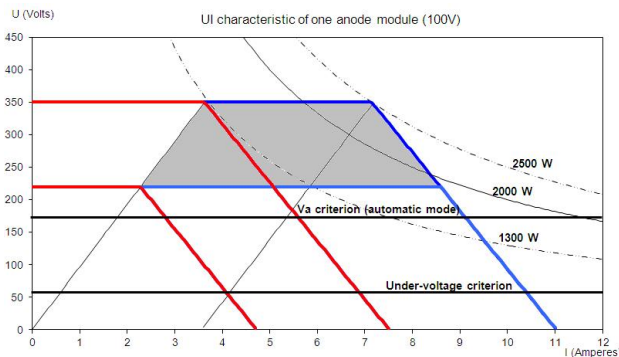


Figure 6. Anode output characteristic

- ◆ 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 trim 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
 - Thermo-throttle and Magnet supplies
 - TSU and Valve Driver
 - Sequencer
- ◆ Same baseplate size (390mm x 190mm) and fixation holes as current PPU Mk1, see Fig. 7.



Figure 7. PPU Mk2

5.4. PPU Mk2 Qualification

A Qualification Model was built and tested. Figure 8 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 thermo-throttle supply active: above 94.4% up to 2.68kW.

Similarly to PPU Mk1, 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 13 shows the voltage-current characteristic measured on the PPU Mk2 with the anode voltage set at 300V and the knee-current at 5A.

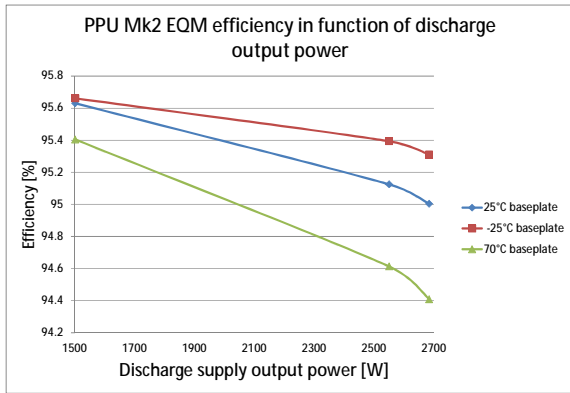


Figure 8 : EQM efficiency at 350V

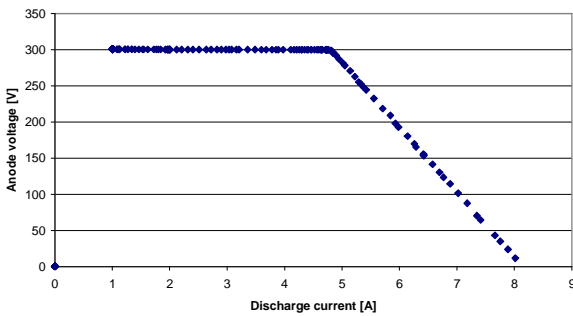


Figure 9 : Anode voltage-current characteristic (with voltage setting at 300V and knee-current at 5A)

Thruster start-ups were recorded on the Demonstrator Model using a representative thruster simulator based on initially discharged capacitors. Figure 10 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.

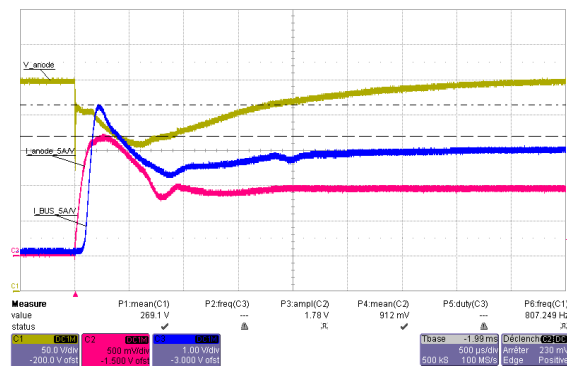


Figure 10 : Thruster start-up

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 simulator of the worst-case thermothrottle current to discharge current transfer-function. Figure 11 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. Tests were also performed where a perturbation (sine and triangular) is injected in the transfer-function simulator. The perturbation rejection performance has been measured and is in line with the analysis.

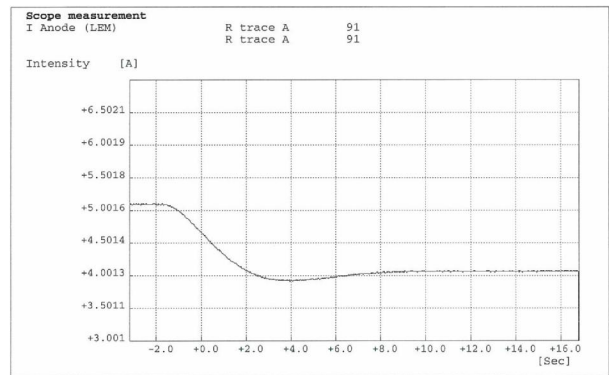


Figure 11 : Discharge current step change response

The PPU Mk2 mechanical qualification, including vibration and pyro-shock test is successfully completed. The thermal vacuum qualification tests concluded by a pressure increase test up to 2Pa has also been successfully concluded. The TVAC campaign has been followed by a complete EMC test campaign including different LISN configurations to cover the SB4000, E3000 and Alphabus platforms. The Qualification Tests Review Board has been successfully held in April 2014, the PPU Mk2 Final Qualification Review is planned in June 2014 and coupling tests with PPS1350-G and SPT-100 are foreseen later in 2014.

6. 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 requires higher power thrusters, and thus 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) has started 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 analyses conducted 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 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.

The Study Phase was concluded in January 2014 with the selection of an optimized packaging, with a reduced number of sub-assemblies to optimize the PPU Mk3 recurring price.

The development phase is now running to deliver PPU Mk3 flight models in 2016.

7. Conclusion

Up to now 47 flight models of PPU Mk1/Mk2 have been ordered, 27 delivered and 16 are in flight:

Customer	Program	PPU	Status
Snecma	ESA - Stentor	2 PPU Mk1	Delivered in 1999, lost due to launch failure
Thales Alenia Space	Astra-1K	2 PPU Mk1	Delivered in 2000, lost due to launch failure
	AlphaSat PFM Inmarsat	2 PPU Mk1	In orbit since July 2013
	To be allocated	4 PPU Mk2	To be delivered in 2015 till 2016
Snecma	ESA - Smart-1	1 PPU Mk1	In orbit since September 2003; mission completed after 4958 hrs
Airbus DS	Intelsat 10-02	2 PPU Mk1	In orbit since June 2004
	Inmarsat 4-F1	2 PPU Mk1	In orbit since March 2005
	Inmarsat 4-F2	2 PPU Mk1	In orbit since October 2005
	Inmarsat 4-F3	2 PPU Mk1	In orbit since August 2008
	KaSat (Eutelsat)	2 PPU Mk1	In orbit since December 2010
	Yahsat-1A	2 PPU Mk1	In orbit since April 2011
	Yahsat-1B	2 PPU Mk1	In orbit since April 2012
	DirecTV 15	2 PPU Mk1	Delivered in 2012
	Sky Brazil	2 PPU Mk1	Delivered in 2013
	SES-10	2 PPU Mk1	To be delivered in 2014
	To be allocated	4 PPU Mk1	To be delivered from 2014 till 2015
	To be allocated	8 PPU Mk2	To be delivered from 2015 till 2016
Snecma	OHB -SmallGEO	2 PPU Mk1	Delivered in 2012
IAI	AMOS 6	2 PPU Mk1	To be delivered in 2014
TOTAL		47 FM	

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
- ◆ 24 450 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. The successful PPU Mk2 QTRB consolidates the delivery of PPU Mk2 flight models in 2015. In order to address 5kW thrusters, the PPU Mk3 development is on-going, to provide flight models in 2016.