Development of a Cold Gas Attitude Control System for a Lander Demonstrator

K. Odic, C. Muñoz-Moya, N.Sauvage [1],
[1]*Astrium GmbH - Space Transportation, 28199 Bremen, Germany,*

ASTRIUM ST is currently developing a terrestrial Lander Demonstrator in the frame of a R&T project. The propulsion system of the demonstrator consists of a MPS and an ACS and this paper will present the ACS part of the Lander platform. The ACS is a cold gas based propulsion system aiming to counteract the MPS induced disturbances and thus ensure the flight control and stability by pitch, yaw and roll manoeuvers. This is an autonomous system, operating in a blow-down configuration and mostly build with COTS components to reduce the development duration and cost. This document presents, in addition, the transient Ecosim model used to investigate the functional aspects of the system, and further develops the objectives of using Ecosim model as a tool, namely: to support the establishment of the technical specifications, to accelerate the development process by reducing test campaign duration to its minimum, to feed the vehicle flight simulator with ACS behavior model. The Ecosim model approach is based on the object-oriented simulation language with dedicated modeling on all relevant physical process incorporated in components. The component model are either resistive (friction), capacitive (storage mass, energy) or inductive (storage momentum) and are interconnected via lines of type fluid/thermal at the relevant ports. In this approach a number of variables are set in the components via physical and geometrical parameter statements. Further validations between the results of the performance test campaign and the numerical models are presented and refinements to be done to improve the models capability are discussed. Finally an outlook is given on the future steps in the Lander demonstrator R&T program of Astrium.

Contact Author: E-mail: karine.odic@astrium.eads.net, Tel: +49 421 539 5147

NOMENCLATURE

ACS = Attitude Control System
BOM = Beginning Of Mission
EOM = End Of Mission
FCSW = Functional Chains and SoftWares
MPS = Main Propulsion System
SA = Structure Assembly

I. INTRODUCTION

Astrium ST is currently developing a Lander Demonstrator in the frame of a R&T project. The project aims at providing a technology maturation platform to support the business development opportunities on the markets of light weight and highly reactive end-game space vehicles.

The current terrestrial vehicle main function is to perform autonomous demonstration flights on ground in a dedicated test facility, targeting Planetary Lander applications. This Multi-purpose carrier platform has the advantage of being reusable and cost effective.

The vehicle is composed of 4 subsystems:

- Structure Assembly (SA),
- Attitude Control Subsystem (ACS),
- Functional Chains and SoftWares (FCSW),
- Main Propulsive Subsystem (MPS).

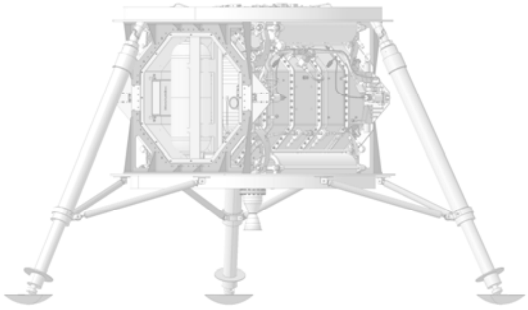


Fig. 1: Terrestrial Lander Demonstrator

II. COLD GAS ATTITUDE CONTROL SYSTEM

The Attitude Control System (ACS) shall provide 3-axis control to the vehicle and its missions. Mainly the performance needs (in terms of thrust level and as a consequence also the total impulse to be delivered) are driven by the sub-function of counteracting the MPS induced disturbances due the unavoidable CoG offset from the thrust axis of the main thrusters. An additional aspect is the need for high frequency activation of the ACS to allow the control chains and the needed modulation to work properly taking into account the already high frequency activation of the MPS.

As a consequence the ACS had the requirements:

- to deliver a useful total impulse of 1300 N.s per ground flight;
- to have thrusters providing a specific impulse Isp ≥ 55s (End Of Mission) in steady state firing and in pulse mode firing conditions for the project operating pressure and temperature ranges;
- to have an overall mass budget not exceeding, in Lander configuration ready for flight, (with loaded propellants): 43 kg.

ACS is a cold gas propulsion system operating in a blow-down configuration. On one hand, the N_2 was the most promising candidate chosen out of a trade-off amongst other cold gas candidates, such as CO_2, He, Freon-14, due to its good notes in terms of mass, equipments qualification, performances with regard to development slot limitation. On the other hand, the blow-down had no complexity in terms of function development and therefore less programmatic constrain in terms of schedule and costs.

The figure 2 below displays the ACS flow schematic with the following components:

- Storage tank: reservoir for propellant in the system.
- Manual valves: to fill & drain the tank with the desired gas.
- Filter: to protect the isolation valve from any particle contamination (and risk of subsequent leakage).
- Isolation valve: to separate the tank from the thrusters as safety device as well as to prevent major losses of propellant gas during stand-by phase.
- Test port to pressurize/service the downstream lines.
- Thrusters/Triads including an integral inlet filter element.
- The associated tubing.

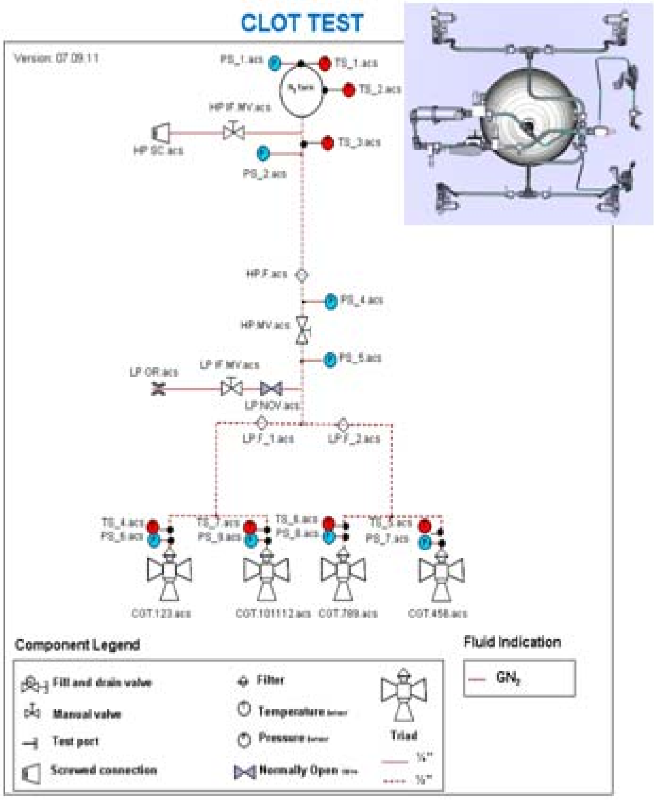


Fig.2: ACS sub System synoptic

The ACS dedicated developed equipments were the following:

- ACS Thrusters have been manufactured at Moog Inc (US)
- ACS High Pressure Tank: the High Pressure Nitrogen tank was specifically designed and manufactured by a US company in order to optimize cost, performance, and qualification needs with regard to safety constraints.

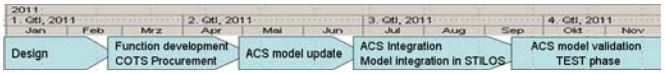
Due to cost and time constraints, the project objective was to use as much as possible COTS equipments, therefore the rest of the components were purchased world-wild:

- Filter
- Manual Valve
- Fill & Drain Valves
- Pressure Sensors
- Temperature Sensors
- Piping, Fittings & Manifolds.

Mechanical, electrical and fluidic interfaces were established at vehicle level. Mechanical studies justified all interfaces in contact with the Structure Assembly (internal and external interfaces) for the ACS sub-system. The ability of the functional chains to activate electrical equipments of other subsystems (valves, thrusters) was demonstrated via specific tests with real equipments on a dedicated platform. External interfaces were checked during functional tests.

III. DEVELOPMENT LOGIC OF THE ACS

Due to the engineering approach (margin management, reliability of the functional models), the complete development of the ACS from design-freeze till integration and final test took less than one year (Fig.3).



Confidence in engineering and in simulating model (upstream the specification) lead the project to a development logic and validation phases, which were not following a classical way: the subsystems was integrated before being fully validated via tests (for example no bench tests were conducted before final ACS integration).

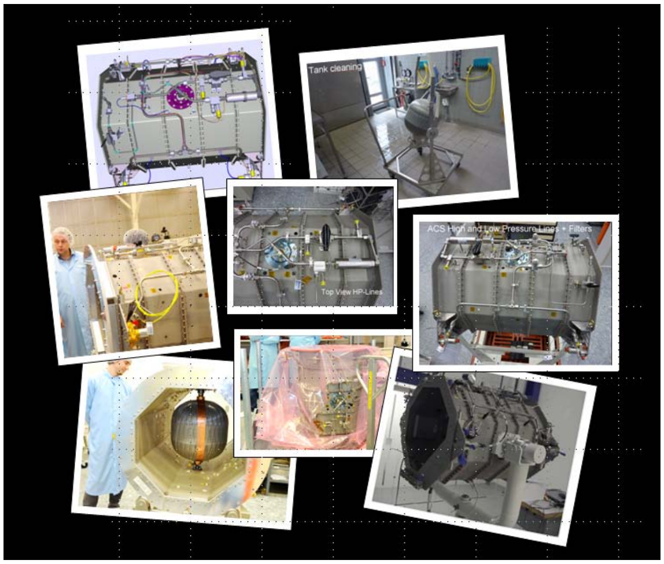


Fig. 3: ACS sub-system development from CAD design till tests

After integration the dry mass of the ACS reached a value compliant to requirement, namely: 33 kg.

The functional aspects of the complete system and the transient performance predictions of the ACS have been analyzed with the Ecosim software, which is based on the object-oriented simulation language with dedicated modeling on all relevant physical processes incorporated in components; the diagram below displays the ACS Ecosim flow diagram (Fig: 4).

For all the simulations performed under Ecosim, real gas and non-adiabatic assumptions have been taken (environmental heat flux through free convection element). In terms of components, simple valve models were selected to mimic the high frequency activation of the thruster throats. The mass flow, pressure, temperature, mass, pressure loss were extracted from the Ecosim model and the thrust and the Isp were calculated analytically. The total impulse was determined by integrating the thrust over time.

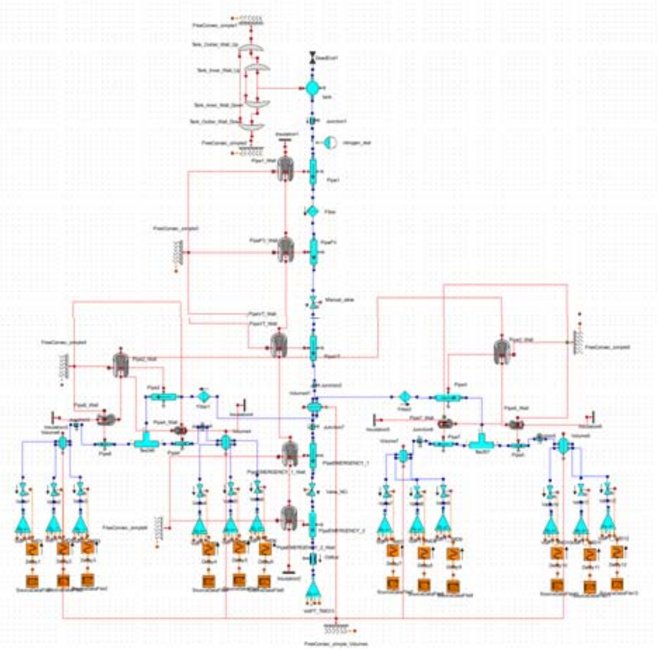


Fig.4: ACS Ecosim* diagram (*Ecosim tool commercialized by EAI).

In practical terms, the transient Ecosim model was used:

a- to support the establishment of the technical specifications,

b- to accelerate the development process by reducing test campaign length,

c- to feed the vehicle flight simulator with ACS behavior model.

a- For hardware component and design configuration selections, impact studies on the performance of the system was undertaken using the ESPPS libraries. Initially the components to be used in the ACS subsystem were unknown and the impact study was built for the filters, valves and pipes in order to accommodate all then foreseen possibilities.

<u>Thruster model:</u> during the impact study, because simple valve model was selected to mimic the high frequency activation of the thruster, a theoretical approach had to be developed in order to take into account the decrease of pressure over time. The thrust equation was expressed as,

$$F_{total} = \dot{m}V_e + A_e\left(p_e - p_a\right)$$

where:

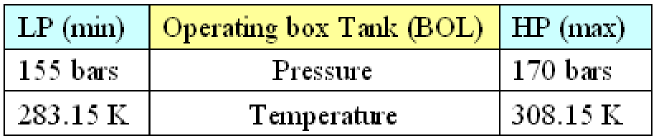
Ve, exit velocity in m/s
Ae, exit area of the nozzle in m2
pe, exit pressure in Pa
pa, ambient pressure in Pa

The value for the mass flow could be obtained from the Ecosim model read out. The exist area and ambient pressure are known design inputs. Thus, with this approach the problem was limited to know the exit pressures and velocities. Since the nozzle was not modeled, it is not possible to obtain accurate values from Ecosim. So in a first step the expansion of the gas needed to be approached in a simplified and conservative manner: no nozzle assumed (only throat); this method should provide the worst case scenario performance.

In the thrust expression $F_{total} = \dot{m}V_e + A_e\left(p_e - p_a\right)$, Ve becomes the sonic speed at the throat, Ae becomes At and Pe becomes Pt or the critical pressure at the throat given by, $\frac{p_c}{p_t} = \left(\frac{k+1}{2}\right)^{\frac{k}{k-1}}$. The sonic speed can be calculated through $V = \sqrt{\gamma RT}$ and the mass flow, temperature and chamber pressure are taken from Ecosim, thus the overall expression becomes;

$$F_{conservative} = \dot{m}\sqrt{\gamma RT} + A_t\left(\frac{p_c}{\left(\frac{k+1}{2}\right)^{\frac{k}{k-1}}} - p_a\right)$$

The selected mission for the simulations was the 20 ms ON / 20 ms OFF mission, with 4 nozzles firing simultaneously. For the manual valve and filter characteristics two extremes for the flow factor were chosen for the simulation, namely K_v of 1 and 6. An operating pressure and temperature box at tank level was chosen in order to envelop any possibilities in terms of initial conditions and therefore performance.

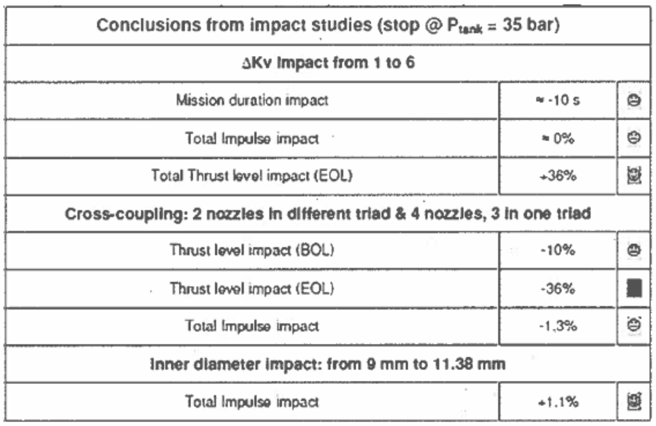


LP (min)	Operating box Tank (BOL)	HP (max)
155 bars	Pressure	170 bars
283.15 K	Temperature	308.15 K

The unique loading pressure of the vehicle was 163 bar. For the initial pressure and temperature the most sizing case in terms of mass flow and therefore ΔP was the HP case (P = 170 bar, T = 35 °C) and the most dimensioning in terms of performance was the LP case (P = 155 bar, T = 10 °C). They were defined such that they comply with the vehicle and thruster requirements, namely:

Beginning of life temperature from 10 °C to 35 °C

- Thruster qualification MEOP of 172.4 bar
- Minimum BOL pressure of 155 bar due to:
    - Temperature allowed variation of +/- 5 °C
    - Uncertainty of the Pressure Sensor of +/- 1.75 bar
    - Leaking effect of the thruster of 0.5 scc/s



Conclusions from impact studies (stop @ P_{tank} = 35 bar)		
ΔKv Impact from 1 to 6		
Mission duration impact	≈ -10 s	☺
Total Impulse impact	≈ 0%	☺
Total Thrust level impact (EOL)	+36%	▣
Cross-coupling: 2 nozzles in different triad & 4 nozzles, 3 in one triad		
Thrust level impact (BOL)	-10%	☺
Thrust level impact (EOL)	-36%	■
Total Impulse impact	-1.3%	☺
Inner diameter impact: from 9 mm to 11.38 mm		
Total Impulse impact	+1.1%	▣

b- During development phase; simplified Ecosim models were elaborated in order to support elementary operational tests and dedicated component qualification tests:

- ➢ Tank thermo-mechanical model Support:
    - ✓ Slow-DP Test: deloading prediction of the tank.
    - ✓ Quick-DP Test: At SCI during the tank qualification

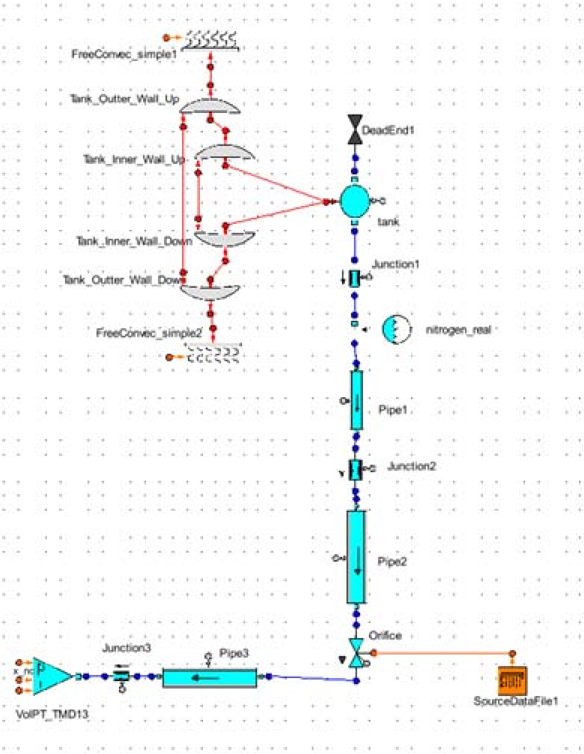


Fig. 5: Tank thermo-mechanical diagram

Validation of the thermodynamic Tank model: the test Results and the ACS HP tank simplified Ecosim model were coherent in terms of Pressure and Thermal point of views (P, T, m).

- Open Loop Test at System Level: ACS model correlation
  - ✓ Pressure drop Test: Investigation of the component induced pressure loss with different mass flow.

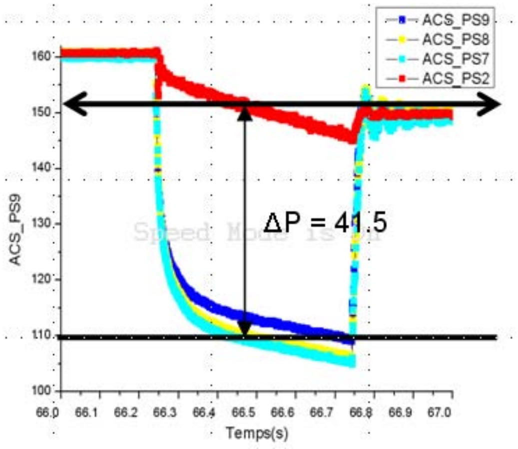


Fig. 6: Pressure through the system

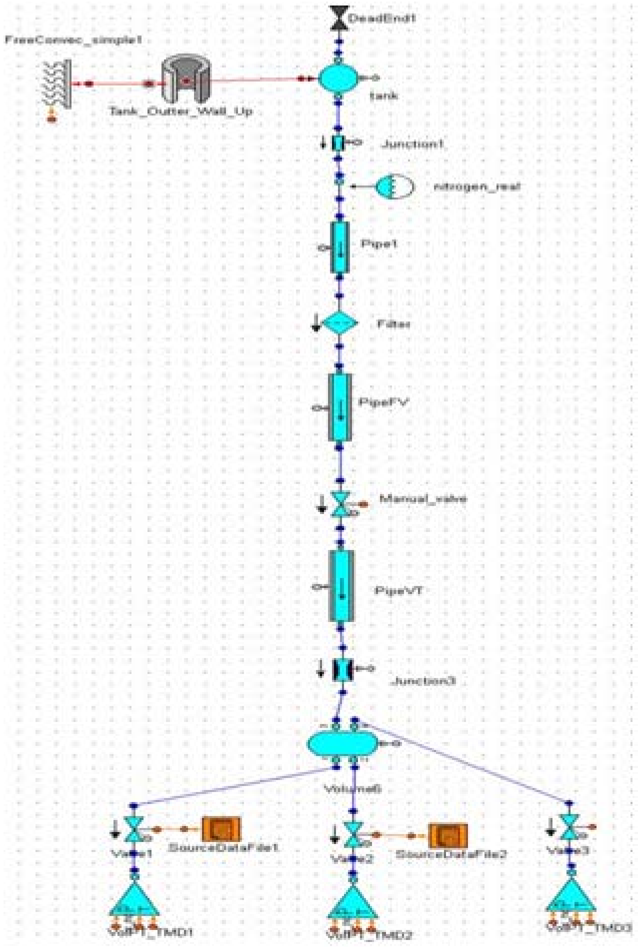
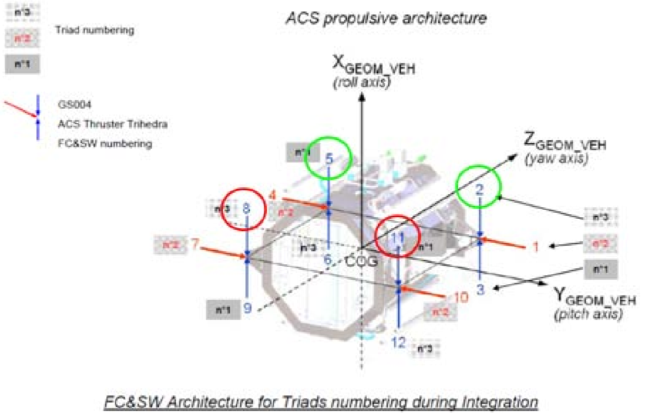


Fig. 7: Simplified ACS diagram

- ✓ Angular Displacement Test: Performing several simple Roll/ Pitch manoeuvres to identify the physical characteristic: average Thrust.



c - The vehicle flight simulator was fed with ACS propulsive behavior model. The Ecosim models supported the GNC to have of representative evolution of the pressure, thrust, Isp, temperature and consumed mass given representative activation profiles.

5 Empirical functions are needed to update the model: P(M); F(P); Isp(P); T(P); M(Total Impulse)

- Current Pressure Evaluation: this function evaluated the current gas pressure given the current total ACS gas mass consumed
- Current Thrust evaluation: this function evaluated the available thrust given the current pressure and the number of currently activated nozzles. In the current specification only 0,2 or 4 nozzles could be activated at the same time. The method to calculate thrust used in the impact study is changed on the performance analysis in order to correlate its output with a given data set of Moog experimental values. During the procurement of the thruster triad performed a number of steady state firing points over a pressure range in pressure regulated mode at sea level.
- Current ISP Evaluation: this function evaluate the Isp given the current pressure and the number of currently activated nozzles

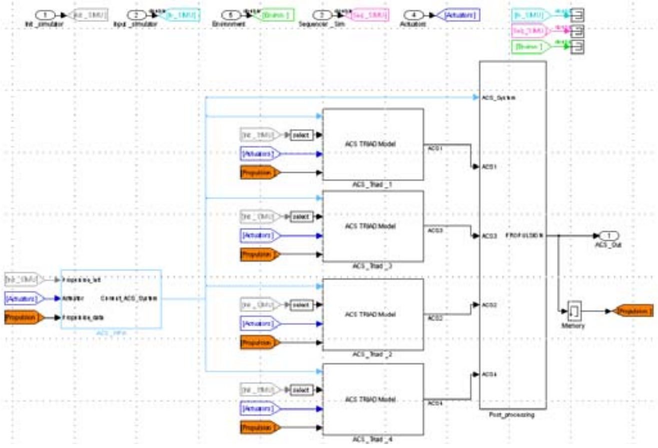


Fig. 8: Simulink diagram

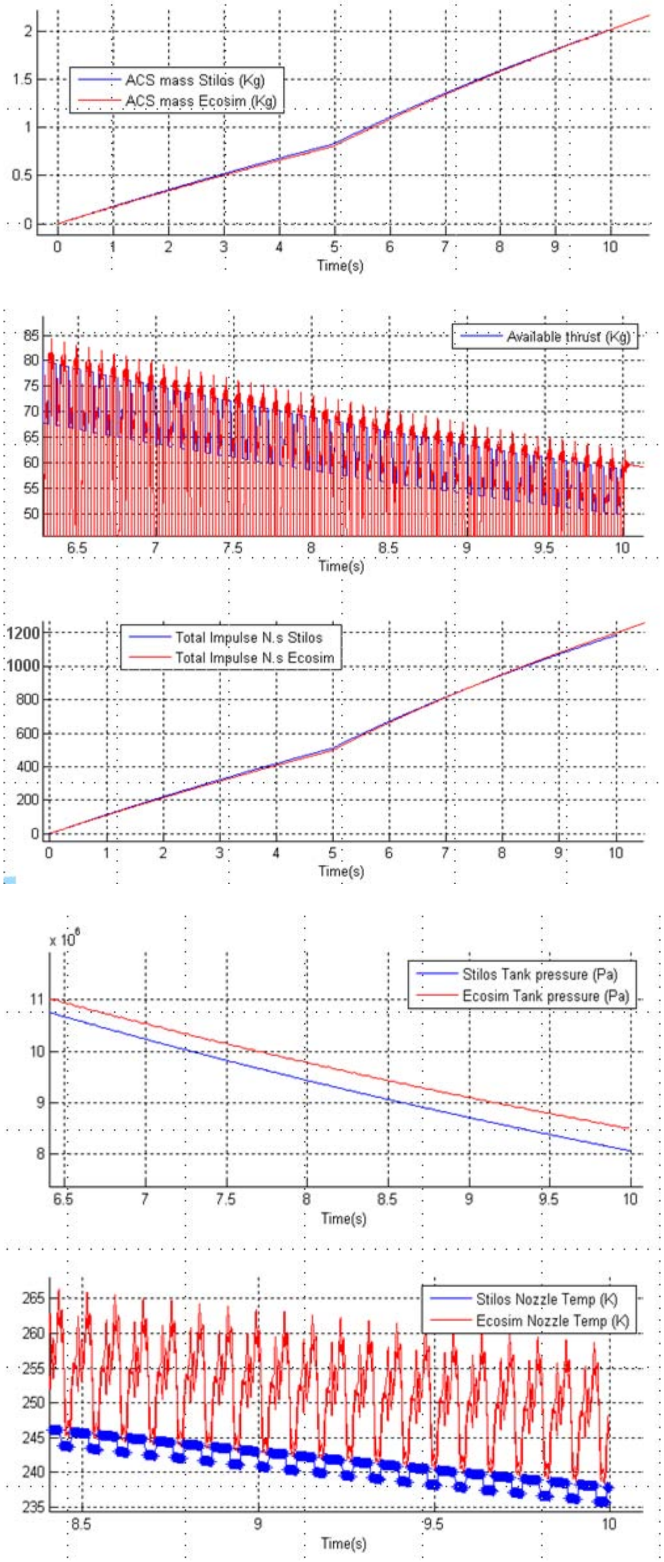


Fig.9: Simulink predictions.

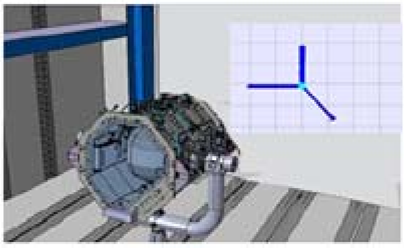
IV. VALIDATION BETWEEN THE MODEL RESULTS AND THE PERFORMANCES

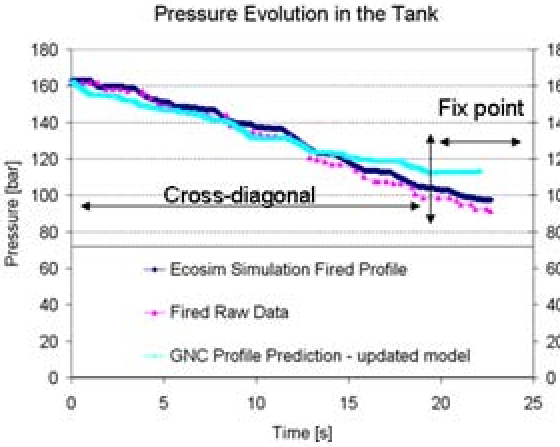
Closed Loop on Target system tests were performed with the full operational ACS and FCSW on-board the SA: tests consisting of following autonomously a laser spot beamed on the wall. Those tests without the MPS validated the control capabilities of the vehicle design.

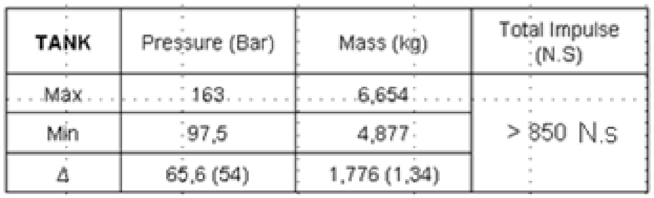
The main objectives of the test were:

- Validation of pointing accuracy
- Thermal and Mechanical models checks
- Validation of simulation tools (Ecosim and GNC models)
- Partial validation of operational sequence
- Partial validation of EGSE

➢ *Simple Cross-Diagonal Test:*



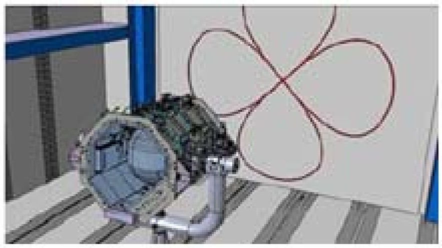


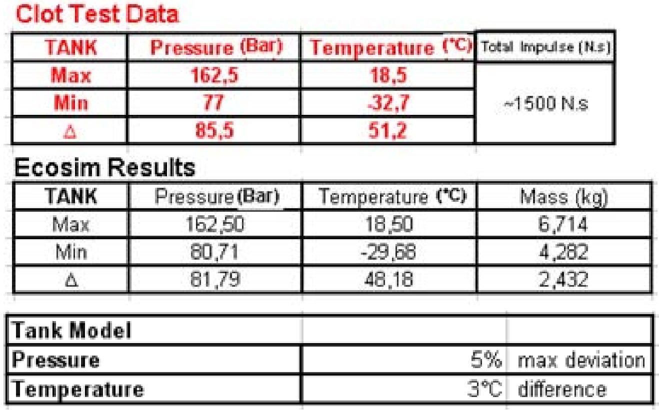


TANK	Pressure (Bar)	Mass (kg)	Total Impulse (N.S)
Max	163	6,654	> 850 N.s
Min	97,5	4,877	
Δ	65,6 (54)	1,776 (1,34)	

Fig. 10: Cross Diagonal test results

- *Complex Double Lemniscate Test*





Clot Test Data

TANK	Pressure (Bar)	Temperature (°C)	Total Impulse (N.s)
Max	162,5	18,5	~1500 N.s
Min	77	-32,7	
Δ	85,5	51,2	

Ecosim Results

TANK	Pressure (Bar)	Temperature (°C)	Mass (kg)
Max	162,50	18,50	6,714
Min	80,71	-29,68	4,282
Δ	81,79	48,18	2,432

Tank Model		
Pressure	5%	max deviation
Temperature	3°C	difference

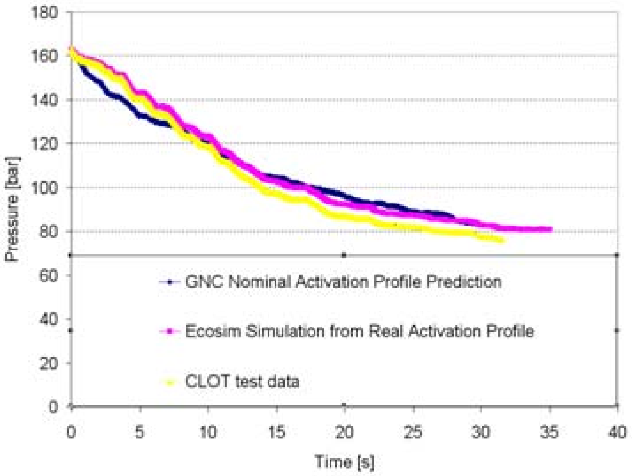


Fig. 11: Lemniscate test results

The overall behavior of pressure sensors showed comprehensive results upstream of the system: it was a maximum deviation of 5% between the model and the real data. The measurement of pressure downstream of the system, closer to the triads, was affected however by the cross coupling effects and the test showed that the current Ecosim model was not inducing enough friction through piping.

Thermal predictions in the tank were properly predicting the expansion of the real gas nitrogen; only 3°C deviation was observed, however modeling issue for the downstream-lines displayed large discrepancy, Ecosim model was much more conservative than reality.

For the performance prediction, the thrust values obtained were computed through an empirical equation based on the MOOG's thrust-pressure correlation. Two different calculations were made, one based on empirical data from the test and the other based on the simulated values. Both results show that the cross coupling impact is approximately up to 25% in thrust, or approximately 20 N for a 80 N thrust range (reduction from 80N to 60N of thrust when two nozzles from the same triad are simultaneously firing).

The Isp evolution ranges from 67 to 70 s at BOL conditions, to 62 - 63 s at EOL conditions.

The Total impulse delivered during the double Lemnisacte test was at least equal to 1500N.s., having still 77 bars left in the tank.

V. CONCLUSIONS & OUTLOOK

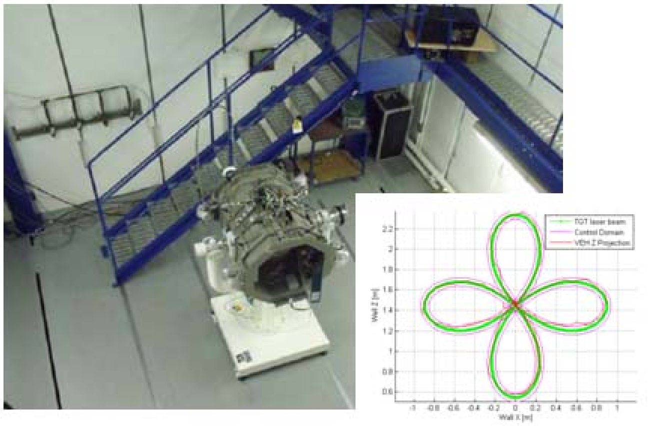
The simulations are in reasonable agreement with the real data; Ecosim was considered as a reliable tool to develop such an ACS sub-system within our specific frame. The overall thrust model worked accurately however it did not cover transient effects like pressure peaks. Cross-coupling results could not lead to proper conclusions. Transient phenomena such as the back flow in the tank or piping buffer effect were observed; a more detailed study would be recommended to increase the knowledge about the current model. Thermal prediction was the most inaccurate and should be further developed together with thermal experts.

The ACS was developed on Time - Cost - and Quality: every requirement were satisfied:

	Requirements	ACS	Compliance
Useful Total Impulse [N.s]	1300 N.s	> 1500 N.s	☑
Specific Impulse Isp [s]	≥ 55 s (EOM)	62 (EOM)	☑
ACS Mass [kg]	< 43 kg	33 kg	☑

The close-loop on target (CLOT) test without MPS disturbances already demonstrated high control accuracy of the ACS system.

The transient Ecosim model used to investigate the functional aspects of the ACS system was a good tool and is further used to develop the main thruster of the MPS.



Based on these successful assessment of the ACS performances, the sub-system was considered as a baseline and the Lander platform could enter into its next step of implementing the MPS on the vehicle configuration.. Thanks to its main propulsion system the vehicle will now be able to perform an autonomous Lander mission scenario during which the developed ACS will demonstrate its capability to control the vehicle in such environment.

Only minor upgrades were brought on the ACS sub-system in order to be compliant with the final mission of the platform (mostly safety related and reduction of data acquisition).

For this mission, the vehicle, will take-off from ground, then climb to a maximum of 5 m altitude and then perform a controlled descent up to soft landing on ground (w/o lateral displacement during the first attempt). For safety reason, the vehicle will be attached to a tether in order to prevent from crash. Prior to the flight, a so-called strap-down test will be performed, in the test facility in order to serve as an ultimate system validation.