DOI: 10.13009/EUCASS2019-1049



# Space Rider Aerodynamic Surface Control System

*Pierre Demuysere* – Guillaume Houchard** – Guerric de Crombrugghe de Looringhe****
*SABCA chee de Haecht 1470 - 1130 Brussels - Belgium*
* *Pierre.Demuysere@sabca.be*
** *Guillaume.Houchard@sabca.be*
*** *Guerric.deCrombrugghe@sabca.be*

## Abstract

The Space Rider is a European mini-shuttle project destined to bring payloads on orbit for a duration of up to two months and return them back safely to the Earth. It consists out of two major element: the Re-Entry Module (RM) and the AVUM Orbital Module (AOM).
SABCA is responsible for the design and manufacturing of the Aerodynamic Surface Control System (ASCS) on the RM and the Thrust Vector Control System (TVCS) of the AOM. Both of these systems consist out of:
- two Electro-Mechanical Actuators (EMA);
- an Actuators Control Unit (ACU) containing all the power and control electronics;
- a battery pack for the power generation; and
- all the necessary cables and harnesses.

For the ASCS, the mechanical levers between the actuators and the flaps are also included. The ASCS system design has been validated in-flight during the IXV mission.
SABCA has taken, in the development of these systems, a “modified off-the-shelf” approach. The TVC of the ZEFIRO stages of Vega has been adapted for the ASCS, while the TVC of the AOM is derived from the AVUM stage of Vega. The changes are linked to the new mission profile. The main drivers were the long exposure to space radiative environment and the need for reusability. This approach allows leveraging on existing qualified products, and therefore reducing development cost and duration.
All the functions and components were thoroughly analysed and, when necessary, adapted to ensure that the system as a whole complies with the reliability figure necessary for such a multi-flight mission with long stays on orbit. Lessons learnt of IXV mission and VEGA production experience were also useful : years of tests on VEGA engineering equipment gave, before starting Space Rider development, a good idea of the limits of this equipment and of its potential to reusability.
The adaptations needed turned out to be limited with respect to the VEGA definition. Some tests shall be foreseen to ensure that the equipment meets the new constraints in terms of reusability and radiation. These tests are mainly linked to performance (extended duty cycle) and vibration at subsystem (ASCS) level which are not covered by the qualification on VEGA or IXV program.

## 1. Introduction

The IXV completed successfully its mission on February 11th, 2015, ending by a splashdown in the Pacific Ocean.
Real-time data showed that the FpCS performed its mission in a nominal way. A post-fligth analyses was performed that enabled to both validate the overall vehicle and Flap Control System architecture and behaviour, but also to acquire valuable data about the effective environment seen by the vehicle and about its behaviour in flight and during the re-entry.
Those data allowed to improve the parameters used in the models, to reduce the system margins and then to refine the FpCS requirement for the Space Rider studies.
This heritage enabled to take a maximum benefit of the performed studies on IXV to identify the delta studies and qualification activities necessary to transform a demonstrator design into a reliable vehicle able to perform multiple missions including a long stay in orbit.
SABCA is performing also the same studies in the frame of the AVUM Orbital Module TVCS, in order to identify the need of modifications / delta qualification to be compatible with the Space Rider mission.

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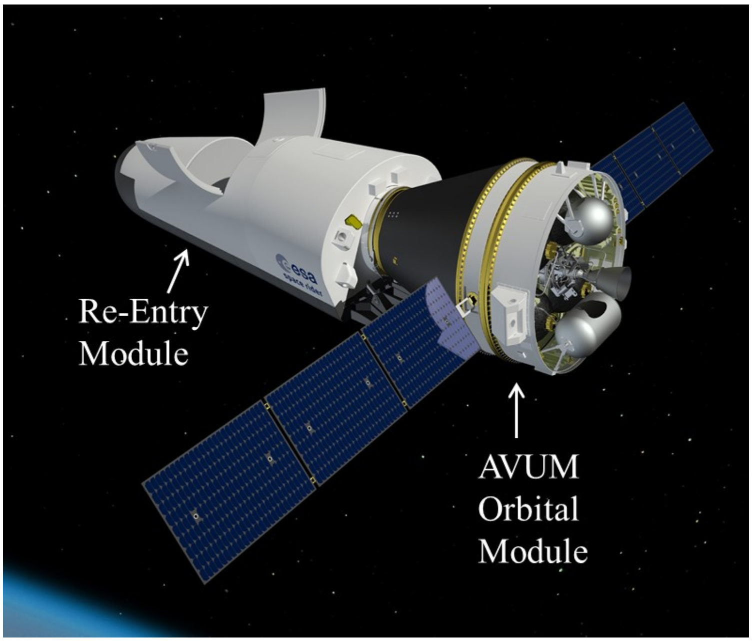


## 2. IXV heritage

### 2.1 IXV Mission profile

The IXV mission profile included several phases, as illustrated by the picture below:

- The launch phase, on board of the VEGA Launch Vehicle, taking off from the Centre Spatial Guyanais (CSG), in Kourou, French Guyana.
- The ballistic phase, up to 415 km altitude.
- The re-entry phase, between 120 km altitude and 40 km altitude.
- The descent phase, between 40 km altitude and sea level, with parachutes, ending with the splashdown in the Pacific Ocean.

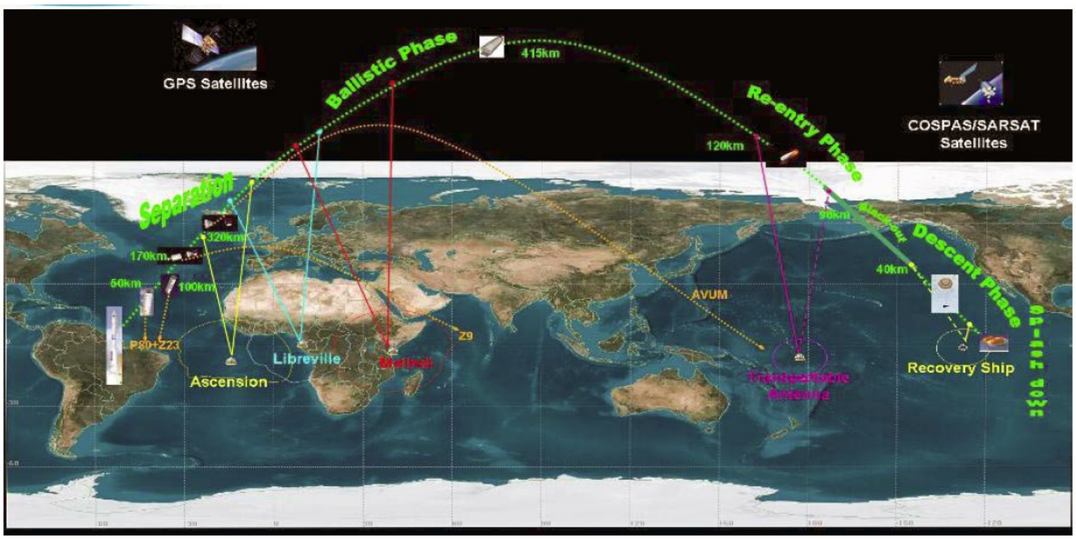


Figure 1 : IXV Mission profile.

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### 2.2 IXV FpCS architecture

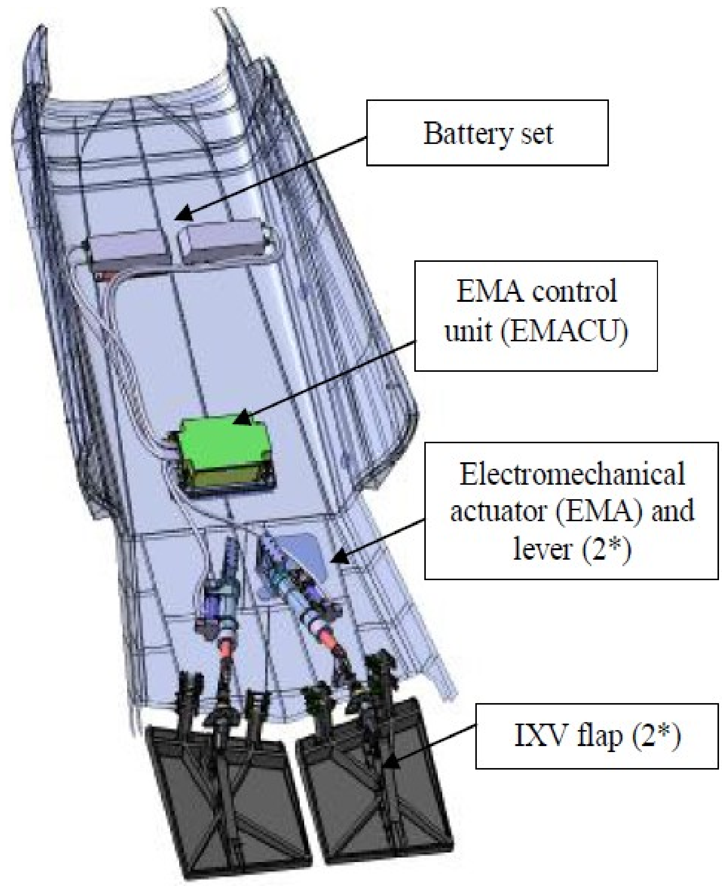


Figure 2 : IXV Flaps control System

#### 2.2.1 Mechanical system

The mechanical system of FpCS consisted in two EMAs, two levers (to link the flap rod to the EMA) and the necessary shaft of the levers.
The FpCS EMA consisted of a brushless permanent magnet synchronous motor that drives a roller screw through a gearbox.
The EMA linear position was measured by a LVDT, while the motor angle was measured by a resolver placed on the motor axis. The EMA electrical motor is equipped with a temperature sensor.

The EMA definition was derived from the VEGA ZEFIRO actuator definition (COTS approach), with several modifications:

- ✓ the EMA pin-to-pin length and strokes was specific to the IXV application;
- ✓ the actuator design included a blocking device; therefore, the design of the actuator housing was also modified;
- ✓ the accuracy of the actuator position sensor (LVDT) was improved, in order to meet the flap control requirements;
- ✓ the actuator anti-rotation interfaces was surface hardened and dry lubricated, in order to be compatible with the IXV operational and environmental constraints.

The IXV FpCS PFM actuators are shown below.

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ASCS EMA

This heritage contains also the brake system, added w.r.t. VEGA design in order to block the flap control system during its inoperative phase. The qualification perform in the frame of IXV program is partially reuse to justify requirements which have not changed.

Consequently, the ASCS Space Rider program is focused on the changed/new requirement in order to limit the cost. The impact of the material change to meet the changed/new requirements is analyzed in order to be sure that the IXV heritage is still applicable.

Moreover, according to IXV flight results, some IXV requirements have been relaxed for Space Rider unless more mission and longer mission are foreseen for the new program.

Among those design modifications, the implementation of a blocking device for the IXV application was the most important one, since this critical function does not exist in the VEGA ZEFIRO TVC design, and required a special attention during the design phase of the IXV FpCS project.

In particular, the FpCS blocking device had to be designed in order to:

- ✓ provide the required braking torque ( ~ 3 Nm) with adequate margin, according to ESA ECSS standards;
- ✓ meet the IXV requirements in the whole temperature range, from - 10°C to + 120°C, in terms of power consumption (< 40 watts), release and engagement times (< 220 msec);
- ✓ remain engaged during the VEGA launcher vibrations at lift-off;
- ✓ remain engaged during the high shocks at IXV separation from VEGA launcher;
- ✓ remain released during the high shocks at the end of the re-entry phase, at parachutes opening (MORTAR shocks).

Basically, the blocking device is a passive static teeth brake actuated by an electromagnet, as shown by the pictures below.

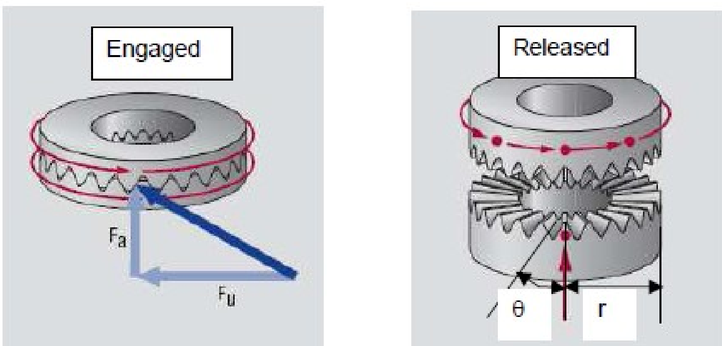


Figure 2 : IXV Flaps control System

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When the brake is powered off, the armature is pushed in contact with the disc by springs: the flap mechanism is blocked.
When the brake is powered on  the armature is lifted by the electro-magnet: the flap mechanism is released.

This concept was selected because the braking function can be achieved for any value of the friction coefficient; this would not be the case for a “conventional” disc brake: the braking function might not be achieved for low values of friction coefficient, that might vary significantly with the operational (load, speed) and environmental (air, vacuum, temperature) conditions.

### 2.2.2 FpCS EMA Control Unit (EMACU)

The electronic box controls the two EMAs. It receive low power for digital process and high power coming from the two batteries for EMA motor supply. It is composed of a Digital Control Module (see boards on picture hereunder) and a power module.

The EMACU consists of:
- the EMACU hardware (HW), consisting of:
  - o the Digital Control Module (DCM) implementing the EMACU software (SW);
  - o the Power Module (PM), which is a power distribution unit;
- the EMACU software (SW) implemented in the Digital Control Module (DCM).

The DCM receives the actuator position set point commands from a single 1553B bus coupling function, unique to both lanes (EMA1 and EMA2). It performs, for each lane, synchronous acquisition of the measurements made on the EMA and EMACU, and implements the closed loop control of the FpCS through the SW uploaded in a highly secured processor called HBRISC2, to convert the position orders into control voltage orders that are sent to the Power Module (PM) inverters.

The PM provides the AC power supply to the two EMA’s from DC power supply of the battery set, using IGBT inverter modules.

The FpCS EMACU hardware is identical to Vega IPDU hardware, except for the damper interface parts and the inverter IGBTs. The damper interface parts length has been increased with regard to Vega definition, in order to ensure proper behaviour under vibrations and shocks.
At inverter level, the power semi-conductors have been upgraded to achieve less power dissipation to prevent overheating during the re-entry phase; however, VEGA TVC and IXV FpCS modules have the same geometrical envelope and mechanical interfaces.

The FpCS software is based on the Vega software, with only specific parameters values for IXV application.

The overall EMACU box volume is about 26 dm3.

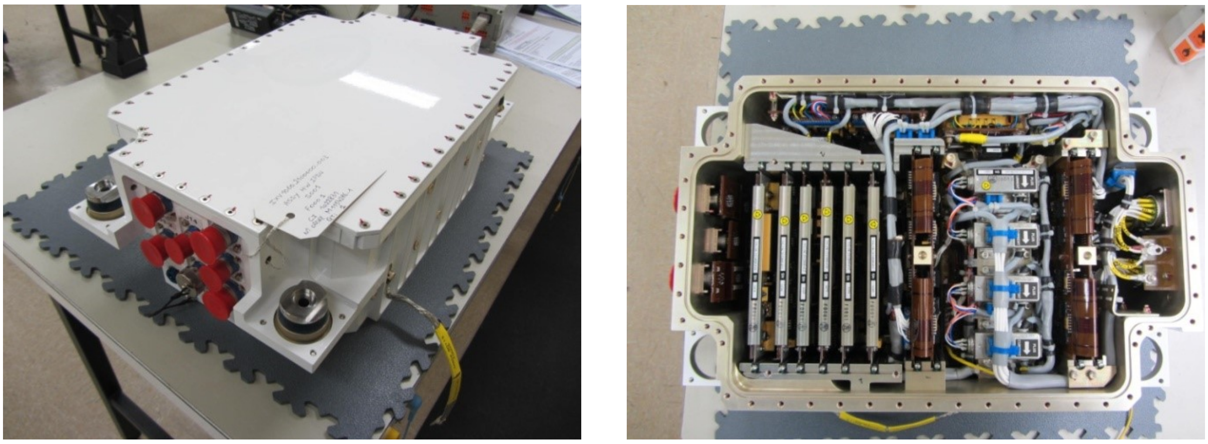

Figure 4: EMACU

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### 2.2.3. Batteries and harness

The two batteries used for the IXV mission are SAFT  15S VL8P   coming from VEGA launcher. Harness was manufactured by SABCA.

### 2.3. IXV FpCS qualification tests

The IXV development logic was based on the use of a proto-flight model (PFM).

Thanks to the fact that the design modifications from VEGA ZEFIRO TVC to IXV FpCS were limited as much as possible , the FpCS qualification test campaign was limited to the tests described below.

Most of the qualification tests were performed with the proto-flight model (PFM), whilst the more severe tests (EMA and levers: pyro-shocks and duty cycles) were performed with breadboard (BB) components, having the same definition as the PFM.

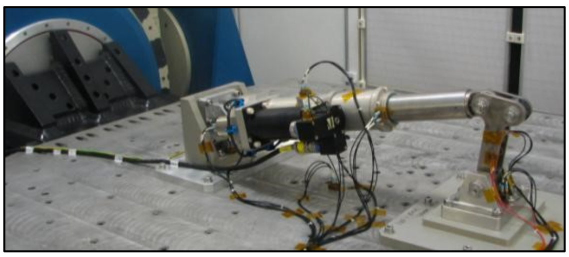
### 2.3.1 PFM EMA and lever vibrations tests

The PFM EMA and lever were tested according to the pictures below.

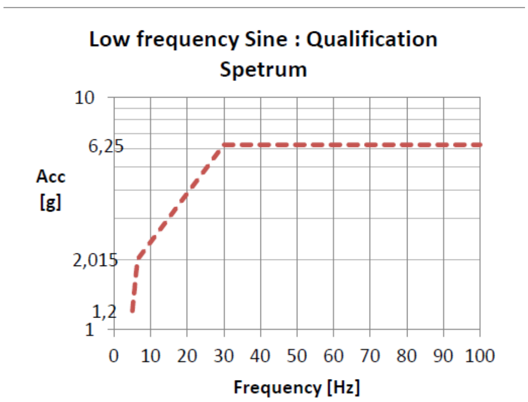
During the vibrations tests, the brake was engaged; this test configuration was representative of the launch phase (flaps positions blocked – brakes engaged).

After vibrations, the absence of cold welding was verified through a specific test under vacuum, by measuring the brake release current.

The objective was to demonstrate that 1) the flaps positions would remain blocked during the launch phase, and 2) that no cold welding would prevent the brakes release under vacuum at the beginning of the re-entry phase.



*FpCS EMA and lever on shaker*




*Sinus vibrations*

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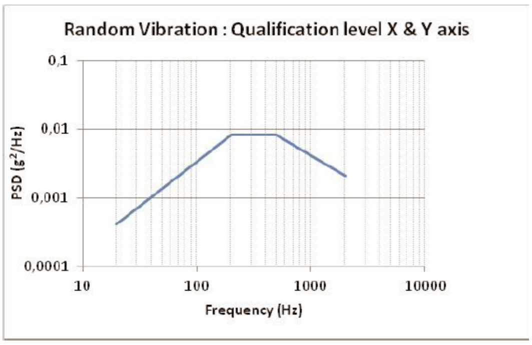
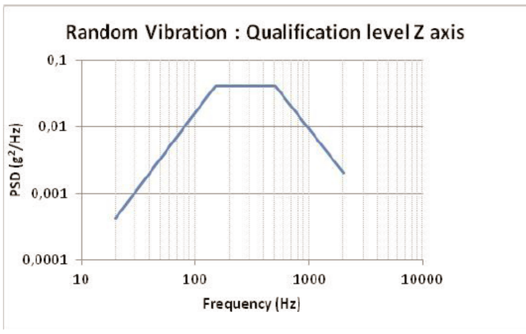



*Random vibrations - X & Y axes.*




*Random vibrations – Z axis*

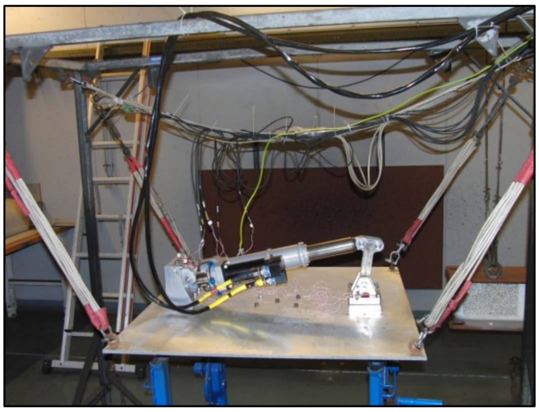
Figure 5: EMA and lever tests

### 2.3.2 BB EMA and lever shock tests

Two types of shocks were performed:

- Separation shocks, with FpCS unpowered and brakes engaged; this test configuration covered the shocks occurring at the IXV separation from VEGA, when the flaps positions were blocked in position.

- MORTAR shocks, with FpCS powered, active EMA controlled in an oscillating movement around +39.67 mm (amplitude: 0,79 mm; frequency: 0,3 Hz) and brakes released; this test configuration covered the MORTAR shocks occurring at the end of the re-entry phase, when the flaps positions were actively controlled.



Pyro-shocks tests set-up

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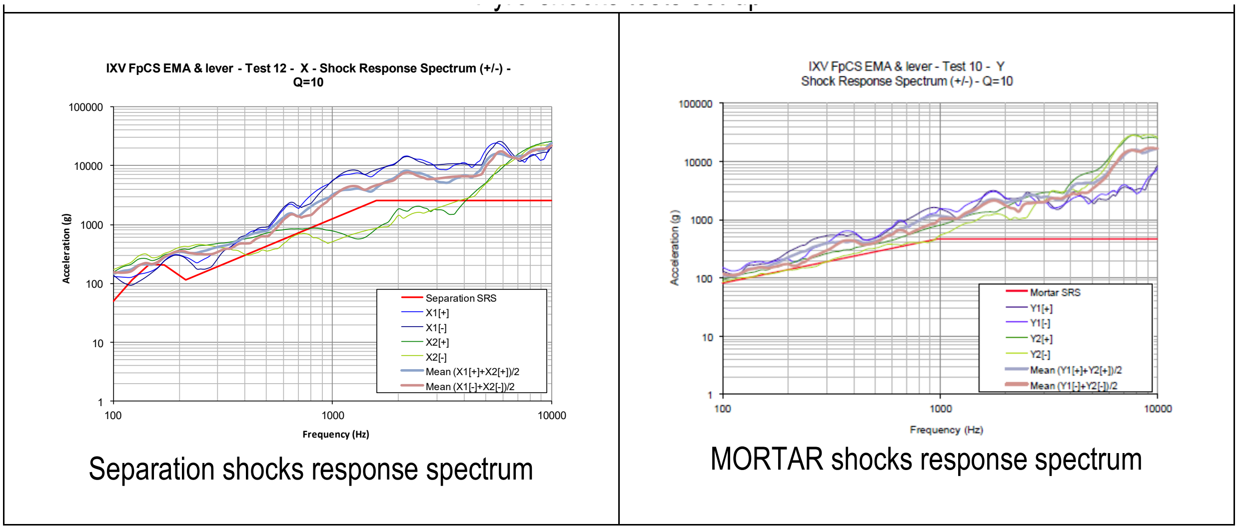


Figure 6: Pyro-shock tests

During the separation shock, the brake behaviour was monitored, by applying a torque on the motor shaft and measuring the resolver position; a little brake jump was recorded, corresponding to a motor rotation angle of about 9 degrees (3 brake teeth), an EMA elongation of 54 µm and a flap rotation of 0,02 degree, which was considered acceptable at System level by TAS-I.

### 2.3.3 PFM FpCS thermal vacuum cycling tests

Those tests were performed at the Centre Spatial de Liège (C.S.L.), Belgium, with the PFM EMACU, EMA & lever, and batteries.

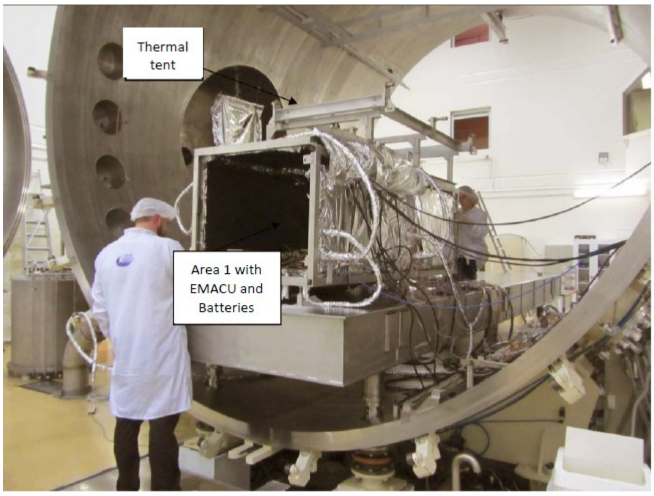


Figure 6: Thermal tent in vacuum chamber at the Centre Spatial de Liège (Belgium).

### 2.3.4 Brake specific tests

As the brake was a system added specially for the IXV, several specific tests were performed :

- ✓ Endurance tests in vacuum: the brake was properly released/engaged for about 1000 times in vacuum; after those tests, the brake parts were in good condition, grease was still present on armature and disc.
- ✓ Random vibrations tests: during this test, the brake remained properly engaged.
- ✓ Temperature tests at – 10°C, + 20°C, + 120°C.

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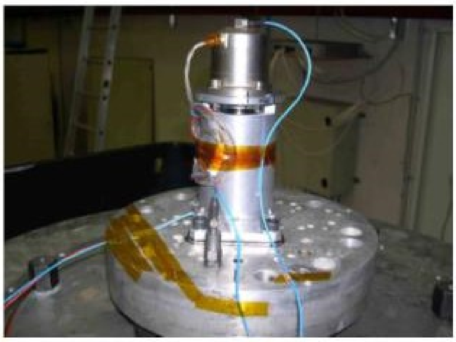
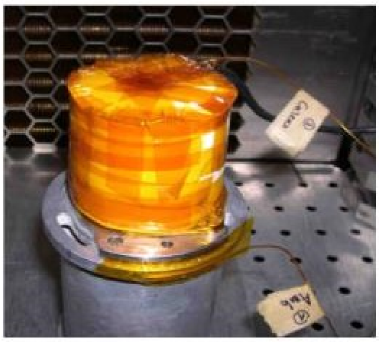
Breadboard brake

Brake test in vacuum chamber



Brake vibrations tests



Brake thermal tests

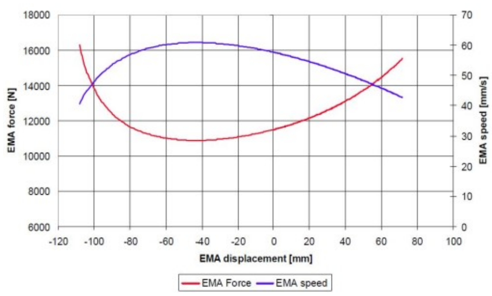
Figure 7 : Brake specific tests

### 2.3.5 Duty cycle tests

- **BB EMA and lever**

Those tests were performed on a specific IXV FpCS Load Test Bench (LTB), that was representative of the flap kinematics and able to deliver the specified force at the actuator (EMA) rod end.

IXV FpCS Load Test Bench (LTB) and Command & Control Test Bench (CCTB)




IXV FpCS EMA force and speed vs displacement.

Figure 8 : Mechanical tests on EMA and lever

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- **PFM EMACU and QM batteries**

The objective of those tests was to verify:
- ✓ The Batteries consumption and the power/energy budgets,
- ✓ The thermal behaviour of the FpCS equipments (EMA, EMACU and batteries).

Figure 9 : Vacuum chamber (SABCA facilities)

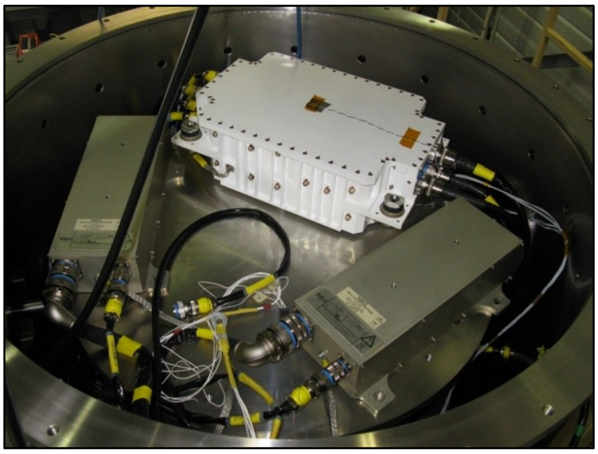
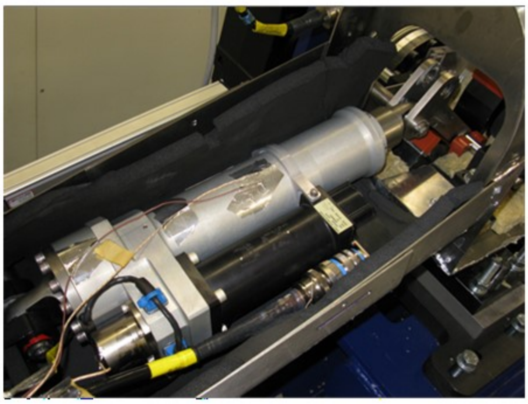


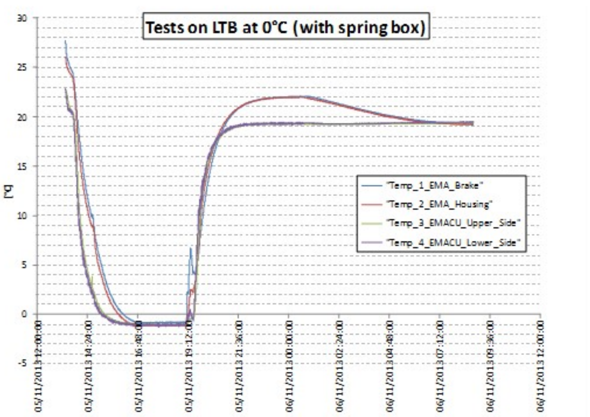
Figure 10 : FpCS Electronics and Batteries inside vacuum chamber

- **PFM FpCS thermal performances tests**

The PFM EMACU, PFM EMA (S003) and lever (S003) were tested at extreme temperatures, representative of the mission profile during the re-entry phase, and demonstrated the ability of those equipments to sustain the qualification temperatures without any degradation of their performances, in terms of step response and bandwidth, for instance:
- ✓ For the actuator (EMA), the ambient temperature range was between 0°C and + 114°C;
- ✓ For the electronic box (EMACU), the ambient temperature range was between 0°C and + 70°C.



PFM EMA (S003) and lever (S003) in thermal enclosure on Load Test Bench (LTB).



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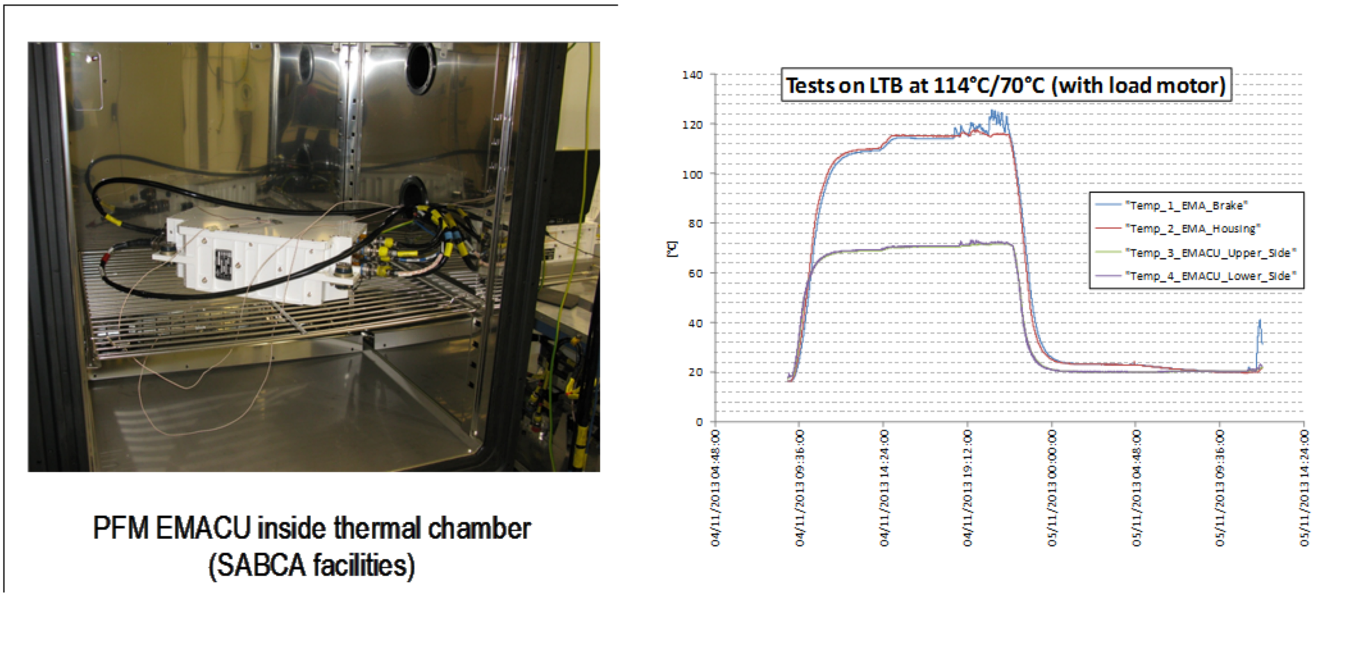


Figure 10 : PFM EMA & lever, EMACU - Temperature tests under external load

## 3. Mission extension

### 3.1 Additional phases

Compared to the IXV mission, the duration of the Space Rider orbital phase is extended by 2 months. This longer mission duration impacts the radiation level and reliability figures. Consequently, further dedicated analyses are performed to verify the compliance of this extension with the mission requirements.

### 3.2 Re-usability

Considering that the Space Rider has to operate for 6 flights, inspection checks will be carried out between each flight to evaluate whether components can be reused without any repair or replacement or if a refurbishment is necessary.
For this purpose, in-flight failure detection using ACU data enables to assess the reusability of the Space Rider. Undetectable in-flight failures are captured using reduced acceptance tests such as performance signatures (steps, triangles), battery capacity and IPDU checks. In order to minimize cost and delay between flights, those tests are tailored to avoid as much as possible RM ASCS disassembly.

## 4. Delta qualification plan

### 4.1 Mechanical system

Similarly to the ASCS equipment, an EQSR (Equipment Qualification Status Review) has been performed on the EMA-Lever system.
A detailed comparison between IXV heritage and Space Rider requirements highlighted the components in need of requalification.
For instance, the minimum temperature requirement for the IXV mission was 0°C due to the short duration of the mission (i.e. approximately one hour between lift-off and re-entry) while, for the Space Rider mission, a minimum EMA temperature of -20°C before re-entry is specified as a result of the longer duration of the mission. This new

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temperature requirement is in line with VEGA requirements/qualification process, but the braking system (inexistent on VEGA) has not been qualified to operate at such temperature. Therefore, two delta-qualification approaches are considered :

- ✓ Delta qualification of the braking system, including a justification of the possible interaction between the braking system and the EMA
- ✓ Delta qualification of the whole EMA-braking system assembly

At this point, a trade-off between technical justification and cost has to be made.

Another point was the sinus vibration requirement : the range has been extended from 100Hz to 110Hz.

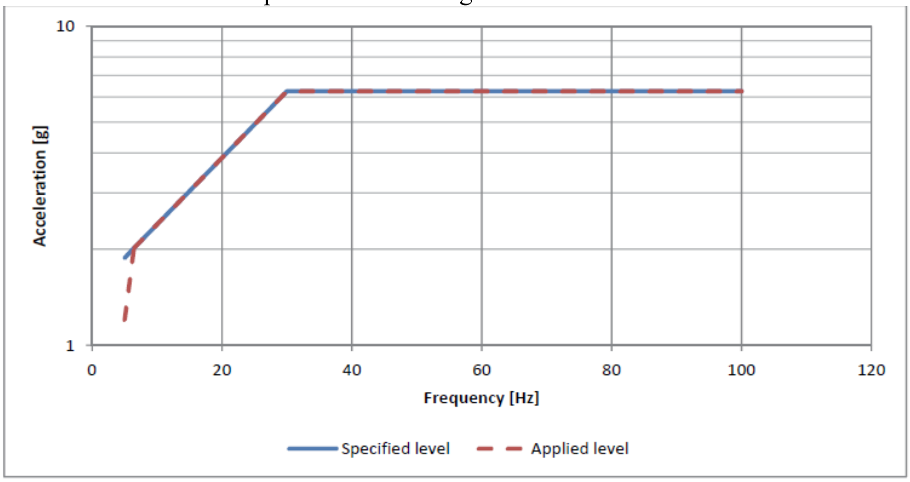


Figure 11 : Sine vibration requirement for IXV EMA

| EMA - IP & OOP | | |
|---|---|---|
| Frequency [Hz] | Acceptance [g] | Qualification [g] |
| 5 | 1.50 | 1.88 |
| 30 | 5.00 | 6.25 |
| 110 | 5.00 | 6.25 |

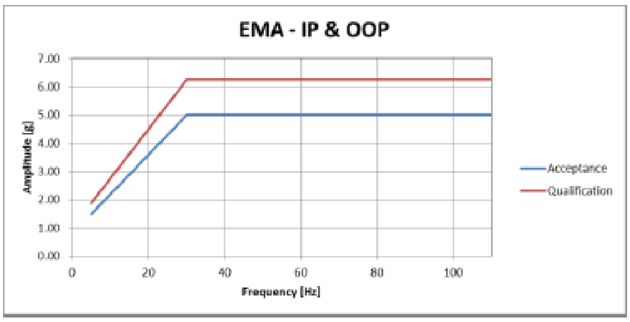


Figure 12 : Sine vibration requirement for SR EMA

This extension of range is managed by the EQSR, a delta qualification will be done to cover his point.

A performance qualification of the mechanical system is considered due to the modification of the electronic software parameters. These performance requirements will be evaluated on an adapted IXV inertial test bench (see Figure 8)

In particular, the bandwidth will be re-qualified because the requirement change from 5Hz at -3dB to 10Hz at -3dB. A preliminary worst case analysis shows that the bandwidth is around 9Hz (see green curve hereunder).

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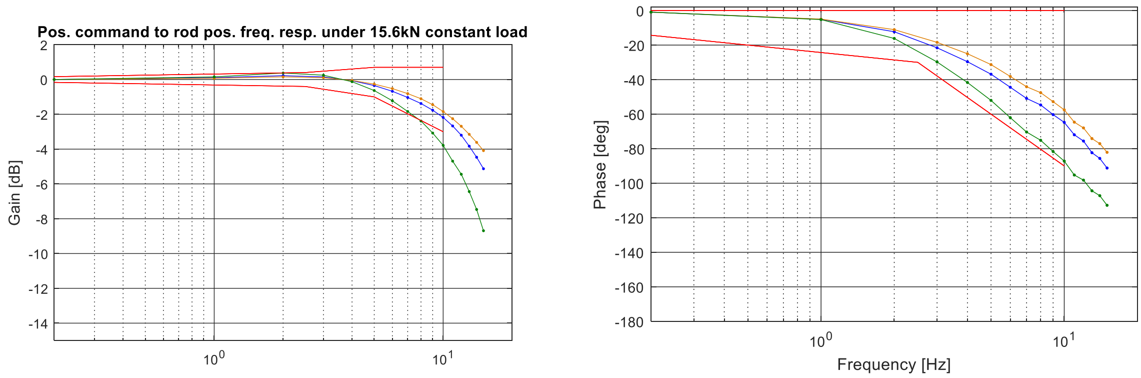


Figure 13 : Preliminary system analysis – bandwidth of SR EMA (green : worst case, blue : nominal case)

### 4.2 Electronic equipment

The electronic hardware was initially developed with low radiation requirements in the framework of the VEGA program. Due to short duration of the IXV mission, the rad-hard policy for EEE component is still applicable for both programs.
For the Space Rider mission, the Total Ionizing dose is significantly higher than VEGA missions because it takes into account 6 missions of 2 months each. Hence, it will operate a total of 12 months in low orbit, for up to 3 000 rads exposure approximately.
This higher radiation requirement has been accounted for by a thorough verification of the EEE components. Fortunately, most of the components have documentation on their radiation tolerance but few have no radiation response information available.
For these components, considering that the new TID level is higher than that of VEGA/IXV, a compromise has been made between the procurement of new equivalent rad-hard components and the testing of current components in order to quantify their derating.
Due to the high cost of rad-hard components, the testing and acceptance of the current components can prove to be cost-effective. Moreover, it has the advantage to avoid delta-qualification or justification of these new components with respect to the mechanical environment of the EMACU (random vibration, shocks,…).
On the other hand, it is also important to highlight that, since the development of VEGA during the 2000’s, some components are now obsolete and they are managed as strategic stocks for VEGA but their rad-hard equivalent are also obsolete and difficult to find. Therefore, the choice between the testing of current components for radiation qualification or the procurement of new rad-hard components will drive the qualification strategy of the EMACU.
Some mechanical issues also appear due to requirements change : for sine vibration, the heritage is sine vibration at 10g between 15Hz and 100Hz.

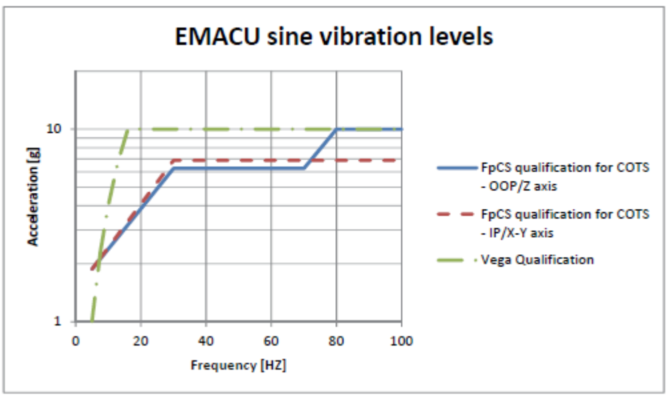


Figure 14 : Sine vibration requirement for IXV EMACU

The new requirement is higher :up to 15.63 g between 45 Hz and 75 Hz.

| EMACU - IP & OOP | | |
|---|---|---|
| Frequency [Hz] | Acceptance [g] | Qualification [g] |
| 5 | 1.50 | 1.88 |
| 30 | 8.00 | 10.00 |
| 40 | 8.00 | 10.00 |
| 45 | 12.50 | 15.63 |
| 75 | 12.50 | 15.63 |
| 80 | 8.00 | 10.00 |
| 110 | 8.00 | 10.00 |

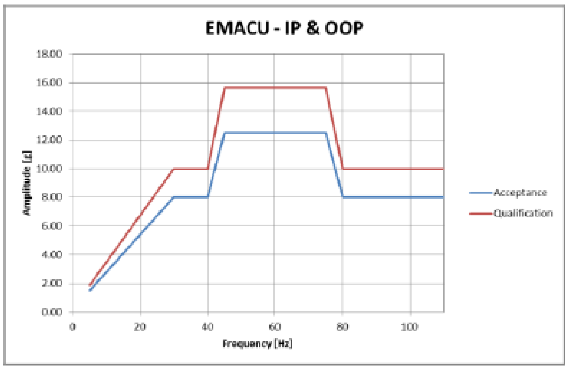


Figure 15 : Sine vibration requirement for SR EMACU

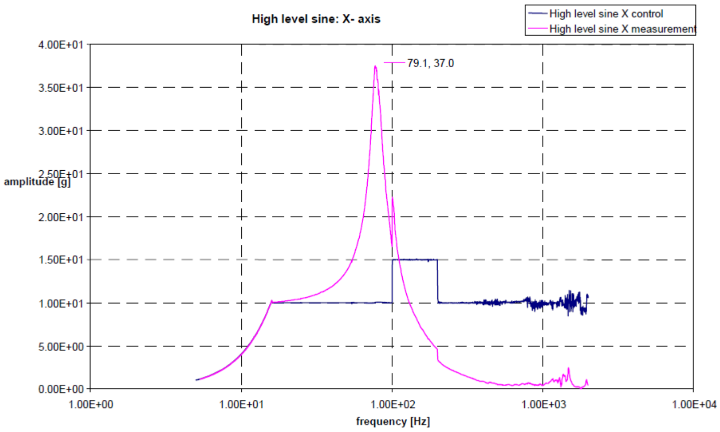


Figure 16 : Sine vibration results for EMACU

Due to the proximity to resonance of the electronic box (around 79Hz), this requirements has to be managed by mechanical analysis in order to both lower the requirements (at system level) and check the ability of the EMACU to survive higher level at its resonance (sub-system level).

### 4.3 Batteries

The two batteries used for the IXV mission comes from the VEGA launcher. However, since the IXV flight mission, these batteries are now obsolete and a new one has been qualified for VEGA. Moreover, an EQSR for Space Rider has been carried out and , it highlighted that delta qualification is needed, in particular, to meet temperature and shock requirements. Indeed, the intensity of the shocks experienced by the batteries is lower than for VEGA mission, but they are more frequent). The space Rider requirements ask for -20°C in operative condition while they have been tested at -2°C (see figure hereunder).

### 4.4 Software

Considering only few control parameter are changed in the software used, the validation of its new version will consists of a range analysis. Subsequently, the software will be uploaded in the hardware in order to ensure the compliance of the new parameters with the system requirements. Further validation performance testing will then be carried out at the system level : duty cycle, steps bandwidth,…

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## Conclusions

The key challenge of the phases B and C of the Space Rider ASCS was to identify the minimal modifications and delta qualification necessary to meet the new requirement, in order to take advantage of the validated system.

Both PDR and EQSR have been successfully achieved, the design has been updated and all tasks and tests necessary to modify and qualify the system for the Space Rider mission, the re-usability constraints and the updated requirement set, have been identified.

In particular, a complete screening of the components capability to sustain radiations was performed. A reusability policy addressing potential refurbishment or replacement for limited shelf life or obsolescent components was defined. For the components without available data relative to their capability to support radiations, trade-offs have been performed between additional qualification tests or replacement by radiation tolerant ones. Risk and reliability analyses have been conducted and associate action plans have been set up.

As a consequence, SABCA has updated the definition of the IXV FpCS and secured this system to become the Space Rider ASCS. It is now about ready for the CDR process that should take place in Summer 2019.

## Acknowledgments

Space Rider is a Project of the European Space Agency, with THALES ALENIA Space Italy and AVIO SpA as co-Primes. We thank them all for enabling this promising program and for trusting SABCA for the AOM and RM actuation control systems development.

## Abbreviations and acronyms

| | |
|---|---|
| ACU | Actuator Control Unit |
| AOM | AVUM Orbital Module |
| ASCS | Aerodynamic Surfaces Control System |
| BB | Breadboard |
| DC | Direct Current |
| DCM | Digital Control Module |
| EQSR | Equipment Qualification Status Review |
| EEE | Electrical and Electronic Engineering |
| EMA | Electro Mechanical Actuator |
| EMACU | Electro Mechanical Actuator Control Unit |
| FpCS | Flap Control System |
| HW | Hardware |
| IGBT | Insulated-Gate Bipolar Transistor |
| IXV | Intermediate eXperimental Vehicle |
| LTB | Load Test Bench |
| LVDT | Linear Variable Differential Transformer |
| PFM | Proto Flight Model |
| PM | Power Module |
| RM | Re-entry Module |
| SW | Software |
| TVCS | Thrust Vector Control System |