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Space Rider Aerodynamic Surface Control System

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Abstract

The Space Rider is a European mini-shuttle project lead by ESA and destined to bring payloads into orbit for a duration of up to two months and return them back safely to Earth. It consists out of two major element: the Re-Entry Module (RM) developed by TAS-I and the AVUM Orbital Module (AOM) derived from the AVIO VEGA 4th stage.

SABCA is responsible for the design 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 (EMACU) containing all the power and control electronics;
- two battery packs for the power generation; and
- all the necessary cables and harnesses.

For the ASCS, two mechanical levers transfer the displacement of the actuators to the flaps. 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.

After the ASCS EMA control mission, the EMACU will also be used to control the winch parafoil motor in order to ensure the precision landing.

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.

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The reusability analysis has been deeply conducted in order to avoid dismounting of equipment between flights. The reusability analysis highlights the most important tests to be perform in order to insure a good reliability for the next mission.

The CDR has validated the adaptations needed to ensure that the equipment meets the new constraints in terms of reusability and radiation, and the additional tests to qualify it. 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

Keywords : Space, Rider, Aerodynamic, Control, Surface

Abbreviations and acronyms

AOM	AVUM Orbital Module
ASCS	Aerodynamic Surfaces Control System
BB	Breadboard
CDR	Critical Design Review
DC	Direct Current
DCM	Digital Control Module
EQSR	Equipment Qualification Status Review
EEE	Electrical and Electronic Engineering
EMA	Electro Mechanical Actuator
EMACU	ElectroMechanical 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
PDR	Preliminary Design Review
PFM	Proto Flight Model
PM	Power Module
RM	Re-entry Module
SW	Software
TVCS	Thrust Vector Control System

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.

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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.

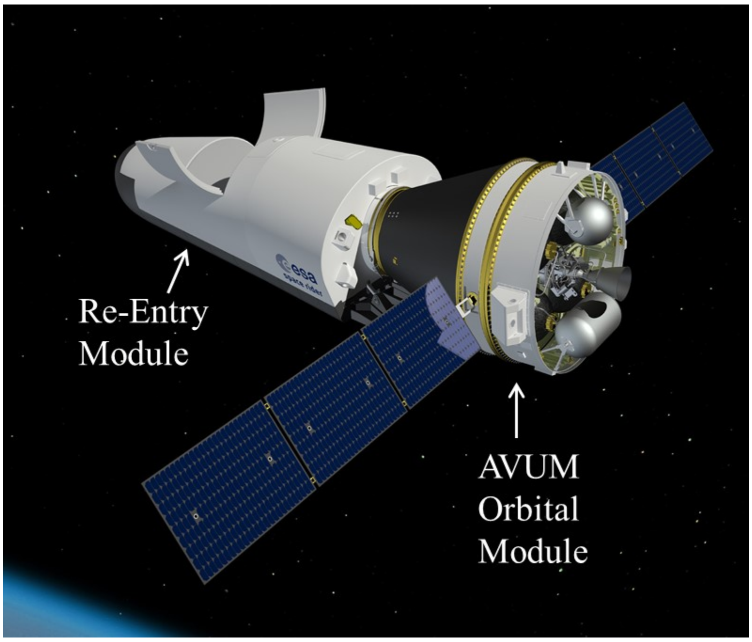

Fig 1. Space Rider in orbit

2. IXV heritage and Space Rider use

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.

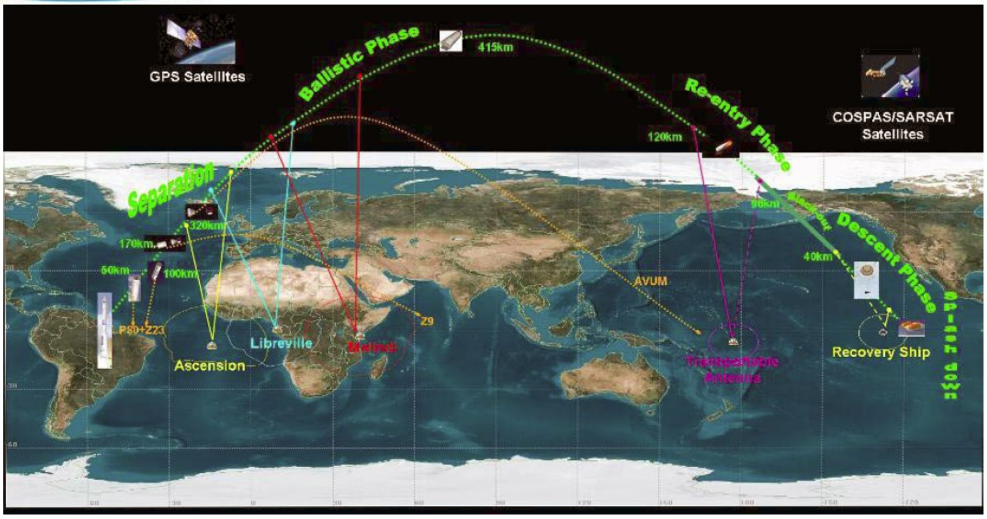

Fig 2. IXV Mission profile

2.2. ASCS architecture

The main components of IXV FpCS and Space Rider ASCS are the same.

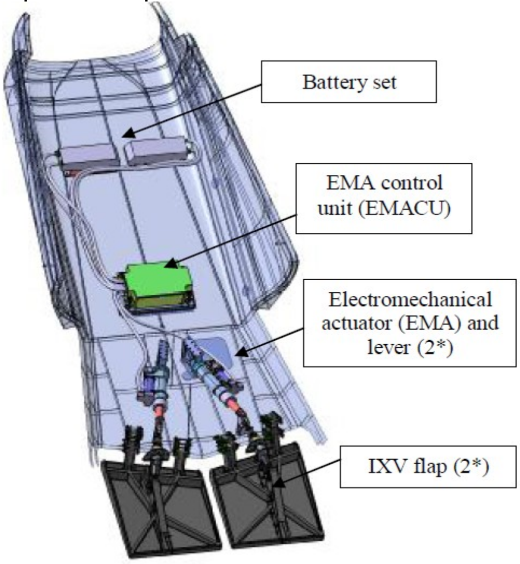

Fig 3. IXV Flaps control System

2.3. Mechanical system

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

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

- ✓ the EMA pin-to-pin length and strokes is specific to the Space Rider application;
- ✓ the actuator design includes a blocking device; therefore, the design of the actuator housing is also modified;

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- ✓ the accuracy of the actuator position sensor (LVDT) is improved, in order to meet the flap control requirements;
- ✓ the actuator anti-rotation interfaces is surface hardened and dry lubricated, in order to be compatible with the Space Rider operational and environmental constraints.

The PFM actuators are shown below.

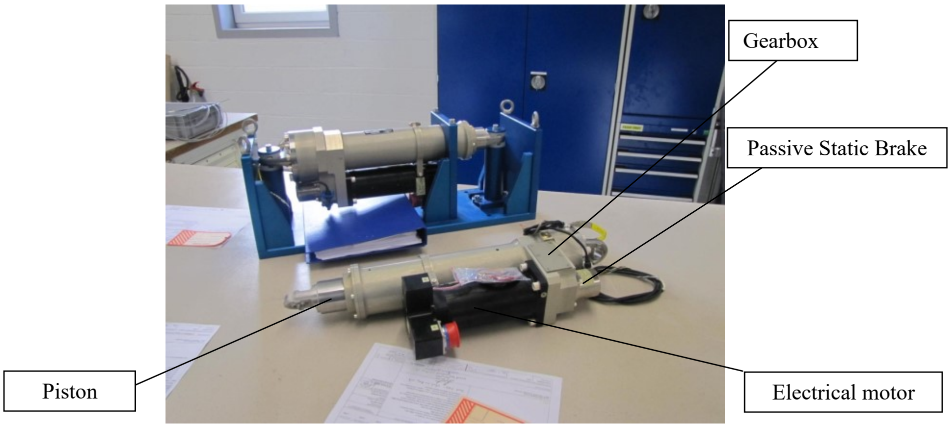

Fig 4. ASCS EMA

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 although more and longer missions 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.

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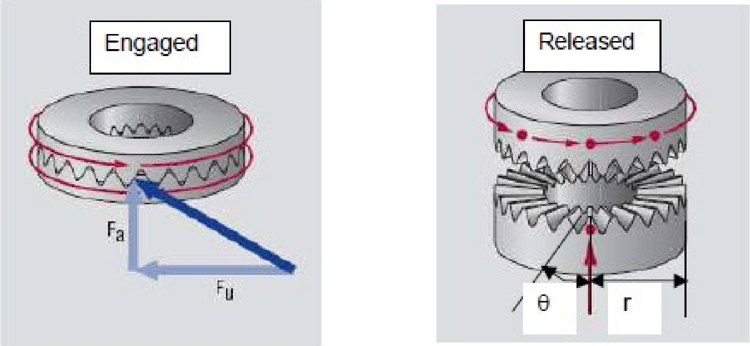


Fig 5. IXV Flaps control System

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.

2.4. 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:
  - the Digital Control Module (DCM) implementing the EMACU software (SW);
  - 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.

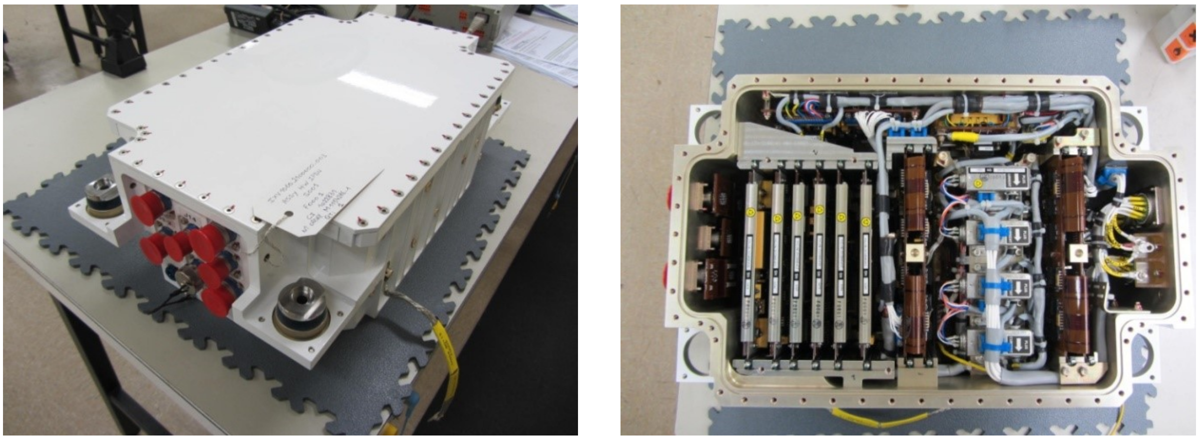


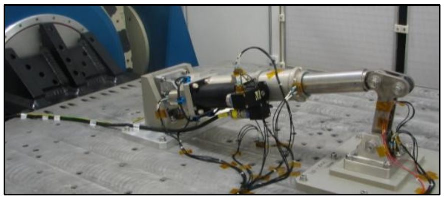
Fig 6. EMACU

2.5. Batteries and harness

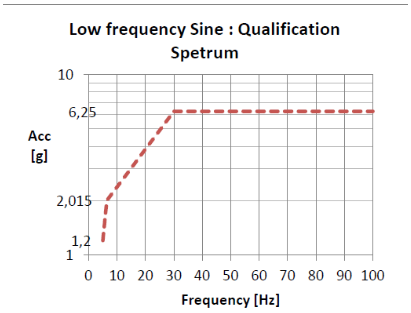
The batteries used for the mission are SAFT 15S VL8P coming from VEGA launcher. Harness is manufactured by SABCA.

2.6. IXV FpCS qualification tests heritage

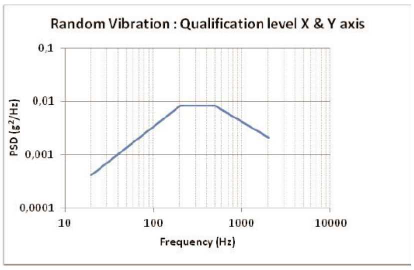
During the IXV campaign, most of the system have been delta qualified w.r.t. VEGA heritage. This IXV qualification heritage is one of the most important basis for the Space Rider application.
The EMA and lever (lever is specific and did not exists in VEGA design) have been teste with to check their compatibility to environmental requirement :



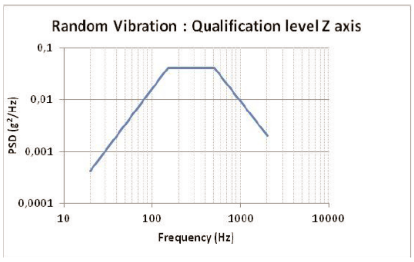
FpCS EMA and lever on shaker



Sinus vibrations



Random vibrations - X & Y axes.



Random vibrations – Z axis

Fig 7. EMA and lever tests

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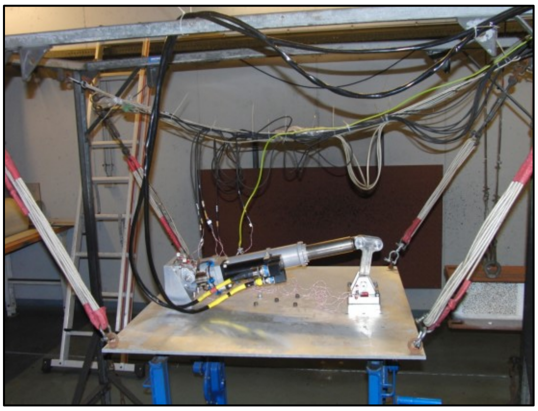
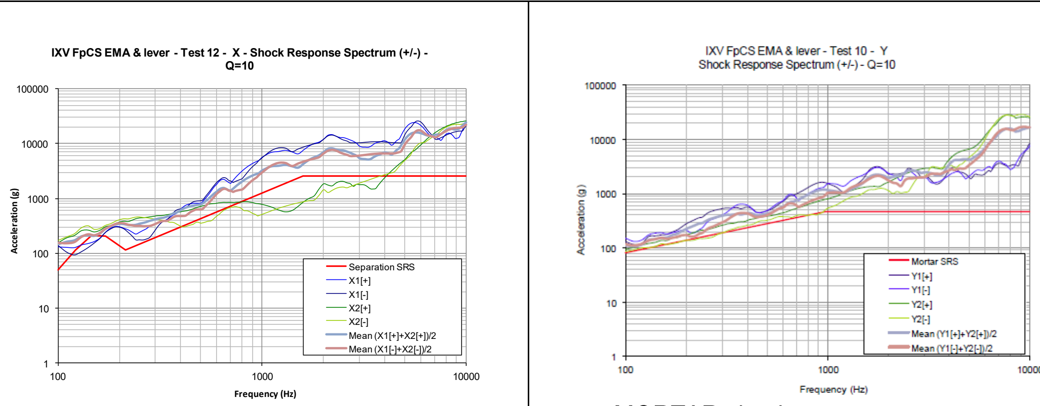


Pyro-shocks tests set-up



Separation shocks response spectrum

MORTAR shocks response spectrum

Fig 8. Pyro-shock tests

The main aim of these tests was to demonstrate that the blocking device stay in place while vibration and pyroshock occurred and that these environments did not degrade the system performance.

The system was also tested in thermal vacuum condition during the IXV campaign.

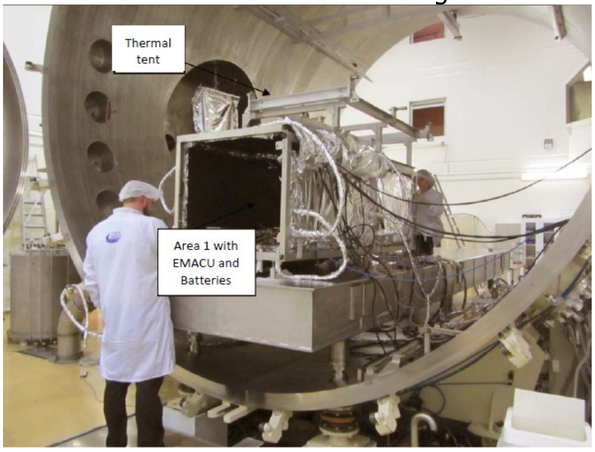


Fig 9. Thermal tent in vacuum chamber at the Centre Spatial de Liège (Belgium).

System duty cycle test has been performed in SABCA premises on an EMA load controlled test bench.

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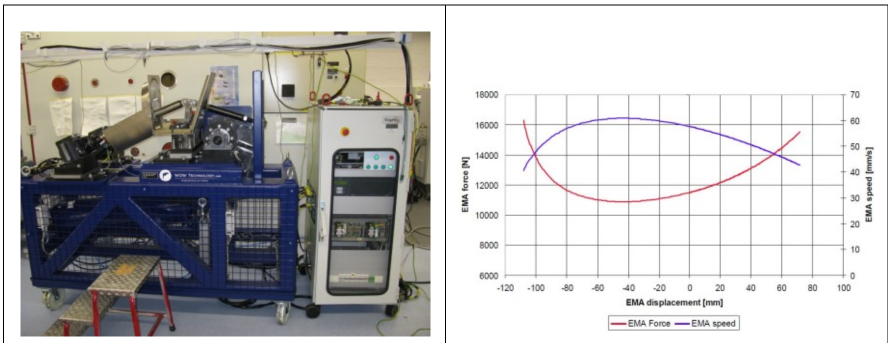
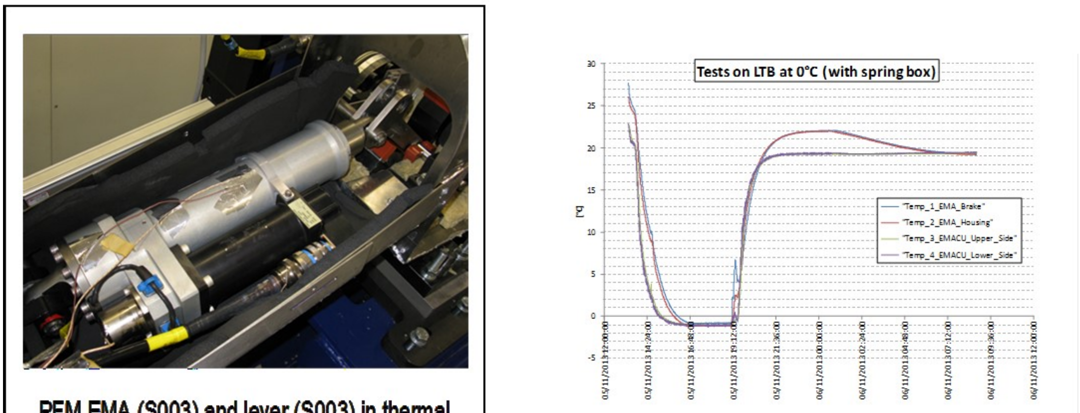


IXV FpCS Load Test Bench (LTB) and Command & Control Test Bench (CCTB)

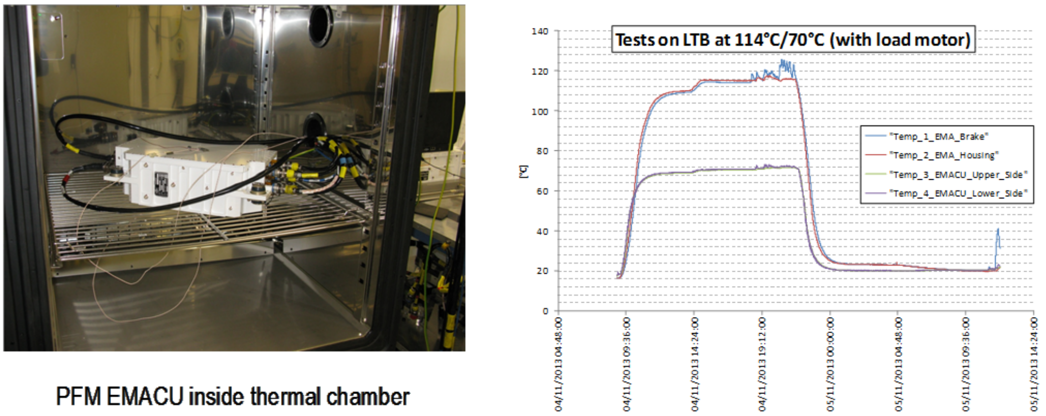
IXV FpCS EMA force and speed vs displacement.

Fig 10. Mechanical tests on EMA and lever

These test bench allows to test EMA performance in hot and cold conditions :



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



PFM EMACU inside thermal chamber (SABCA facilities)

Fig 11. PFM EMA & lever, EMACU - Temperature tests under external load

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3. Space Rider 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.

The mission is divided according to the following sequence :

- Launch phase : The ASCS is blocked and shall survive the mechanical environment
- Orbital phase : The ASCS system is mainly off. It will be activated for some checks during this phase.
- Re-entry phase : The ASCS controls the Space Rider module during the atmospheric re-entry
- Descent phase and precision landing : the Battery and EMACU of the ASCS is used for the control of the winch parafoil.

Before and after the mission, some tests are performed on ground to check the health of the system.

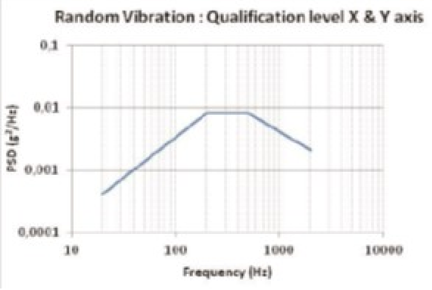
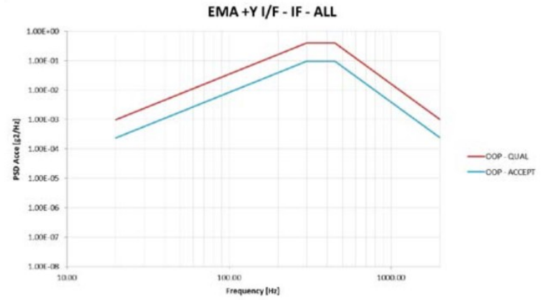
3.2. Re-usability

Considering that the Space Rider shall 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 EMACU 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 EMACU 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 VEGA/IXV heritage and Space Rider requirements highlighted the components in need of requalification.

	Heritage level	Space Rider level
Random EMA	 	 ⇨ 0.4g²/Hz between 300Hz and 450Hz waivered with the agreement of TAS-I because much higher tan hertitage

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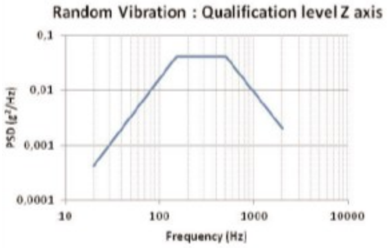
<td>
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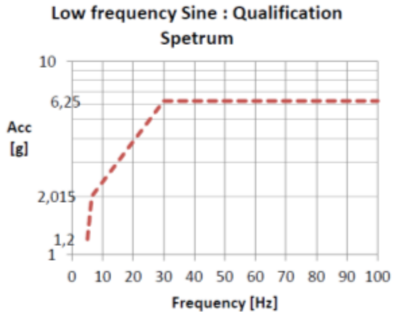
<td>
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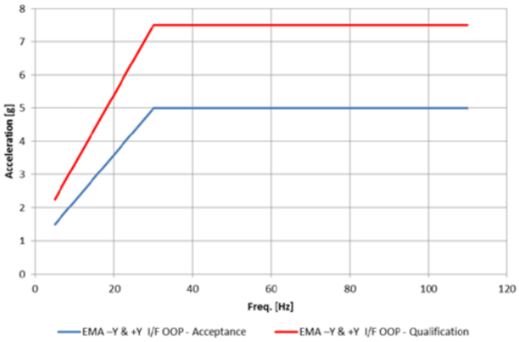
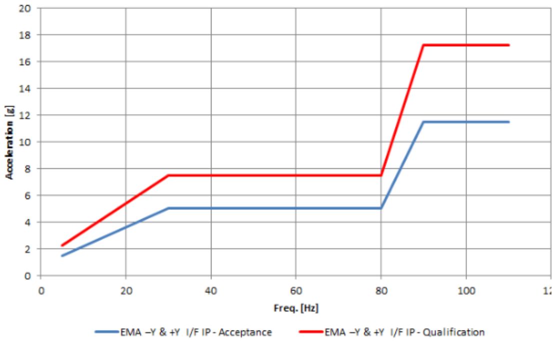
<td>



⇨ Level @17.5 g waivered with the agreement of TAS-I because much higher tan hertitage</td>
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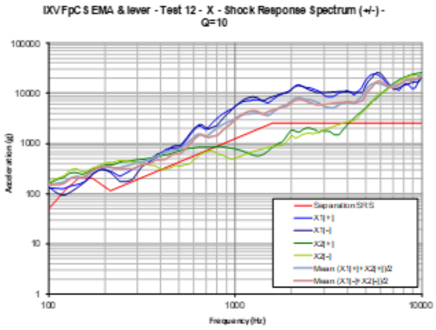
<td>
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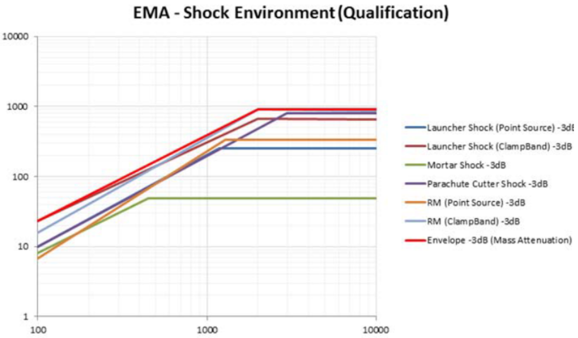
<td>

⇨ Level covered by heritage</td>
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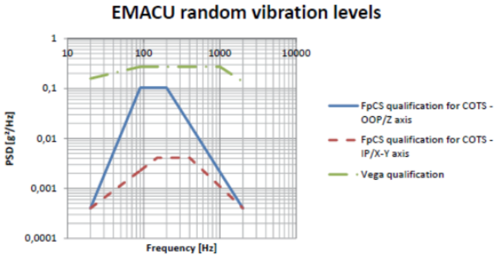
<td>
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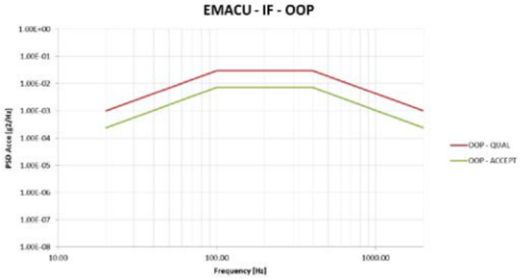
<td>
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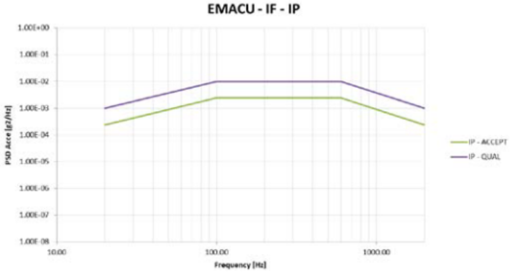
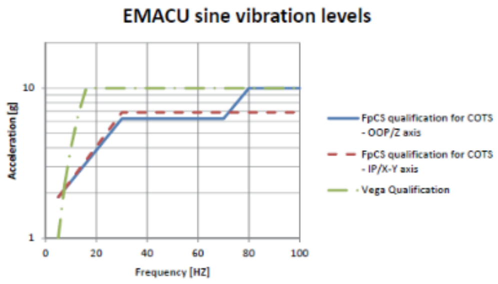
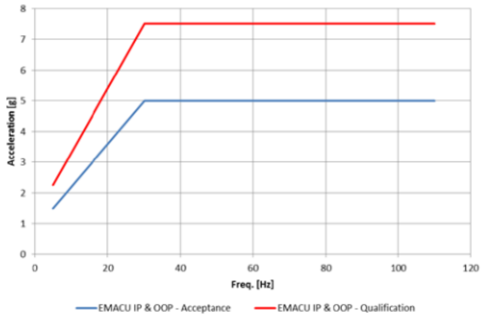
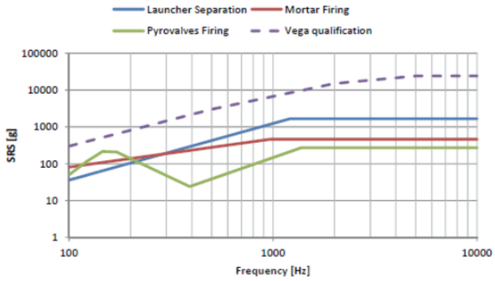
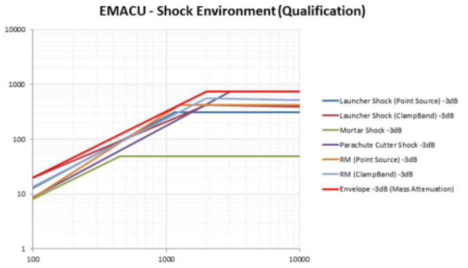
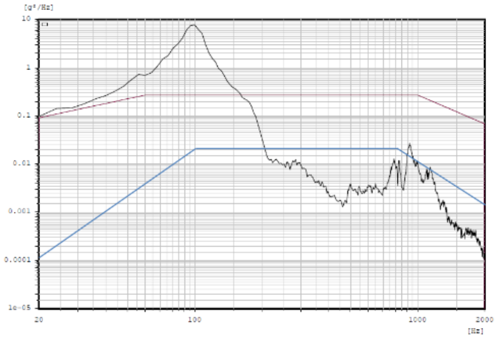
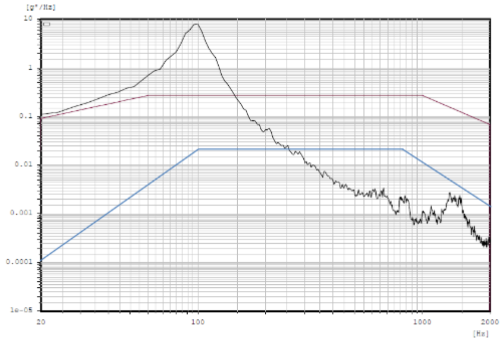
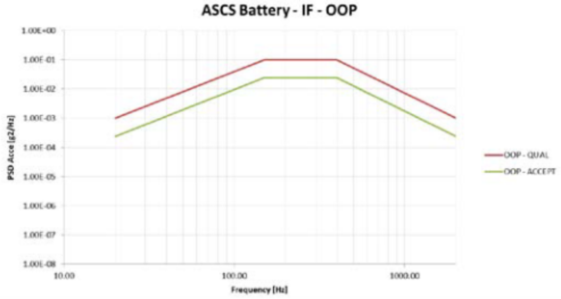
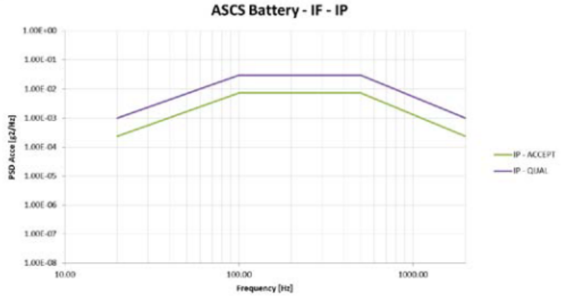
		 ⇨ Covered by heritage*
Sine EMACU		 ⇨ Covered by heritage*
Pyroshock EMACU		 ⇨ Covered by heritage*
Random Battery	 	 ⇨ Covered by heritage until 280Hz, waivered for higher frequencies  ⇨ Covered by heritage until 320Hz, waivered for higher frequencies

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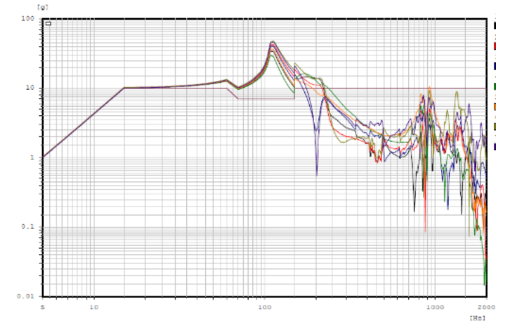
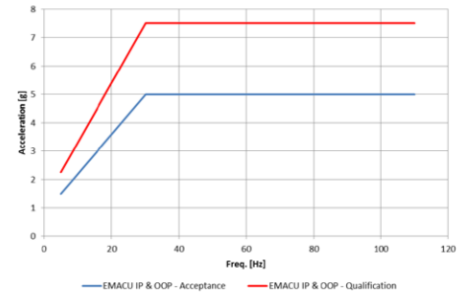
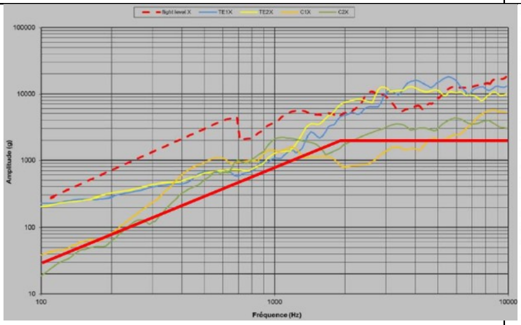
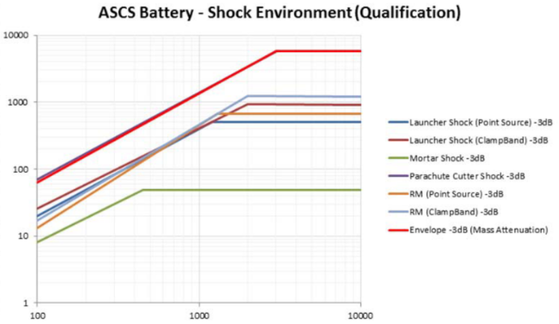
Sine Battery		 ⇨ To be tested
Pyroshock Battery		 ⇨ To be tested, C1X and C2X curves do not meet the requirement of 5800 g**

*The electronic components changed by rad-hard equivalent have the same mass, packaging, placement so no mechanical delta qualification is needed
**The battery set need to be qualified for 3 shocks in each axis, however by heritage, it is only qualified for 2 shocks. After EQSR, it has been decided to re-qualify the battery w.r.t. the Space Rider ASCS requirement.

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 9Hz at -3dB. A worst case analysis shows that the bandwidth is more than 10Hz (see curves hereunder).

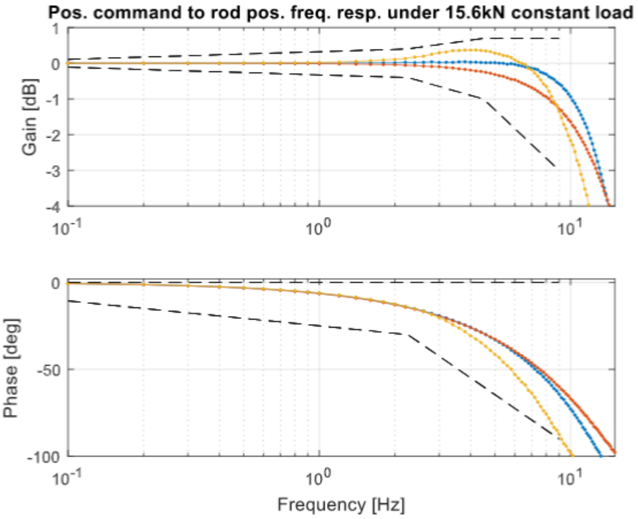


Fig 12. System analysis – bandwidth of SR EMA

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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/TNID 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 of some components has been performed to check their compatibility with the radiation level.
These tests reveals high margins of radiation on these components.

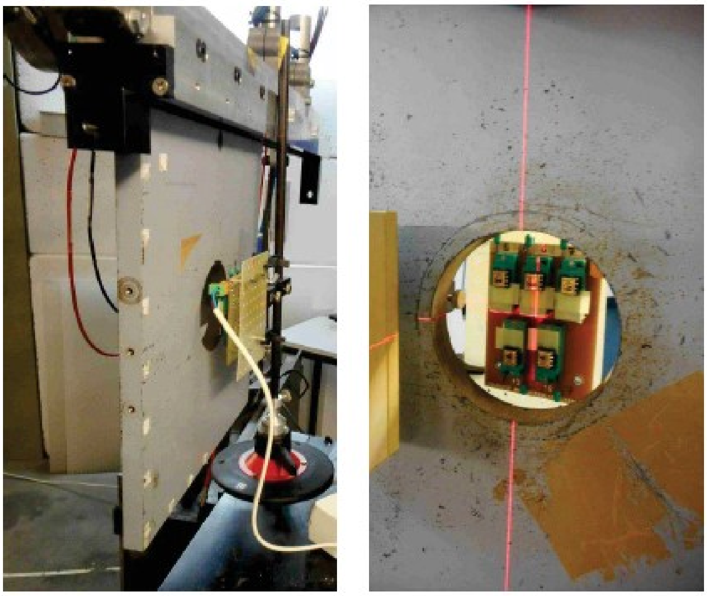

Fig 13. Proton Displacement damage test on isolation amplifier

However, for four of those components, they have been replaced by rad hard alternatives with same mass and packaging, avoiding to question the mechanical behaviour and vibration qualification status.

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 (and mechanical equivalent in order not to question mechanical behaviour of the EMACU and be covered by the heritage) 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 drove the qualification strategy of the EMACU : is has been preferred to keep the hardware as close as possible to the VEGA/ IXV one.

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 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 asked in the past for -20°C in operative condition while they have been tested at -2°C (see figure hereunder), This has been solved without need of new test thanks to a survival heater install on the battery.

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,…

5. Contribution to landing mission

5.1. Parafoil mission

After the re-entry and the use of the ASCS, the Space Rider RM will deploy a parafoil. This parafoil will be actuated by two motors controlled by the same EMACU as for EMA ASCS. This is possible because of the use of the same motors for landing mission and ASCS mission. Another advantage is that this motor, already foreseen to be used on Space Rider RM is qualified for the mission. A "Branching Unit" (BU) will allow to switch the power and data cable from EMAs to Winch motors.

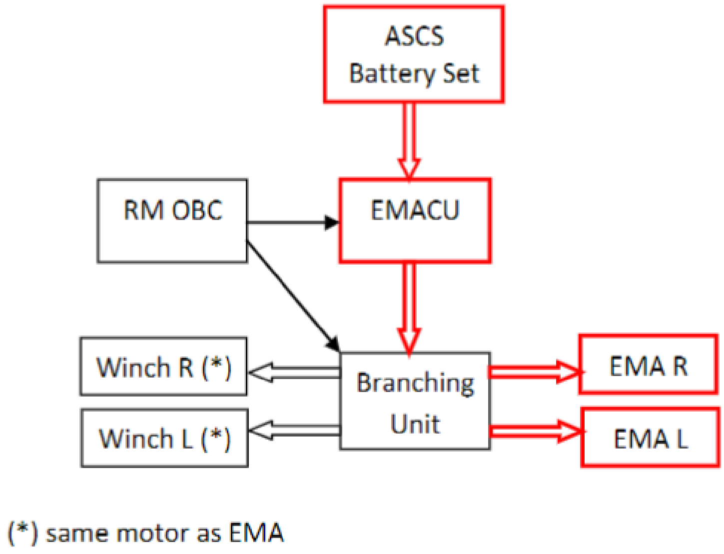

Fig 14. Branching Unit, EMAs, Winch motors and EMACU

It appears difficult to change the software of the EMACU during the flight, so it has been decided to keep the same software with the same parameters for both ASCS and winch parafoil mission. Fine tuning and compromises on performance has been done to meet the requirements of both missions. The FMECA and system user manual has been updated to consider this new use of the Battery and EMACU.

5.2. RAMS

Due to the addition of the parafoil mission, but also due to the multiple mission, the Failure Mode, Effect, Consequence and Analysis has been reworked. Computation has been made in order to check that a reliability figure before each flight is met.

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This computation takes into account the reusability analysis and the tests performed on the system on ground, these tests allow to check the health of the ASCS and to re-increase the reliability figure without dismounting the equipment.

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 CDR 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. 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. A reusability policy addressing potential refurbishment or replacement for limited shelf life or obsolescent components was defined. Reusability and reliability analyses have been conducted together allowing to show that each mission starts with a reasonable reliability figure after few tests.

Therefore, SABCA has updated the definition of the IXV FpCS and secured this system to become the Space Rider ASCS. It is now ready to manufacture and then perform the delta qualification.

The major surprise in this development is the demonstration of the EMACU versatility: it will be used for the parafoil winch actuation system without hardware modification (only software parameters), while it was initially design for the aerodynamic surfaces control only.

In parallel, SABCA prepares a new ASCS generation, compatible with the Space Rider mission requirement and the future constraints associated to the space context evolution.

Acknowledgments

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