ARES14BI "HYDRA" – A TWO-STAGE EXPERIMENTAL ROCKET PROJECT WITHIN THE PERSEUS PROGRAM

Valentin Guinet and Bastien Gauthier***
**ISAE-SUPAERO, SUPAERO Space Section*
valentin.guinet16@isae-alumni.net
***CENTRALE LYON, Centrale Lyon Cosmos*
bastien.gauthier@ntymail.com

Note : These authors have contributed equally to the work described hereafter.

Abstract

The ARES14BI "Hydra" project was part of the PERSEUS program, an initiative launched by the French Space Agency (CNES) in 2005 to find innovative solutions by involving students. Hydra was a two-stage experimental subsonic rocket of about 25kg and 3.80m, developed as a technology demonstrator to test multiple sub-systems such as a pneumatic interstage separation system, an umbilical management system and a pyrotechnic sequencer. The second stage did not have propulsion but was fitted with an empty motor casing adapted for measurement purposes. The sensors on board allowed the qualification of multiple technologies for ulterior demonstrators.

1. Introduction

The ARES14BI "Hydra" project was part of the PERSEUS (Projet Étudiant de Recherche Spatiale Européen Universitaire et Scientifique) program, an initiative launched at the 2005 Paris Air Show by the French Space Agency (CNES). This program aims at fostering innovative technological solutions in all areas related to launchers while involving students as much as possible and applying an industrial approach.

This step-by-step approach is directly put into action through multiple projects with different partners, and Hydra indeed involved engineering students from ISAE-SUPAERO (Toulouse, France), Ecole Centrale Lyon (Lyon, France) and IPSA (Paris, France) as well as industrial and research partners. By cutting across the barriers between education, training and research, the students are introduced to a professional and stimulating environment.

As one of different PERSEUS projects, Hydra was an experimental rocket of about 25 kg for 3.80m. More precisely, this two-stage technology demonstrator was developed to test multiple sub-systems, such as a pneumatic interstage separation system, an umbilical management system and a pyrotechnic sequencer. The second stage only had a dummy motor, representative in terms of mass but only fitted with a simple igniter, pressure measurement electronics and video camera in place of propellant grain. The pneumatic separation system was designed to create a differential speed between the stages of at least 1 m/s and to be scalable for use on a larger launcher. The umbilical management system aimed to avoid the collision between the cables connected to the upper stage and the fins of the lower stage before leaving the launch pad. Finally, the pyrotechnical sequencer was designed to ensure safety both during motor installation by the pyrotechnicians and during the flight by preventing any unwanted and/or dangerous firing. The whole rocket had been conceived and built over two years, between 2013 and 2015. Additive manufacturing was used to reduce the mass and enable complex mechanical parts in some subsystems.

This project was unique because it had linked together many actors from different entities and cities. Under the CNES direction, the project had evolved between the regular PERSEUS partners and two space clubs, Centrale Lyon Cosmos (CLC) and SUPAERO Space Section (S3). Many reviews were organized to keep the teams together and be sure everyone was aware of the current status of the launcher and was pushing in the same direction.

The picture-perfect flight happened on the 23rd July 2015 on the Ger military camp near Tarbes, in France. Thanks to the collection of pressure sensors and the three inertial centrals aboard, a large data analysis has been done, mainly to characterize the in-flight performances of the pneumatic separation.

2. Acronyms

Most acronyms have their meaning in French. The letters may not correspond to the English translation.

ARES	Advanced Rocket for Experimental Studies
CFD	Computational Fluid Dynamics
CLC	*Centrale Lyon Cosmos*
CNES	*Centre National d'Études Spatiales*, French space agency
FDM	Fused Deposition Modeling, a 3D printing technique
FPI	*Faux Propulseur Instrumenté* (Simulated Booster)
IMU	Inertial Measurement Unit
RAV	*Revue d'Aptitude au Vol* (Flight Readiness Review)
SAO	*Système d'Arrachage des Ombilicaux* (Umbilicals Management System)
SCUBE	*SUPAERO Space Section*
SERA	Supersonic Experimental Rocket ARES
SSIE	*Système de Séparation Inter-Étages* (Pneumatic Interstage Separation System)
TRL	Technology Readiness Level

3. Project management

3.1. The PERSEUS Program

The PERSEUS Program aims to coordinate different partners with a dedicated organization. Indeed, involving students in industrial space projects requires a very specific project management, as explain in reference [1]. To be more specific, the large turnover of students improves the innovation but induces a significant lack of knowledge about launch systems. The PERSEUS organization first goal is to reduce these drawbacks by giving formations to the students, involving the teachers in the knowledge transmission and manage a documentation portal for the PERSEUS community.

The PERSEUS project management relies on the repartition between several macro-projects divided in four main categories, which should be reunited in the end to fit the long-term vision of the program:

- Nano Launch Vehicle concepts
- Studies or software developments
- Ground demonstrators
- Flight demonstrators

These categories are detailed in [2], but only the last one will be relevant in this paper, because it includes the ARES macro-project, and thus the Hydra launcher.

For this kind of projects, the PERSEUS staff supports the student teams through the entire life of the project and helps both for the management aspect and the technical developments, with regular meetings and video calls.

3.2. The Hydra Project

The Hydra Project follows the classical PERSEUS organization, but is of larger scale. Indeed, as this is the first two-stage launcher of the program, it requires more workforce. It involves student associations (CLC, SCUBE, IPSA) from several engineering schools in France, as well as regular PERSEUS partners (GAREF, MI-GSO). This totalizes about 15 students over two years. As the launch is done during the C'Space, an external event organised by CNES and the Planète Sciences association, the week launch is set and cannot be delayed.

Figure 1: Hydra Project organisation

The work repartition gives the first stage responsibility to the CLC, the second stage to the SCUBE association. However, given the students' planning in the engineering schools, the tasks are done with agility.

4. Review of the technological demonstrator

4.1. Generalities

The Hydra launcher, like all the ARES previous launchers, has a 160mm exterior diameter. Its specificity with regards to the ARES family is that this a two stages experimental rocket. The total length is 3.90m, with 1.3m for the first stage and 2.6m for the second stage, while the total mass (with motor) is 24.7kg, divided in 10kg + 14.7kg. Both stages sport 3 composite fins.

It is important to note that due to the French regulation over the launches, each part ejected from the launcher must be recovered. In order to do so, parachutes are installed for each stage of the rocket, which impose additional mass. Moreover, the stability of the system cannot be improved via gyroscopic effect because it could prevent the parachutes from opening correctly. To counterbalance this, the fins must be wider than those on a spinned rocket.

The demonstrator used standard PERSEUS avionics modules for data handling, telemetry and timers.

Figure 2: Main view of the demonstrator installed on launch ramp

4.2. Experiments

4.2.1. Inertial Measurement Units

Three IMUs are installed on-board, two of them on the upper stage and one on the lower stage. By recording the accelerations, angular velocities and direction of the magnetic field, they enable *a posteriori* a characterization of the flight, as well as a confrontation of the results to the expected trajectory.

Two different IMUs have been used on multiple PERSEUS demonstrators and on Hydra. Both stages were equipped with a custom-build SYSTAR2011 module by SYSNAV which records @819Hz on an internal microSD card the 3D outputs of an accelerometer, a gyroscope and a magnetometer. The upper stage was also fitted with an IMU based on a MTi module from XSens which provides similar measurements @100Hz on the USB bus (transmitted via telemetry during the flight).

4.2.2. Pressure measurements

Using pressure measurement boards developed internally by the SUPAERO Space Section on behalf of PERSEUS, many recordings were performed, both for trajectory studies (velocity, altitude, etc.) and technological experiments (SSIE pneumatics monitoring). Equipped with an ATMEL SMA7X MCU, these boards can provide measurement of multiple sensors on the main data USB bus @100Hz (with possibility of daisy-chaining).

4.2.3. Pneumatic Interstage Separation System (SSIE)

The Pneumatic Interstage Separation System is the main experiment of the Hydra demonstrator. It was developed at IPSA Paris on behalf of PERSEUS and under the supervision of Sylvain PERNON to prepare for multi-stage performance launchers of the PERSEUS-SERA family.

The SSIE is pneumatic to allow students to manipulate the system at all stages of assembly and preparation, until the motor insertion, to comply with the regulation on pyrotechnics. The pneumatic solution appeared to have a good performance to mass ratio and has the advantage to both secure the stages together during the first phase of the flight and separate them at the given time.

The SSIE is installed on the lower stage, with a specific aluminium ring at the rear end of the upper stage with notches for the fastening hooks. Air is stored in 6 pressure tanks filled at 10 bars and distributed via solenoid valves in the 3 double-acting cylinders. To ensure synchronisation of the cylinders at separation, they are fastened to a common aluminium ring. When the external sequencer orders, the system performs separation with a difference of velocity of at least 1 m/s (design criteria for heavier demonstrators).

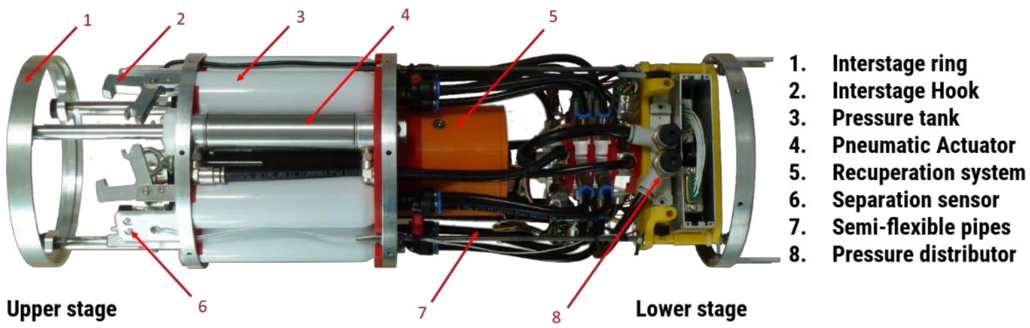

Figure 3: Main view of the SSIE system in opened configuration

The pneumatic system also offers the possibility of having the lower stage recuperation system integrated at its centre, which increases the compactness of such a system.

The pipes linking the pressure tanks to the actuators via the pressure distributor are semi-flexible: doubled by an aluminium sleeve, flight vibrations have a limited impact on them. This limits the probability of a pipe disconnection. However, it imposes difficulties during the integration phase because the pipes have to be pre-formed.

Three high-pressure sensors are installed on the system to monitor the system status before launch.

Since phases such as the deployment of the first stage parachute and the second stage ignition order depend on the separation confirmation, three ways to detect separation are installed and used with a majority vote, making use of different physics. There is a mechanical sensor (a button in the lower stage with a rod clicking it on the upper stage), an electrical shunt which is cut by the separation (by disconnecting the connectors linking the stages) and an inductive sensor (adjusted with a steel screw on the upper stage).

4.2.4. Umbilicals management system (SAO)

Since the dual stage configuration imposed two sets of three fins that were designed angularly opposed, the umbilical management system had to be revamped. Indeed, what was commonly used on PERSEUS rockets were micro-D connectors attached to the launch ramp, which in our configuration threatened to collide with the fins.

As part of an academic project, a new system was developed by Fabien Royer for the SUPAERO Space Section on behalf of PERSEUS. It is meant to prevent dangerous collisions as well as provide a cleaner, really linear disconnection of the connectors. FDM 3D printing was used to speed the iterative design process.


Figure 4: SAO system in ready-to-launch configuration, during test and on launch pad

4.2.5. Simulated Upper Stage Motor (FPI)

Due to operational and administrative difficulties, it was decided to design the demonstrator with a dummy motor in the second stage. This assembly served four main roles: partially simulate the mass and inertia of a real motor, record a video of the separation, perform pressure measurements, and accommodate an igniter.

The system is composed of 3 parts: a real motor casing in aluminium, a 3D printed assembly housing additional mass, a camera and a pressure measurement board, and a fixed, 3D printed adapter fixed inside the tube so as to have a “plug and play” system.

Figure 5: Dummy motor in opened configuration, with the casing and the main half of the 3D-printed assembly

4.2.6. Pyrotechnic Sequencer

To ensure security of the pyrotechnicians at all instant during the preparation phases on the launch pad, a special pyrotechnic sequencer was developed by GAREF Aerospatial on behalf of PERSEUS. Developed following safety guidelines by CNES and with operations in mind, it is composed of a ground segment rack and an on-board module with its independent energy source. The on-board module includes multiple relays, some activated via the ground segment at different stages of the preparation by the pyrotechnicians, others activated on board at reception of the firing order.

Figure 6: Ground segment for the pyrotechnic sequencer and installation of the igniter by the pyrotechnician

5. Qualification and tests

All the subsystems of the demonstrators have to be qualified or tested before the flight, with the results of such studies validated during project reviews. The reuse of some key elements such as the avionics makes it easier to get through these stages thanks to the accumulated experience over the years.

For new critical systems, procedure and tests had to be created and performed.

In the case of the interstage separation system, tests on ground were performed multiple times before and after the flight to validate the repeatability of its performance and behaviour, using IMU data and high-speed video capture. They were also used to corroborate events identification on the timeline.

Figure 7: Capture of the test performed on the ground (separation between stages, off load behaviour)

Tests were also used for the umbilical management system to validate the different dynamic phases and their timing. It was indeed critical to validate that the system would retract inside the demonstrator on time in order not to hit some elements of the launch ramp.

Figure 8: Stills of the test performed on the ground on the umbilical management system

6. Flight data analysis

6.1. Trajectory

Since the launch of Hydra happened during the C'Space 2015 organized by the "Planète Sciences" association, basic simulations of the flight were run using Planète Science's software. Given the substantial mass of the demonstrator and the relatively small motor, reached altitude and maximum velocity were quite low, as expected. The results from simulations and flight data given Figure 9 and Figure 10 are summarized in Table 1.

Deployment of the parachutes occurred on time and descent velocity was in the expected range. Due to the low peak altitude, both stages were recovered easily and in perfect condition not far from the launch pad and from each other.

Table 1: Comparison of expected results and flight data

	Max altitude (1st stage, m)	**Max altitude (2nd stage, m)**	**Max velocity (m/s)**	**Velocity at separation (m/s)**
Expected	703	736	111	102
Flight data	660	753	102-107	98

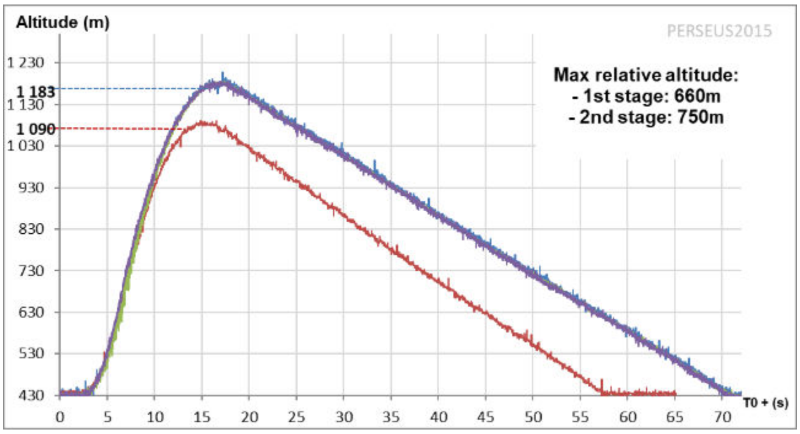

Figure 9 : Altitude vs Time flight data (pressure measurements & IMUs)

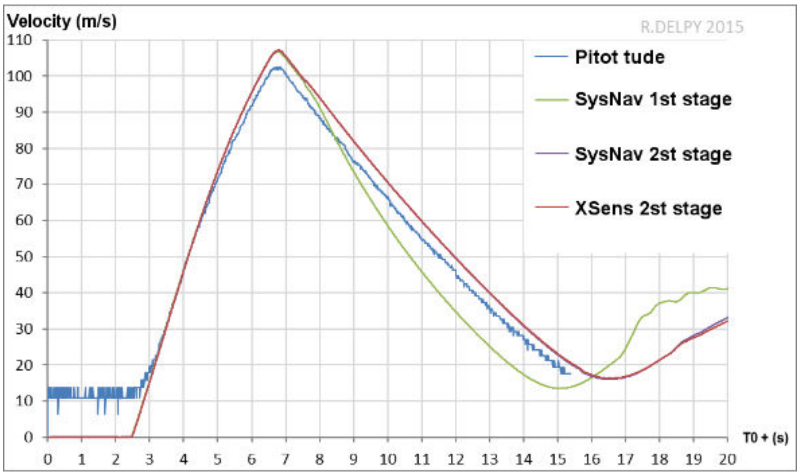

Figure 10: Velocity vs Time, flight data (pressure measurements & IMUs)

6.2. Experiments

6.2.1. Interstage Separation System (SSIE)

Data recorded at high frequency by the SysNav IMUs in both stages makes it possible to study the separation process in great details and build a timeline of the different events based on the accelerations, see Table 2.

Table 2: Timeline of the separation

Event	**Relative date (s)**
Separation order	0.00
Fastening hooks unlocked	0.02
Separation detected, pistons have moved of <1cm	0.04
Synchronization ring impacts 2nd stage	0.05
Velocity difference max achieved, ~1.1m/s	0.08
End of contact between the stages	0.08
Pistons fully deployed (~7cm)	0.11

It is interesting to note that the pistons seem to slightly slow down near the end position, resulting in an end of contact between the stages before full deployment. The measurements validate the difference of velocity imposed on the stages, at 1.1m/s, resulting in a difference of approximately 2m after 1s and 7.5m after 1.6s (date of ignition order).

A review of the angular velocity data confirms the timeline, showing clearly a decoupling between the stages rates at Tsep + 0.02s (hooks unlocked), then a coupling again after synchronisation ring impact on 2nd stage around Tsep + 0.05s, and then a final decoupling at separation (Tsep + 0.08s). This set of data also reveals a slight opposed modification of the angle of attack of the stages, which is damped in less than 0.5s.

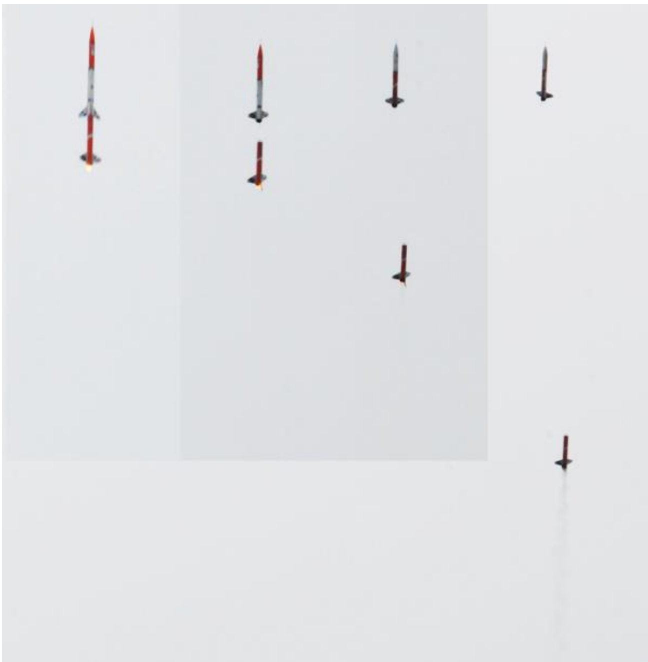

Figure 11: Pictures of the separation as seen from the public zone (Credits: Tanguy JEANNE)

Pressure monitoring in the tanks during the preparation phase and until approximately 0.4s before the separation (last data received before stages disconnection) shows great stability and leak-tightness of the system. This confirms the choice of the semi-flexible pipes mentioned in §4.2.3.

6.2.2. Umbilical Management System

The main result of this experiment is the system behaviour itself. Several phases - seen on Figure 12 thanks to a high-speed camera - have to be noted:

1. Initial situation. The SAO is attached to the launcher electronically and mechanically to prevent the system from misconnections.
2. Take-off. The cable fixed on the launch pad remove the mechanical link. Note that the SAO can translate inside a define range on the rail.
3. Electronical disconnection. The ground signal are now lost; only telemetry is received.
4. SAO blocked. The SAO is blocked in its range while the launcher draw away.
5. Lower fins passing. The first stage fins are passing by without impact.

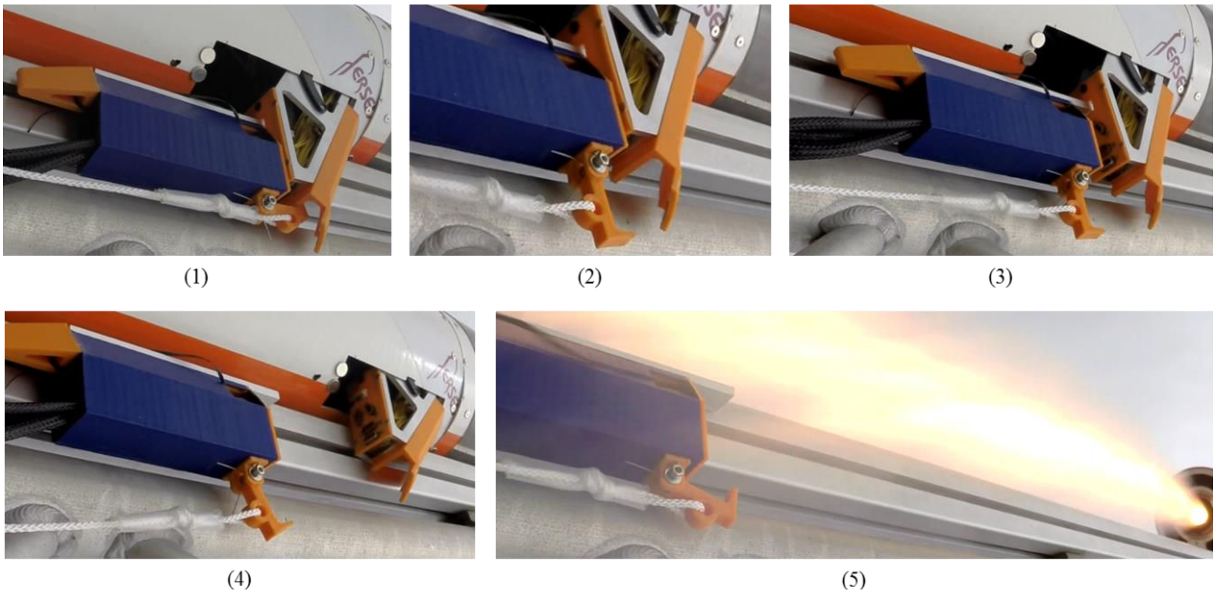

Figure 12: Stills of the high-speed video of the system during launch

The behaviour of the system in real conditions has been assessed using a GoPro camera installed on the ramp and recording video @120Hz. This validated the cinematics and the robustness of the assembly, and no damage or wear signs were observed during inspection of the parts after the flight. In particular, the FDM 3D printed assemblies did not suffer from the motor exhaust and the fins cleared the ground.

Important recommendations and design tweaks were also collected during preparation phases and on launchpad, paving the way for new versions on the system with improved features (see 7.1.2).

6.2.1. Simulated Upper Stage Motor

The part of the assembly designed to contain the exhaust gas of the igniter and hold the igniter in place encountered no issue during the flight. However, the pressure measurements, installed to validate CFD simulations performed as part of an academic project at ISAE-SUPAERO, did not provide conclusive results. The camera provided interesting footage of the flight after separation and after a short time of dazzling. The images were used to corroborate the distance between the stages with the results of IMU data integration during a few seconds after separation.

Figure 13: Views from the rear end of the upper stage shortly after separation

6.2.2. Pyrotechnic sequencer

The pyrotechnic sequencer receipts the separation confirmation sent from the XSens - which handled the majority vote described §4.2.3 – and, at the end of the integrated timer, the ignition order is output. It can be confirmed with the status change recorded by the on-board computer and heard on the video (firing of the igniter). Manipulation of the system by the pyrotechnicians was seamless after a training session, although more work and iterations on the mechanical interface for the electrical connection of the igniter are required.

7. After ARES14BI “Hydra”

Multiple projects have used or are currently using the results of the development end flight of Hydra. Two main examples are developed in this section.

7.1.1. Kerberos technical demonstrator

“Kerberos” is a technical demonstrator in development at the SUPAERO Space Section within the PERSEUS program. The real sequel of “Hydra”, it is meant to be a 2-stage rocket with a form factor similar but multiple improvements, such as a motorized upper stage, a teleoperated pneumatic system to manipulate the stages and ease the work of the pyrotechnicians, a revised interstage separation system, etc.

Figure 14: The Two-staged Rocket Manipulation System under test

7.1.2. Evolutions of the Umbilical Management System

Since the system addressed a repeated issue with the PERSEUS demonstrator and performed well during the operations and flight of Hydra, it was decided to continue with the design principle and update it with the gained experience and for use on different rockets. The sequels of this subsystem have been used with success on the SERA2 and SERA3 rockets both supersonic and launched from the Esrange Space Center near Kiruna, Sweden.

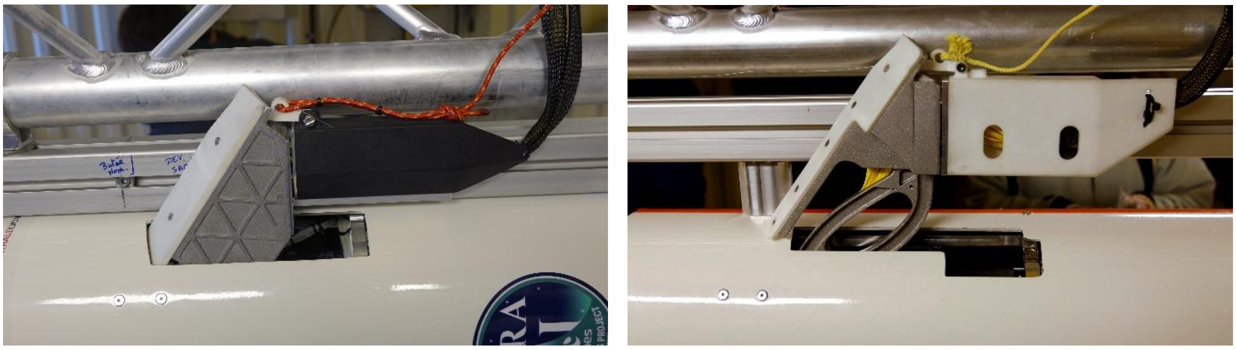

Figure 15: Details of the Umbilical Management Systems used on SERA2 (2016, left) and SERA3 (2017, right)

The new designs make use of more advanced materials such as 3D-printed nylon and aluminium elements and address some flaws in the initial design such as protection of the cables in the on-board part or the mass of the system. In the case of SERA3 in particular, the system had to be redesigned to compensate with a greater distance to the launching rail due to a bigger diameter for the lower part of the rocket.

8. Conclusion

The whole launcher and ground systems have shown great stability and repeatability, as demonstrated by the comparison between the ground tests before and after launch and flight data.

On top of the major ameliorations specified above, many other sub-systems have been improved. The recovery of Hydra in perfect state allowed several post-flight analyses, which were useful to increase TRL on many subsystems. The project also developed the multi-stages competences for the CLC and S3 space clubs and the PERSEUS program. The Hydra project validated technological solutions and organizational processes, so they can be adapted to the "Performance" branch of the PERSEUS program (see reference [3]), which launch supersonic demonstrators in Sweden. Moreover, this project gave professional skills to the engineering students who worked on Hydra, and more generally on projects within the PERSEUS program.

9. References

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