SERA-1, THE FIRST SUPERSONIC ROCKET DEVELOPED IN THE FRAME OF PERSEUS PROJECT

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ABSTRACT

SERA-1 is the first supersonic rocket developed in the frame of PERSEUS, a French project that promotes students activities in space launch vehicle fields.
The objective of the rocket was to validate technologies for supersonic flights (Mach > 1.2), to allow a complete restitution of the trajectory and the atmosphere met during the flight, and to qualify PERSEUS procedures for the sizing of atmospheric demonstrators of a future nanosatellites launcher. The project took place on almost 2 school years from September, 2012 till June, 2014.
SERA-1 has successfully flown on May 7th, 2014 from Esrange Space Center at Kiruna (Sweden) during a one week students launch campaign as part of EASP program. SERA-1 is a 3 m long, 25 kg lift-off mass rocket that was propelled by a Pro98-6G Green3 CESARONI engine. It has reached an altitude of about 5 500 m with a maximum speed greater than Mach 1.3.

THE PERSEUS PROJECT

Objectives

The PERSEUS project (Projet Etudiant de Recherche Spatiale Européen Universitaire et Scientifique) belongs to the program of preparation of the future of the CNES Launcher Directorate, in consistency with the other projects (R&T, X-Demonstrators …). PERSEUS objectives are:

- To promote innovations and test promising technologies applicable to space transportation systems,
- To realize these activities by young peoples within an university or associative frame, driven by an educational initiative, increasing their motivation for space jobs,
- To develop a set of ground and flight demonstrators, enabling the definition of a detailed preliminary project of a nanosatellites launch system.

General overview

The guidelines of PERSEUS are that the motivated students are invited to work on parts of global space demonstrators at a subscale level of a Nanosatellites Launch Vehicle (NLV) which corresponds to more or less powerful experimental rocket. They can work either during the classical pedagogic frame proposed by their university, either in a space association, or either as researchers in a laboratory. The CNES, with the help of partners, is coordinating all these activities in order to achieve a complete life cycle of prototypes: objectives, studies, development, realization, ground and flight test and exploitation.

In the last ten years, the PERSEUS university network has attracted more than 250 students per year, working on 60 projects. Some studies have been extended beyond France, reaching students, researchers and space industries from different places in Europe. A step-by-step approach is the best way to guarantee a real progress in the demonstrators, while respecting a simplified version of management and procedures usually used in the aerospace industry. A first overview of the project is necessary to integrate the different studies ending with ground demonstrations: avionics and electrical technologies applications (range of On-Board Computers and Inertial Measurement Unit), advanced propulsion technologies (bi-liquid propulsion), materials technologies (composite, combustion chamber, nozzle…).

Main demonstrators in PERSEUS

In order to qualify these concepts and technologies, different flight demonstrators are developed within the framework of PERSEUS.

- The SERA rocket series with the successful flight of SERA-1, which will be described in this article,
- A flying test bench in order to test various separation system of a rocket from the carrier; this airborne carrier, EOLE, has been developed and the flying campaigns have been performed successfully at Saint Yan Airport,
- The works on a first ground test of a Lox/Ethanol bi-liquid rocket engine (MINERVA); first firing tests of this engine are expected before the end of 2015.

Figure 1: PERSEUS flight tests program

A complete presentation of PERSEUS project is given in [1].

THE SERA-1 PROJECT

The SERA Rocket Series

In order to achieve the 100km suborbital flight goal, a new series of rockets are currently under development. These rockets, called SERA (Supersonic Experimental Rocket ARES) are supersonic rockets with a high degree of technologies, derived from ARES subsonic experimental rockets launched in France and developed by students' team of various universities or French engineering schools. The main objectives are to:

- Validate technologies that allow flights at supersonic speed,
- Reach altitudes greater than 5 km, and
- Prepare the development of more powerful rockets.

SERA rockets are part of the EASP initiative (Esrange Andoya Special Project) and are launched from Esrange (Kiruna, Sweden).

Introduction of SERA-1

Figure 2: Mission patch

SERA-1 is the first French supersonic rocket developed by students since 1998 and the 20th rocket developed inside PERSEUS.

The particularity and the interest of this project is the strong implication of students in the design, development, realization, and operations on the entire rocket, associated with a multidisciplinary PERSEUS project team to ensure the good realization of the project.

The main objectives of this project were to:

- Achieve a supersonic flight (greater than Mach 1.2),
- Culminate above 5 km,
- Perform a dedicated launch campaign in an operational space launch base,
- Have a strong implication of students in the design, the development, the operations and the exploitation of the rocket,
- Qualify and use a new engine inside PERSEUS (CESARONI PRO 98-3G Green 3)

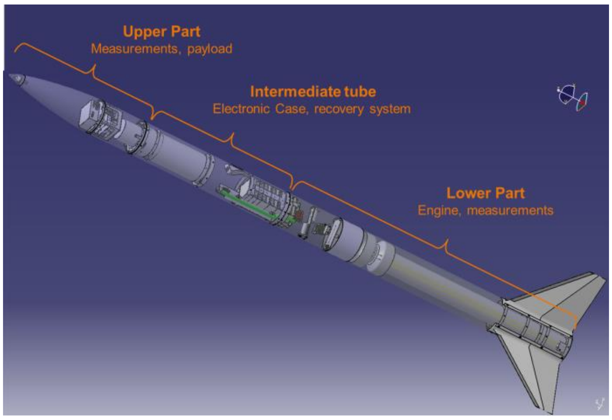

Figure 3: SERA-1 rocket overview

Organization and management in SERA-1

Three students' teams were primary involved in the development of the rocket and were in charge of the conception, the development and a part of the operations:

- S3, non-profit students association inside the "Institut supérieur de l'aéronautique et de l'espace" (ISAE)
- OCTAVE, non-profit students association inside University of Evry Val d'Essonne
- aeroIPSA, non-profit students association inside the "Ecole d'ingénieur de l'air et de l'espace" (IPSA)

In addition, several projects have been made in different university to help the definition of the rocket. For instance, students in a multi-year project inside ISAE have defined and test the fins of SERA-1.

For the first time in PERSEUS, an external payload has been integrated in the rocket. This payload was developed by students from Lulea University of Technology based at Kiruna. The experiment, called MADS (Magnetic Attitude and Determination System) aimed to design an attitude determination system relying on a single sensor: a magnetometer.

As it was also the first time in PERSEUS that there was a rocket project launched outside France and with the collaboration of several universities, a dedicated organization has been put in place. The project and quality management was entrusted to Bertin Technologies for its ability to manage complex project associated with a project team constituted of GAREF AEROSPATIAL and IPSA.

The approach for project management is based on simplified industrial management procedure elaborated in accordance with CNES (management by phases and reviews).
Project reviews are very important as it:

- Allows students to introduce their works and achievements to recognized experts of various disciplines (structure, aerodynamic, propulsion, avionics…), and
- Gives a go/nogo for the following activities.

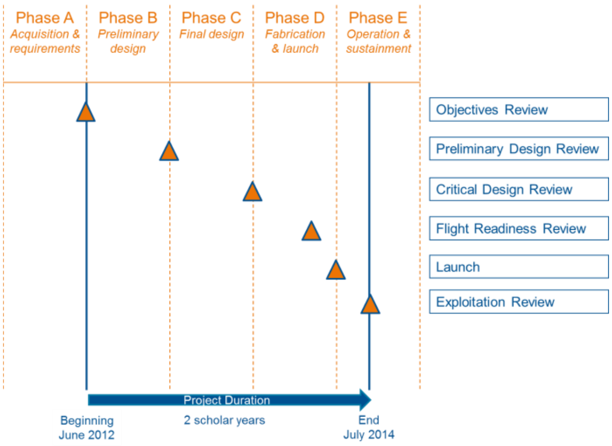

Figure 4: SERA-1 project reviews

During the development of the rocket, each team had its own role and was in charge of dedicated sub-systems. Nevertheless, different teams can be involved in the same subsystems. Taking into account return of experience of past projects, a common integration site was implemented to perform final assembly, integration and tests (AIT) of the rocket. About ten dedicated sessions were necessary to suit the planning and to have a validated rocket before sending it to Kiruna.

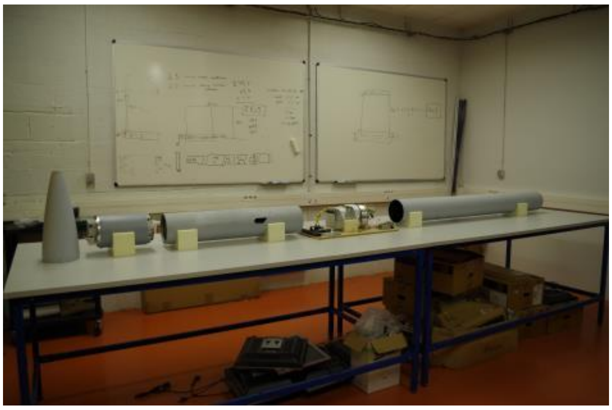

Figure 5: First version of the rocket assemble

Technical description

SERA-1 integrates a mix of robust sub-systems developed inside PERSEUS for several years and innovative technologies.

Particularly, SERA-1 is characterized by:

- Optimized electronic case,
- Patch antenna with a 360° emission,
- Lightweight structure based on patented composite materials process (tubes, fins, thrust plate),
- Radio transparency fibre-glass fairing,
- Nose cone with pressure probes in additive layer manufacturing (aluminium powder),
- Reliable recovery system based on the release of two different parachutes,
- External payload MADS,
- Off-the-shell engine: CESARONI PRO98 6G Green 3,
- Complete restitution of the trajectory.

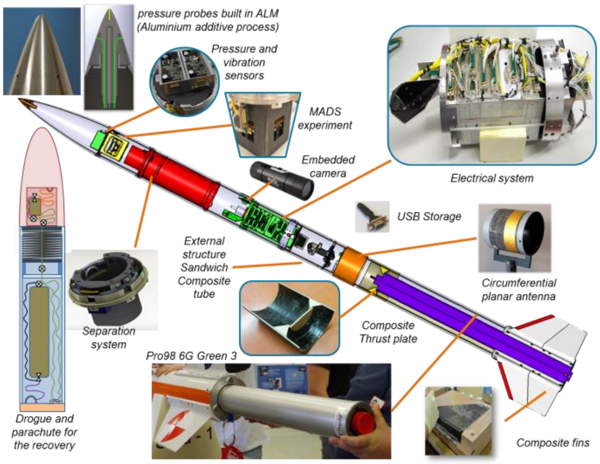

Figure 6: SERA-1 technological decomposition

A more detailed description of technical sub-systems is given in the last paper presented during the ESA PAC conference in 2013 [2].

System analysis was performed at the beginning of the project to set the requirements for SERA-1. These calculations showed that, to achieve a supersonic speed with sufficient margin, the mass of the rocket without engine had to be 12 kg. During all the development phases, this mass objective has been carefully followed. Finally, as presented on table 1, the mass objective has been achieved.

Final mass budget		
Payload (MADS Experiment)	0.25	kg
Upper part (inc. Fairing & P/L support)	0.75	kg
Carbon fibre tubes	2.9	kg
Composites Fins	1.9	kg
Separation system	0.7	kg
Recovery system	1.7	kg
Electrical systems	2.8	kg
Pressure & Vibrations deported sensors	0.5	kg
Cameras	0.3	kg
Telemetry	0.25	kg
Engine (loaded)	13.2	kg
TOTAL	**25.3**	**kg**
Mass w/o engine	**12.1**	**kg**

Table 1: Final mass budget

System analysis and pre-flight trajectory

In PERSEUS project, several tools/softwares have been developed to help the design of suborbital rockets. These tools are continuously improving using the experience feedback of the different projects. For SERA-1, the system loop relied on:

- Calculation of the aerodynamic coefficient,
- 3DDL trajectory simulation of the rocket (ANDROMEDE),
- Stability analysis.

Several system loops have been performed at the various stage of the project taking into account the evolution of the design. These calculations have particularly allowed to make sensibility analysis on the launcher inclination and the dry mass, and to check the static margin of the rocket.

LAUNCH CAMPAIGN

The launch campaign took place at Esrange from May Sunday 4th May 2014 to Wednesday 9th May 2014 with more than 40 people involved including nearly 30 students. Only a part of involved students on SERA-1 had the opportunity to participate to this launch campaign, mostly for logistics and budget reasons. It has been given like a reward for their work on the rocket and a chance to be an actor of the flight.

The campaign has been decomposed in 2 parts:

- A first week of “Pre-campaign”, with a reduced team of 4 people, in order to prepare the logistics, safety issues and to finalize organization of the launch campaign;
- Then a second week of “Launch campaign” with the rest of the operational team to conduct the flight and a first post-flight data analysis.

Operations have started on Monday 5th May morning with a guided tour of Esrange. Then, teams had a first look at all the equipment and the different parts of the rocket to ensure no problem during the transportation occurred. Launch campaign participants have then been split into dedicated teams: Rocket team, telemetry team, launcher team, engine team and final operation team.
On Tuesday 6th, teams have prepared the rocket, make the last working tests with the MADS payload and verified that all parameters was nominal and systems working well.

Figure 7: Students at work

Wednesday 7th was our first launch window with Thursday 8th in backup in case of bad weather conditions. During the morning, a practice countdown was performed to test all the operations, including an engine firing simulation. This practice countdown has conduct to adjust the chronology and to identify minor problems that have been solved for the hot countdown.

Figure 8: Rocket on launcher

The hot countdown has started the same day at 2 PM. Thanks to the practice in the morning, the hot countdown was very smooth and no major problem occurred. Rocket has finally lift-off during the foreseen time slot on Wednesday afternoon. SERA-1 has perfectly flown and has been quickly recovered thanks to the anticipated impact perimeter and the GPS beacon embedded on the main parachute. After the flight, a preliminary exploitation review has been made at Esrange to present the first results and videos of the flight.

Figure 9: Recovery in perfect state

Unfortunately, after the flight, we discovered that MADS experiment haven't worked. A first investigation was done on site and quickly, the problem was identified: the ignition signal that should have started the payload hadn't been detected. Further investigations were performed in France after the campaign and finally the origin of the problem was a technical issue on the amperometric claw that was used to detect intensity of the ignition signal. For the next rockets, payload requirements will be changed to use another mean to detect ignition.

DATA EXPLOITATION

Overview of the flight

The different characteristic times encountered during the flight are shown in Fig. 10.

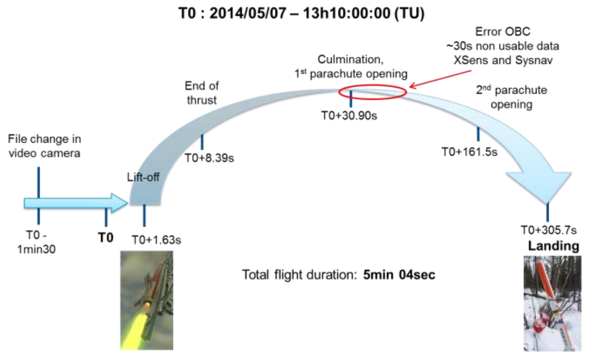

Figure 10: Flight chronology

Measurement plan

SERA-1 is an experimental rocket and the measurement plan and data exploitation are part of the objectives. The measurement plan used on SERA-1 is detailed in Fig. 11 and consists of the measurements of:

- Inertial parameters,
- Muti-axis magnetics field,
- Vibration in the fairing,
- Pressures at different points: static pressure (inside and outside the rocket), total pressure, rocket incidence and base pressure,
- Video cameras to visualise the rocket behaviour (one towards the horizon and one downward centred on a fin)
- Payload magnetic experiment

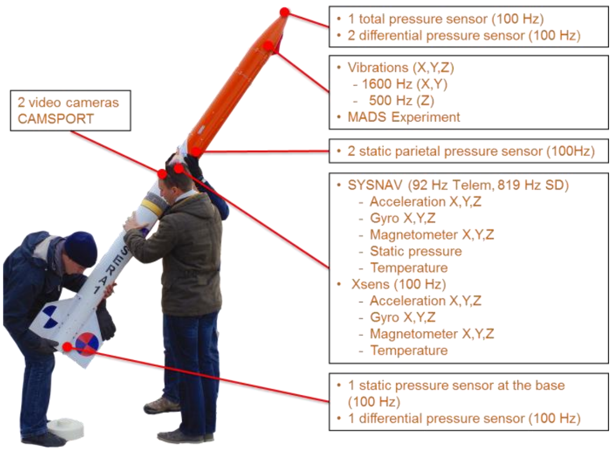

Figure 11: SERA-1 Measurement plan

Flight data analysis

Data exploitation is a project on its own and several exploitations have been made or are always in progress. We present here some extracts of these analysis.

The main flight parameters obtained after the flight are shown in Table 2.

Trajectory parameters		
Altitude	5 450	m
Culmination	5 150	m
Mach max	> 1.3	
Relative velocity	405	m/s
Maximum longitudinal acceleration	10.7	m/s²
Maximum dynamic pressure	140	KPa
Maximul thrust	2.5	kN

Table 2: Flight data

Firstly, on Fig. 12, the trajectory is restored using the two IMUs.

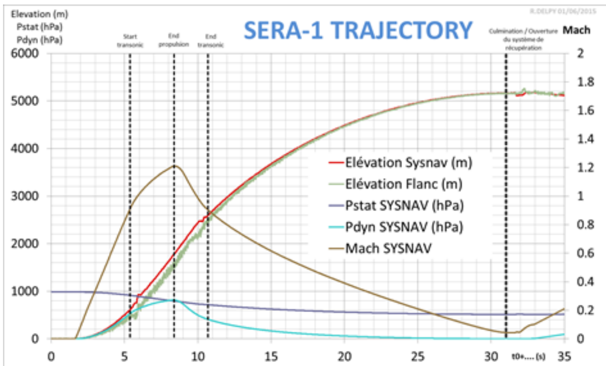

Figure 12: Trajectory

Note that in this graph, Mach value is underestimated because of the exploitation method used in this calculation.

This trajectory was conformed to our pre-flight calculation that was provided to SSC for safety studies. The pre-flight calculation is presented in Fig.13 (thrust phase in red and ballistic phase in green). The grey zone on Fig. 13 was the estimated impact area under parachute calculated with wind forecast and the point in yellow is the real impact point. There is a very good correlation between the real flight of the rocket and the pre-flight trajectory.

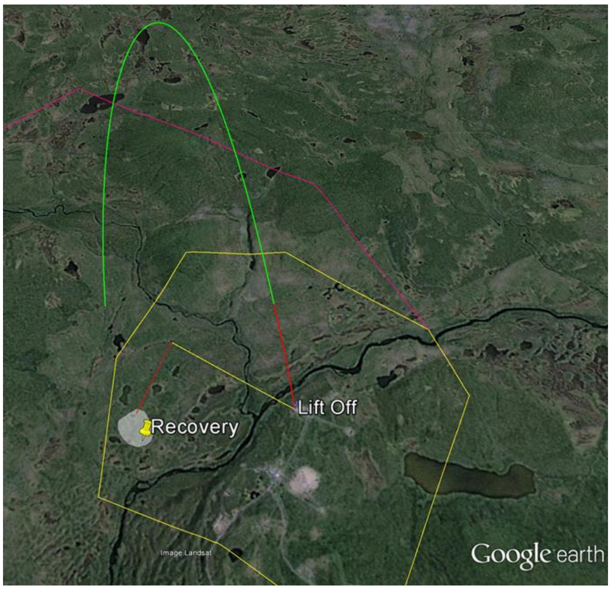

Figure 13: Pre-flight trajectory and real impact point

Another way to retrieve the trajectory and the attitude of the rocket is to use magnetometers. One of the main interest of magnetometers is the absence of derive compared to classical IMU and the precision achieved if correctly calibrated.

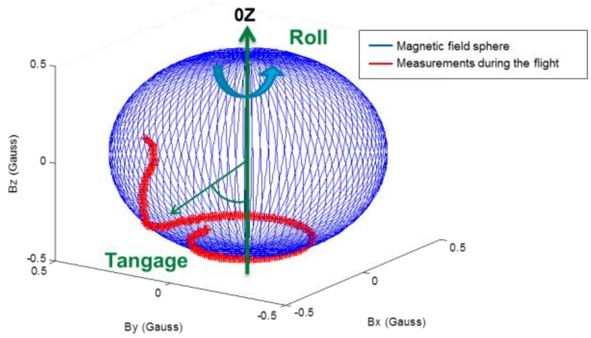

Figure 14: Trajectory obtained by magnetometers

The trajectory obtained is presented on Fig. 14. The blue sphere corresponds to the magnetic field in all directions. The red line is the points of the magnetic field measured during the flight of the rocket starting from the exit of the launcher (T0 + 2.27s) until culminating (T0 + 31.54s).

The accelerations are presented on Fig. 15. We can see on this figure a difference with the two IMUs that maybe due to the difference of positioning of these IMUs in the rocket. The thrust law recover has small difference with the reference obtained during qualification test (blue dash line). One interesting fact extract from Fig. 15 is the ignition delay. Indeed, Cesaroni engines are known to have a long ignition delay. This is not important for a single stage rocket but as we planned to develop in the future a two stages rocket, ignition delay has to be managed. In SERA-1, the Cesaroni Pro98 6G has been modified to integrate a Pro38 to ignite the rocket motor. This modification has permitted to reduce the ignition delay to about 1.6 seconds as we can see on Fig.15 (T0 corresponding to the igniter burn).

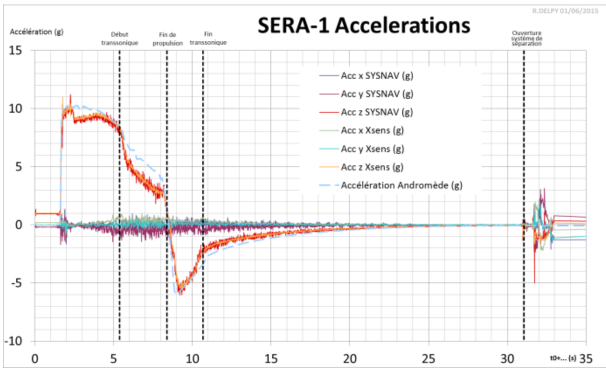

Figure 15 : Acceleration X, Y, Z

Finally, the maximum longitudinal acceleration of the rocket is about 10.7 g very close to the value calculated with ANDROMEDE, our homemade 3DOF simulation tool. We can also see the exit of the launcher at 2.2s.

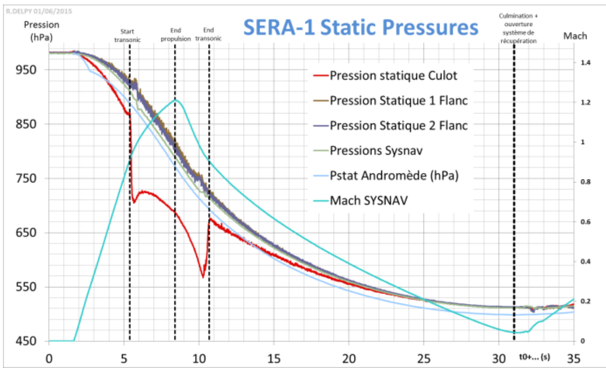

Figure 16: Static pressure measured during the flight

Last figure presented, Fig. 16, shows the evolution of static pressure during the flight. The gap between parietal pressure (in brown and dark blue) with Sysnav pressure (measurement inside the box of the IMU) in Fig.16 can be explained by the emptying phenomena (diminution of atmospheric pressure with altitude). The red line is very interesting. It represents a parietal static pressure at the base of the rocket between two fins. We can clearly see the transonic phase due to the transonic shockwave displacement with this pressure probe.

In conclusion, the main objective of SERA-1 has been achieved with a maximum speed greater than Mach 1.3.

CONCLUSION

Since the last publication of ARES rocket status presented in 2013, a significant step has been reach with the development of SERA-1 and the use of a professional launch site, Esrange. This project has allowed realizing a supersonic rocket project from the preliminary design to the exploitation in a student context. This has been done thanks to the previous experience achieved in the project with the realization of about twenty rockets. SERA-1 is also the first real inter-association project with Swedish-French collaboration inside PERSEUS.

SERA-1 was a great success for PERSEUS and opens the path to the development of a family of supersonic rocket with a strong implication of students. Management rules and technical documentation will serve as reference for future rocket developments.

In terms of results, the primary objectives have been achieved with a supersonic flight and a good restitution of the trajectory. We have demonstrated that the rocket has reached more than Mach 1.3 with a culmination of about 5200 m. This makes it a record inside PERSEUS project. The rocket was recovered in a very good state under the two system parachutes.
The main problem encountered was on the payload MADS that hasn't worked due to a detection problem. Nevertheless, this cooperation has been rich in exchange and collaboration. It was the first time that a PERSEUS rocket has to manage a completely external payload.

The next rocket, SERA-2, is planned for April 2016 at Esrange. It will confirm the design with an extended measurement plan and validate the new organization in the project.

Finally, with the development of SERA1 rocket, PERSEUS proposes a unique initiative to work on an entire supersonic rocket. PERSEUS is always looking for motivated students' team to work on these projects!

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Figure 17: SERA-1 Launch Campaign Teams

ACKNOWLEDGMENT

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