

# Structural design of PERSEUS first bi-liquid demonstrator: ASTREOS-1

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## Abstract

The PERSEUS project provides the opportunity for motivated students to pool their knowledge to the development of space launchers vehicles. Their applicative work refers to a subscale of a Nano Satellite Launcher which corresponds to an experimental rocket. They can work either through the classical pedagogic frame proposed by their university, either in a space association or as researchers in a laboratory. The CNES, with the help of its PERSEUS partners, is coordinating all these activities in order to achieve a complete life cycle of prototypes: objectives, studies, development realization, reviews, ground or flight test and exploitation. This paper will focus on the structural design of PERSEUS's first bi-liquid propelled rocket: ASTREOS-1. The structure of this new demonstrator will integrate various mechanical, electrical and fluidic equipment required for mechanical integrity, propulsion, ground communication, recovery, etc. The main rocket sections are described, with their development axes, current status and perspectives.

## 1. Introduction: ASTREOS-1 in PERSEUS

At the crossing between academic institutions and the space industry, the PERSEUS program of the French space agency (CNES) offers future engineers the opportunity to design, manufacture, test and launch some experimental sounding rocket demonstrators. PERSEUS is in partnership with around thirty of student associations, engineering schools and universities, some small and medium enterprises, and also with Ariane-Group, the European leader in the access to space. Through those collaborations, the project has a strong vocation to achieve numerous launches and rapid innovations from one launcher generation to another.

After several successful launches of solid-fueled rocket (including SERA 4, launched in early June), PERSEUS is now developing ASTREOS-1, a bi-liquid propelled rocket. The development of such a rocket was made possible thanks to the MINERVA project, dedicated to the development of the first PERSEUS bi-liquid engine [1]. For PERSEUS, developing a bi-liquid propelled rocket implies facing new challenges, and allows to develop new skills within the team, in order to pass them on to the students. This project enables the team to develop its knowledge on the fluidic components (solenoid valves, pressure regulators, composite tanks, etc.) needed to build the propulsion system. For budgetary and flexibility reasons, most of the components implemented on the rocket will be off-the-shelf components. Consequently, the structure of the rocket will have to adapt to these standard components to ensure their mechanical integration. Moreover, this bi-liquid propulsion system creates new needs on the ground segment side. Indeed PERSEUS is working on a more complex ground segment equipped with fluid ground equipment, in order to perform the launcher tanks filling, emptying and the sanitation of the on-board fluid circuit, [2].

ASTREOS-1 will be the first member of the ASTREOS family, a succession of several intermediate launchers, which will capitalize as much as possible on the developments and the experience acquired with the previous SERA flight demonstrators family. The overall goal of the ASTREOS branch demonstration is to contribute to the acquisition of the technologies and competencies for a sounding rocket enabling reusability, through series of tests at a representative scale, on ground and in-flight. More concretely, this vehicle family aims to validate technologies such as a bi-liquid propulsion system, new modular avionics, reaction control system, recovery system and range communication system required for a reusable vehicle. Following the iterative and incremental workflow of the program, ASTREOS demonstrators will progressively integrate these technologies from one intermediate launcher to another, taking PERSEUS to a higher level of complexity.

## 2. Mission requirements

The main objective of ASTREOS-1 is to carry out the first flight test of the MINERVA propulsion system, validating all the associated equipment and procedures, without any performance objective. Still, to ensure that the demonstrator's operation runs smoothly during its launch campaign, its structure must meet a number of functional and technical requirements, which are described below:

Functional requirements:

- Scalability: because of the incremental logic, the development of the structure will have to be scalable, so that new systems can be implemented or certain technological choices modified according to future needs;
- Mechanical: the structure must be robust and as simple as possible, maximizing the available internal volume to facilitate the integration of all systems. In addition, the choice of materials to be used for the structure must favor the use of mature technologies. Wherever possible, eco-design will be favored;
- Thermal: the rocket structure will not incorporate active temperature control systems. Passive systems such as thermal protection may be considered, but the aim is to ensure thermal control via the management of operations in chronology and, if necessary, by a passive ground system (such as an external, non-flying protection box). Wherever as possible, mechanical and fluidic interfaces will have to cope with any dimensional instabilities associated with extreme temperatures (cryogenics, engine combustion, etc.);
- Avionics: the launcher structure must incorporate the different avionics circuit boards in standard metal housings and allow cables to pass through from those to the electronic components to be activated or requiring data acquisition;
- Propulsion: the structure must enable integration of the propulsion system, with a compact and functional fluid architecture.

Technical requirements:

- Dimensions: the inside and outside diameters of the rocket body are 250 and 253 mm, respectively (excluding external equipment such as outside lines, fins, etc.). There is no requirement for the overall height.
- Performance: as the demonstrator will have to integrate numerous components and a significant mass of fluids, a compromise has to be made between lightness and robustness (resistance to general static and vibratory forces);
- Environment: the launch campaign will take place at the SSC space base in Esrange (Sweden). The launcher's structure and materials must therefore be compatible with:
  - The environment (weather conditions, etc.);
  - Existing resources on the base (antenna for example). Otherwise, specific developments will have to be carried out in consultation with SSC;
  - SSC base and CNES safeguard requirements.

## 3. Global architecture

Due to its bi-liquid propulsion system, ASTREOS-1 will differ from its solid propelled predecessors, both in size and take-off weight. Indeed, this propulsion system is quite complex and heavy, therefore its integration involves the development of a significantly larger rocket structure, accompanied by major issues in terms of mechanical layout, mass and space savings.

So far, this first demonstrator has been designed as a single-stage rocket with four fins, a length of 6.3 meters, an internal diameter of 250 millimeters, and an estimated mass of approximately 170kg (including 35kg of nitrogen and propellants). These parameters have to be taken as orders of magnitude, since they will probably change as ASTREOS-1 is being defined and designed. The rocket culmination height will vary between 1300m and 2700m, with a maximum velocity ranging from 170 to 230 m/s, depending on the mass of the structure.

The overall architecture of the demonstrator (cf. Figure 1) can be split into 6 main products called “sections”:

- The engine bay
- The LOX section
- The ethanol section
- The nitrogen section
- The avionics section
- The recovery system

The architecture of those main products is detailed in the following chapters. All these products will be mechanically linked in series along the rocket and will interact through electric and fluid lines. Therefore, mechanical interfaces between sections must allow electric cables or propulsion pipes to pass from a section to another, be easily assembled/disassembled and resist to mechanical stresses during the flight. The structure will also integrate electric and fluidic ground/board interfaces.

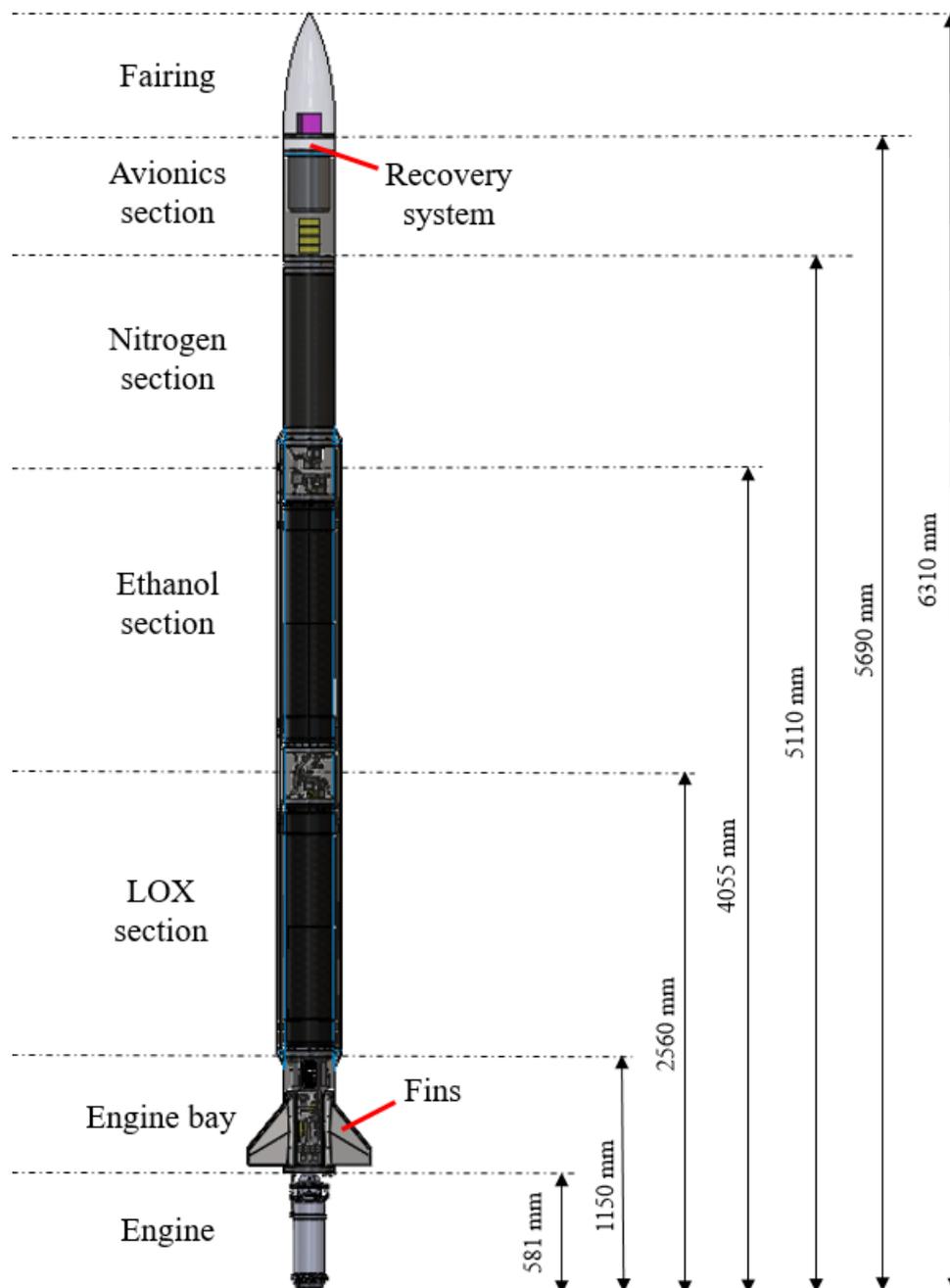


Figure 1: global ASTREOS-1 architecture (current CAD)

### 3.1 Piping & Instrumentation diagram (P&ID)

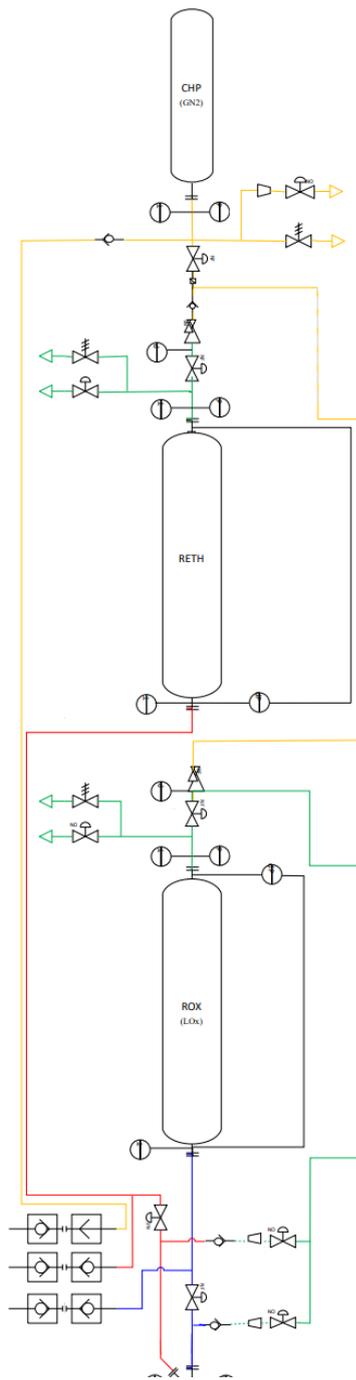


Figure 2: ASTREOS-1 P&ID

The ASTREOS-1 engine is a bi-liquid pressure-fed engine, which means that the propellants (LOX and ETH) will be fed to the engine using a blow down pressurization system. Although this configuration produces relatively modest thrust along with a low efficiency [3], it remains one of the simplest liquid-propellant rocket engine configurations, ensuring a constant and reliable thrust. The alternative use of turbopumps does not seem to be suitable for a launcher of such scale, due to the complexity of this kind of equipment.

The P&ID of the propulsion system (cf. Figure 2) has been designed with the help of our partner Ariane-Group, using the expertise of the Vernon site. It comprises two propellant circuits and a pressurizing circuit interconnected with each other.

The propulsion system uses nitrogen as the pressurizing gas in a three-part circuit: a high-pressure section (240 bar) and two low-pressure sections (30 bar). The high-pressure nitrogen circuit consists mainly of a line connected to the ground segment for the CHP filling, and two lines transporting the gas to the low-pressure sections. Connected to the ETH and LOX circuits, these two low-pressure nitrogen circuits inject the gas into the tanks in order to push the propellants towards the engine. The low-pressure nitrogen circuit which is connected to the LOX circuit also has a line connected to the engine feeding, in order to flush the engine and eliminate any residual impurities before ignition. The use of a high-pressure nitrogen circuit upstream of low-pressure circuits ensures that the pressure of the nitrogen injected into the propellant tanks is sufficient (30bar). Indeed, in the event of a significant drop of pressure along the nitrogen lines, the pressure in the low-pressure nitrogen circuit can be increased by adjusting the pressure reducer that links the high and low pressure circuits.

The two propellant circuits, ETH and LOX, are relatively simpler, since they solely consist of two lines. A first line connects each tank to the engine to supply the latter, and a second line interfacing with the ground supply is connected to the first to fill the tank in the opposite direction of the engine supply.

Several components have been identified to be implemented along these lines to ensure smooth operation of the propulsion system:

- Fluid flow will be regulated by opening and closing solenoid valves;
- Check valves will be used to enforce unidirectionality in some lines;
- Filters will prevent contamination of the on-board circuit caused by potential impurities coming from the ground circuit;
- Pressure/temperature sensors will allow to check fluid status;
- Safety valves will prevent the risk of explosion in the event of circuit overpressure;
- Etc.

All of these components have been identified to operate in nominal thrust phase, where pressure levels and flow rates are at their highest.

### 3.2 Engine bay

The engine bay (cf. Figure 3) is the rocket section between the engine and the LOX section. This section must fulfill a large number of functions, mainly linked to mechanical, fluidic and electrical interfaces with the engine and other on-board and ground subsystems.

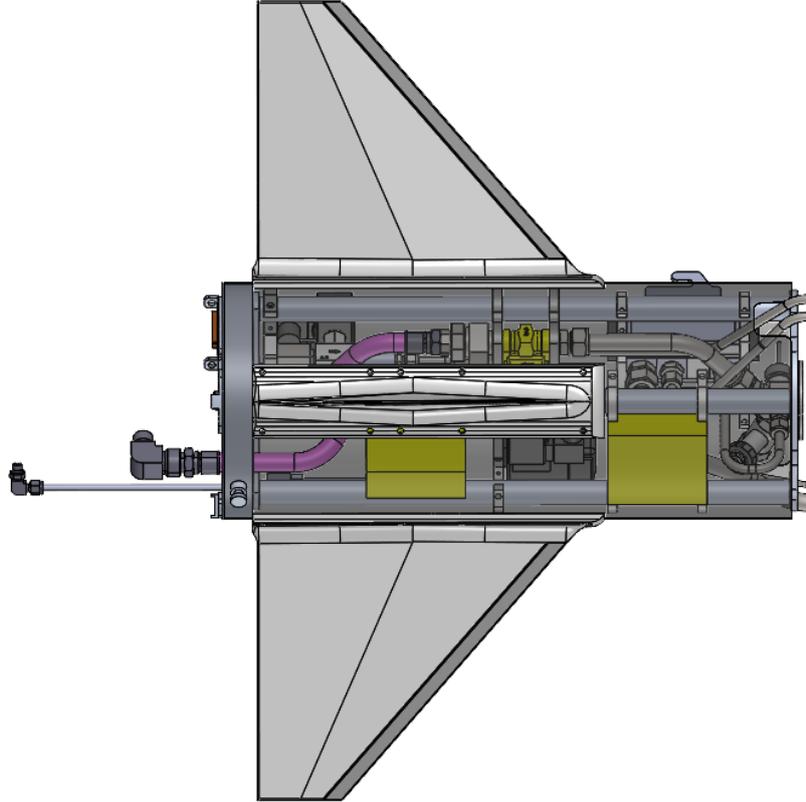


Figure 3: Engine Bay architecture (current CAD)

Regarding propulsion, the engine bay contains the filling lines for the various on-board tanks (CHP, RETH and ROX) and the engine supply lines (cf. Figure 4). As a result, a large number of fluidic (solenoid valves, ground/board connectors, hoses, etc.) and electronic components (sensors and acquisition/control cards) have to be mechanically integrated into the engine bay, making it the greatest space-constrained section of the rocket.

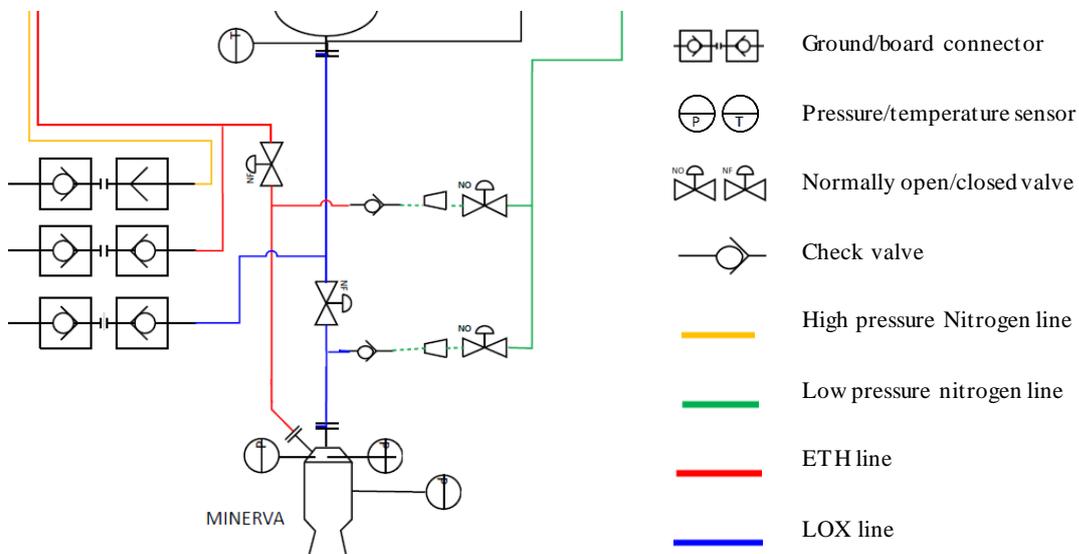


Figure 4: Engine Bay P&ID

From a structural point of view, the main function of the engine bay is to take up the MINERVA's thrust. To this end, this section of the rocket includes a thrust resisting part, for which several concepts are currently being studied. The most discriminating factors for this type of structural part are geometry and material. For solid-propulsion demonstrators, a conventional solution is to place a thrust ring at the interface between the rocket fuselage and the solid rocket engine inside (cf. Figure 5).

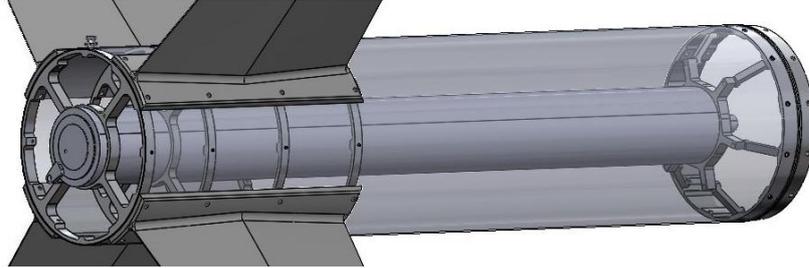


Figure 5: Conventional configuration for solid propelled engine thrust resumption

In the case of ASTREOS-1, the thrust take-up part must transfer the thrust from the engine located outside the fuselage to the LOX tank (which acts as a structural part). In addition, a relatively large space must be left between the tank and the engine to integrate the fluidic and electronic components mentioned above. For this reason, one of the thrust part designs proposed for ASTREOS-1 consists of two parts acting as mechanical interfaces (one for the engine and one for the LOX tank), connected by tubes to transmit forces from one interface to the other (cf. Figure 6). The length of these tubes defines the space available for the propulsion system components.

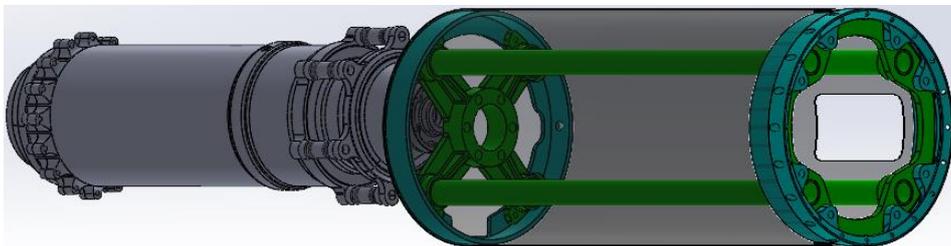


Figure 6: Current ASTREOS-1 thrust resumption part design

Finally, the engine bay must mechanically support the fins and take up their aerodynamic forces. To avoid multiplying the number of mechanical integration parts, and to save mass, a new thrust transfer part design is currently being studied, to pool thrust transfer, propulsion component integration and fins integration.

### 3.3 LOX section

The LOX section (cf. Figure 8) comprises the assembly of the Liquid Oxygen Tank (storing the LOX), along with various fluidic components conveying the pressurized Nitrogen into the Tank, situated both above and below it, representing the entry point and the exit point of the tank. (P&ID of the section is presented on Figure 7).

Upon entering the LOX inter-tank, the Nitrogen propellant flows into the pressure regulator, which subsequently produces an output that is divided into three ways: a pressurization valve, a temperature sensor, and a sweep tube. Once the propellant passes through the valve, it enters the “Chandelier” piece (named after its shape), which facilitates the uniform distribution of the propellant among the different components: the vent valve, the safety valve, and the tube connected to the differential pressure sensor located at the bottom of the tank.

The design of the chandelier piece has been engineered to ensure a compact, simple, yet effective configuration that optimizes the rapid conveyance of the propellant. Moreover, this particular component serves a dual purpose: not only does it convey the propellant, but it also provides support for the pressure regulator while featuring a recess that perfectly mimics the regulator's shape, securely holding it in place. Additionally, the compactness-focused design has yielded a configuration that obviates the necessity of employing interconnecting tubes to link the various components. Instead, direct fittings have been implemented to establish connections between them. The chandelier is screwed onto a secondary component, which comes into direct contact with the LOX tank, enabling the entry of nitrogen.

On the opposite side of the tank, the oxygen exits by traversing several additional components, including a differential pressure sensor (responsible for measuring the pressure between the initial and final points of the LOX tank), a temperature sensor, a tube for filling the tanks, and another tube for delivering oxygen into the combustion chamber.

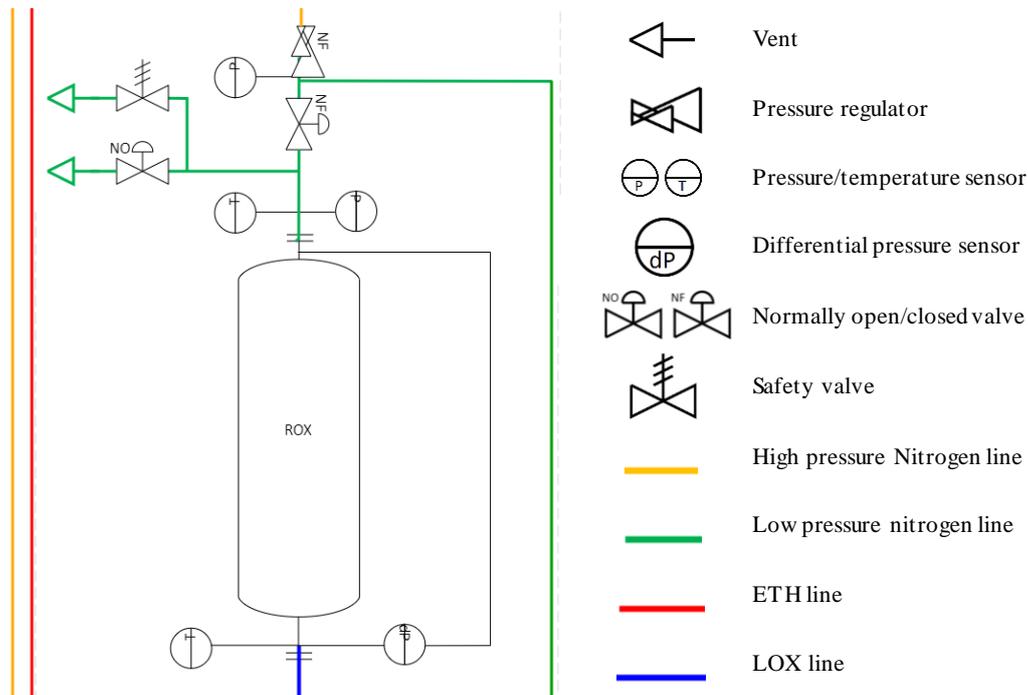


Figure 7: LOX section P&ID



Figure 8: LOX section architecture (current CAD)

### 3.4 Ethanol section

The architecture of the ETH section remains on the same basis as the LOX section. The ethanol section is also divided in two parts, with the upper one dedicated to relax the high-pressure nitrogen and inject it in the tank to expel ethanol at the correct rate. The lower one allows to convey ethanol into the combustion chamber. Again, the lower part of the section accommodates the integration of a temperature sensor and a differential pressure sensor at the exit of the tank, measuring the differential pressure spanning from the entry point to the exit point of the ethanol tank.

As it can be seen on this rocket section P&ID (cf. Figure 9), the fluidic equipment is very similar as the one integrated in the LOX section previously described. Operation is equivalent, as the fluids (nitrogen in the upper part and ethanol in the lower part) follow the same circuit with the same type of component sequence.

The current ETH section architecture is presented on Figure 10. The upper part comprises basically the same components as the upper part of the LOX section, but another concept is proposed for the assembly. Once again, the design tends to create a compromise between space and mass savings, limitation of pressure loss and an easy assembly/disassembly for maintenance. For this section and the LOX one, tubes along the tank will be covered by a fuselage part to ensure an aerodynamic design.

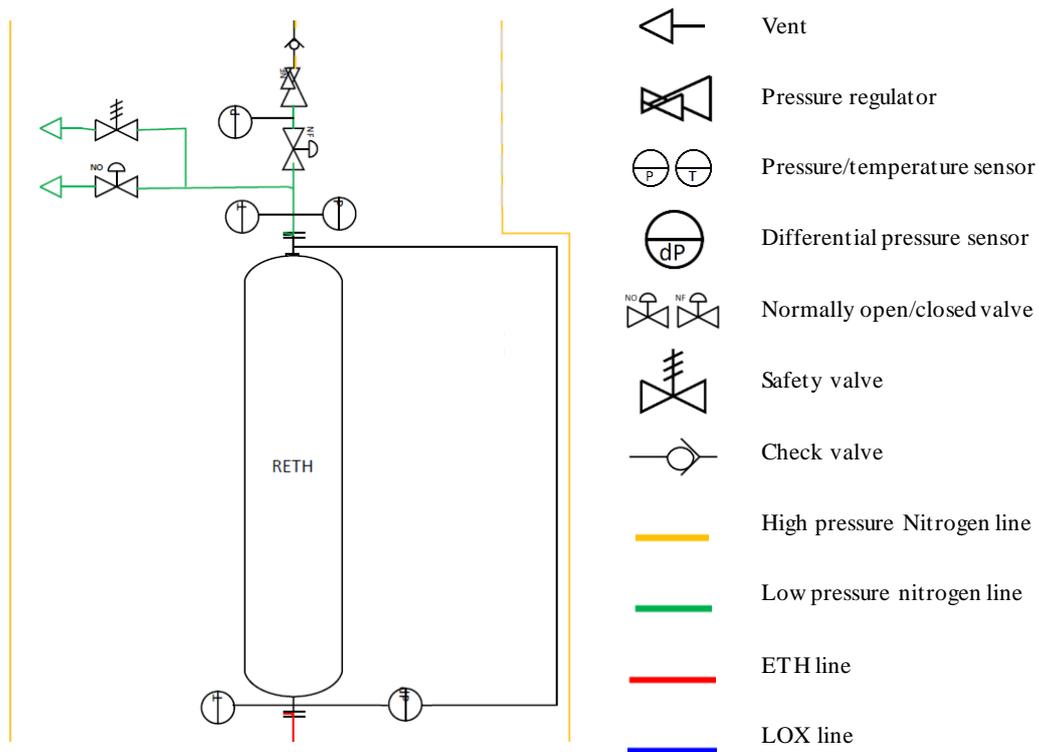


Figure 9: ETH section P&amp;ID

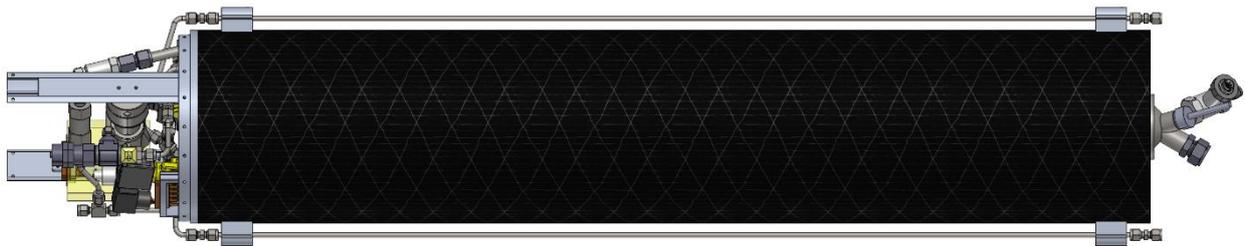


Figure 10 : ETH section architecture (current CAD)

### 3.5 Nitrogen section

The nitrogen section is an essential part of the launcher since it allows to store and deliver the nitrogen. This rocket section comprises the CHP and the main part of the high-pressure nitrogen circuit connected to the low-pressure one at the LOX and ETH sections via pressure regulators.

Concerning the fluidic equipment of the nitrogen section, a set of valves, sensors, and filters are linked according to the P&ID in Figure 11. As in the LOX and ETH sections, those components maintain the section at nominal working pressure while allowing the measurement of the nitrogen's pressure and temperature during tank filling, engine feeding and a potential emptying phase.

Once again, mechanical layout of nitrogen circuit components (cf. Figure 12) is following the same principle as in the LOX and ETH sections, taking into account space and mass savings, minimum pressure loss and ease of assembly/disassembly. The main difference with the previously presented sections in terms of structure is the tank integration. Indeed, in the nitrogen section the tank has a diameter measuring below 253 mm, and the shape of each of its ends implies a different mechanical integration in the rocket. Hence this tank will be integrated into a composite fuselage tube thanks to two rings, with compressible elastomer interfaces. By deforming in compression against the tank wall, these interfaces will help avoid generating excessive stress on the highly pressurized tank.

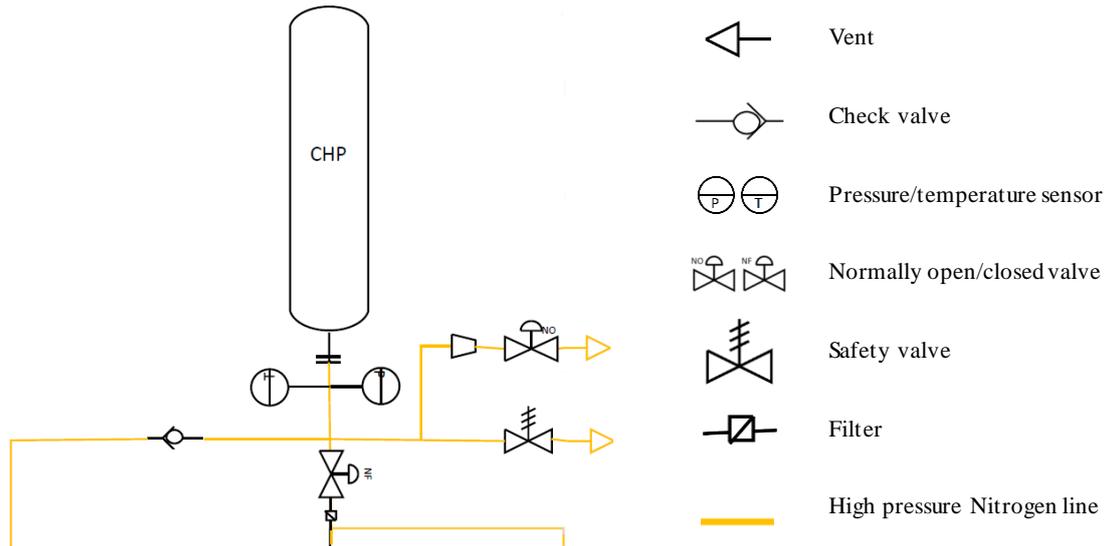


Figure 11: Nitrogen section P&amp;ID



Figure 12 : Nitrogen section architecture (current CAD)

### 3.6 Avionics section

The ASTREOS-I avionics system is made up of several modules: An OBC (On Board Computer) incorporating navigation and data saving, several control acquisition cards constituting the sensor measurement chain and the solenoid valve control, a sequencer which triggers the separation/recovery system, and finally a power distribution card to supply the rocket electrically from batteries. Modularity was the key consideration element in the development of these boards, enabling avionics to be provided for the next iterations of ASTREOS and DREAM-ON.

All those modules will be contained in aluminum housings, with Sub-D connectors interfaces. In order to mechanically integrate those modules, a considered solution is to repeat the SERA4 concept and adjust it to ASTREOS-1 diameter. In this case modules will be integrated in series with an aluminum skeleton (cf. Figure 14 and Figure 13). This skeleton is made of four profiles maintaining the modules, linked with several rings allowing mechanical junction with the fuselage and end connectors. The idea is to be able to remove the skeleton from the fuselage tube to have access to its different modules (for setting memory cards, perform maintenance, etc.).



Figure 13: SERA4 avionic section skeleton

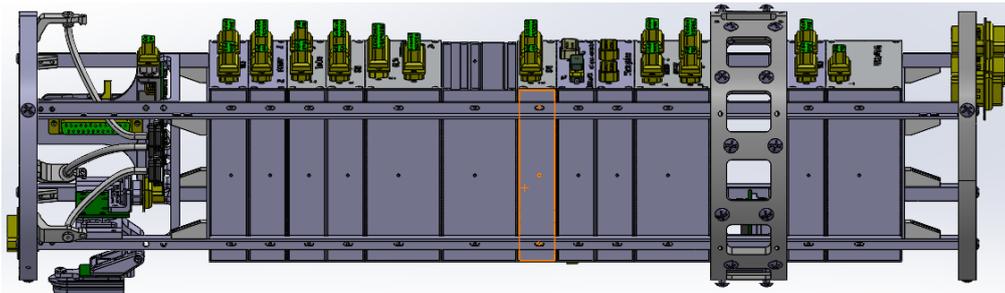


Figure 14: SERA4 avionics modules integration

### 3.7 Recovery system

As the name suggests, the recovery system enables the rocket to be recovered by slowing its descent using parachutes preventing excessive damage at landing. This system is quite conventional, consisting in a separation system and two parachutes contained in two separate compartments: a drogue in the fairing and a main parachute in the avionics section. After separation, the fairing is ejected under the effect of aerodynamic forces relative to the rest of the rocket, releasing the drogue, which is connected to the avionics section by a line and a catch. This line is also connected to the main parachute, and when the drogue reaches its target altitude during the first phase of the descent, the avionics section's latch opens. The drogue then deploys the main parachute, which slows the rocket's descent until its landing. A trade-off is currently underway to identify a separation system concept.

## 4. Interfaces with ground support equipment

ASTREOS-1 has 3 types of interfaces with the ground segment: fluidic, electrical and mechanical. The electrical interface is currently located at the bottom of the engine bay and will be passively disconnected during launch. The mechanical interfaces are located on the engine bay and on the nitrogen section. A first part will interface with the bottom of the engine bay (without interfering with the MINERVA) to lock the rocket in translation along the rail and support it in a vertical position after the ramp has been erected. The second mechanical interface between ASTREOS-1 and the ramp will consist of two guide pins inserted in the rail. These will support the weight of the launcher when the ramp is in the horizontal position and ensure minimum friction during the sliding at the start of the thrust phase.

Fluid interfaces equipment are hydraulic quick couplings linking the ground fluid supply with the on-board fluid circuit for filling and emptying ethanol, LOX and nitrogen. Like the electrical umbilical cables, these quick couplings will be integrated at the bottom of the engine bay. Several types of hydraulic quick couplings are available on the market. Some can be disconnected by breaking a screw, while others can be disconnected by turning and/or pulling a sleeve, generally placed on the female part of the coupling. In the case of ASTREOS-1, the aim is to achieve passive disconnection under the effect of engine thrust, without any operator intervention. For this reason, hydraulic quick couplings which disconnect by means of a simple pulling sleeve on the female part (cf. Figure 15) are the most suitable. The female part will be held in place at its sleeve on a pull-out module fixed to the ramp, and the male part will be integrated on board. In addition, to ensure sealing after disconnection, both parts of the coupling (especially the male part) must also be fitted with a shut-off valve. This type of coupling is commonly referred to as a "double shut-off" coupling.

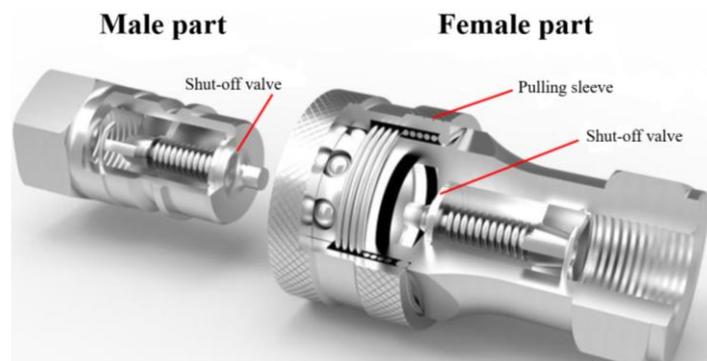


Figure 15: Push-pull hydraulic quick coupling with double shut-off valve

## 5. Rocket preparation

The rocket will be transported to its launch base partially disassembled. It will then be assembled, transported to the launch pad and ramped using a kart (cf. Figure 16) [2]. This mobile kart will serve as an assembly bench, with mobile supports placed under each section to separate them, for example to access the internal components of a section and carry out maintenance operations. This is one of the reasons why the ASTREOS-1 structure has been developed on a modular basis, with sections that can be dismantled from one another using hydraulic couplings, Sub-D connectors and mechanical connection rings.

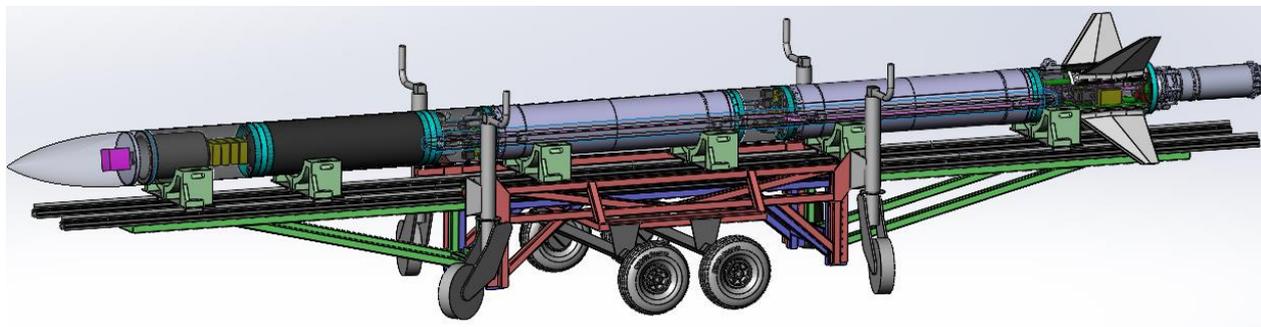


Figure 16: ASTREOS-1 on its kart

## 6. Synthesis and perspectives

All of these various endeavours on ASTREOS-1 structure, taking into account the rocket maintenance, propulsion, avionics, and ground segment stakes allow the project to take a new step towards the launch of its first bi-liquid propelled rocket. A number of tasks remain to be completed before ASTREOS-1 is ready for launch. The last significant developments on the design of the demonstrator structure were the mechanical layout propositions of the LOX, ETH and Nitrogen sections. A qualification phase is currently ongoing through mechanical simulations (static and vibratory to check robustness) and fluidic simulations (to check that sufficient flow rates can be achieved).

Thanks to the flexibility of their modular structure, ASTREOS demonstrators can be used to host on-board experiments or test new rocket sections proposed by schools or even start-ups that are partners in the project. In longer term, this launcher series will contribute to the success of the DREAM ON challenge, which aims to develop a fully reusable bi-liquid LOX/CH<sub>4</sub> propelled rocket with a target apogee of 5km.

## Acknowledgement

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## Acronyms

ARES: Advanced Rocket for Experimental Studies

ASTREOS: Ares Supersonic for Technologic Researches in Ethanol-Oxygen System;

CAD: Computer Aided Design

CHP: Capacité Haute Pression (highly pressurized tank);

CNES: Centre National des Etudes Spatiales (National Center for Space Studies)

DREAM ON: Disruptive Reusable Experimental Advanced Methane Oxygen Nanolancher;

ETH: ETHanol;

LOX: Liquid OXYgen;

MINERVA : Moteur INnovant Experimental pour les Recherches sur les Véhicules Aérospatiaux (Innovative Experimental Engine for Aerospace Vehicle Research);

P&ID: Piping and Instrumentation Diagram/Drawing

PERSEUS : Projet Étudiant de Recherche Spatiale Européen Universitaire et Scientifique (European University and Scientific Space Research Student Project);

RETH: Réservoir ETHanol (ethanol tank);

ROX: Réservoir OXYgène (oxygen tank);

SERA: Supersonic European Rocket ARES;

SSC: Swedish Space Corporation;