PERSEUS: May the Force be with You

These are the voyages of the Starship, PERSEUS

Its continuing mission: to explore new worlds,

To boldly go where no student has gone before

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Abstract
In a context of disruptive innovation, CNES (Centre National d'Etudes Spatiales), the French Space Agency, as the driving force behind France's space ambitions, has the main objective, through the Space Transportation Directorate PERSEUS (Projet Étudiant de Recherche Spatiale Européen Universitaire et Scientifique) program, to arouse the interest and vocation of the new generation for careers and entrepreneurship in the space sector, by projecting them into a future of discovery, science and technology, but also by raising their awareness of the societal, environmental, economic, strategic and political dimensions of space which are more important than ever.

Relying on innovation platform PERSEUS through pedagogic and ambitious ground and flight demonstrator projects, CNES is driving Padawans through the space side in order to help them become change actors of tomorrow.

1. PERSEUS in a nutshell

"If you are working on something exciting that you really care about, you don't have to be pushed. The vision pulls you," "People with passion can change the world for the better" ***Steve Jobs***

A powerful vector of growth, the space sector represents a high-tech industry, providing highly qualified jobs. As such, it is an important driver of innovation, whose technological developments not only influence but also benefit from those of many other strategic sectors (microelectronics, aeronautics, defense). By relying on the digital revolution, technologies and space data also have a leverage effect on the development of new economic ecosystems. The downstream space sector constitutes an important growth reservoir, with the development of new applications and new services using space data in areas of the future, notably for the benefit of sustainable development (green growth, health, mobility, land use planning, water resource management, natural risk management, agriculture, forestry, fishing, etc.). Space is fully integrated into the digital revolution, thanks to the increasing number of satellites, which provide and transport a growing flow of data. Data is transforming multiple economic sectors, such as telecommunications, transport and health, but it is also at the heart of major societal issues, between national sovereignty and scientific knowledge. This breeding ground has favored the development of an economy around space, based on a global and multipolar ecosystem where interact closely with industrialists mastering the space environment, SMEs, start-ups as well as internet giants and other users of space data, whether public or private. The space value chain, long focused on infrastructure and the upstream sector, has now shifted to the downstream sector and the data economy.

The “NewSpace”, which constitutes a major paradigm shift, has emerged in this new context. Challenging the economic patterns established in the space industry for several decades, new players, some of them from the digital world, are relying on disruptive methods and technologies. They constitute serious competitors for the established players, but also drivers of growth, particularly in the development and use of space applications. The "NewSpace" is an accelerated and global evolution of the space domain involving many new public and private actors and new methods; a new space of risks and opportunities.

It is paradoxically in this context of competition that the needs and opportunities for cooperation are intensifying.

In this ever-changing landscape, the role of CNES, as one of the stakeholders in Europe for future transportation systems preparation, and with its 60 years of experience, is to provide its expertise to promote the development and growth of this new economy by creating a bridge between the historical players and the start-ups of the New Space, and thus build a new dynamic for French and European space transportation.

More broadly, CNES is currently mobilized to facilitate the emergence of a space innovation, focusing in particular on the development of an application ecosystem by accelerating the decompartmentalization, creating links between the space industry and other economic sectors. CNES has launched the Connect by CNES initiative, which offers a complete range of support services (ideation, training, incubation, acceleration, technical expertise technical expertise, labeling, and financing) for companies and institutional players in the space sector and institutional players in the space sector who wish to use space technologies or solutions.

As the central actor in France for Space education, initiatives conducted within the CNES implying the academic world and students are also completely part of this strategy. Hence, projects such as Nanolab Academy, Pragmatic [1] at the Satellite Directorate, student competition “Launch the Future” [2] or PERSEUS [3], initiated in 2005 at the Space Transportation Directorate, find naturally their place in this context.

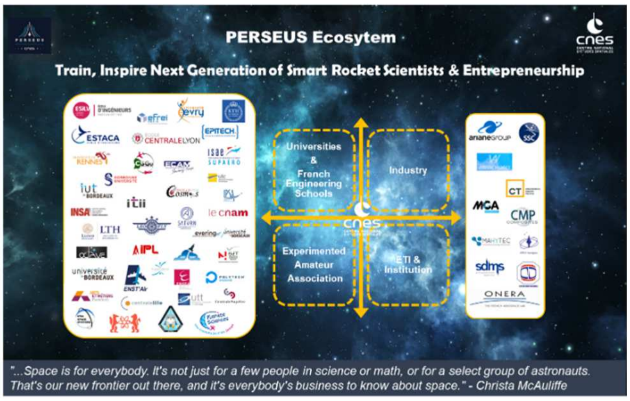
PERSEUS’ DNA, its mission statement "To inspire, move, and rose interest and vocation of the next generation for the space world and entrepreneurship...” is declined through its vision statement: " … by making it accessible and useful to all, by combining the power of creativity and the collective spirit of co-creation with that of technology and rockets, by projecting students into a future of discovery and science through ambitious ground and flight demonstrator projects while also making them aware of the environmental, societal, economic, strategic, and political dimensions of space that are more important than ever so that they can impact the world around them.

Demanding and ambitious, it is the pleasure and the desire to fulfill oneself that guide the approach of the new generation. In order to accompany them in this approach, spread the space culture within the society and enhance the value of space professions and entrepreneurship, PERSEUS, among other things, seeks to:

✓Attract and foster the emergence of talents in the field of space transportation systems through innovative and promising technical challenges.

✓Deploy the ecosystem conducive to the development of vocations for the creation of companies in the space field.

Thinking about space transport for example, new systems aims at breaking the space cost barrier through all levers: simplification, rationalization, reusability and eco-design. This new paradigm offers numerous opportunities to bring innovations which could feed Millenials 2.0 generation in quest of permanent challenges.



In order for instance to catch up as quickly as possible the players from the “NewSpace” who demonstrate rocket boosters’ recovery and reusability on a regular basis, CNES promotes several initiatives at different scales, whether it be with students, academics, SMEs or big players, aiming at fostering key competencies for reusability in Europe. Callisto [4] or THEMIS [5] projects to name some of them are part of this process. Within PERSEUS’ academics framework, the DREAM-ON challenge is so the receptacle of the required technologies for reusable sounding rockets, relying on LOX/CH4 propulsion. In this same logic, an increasingly important part is and will be given to eco-design.

Through its various actions, the PERSEUS program wants to echo the concerns of society and offer a space of freedom where the students can be actors of the change to reinvent the space of tomorrow…and maybe beyond. Indeed, the universe proposed in PERSEUS wants to be convivial, able to support a collective expression and to have a sense. The PERSEUS constellation is made up of about 35 university and associative stars representing approximately 350 students spread over a hundred activities. They all share the will and motivation to take up the challenges inherent in this program. In this perspective, students are entrusted with multi-task, multidisciplinary activities corresponding to the different themes that can structure the design of a space transportation system. The students part of this community can rely on wealthy of the involved profiles (students from different universities, Laboratories, Industries from legacy and New Space), the technical excellence the program wants to pursue, the knowlegde transmission and share, the taking of initiatives to make emerge new ideas, build new vision to support an entrepreneurial impulse which could impact positively the daily life and make a better world.

2. Looking back into the mirror …

*"If you can't fly then run, if you can't run then walk, if you can't walk then crawl, but whatever you do you have to keep moving forward." **Martin Luther King Jr***

These ideas and vision are particularly reflected in the actual proposed technical roadmap, namely an incremental development logic of demonstrators which aims to tackle technological bricks of reusability through the DREAM-ON challenge. This roadmap is built on the achievement of PERSEUS of the last 17 years.

The technical objectives in the early years of the project were to achieve 3 ambitious demonstrators also in connection with some objectives of CNES at the time:

- EOLE [6] an airborne platform: flying testbed developed to test the Separation and Release Devices by launching an ARES rocket with the support of ONERA and Aviation Design (its flight was performed in French Guiana in August 2019)
- HERA a hybrid rocket engine 10kN of thrust,
- ARCADIA an experimental rocket powered by this engine capable of exceeding an altitude of 100 km. Subsequently, ARCADIA has been repositioned as a target in 2010 to turn to intermediate steps.

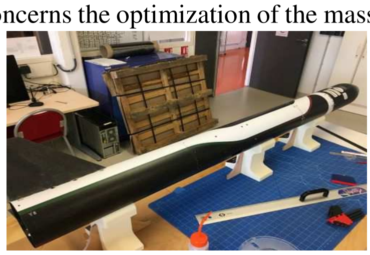
On this basis, various initiatives and achievements have been conducted with partners also present (ONERA, ROXEL, Bertin technologies/CTI Ingenierie ..) which has allowed schools / universities to acquire certain skills, the establishment of test facilities, and the development of technology bricks, and systems with sufficient potential that have contributed to feed the two families of flight demonstrators: conventional launch from the ground (ARES, SERA) and airborne launch (EOLE) All the classical disciplines necessary for the definition, realization and operations of an operational launcher have been put into practice in the project. An essential element of the functioning of the project was and remains obviously the perpetuation of the assets at the student level in order to be able to ensure a significant progression in the achievements.

The PERSEUS roadmap has thus evolved during these 17 years with a continuity at the level of the technical challenges and in a logic of progression and complexity in terms of rockets realized. About twenty experimental rockets (ARES) have been launched during the national launching campaigns C'Space, organized by the DCO.

The objective of the ARES [7] experimental rockets is to study and realize modular experimental rockets in order to :

- to be used as test bench in flight for the technologies developed in the other demonstrators,
- to qualify the PERSEUS procedures for the dimensioning cases of a launcher in atmospheric flight: passage of the transonic regime and behaviour at the maximum dynamic pressure

These rockets are centered around innovation and modularity. A particular study concerns the optimization of the mass of the structure and the equipment.



All ARES rockets are defined according to common characteristics, such as:

- ✓ an external diameter of the structure of 160 mm,
- ✓ a recovery system by axial separation and deployment of parachutes,
- ✓ an external structure made of innovative sandwich composite tubes,
- ✓ light fins easy to assemble and disassemble,
- ✓ the use of the PERSEUS launch pad (for launches from the ground)

The development of ARES rockets responds to one of the educational missions of CNES and offers the opportunity to integrate new schools/universities into PERSEUS through "technically affordable" demonstrators. These rockets, which culminate in a one-week launch campaign each summer in Tarbes on a military site, can reach an altitude of 1.2 to 2.5 km for the highest. The altitudes of these experimental rockets are very modest for essentially two reasons:

- The realization and the implementation of these rockets by motivated but not very experienced students,
- The constraints of safeguarding the launching site which strongly limit the apogee.

The continuity of the ARES flight demonstrators or support of embarked experiences at C'Space is essential because it is a great source of motivation for the new generations of students. These demonstrators have therefore the interest to coordinate student works while testing very recent technologies in all fields. An ARES rocket will soon be launched from French Guiana at the end of 2022 with the support of CSG teams, thus reinforcing the links with the universities of Kourou and Cayenne.

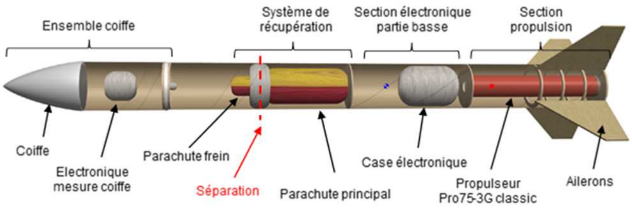


Figure 2: Guyana ARES

But the current limitation of these demonstrators ARES is that the flight remains clearly in subsonic regime. Consequently, in order to be able to propose to the academic world studies compatible with the classical dimensioning cases of an operational launcher in the atmospheric phase (transonic passage, maximum dynamic pressure in supersonic regime) the SERA project [6] was decided mid-2012. A first launch was realized in May 2014 and two others followed thereafter. SERA 4, the last member of the SERA family of solid rocket demonstrators, will be launched in October 2022 from French Guiana.

The many projects and demonstrators implemented in the past have thus made it possible to learn, understand and progress in the many disciplines and questions relating to rockets (subsonic regime, supersonic, general efforts, telemetry, avionics, composite structures, hybrid propulsion, solid propulsion, bi-liquid propulsion ground tests...).

For example, the first tests of the biliquid Lox-Ethanol MINERVA engine (5KN thrust engine with a combustion time of 20s for the first example) were carried out in 2016, on the multi-fuel test bench built with the support of R&T at ROXEL. These tests resumed in June 2022, once the engine test bench has been relocated in 2021 to its new environment at the ArianeGroup test site in Vernon.

These achievements during these first 17 years have provided a solid technical foundation within the PERSEUS program for the students that will enable them to meet future challenges.

SERA 4, symbol finally of all these achievements which allowed PERSEUS to go up in technological maturity, will thus constitute, with the MINERVA engine, the base, for the development of the first bi-liquid rocket ASTREOS, one of the parts of the new orientations of the project, and to bring PERSEUS to a higher level of complexity.

We build the future on our success story!

3….before a forward leap into next years

"Shoot for the moon; Even if you miss, you'll land among the stars" ***Oscar Wilde***

In 2018/2019, in line with the recent market trend and overall strategy of the CNES Space Transportation Directorate, the PERSEUS roadmap has evolved to turn to biliquid propulsion and move towards a reusable lox/methane sounding rocket demonstrator. So The objective in the medium term of PERSEUS is to answer the challenge of the reuse with biliquid sounding LOX/Methane rockets. 2 large families of demonstrators, corresponding to an increase in complexity of the technological bricks involved, have been defined in order to mark out the way towards this objective: ASTREOS and DREAM ON.

- ASTREOS : family of demonstrators of bi-liquid rockets recoverable under parachute: launch target of ASTREOS 1 in May 2024 with all the associated technological building blocks.

  ASTREOS Branch is a demonstrator project being part of the CNES PERSEUS roadmap. Demonstrating critical technologies and capacities, it shall serve as a stepping stone for a notional reusable DREAM ON sounding rocket. Capitalizing as much as possible on the developments and the experience acquired with the SERA family of flight demonstrators, the overall goal of the ASTREOS Branch demonstration is to contribute to the acquisition of the technologies and competences for a sounding rocket enabling reusability, through series of tests at representative scale, on ground and in-flight. The objective of these vehicles family is to validate the technologies such as liquid propulsion system, ground support system, avionics, reaction control system, recovery system and range communication system required for a reusable vehicle. The project consists actually in several "system level" hardware setups that will allow to proceed with intense testing along the 2023-2029 period, with more or less a test/Launch campaign every year. The Agile development logic for PERSEUS consists in setting a path featuring intermediate hardware valuable tests well before 2025 (i.e. with meaningful objectives). They all contribute to the overall DREAM ON Roadmap, give a dynamic rhythm to the project with (= 1 concrete objective each year) and allow to gain experimental maturity in view of the final "DREAM ON" design.

  The underlying design concept of ASTREOS demonstrators lies on "technically affordable components" for the students and Innovation principles, especially those maximizing reuse and pragmatism. As a consequence of these principles and of the iterative design, the vehicle architecture is organized around modules that could be independently updated along the project.

- DREAM-ON: family of reusable bi-liquid rocket demonstrators

  As this is more of a long-term objective, no calendar target for possible achievements or launches is specified here. However, concept studies (diameter 250/650; single-engine/cluster of engines...) have been and are launched allowing also to approach three possible modes of recovery for PERSEUS:
  - The descent under parafoil (studied in particular in the form of on-board experiments at C'Space)
  - Ballistic descent with retropropulsion (VTVL ascender trajectory)
  - The winged descent

The implementation of these families of demonstrators will be based on the development of 2 important technologies, responding to an incremental logic of increasing complexity and allowing to address 2 complex issues for students:

- ✓ the Guidance Navigation Control (GNC) part to master recovery and reuse with the Mini-Apterros, Smartcatcher and ROAR sub-demonstrators.
- ✓ the bi-liquid engine part with the MINERVA engine part also of the sub-demonstrator ROAR. Indeed, ROAR has the peculiarity to integrate both the MINERVA engine in its development and test logic for the functional part of ASTREOS stage and also the VTVL GNC part (with the development of the vectorization theme) of DREAM ON.

These sub-demonstrators are an integral part of the development plan for the two families of ASTREOS and DREAM-ON demonstrators.

Within the ASTREOS and DREAM ON families, the development of the different demonstrators will hence follow an incremental logic (see flowchart), which will allow the introduction of new functionalities or technologies for each version while increasing the performances. ASTREOS and DREAM-ON will evolve over time.

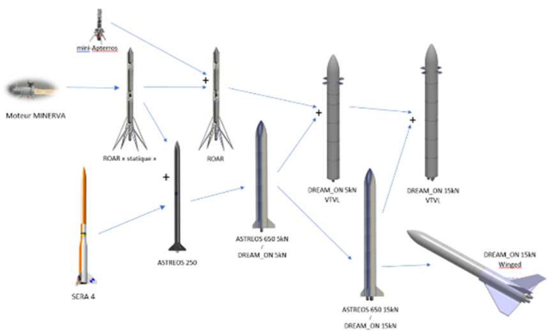


Figure 3: PERSEUS Incremental Roadmap Logic

3. Thematics & Key Technologies roadmap, Demonstrators development overviews

"Knowing is not enough, we must apply. Willing is not enough, we must do." **Bruce Lee**
"Welcome the doubt, Embrace doubt…otherwise you will never know what you're truly capable of" **Ginger Runner**

To progress towards the DREAM-ON test-bed/demonstrators, some key and complex technologies need to be mastered, which can be tough and sometimes discouraging for students who have not for some of them the possibility to be involved on the "long term" in the project. Thus, in order to meet the students' need for experimentation, taking into account the academic rhythm on which this program depends, and while relying on past experience, the proposed technologies roadmaps favors an incremental but flexible and agile approach that makes it possible to take into account different possible paths to achieve concrete realizations each year. As early mentioned, these bricks will be part of the different incremental demonstrators and the specific themes of PERSEUS. The rationale in the roadmap is to embrace in the same time COTS technologies as well as mid-term and long term promising and bets technologies. We want to promote incremental innovation as well as innovative and potentially riskier ideas. These roadmaps have and can added to the breadth and depth of participation. The development of these key parameters enable the progress of the different demonstrators and sub-demonstrators performed by the students and supported by technical specialists and experts.

One path to success to ASTREOS 1 implementation lies in the development all the **GSE (Ground Support Equipment)** and related operations including the launcher rail, propellant storage and filling system, disconnection system and safety equipments. To meet the need for launch autonomy for the various demonstrators and the bi-liquid filling problems of these future launchers, the PERSEUS project is currently developing its own mobile launch pad. Even if we cannot speak of technologies in the literal sense, preparing and training a ground operating team is also a key parameter. Augmented and virtual realities to help students rehearse the various ground operations on the rocket itself can be a means of training in the various procedures and reducing risks.

The development of the bi-liquid line is conditioned to the implementation of the **Propulsive Assembly** with in particular the functional and firing tests of the Minerva engine. The PERSEUS propulsion bench on the Vernon plateau is an important cornerstone in the new direction undertaken. It will make it also possible to validate the performance of tanks with composite liners, this **Structures and Materials** technology being one of the critical aspects of the propulsion system. From the point of view of the recovery strategy of the vehicle (Vertical Take Off, Vertical Landing), the development and a characterization in cryogenic conditions of the Pintle technology in order to allow a certain modulation of thrust of the engine represents also an important milestone.

Nevertheless, the Vertical Landing strategy is not the only one studied within PERSEUS. A recovery of the vehicle by means of a parafoil is also envisaged within the studies of the DREAM-ON rocket - a system which could also be tested with the rockets planned during **C'Space Campaign** - and seems initially more affordable for the students compared to the Vertical Landing and the control of the Thrust Vector Control (TVC), which constitutes nevertheless one topic to study.

Whatever the options studied or retained at the **System level**, it is imperative today to develop for certain aspects the whole **Avionics** chain with the **Guidance Navigation Control** part. This New Generation Avionics will have to be more modular, integrate as much as possible the wireless protocol, build perhaps on a hybrid navigation while relying on standards such as Open Powerlink

On these themes, a certain synergy and overall coherence (up to a certain stage obviously taking into account the performances serached in PERSEUS) within R & T CNES projects but not only can be expected with the development of the ASTREOS and DREAM-ON demonstrators.

If the practical aspects and the will to realize as soon as possible and as often as possible prototypes are put forward within PERSEUS, the part **Modeling / Simulation and Tools** is not neglected and will have to accompany the whole of the developments of each brick through the various topics: tool of trajectory of return of the vehicle, calculations of behaviour of the tanks, validation of the Avionics...

These technologies pave the way to the DREAM-ON mission and objectives and find their echoes, their expression through the different sub-demonstrators and demonstrators.

<u>From technological bricks to the DREAM-ON demonstrator:</u>

Several system demonstrators within PERSEUS are currently under study:

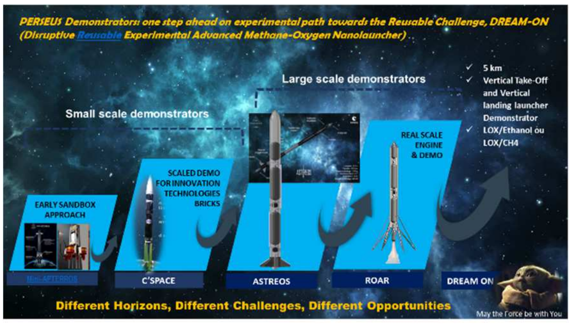


Figure 4: PERSEUS Core Prototyping Projects

- ✓ On-board experiments (modular avionics, roll control, parafoil ...) within rockets at C'Space to feed the development of technologies transposable to the ASTREOS and DREAM-ON demonstrator families
- ✓ A captive reusable biliquid first stage sub-demonstrator (VTVL) called ROAR, whose small-scale precursors Mini-APTERROS aiming at mastering the Guidance Navigation Control part should make their first flight tests in summer 2023 and which will prefigure the capabilities and the flight domain of the ROAR demonstrator Nevertheless, before carrying out the captive flights of the ROAR demonstrator, this one will initially have vocation to demonstrate, through static tests, the viability and the functionality of the propulsive stage scale 1:1 on the basis of the MINERVA Lox/Ethanol engine of a thrust of 5kN. These static tests will make it possible to support in part the design of the ASTREOS rocket
- ✓ The "ASTREOS" experimental rockets (evolution of the SERA rockets) to confront the transonic and supersonic regimes, essential stages mastered in the framework of operational launchers, and to implement the bi-liquid propulsion prefiguring what will be the DREAM-ON demonstrator;
- ✓ The DREAM-ON challenge, whose objective is to develop a reusable first stage demonstrator:
  - o 5 kms culmination
  - o dry mass of 50 kg
  - o Lox/LCH4 engine propulsion of 500 daN thrust

3.1 Mini-Apterros & Smartcatcher Status

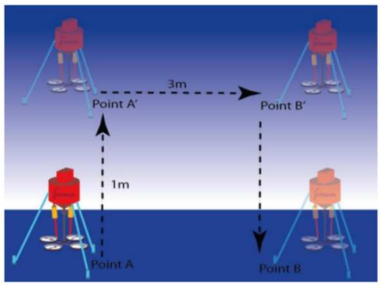


Figure 5: Mini-Apterros Mission

The Mini-APTERROS project aims at setting up a fundamental technological brick necessary for the realization of a reusable biliquid VTVL (Vertical TakeOff Vertical Landing) first stage demonstrator, which will prefigure the rocket demonstrator of the DREAM-ON (Disruptive Reusable Experimental Advanced Methane Oxygen Nanolauncher) challenge. This element is the control of the GNC (Guidance Navigation and Control). In a first step, the objective is to work on the GNC by making an application on a small scale demonstrator, based on technologies from drones easily accessible to students. The Mini-APTERROS vehicle will therefore be of low mass (<10kg) and its field of evolution will be that of an aviary in order to guarantee the respect of the legislation and the safety of the operators. The Mini-Apterros demonstrator is a reusable thrust vectoring stage model. The particularity of the Mini-Apterros is that it uses only an electric propulsion to simulate a chemical propulsion (solid or liquid propellants). Currently, three institutions associated with the PERSEUS project work on this sub-demonstrator: University of Rennes 1 (UR1), ENSEA Cergy and ENSAM Bordeaux. The two first use a classic GNC algorithm whereas the last on will rely on deep learning reinforcement.

3.1.1 Vehicle & Engine

This prototype of UR1 Mini-Apterros for example can be decomposed into several bodies; to simplify the dynamic model we will count two: the frame or main body and the exit nozzle. These two bodies are in cardan linkage one with respect to the other, the orientation of the nozzle is carried out by two linear actuators. The Rack has been designed in several parts to meet the needs in terms of space occupied by the various components necessary for the operation of the demonstrator. In this respect, the Rack contains : The equipment part (the body) in charge of accommodating the electrical and electronic components of the demonstrator as well as the air reserves of the anti-roll system; The propulsion/piloting part, accommodating the engine part of the demonstrator (The upper part of this stage allows the

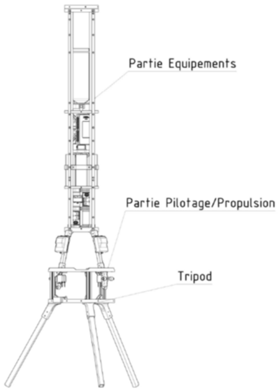


Figure 6: Mini-Apterros Rack

fixing of the motorization (turbines), the anti-roll system and the mechanism of vectorization of the thrust (TVC). This TVC will find its extension in future ASTREOS sounding rockets) - The tripod, linked to the propulsion/piloting part of the frame, allows the contact with the ground of the Mini-Apterros. The purpose of the Mini Apterros engine assembly is to simulate a vectored thrust engine. It is composed of several elements:

- The main casing which recovers the air pumped by the turbines and gathers the 4 air flows in a single
- A junction piece which guides the flow to the outlet nozzle in order to avoid creating a singularity in the flow
- The outlet nozzle, which can be oriented to vectorize the thrust

Figure 7: Mini-Apterros Prototype

The upper part of the propulsion casing meets a requirement of cancellation of the gyroscopic effect due to the operation of the electric turbines, one will use for that two rotary turbines and 2 turbines counter-rotating turbines. Moreover in order to cancel any thrust other than in the axis of the engine (due to the entry of the air flow in the turbines) the sites of reception of these turbines were placed by rotation of 90° around the central axis of the casing.

3.1.2 GNC & Embedded Software

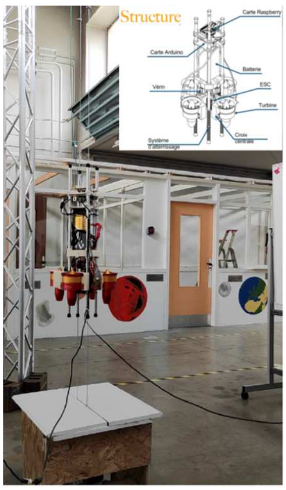


Figure 8: Mini-Apterros ENSAM Bordeaux (MAMBA)

The main objective of the Mini-Apterros demonstrator is to develop a GNC research platform, to investigate the efficiency of different modern algorithms in the landing phase of a reusable space launcher first stage. Among them, the Deep Reinforcement Learning studied by ENSAM Bordeaux is a promising track which is considered within PERSEUS framework as a mid-long term technology to develop. Indeed, among the many Machine Learning algorithms that exist today, Deep Reinforcement Learning (DRL) is the most used for the control of robots or mechatronic systems. The principle and ingredients of DRL are shown in figure below:

The agent is the neural network (NN). For a state and a reward given by the (reward) given by the Environment, it chooses the "best" action to perform on the Environment. The Environment is the system controlled by the agent : it receives an action At and it sends back to the agent its new state St+1, and the reward Rt+1 associated to this new state. For the Mini-APTERROS project, the Agent is the "trained neural network" computer program and the Environment is the Mini-APTERROS vehicle equipped with its sensors and actuators.

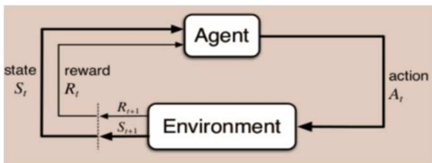


Figure 9: Principle and ingredients of DRL

Besides the development of an operational vehicle, the following tasks regarding DRL GNC have been done during the project:

- The development of simulations of the two sub-demonstrators CartPole and Balancing Robot as well as the Mini-APTERROS vehicle in several computing environments and the DRL associated neural network control: the CartPole (control of the simulated system and the hardware system) and the Balancing Robot (control of the simulated system).

- Conclusive "1D flight" tests to launch/land the vertically guided vehicle, piloted :
  - ◦ manually,
  - ◦ by a simplified PID controller,
  - ◦ finally by a PPO-type DRL network, trained on a simple simulator in the Gym environment.

These flights validated several important points of the project:

- the effectiveness of the Mini-APTERROS vehicle structure designed and built to support the required functionalities for the flight,
- the choice of the turbines and the power circuit which feeds them (ESC & battery),
- the control of the turbines by PWM signal generated by the Arduino board in communication with the Raspberry Pi board,
- the possibility of controlling by a PPO type neural network the take-off/landing of the vehicle forced to move vertically (one degree of freedom: vehicle altitude).

The main advances expected in the AI field for the next months are :

- Statistical processing of the PPO network trainings allowing to define and calculate a significant metric of the significant metric of the "quality" of the network training;
- the PPO network control of the Balancing Robot hardware demonstrator;
- the PPO network control of the Mini-APTERROS vehicle in 3D flight (simulated and real).

3.1.3 Smartcatcher

In parallel, the objective will also be to conduct recovery tests using a structure, the Smartcatcher, developed in collaboration with ArianeWorks. The SmartCatcher [9] is a project to design and build a mechatronic launcher demonstrator recovery system for ArianeWorks. This scale 1:10 scale model (compared to the full size one foreseen for THEMIS) is already operational.

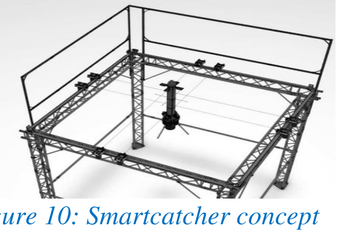


Figure 10: Smartcatcher concept

3.2 Roar Status featuring Minerva Test bench & Engine

The ROAR sub-demonstrator therefore has a double objective:

- to ensure the static functional tests of the propulsion system of the ASTREOS demonstrator by integrating the flight tanks and by unfolding the flight sequence from a functional point of view
- following the Mini-Apterros sub-demonstrator described above, to consolidate, implement and validate the GNC, fundamental technological brick necessary to the realization of a reusable biliquid first stage demonstrator, but at a scale quasi-representative of the DREAM-ON VTVL demonstrator, since integrating the flight tanks and the piloted engine, in order to produce a mission between two platforms with limited vertical and horizontal displacements, initially in captive flight then in free flight

The ROAR vehicle will thus be rather simple in its structural part since it is made up of tubes, the remainder corresponding to the whole of the lines and the valves coming to supply the tanks and the MINERVA engine

3.2.1 Minerva Test bench

Moving to the site of Roxel, ancient partner of PERSEUS to the site of Vernon has been a huge step for the Program in order to progress towards a biliquid vehicle.
In this respect, the update and redefinition of the Minerva propulsion test bench on the Vernon plateau at PERSEUS' partner ArianeGroup has been essential in order to carry out and operate soon the numerous cryogenic engine and stage tests. The test bench will allow students to operate an engine up to 10 kN with propellants like Ethanol, H_2O_2, Methane, Lox. After some reception tests (chill-down, pressurization, injection …) already performed, **the bench is now ready for firing tests.**
It should be noted that this bench will not only be available to PERSEUS students but will also be open to external entities under certain conditions.

Figure 11: Minerva Test Bench

3.2.2 Minerva Engines development & status

From the use of ablative materials to the implementation of a regenerative cooling circuit and later an electromotopump engine, **different engine evolutions** are foreseen to tackle the challenge of the bi-liquid propulsion. The development of these variants will obey to an incremental technological rationale which will enable students and Perseus project to improve their knowledge and master of this challenging field. Conjointly of the use of impact injectors on first engines, one of potential key technologies for example for the VTVL to embrace is the complex development of pintle injectors. These evolutions of the Minerva Rocket Engine will feed the versions of the ASTREOS sounding rocket family and also the DREAM ON rocket branch.

4 versions are currently studied:

- ✓ The very short term ablative version aka **MLE5K** for **M**INERVA **L**ox-**E**thanol **5k**N [10] of thrust developed in particular with Evering School (chamber body conception and production) and Ecole Centrale Lyon (transient and steady phases simulations through EcosimPro). Classical impinging triplet injectors (F-O-F) were designed in order to atomize the fuel and oxidant mixture in a chamber insulated with ablative protection. The rate flow of the 7 injectors was defined in order to have a 5 kN engine thrust. The estimated chamber pressure is fixed at 10 bar and the combustion time is 20 s. The estimate efficiency is 0.95 for a vacuum ISP of 295 s. **This version will be tested in June 2022.** A lighter ablative version is planned at the end of 2022 including impact or pintle injectors studied at Ensam Lille and Aix en Provence.

- ✓ A pressure regulated regenerative cooled engine mainly developed inside Ecole Centrale Lyon and Ecole Centrale Paris and involving also Polytech'Orléans for the conception of an igniter and the associated test bench. This mid-term engine evolution will be embarked within ASTREOS 2 or 3. A first prototype is deemed to be available beginning of 2023.

- ✓ A electromotopump Lox-Ethanol mid/long term engine delivering 10 kN thrust and 40 bars in the chamber, relying on the studies performed both by ENSTA Paris and IPSA student association Innovative Propulsion Laboratory (IPL) regarding the Ethanol and Lox (50, 000 rpm) electropumps [11]

- ✓ Called Mini-Viserion [12], this mid-term LOX/CH4 rocket engine with a nominal thrust of 5kN is entirely designed by the IPL teams. This project involves the design of a pintle-type injection system and a regenerative cycle combustion chamber. But it also involves the design of a thrust recovery device allowing TVC and a patented adaptive divergent nozzle with its deployment system.

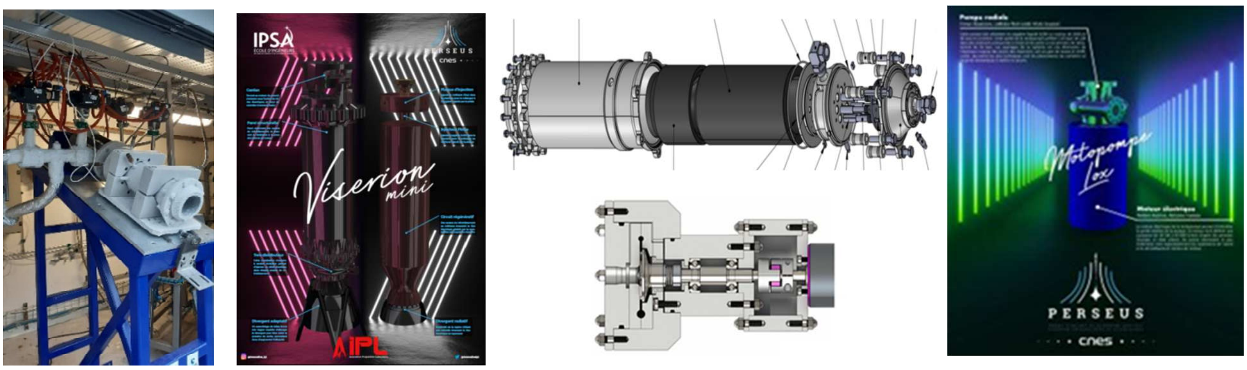


Figure 12: Minerva different engines version

- ✓ Another short term major upgrade envisaged for the biliquid propulsion work within the PERSEUS project is to switch from the liquid Oxygen to H202.

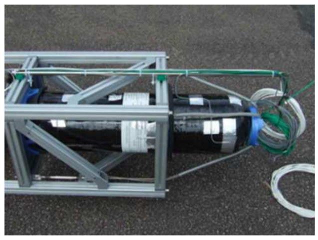
3.2.3 Battleship status

Based partially on the work performed at INSA Rouen since 2016 with the incremental conception and deployment of a water pressurization test bench permitting to simulate and validate some functions and technical choices, the purpose

Figure 13: INSA Rouen Pressurization Test bench Evolution

of the building of the Battleship at Vernon is to be in position to test and validate the functional behavior of the propulsive assembly of ASTREOS 1 in an incremental way. The materials making up the stage will be available at very different times: the "Battleship" structure will allow to support the elements of the stage independently from each other; the test plan will have to be adapted to the available materials in order to carry out the possible validations as soon as possible. The circuits of the propulsion system are cut into several sub-circuits (called "configuration") . A configuration represents a set of components organized in such a way that they allow to validate the functions for which the configuration is defined. These configurations will be thought and integrated on the battleship structure so that the sum of the configurations gives us at the end the Flight configuration. Thus in spite of a cutting of the circuit and more numerous tests, the successive incrementation does not lose much efficiency to these functional tests. Therefore, here again, the tests will evolve gradually, beginning with a GN2 configuration. **First battleship tests will occur in June 2022**.

Figure 14: ROAR battleship



3.3 ASTREOS 1 in short

3.3.1 Missions objectives and major specifications

ASTREOS-1 is a single-stage rocket, propelled by the MLE5K-V1 ablative engine of 5 kN thrust developed as part of the MINERVA sub-demonstrator. The propulsion system is based on an on-board pressurization of the tanks (Pressure-Fed). Apart the cryotechnic rocket engine, the vehicle architecture includes two cryotechnics tanks, one High Pressure GN_2 capacity for LOx and Ethanol tank pressurization. The overall length is above 6 m for an external diameter (excluding pipes/housings) of 250 mm and a total dry-mass of 120 Kgs. 4 fins will equip ASTREOS 1 but no booster and active control system are foreseen in this vehicle.

Figure 15: ASTREOS 1 Overview

3.3.2 Propulsion Bay

3.3.2.1 Engine Bay

The propulsion system is based on the MLE5K on its light ablative version presented in the previous lines. In parallel, the aft-bay assembly, including engine thrust frame, has been studied by Ecole Centrale Lyon and through an internship.

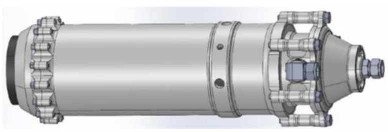
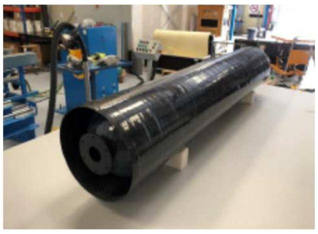


Figure 16: ASTREOS 1 Aft and Engine Bay

3.3.2.2 Tanks Bay

The 2 structural tanks will be in welded aluminum for the Lox part (developed by SDMS) and in composite with carbon fiber around an aluminum liner for the Ethanol part. This last patented one has been developed through PERSEUS by CMP Composites [13]. The implementation of a dedicated system to insulate the Lox tank has been studied by CTI Ingenierie and University of Technology of Troyes and is still under consideration for ASTREOS 1. The Pressurization will be ensured through the High Pressure Capacity manufactured by Mahytec.



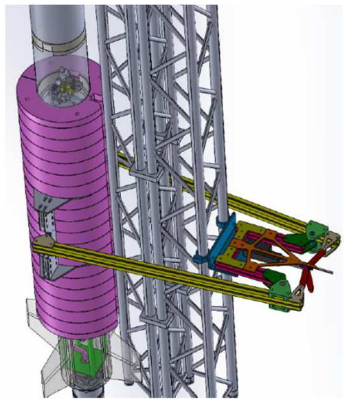


Figure 17: ASTREOS 1 Tanks Bay

3.3.2 Structures

The skirt (250mm) will be realized in 3D printed titanium as it has been on the SERA 4 rocket. A spot is also dedicated to a 0.5kg payload under the nosecone. If the planning allows it, the objective is also to embark the biodegradable fairing currently developed by ENSAM Angers.

3.3.3 Flight Control Bay: Avionics & GNC

The avionics domain meets a set of objectives and missions:

- Restore the trajectory and the flight environment
- Continuously measure the state of the propulsion system
- To ensure the neutralization of the demonstrator if necessary
- To allow the recovery of the demonstrator
- Guarantee a bidirectional communication with the ground segment

In order to fulfill these missions, the avionics have been divided into thematic products that respond to one or several main functions. The logic of this division can be found in the following 9 products for ASTREOS-1 [14]:

- Central system or On-Board Computer (OBC)
- Guidance, Navigation and Control System (GNC)
- Measurement and control systems
- Timecode system
- Sequencer
- Power distribution system
- Communication system
- Video system
- Recovery system

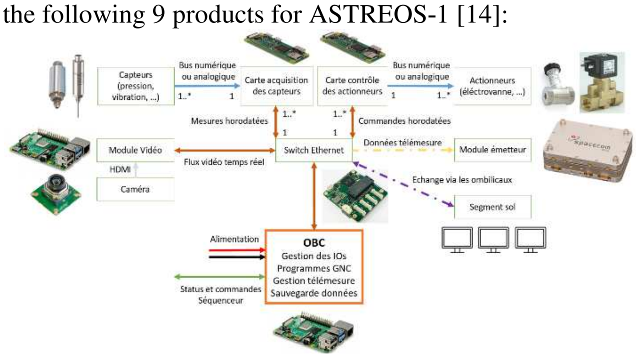


Figure 18: ASTREOS 1 Avionics

These products include Telemetry at 2,28GHz with a QPSK modulation compatible of professional launch site such as Kiruna in Sweden or Kourou in French Guyana and a set of ground installation in order to check the rocket behavior during the chronology, including the hot count down. The On-board real-time guidance & control trajectory optimization is also part of the current development for ASTREOS.

The rocket currently considered in the development of this system is the ASTREOS-1 rocket, but in order to facilitate the technological bricks to come, in particular related to GNC, such as the vector thrust control or the descent under parafoil, the OBC, as the heart of Avionics, must be modular and evolutive. It will therefore be possible to easily modify and adapt the OBC on the next ASTREOS demonstrators up to DREAM ON with an increase in the number and complexity of critical functions that will require potential redundancy.

This logic has already been successfully initiated on the SERA IV demonstrator, with an OBC entirely realized for the first time in-house by the PERSEUS project. Numerous technological bricks have thus been developed, but the ASTREOS demonstrator takes this strategy much further, with a search for innovation and technological coherence.

Thus, many outdated orientations and obsolete technologies are questioned and replaced. For example, rather than resorting to specific electronic board designs, which are expensive and not very scalable, it is preferred to use generic COTS that are easily accessible and adaptable.

In the same way, rather than using a set of heterogeneous protocols, with specific limitations (throughput, signal attenuation, peer-to-peer cabling...), it is preferred to globally deploy a single critical real-time Ethernet protocol in order to get rid of the numerous limitations identified on the previous demonstrators. This architecture has the advantage that students can easily contribute and can propose evolution.

Figure 19: ASTREOS 1 Raspberry Pi4 and Pi0

3.3.4 Separation and Recovery device

Figure 20: ASTREOS 1 Separation and recovery device

The approach pursued by University of Rennes 1 and SUPMECA St-Ouen was to design a system close to that of the SERA rockets by redefining in a new way the operation of the separation. The ring in the center of the system pivots thanks to a gear and releases the upper ring which is ejected by the springs, allowing the parachute to go out, to open and to and slow down the fall of the rocket. The upper ring is attached to the lower ring to the lower ring by means of the hooks and ball bearings. It is when the hooks are no longer in contact with the bearings that the separation takes place.

The development of this system lied on the possibilities brought by the « Model Based System Engineering » (MBSE). It was the first iteration of the MBSE tool around ASTREOS/DREAM-On development.

3.3.5 Ground Segment

The ramp which is currently under development [15] will be completely dismantlable allowing flexibility and will be stored at Ariane Group Vernon in a dedicated PERSEUS test area. It will include a part of the servitudes. With a length of 12m in order to reach the aerodynamic stability of the rocket in exit, this ramp, entirely modular, will make it possible to guide launchers of a diameter from 250 to 650mm being able to go until 300Kg of empty mass. In development for 1 year, many students and trainees (ESTACA, Technological Universities of Compiègne, Belfort, Troyes, EIGSI) have participated and still participate in the system studies and qualification of the subsystems. The ramp is currently being installed, the first tests coordinated by the PERSEUS ground segment being expected during the summer with the mechanical test campaign. The combined tests in conjunction with the onboard team are expected for the end of 2022 - beginning of 2023 for an operational deployment in Sweden in 2024 for the flight of ASTREOS 1. At the same time, the development of a kart aiming to transport the rocket from the integration site to the ramp is underway.

Figure 21: PERSEUS Ramp

Figure 22: Ramp deployment at Vernon

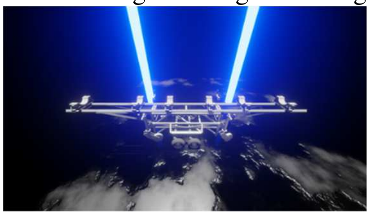


Figure 23: PERSEUS Kart

3.4 DREAM-ON: conceptual design

Aside the activities pursued through ASTREOS development, some concepts and options have been explored in order to fulfill the missions of DREAM-ON. DREAM-ON single Minerva engine main demonstration flight missions foreseen in a VTVL configuration are: “Hop missions”. It is envisioned to conduct a set of “step by step” qualifications flights by increasing gradually the altitude reached by the vehicle. A hop test consists in a vertical lift-off, a hovering phase, and a vertical landing at the same location, without engine cut-off. The Vehicle shall be able to lift-off from its legs and land on its own legs. No translation of the vehicle during flight is foreseen.

The “Hop missions” will be a cornerstone for the future evolutions of DREAM-ON whatever its missions or design. Indeed, a multi-engines version could be considered requiring the study of a solution of stabilization and piloting by grids in descending phase of DREAM-ON demonstrator. A first reflection was carried out on the various possible solutions of stabilization and piloting within the framework of a return to the ground of the Toss Back type. It was found that the grid system, or cellular ailerons, have the best compromise of controllability/actuator power required, even though they present a certain complexity in terms of aerodynamics.

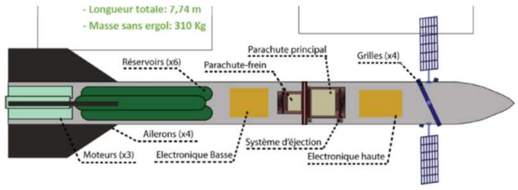


Figure 24: DREAM-ON Extended Concept

In parallel with the theoretical study and simulations, the team has begun the mechanical design of a scale model with the aim of an eventual flight test. The proposed experiment is to release under balloon a demonstrator equipped with this piloting device and to test its ability to respond to commands. This experiment aiming at a test within the framework of C'Space, it was judged too complicated from a flight safeguard point of view to carry it out under acceptable conditions. The students plan to make tests in wind tunnel of reduced scale models in order to feed the numerical simulation models.

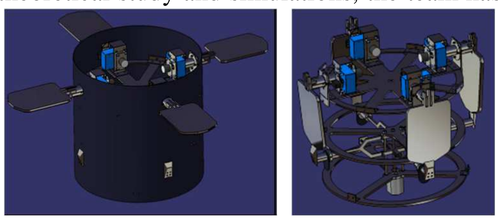


Figure 25: Grid Fins Systems Concept

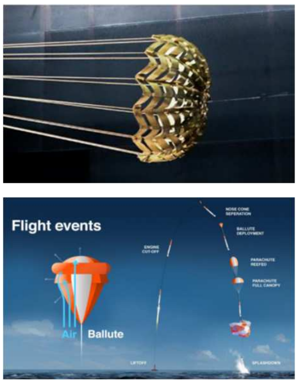


Figure 26: Ballute and hemispherical Systems Concept

The design of DREAM-ON also raises the question of the dimensioning of a high speed braking solution (still subsonic). This study is led by Supaero. This type of parachute was, at the base, imagined for a braking solution within the framework of a demonstrator of piloting by grids, requiring a high speed of fall and ending by a recovery under parachute.
The team has previously studied two high speed parachute solutions:

- The hemispherical "ribbon" parachute
- The ballute (contraction of balloon-parachute)

These two solutions bring various characteristics in terms of braking capacity, behavior at opening, stability after opening and limit speeds. Some calculations of dimensioning were carried out on the system of hooking in the rocket. This study constitutes a first approach and will be resumed next year to go further in the concepts and to think about characterization tests.

Data issued from these two previous systems proposed and simulations will feed the current development of a novel trajectory simulator. Indeed, the concern of the different existing trajectory simulation solutions is that they only allow the calculation of "classical" sounding rocket missions, without the possibility of estimating the descent trajectories other than under a classical parachute. However, it is planned for the DREAM-ON family to be able to experiment with different recovery approaches with a view to reuse, including the most demanding one which is the TossBack (or VTVL trajectory) with a re-ignition phase of the propellant with a view to braking and landing. The Supaero students have therefore proposed to develop a new trajectory simulator, combined with a flight plan optimizer, allowing to estimate the achievable performances with a given launcher configuration, or conversely to calculate the quantities of propellants needed for the up and down phases for a given performance. A first approach consisted in writing the flight and simulation laws in 1D and integrating the first flight plan optimization algorithms. The first results seem to be satisfactory, although the aero models are still relatively simplified. Work on the 2D simulation has been started but the project could not go any further this year and will be resumed next year to continue it. The structure of the program is modular and planned to be evolutive in order to add behavior laws, models, etc. Besides VTVL option, the descent under parafoil will be also considered. In this perspective, this simulator could also take benefit of the results of the IPER rocket of ISS from

IPSA [16] which will be launched during the C'Space campaign in Summer 2022. This launch will constitute a first attempt of this complex technology within PERSEUS program. This first experimentation should allow a transposition to a like-ASTREOS 1 rocket.

Even if other studies are considered for DREAM-ON as such the landing legs solution for example and will be pursued, the priority is put today on ASTREOS 1 in order to be in time for a flight in 2024.

4 Organization

"The measure of who we are is what we do with what we have" ***Vince Lombardi***

As the space sector is going through a rapid evolution, an acceleration of the pace of innovation, an expansion of entrepreneurial ecosystems from upstream to downstream and the emergence of new players, it is important a question of accompanying this movement while also evolving with a cultural shift to be set up through more dynamic organizations. Innovation as well as creativity can be chaotic. That's why they require discipline and management.

Sharing unifying, core values and common principles with all actors of academic world and industrial team is a major component of Perseus Program:

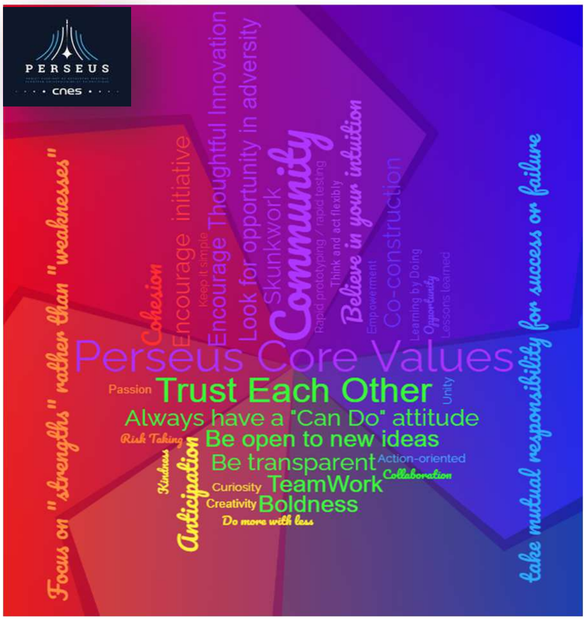


Figure 27: PERSEUS Core Values

Around passion and enthousiam, the objective is to act as an integrated team, encouraging direct communication between all members, allowing each team member to learn, grow and develop over the course of the program. As a team, a cornerstone is to trust oneself and trust each other and not blame each other - look for constructive ways to make things right when things go wrong. To progress on our demonstrators, while promoting and stimulating innovation, often the adaptation of existing solutions can facilitate the decision by minimizing the risks The
The motto is to follow its intuition, make collaborative decisions and dare in order to go together further to success, to serendipity and beyond.

The PERSEUS program is organized around the Perseus project platform (3P) located in the CNES headquarters at Paris, Les Halles. The project platform has a space for the integration of mechanical and electronic parts. The 3P consists in a fully integrated project team with a certain level of freedom and flexibility, and the support of teachers, specialists and experts from CNES, Industries such ArianeGroup, SMEs enabling hence the overall coordination and synthesis level of the Program. Indeed, one of the guidelines of PERSEUS, in addition to the students who are at the heart of the program, is also to identify and highlight SMEs that could bring added value to the program through a particular technology for example. This setup hence allows to adequately steer design choices and scout original technology paths. The mindset is similar to, although not identical, what has been successfully implemented in the US industry for tackling demanding aerospace challenges, such as the Lockheed Martin Skunkworks or the Boeing Phantom Works.

The organization of the program also relies on the establishment of the "Talkspirit" collaborative platform which allows participants in the program to ask questions, share their progress, capitalize their work through the dedicated documentation, be aware of the latest activities on PERSEUS but also those of CNES in general and ease the progress of the Project. In fact, the teachers in university and the lead students in association are invited to transmit their knowledge to the new generation in order to progress on the demonstration realizations rather than starting from zero each year!...and the Talkspirit collaborative platform is an excellent mean for that purpose. An annual seminar is also held in winter, where all the students are invited to present their own work (oral and poster forms) to the industrial and scientific community.

The will of the PERSEUS project team is to implement a work logic that is notably compatible with the main actors of the project, the students, their calendar rhythm, their skills...

In this sense, in terms of Program management, a hybrid combination and contextualized application of Design Thinking, Lean Startup and Agile (DTLSA) approaches could constitute an appropriate response to the atypicality of the PERSEUS project. It is a long term process as far as its implementation is concerned.

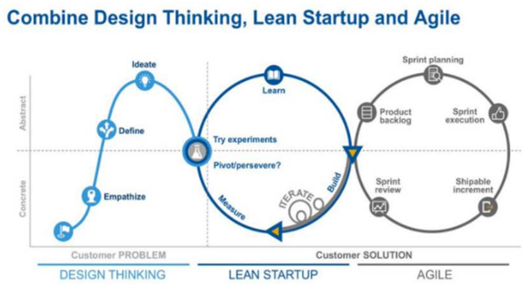


Figure 8: DTLSA

A relevance

The classical V approach to development is not totally adapted to PERSEUS. PERSEUS presents particularities that make the adapted and complementary application of DTLSA approaches relevant; PERSEUS Program carries large specificities which call for this kind of adapted Program management methodology:

- Project driven by the student schedule and costs, more than by technical excellence because the activities focus on the development of experimental demonstrators
- Student activities: the rhythm of the activities is mainly based on the school year and the students' willingness/availability
- Technical expression of the needs is multiform during the project
- No definitive specifications but an evolving specification linked to the demonstrations to be implemented
- Willingness to start test/learn/improve cycles very quickly
- No extreme optimization of the product but an objective of gaining experience to cover a wide spectrum of functionalities and technological bricks
- Application of products and evaluation of solutions to major challenges
- Rapid and low-cost development for demonstrators
- Ambitious goals that call for new solutions and innovative technologies
- Continuously adapt the work plan with proper risk management to match the final demonstration objective.

A theoretical basis

In the ideation phase, Design Thinking brings to light the needs not satisfied by existing solutions. Design Thinking generates an idea and hypotheses. Lean Startup validates and adjusts the proposed solutions, while the Agile frameworks (Scrum, Kanban ...) materialize them technically. The Icescrum tool is used within PERSEUS as well as Program Increments milestones The so-called "SAFE" variation of Agile approaches has been practiced for some time in our immediate environment and is adapted to our engineering culture. As mentioned in the introduction, the Space Transportation Directorate's desire is to instigate and participate in new organizational modes to prepare for future launchers. It is this basis that is used to define the PERSEUS project framework that allows the organization to turn towards action. Indeed, it seems essential to us through Perseus, as a platform of innovations, to make students aware of the innovative project management methods present today in the industrial world. The complementarity of the approaches favors innovation in its entirety, throughout the project.

A running-in period

The implementation will take place throughout the year, in line with the rhythms and constraints of the student world, which will not prevent us from continuing to adapt these approaches in a continuous improvement process.

These three approaches are therefore implemented within the PERSEUS project in order to bring adapted, relevant and innovative answers to the problems and challenges inherent to the demonstrators to be implemented, by prototyping and testing MVPs or POCs rapidly (which by the way answers to the need expressed by the students to be able to achieve concrete but ambitious experiences at the end of the school year), through an iterative Agile development (Scrum, Kanban...), to test the ideas resulting from Design Thinking, validate the concepts retained and thus progress towards the challenge of reuse and eco-design.

5. Conclusion

Space remains an immense field of scientific exploration and this is all the more marked today when the current period is conducive to a new boom, driven by scientific, strategic and economic ambitions. In this constantly evolving environment, the ambition of the PERSEUS program team of the CNES Space Transportation Directorate, together with the supervisors and volunteers, actors such as ArianeGroup, SMEs and start-ups, is to encourage this bubbling up by placing the world of students and research at the heart of the process and activity in order to prepare the future of European space transportation, the next generation or generations of launchers. For Preparing the future also means encouraging students to embrace careers in space, making them actors of the adventure and dream of space by

- encouraging the proliferation and exchange of new ideas from the fertile ground of the academic world on all components of space transportation beyond launch systems
- stimulating innovation, co-creation and development of breakthrough solutions or technologies that encourage experimentation
- imagining new concepts for space transportation systems, including environmental and climate considerations
- and thus giving the keys to a better understanding of the professions and the challenges of space, while facilitating an entrepreneurial impetus

Carried by the experiments implemented and the demonstrators developed since 2005, PERSEUS program is moving forward towards the challenge of the bi-liquid and the reuse through the ASTREOS and DREAM-ON vehicle families. Through these ambitious projects, CNES and PERSEUS wish to prepare students to bring an answer to the major stakes of the 21st century, so that they can be key actors of change to reinvent the space of tomorrow

Acknowledgements

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We would also like to acknowledge thank the CNES and all of the employees of the CNES who work hard to support the PERSEUS Program we would like to thank them all for the financial, legal, technical and advise support.
New Horizons, New Opportunities, New Spaces: Space central to the big challenges of the next decade!

For more information, please visit : www.perseusproject.com

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Acronyms

3P : Plateau Projet PERSEUS
APTERROS : Advanced Propulsion TEchnology for Reusable Rocket and Operating System
ARES : Advanced Rocket for Experimental Studies
ASTREOS: Ares Supersonic for Technologic Researches in Ethanol-Oxygen System
DREAM-ON: Disruptive Reusable Experimental Advanced Methane Oxygen Nanolauncher
GNC: Guidance Navigation Control
MINERVA : Moteur INnovant Experimental pour les Recherches sur les Véhicules Aérospatiaux
MLE : Minerva LOX Ethanol
PERSEUS : Projet Etudiant de Recherche Spatiale Européen Universitaire et Scientifique
POC : Proof of Concept
PPO : Proximal Policy Optimization
ROAR : Reusable Oxygen ethAnol/methAne Rocket
SERA : Supersonic European Rocket ARES
RSS : Release and Separation System (DSL in French)
TVC: Thrust Vectoring Control
VTVL: Vertical take-Off Vertical Landing