The 5th element: Modular ground support equipment to new PERSEUS bi-liquid launcher

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Abstract

The ground elements of a space launch system comprise various mechanical, electrical, fluid and IT equipment, required to move, maintain and guide the launch vehicle, to supply it (whether with fuel, energy or utility fluids), to monitor and control operations during the launch campaign and to provide safeguard functions ensuring safety of goods and persons. This paper recalls PERSEUS objectives and how they apply to the Ground Segment: it is set to grow in importance with the advent of ASTREOS liquid-propelled rockets in the medium term and recovery aspects addressed by DREAM ON challenge in the longer term. The main components are described, with their development axes, current status and perspectives.

1. Introduction: ground segment in PERSEUS

The ground segment is the whole set of infrastructure and installations allowing the launcher to be ready to operate (transfer, installation on the table or launch pad, connections, fluid management, etc.) and to function properly until lift-off. It is essential to the launch and to the launch campaign in general, and can therefore be considered the “stage 0” of the rocket.
The current trend in space systems, and more particularly for the space launch systems of interest here, is towards modularity (and use of standards) to adapt to multiple interactions, lower costs, and increase flexibility and resilience. PERSEUS follows this trend, with emphasis on low cost and adaptability of system designs, in addition to a strong involvement of students in developments and demonstrations phases.

PERSEUS is a CNES project aiming at the realization of innovative launcher demonstrator by involving the student world in the achievements. The project is indeed in partnership with dozens of student associations spread throughout France but also with schools and universities. The objective is thus to be able to give exploratory studies or development bricks to the students while training them in the space trades.
The project has a strong vocation to achieve numerous launches and rapid innovations from one generation to another, so the last launch of the SERA 4 rocket with powder propulsion will take place in 2022 and the new generation of ASTREOS launcher with liquid propulsion will take place within 2 years. The objective is the incremental logic in agile method, so each new launch will allow the development of a new launcher and bring continuous improvement.
In this development logic, the PERSEUS project aims at the challenge of reusing a first stage of a demonstrator representative of a mini-launcher. This goal is called DREAM ON (Disruptive Reusable Experimental Advanced Methane Oxygen Nanolancher).
During the next 2 years the PERSEUS project will focus on a system-of-interest called ASTREOS, which is a demonstrator for a recoverable first stage, with its associated ground segment. This new demonstrator requires a larger part of ground equipment than previous ones, whose iterative development is planned in parallel of the successive versions of its flight segment.
Because of the bi-liquid propulsion which will be used for the first time on PERSEUS by ASTREOS, fluid ground equipment has been designed with the help of our partner Ariane Group using the expertise of Vernon site. Previous PERSEUS launch campaigns have used either a launch rail of Swedish Space Corporation available at ESRANGE or the initial PERSEUS launch rail only used in France. Today, the PERSEUS launch rail is only used for C’SPACE campaign and student experimental rockets. Neither SSC launch rail nor PERSEUS launch rail is compatible with the upcoming ASTREOS demonstrators due to fluid and size requirements.

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According to the PERSEUS project road map, ground support equipment will become an important part of the development compared to the previous solid propulsion launcher demonstrators.

2. Breakdown of PERSEUS Ground Segment Equipment

The ground segment developed under the PERSEUS program is fully modular and adaptable; the plan from ASTREOS-1 demonstrator to DREAM-ON is to launch at least one launcher per year and to include the possibility of launching from different locations. PERSEUS needs to be modular, versatile and mobile so that it can be launched from anywhere with a minimum of changes and constraints. Currently, the minimum requirement for launching a bi-liquid demonstrator such as ASTREOS is to have a location with a concrete slab that accepts the mass and size of our mobile launch rail, sufficient electrical power and buildings to comply with the ATEX environment rules and to carry out the assembly of ASTREOS rocket.

2.1 Mission requirements and life cycle phases

The minimum mission profile required for the PERSEUS ground segment includes the following 8 phases:

- Transport: due to the multiple vehicles to launch and the diversity of launch bases used, the first step is a transport phase. There are different location in France for all the equipment, the 3P office in the centre of Paris and a testing area and storage in Normandy within the Ariane Group site.

- Storage: storage needs to be anticipated because it is the longest life phase for all ground segment equipment, there are different kinds of storage (waiting for the launch campaign, waiting in the launch area, waiting to return to France). For the PERSEUS ground segment the most important is to anticipate the MOC (Maintenance in Operational Condition).

- Distribution: distribution is the first mission of all ground segment, here the support is electrical and fluid (Ethanol, Nitrogen and Liquid Oxygen for ASTREOS-1).

- Integration and check of the vehicle in the launch preparation building: once the ground segment is assembled and ready for the launch sequence, all the integration and checks on the rocket can be carried out in an assembly building. The ground segment assists the avionics and propulsion/launcher teams during the last check and procedure before closing the rocket. As it will be further developed, the assembly of the rocket is realized directly on the kart vehicle.

- Preparation before the launch: During this step the launcher is transported to the launch area and connected to the launch pad rail. All the connections (mechanical, electrical and fluid) are made. The entire launch area is evacuated at the end of this phase before the launcher is erected by the ramp. This phase ends with the filling of the ASTREOS embedded tanks.

- Safety monitoring: When the launcher is up-right on the launch rail and during flight, the ground segment is responsible for the safety of the entire launcher and the installation. It requires a real time surveillance of the launcher, the ground segment and all the interfaces.

- Launch sequence: The launcher must be guided during the launch sequence to maintain the right flight angle until it leaves the rail.

- Mission support: Surveillance, flight analysis after the launch.

Many other features are already identified for the recovery of the rocket family following ASTREOS, named DREAM ON. The ground segment to be deployed for this demonstrator will depend on the kind of recovery (VTVL–Vertical Take-off Vertical Landing- or Smartcatcher), and the goal will be to return the demonstrator into a safe mode.

2.2 Main products of ASTREOS ground segment

To ensure a quality of service for the launcher with minimum adaptation time, the ground segment has been developed with a committed modularity. The ground segment has been divided into 5 main products to meet the minimum requirements of the mission profile:

- A mobile launch rail
- A transport and connection vehicle
- A ground station:
    - Ground station and control bench of the ground equipment
    - A monitoring ground station with TM/TC (telemetry/tele command) with the vehicle
- A fluid ground support equipment
- A flight safety support

2.3 Distribution of ground segment systems at the launch base

Whether the launch takes place from the ESRANGE site in Sweden or the CSG site in French Guiana, the ground segment in the operational context of the launch will be physically spread over 4 distinct areas:

- Firing Point Area
- Church Assembly Hall
- Launch control bunker
- Scientific Room

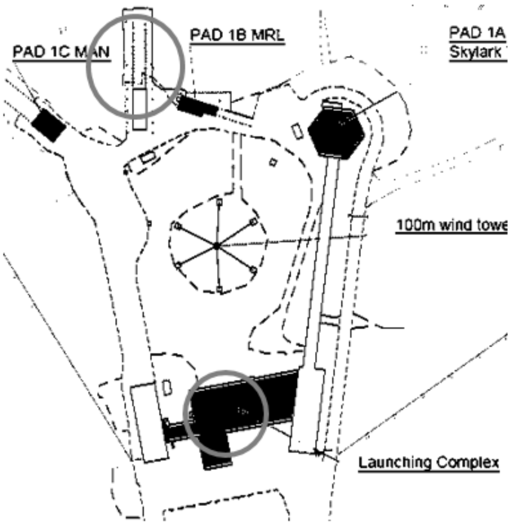

Figure 1: Example of ground segment installation at SSC ESRANGE site

On figure 1, the grey circle at the top indicates the firing point chosen for ASTREOS-1 on the ESRANGE site: it is the ESRANGE Man 2 in which the launch ramp and support facilities will be installed (fluid system, camera, ground station, network circuit ...). The diagram below on figure 2 represents the layout of the firing point. We find the ramp and the fluid supply tanks arranged in a star shape (with a minimum distance of 10m between each to be confirmed, for safety reasons).
The second grey circle at the bottom of figure 1 indicates the assembly shed «Church» in which the launcher will be integrated and assembled before moving to the firing point via the transport and connection kart.

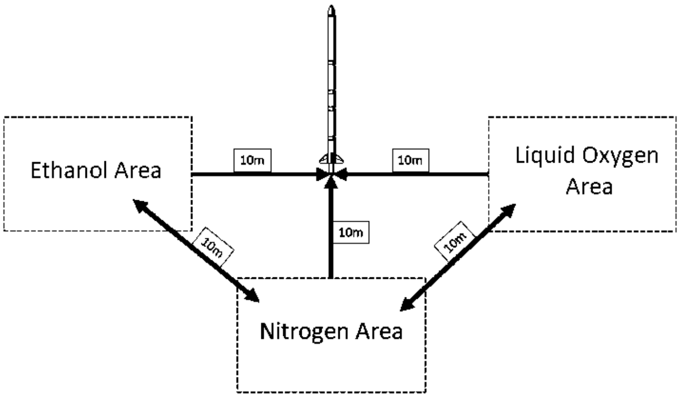

Figure 2: Layout of the firing point

The control bench and ground station equipment needed to operate the firing point for the GO at launch, both the control bench and the ground station equipment are needed and will be inside the bunker.
Finally, the last physical place is the Scientific Room and the TV Room, visible on figure 3, which stands for the PERSEUS mission room. The ground station redirects data and video streams in this room to display on screens ground segment information, operations flow and flight monitoring.

Figure 3: Scientific Room and the TV Room at SSC ESRANGE site

At first the mobile launch rail is necessary for ASTREOS because it's not a propulsion guided rocket so it needs to be guided by a rail in order to have an aerodynamic stability. A second product of the ground segment derived from the first is the kart vehicle that is a multi-purpose product with different functions. Together these 2 products allow to assemble, transport, connect to the rail and launch the rocket.

3. Mobile launch rail

The launch rail assembly developed in the PERSEUS project is a mobile rail. It has to be compatible with SSC or Guyana space facilities. It is mobile as it can be installed and uninstalled where the future demonstrator will be launched. This launch rail product will be set-up and tested at the Ariane group site with a PERSEUS testing area.
With a ground footprint of 15m in horizontal position, the boom of the launch ramp is 14m to allow a guidance of 12m of the demonstrator, visible on figure 4.

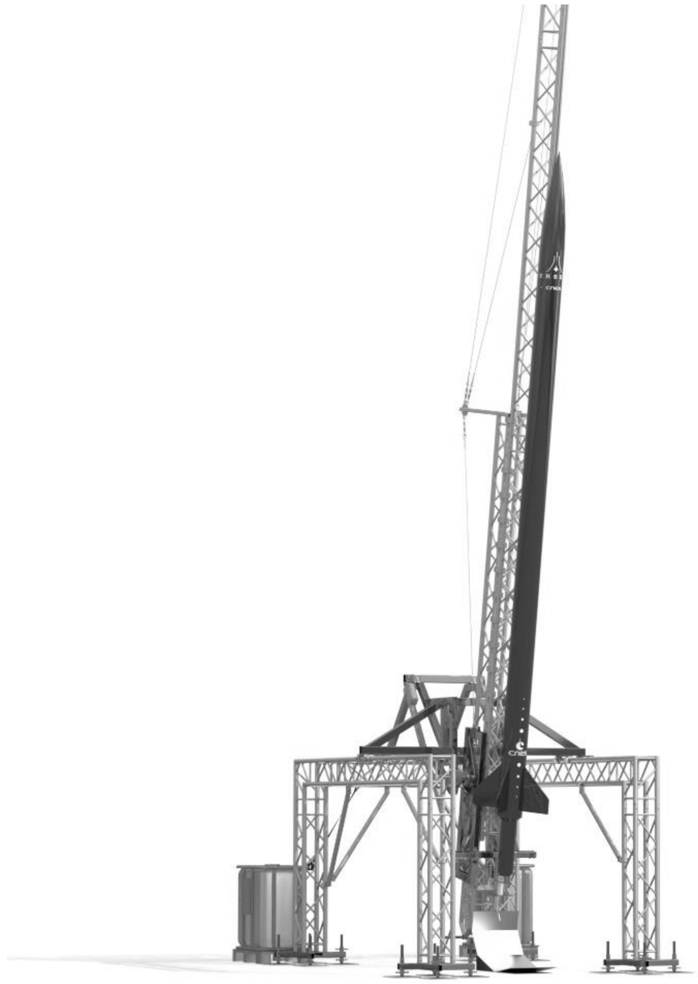

Figure 4: View of the mobile launch rail oriented at a 80° flight angle.

The objectives of the launch pad are to:

- Connect ASTREOS to the guide rail
- Support the rocket during the up-righting of the rail
- Up-right the rail at the desired angle
- Guide the launcher during take-off to the requested angle of flight
- Isolate the cryogenic tank from the launcher
- Host ground electrical equipment

During the installation the mobile launch rail is oriented to the correct ground azimuth targeted for the flight. This angle can hardly be adjusted then without uninstalling some part the launch ramp.
At the current state of development, the launcher requires a minimum guidance of 12m to exit the ramp with enough aerodynamic stability. The launcher will be connected to the rail via the kart, as seen previously, and custom guide pieces. It is also at this stage that the launcher will be connected to its electric and fluid umbilical.
All subsequent steps will then be fully automated by the control bench without the presence of any operators in the vicinity of the launch area. The first step consists to put in vertical position the launch pad, to bring the ASTREOS demonstrator to its angle of fire. To do so, the ramp uses industrial electric type cylinders, the set provides a thrust of up to 2t. As we put the launcher in vertical position, another by-product will be used to help the launcher to support the mechanical loads during this dynamic phase. This product is actually in development phase and will be placed directly on the launch rail. Once vertical, the tank filling steps will follow.
The launch rail can be mounted and ready to launch in 2 to 3 days, it requires to know before the azimuth of the launch.

The launch pad is currently being installed in the PERSEUS test area at Ariane Group Vernon. Lifting operations were carried out to install the pivot structure, which was custom-made. The boom of the ramp is expected in integration for the summer of 2022 and the integration of electric cylinders for the end of the year. The ramp testing campaign could begin by the end of 2022, allowing the combined tests to be carried out as soon as possible by the launcher system.

4. Vehicle of transport and connection to the rail

Named as the kart, this vehicle has different functions:

- Transport the rocket (whether in parts or full integrated)
- Support the assembly of the rocket
- Connect to the rail

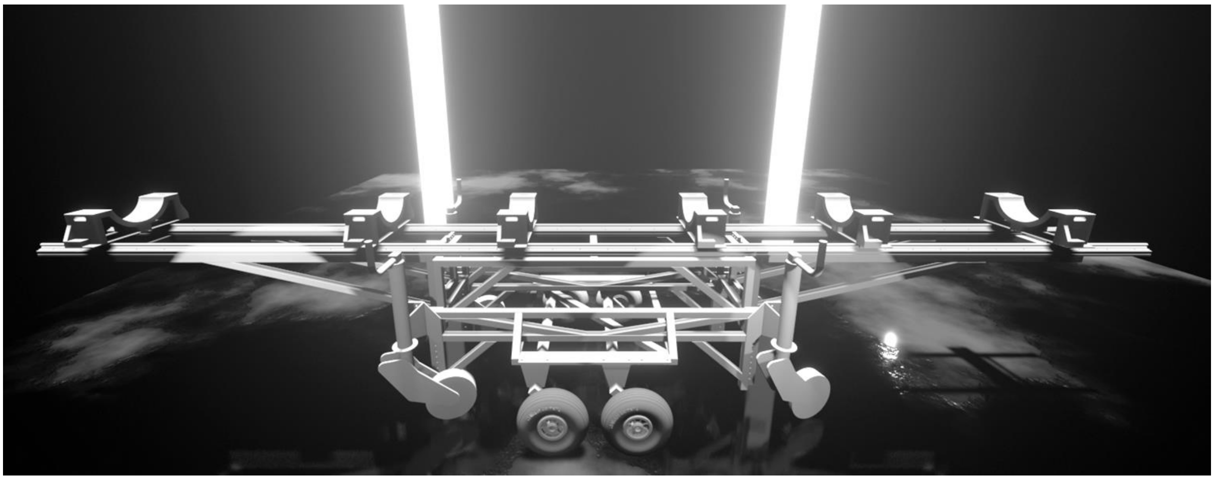

Figure 5: View of kart system for ASTREOS:
6 supports cradles (2 by launcher stage), 4 jockey wheels and 2 car axles

The layout of the chassis for the kart system is visible on figure 5: for the launcher assembly, cradles are present on the straight guide rail serving as an assembly rail. This is the added value of this system, which consists in attaching the starter's assembly bench directly to the kart, which makes it possible to have a versatile system that will be used for both transport and assembly. The transition between the rocket closing and moving sequences will take place directly on the kart. We thus find the same behaviour of assembly bench as for SERA 4.

The kart is an assembly bench mounted on wheels, with a couple of support cradles on each part. This support allows to move and connect the different stages of the ASTREOS demonstrator during the preparation. On this step the vehicle is used to support the launcher assembly, it allows to have the launcher directly ready to be transported on the kart and with the right configuration (horizontal position and the rail interface connector on the top of the launcher). The second way of using of the kart is the transport to the launch pad, only the 4 central wheels are used. It is based on a trailer design, the 4 industrial jockey wheels are not used during this phase. The jockey wheels are placed on the high position before rolling out the launcher by using the crank casement of each wheels.

When the vehicle arrives, the four jockey wheels are deployed and lift the vehicle up, the 4 conventional wheels in the centre then no longer touch the ground. The position of ASTREOS on the launch rail is achieved by means of the jockey wheels, which are free to move in all directions. The launcher is guided with an X and Y direction to be aligned and linked. The modularity of this vehicle lies in the possibility to have different rocket diameter of the ASTREOS family, only the support cradle will have to be changed; from now on 3D printing is used to manufacture the support at the correct diameter.

This version of the kart design is a second version, improved by our agile method and prototyping; indeed a first version was imagined and its prototyping achieved with wood in a FabLab (fabrication laboratory) – ElectroLab at Nanterre near Paris. An analysis and feedback on the prototype led to this second version.

5. Fluid Ground Support Equipment

5.1 General overview

The fluid system is an essential component of ground systems since it allows to store propellants and deliver them to the launcher (these new functions lead to the need for a new specific PERSEUS ground segment). It must allow the ground station control bench to manage and control fluid operations. The fluid system has to be compatible with the launcher interface, which derives from the design of the tanks and the power supply within the rocket. It is therefore designed in close collaboration with the launcher and propulsion system teams as well as with the Ariane Group Vernon team.

The fluid ground support equipment is based on the use of 3 different propellants and can be broken down into 3 filling subsystems and 1 ignition subsystem:

- Nitrogen Tank System (pressurization fluid)
- Ethanol Tank System
- LOx Tank System
- Ignition system

The ground fluid system is currently designed taking as a constraint the need to fill to its full capacity the ASTREOS-1 rocket. The system is intentionally modular to be compatible with future designs.
The ASTREOS tanks have a storage capacity of 47L. In order to ensure the filling of the latter, the ground storage tanks will have a larger storage capacity. Indeed, the system will have to test the filling lines to ensure their proper preparation by performing a filling test, then the launch requires to fill the embedded tanks completely. In case of launch abortion, after emptying the on-board tanks, another filling is mandatory for another launch attempt.

The ground fluid system has been developed to allow the fluid supply of the ASTREOS-1 launcher. Design margins were taken to easily evolve from ASTREOS-1 to ASTREOS-X and DREAM ON without a complete redesign of the ground fluid system. The minimum design margin corresponds to the filling of 3 ASTREOS embedded tanks. Given that the ASTREOS-1 tanks will only be 30% filled, this leads to a volume margin of 9 fills in ASTREOS-1 to compensate for aborted launches.

The essential components of the fluid system are divided into four sub-systems:

- Liquid Oxygen Tank
- Ethanol Tank
- Nitrogen Tank
- Ignition System (Propane)

Each tank system includes a set of lines, valves and sensors that will be specific to the fluid being piped.

Details of the fluid subsystems and their functions are detailed below:

- Nitrogen System
    - Filling: High Pressure Nitrogen will be delivered directly to its edge tank, without interaction with other fluids. It must arrive in the embedded tank at a pressure of 240 bar.
    - Sanitation: the sanitation part will be carried out at low pressure, to allow a sweep of all the lines of the system. The purpose of this sweep is to flush out all impurities in the lines to avoid unnecessary interactions while filling with other fluids. This will be the first step in the filling sequence. It will be pressurized at a value slightly higher than the respective load loss of each line (Nitrogen, LOx and Ethanol)
- Ethanol system: this fluid is one of the 2 propellants of the MINERVA bi-liquid engine. It will therefore be piped to its tank after cleaning. It will be at room temperature, in liquid state and will not require any specific equipment
- LOx system: this fluid is the second propellant of MINERVA, and will also be sent to the embedded tanks after sanitation. Since it will be in a liquid state, some specific equipment will have to be defined anticipating the extremely low temperatures required to keep oxygen in this state.

The positioning of the ground tanks on the launch zone will vary according to the launch site. Thus it was chosen to work only with flexible lines connecting mobile filling trays (see 2 examples on figure 6) that will be positioned on the launch area. Some trays such as the ground/launcher connection trays and ASTREOS rocket filling valves will be placed directly on the sides of the launch ramp.

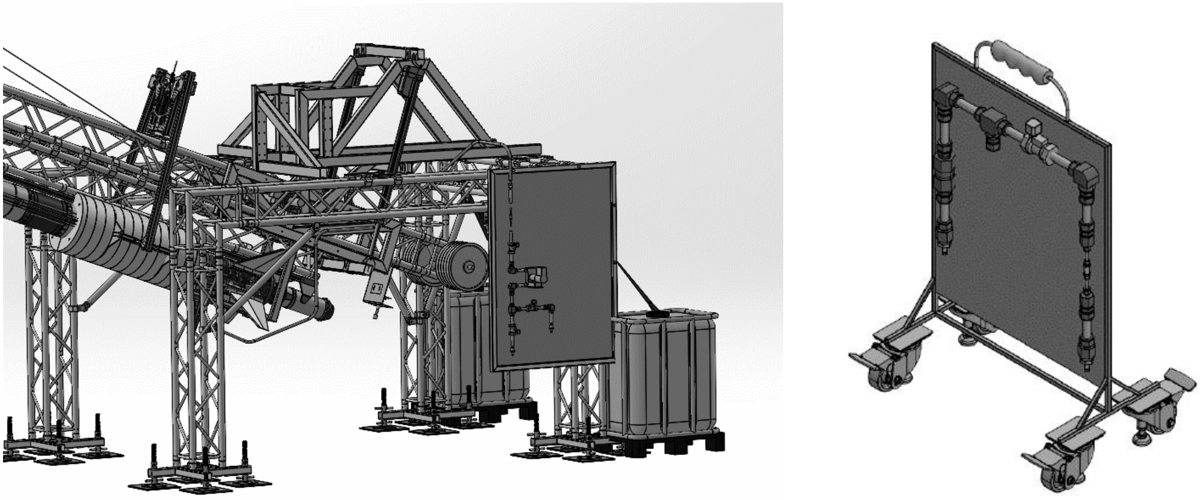

Figure 6: Fluid panel on the mobile launch rail on the left, mobile fluid panel on the right

The fluid ground segment is designed taking into account a filling by Ethanol, which has a voluntarily simplified line: the ground segment's future objective is to switch to Methane, following the various evolutions of the ASTREOS range.

5.2 Cryogenic tank insulation

There has been a focus on the launcher cryogenic tanks insulation because a major part of losses by evaporation occurs in the embedded tank.

To not have to compensate the losses by evaporation, a concept of an insulating box placed by robotic arms has been imagined. These custom-made insulating boxes allow the tank to be insulated without having direct contact with the external wall. In this way the robotic arm can open the caisson just before the launch without being stuck to the external skin of ASTREOS. By moving the box away at the last moment before take-off, the system can be reused while allowing continuous insulation until the moment before T0. A single electrical cylinder will synchronize the opening by symmetry of the two half boxes surrounding the rocket.

Once the launcher is filled and the rail directed to the correct angle of fire, the launch can take place and the launch pad completes its mission.

Simulations ran on the designed insulation system quantifies the boil-off rate as shown on figure 7; on the end, the LOx saving for one filling of 47 L is 1L for 10 min of waiting on the launch pad.

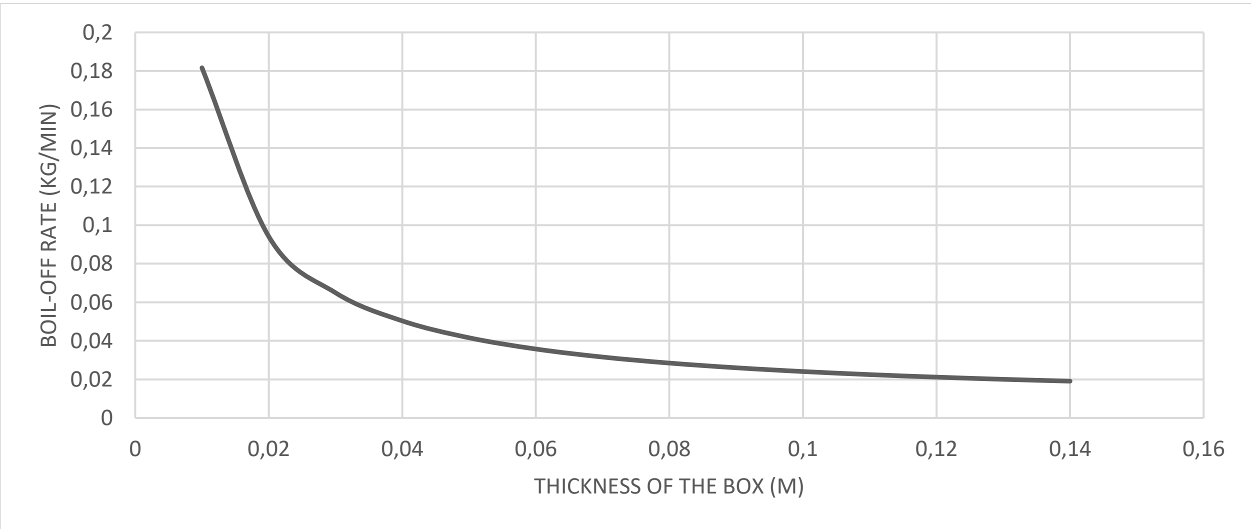

Figure 7: Boil-off rate as a function of the box thickness

6. Ground station and control bench of ground equipment

6.1 SCADA: Supervisory Control and Data Acquisition

The purpose of the control-measure network is to facilitate the communication between each system of the ground segment. It is responsible for recording and distributing measurement and control data. The data will flow between the different areas of the ground segment through the Ethernet network already present or that will be installed by the PERSEUS team.
The ground station systems are used to perform the following general functions:

- Ensure the communication between the different systems of the ground segment (tanks, control bench, man-machine interfaces, edge)
- Manage the vehicle command and surveillance through the ground/vehicle interface
- Manage ground control and process monitoring for vehicle operations
- Ground safety check
- Acquire vehicle telemetry (TM), deliver it in real time (until landing)
- Access operational real time video images
- Synchronize operations
- Visualize in real-time on-board TM and ground information

A «Machine to Machine» (M2M) messaging protocol must be chosen to implement the control-measure network. It is a technology widely used in the Internet of Things (IoT) framework to make several machines communicate with each other on a network. Several protocols exist, and for each protocol, several open-source implementations exist.
One protocol have been identified, it works with systems for sharing data by subscribing to some specific types of data. In its use we find the same concept of «subscriber» and «publisher». The big difference here is that the system is centralized. All data goes to a "Broker" which redistributes it to interested users. Like some other protocols, it can also be associated with an archiving service that records data as it goes along. A dozen open-source dashboards solutions exist and support MQTT (Message Queue Telemetry Transport, see [1]) as a real-time data source.

The network is designed in a hub-and-spoke format, with a MQTT server, called a “broker” because it is in charge of receiving, recording, and distributing messages that circulate on the network.
The operating principle of MQTT is as follows: data exchanged on the MQTT network are called "message", a message can have a size ranging from 1 o to 260 Mo, the data transits in the form of string format. Each machine connected to this network is called "customer", it is connected to the network by connecting to the broker. A machine that creates/publishes messages is called "publisher", a "publisher" generates messages that are sent to the broker to which the machine is connected.
A machine that consumes or reads messages is called "subscriber", it is subscribed to receive data from the broker. A machine publishes or subscribes to “topics”. Each topic corresponds to a data whose value may change. The topics are organized in a tree structure, it is possible to subscribe to all the changes belonging to the same tree structure (For example, the pressure measurements of the LOx tank on the ground will be published and accessible via the path "Ground/tanks/LOx/pressure").
A machine subscribed to a topic will receive all messages sent on that topic as soon as they have been received by the broker.
A machine can be both publisher and subscriber.
A machine can connect to several topics, as will be the case of the monitoring HMI stations.

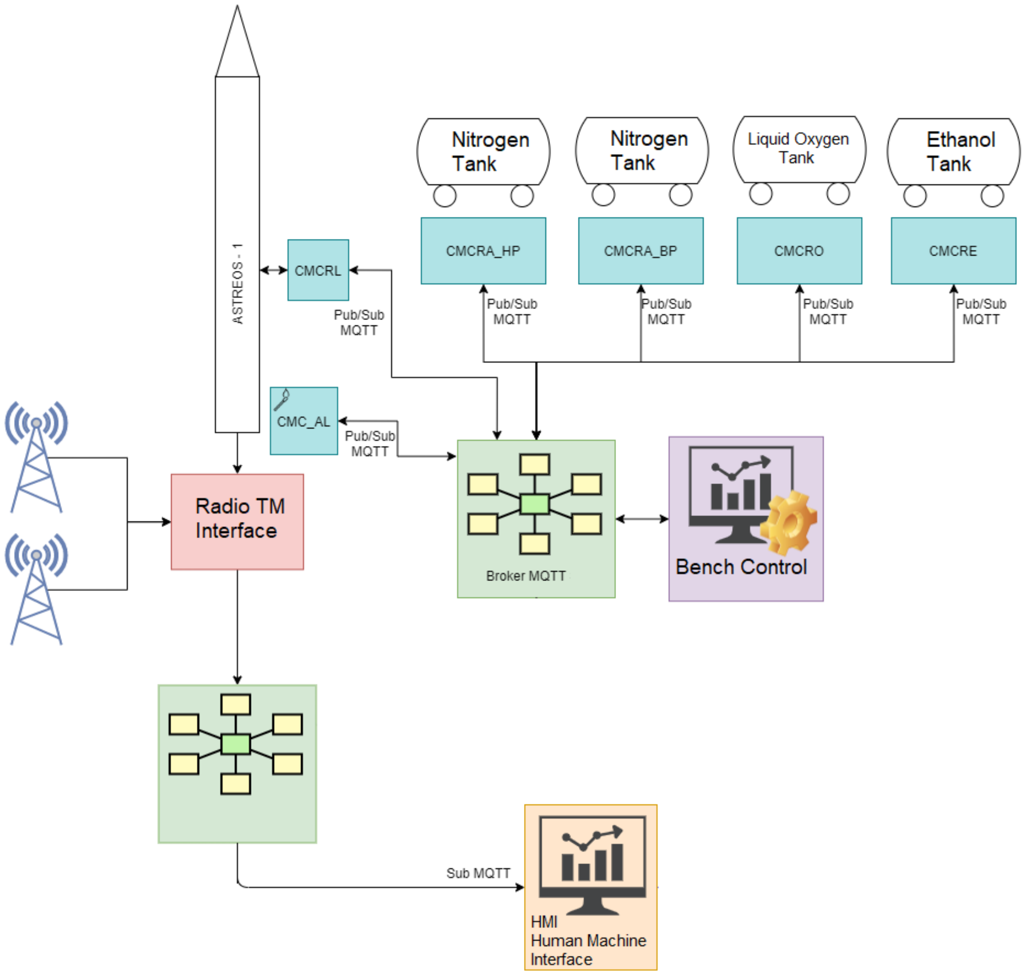

Figure 8: Example of an ASTREOS-1 ground segment with MQTT protocol

The ground segment measurement-control cards communicate exclusively with the broker. The machines used for the control bench or the monitoring of the data collected through HMI (Human-Machine Interface) will connect to the broker as well. The broker's job is to quickly transfer the data to the machines that request it, and to save it on disk in a database at the same time. The broker is also in charge of guaranteeing the origin of control bench orders via secure authentication. Thus a message publication - that can be orders such as the opening of valves and cylinders - can only be done by a machine that has received a certificate of connection recognized by the network, for which the project will be responsible.
Figure 8 sums up an architecture of the ground segment designed for ASTREOS-1 based on MQTT, with cards for measurement-control referred to as "CMCxx".

6.2 Tracking video

The remote control system is based on visual tracking/control based on an AI for image recognition based on the YOLO model (You Only Look Once). Based on the recognition of a rocket in the field of view it will track the launcher during take-off.

In order to improve its recognition accuracy, another technology will be added to allow the most appropriate image processing according to the weather conditions of the moment.
This AI will be linked to a mechatronic interface on stepper motors in order to control the position of the camera.

This system has many constraints specific to the ground segment and its equipment such as power supply requirements limited by the ground segment resources or weather conditions that may prevent the tracking system from working properly.

7. Synthesis and perspectives

Most of the products presented here and currently in short-term development are only the products strictly necessary for mobile launches for ASTREOS. Many other products will be forthcoming following the improvements and evolutions of the ASTREOS launcher or technologies that will be tested.

The topics of the ground segment are becoming more and more concrete, especially on the ramp and the Ethanol segment for which some final solutions are being tested or in realization phase.
Since the ground segment is a topic often little known to the general public and students in particular, the PERSEUS project thus makes it possible to train and involve schools/associations and students on “stage 0” of the ASTREOS demonstrators and future launcher projects.

The future activity of the ground segment on the PERSEUS project is to achieve continuous product improvement based on feedback from field or testing and to prepare to support the future demonstrators. The growing share of the GNC (Guidance Navigation and Control) with projects like Mini-APTERROS, ROAR and the future of ASTREOS called DREAM-ON prefigures a ground recovery of the launcher.
The ground segment is now beginning to prepare to meet these needs, with exploratory studies conducted by university teams. A first study on a robot for securing and neutralizing a reusable launcher is underway by schools (ESIGELEC and TOP AERO association of Sorbonne Universities). The mission of this robot is to secure the launcher with respect to its propellants remaining on board and to return it to safe mode by emptying it. This robot is an example of the developments imagined on the long-term road map of the ground segment. Another example is the future willingness to switch from ethanol to methane, which will bring new ideas and products to our mobile launch area.

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[1] MQTT Version 5.0 OASIS Standard 07 March 2019 : https://docs.oasis-open.org/mqtt/mqtt