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ALTAIR Semi-Reusable Air-Launch System - Current Design and Status of Flight Experiments

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Abstract
The H2020 (Horizon 2020) ALTAIR project (Air Launch space Transportation using an Automated aircraft and an Innovative Rocket) is focused on a cost-effective launch system for small satellites up to 150 kg in SSO (Sun Synchronous Orbit). The ALTAIR vehicle can be described as a semi-reusable air-launch system made of a reusable automated carrier designed specifically for the launch mission and an expendable launcher using hybrid propulsion for the two main stages and monopropellant H_2O_2 liquid propulsion for the upper stages. The 4-year H2020 ALTAIR project, performed by a Consortium of 8 Partners from 6 countries and coordinated by ONERA, aims at demonstrating the economic and technical viability of this concept in order to pave the way for a future available, reliable and competitive European launch service for the access to space of small satellites.
The first part of this paper presents the current design of the ALTAIR system, which is made of three subsystems: the carrier, the launcher and the ground segment. All of these three subsystems have been designed towards the goal of cost-effectiveness, which is achieved jointly through the concept of operations, a cost-oriented design approach for all subsystems and a MDO (multidisciplinary design optimisation) approach. The global design approach as well as the major lessons learned from the design tasks will be presented.
In addition to the design tasks, which make the bulk of the project's technical work, ALTAIR includes flight experiments with the existing flying subscale EOLE demonstrator (developed under ONERA's project management for the CNES PERSEUS project). The objective of the flight experiments is to validate key technologies, including the launcher avionics and its release sequence.
A detailed description of the design task is reported in the first part of the paper. On the other hand, the second part of the paper will be devoted to this flight experiment program, which is the focus of the 4th and last year of the ALTAIR project and is currently underway. The objectives and logic of the flight experiment program will be detailed. Moreover, the current status and first results will be presented.

1 Introduction

Today, there exists an increasing demand for small satellite launch. Indeed, miniaturization and the availability of Commercial Off-the-Shelf (COTS) now enables with small platforms (< 200 kg) satellite applications that used to require larger platforms. Small satellites are considered for a large range of applications (telecommunications, science, etc.) and there exists many small satellites constellation projects (OneWeb, SpaceX, …). Today, there exist launch options for small satellites but all of them have severe constraints:

- Piggy-back launch (launch as a secondary payload).
- Cluster launch (launch of a cluster of small satellites using a heavy launcher).

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Indeed, in the case piggy back launch, the target orbit and the launch date are fixed by the primary payload. In the case of cluster launch, a single small satellite cannot be launched “on demand” unless there is the correct number of small satellite payloads to launch at the same time.
For these reasons, there is a need for a dedicated small satellite launch system that would meet the market needs in terms of cost, reliability and availability without the constraints of existing launch options.
The ALTAIR project, launched in the frame of the European Union’s Horizon 2020 research and innovation programme, is intended to pave the way for a future launch system that could address this need.
ALTAIR is a 4-year project (December 2015 – November 2019). Its total budget is around 4 M€, including a 3.5 M€ from the European Commission and a 0.5 M€ from Switzerland
Its strategic objective is to demonstrate the economic and technical viability of a future available, reliable and competitive European launch service for the access to space (Low-Earth Orbit) of small satellites in the range 50-150 kg.

The ALTAIR Consortium is made of 8 Partners from 6 countries:

- ONERA – The French Aerospace Lab, France (Coordinator)
- Bertin Technologies, France
- GTD Sistemas de Información S.A., Spain
- NAMMO Raufoss SA, Norway
- Piaggio Aerospace, Italy
- CNES, France
- Swiss federal Institute of Technology Zurich (ETHZ), Switzerland
- SpaceTec Partners SPRL (STP), Belgium

The roles and expertise of ALTAIR Partners is detailed in the following table:

Expertise	Partner name	Profile
Aerospace vehicle system study (aircraft, space transportation systems). Specific background in air launch systems, from early system design (Dedalus/L3AR, Aldebaran) to small scale demonstration (EOLE demonstrator). Multidisciplinary Design Optimisation (MDO). Aerodynamics Guidance/control. Interdisciplinary project management.	Office National d’Etudes et Recherches Aérospatiales (ONERA) - France	RTD organisation
Launcher system study, including launch system for small satellites. Launcher technology Market studies, business analysis	Bertin Technologies (Bertin) - France	Industry
Launcher on-board software and avionics. Ground control segment systems for launchers	GTD Sistemas de Información S.A. (GTD) - Spain	Industry
Rocket stage design. Hybrid propulsion.	NAMMO Raufoss SA (NAMMO) - Norway	Industry
Aircraft design, manufacturing, certification and development. Aircraft avionics including Unmanned Air Vehicles. Aircraft payload release system.	Piaggio Aerospace (PAS) - Italy	Industry
Ground segment and ground operations Support to concept development (viability, reorientation). Flight test center for Beyond Visual Line of Sight Flight (CSG)	CNES – France	RTD organisation
Light weight structures, characterisation	ETHZ - Switzerland	RTD organisation
Communication and user uptake / dissemination activities. Market studies	SpaceTec Partners	SME

Table 1: ALTAIR Consortium

2 Altair project presentation and main results

2.1 ALTAIR concept

The ALTAIR system is based on the concept of air launch. The vehicle part of the system is made from two vehicles:

- A reusable unmanned aircraft carrier.
- An expendable 3-stage rocket.

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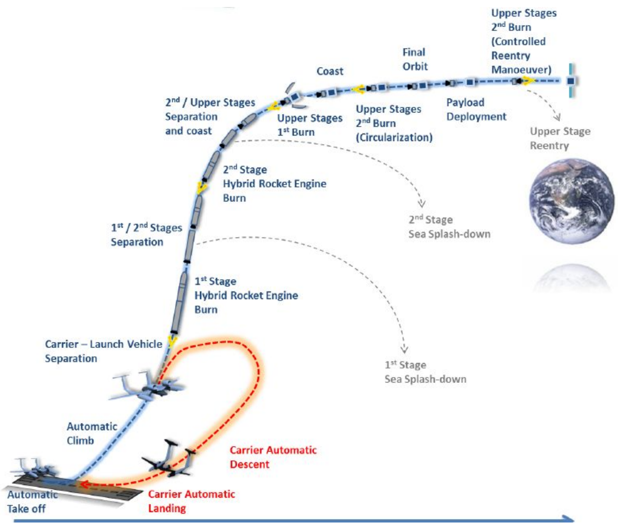

Figure 1: ALTAIR mission profile

The carrier brings and releases the rocket at a given altitude. The starting of the rocket at a high altitude instead of the ground level has two benefits on the rocket performance:

- Reduction of drag losses.
- Reduction of the nozzle losses.

Due to this gain of performance, the air-launched rocket is smaller than the equivalent ground-launch rocket with the same performance.

Figure 2: Artist's view of the ALTAIR system after release of the rocket by the carrier

2.2 Methodology

In a first stage, the ALTAIR work has consisted in defining a preliminary mission definition and high level requirements.
These elements has been continuously evolving throughout the project according to the advances of the design tasks and the updates if the market analysis.

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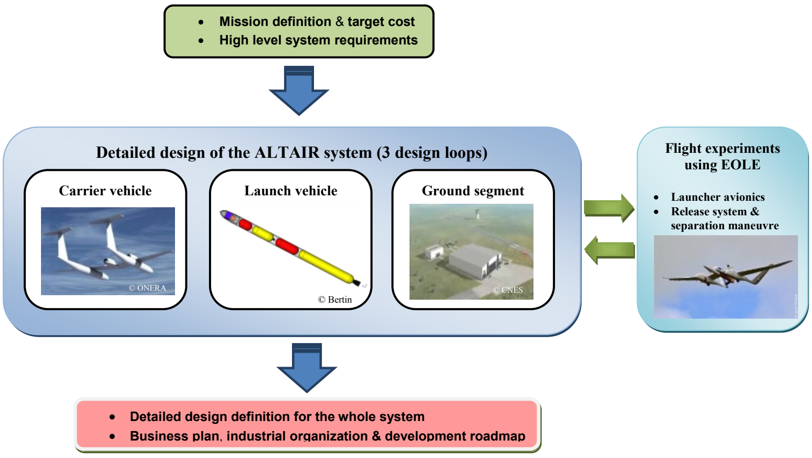

Figure 3: ALTAIR overall approach & methodology

Then, the bulk of the ALTAIR work has consisted in design task (each one being the subject of a given work package):

- The carrier vehicle (WP3)
- The launcher vehicle (WP4)
- The ground segment vehicle (WP5)

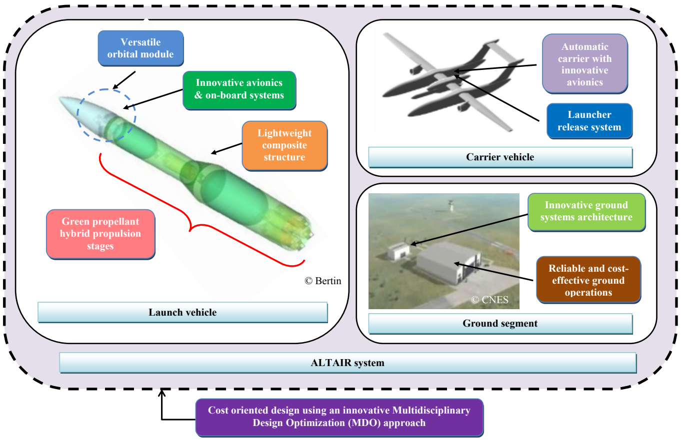

Figure 4: Global view of ALTAIR design work

3 Results

3.1 Target mission and release conditions

The following reference target mission has been defined according to a market analysis (which has been updated throughout the project):

Mission		
Performance	[kg]	150.0
Payload envelop diameter	[m]	1.2
Payload envelop length	[m]	1.5
Type of orbit	-	SSO
Apogee Altitude	[km]	600.0
Perigee Altitude	[km]	600.0
Inclination	[deg]	97.8

Table 2: ALTAIR target mission

The cost target is 5 M$/launch, considering a launch rate of 30 launches / year.
A thorough multidisciplinary study and sensitivity analysis has led to the following release conditions:

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Initial conditions (at separation) of the launcher		
Launch base name	-	CSG
Altitude	km	12.0
Mach	-	0.65
Relative velocity	[m/s]	179.7
Flight Path Angle	[deg]	20.0
Flight azimut	[deg]	-11.5
Latitude	[deg]	5.2
Longitude	[deg]	-55.0

Table 3: Initial release conditions

3.2 Carrier

The following figure illustrates the carrier CONOPS (CONcept of OPerationS):

Figure 5: ALTAIR CONOPS: COP (Carrier Operator) vs. Autonomous Operation

The mass break down of the carrier is the following:

	Weight(t)
Structures	21.05
Power plant	6.30
Systems	4.43
Operative Empty Weight (OEW)	31.78
Fuel (2 h mission+reserve)	6.09
Launcher weight	26.63
Maximum Take-Off Weight (MTOW)	64.50

Table 4: Carrier mass breakdown

Figure 6: View of the carrier with the launcher attached

3.3 Launcher

The launch vehicle has a 3-stage architecture:

- 2 main stages: NAMMO hybrid propulsion (same hybrid motor design: 7 for 1st stage, 1 for 2nd stage).
- Orbital Module (H_2O_2 monopropellant).

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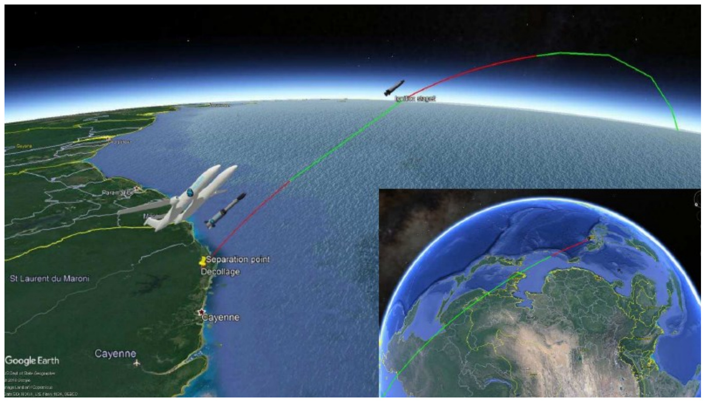

Figure 7: ALTAIR rocket (left) and trajectory (right)

The main mission parameters are provided in Table 5.

General Parameters		
Performance	**[kg]**	**~ 150**
Fairing Mass	[kg]	70
Reference orbit	-	SSO, 600 km
Total Length	[m]	18.40
GLOM	**[t]**	**26.6**
Intermediate Orbit (Stage 2 burnout)	-	-50x600 km
Launch Base	**-**	**CSG (Air Launch)**

Table 5: ALTAIR LV mission general parameters

In addition to the two main hybrid propulsion stages, the launch vehicles includes an Orbital Module (or "upper stage") using monopropellant H2O2.

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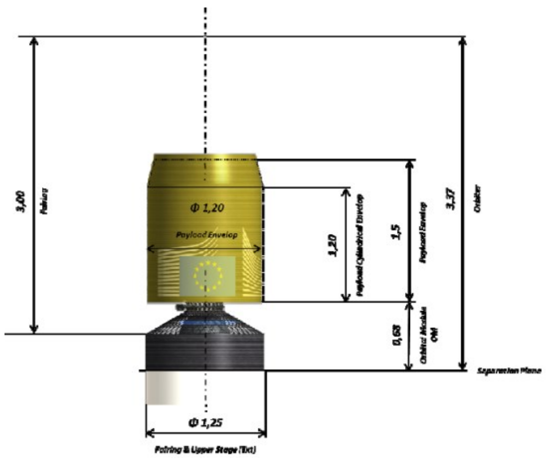

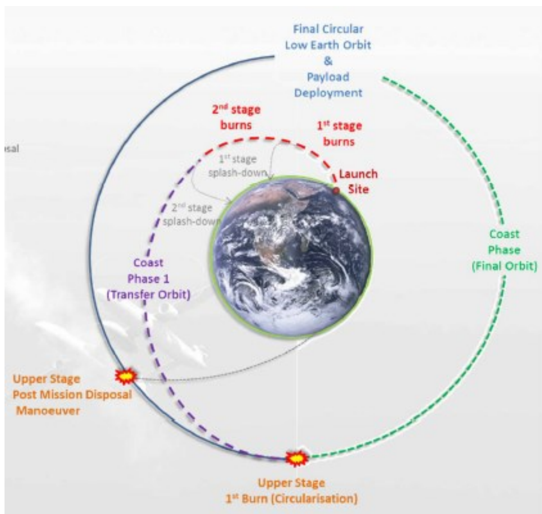

Figure 8: Orbital module (left) and mission profile (right)

3.4 Ground segment

The Ground Segment work has included the following tasks:

- Functional analysis of the ground segment.

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- Detailed specification of the systems.
- Preliminary architecture design.
- Preliminary CONOPS.
- Preliminary cost estimation based on parametric and statistical approaches.

Several possible sites have been studied.
In the end, 2 “best candidates” have been identified:
- Guyana Space Centre (CSG)
- Andoya Space Centre (ASC).

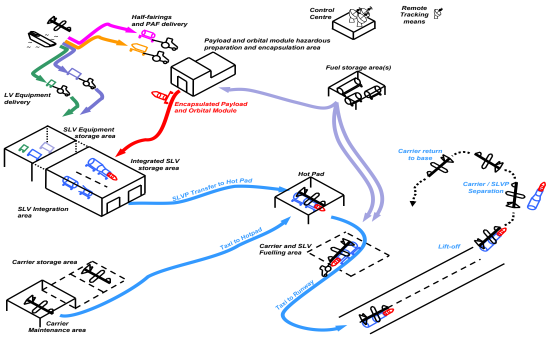

Figure 9: Schematics of the operations

Figure 10: One of the two best candidate sites identified: the Guyana Space Center

4 Flight experiments

In relation with the overall ALTAIR project work plan, flight experiments are considered as complementary means to the design studies. They are used to provide real hardware systems in the loop in order to meet realistic conditions and phenomena.

Those experiments use the already existing flying scale demonstrator EOLE which has been designed and developed by ONERA, under CNES support[1]. EOLE is an experimental flying platform dedicated to study air-launch-to-orbit systems: investigating in realistic conditions the separation phase between the carrier and the launcher, testing various separation procedures and technologies, etc. [1]. EOLE is used as a test bench to immerse in realistic conditions sub-systems tested for the ALTAIR project. EOLE wingspan is 6.7 m and its MTOW (Max take-off weight) is close to 160 kg. It can carry a max payload of 40 kg.

[1] The development program of the flying scale demonstrator EOLE has been funded within the CNES PERSEUS project [2].

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Figure 11: Picture of the flying scale demonstrator EOLE in flight for the PERSEUS Project [1][2]

The flight experiments are focused on two specific topics: test in flight the on-board software designed for the ALTAIR launcher, installed in a mock-up of the ALTAIR launcher, and test in flight the ALTAIR separation phase designed for the ALTAIR carrier, including the release system activation and the launcher release.

4.1 Tests about the launcher on-board software

Concerning the launcher on-board software, the main objectives of the flight tests are to validate its functions in the course of the various mission phases. The flight tests aim to validate and evaluate the algorithms and strategies of the critical ALTAIR launcher avionics sub-systems: navigation and safety. Moreover, those algorithms and strategies cover nominal and non-nominal scenarios focused above all on avionics initialization, separation manoeuvre and release consent procedure.

During the carried phase, the tests will aim to validate in-flight initialization of the launcher on-board system during the separation manoeuvre, which is concerned with the safety impact point and impact area, the release consent procedure and the navigation alignment procedure. During the ballistic flight after release, the tests will aim to assess the release perturbations toward navigation performance and safety ignition consent (dynamic state propagation). Figure 12 illustrates the tests performed about the launcher on-board system and its correspondence toward the main ALTAIR mission phases.

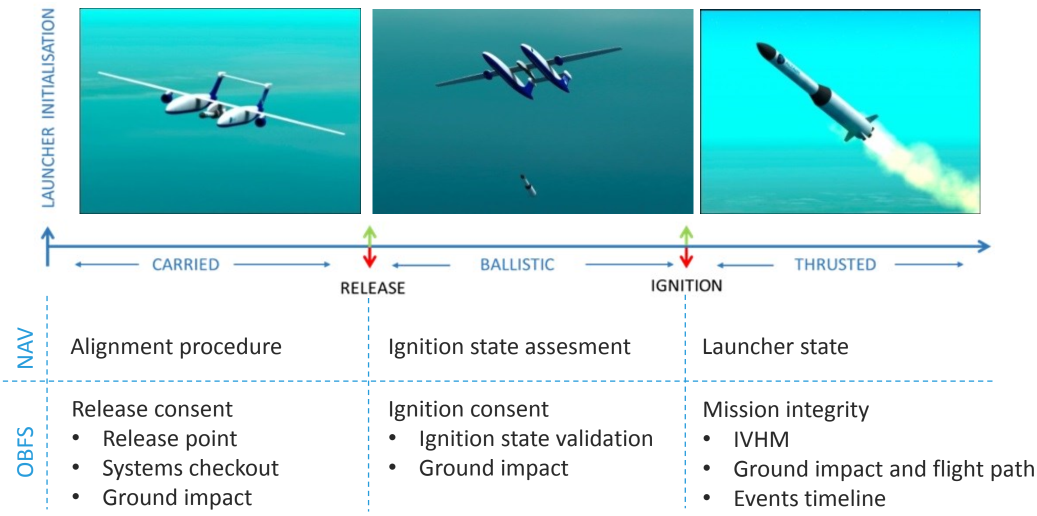

Figure 12: Launcher on-board system tests toward the ALTAIR mission phases

For performing those tests, a dedicated on-board system representative of the one designed for the ALTAIR launcher is mounted in a launcher mock-up. This mock-up is a 1:13 sub-scale of the ALTAIR launcher.

For the experiments purpose, two computers have been developed by GTD. A first computer (Downstream Computer) is installed in the launcher mock-up for collecting flight data and a second computer (Upstream

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Computer) is installed in EOLE for recording all the data. In the launcher mock-up, the computer is fed by an Inertial Measurement Unit (IMU) using Global Positioning System (GPS) hybridization. This computer sends data through a datalink antenna to the computer located in EOLE. This datalink is implemented in order to record the flight data during all the ballistic flight of the launcher, which will then be loss after its release. Figure 13 illustrates the launcher mock-up with its internal layout.

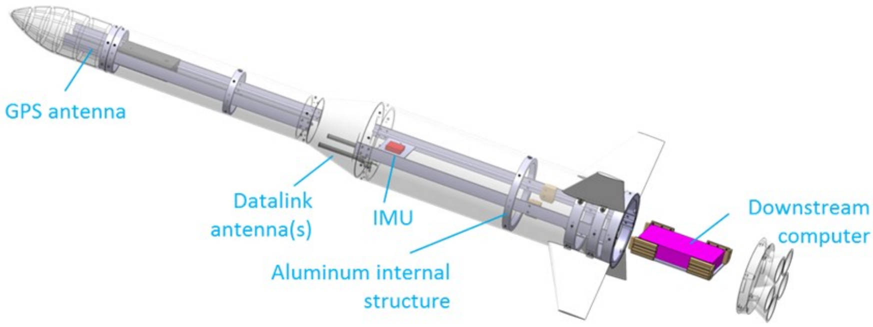

Figure 13: Launcher mock-up CAD and internal layout

This experimental system is used to test the hybrid navigation architecture and algorithms for Global Navigation Satellite System (GNSS) and IMU in captive flight (including the separation manoeuvre) and launcher free flight. Moreover, it is used to test the on-board safety architecture and algorithms for the impact prediction, dynamic propagation and safety decision making strategies for all the launcher flight phases.

Those tests provide safety and navigation real data from trajectories defined to cover nominal and non-nominal scenarios during separation manoeuvre and launcher free flight. The real data are analysed to validate the algorithms against simulated data from avionics simulators in terms of precision and real-time performance, and to further analyse raw data in order to evaluate the architectures and strategies adequacy to ALTAIR system requirements.
The functions implemented in the on-board equipment are:

- The autonomous safety module, implementing:
  - Impact point and area.
  - Attitude propagation.
  - Mission diagnosis.
  - Release consent procedure.
  - Real-time decision making for safety events.

- The navigation module, mainly represented in the algorithms of:
  - Navigation alignment.
  - Hybrid navigation.

The data collected concerns:

- Navigation data provided by the navigation instruments (IMU and GPS): these data is a key contributor to allow the exploitation and analysis through simulation of real trajectories under the configuration of multiple scenarios unable to be executed in flight tests.
- Algorithms data: the data output from the algorithms executed in-flight.
- Equipment status: performance and status data from hardware and software modules for monitoring purpose during flight tests campaigns.
- Test scenario status: parameters and indicators from the test scenario in real-time assessing the appropriate execution.

The objective of the flight experiments, from the launcher avionics point of view, is to test:

- Alignment manoeuvres such as Straight Flight, Coordinated Turn, Thach Weave and Wing Rock.
- Impact assessment on ground:
  - Impact on ground:
    - Isolated: The safety algorithm takes the IMU processed navigation data as an input.
    - Coupled: The safety algorithm takes the on-board navigation data previously aligned.
  - Free fall attitude propagation after release.

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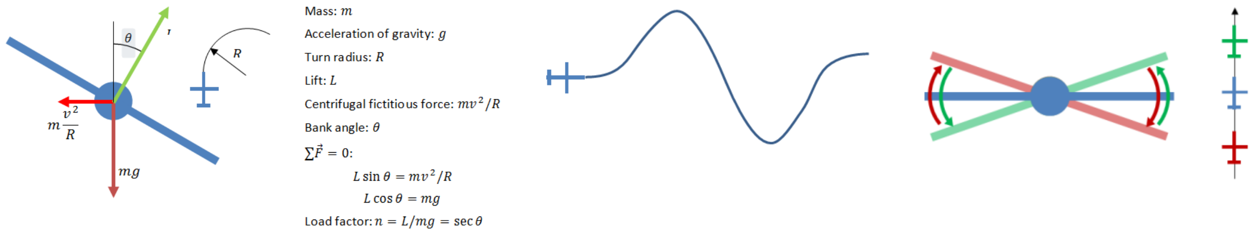
- Degraded scenarios:
  - Malfunctioning GNSS.
  - Malfunctioning IMU.
  - Degraded Navigation data (input for safety assessment).



Coordinated Turn | Thach Weave | Wing Rock

Figure 14: Alignment manoeuvres description

4.2 Tests about the release system

The flight experiments help to validate the ALTAIR release system physical principle based on Hold-Down Release Mechanism (HDRM). In particular, during the flight experiments, the launcher mock-up is released during the execution of the release manoeuvre, which is representative of the manoeuvre selected for the ALTAIR system.

For performing those tests, a release system mock-up representative of the one designed for the ALTAIR carrier has been designed, manufactured and then assembled to EOLE. With such system, the launcher mock-up, equipped with the on-board system described before, can be attached to EOLE and then released.

The release mechanical system has been developed by Piaggio Aerospace and is composed by a central plate and two arms, representing the pylon of the ALTAIR release system. The central plate is used to attach the release system mock-up to EOLE, to house experimental equipment and to attach the two arms where HDRMs are located. As for ALTAIR release system, a couple of two lateral stabilizers are used to laterally stabilize the launcher, which could be subject to lateral forces (e.g. crosswind). The introduction of the lateral stabilizers is mandatory on both scales since HDRMs can only bear axial stresses and not lateral ones.

The release system mock-up is illustrated in Figure 15. The integration of the launcher mock-up is illustrated in Figure 16 and the integration of the release system mock-up with EOLE is illustrated in Figure 17.

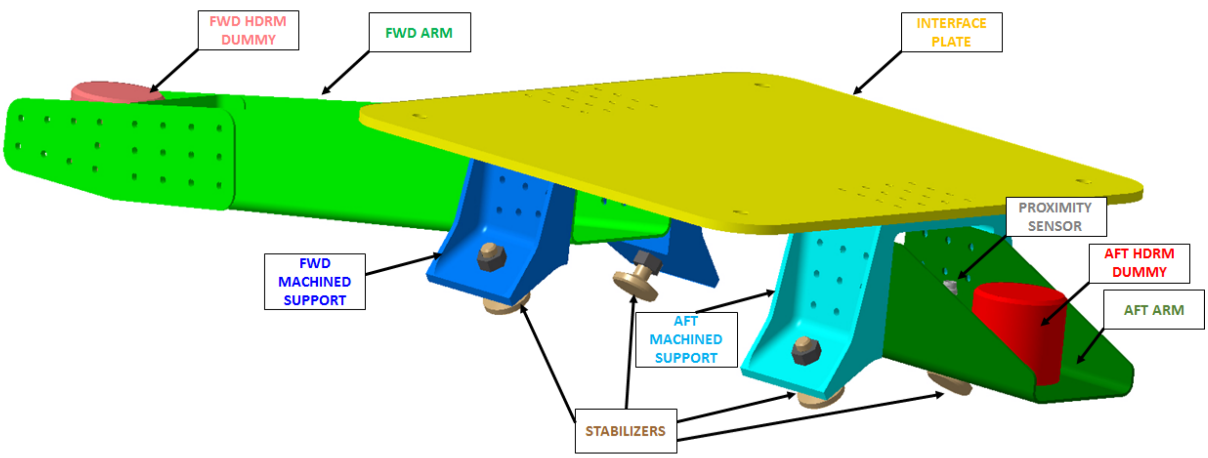


Figure 15: Release system mock-up CAD

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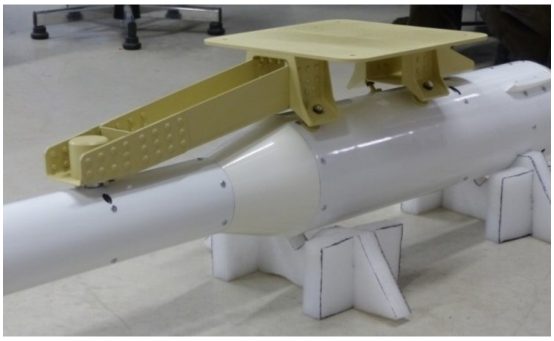

Figure 16: Picture of the launcher mock-up attached to the release system mock-up

The ALTAIR release system is attached to the carrier through four discrete attachment points. The release system mock-up has also to be attached through four attachment points located on an interface plate of EOLE central pod. As for the ALTAIR carrier, the two forward points are linked to the internal wing front spar and the two rear points are linked to the internal wing rear spar, as illustrated in Figure 17. Thus attachment of the release system is similar in both scale, but, due to the presence of the attachment plate in EOLE central pod, the load paths are different.

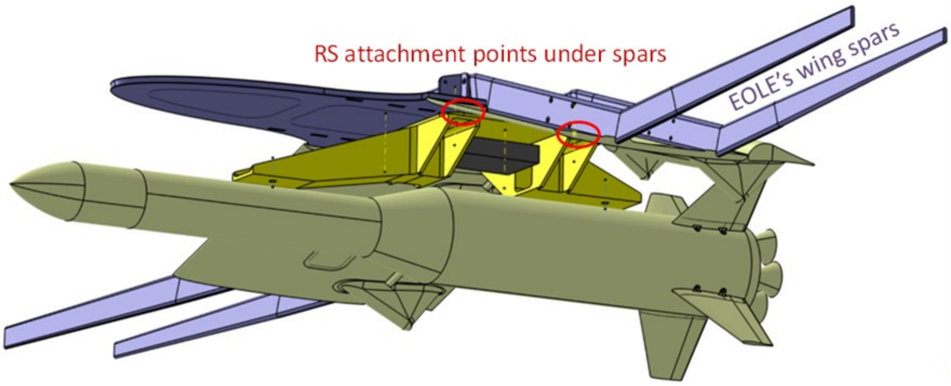

Figure 17: Assembly of the release system mock-up under EOLE central pod

For both ALTAIR and EOLE release systems, the launcher and carrier's Centre of Gravity (CoG) location are at the same longitudinal position in order to avoid or at least to minimize any possible perturbations and destabilization of the carrier due to the release of the launcher.

For the ALTAIR release system, it has been decided to use four HDRMs (two front HDRMs at the same longitudinal position and two rear HDRMs at the same longitudinal position) to have an adequate redundancy and to hold launcher weight. Such redundancy entails additional failure cases to consider for avoiding or at least preventing desynchronization between the HDRMs activation. Thus, a trade-off must be defined between HDRMs redundancy and release system activation reliability. These devices will be specifically developed for the ALTAIR Project, and cannot be commercial off-the-shelf devices due to the high loads to support. For the release system mock-up to be mounted under EOLE carrier, cost reasons led to choose Commercial Off-The-Shelf (COTS) devices. Considering also the loads and the capabilities of available COTS HDRM, together with cost assessment, only 2 attachment points are integrated, one forward and another backward relative to the launcher's CoG.

Contrary to the ALTAIR release system, the mock-up designed for the flight experiments has to house a computer (Upstream Computer) for launcher experimental on-board system data acquisition, as explained in section 4.1. This only generates a difference on the release system installation and not on the release system principle.

As a consequence, the release system mock-up for EOLE is not a simple down-scale model of the ALTAIR's one, but an adaptation of the ALTAIR release system to EOLE demonstrator, by fixing the same separation concept through the use of HDRMs.

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The release order comes from EOLE's autopilot, during the release manoeuver running. These manoeuver is trigged by flight tests team decision after an overall check of the system status, i.e. status of EOLE, release system and launcher. Data required to take decision are gathered through EOLE autopilot then sent to the ground via the downlink, while the decision comes from the ground using the uplink.

The thoughts performed for the release system activation analysis, based on the HDRM technology defined for the ALTAIR system, led to gather important guidelines and requirements. The effective manufacturing and tests of HDRMs devices used as release system actuators and their real operation brought important feedbacks that will help going deeper in the ALTAIR release system and ALTAIR launcher attachment points definition.

4.3 Tests related to the separation phase

The release system activation will be performed during a separation manoeuvre representative of the one designed for the ALTAIR system, as represented in Figure 18. Simulations have been performed in order to define separation manoeuvre control laws, on the basis of the ALTAIR separation manoeuvre, and assess their robustness before activating them in flight. Once implemented in EOLE autopilot, tests in flight provide validation of the physical principle of the release system and the overall separation sequence down selected for the ALTAIR system.

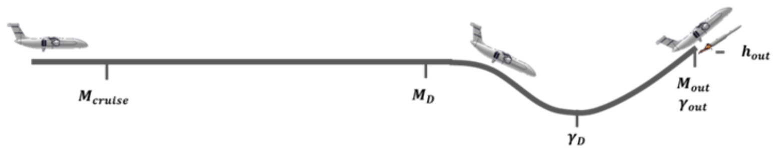

Figure 18: ALTAIR release manoeuver

The flight conditions at the release, for both scales, are described in Table 6.

	ALTAIR system	EOLE experiments
Release altitude: h_{out}	12000 m	1000 m
Release Mach: M_{out}	0.65	0.2
Release flight path angle: γ_{out}	20°	20°
Normal load factor: n_z	1.5 g	1.5 g

Table 6: Release flight conditions for ALTAIR system vs. EOLE experiments

The separation manoeuvre control laws and all the laws for EOLE automatic flights have been developed by ONERA (attitude control law, guidance laws for the separation manoeuver, the launcher on-board system alignment manoeuvers and the ground track following) [3][4][5].

4.4 Flight experiments campaigns

Two main campaigns are planned for the ALTAIR project. A first campaign deals with safety procedure validation (launcher impact point and impact area assessment) and navigation alignment procedure validation with soft trajectories. On account of the small flight area required, those tests take place in the French civilian airfield of Saint-Yan and are performed through Visual Line Of Sight (VLOS) flights at low altitude. The separation manoeuvre is tested in several initial conditions but the launcher mock-up is not released.
The second campaign aims to submit the launcher on-board system to more aggressive trajectories and, at the end, release the launcher mock-up. Higher altitudes and higher speeds are planned, allowing navigation alignment procedure validation with more dynamic trajectories. At the end, the full separation manoeuvre will occur including the release system activation and the launcher ballistic flight. This second campaign will held at the French Guyana Space Centre (CSG) of Kourou.

Both flight tests campaigns are performed with dedicated permit to fly delivered by the French Aviation authority Directorate-General for Civil Aviation (DGAC), specifically delivered for each flight tests centre. The safety management are operated in close collaboration between the flight tests team and the flight tests centres. About this topic, a deep safety management analysis has been performed by the French Guyana Space Centre of Kourou to allow such operations [6].

The Saint-Yan flight area is defined around the Saint-Yan airport. The Saint-Yan airport only allows performing VLOS flights. The flight area limit is 1 km around the pilot and 500 m Above Ground Level (AGL) (750 m above

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mean sea level). For the flight tests, a specific non-permanent restricted flight area is set at Saint-Yan airport and activated at the request of the flight tests team through NOtice To AirMen (NOTAM) broadcasting. Figure 19 shows the flight area defined at Saint-Yan. The experimental program is dedicated to perform the required sequences for the launcher on-board systems through manoeuvres during hippodrome trajectories, the degraded scenarios activation and last with a release manoeuver trial, at a flight altitude of 600 m Above Mean Sea Level (AMSL), without activating the release system but getting through each sequences of the separation manoeuver including the internal tests for the release order sending.

Figure 19: Saint-Yan flight area

The flights tests at Saint-Yan began in July 2018 but could not be completed for technical reasons. After solving them, three successful flights were performed in May 2019 and achieved the planned flight tests program.

Figure 20: EOLE equipped with the ALTAIR experimental systems during the May 2019 Saint-Yan flight tests

The Guyana Space Centre flight area has been defined within a permanent prohibited flight area. This area goes from 0 to 24 500 ft AMSL (7 468 m AMSL) and covers a wide range. Figure 21 represents the ground limit of the permanent prohibited flight area on a Google Maps view.

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Figure 21: Guyana Space Centre permanent prohibited flight area

The low altitude operations (take-off, landing, VLOS flights, etc.) will take place around the Kourou airport, which is inside the permanent prohibited flight area, and the high altitude operations will take place above the sea.

According to the available flight area, the possible manoeuvres can be more dynamic than the ones tested at Saint-Yan. In particular, manoeuvres can be made at higher speed and can also contain several sequences repetitions. This offers the possibility to cover almost all the manoeuvres required.
In addition to the wide available flight area, the Guyana Space Centre offers the possibility to activate the release system during a release manoeuvre and to perform a launcher mock-up ballistic flight. This operation is planned for the last flight. The release manoeuvre begins at around 1000 m AMSL and the maximum altitude reaches 1500 m AMSL at the end of the release manoeuvre. The launcher mock-up has no propulsion on-board. It is naturally stable on every axis and is not controlled after its release. Its ballistic flight will end with the launcher mock-up loss in the sea.
The flights tests at CSG are planned during the autumn of 2019.

5 Conclusion

The ALTAIR project has pushed further the study of the air-launch concept in Europe.
The main outcome of the project is:
- A first deep analysis of a European air-launch system for small satellites
- The demonstration of concept feasibility, with sufficient operation flexibility and low recurring cost (supported by an economic study and a market analysis)

The main identified drawback of the ALTAIR concept is the carrier development cost and the low number of carriers to be built (only 2 for an operational Altair system). Although the current version of the Altair system is credible, some variants/adaptations of the current concept are considered in order to study how these issues could be addressed.
The end of 2019 ALTAIR work will be devoted to final flight test campaign at CSG, including the test of launcher release.

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Glossary

AGL	Above Ground Level
ALTAIR	Air Launch space Transportation using an Automated aircraft and an Innovative Rocket
AMSL	Above Mean Sea Level
BVLOS	Beyond Visual Line Of Sight
CAD	Computer-Aided Design
CoG	Centre of Gravity
CSG	Guyana Space Centre
CONOPS	CONcept of OPerationS
COTS	Commercial Off-The-Shelf
DGAC	Direction Générale de l'Aviation Civile
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
CSG	Guyana Space Centre
HDRM	Hold-Down and Release Mechanism
IMU	Inertial Measurement Unit
LV	Launch Vehicle
MTOW	Maximum Take-Off Weight
NOTAM	Notice to airmen
NAV	Navigation
OBFS	On-Board Flight Safety
OEW	Operative Empty Weight (OEW)
PERSEUS	Projet Etudiant de Recherche Spatiale Européen Universitaire et Scientifique
RS	Release System
VLOS	Visual Line Of Sight

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