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FLIGHT EXPERIMENTS FOR THE ALTAIR SEMI-REUSABLE AIR-LAUNCH SYSTEM WITH THE DEMONSTRATOR EOLE

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Abstract

ONERA and the French space agency CNES, in close collaboration, have been studying innovative air-launch-to-orbit systems for many years. In that frame, they have proposed a two-vehicle concept where an unmanned dedicated carrier releases a launcher at predetermined separation conditions in terms of Mach number, altitude and flight path angle.

Fully related to these studies, ONERA under CNES support, conducted the development of a flying automatic subscale demonstrator, called EOLE, which aims to be an experimental platform for testing various launch conditions and separation technologies. EOLE's main objectives are to investigate the definition and the implementation of the launch separation conditions and to identify the relative behaviours of both vehicles (carrier and launcher) during the separation phase.

From 2018 to 2019, the demonstrator EOLE was used as a flying test bed within the European Horizon 2020 ALTAIR project. The ALTAIR project is focused on a cost-effective launch system for small satellites up to 150 kg in Sun Synchronous Orbit. The ALTAIR system 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 stage. This 4-year project, performed by a consortium of 8 partners from 6 countries and coordinated by ONERA, aimed 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.

In relation to the overall ALTAIR project work plan, flight experiments are included as complementary means to the design studies. They are used to test representative avionics equipments in the loop in order to meet realistic flight conditions. The flight tests are focused on two specific topics: testing the on-board software designed for the ALTAIR launch vehicle, installed aboard a subscale mock-up of the ALTAIR launcher, and testing the separation phase designed for the ALTAIR carrier, including the release system activation and the launcher release. The flight tests involve 4 of the 8 ALTAIR partners: ONERA, CNES, GTD Sistemas de Información S.A. and Piaggio Aerospace.

In the first part, the paper describes the European Horizon 2020 ALTAIR project. Then, it describes the demonstrator EOLE and its development program. Finally, it details the flight tests campaigns performed with the demonstrator EOLE for the ALTAIR project.

Keywords: air-launch system, flight tests, demonstrator

1. ALTAIR European Air-Launch System and Subscale Flight Tests Approach

1.1 European Horizon 2020 ALTAIR Project

As an answer to the increasing market of small satellites (< 200 kg) and the need for Europe to dispose of a launch system fully adapted to this kind of payload, the ALTAIR project was started in December 2015 by a consortium of 8 partners from 6 European countries: ONERA – The French

Aerospace Lab (France) acting as coordinator, CNES (France), GTD Sistemas de Información S.A. (Spain), Bertin Technologies (France), Swiss federal Institute of Technology Zurich (Switzerland), Piaggio Aerospace (Italy), NAMMO Raufoss SA (Norway), and SpaceTec Partners SPRL (Belgium).

ALTAIR is part of the European Horizon 2020 research program and is funded by the European Commission (3.5 M€) and Switzerland (0.5 M€).

The 4-year ALTAIR project aims at demonstrating the economic and technical viability of a future launch system for the access to space (Low-Earth Orbit) of small satellites in the range 50-150 kg. The challenge is both technical and economic, as the system should be not only performant, available and reliable, but also economically competitive. In order to address this challenge, the ALTAIR Consortium proposes an innovative launch system based on the concept of air-launch relying on an automated aircraft carrier designed specifically for the mission, as described in section 1.2.

1.2 ALTAIR European Air-Launch System

The ALTAIR system is based on the concept of air-launch. The vehicle part of the system is made from two vehicles, as illustrated in Figure 1 [1][2]:

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

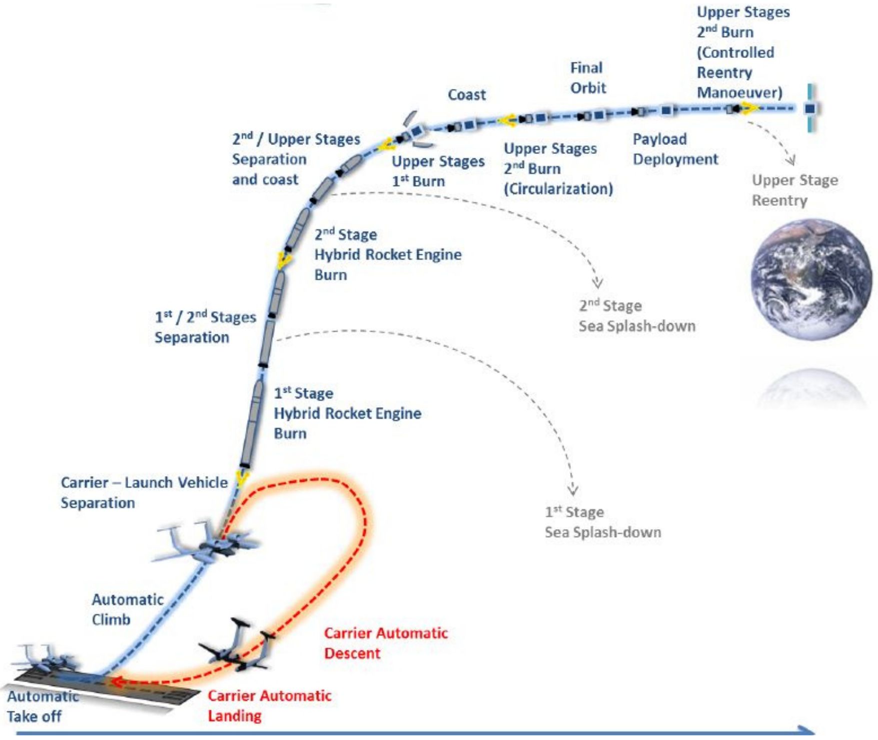

Figure 1 – ALTAIR mission profile. (credit: Bertin Technologies)

The carrier brings 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 nozzle losses.

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

1.2.1 Target Mission and Release Conditions

The following reference target mission has been defined according to a market analysis (which has been updated throughout the ALTAIR project). The cost target is 5 M$ per launch, considering a launch rate of 30 launches per year.

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 1 – ALTAIR target mission.

A multidisciplinary study and sensitivity analysis has led to the following launcher release conditions:

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 2 – ALTAIR launcher release conditions.

1.2.2 ALTAIR Carrier

Figure 2 illustrates the ALTAIR carrier concept of operations.

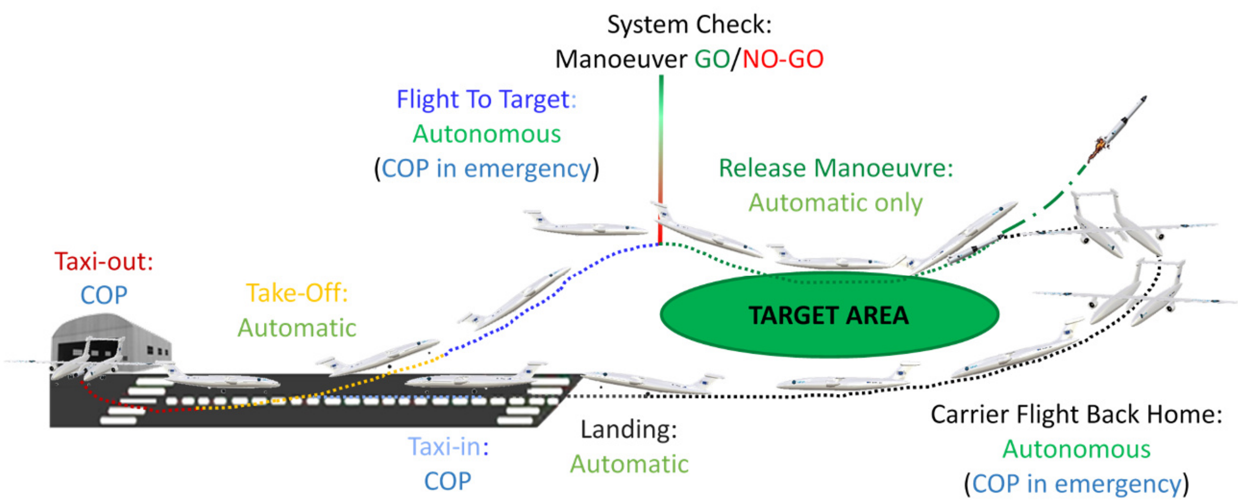

Figure 2 – ALTAIR carrier operations (COP) vs. autonomous operations.
(credit: Piaggio Aerospace)

Figure 3 – ALTAIR carrier with the launcher attached under the central pod.
(credit: Piaggio Aerospace)

The mass breakdown of the carrier is the following:

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

Table 3 – ALTAIR carrier mass breakdown.

1.2.3 ALTAIR Launcher

The ALTAIR launch vehicle has a 3-stage architecture:

- Two main stages: NAMMO hybrid propulsion (same chambers: 7 for stage 1, 1 for stage 2).
- Orbital module (H2O2 monopropellant).

Figure 4 – ALTAIR launch vehicle. (credit: Bertin Technologies)

General Parameters		
Performance	**[kg]**	**148**
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 4 – ALTAIR launch vehicle general mission parameters.

Main flight parameters		
T/W @ Lift-off	-	2.1
Longitudinal maximum acceleration - Stage 1	[g]	8.8
Longitudinal maximum acceleration - Stage 2	[g]	10.1
Transversal maximum acceleration (longitudinal acceleration)	[g] ([g])	0.75 (2.6)
Max Q (kPa)	[kPa]	36.3
Pdyn @ separation 1-2	[kPa]	3.3
Altitude @ separation 1-2	[km]	53.5

Figure 5 – ALTAIR launch vehicle main flight parameters (left) and trajectory (right). (credit: Bertin Technologies)

In addition to the two hybrid propulsion main stages, the ALTAIR launch vehicle includes an orbital module (or "upper stage") using monopropellant H2O2.

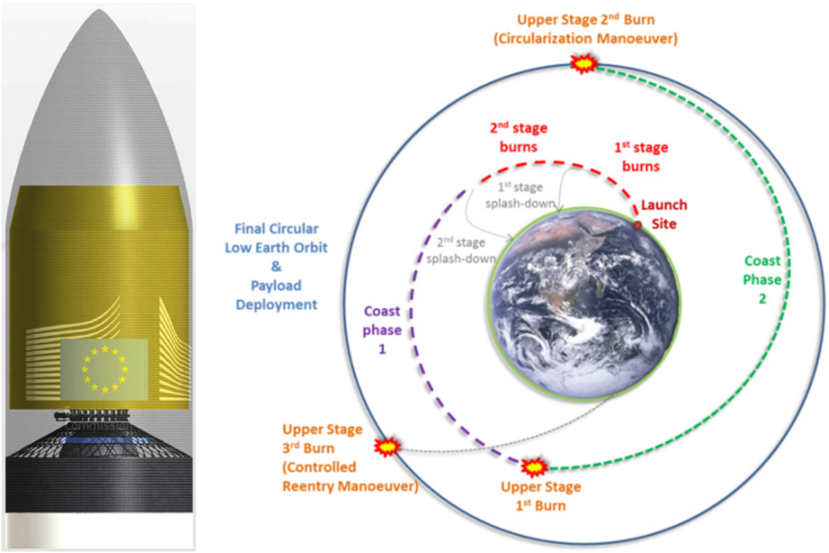

Figure 6 – ALTAIR orbital module (left) and its mission profile (right). (credit Bertin Technologies)

1.2.4 ALTAIR Ground Segment

The ground segment definition has included the following tasks:

- Functional analysis of the ground segment.
- Detailed specification of the systems.
- Preliminary architecture design.
- Preliminary concept of operation definition.
- Preliminary cost estimation based on parametric and statistical approaches.

Several possible launch sites have been studied and in the end, two "best candidates" have been identified:

- Guyana Space Center (CSG).
- Andøya Space Center (ASC).

1.3 Support of the ALTAIR System Design Studies with Subscale Flight Tests

Beside the system design studies, the ALTAIR project includes an experimental workpackage dedicated to perform flight tests [1][2]. The main objective of those tests is to validate some of the specific elements of the ALTAIR system in conditions representatives of the free flight. For that purpose, the experimental workpackage is directly fed by the design workpackages to develop and test, at a given subscale, sub-systems representatives of the full-scale ALTAIR system. With regard to the particularity of the ALTAIR air-launch system, the flight tests are focused on two of its features:

- The separation phase during which the launcher is automatically separated from the carrier throughout a dynamic manoeuver. The flight tests aim to reproduce the ALTAIR separation manoeuver dynamic, including the activation of a release system representative of the ALTAIR release system.
- The launcher on-board system and its new functions specifically defined within the ALTAIR project and mainly resulting of the airborne part of the launcher flight. Those functions concern the navigation and the safety management.

For the flight tests purpose, experimental sub-systems typical of the ALTAIR air-launch system have been specifically developed, as described in section 3. Those elements have been then mounted or implemented on the demonstrator EOLE, which has been used as a flying test bed. Section 2 describes the demonstrator EOLE and its development program.

2. EOLE Flying Subscale Demonstrator

2.1 EOLE Demonstrator Genesis

In the frame of activities done in close collaboration between CNES and ONERA during the last years of 2000 decade (namely DEDALUS [3] and L3AR projects), the idea of using a Flying Scaled Demonstrator (FSD) has emerged as a potential technical mean to address the critical phase of the air-launch mission, which consists of the launcher release from the carrier [4]. A multidisciplinary working group, set up to evaluate the feasibility of such an idea, concluded positively and delivered a set of top level requirements toward a flying demonstrator suited for this kind of experiments.

In the same period, CNES launched the PERSEUS project (https://www.perseusproject.com/) toward students, with the aim to give them the opportunity of designing, building and testing parts of space launch concepts at reduced scale. As air-launch concepts of operation were in the scope of this project, PERSEUS offered the opportunity to support EOLE development and the decision to proceed was taken. For that reason, many students from universities such as Université d'Evry Val d'Essonne (UEVE), engineering school such as ISAE-Supaero, ENSAM ParisTech, IPSA and scientific associations such as GAREF and Planète Sciences, were involved in the development program, through internships or students team's projects. Close to 70 students have participated to help EOLE experimental system to become a reality.

The main capability of EOLE FSD is to release in safe and controlled conditions launcher mock-ups in order to capture in-flight relevant data of the behaviour of the two vehicles during various release manoeuvers, using also various experimental release systems. The objective is to help understanding, modelling and simulating this critical part of the air-launch mission. A secondary capability of EOLE consists of carrying prototypes of launcher's on-board equipments in order to test them in realistic flight conditions, for example under load factor.

In relation with the full-scale concept of operations studied at the time of EOLE initial definition, some investigations related to scale's similarities were performed to set up a first design of the FSD. According to the objective to catch the vehicles' relative behaviours during the release manoeuver, Froude scaling was of first importance, and served as a basis to define an initial set of characteristics for the FSD. On this basis, a multidisciplinary design process was performed to go from this initial design to a more realistic aircraft configuration, namely EOLE, taking into account operational constraints and French UAV regulations in force at this time. Figure 7 illustrates this process.

At the end, EOLE resulted from a compromise between similarity objectives and operational constraints, which leads to manage a lower wing loading than required. As a consequence, no direct transposition was possible, but a methodology based on simulations was set up and consolidated through EOLE development to help the design of a full-scale air-launch concept.

Once designed, EOLE was co-patented by CNES, ONERA and Aviation Design. The latter is a French SME specialized in flying demonstrator and UAV manufacturing, acting as CNES sub-contractor to develop with ONERA the EOLE experimental system.

Hence, the EOLE development project was managed by ONERA, involving Aviation Design as the main partner. It was cadenced in three main steps, with interim review milestones in compliance with CNES program management process. First step, dedicated to preliminary design was done from

2009 to 2010. Then the detailed design, manufacturing and integration were done in two years (from 2010 to 2012). The third and final step consisted of qualification and tuning tests, from ground to flight, and lasted 5 years (from 2012 to 2017).

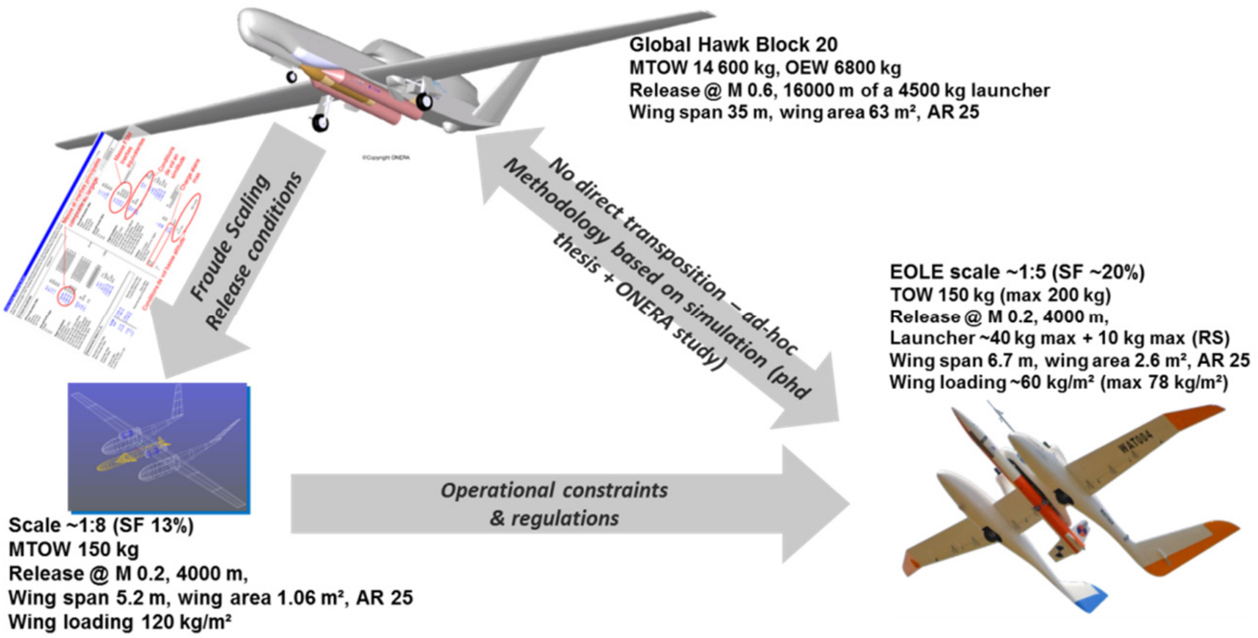

Figure 7 – FSD overall definition process. (credit: ONERA & Laurent Michelet)

2.1.1 EOLE Characteristics and Performances

EOLE is fully designed in relation with the aim to carry and release a launcher which represents a large amount of the total mass of the flying system. To minimize disturbances and avoid risks of collision between EOLE and the launcher during the separation, a twin fuselage was selected to carry the launcher in the symmetry plan, easing their center of gravity colocation. A twin engines configuration was also chosen for safety purpose, and located above a gull wing suited to increase ground clearance. This arrangement accommodates a wide free space under a central pod, on which the release system is locked through a standard interface. This central pod includes in its upper part the safety parachutes and a part of the onboard avionics. A V-tail ensures also a free space behind the launcher and limits the tail blowing with the jet engine hot flow.

As launcher mock-up weight was expected in the 10 kg to 40 kg range, EOLE was designed for a payload of 50 kg, including a provision of 10 kg for the release system. Considering the full-scale flight conditions and the main release manoeuver which consisted of a constant-g pull-up, the design release performances for EOLE was set at Mach 0.2, 4000 m altitude under a 3g pull-up manoeuver.

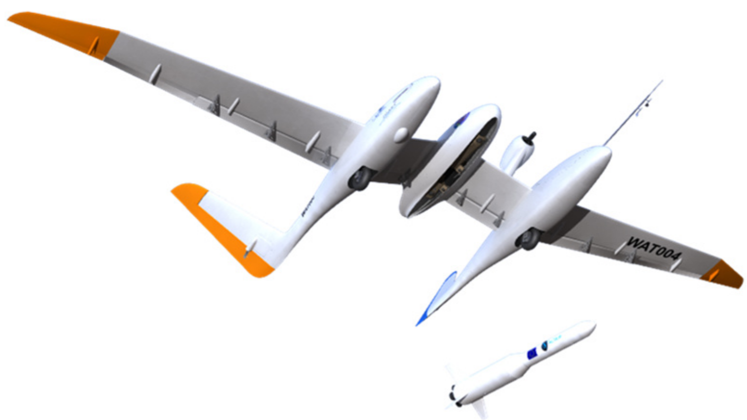

Figure 8 – View of EOLE overall airframe architecture. (credit: ONERA)

From those considerations, the design process has frozen the EOLE main features, which are:

- A nominal take-off weight of 150 kg, with structural provision to increase it safely at 200 kg.
- A 6.7 m span wing using an in-house ONERA airfoil, with an area of 2.58 m² and an aspect ratio of 17.
- Two AMT Titan turbojet with a unitary sea level static thrust of 40 daN.
- A demonstrated ability to handle at least 4 g pull-up manoeuver @ at a flying weight of 150 kg and 3 g @ 200 kg.
- An operational ceiling greater than 4 000 m, a max speed close to 110 m/s or Mach 0.32, an endurance up to 45 min and a maximum range close to 250 km.
- A fully automatic flight except for take-off and landing, which are manually piloted.
- An ability to perform automated Beyond Visual Light Of Sight (BVLOS) flight in segregated areas.

The later feature comes from the release conditions, which are clearly out of the visual range of a pilot on-ground. It leads to design an avionics architecture robust to the single failure for any of the systems, and robust to a double failure for equipment involved in the flight safety management. The safety chain is based on two independent operating ways, with their own data uplink, one dedicated to the flight tests center safety officer and another one for the flight tests team. The safety procedure consists of ejecting a safety parachute to stop the flight, stopping the engines through redundant fuel valves, and deflecting ailerons to a spiral turn. Moreover, the activation of the safety procedure can occur automatically on onboard decision from an internal permanent survey protocol, which scans and detects onboard systems failures.

2.2 EOLE Development Program

Beyond the design phase, Figure 9 depicts the set of ONERA’s multidisciplinary activities performed in order to develop EOLE [4].

- Wind tunnel testing (L2 wind tunnel, ONERA center of Lille) in complement with CFD computations to provide a wide aerodynamic database for handling qualities and performance analysis, then flight control laws definition.
- FEM computations and static bending tests (done up to the wing primary structure break, with the collaboration with ISAE-SUPAERO) to validate the wing structure (torsional resistance of the fuselage-tail joining section was also computed and validated through experiments on a test-bench).
- Ground Vibration Testing (GVT) in the ONERA center of Meudon facility to feed a flutter analysis.
- Performance assessment and handling qualities analysis then control laws definition, using in-house methods & tools [5][6][7].
- Flight control laws were implemented into the onboard flight computer and also used to feed a flight simulator for on-ground pilot training and flight experiments preparation.

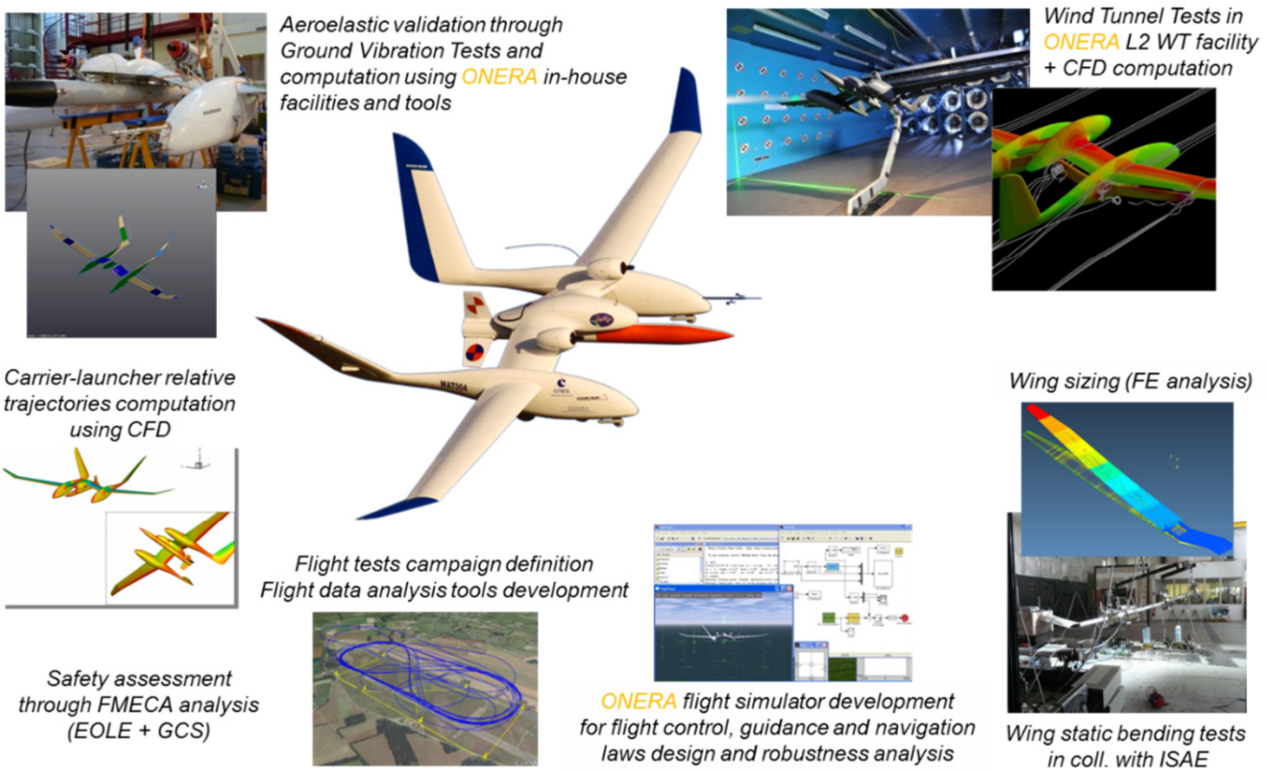

Figure 9 – Main ONERA activities for the EOLE development program.
(credit: ONERA & Laurent Michelet)

In close collaboration with ONERA, Aviation Design has performed the detailed design of the airframe, the avionics and the ground station, starting from its know-how built on several other UAV or flying demonstrator projects with the industry.

The airframe is fully made in composite materials (either using glass fiber or carbon fiber materials, partly including honeycomb or NOMEX®) and manufactured through molding using molds done by numerical control machining.

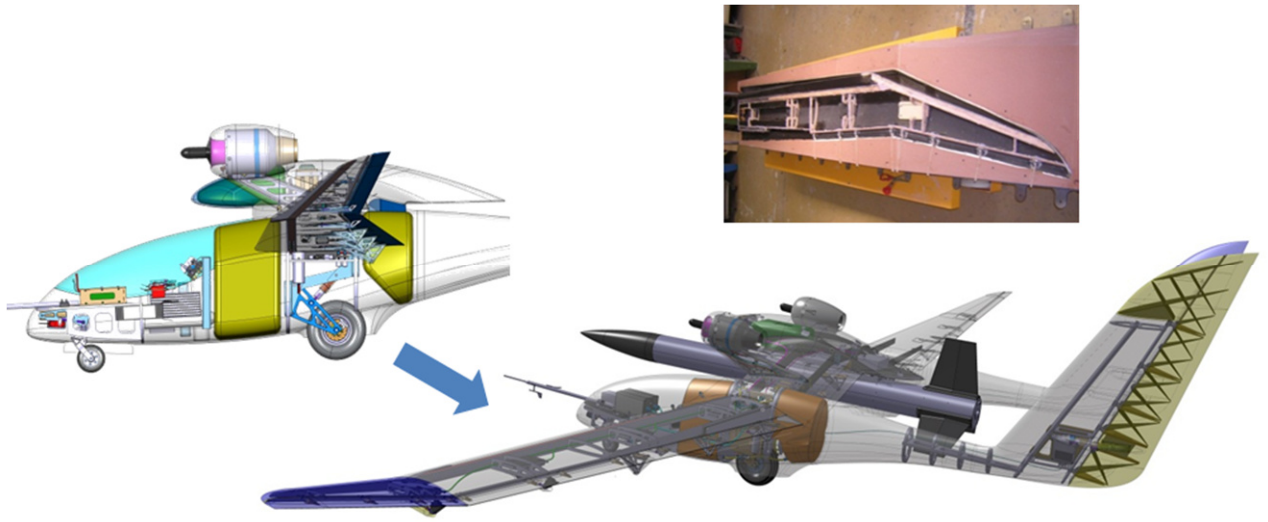

Figure 10 – Detailed design and manufacturing details of the airframe. (credit: Aviation Design).

Avionics is in-house made and includes COTS actuators and sensors such as the IMU. Ground control station and data links are also in-house equipments, both for hardware and software.

An upgrade of the PERSEUS' ARES launcher, instrumented with this own down datalink and potentially thrusted, was set up by UEVE, Garef and IPSA to be carried and released by EOLE, with a first standard release system designed and manufactured by UEVE.

The first experiments of the qualification process started in 2012, firstly by ground tests for onboard avionics then for the overall system. The maiden flight occurred in 2013 from the Saint-Yan airfield (France) under a Permit-to Fly delivered by the French Civil Aviation Authority DGAC. Development and qualification flights done from this airfield were performed within a segregated area corresponding to a cylinder of 1 km radius (centered on ground installation location, near the runway) and 500 m height above ground level.

Figure 11 – EOLE during flight experiments at Saint-Yan airfield, with/without the launcher mock-up. (credit: Laurent Michelet)

From 2013 to 2014, six flight experiments campaigns were managed in order to successively open the flight envelope, then to tune the flight control laws of the stabilized mode, and finally to commute to the guidance and navigation modes.

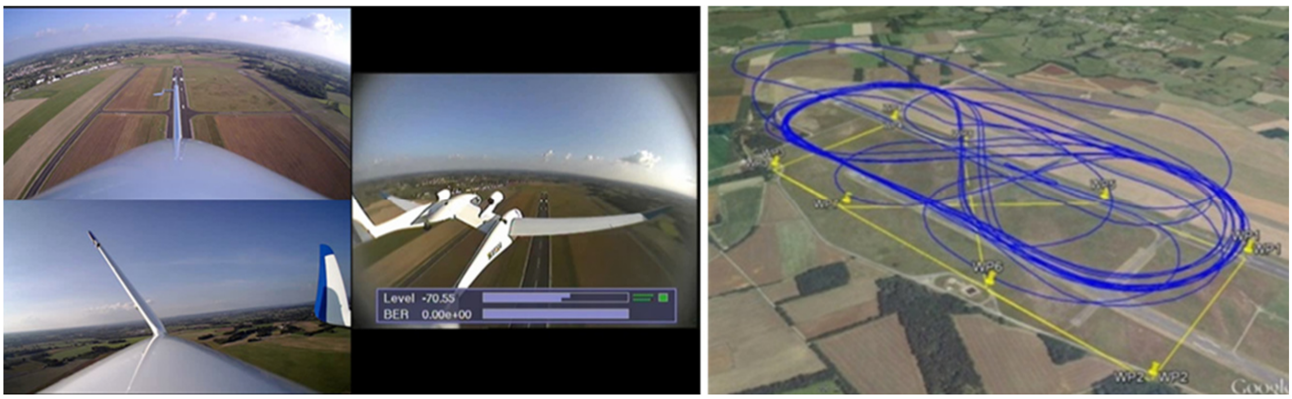

Figure 12 – EOLE experimental system setting up and qualification at Saint-Yan airfield. (credit: ONERA)

The specific separation manoeuver guidance law was also experimented with lower dynamic parameters according to the rather limited flight space, in order to validate the corresponding trajectory, which consists of a pull-up manoeuver followed, after the release, by a 180° turn at low speed in order to take an opposite direction.

However, no release was done at Saint-Yan airfield as this kind of experiment is prohibited over such an open ground area, despite its low populated density.

At the end of this set of flight tests campaigns performed at Saint Yan airfield, a formal review concluded that EOLE was ready to start BVLOS experiments. This review has also stated on how to proceed for future BVLOS experiments. A gradual approach was discussed and validated with the aim to enlarge progressively the flight envelope (higher altitude and higher speed), and to test progressively the ability of the systems – especially the datalinks – to operate at larger range, typically up to 25 km from the ground control station, the EOLE flying demonstrator.

3. Flight Tests Using the Demonstrator EOLE for the ALTAIR Project

In the frame of the ALTAIR project, the demonstrator EOLE is used as a flying test bench in order to place experimental sub-systems in conditions representative of the free flight environment. For that purpose, experimental sub-systems, typical of the ALTAIR air-launch system, have been specifically developed to be mounted or implemented on the demonstrator EOLE [1][2].

3.1 Specific Experimental System Development for the ALTAIR Project

As indicated in section 1.3, the flight tests are focused on two specific characteristics of the ALTAIR air-launch system: on the one hand, the launcher on-board system specifically designed for the ALTAIR launch vehicle, and on the other hand, the separation phase including the particular separation manoeuver performed by the ALTAIR carrier and its release system activation. Those experiments have led to develop experimental sub-systems that are described in the sections 3.1.1 to 3.1.5.

3.1.1 Mock-Up of the ALTAIR Launcher On-Board System

The experiments about the ALTAIR launch vehicle on-board system concern two critical functions: the navigation function and the on-board flight safety management.

For the navigation function, the tests aim to validate the launcher on-board system alignment procedure required just before the launcher separation. For the on-board flight safety management, the tests aim to validate the safety procedures defined for both launcher release and launcher ignition consents, involving the algorithms implemented for the systems checkout and the states estimation (ground impact prediction, launcher state assessment at engine ignition, etc.). Those functions and the associated algorithms are derived from the workpackage dedicated to the ALTAIR launch vehicle design and they are implemented in an experimental set of equipment representative of the ALTAIR launch vehicle on-board avionics. This experimental system is composed of an on-board computer and a VECTOR-NAV 200 dual antenna GNSS-aided inertial navigation component. Those elements are installed into a mock-up of the ALTAIR launcher which is then attached to the demonstrator EOLE. Thanks to EOLE, this launcher mock-up is placed in airborne flight conditions and, at the very end of the flight tests campaigns, is released during a separation manoeuver. In order to record the information collected by the launcher mock-up during its ballistic flight after the release, a twin on-board computer is mounted on EOLE. This twin computer receives the launcher mock-up on-board system data through a WiFi datalink. All the experimental devices concerning the launcher on-board system and their arrangement in the launcher mock-up are represented in Figure 14.

3.1.2 Subscale Model of the ALTAIR Launcher

The launcher mock-up has been developed in order to accommodate the on-board system described in section 3.1.1. This mock-up represents a 1:13 scale model of the ALTAIR launch vehicle. Its body is based on carbon fiber tubes and its internal structure is made of aluminum. The nosecone, the central skirt and the aft part with dummy nozzles are made with additive printing. Figure 13 shows the launcher mock-up overall geometry and Figure 14 illustrates its internal structure and the integration of the experimental on-board system.

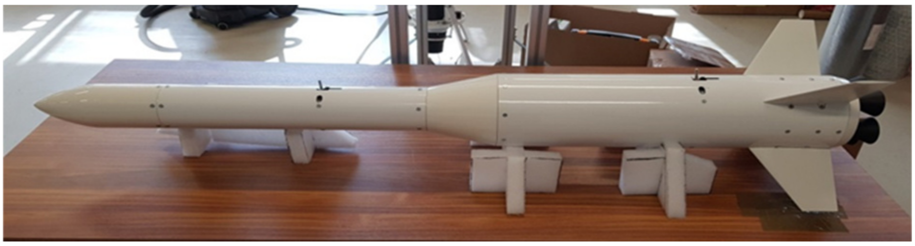

Figure 13 – Launcher mock-up (scale 1:13 of the ALTAIR launch vehicle). (credit: Université de Rennes 1)

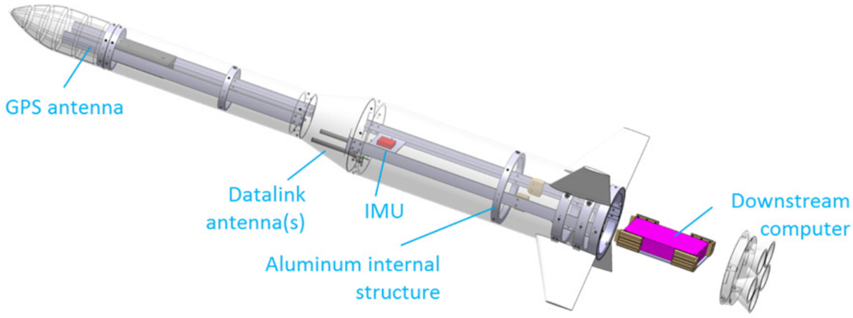

Figure 14 – Launcher mock-up internal structure and equipment. (credit: Université de Rennes 1)

Finally, the launcher mock-up is fitted with two attachment points. Their design and manufacturing have been the subject of deep investigation in order to ensure the whole experimental system safety in case of disturbances (i.e. minimize risks of collision during the launcher mock-up release from the demonstrator EOLE) and to be compatible with the flight tests operations (i.e. allow quick and easy assembling/disassembling operations). Those attachment points are highlighted in Figure 15.

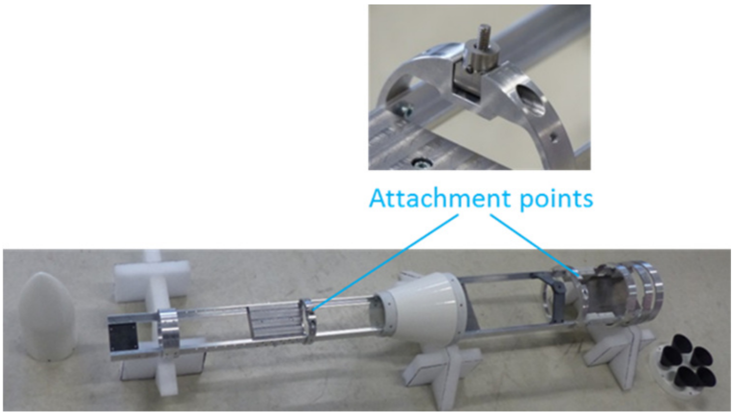

Figure 15 – Focus on the launcher mock-up attachment points. (credit: ONERA)

3.1.3 Mock-Up of the ALTAIR Release System

In addition to the ALTAIR launcher mock-up and its equipment, a mock-up of release system has been developed. This experimental release system is representative of the one defined for the ALTAIR carrier in the dedicated workpackage. It uses the same physical principle based on Hold-Down Release Mechanisms (HDRM). The release system mock-up is composed of two HDRM which allow locking and then releasing the two attachment points that are present on the launcher mock-up side. As for the full-scale ALTAIR release system, the mock-up HDRM are positioned at equal distances around the launcher mock-up center of gravity. Figure 16 illustrates the overall geometry of the release system mock-up and Figure 17 shows a photo of the release system mock-up assembled with the launcher mock-up. This last figure brings to light the four lateral stabilizers present to maintain the launcher mock-up body, in the same way as the full-scale ALTAIR release system.

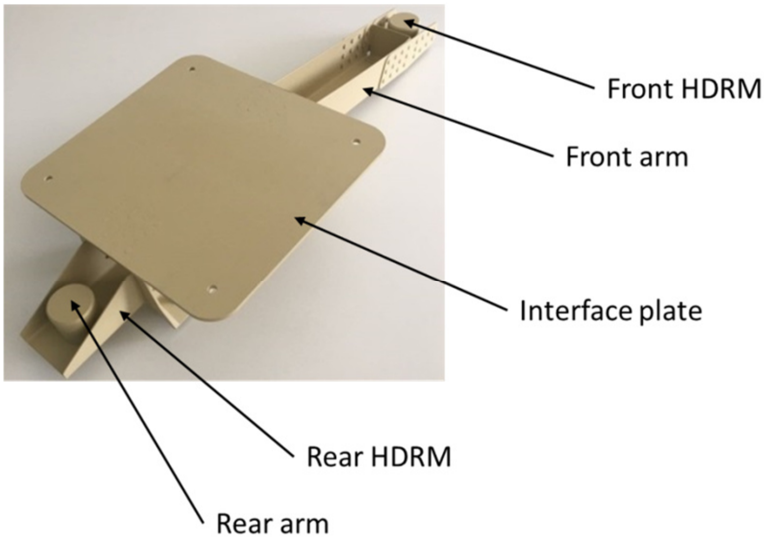

Figure 16 – Release system mock-up. (credit: Piaggio Aerospace)

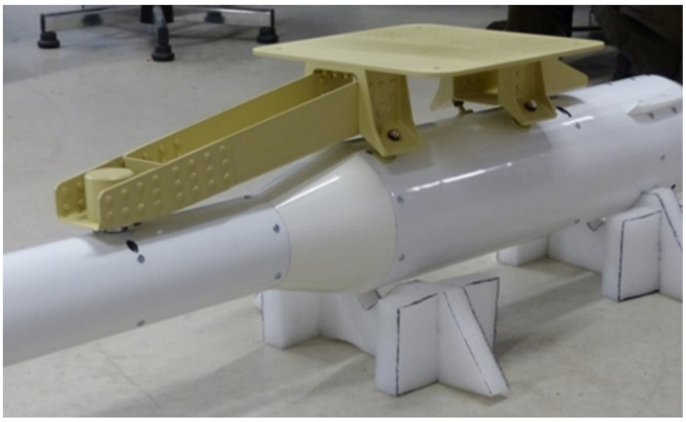

Figure 17 – Release system mock-up assembly with the launcher mock-up. (credit: ONERA)

Finally, the release system mock-up is attached to EOLE through its interface plate which is screwed under EOLE's central pod. For the flight tests campaigns, a fairing has been specifically manufactured to protect the release system. Equipment related to the ALTAIR release experiment and carried on by EOLE, including the electronics driving HDRM devices, are attached to the interface plate, as illustrated in Figure 18.

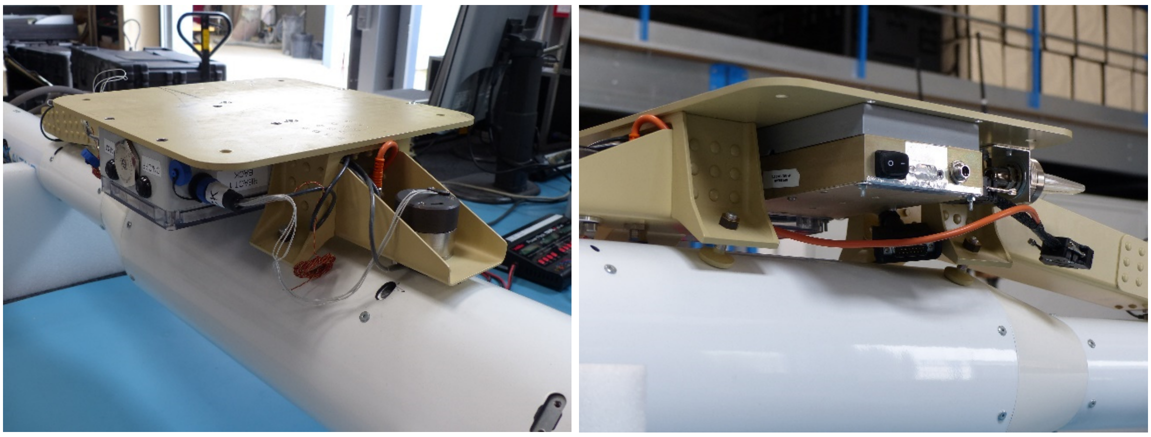

Figure 18 – Rear HDRM and associated computer (left),
twin computer for launcher data recording (right). (credit: ONERA)

3.1.4 GNC Laws for Reproducing the ALTAIR Separation Manoeuver

Beside the experimental hardware manufactured for the flight tests and described from sections 3.1.1 to 3.1.3, Guidance, Navigation and Control (GNC) laws have also been developed. The main topic of the GNC development focuses on the separation manoeuver with the objective of reproducing the ALTAIR separation manoeuver dynamic with the demonstrator EOLE. This manoeuver, defined in the workpackage dedicated to the ALTAIR carrier design and illustrated in Figure 19, is composed of three steps: an acceleration segment at constant altitude, a pull-down segment and a pull-up segment under normal load factor. The separation flight conditions defined for the ALTAIR system and the related conditions defined for the flight tests with the demonstrator EOLE are indicated in Table 5.

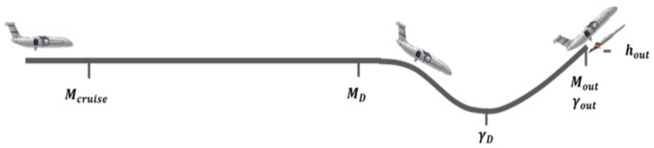

Figure 19 – ALTAIR separation manoeuver. (credit: Piaggio Aerospace)

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

Table 5 – Separation flight conditions for the ALTAIR system vs. flight tests.

In addition to the laws about the separation manoeuver, specific GNC laws have also been developed in order to perform the alignment manoeuvers required for the tests dedicated to the launcher on-board system alignment procedure mentioned in section 3.1.1.

3.1.5 Integration of the Experimental System with the Demonstrator EOLE

The mock-up of launcher on-board system is integrated into the launcher mock-up, as described in section 3.1.2. Then, the release system mock-up is mounted under the central pod of the demonstrator EOLE and protected in a fairing. Finally, the launcher mock-up is screwed to the release system mock-up through the two HDRM. Figure 20 represents the experimental system assembled to the demonstrator EOLE.

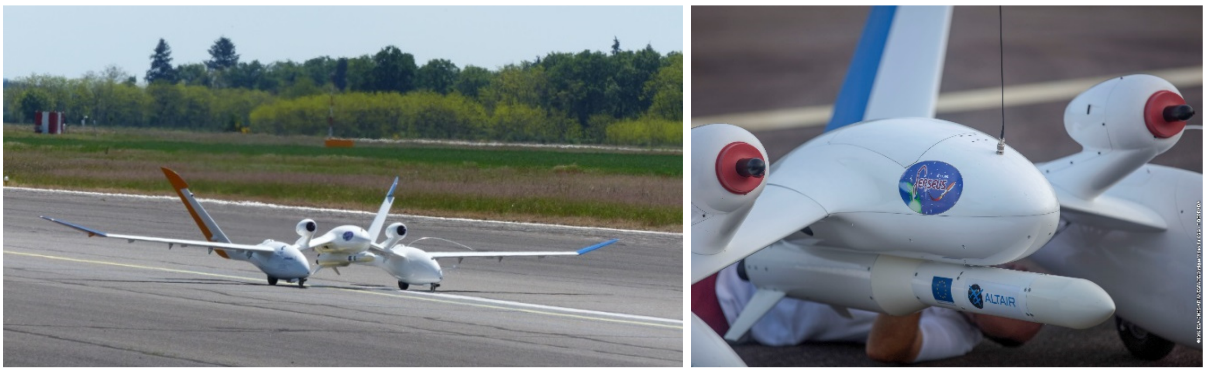

Figure 20 – Experimental system assembled with the demonstrator EOLE. (credit: ONERA)

Finally, all the GNC laws mentioned in section 3.1.4 have been implemented into the on-board system of the demonstrator EOLE.

3.2 Flight Tests Campaigns for the ALTAIR Project

The experimentations have been divided in two flight tests campaigns [1][2].

3.2.1 Visual Line of Sight Flight Tests Campaign

The first campaign focuses on a low altitude and low speed flight envelope, restricted to Visual Line Of Sight (VLOS) conditions. This campaign occurred in the French civil airport of Saint-Yan. During this campaign, three categories of tests have been conducted along the several flights.

First, the VLOS flights were used to test four different launcher on-board system alignment manoeuvers described in Figure 21: Straight Flight, Coordinated Turn, Wing Rock and Thach Weave. During the flights, each manoeuver have been repeated at different flight conditions, as indicated in Figure 21. Moreover, the tests have concerned nominal but also degraded conditions. Those degraded conditions have been faked by simulating the failure of some of the launcher on-board system components (malfunctioning GNSS, malfunctioning INS, degraded navigation data).

The campaign concluded on the validation of the launcher on-board system alignment algorithms and the selection of the Thach Weave manoeuver to be used for the ALTAIR system. Figure 22 illustrates the data collected during an alignment with a Thach Weave manoeuver.

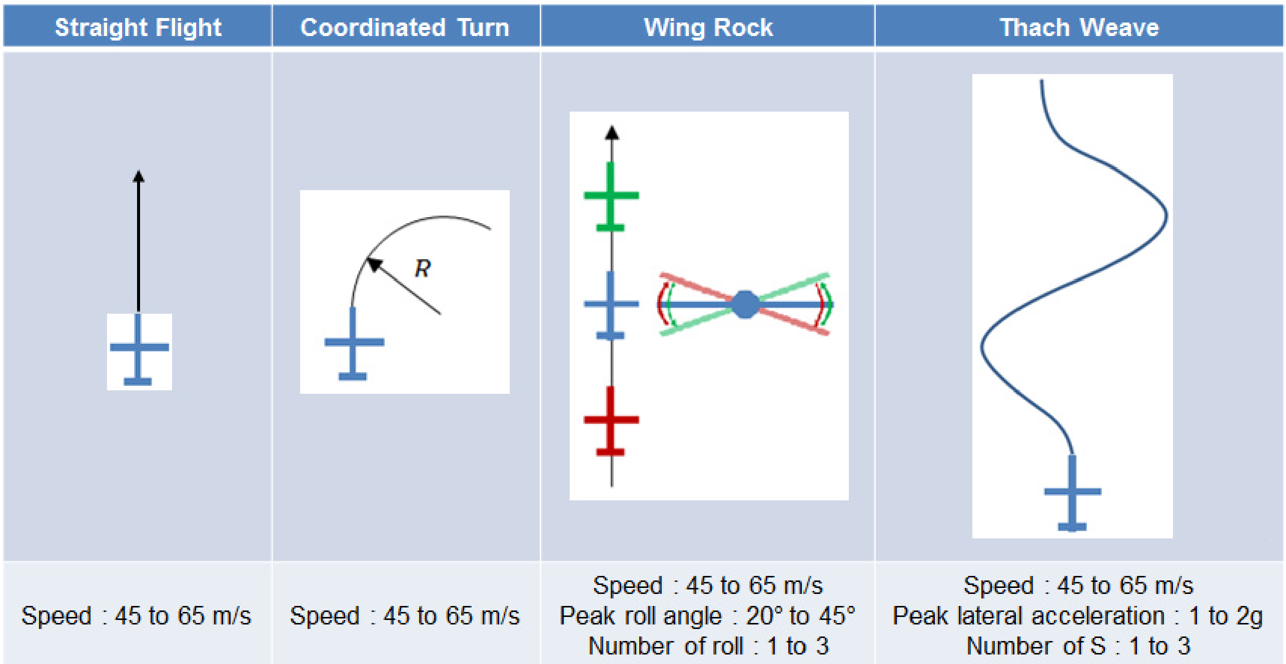

Figure 21 – Alignment manoeuvers. (credit: GTD Sistemas de Información S.A.)

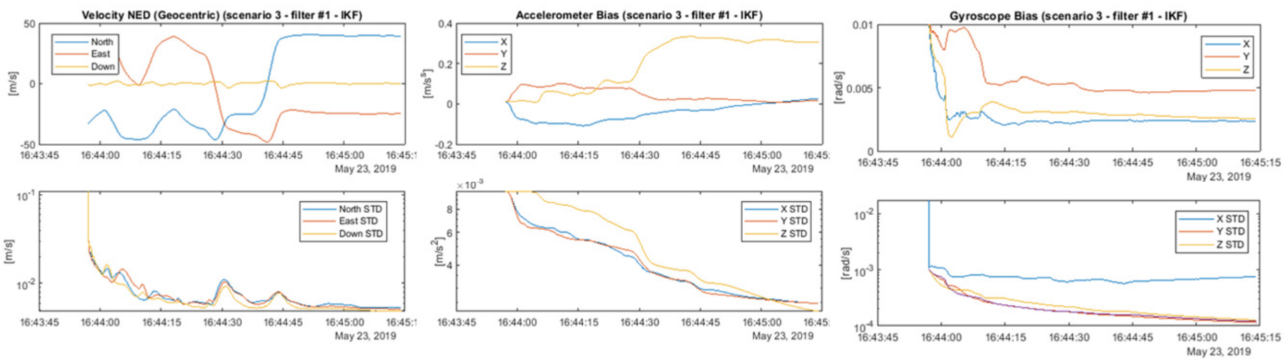

Figure 22 – Alignment with a Thach Weave manoeuver. (credit: GTD Sistemas de Información S.A.)

Then, the VLOS flights were used to test the launcher on-board system safety management procedures related to the launcher ground impact prediction. For those tests, the safety algorithms took as inputs either the VECTOR-NAV 200 navigation data or the on-board navigation data previously aligned. Those tests have been performed at several speeds (from 45 to 65 m/s) and altitudes (from 200 to 500 m above ground level) and, as for the alignment manoeuvers, they have considered both nominal and degraded conditions. The campaign contributed to validate the on-board flight safety management through the following elements:

- Evaluation of the real-time performance, accuracy and precision of the impact point and impact area algorithms.
- Detection of sensible ground areas to be protected from launcher impact towards release order acceptance.
- Detection of target areas for secure/controlled launcher release towards release order acceptance.
- Detection of dynamic events during ballistic flight towards ignition acceptance.

Figure 23 illustrates the launcher on-board system answer with regard to different categories of ground areas.

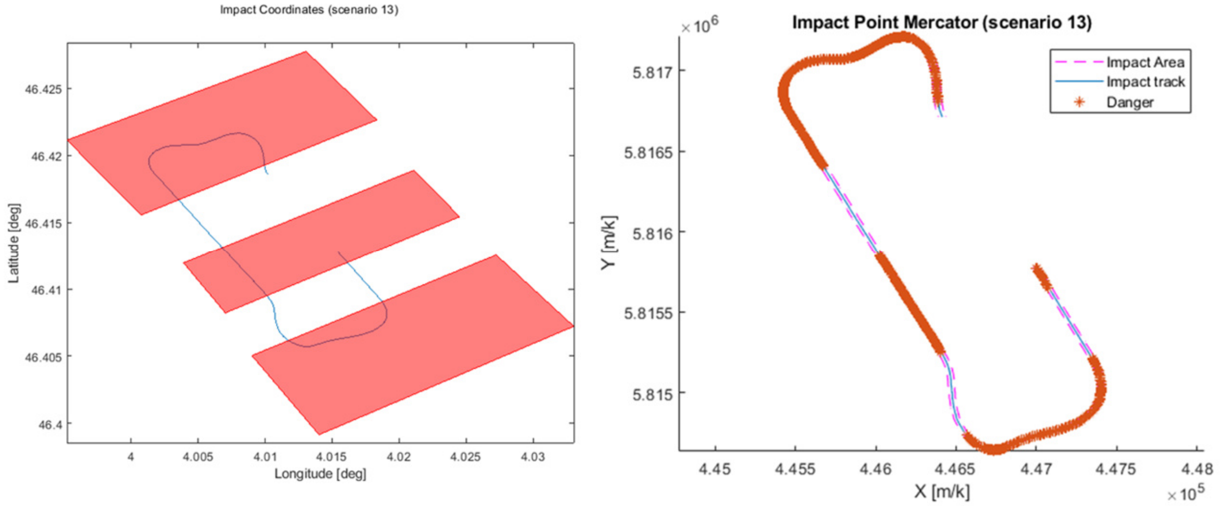

Figure 23 – Safety output vs pre-loaded prohibited ground areas.
(credit: GTD Sistemas de Información S.A.)

Finally, the VLOS flights were used to test the implementation of the separation manoeuver and its proper functioning. During those flights, the release system actuators were inhibited in order to prevent any launcher separation, but all the separation manoeuver steps were tested, including the release system actuation order generation. Figure 24 illustrates the speed and altitude evolution of the demonstrator EOLE during one of the separation manoeuver tested in VLOS conditions. The campaign concluded positively, opening the way to go to the next and final step: the effective release of the launcher mock-up in BVLOS conditions.

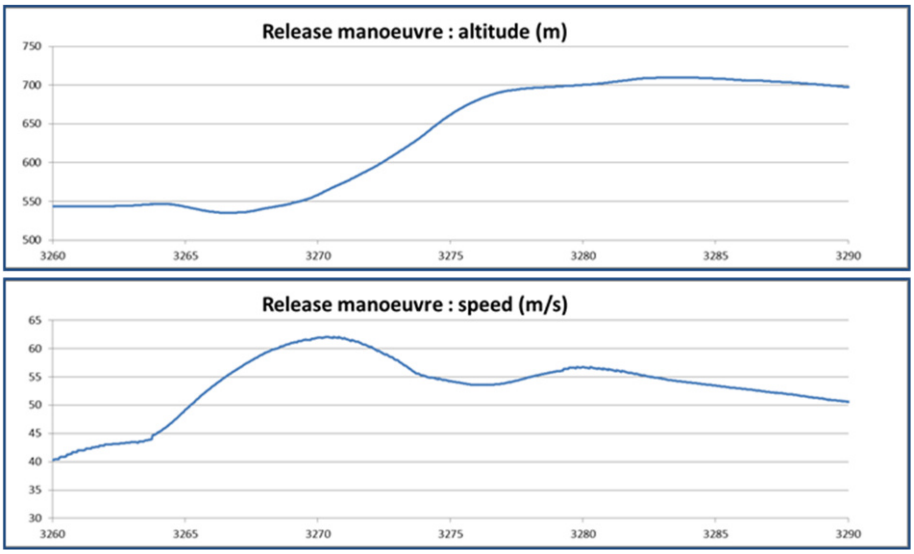

Figure 24 – Separation manoeuver in VLOS conditions. (credit: ONERA)

3.2.2 Beyond Visual Line of Sight Flight Tests Campaign

The second and last campaign is dedicated to higher altitude and higher speed flight envelope, in Beyond Visual Line Of Sight (BVLOS) conditions. This campaign occurred in the Guyana Space Center (CSG) of Kourou [2][8].

The main objective of this campaign is to perform the release of the launcher mock-up during a separation manoeuver and then collect data during its ballistic flight. In addition, the high altitude and high speed flight envelope available at the CSG allowed reproducing the selected Thach Weave manoeuver and the launcher on-board system safety management tests in more aggressive flight conditions than during the previous VLOS flight tests campaign.

Figure 25 illustrates the flight path of the last flight of the CSG campaign where several tests are visible.

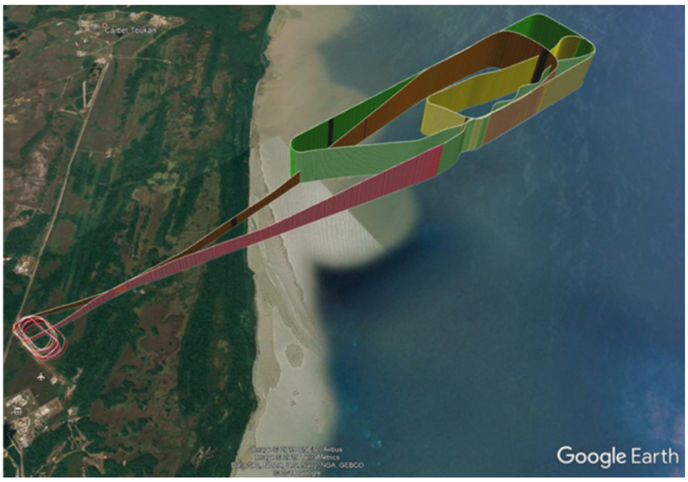

Figure 25 – Flight path of the last flight at CSG. (credit: ONERA)

First, the green part highlighted in Figure 26 (left) shows a Thach Weave manoeuver composed of three S occurrences, performed at 1000 m above mean seal level and 45m/s. Then, the orange part highlighted in Figure 26 (right) shows the separation manoeuver performed at 1000 m above mean seal level and 85 m/s, followed by the return trajectory toward the runway. The red star indicates the exact position of the launcher separation from the demonstrator EOLE.

Figure 26 – Zoom on the Thach Weave manoeuver (left) and the separation manoeuver (right). (credit: ONERA)

Figure 27 shows the data collected by the demonstrator EOLE during the separation manoeuver and Figure 28 shows both EOLE and launcher mock-up evolution around the release time. Figure 29 illustrates three pictures recorded during the launcher mock-up separation from the demonstrator EOLE.

The campaign concluded successfully on the good functioning of the separation manoeuver and a proper separation of the launcher mock-up.

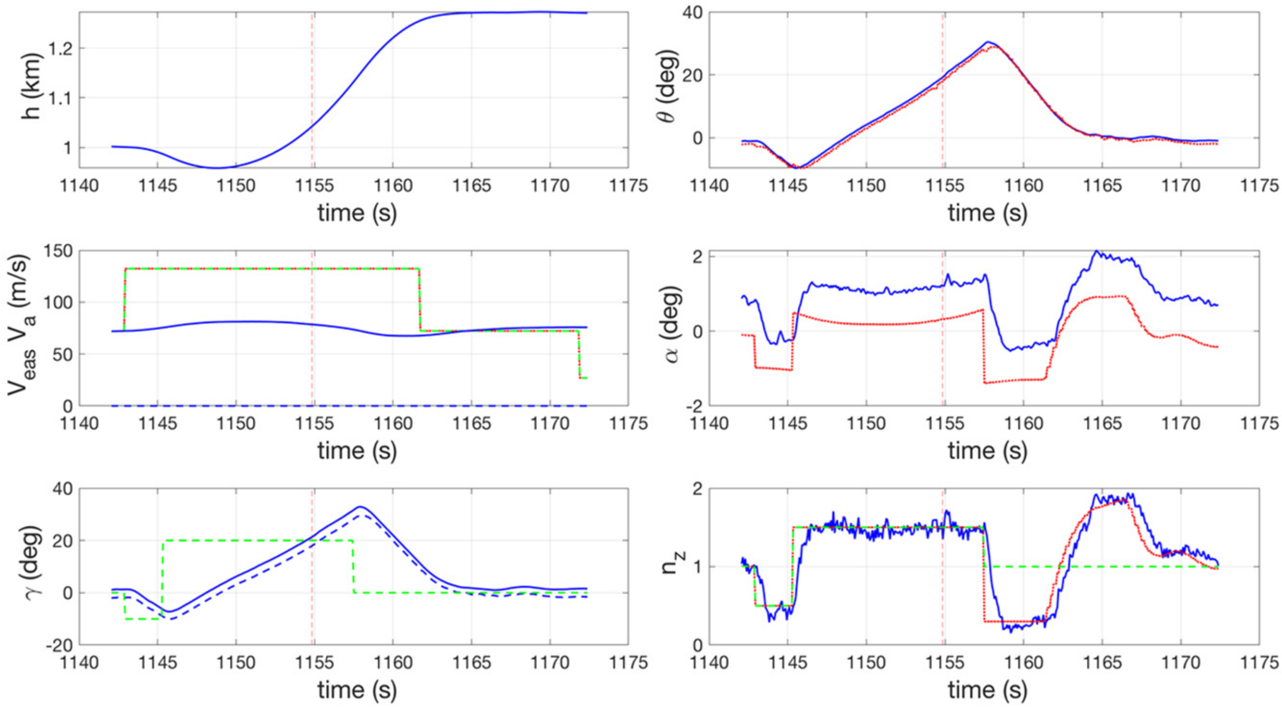

Figure 27 – Separation manoeuver data. (credit: ONERA)

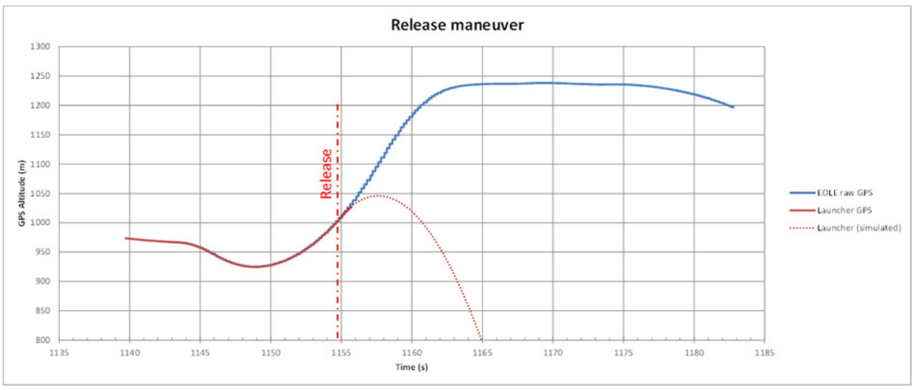

Figure 28 – EOLE and launcher mock-up evolution around the release instant. (credit: ONERA)

Figure 29 – Pictures of the launcher mock-up separation from the demonstrator EOLE. (credit: ONERA)

4. Conclusion and Perspectives

The flight tests performed with the demonstrator EOLE and the analysis of the experimental data collected during the several campaigns provide a valuable source of information toward the design of the ALTAIR semi-reusable air-launch system.

First, the flight tests performed about the launcher on-board system have contributed to validate the on-board algorithms and the software strategies. Regarding navigation, the tests have validated the alignment software performance in term of position, velocity and attitude, with an initialization time lower than 30s. Then, they have contributed to select the Thach Weave manoeuver for the alignment before the launcher separation. In addition, the flight tests have participated to the validation of a flight simulator specifically developed for the launcher on-board system. About the on-board flight safety management, the flight tests have confirmed the viability of the real-time on-board autonomous safety approach considering a low power on-board computer. Finally, they have allowed assessing the real-time computation and performances of the safety algorithms about ground safety.

Then, the flight tests have confirmed that the design selected for the release system guarantees a safe and secure separation of the launcher from the carrier. The data collected during the tests have been compared to numerical simulations, showing that the global relative behavior of both vehicles was well represented by intermediate level aerodynamics simulations. In addition, it has been highlighted that local phenomenon such as suction effects need high level aerodynamics simulations to be well estimated.

Finally, the GNC laws developed and tested with EOLE have proved their high performance to achieve the ALTAIR separation manoeuver.

In addition to all the validations provided by the flight tests on hardware and software, leading to progress on the scale of TRL, the flight tests have also been fruitful about defining the operations of such specific system as the ALTAIR semi-reusable air-launch system composed of a reusable automated carrier and an expendable launcher.

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7. Copyright Statement

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