# Pre-X Mission: Scenario definition with VEGA launcher

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## Abstract

Since Berlin Ministerial Council, VEGA has been selected as the European reference for small payloads and as a consequence for the Pre X mission. In the frame of this decision, trajectories analysis has been performed to state about the feasibility of Pre-X demonstrator mission by VEGA. This paper presents the overall optimisation done by CNES (Centre National d'Etudes Spatiales) to define a scenario which copes with Pre-X constraints and is compatible with the European launcher VEGA.

As Pre-X is an automatic controlled re-entry vehicle, the trajectory optimisation under constraints covers launcher ascendant phase and the re-entry one. The challenge of this analysis was to reoptimise Pre-X re-entry conditions (relative velocity Vr, flight path angle $\gamma$) together with launcher performance (compliant with maximal masse foreseen for Pre-X) taking into account all the constraints linked both to Pre-X mission specification and to launcher definition. The re-entry gate parameters at 120 km altitude have been then defined to allow to reach the experimental objective conditions in term of heat flux and to manage the re-entry corridor from system point of view.

The particularity of such a mission is to take into account, in addition of the specification of the payload (in this case Pre-X injection conditions and its mass), all safety aspects linked to the launcher (Z9 and AVUM safe re-entry) and to Pre-X demonstrator recovery.

Several injection strategies have been analysed (in particular the reference one specified for VEGA launcher) as well as different orbital inclinations. The identification of the main drivers of the whole mission as well as the comprehension of their impact on launcher performance, have allowed defining the appropriated criteria for mission selection.

## 1. Introduction

The VEGA LV has been chosen as baseline for Pre-X in late 2005 in order to cope with Berlin ministerial council decision and be coherent with European demonstrator IXV. However, the DNEPR LV keeps on being the backup and a complete mission analysis and LV compatibility has been performed. In both cases the chosen mission gives the same thermal environment for the Pre-X re-entry phase. In this case, the ascent and descent trajectories are strongly coupled. Safety issues are also a main concern.

This paper will begin by the problem statement and the mission requirements associated to both, Pre-X demonstrator and VEGA launcher. In particular, we will present the results of preliminary analysis performed with the objective of conserving re-entry trajectory which were already specified for DNEPR launcher. This analysis had lead to the selection of the injection strategy. The second part of this paper presents the analysis focused on the equatorial scenario to define re-entry parameters for Pre-X compatible with VEGA launcher definition and performance. The re-entry gate parameters at 120 km altitude have been then defined to allow to reach the experimental objective conditions in term of heat flux and to manage the re-entry corridor from system point of view.

### 1.1 Pre-X demonstrator

The in-flight experimentation of a gliding re-entry spacecraft is considered by CNES as a key element for future space applications. In this frame Pre-X is the CNES proposal to perform in-flight experimentation mainly on reusable thermal protections, aero-thermo-dynamics and guidance to secure the second generation of re-entry X vehicles. A specific guidance navigation and control system is foreseen for this vehicle. Attitude control is performed by body flaps and reaction thrusters overall the hypersonic flight, with a functional and experimental objective.

In addition of the scenario definition with VEGA launcher, a complete system loop has been performed including the operations, ground system assessment, and visibility analysis. The Pre-X program is achieving the Preliminary Design Revue during year 2007. The results of Pre-X phase B activity will provide an input for the phase B of the European re-entry demonstrator IXV.

## 1.2 VEGA launcher

The VEGA LV, described hereunder in figure 1.1, consists of a lower composite composed by three solid propellant stages (P80, Z23 and Z9) and a restartable upper stage named AVUM (Attitude and Vernier Upper Module, $N_2O_4$/UDMH). The development is under the responsibility of ESA/IPT (European Space Agency).

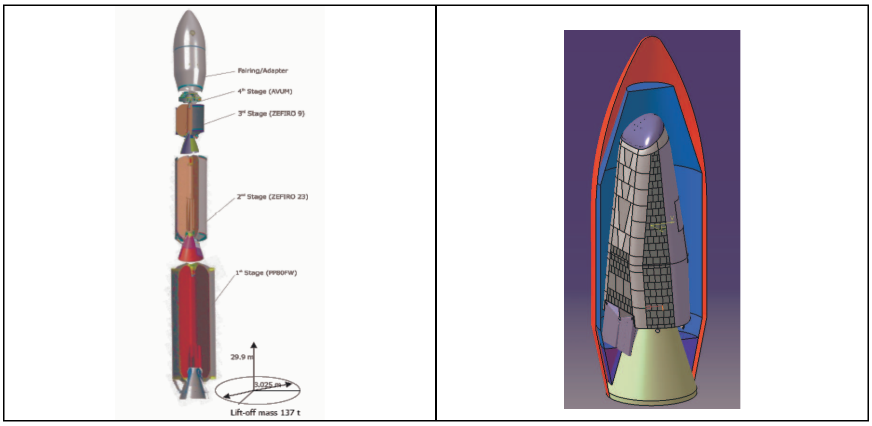


Fig. 1.1 – VEGA launcher [1] with Pre-X fitting inside the fairing

VEGA LV masses considered for trajectory optimisation comes from the User's Manuel [1].

## 1.3 Problem statement and mission requirements

For identical re-entry conditions (relatives), the orbit injection (Keplerien, so absolute) varies strongly as function of the inclination. Hence, the final admissible orbits are different if considering equatorial or high inclinations missions.

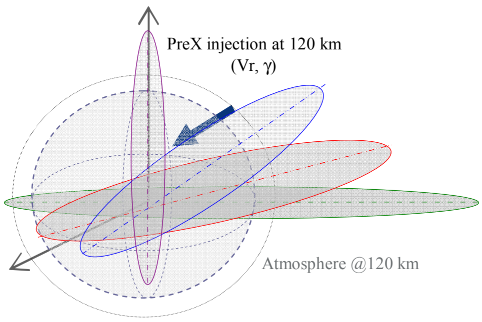



Fig. 1.2 – Pre-X parameters (Vr, γ) @120 km: orbit = f(inclination)

Mission analysis will consider trajectory optimisation that shall be compliant with the following points:

<u>Concerning Pre-X demonstrator:</u>

- Atmospheric re-entry specification (Vr, flight path angle): orbit = f(inclination). It will drive to the re-entry trajectory main parameters that shall be compatible with the Pre-X vehicle sizing.
- Pre-X longitudinal range at the beginning of re-entry phase at 120km to ensure safe splash down on the ocean far from coast.

<u>Concerning VEGA launcher:</u>

- Upper stages fall down management: Z9 and AVUM re-entry and footprint. AVUM re-entry is conditioned by the Pre-X injection at 120 km.
- LV performance from Guyana launch pad should be enough to cover with Pre-X vehicle and specific payload adaptor masses.

## 2. Background analysis on Pre-X mission with VEGA launcher

A first loop was performed at the beginning of Pre-X Phase B taking into account the re-entry parameters specified for DNEPR launcher (7700 m/s, -1.25°). The objective was to conserve if possible all the re-entry studies already done in the phase A.

### 2.1 Considered scenarios according to different Pre-X injection strategies

Three scenarios were considered:

1. Single boost solution with final re-entry orbit (suborbital high inclination),
2. Single boost solution with final re-entry orbit (suborbital low inclination) but driving to the need of AVUM additional boost to reduce perigee altitude to master footprint (right figure 2.1),
3. Multi-boost solution (orbital, VEGA reference Low Earth Orbit mission) with Pre-X and AVUM active deorbiting into final demonstrator re-entry orbit (as shown in the figure 2.2).

Single boost solution is the optimal injection strategy which drives to the maximum launcher payload. The only matter is that it creates a dependency between launcher stages fall down and Pre-X injection point.

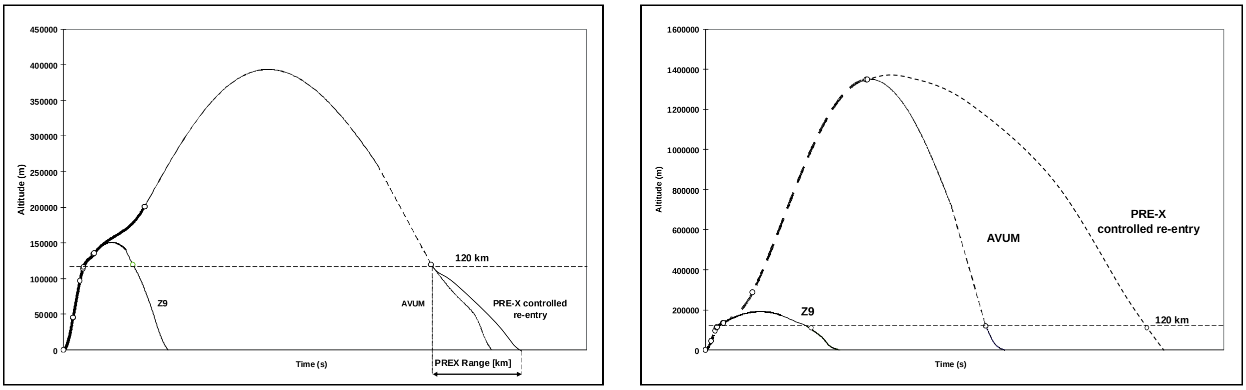



Fig. 2.1 – Suborbital solutions (final re-entry orbit)

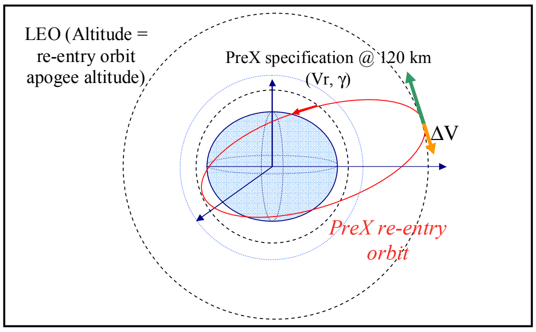



Fig. 2.2 – Multi-boost mission: Pre-X deorbiting

### 2.2 Analysis results and first conclusions

In accordance to the mission statements, inclinations from equatorial up to polar or SSO has been scanned considering both suborbital and orbital scenarios. Reached Pre-X injection parameters at re-entry are the same for all the cases.

The mission feasibility is then analysed first, with respect to the launcher performance, but also regarding the upper stages safe fall-down and Pre-X reachable domain.

In the right figure 2.3, it can be noticed the non feasible inclinations range for both scenarios: orbital and suborbital. Despite the detailed study to cover different injection strategies and inclinations, the number of feasible solutions was limited. This is because of the complexity to manage simultaneously two launcher stages fall-down and the Pre-

X reachable domain, together with the needed launcher performance. Finally, the inclination range compatible with all these requirements is indicated in green in the figure. For both missions, after Pre-X reachable domain deeper evaluation, the range was reduced to the corridor 65-70°.

**Sub-Orbital scenario**

The left figure 2.3 represents the ground track of suborbital mission for different inclinations. It is possible to observe the shift of AVUM impact point which moves backwards for higher inclinations. AVUM impact point is close of Pre-X demonstrator targeted point, and indeed it gives an idea of the feasibility to place Pre-X reachable domain on the ocean.

Suborbital missions (with final re-entry orbit) guaranty the maximal launch vehicle performance but, on the other hand, constraint the choice of upper stages (Z9 and AVUM) re-entry fall-down domain. Therefore, the choice of the inclination is limited, and it determines Pre-X demonstrator recovery area. This type of scenario is the best from performance and injection accuracy point of view, but it is the one with less degree of freedom for the placement of the different fall-down stages and the demonstrator. It is fully strong dependent from Pre-X injection conditions.

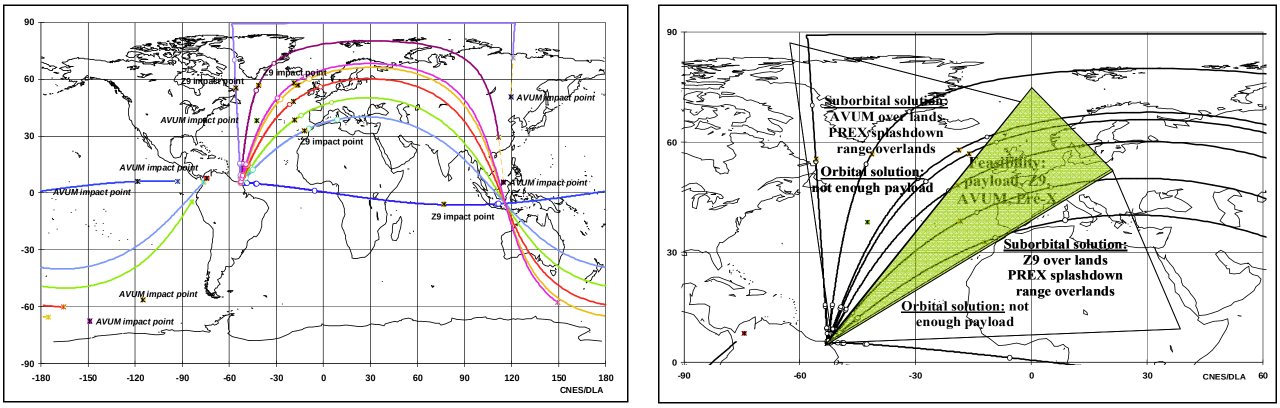



Fig. 2.3 – Choice of inclination

An example of ascent trajectories for intermediates inclinations including the ballistic phase until Pre-X injection up to the beginning of the atmospheric re-entry at 120 km is given in figure 2.4. Enough performance margins are guaranteed for the suborbital scenario with inclinations from 65° up to 70°. These inclinations allow placing the Z9 footprint in the corridor between Ireland and Iceland. Pre-X reachable domain and AVUM fall down are placed on the South Pacific Ocean. Nevertheless, to ensure visibility the network needs in addition of Galliot station, one boat and two transportable stations placed in Azores and in Ireland (for Pre-X separation).

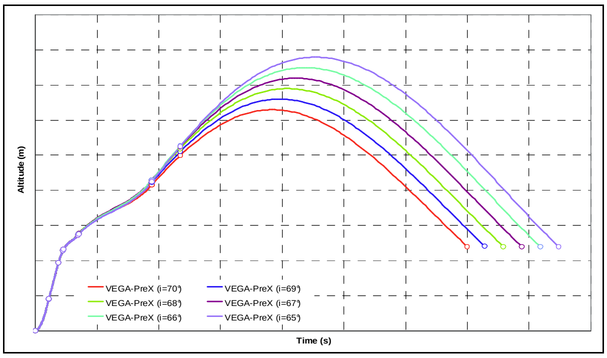



Fig. 2.4 –Suborbital mission- intermediate inclinations.

**Orbital scenario with Pre-X deorbiting**

LEO mission altitude is constrained to the apogee altitude of the final Pre-X orbit to limit as much as possible AVUM manoeuvres (and payload lost).

The main advantage of a LEO mission (multiboost) is that is the reference mission for VEGA launcher. The second advantage concerns the free choice of the ocean for the demonstrator splashdown (recovery); from this point of view the multiboost mission gives the best flexibility. It can be managed by the delay of the deorbiting boost. As example, the figure 2.5 shows the three possible choices to place Pre-X demonstrator recovery domain for the mission of 66° inclination: Indian Ocean, Pacific Ocean and Atlantic Ocean.

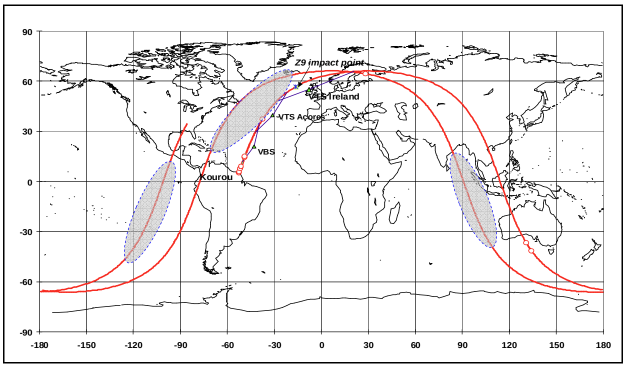



Fig. 2.5 –LEO mission (i=66°) - Pre-X deorbiting and choice of the ocean for recovery.

The main drawbacks of this scenario are the lost of performance due to Pre-X deorbiting, the problems linked to the availability of telemetry stations for direct visibility (same as the suborbital mission for theses inclinations), and the lost of injection accuracy linked to the deorbiting boost which could be done in open loop guidance but also because of an additional degradation due to the delay (around 45 minutes if Indian ocean or one hour if Pacific ocean)**.** Atlantic Ocean is the best choice regarding vehicle recovery and visibility aspects but potential problems shall be foreseen with respect to lateral Pre-X reachable domain.

### 2.3 Comparison suborbital wrt orbital solutions: Injection strategy selection

In the basis of the previous results, it was evident the particular interest of suborbital mission. The reasons are summarised as follows:

- Higher payload injected in final targeted orbit,
- Better injection accuracy: suborbital mission injection is done with closed loop guidance.
- Lower mission duration (deorbiting drives to an important delay),
- Reliability and safety: AVUM and Pre-X deorbiting over flights Europe and India (highly populated areas); therefore, reliability should be rapidly evaluated if retained.

Finally, the lost of accuracy and the reduced choice of inclination were the major issues concerning orbital scenario. Injection accuracy is compulsory to succeed demonstration objectives. Hence, at the end of this first mission analysis phase the suborbital scenario was selected.

Critical points identified up to then were: visibility issues for intermediate inclinations, safety linked to Pre-X reachable domain (Pacific islands, depending on lateral Pre-X range), low latitudes associated to Pre-X recovery, Z9 footprint reduction and its impact on launcher performance. In order to improve these critical points, the baseline of the investigation was then to find a solution compatible with an equatorial scenario. This type of mission improves launcher performance, enables the use of Ariane telemetry network and drives to easier latitudes when regarding Pre-X vehicle recovery.

## 3. Equatorial scenario: optimisation ascent phase and Pre-X re-entry phase

Once selected the equatorial scenario and the injection strategy (suborbital mission), the objective was to reoptimise Pre-X re-entry conditions (Vr, $\gamma$) together with launcher performance (compliant with maximal mass foreseen for Pre-X) taking into account all the constraints linked both to Pre-X mission requirements and to launcher definition. To do so, the system approach is based on a global optimisation of the launcher ascent phase and the Pre-X re-entry phase with, in particular, parametric analysis on the kinetics conditions at the beginning of the re-entry (coupled point) to be compatible with Pre-X demonstrator objectives.

### 3.1 Problem statement

Different couple of Pre-X re-entry parameters were chosen taking into account the impact of the Earth angular velocity. First analytical computations allowed reducing the boundaries of Vr-$\gamma$ domain to be studied. In this case the inclination is fixed to the optimal one. Consequently, the relative velocity and the flight path angle to be reached at Pre-X injection (120 km altitude) result into the orbit definition (apogee and perigee altitudes) and therefore into the launcher optimal performance level.

### 3.2 Results of parametric study

The figures 3.1 and 3.2 show the main results of the mission analysis. Each curve corresponds to a couple of parameters defining Pre-X re-entry conditions (Vr, γ) at 120 km altitude. In what concerns ascent trajectories, maximal performance is guaranteed with the trajectory optimisation without any other constraint. The lost of performance, is given by the trajectory constraint that allows to shift forwards VEGA third stage Z9 impact point on Indian Ocean far away from African coast. Strongly linked, because of suborbital injection scenario (reduced degree of freedom), this constraint impacts Pre-X injection point at 120 km (shifted backwards on the ground track) which gives a first evaluation of the maximal admissible range.

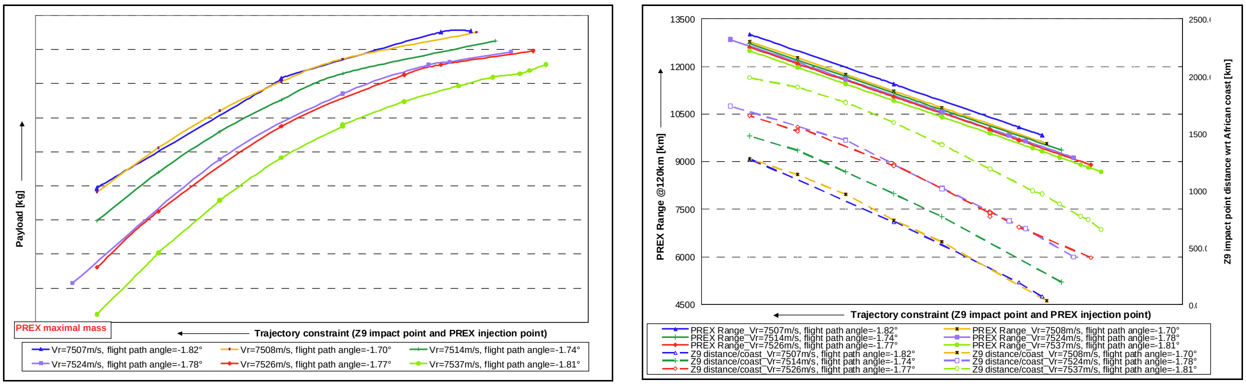



Fig. 3.1 –Performance (payload + specific adaptor) - Pre-X range and Z9 impact point distance wrt. African coast.

Launcher performance will depend indeed on Z9 footprint management (solid rocket motor which drives to a dispersed injection point at stage separation) ensured by the guidance, but also on the Pre-X reachable domain.

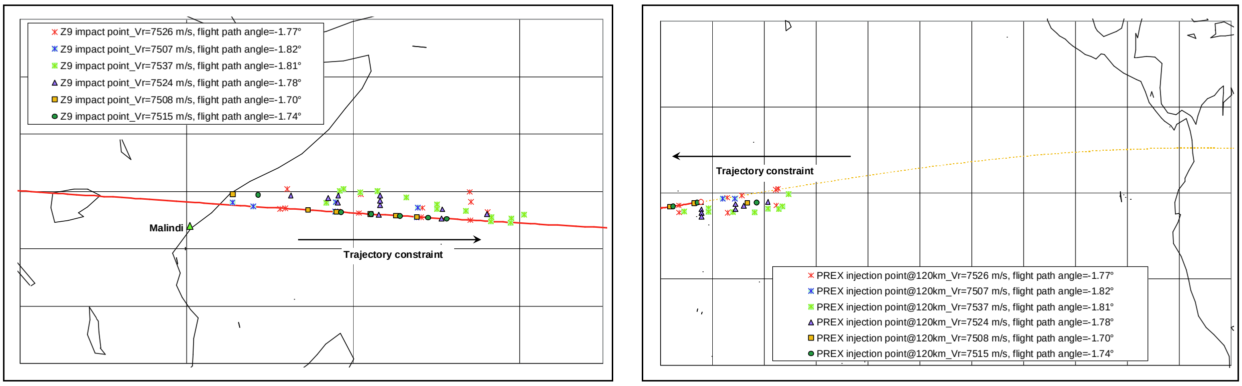



Fig. 3.2 –Z9 impact point wrt African coast (Indian Ocean) and Pre-X injection point@120 km (Pacific Ocean).

Pre-X reachable domain is computed considering the maximum and minimum downrange/cross-range for a nominal angle of attack in hypersonic flight up to Mach 1.5. Some results are given in next figure 3.3.

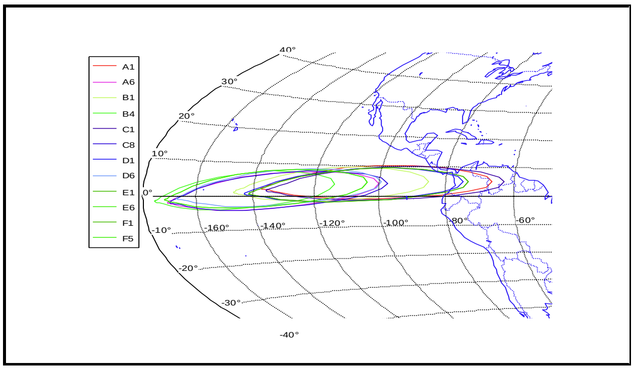



Fig. 3.3 –Pre-X reachable domain results

Concerning re-entry, optimal trajectories have been assessed and the evolution of main sizing parameters is shown in figure 3.4 for different re-entry conditions. We list hereunder the relative conclusions:

- The altitude profile depends on re-entry conditions. No big variations are shown as narrow domain is considered.
- The heat flux at stagnation point depends mainly on vehicle mass and flight path angle. In addition, it is important to notice that low velocities (in the studied domain) do not drive necessarily to reduce level of flux. This phenomenon can be explained by the fact that due to low momentum the flight path angle increases faster. Starting with the same initial flight path angle at re-entry interface when aerodynamic forces are still negligible the impact of this increase of flight path angle may compensate or even exceed that of reduced velocity.
- The maximal dynamic pressure depends slightly on the re-entry conditions but mostly on the vehicle mass.
- The maximal transverse load factor is always much lower than the sizing admissible value.
- The difference between the reachable domain downrange (distance between maximum and minimum longitudinal point at M=1.5) with different re-entry conditions (Vr, γ) varies at maximum 1000 km. The main driver is then the positioning of this domain to ensure safe splashdown on the ocean far from coast.

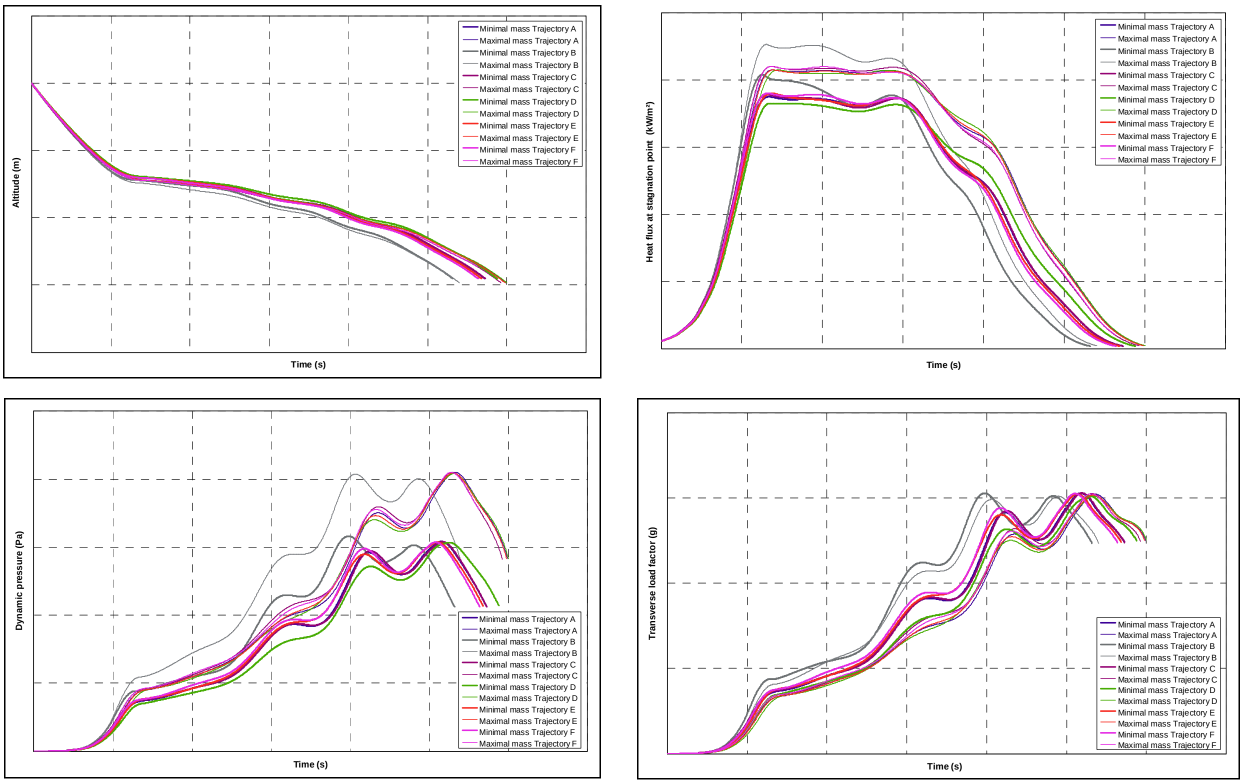



Fig. 3.4 –Pre-X re-entry parameters evolution: Altitude, heat flux, dynamic pressure and transverse load factor.

In conclusion, all the re-entry trajectories inside the Vr-γ domain are admissible from Pre-X vehicle sizing point of view. Up to now, the main drivers of the mission analysis are reduced to:

- Launcher performance and Z9 impact point: third stage footprint shall be acceptable
- Pre-X heat flux at stagnation point and the reachable domain on the Pacific Ocean.

VEGA upper stage AVUM falls down in a safe way in the Pacific Ocean and it is not an issue on this scenario.

### 3.3 Analysis and choice of Pre-X injection conditions

A sensitivity analysis leads to the construction of a total launch-system (including Pre-X demonstrator) design chart to select the optimal combination of launch delivered perigee, apogee, mission payload and targeted injection point. Main findings of the sensitivity analysis are:

- The impact on the performance is more important if considering variation on the relative velocity (-2 kg/m/s) than the one on the flight path angle (-4 kg/°). Even if sensitivity value is higher, flight path angle variation is already limited by the admissible maximal heat flux at stagnation point of the Pre-X re-entry

trajectory ( |γ| not very high) and, on the other side, to avoid atmospheric rebound ( |γ| not very low). Lost of performance in the graphic is up to 200 and 400 kg mostly given by the velocity variation.
- Moving Z9 impact point far away from African coast has a more important impact on performance if the energy of the launcher injection orbit is lower. So high energy orbit gives better performance with identical Z9 impact point.
- Moving Z9 impact point far away from coast drives to move backwards Pre-X injection point with respect to the American coast (so higher range could be admissible). The ratio of displacement is around 2/5.
- Pre-X reachable domain is mostly impacted by Pre-X relative velocity at 120 km injection, as flight path angle variation is really small. Difference of 1000 km has been found inside the Vr-γ domain.
- Maximal heat flux found in the re-entry trajectories are in all cases compatible with the thermal sizing of Pre-X vehicle.
- No island is placed inside the footprint of launcher stages or in the Pre-X reachable domain. Special care has been taken with respect Pacific islands as Galapagos.

Finally, the main driver of the mission analysis is the Z9 impact point. The distance to be respected gives the order of magnitude of launcher performance. Higher energy orbit will reduce the impact on performance of Z9 impact point constraint; but on the contrary, this energy shall be limited as it will increase slightly the heat flux found by Pre-X at re-entry. The Z9 footprint control will be issued from a compromise of lost of performance between trajectory constraint and launcher guidance algorithm.

The following chart gives a synthesis of the orders of magnitudes of the main parameters, allowing the selection of the reference Pre-X mission with VEGA launcher.

Table 1: Synthesis of the parametric study for the equatorial scenario

| Pre-X Maximal longitudinal range (distance from coast: place available for reachable domain) | Payload | Z9 impact point distance wrt. African coast |
|---|---|---|
| ~9500 km | >2300 kg | 600-1000 km |
| ~11000 km | ~2240 kg | 700-1500 km |
| ~12000 km | ~2100 kg | 1300-2000 km |

Payload is coherent with the performance given in the VEGA launcher User's manual [1].

### 3.4 Scenario proposal

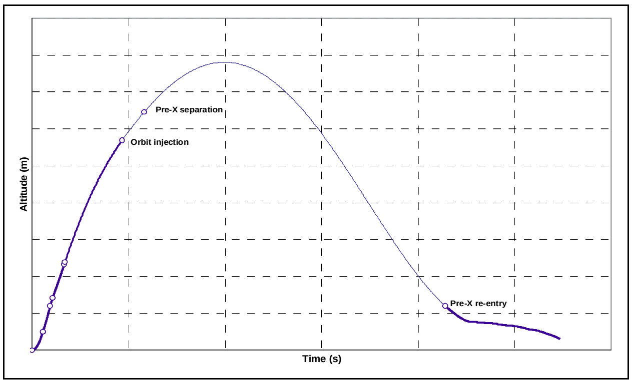
Even if several solutions are valid, in this feasibility analysis with a global optimisation approach, it was however searched that together with maximal launcher performance, safety aspects were at maximum guaranteed by the robustness of the mission definition. A conservative choice avoiding high penalty on launcher performance has therefore been considered with respect to the trajectory constraint. The Z9 impact point guarantees at least 1500 km distance with respect to the coast. Pre-X injection targeted parameters at 120 km altitude are the following:

Table 2: Pre-X injection parameters at 120 km altitude

| Longitude | Latitude | Relative velocity | Flight path angle | Azimuth |
|---|---|---|---|---|
| -175.36° | -2.16° | 7536.8 m/s | -1.81° | 85.01° |

The overall performance of VEGA launcher from Guyana launch pad is over 2200 kg for this mission, compatible with maximal mass foreseen for Pre-X demonstrator and with enough margins to cover specific adaptor and possible losses.

The current baseline mission is performed by the VEGA launch vehicle in a quasi equatorial ballistic trajectory. The spacecraft makes an almost complete earth revolution before splashing down on the Pacific Ocean. The vehicle re-entry point is at 120 km with the injection parameters of table 2 and the mission objectives are fulfilled between Mach 25 and 5. Then the parachute opens and it is finally recovered in the sea. Nominal flight foresees an impact at the mean way between Galapagos and Marquise islands. There the spacecraft is recovered by boat.



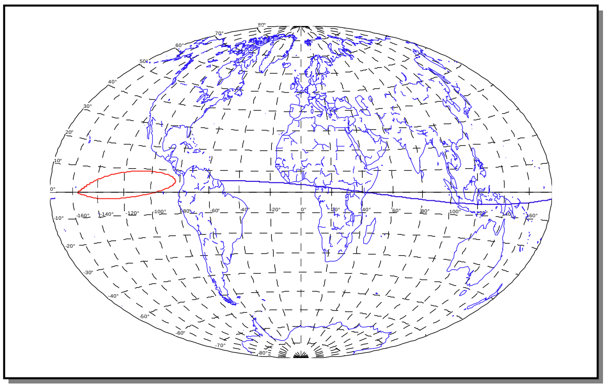



Fig. 3.5 –Pre-X mission with VEGA launcher (Equatorial scenario)

Direct visibility is guaranteed by Ariane station network for the whole launcher trajectory up to Pre-X separation: Galliot, Natal, Ascension and Libreville. In addition, ballistic phase after Pre-X separation is partially covered by Malindi and Biak. However, this last station is not enough to ensure visibility up to vehicle re-entry as visibility is lost 500 s before injection at 120 km. But up to now, only Pre-X visibility at separation is required.

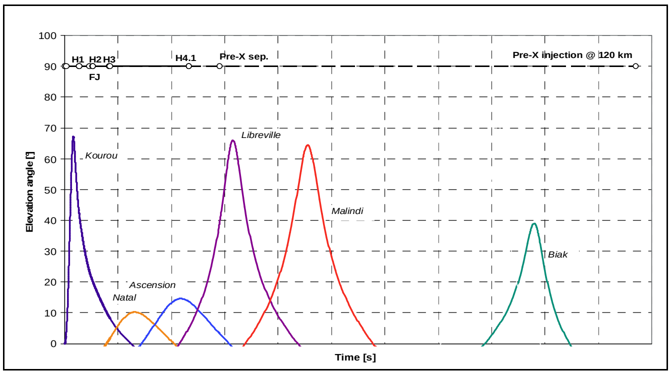



Fig. 3.6 –Tracking network

## Conclusion

A feasibility analysis of Pre-X mission by VEGA launcher has been performed by CNES with an overall optimisation approach. The particularity of such a mission was to cope with Pre-X demonstration objectives compatible with VEGA definition and safety aspects. Several injection strategies and different orbital inclinations have been investigated, but at the end, the analysis has been focused on the definition of Pre-X re-entry gate parameters for an equatorial scenario being the best choice regarding launcher performance, visibility network, and demonstrator recovery area. The identification of main drivers of the whole mission (ascent and re-entry phases) as well as their impact on launcher performance, have allowed the mission selection.

Particular attention has been paid to safety aspects which shall be at maximum guaranteed by the robustness of the mission definition. A conservative choice avoiding high penalty on launcher performance has therefore been proposed. The overall performance of VEGA launcher from Guyana launch pad is over 2200 kg (coherent with the User's Manual performance), compatible with maximal mass foreseen for Pre-X demonstrator and with enough margins to cover specific adaptor and possible losses.

As VEGA LV development is under the responsibility of ESA/IPT, this scenario shall be subsequently consolidated if selected.

## Acknowledgments

The authors would like to thank CNES Pre-X team.

## References

[1] Arianespace. VEGA User's Manual Issue 3, March 2006

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