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Design of CALLISTO Tilt and Reentry flight sequences

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Abstract

CALLISTO project is a joint effort of JAXA/DLR/CNES agencies to demonstrate critical technologies for recovery and reuse of an operational vehicle first stage. In particular, some specific flight sequences are necessary to perform the recovery of the vehicle. This paper addresses two of the CALLISTO mission critical flight phases, namely the so called "Tilt over" and the reentry.

In a first section, CALLISTO Mission sequence is presented. Emphasis is put of the two phases of interest in this paper, from the standpoint of trajectory, and specific constraints and objectives are underlined. In particular, link to the primary goal of reaching the landing site is done. In a second part, the main properties of CALLISTO Vehicle which are taking part of the balance between constraints and objectives are discussed, in particular mechanical and flight control architectures, as well as aerodynamics. Flight control strategy throughout the two flight phases of interest are discussed. Then, specific flight control issues of each phases are tackled, and discussed with regard to their implication toward the other disciplines affecting Vehicle design. Some preliminary simulations are performed enabling to assess performance and compliance to constraints. Outline of coming work is proposed as a conclusion.

Acronyms
FCSA : Flight control system aerosurfaces
RCS : Reaction Control System
TVC : Thrust vector control
VEB : Vehicle Equipment Bay
ALS : Approach and landing system

1. Introduction

JAXA, CNES, and DLR are jointly conducting concept design and project definition activities for a vertical take-off, vertical landing, experimental vehicle called CALLISTO (Cooperative Action Leading to Launcher Innovation for Stage Toss-back Operations) (see [1] & [2]), which objectives are to master key technologies to recover and reuse future operational reusable first stages. The technology performances will be linked with operational capability in order to validate the concepts, verify the cost model hypotheses and identify further enhancement.

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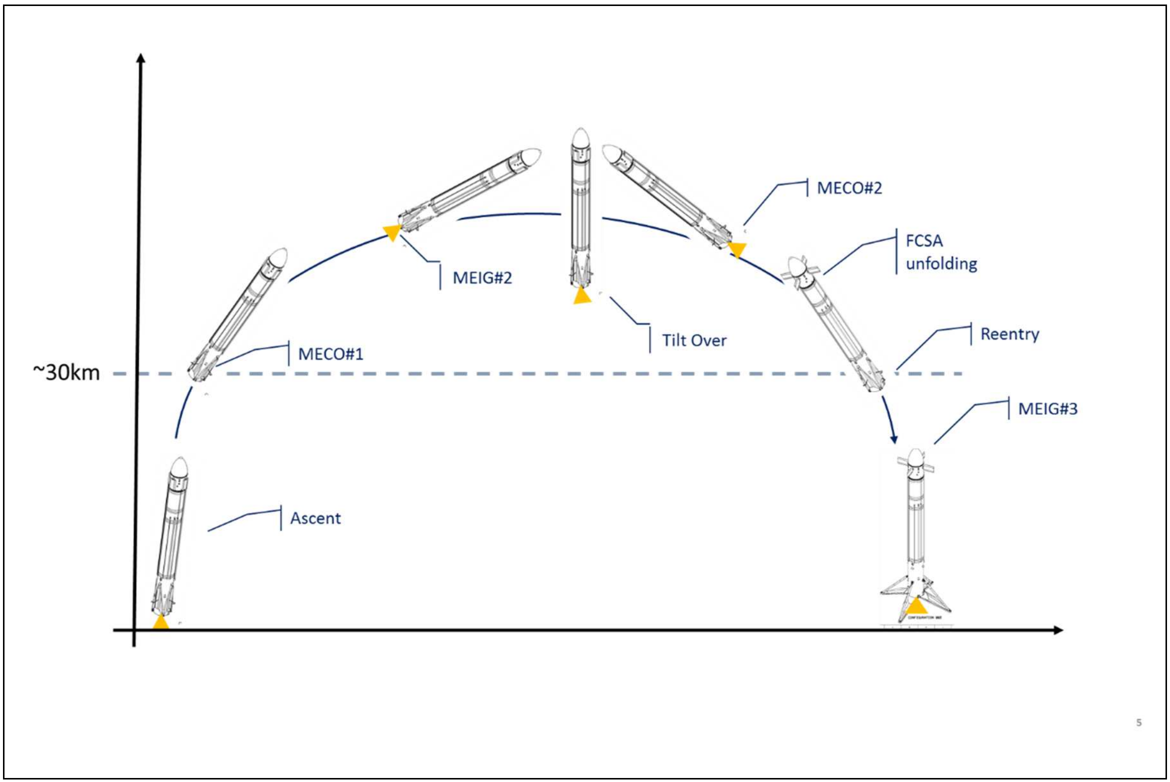
This paper is proposing an overview of the design of two peculiar flight sequences composing CALLISTO vehicle mission architecture, so-called "tilt-over" and "reentry".

1. CALLISTO Missions

Mission profiles have been conceived in a way to demonstrate the objectives described above in one or several flights. Figure 1 illustrates two class of possible demonstration flight profiles, in terms of altitude versus Mach and longitudinal acceleration vs time. Quantitative details on missions can be found in [4]; general mission architectures are sketched on Figure 1:



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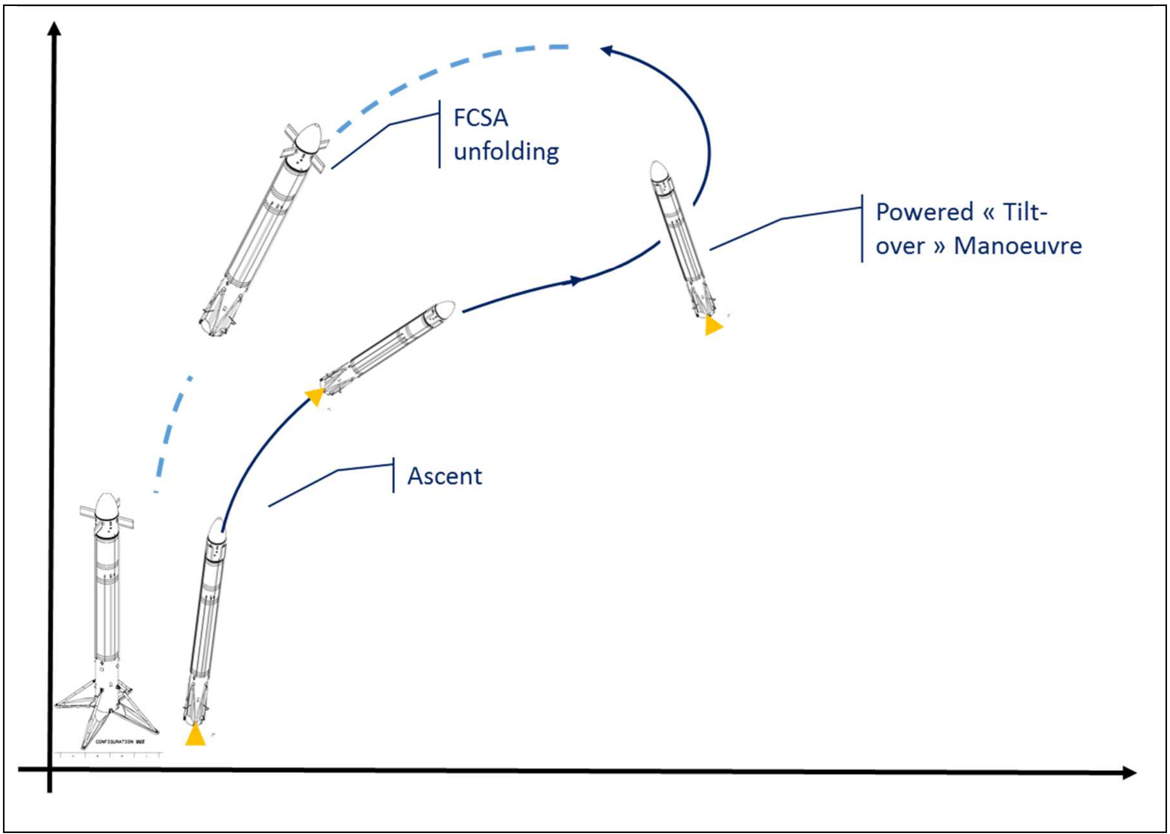

Figure 1. Mission architectures
Flight profile #1 (top) and flight profiles #2 (bottom)

In this paper, two peculiar phases are of interest:

- The phase succeeding ascent phase, called "tilt manoeuvre" during which vehicle orientation is changed in a significant manoeuvre such as to either:
  - Prepare for subsequence boost that will provide ΔV (flight profile #1)
  - Provide velocity vector change (flight profile #2)
- The re-entry phase, during which vehicle will limit dispersions that have been built up along previous flight phases

In both cases, end of ascent phase occurs at conditions where dynamic pressure is still not negligible, so that aerodynamic disturbances applied on the vehicle present a significant challenge from the mission design standpoint, in strong interaction with mechanical and GNC system capability.

In case of flight profile #1, the tilt manoeuvre is performed either:

- under engine OFF conditions, relying on control capability of reaction control systems (FCS/R).
- under engine ON conditions, relying on TVC control capability

In case of flight profile#2, right after end of ascent, main propulsion system is not shut-down, but vehicle enters a maneuver at relatively high dynamic pressure and angle of attack so as to significantly modify velocity slope and to enter into a return trajectory with a target landing site close to Lift-Off site.
Both sequences present similar issues with respect to vehicle System design.

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After this manoeuvre, vehicle is prepared for re-entry in order to either :
- Get back to a landing pad, close to launch site
- Reach an offshore landing site

Reentry occurs at supersonic Mach number, maximum value however depending on the mission.

1. Mechanical & GNC System architectures

CALLISTO Vehicle is a single stage vehicle around 13 meters high and with a 1100mm diameter. General architecture of CALLISTO vehicle is outlined on Figure 2:

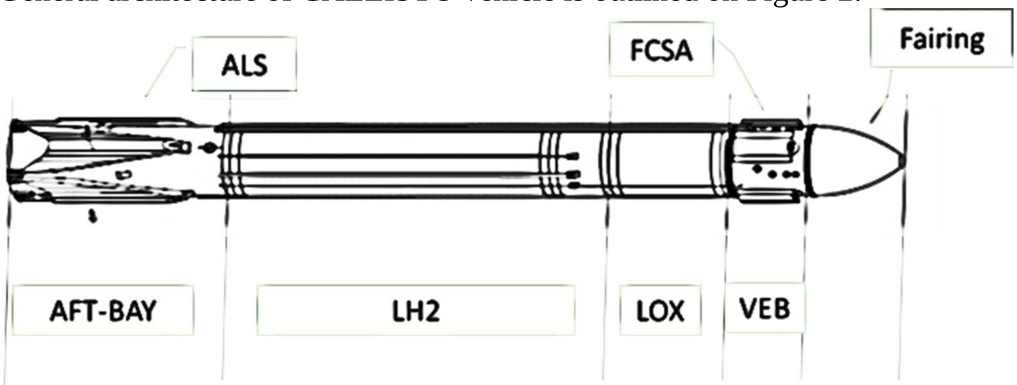

Figure 2. Mechanical architecture of CALLISTO Vehicle

Main items composing CALLISTO vehicle mechanical architecture are :
- ALS : approach and landing system: , unfoldable
- Aft-Bay : accommodating pressurant system and engine, as well as ALS
- Propellant tanks (LOX and LH2)
- VEB : Vehicle Equipment Bay, accommodating avionics, as well as FCSA & RCS control systems (see under)
- Fairing : designed for limiting ascent aerodynamic drag

With respect to conventional expendable launcher, primary structures are undergoing a large set of mechanical load cases. Noticeable ones include reentry and landing, however high angle of attack experienced during tilt over manoeuvre also needs to be monitored in order to check that it doen not lead to sizing cases. Compared to legacy launch vehicle, introduction of loads at various specific locations on the vehicle changes classical load path. Good examples of such peculiarities are FCSA, which loads are directly introduced into VEB, and ALS, which loads are locally introduced to aft-bay.

The various flight phases experienced by CALLISTO vehicle also require a specific flight control configuration with respect to conventional operational launchers, leading to a blend of sensors and actuators whose usage varies along flight in order to cope with the performances requirements of each phase. This configuration is illustrated on Figure 3. Three kind of actuators compose the architecture of the flight control systems on CALLISTO:
- Aerodynamics surfaces (FCSA) : 4 aerodynamics surfaces actuation system, unfoldable that also allows for a 3-axis control of the vehicle when aerodynamic efficiency is high enough
- RCS : ON/OFF thrusters system, located near the top of the vehicle
- TVC : classical two axis main engine gimbal angle actuation system.

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To be noticed that JAXA RSR2 engine, derived from JAXA RV-X RSR engine (see [3]) is throttlable, thus fully taking part in Vehicle flight control strategy.

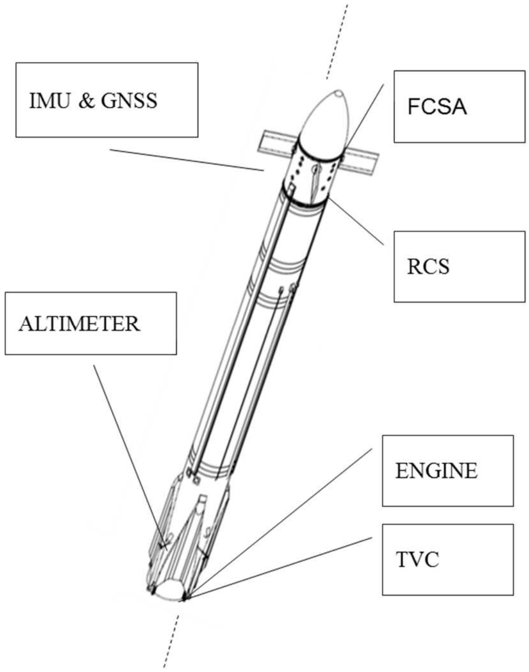

Figure 3. Flight control reentry configuration

2. Tilt manœuvre

Tilt maneuver design is mostly challenging due to the residual atmospheric density around 30-40km, combined with velocity necessary to achieve mission profile. Management of this issue is performed on a tw- fold basis :

- Explicit constraint on Mission profile dynamic pressure at end of ascent
- Detailed maneuver design taking into account GNC system capability as well as mission profile requirements

Usage of explicit dynamic pressure constraint at end of ascent can lead to significant deformation of trajectory profile and was thus used in a limited fashion. At the contrary, extensive study of GNC system limits was performed so as to better formulate mission profile constraints and integrate them explicitly into the trajectory design. In particular, aerodynamic disturbance torque created by build-up of AoA during maneuver was assessed against either TVC control capability and/or RCS control capability depending on the flight profile. Mission requirements were, however, different depending on the flight profile. For flight profile #1, were landing site is located apart from launch site, it is necessary to control the vehicle through an AoA range close from 0° to 180° with an almost constant Mach number, and quite significant remaining dynamic pressure among the whole sequence; This is due to the fact that the vehicle need to achieve the downrange dstance necessary to get to the landing site. Few degrees of freedom would then remain if control capability was to be strong limitation.
For flight profile #2, where launch & landing site are located close one from each other, a trade-off on mission profiles vs control capability can be performed. Indeed, AoA rate build-up during manoeuvre can be designed so as to adapt to vehicle limitations. This, however, leads to extreme

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variations in flight profile as the manoeuvre is the flight sequence during was landing site targeting is performed. Thus, strong coupling is to be managed between:

- Nominal AoA profile
- Downrange change achieved during manoeuvre
- Accuracy of ΔV delivery

Detailed analyses have been performed such as to better understand allowable flight domain inside which vehicle was able to operate without jeopardizing flight control capability, as well as mechanical sizing. Multidimensional domain were defined, on various kinematic and vehicle state parameter, such as illustrated on Figure 4

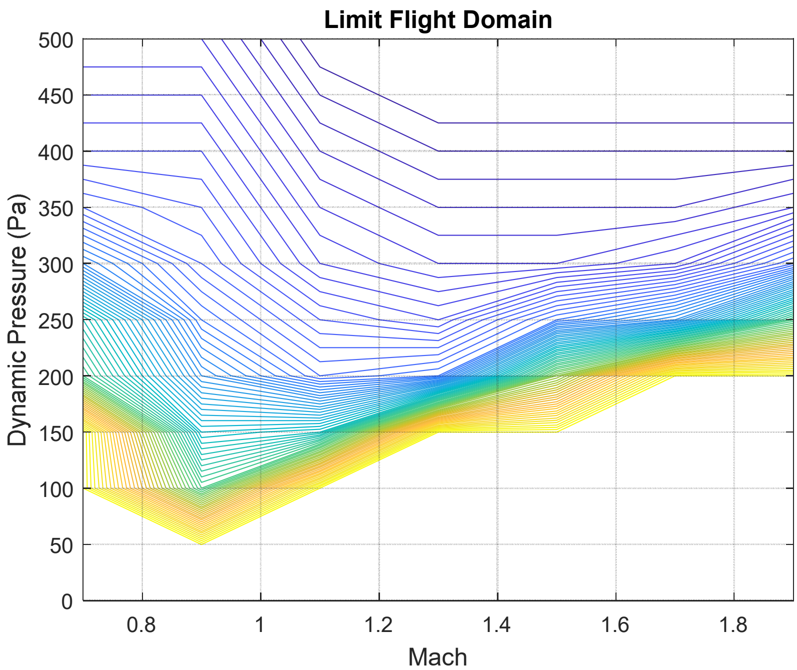

Figure 4. Notional allowable flight domain

Figure 4 is an example of three dimaensionnal representation featuring Mach number in x-axis, Dynamic pressure in y-axis, and the vehicle state parameter of interest as iso-contour plot. Typical parameter of interest include angle of attack, accelerations, thrust, etc.. Each contour line defines a admissible level of that parameter, not to be exceeded considering a given couple (Mach, Q). this approach enables to identify a maneuver design space in to which mission design is to be performed.

According to these limitations, maneuver design has been initiated, with iterations between mission, flight control and stress analyses. Figure 5 illustrates on one side the kind of attitude profile which is followed during powered maneuver and on the other side the comparison between disturbance and control torques:

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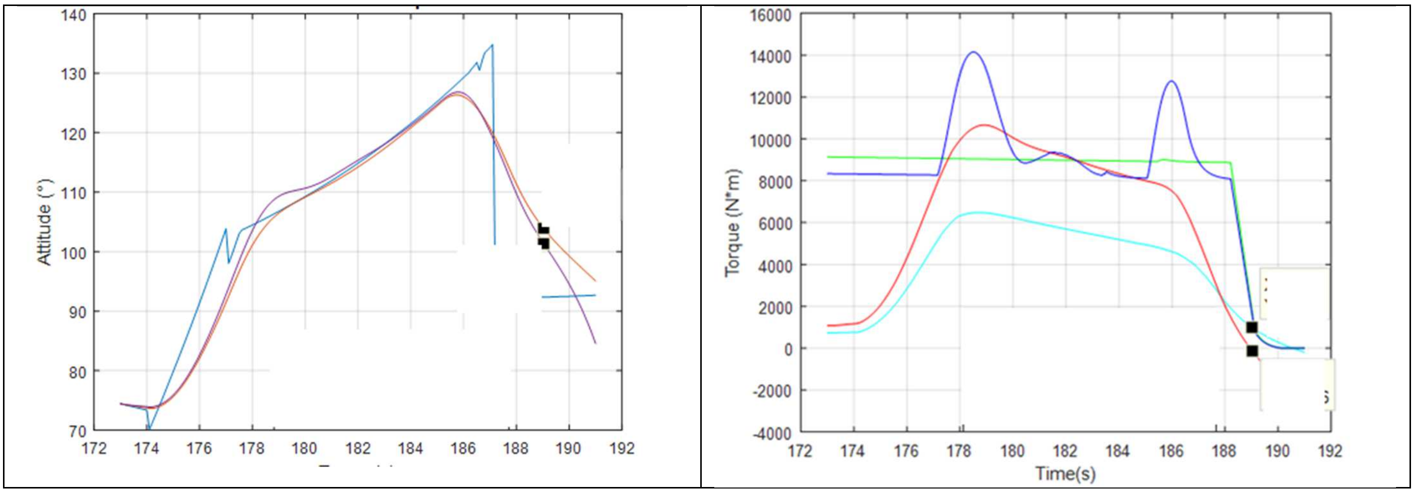

Figure 5. Power tilt-over manoeuvre sequence - Attitude history (left)- control vs disturbance torques (right)

On Figure 5 left side, blue plot represents the guidance command necessary to achieve trajectory profile. On red and purple are the realized attitudes for nominal vehicle characteristics and dispersed characteristics, obtained through simulation of 2D flight dynamics of controlled vehicle. Results show good performance tracking. On the right side, the comparison between disturbances torques and control torques is performed, were light blue and red represent aerodynamic disturbance torques linked to the residual dynamic pressure, for two dispersion cases, and light green and deep blue are the available control torques. At first, it is to be noticed that uncertainties associated to vehicle characteristics (in particular aerodynamics) ane environments lead to very significant increase of disturbance torques. Then, according to inputs commands and disturbances, control torque is determined through a dedicated control strategy, allowing to manage vehicle performance despite disturbances.

3. Reentry design

CALLISTO reentry is performed at relatively low Mach numbers compared to other typical space vehicle reentry, relieving some strong constraints such a thermal loads management ; despite this difference, it is still a critical phase wrt to mission profile success for, at least, two main reasons :

- Reentry phase enables to dissipate some of the kinetic energy accumulated along flight, and thus plays an important role in the energy with will remain to be dissipated by landing boost
- Flight profile dispersions accumulated along flight can be partially compensated during this phase, through the use of vehicle lift capability. Accuracy requirement for CALLISTO being extremely stringent (some meters at end of reentry), making accuracy management a pre-requisite for mission success.

These high level objectives can however be conflicting with system design contraints such as vehicle mass or lift capability. In order to trade the vehicle system level constraint during early design phases, dedicated reentry strategies were developed, giving more insight into CALLISTO technical problematics and highlighting trade-offs and design choices to be made.

Figure 6 illustrates two alternatives of reentry strategy that have been looked at. One left-hand side, reentry strategy has been directed toward early recovery of beginning of entry dispersions. Significant lateral position dynamics is generated leading to two issues:

- Large dispersions on the actual flight profile which is followed

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- Overshoot wrt to reference trajectory, then requiring over compensation of downrange with possible, large downrange errors at landing boost ignition point.

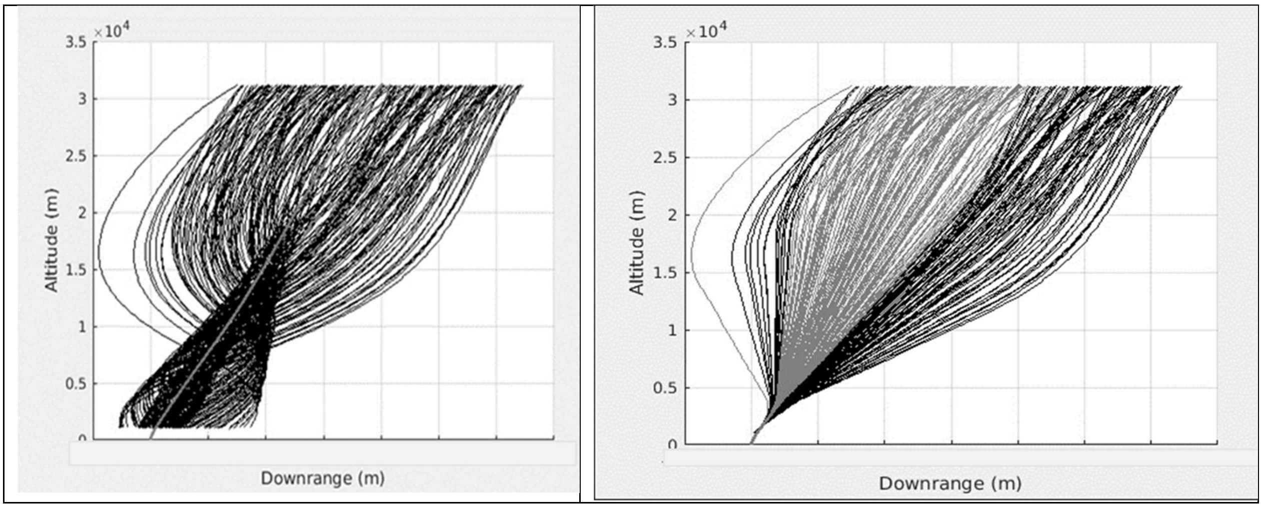

Figure 6. Reentry strategy altitude/Downrange profiles

One other flight strategy that has been studied was targeting smoother recovery of initial dispersed conditions; on Figure 6, light grey represents flight profile which have recovered from these initial dispersions. One can notice that on the second strategy (right hand side) some of these conditions have been recovered, while very few were actually recovered with the first reentry strategy. This is mainly due to a better management of available control energy at vehicle level through aerodynamic flying qualities.

Another major aspects of this second recovery strategy trade-off study is the implication in terms of required aerodynamic performance which is demanded to the vehicle. On Figure 7l , the aerodynamic command which is used to compensate dispersions is potted, for the two strategies.. Left hand side figure exhibits significant command dynamics which is demanded by the error compensation strategy; at the contrary, right hand side figure shows:

- rather smooth command profiles
- Lower mean values

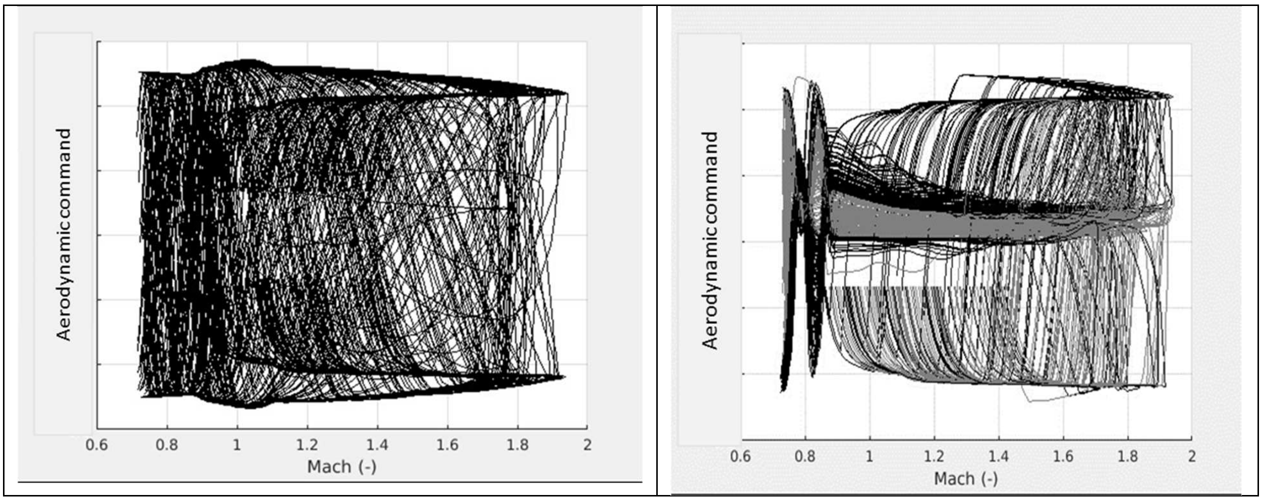

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Figure 7. Reentry strategy command profiles

Command demand does not only affect vehicle actuators, but also general loads through accelerations induced by maneuvers on the vehicle. Thus reentry strategy has also been extensively traded against consequences on the vehicle, such as potential mass increase, resulting in strong design choices.

Systematic analyses of reentry induced loads has been performed such as to highlight conflicting requirements between manouvrablity and mechanical sizing. Figure 8 provides typical analyses of compression flux transiting through primary structures depending on reentry strategy depending on Mach number. Plain lines correspond to the various strategies while red dotted line was defined as being Limit Load not to be exceeded.

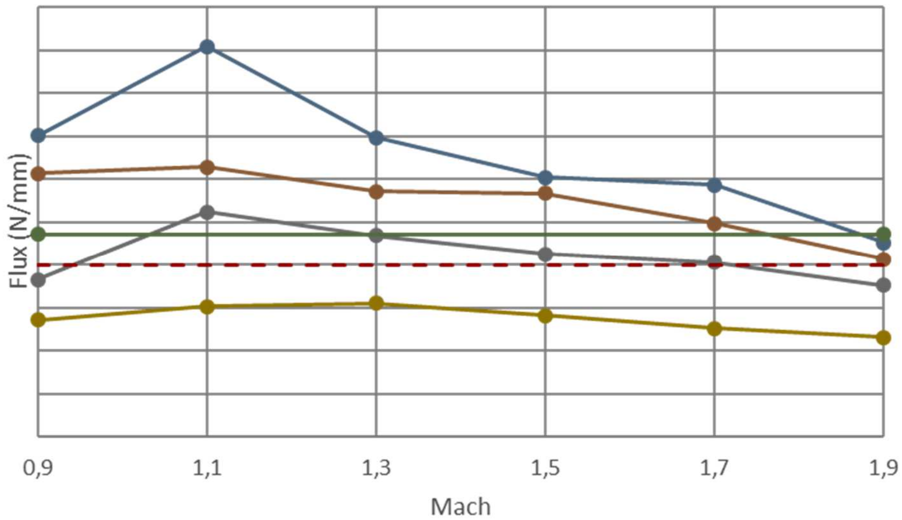

Figure 8. Mechnical stress function of reentry strategy

Through short loop co-engineering, design space was set and addressed, leading to compromises on various systems enginerring disciplines.

4. Conclusion

CALLISTO missions and flight envelopes are tightly linked to vehicle capability in terms of flight control and mechanical sizing.
Through concurrent engineering developed in early project phases, main technical disciplines have been involved into mission design and mission architecture definition.
Two specific flight phases were addressed in this paper, namely “Powered tilt over” and “Reentry”, for which design approach has been presented. Short loops, iterative definition and dedicated design methodology has been successfully developed to address complex mission & vehicle trade-offs.

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