High Lift-over-Drag Earth Re-Entry Strategies for Exploration Missions

HILIFT

Executive Summary Report

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1. ABSTRACT

The objective is to assess the potential benefits derived from the implementation of re-entry strategies requiring the use of lift-over-drag ratios in excess of those achieved by the Shuttle Orbiter and in particular for missions based on the use of a single spacecraft and entry profiles based on aerocapture with a subsequent (orbital) entry, or any other appropriate profile enabled by the spacecraft configuration.

High lift-to-drag ratio entry strategies applicable for human missions from and Beyond LEO are identified and evaluated for several candidate vehicles, besides suitable guidance techniques. The evaluation of the different concepts is carried out considering Flight Mechanics as well as System aspects like aerothermodynamics, advanced TPS materials like Ultra High Temperature Ceramics (UHTC), mass budget and operations.

The performances of the vehicle performing a High Lift entry are evaluated through detailed Monte Carlo campaign with close-loop guidance simulations.

A new concept has been created from scratch. It a sharp leading edge vehicle performing a LEO return mission with direct entry of long duration. Initial feasibility of this concept has been proven. The key enabler technologies have been also identified.

2. INTRODUCTION

2.1. Purpose

This document contains the Executive Summary of the High Lift-over-Drag Earth Re-Entry Strategies for Exploration Missions (HILIFT) study.

The purpose of the HILIFT study is to assess the potential benefits derived from the implementation of re-entry strategies requiring the use of lift-over-drag ratios in excess of those achieved by the Shuttle Orbiter and in particular for missions based on the use of a single spacecraft and entry profiles based on aerocapture with a subsequent (orbital) entry, or any other appropriate profile enabled by the spacecraft configuration.

The study has covered the following activities:

- Survey of Guidance Techniques for Earth re-entry for Human Missions ([RD1])
- Appraisal of Entry Techniques for the Earth re-entry of high L/D Vehicles ([RD2])
- High Hypersonic L/D Preliminary Reference Configurations ([RD3])
- Mission Analyses and Entry Parameters for Human Missions from and beyond LEO ([RD4])
- Guidance Techniques for Earth Reentry for Human Missions from and beyond LEO ([RD5])
- Entry Guidance Performance Verification ([RD6])
- Synthesis and Recommendations ([RD7])

2.2. Scope

This technical note is divided in the following sections:

- The reference documentation is listed in Chapter 3
- An overview of the Project is presented in Chapter 4
- The technical activities are summarised in Chapter 5.
- The conclusions of the study are presented in Chapter 6.

2.3. Acronyms and Abbreviations

The acronyms and abbreviations used in this document are the following ones:

Acronym	Description
AEG	Apollo Entry Guidance
APC	Analytical Predictor Corrector
CIRA	Centro Italiano Ricerche Aerospaziali
CoG	Center of Gravity
CRV	Crew Re-entry Vehicle

Acronym	Description
CSTS	Crew Space Transportation System
CTV	Crew Transfer Vehicle
DMS	DEIMOS Space
DS	Door Stopper
EDL	Entry, Descent and Landing
EIP	Entry Interface Point
ESA	European Space Agency
FTB	Flying TestBed
HILIFT	High Lift-over-Drag Earth Re-Entry Strategies for Exploration Missions
HLSO	High Lift Shuttle Orbiter
HS	High Speed
ISS	International Space Station
LEO	Low Earth Orbit
LLO	Low Lunar Orbit
NASA	National Aeronautics and Space Administration
NPC	Numerical Predictor Corrector
ORT	Orbital Re-entry Test
RD	Reference Document
SAS	Stability Augmentation System
S/C, SC	SpaceCraft
SoW	Statement of Work
SRR	System Requirements Review
SRT	Sub-orbital Re-entry Test
SSTO	Single Stage To Orbit
STS	Space Transportation System
TAS-I	Thales Alenia Space - Italy
TN	Technical Note
TPS	Thermal Protection System
TSTO	Two Stage To Orbit
WP	Work Package

3. RELATED DOCUMENTS

3.1. Applicable Documents

The following table specifies the applicable documents that shall be complied with during project development. They are referenced in this document by the form [AD.n].

Table 3-1: Applicable Documents

Reference	Title	Issue
[AD. 1]	Technical Proposal to ESA for High Lift-over-Drag Earth Re-Entry Strategies for Exploration Missions. In response to ESA ITT AO/1-5636/08/NL/HE.	1.0 16/04/2008

3.2. Reference Documents

The following table specifies the reference documents that shall be taken into account during project development.

Table 3-2: Reference documents

Reference		Title	Issue
[RD1]	HILIFTS-DMS-TEC-TNO001-E	TN4.1: Literature Survey of Guidance Techniques for Earth re-entry for Human Missions. DEIMOS Space	1.0 26/03/2009
[RD2]	HILIFTS-DMS-TEC-TNO002-E	TN4.2: Appraisal of Entry Techniques for the Earth re-entry of high L/D Vehicles. DEIMOS Space	1.0 26/03/2009
[RD3]	HILIFT-DLR-TEC-TN4.3	TN4.3: High Hypersonic L/D Preliminary Reference Configurations.DLR	Issue 1 Rev 1 05/05/2009
[RD4]	HILIFTS-DMS-TEC-TNO003-E	TN4.4-1: Mission Analyses and Entry Parameters for Human Missions from and beyond LEO. DEIMOS Space	1.0 14/09/2009
[RD5]	HILIFTS-DMS-TEC-TNO004-E	TN4.4-2: Guidance Techniques for Earth Reentry for Human Missions from and beyond LEO. DEIMOS Space	1.0 14/09/2009
[RD6]	HILIFTS-DMS-TEC-TNO005-E	TN4.5: Entry Guidance Performance Verification. DEIMOS Space	1.0 22/09/2009
[RD7]	HILIFTS-DMS-TEC-TNO006-E	TN4.6: Synthesis and Recommendations. DEIMOS Space	1.0 22/09/2009

4. PROJECT OVERVIEW

4.1. Introduction

Since the end of the Lunar Space career, human transportation has experienced its main development thanks to the operation of Low Earth Orbit (LEO) infrastructure. Starting for the 3 crew of the Salyut 1 in 1971, the number of humans in LEO stations surpassed 100 people during the Mir Station operation and currently, with the International Space Station (ISS), has reached 220. The total number of manned spaceflights currently exceeds 250, covering operational and demonstration flights, LEO and Moon missions.

The increase in the number of people in space required an evolution in the vehicle for the transportation up to the station and for the return to Earth in order to improve the levels of flexibility and crew comfort. The NASA Space Shuttle is currently the maximum exponent of the development of a crew transportation system for routine access to space of non-professional astronauts.

This study faces a step forward toward the improvement of the crew comfort and operational flexibility for the return of manned missions by using high lift-to-drag (L/D) ratios during the entry. The current level of L/D used by the Space Shuttle is the bottom line.

The performances of a re-entry strategy must be compared with the requirement of the mission for which is intended to be used. The objective of the study is not the definition of detailed mission architecture, but suitable mission requirements are required in order to derive a reference architecture for the evaluation of the performances and comparison with existing entry strategies.

The main effort of the work is devoted to the Flight Mechanics of high L/D re-entry strategies, comprising Mission Analysis, Flying Qualities and GNC, using advanced methods for the prediction and verification of vehicle performances. However, guidance techniques and entry strategies cannot be decoupled from the mission in which they will be applied, thus system aspects need to be considered, in detail namely aerothermodynamics, system architectures, Thermal Protection System and Operations. In other words, the feasibility of an entry concept from a pure Flight Mechanics standpoint needs to be to be feasible from a system's standpoint and consistent with actual or foreseen technological developments.

The entry strategies (short and long direct entry, skip and multiskip entry and aerocapture) are linked to the mission scenario (LEO, Beyond LEO), the characteristics of the vehicle (L/D and sizing) and the guidance technique. This is a 4-dimensional matrix whose elements are the candidates to be traded-off.

Main attention is devoted to the definition of the LEO return scenario, which includes the analysis of appropriate launch strategy and abort modes both during ascent and re-entry.

4.2. Project Team

The project team has been built to cover in detail all of the system and subsystem areas involved in a mission design loop with the aim of increasing the feasibility of the predictions. For instance, mass estimations need to be detailed enough as it is an enabler not only for the entry but mainly for the launch strategy.

Figure 4-1 shows the project team and responsibilities.

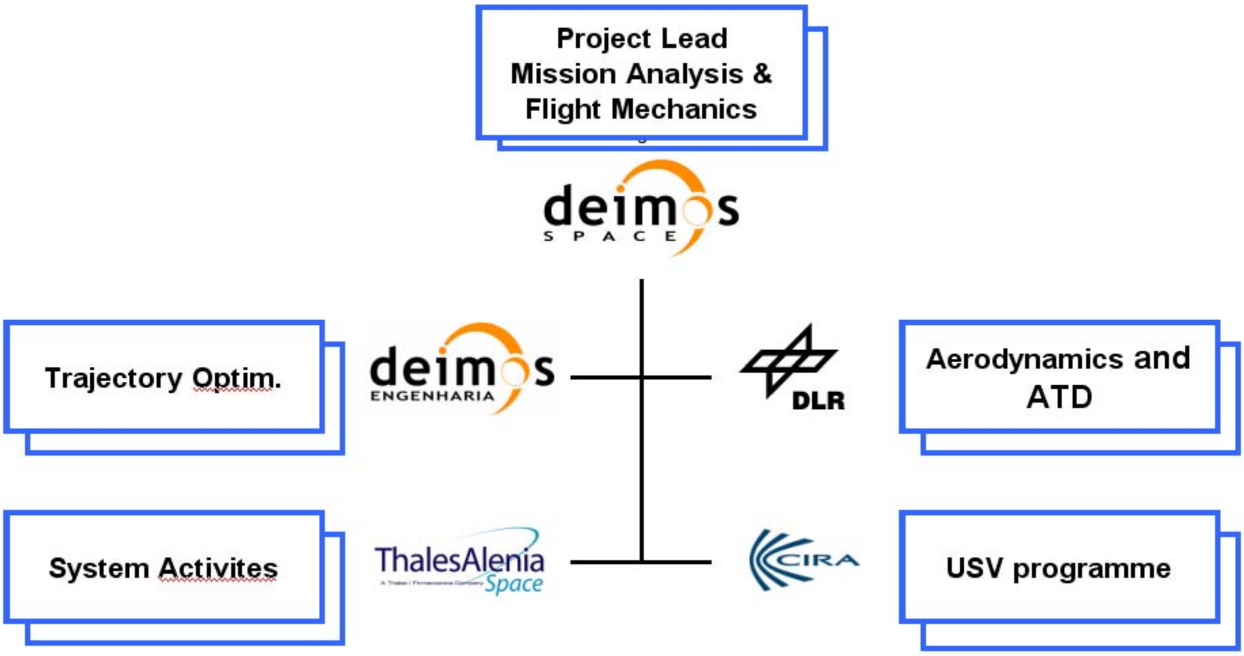


Figure 4-1 Project team of HILIFT

4.3. Project Milestones

The project is composed of the following Major Milestones

- **Trade-off of candidate concepts for High lift Entry (**Figure 4-2**)**

  Several mission scenarios have been studied in order to identify which is the best candidate to carry out a manned transportation mission with High Lift over drag entry.

  The mission scenario is composed of the following elements:

  - Vehicle: Lifiting Body, Winged Body, Advanced Sharp Leading Edge concept
  - Return scenario: LEO and Beyond LEO
  - Entry Technique: short direct entry, long direct entry, skip, multiskip and aerocapture

  In parallel, the activities carried out in the frame of the USV programme related to FTB-X vehicle have been reviewed, as the mission scenario for this experimental vehcileis based on a long direct entry with high L/D.

- **Selected Scenario for detailed assessments (**Figure 4-3**)**

  From the trade-off, the selected concept for detailed assessments is:

  - Scenario: return from ISS
  - Vehicle shape: advanced concept based on sharp leading edges (DS6 vehicle)
  - Entry technique: long entry flight with L/D beyond 2
  - Guidance technique: feedback like

- Guidance method: trajectory tracker

For this concept a complete loop of Mission analysis, Aerodynamics and Aerothermodynamics and System Architecture has been carried out.

- **Trade-off of launch scenario (**Figure 4-4**)**

The feasibility of a Space Transportation System cannot provide a reliable answer without considering the launch strategy. The launch of this kind of vehicle is a challenging task that requires dedicated studies in order to fully assess the feasibility of the mission.

To this end, three potential launch scenarios have been studied, their advantages and drawbacks and has evaluated the feasibility of each concept. The launch systems under study are:

- Conventional Vertical Ground Launch System.
- Airborne Launch System.
- Rail Guided Sled Launch System

- **Mission Performances (**Figure 4-5**)**

The performances of the proposed mission scenario for high lift entry are evaluated through close loop guidance simulations. A guidance function has been evaluated and assessed in a Monte Carlo campaign where uncertaintie4s in the state, system characteristics and environment are considered.

These detailed assessments for the DS6 concept are complemented with a preliminary Guidance evaluation for the FTB-X concept. Both results validate the feasibility of a long direct entry using high lift over drag entry.

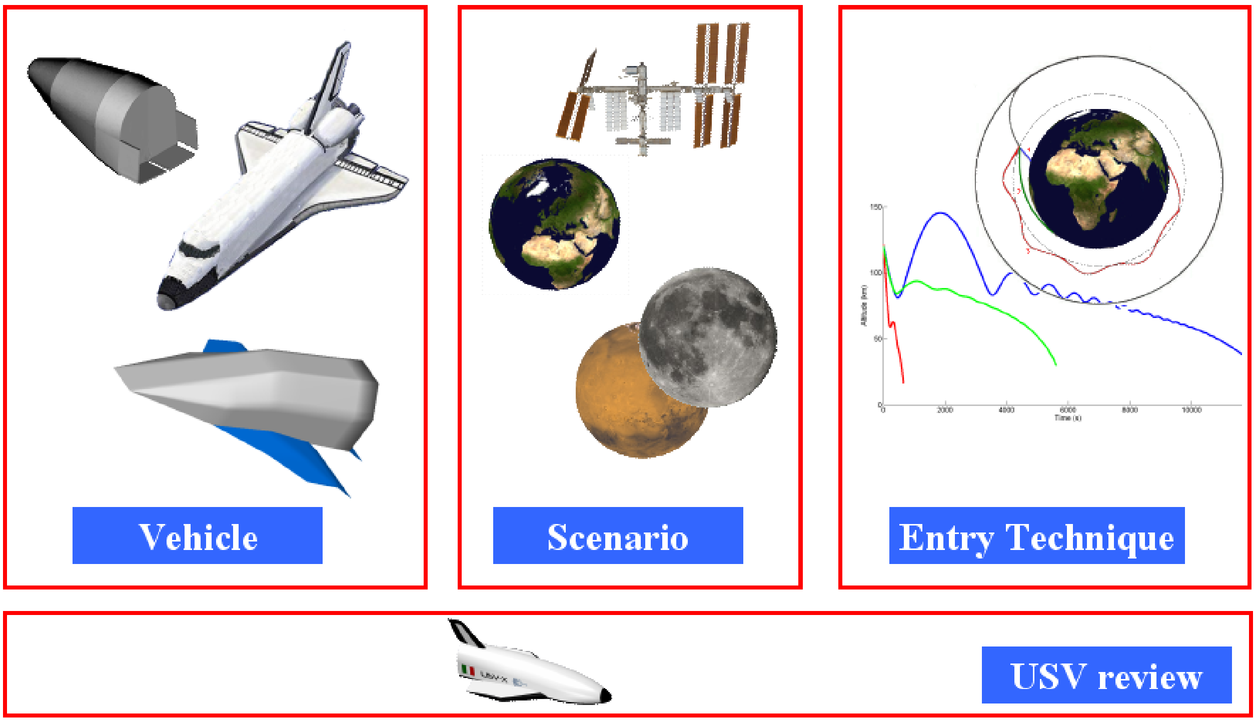


Figure 4-2 1st Milestone: trade-off of candidate concepts for High lift Entry

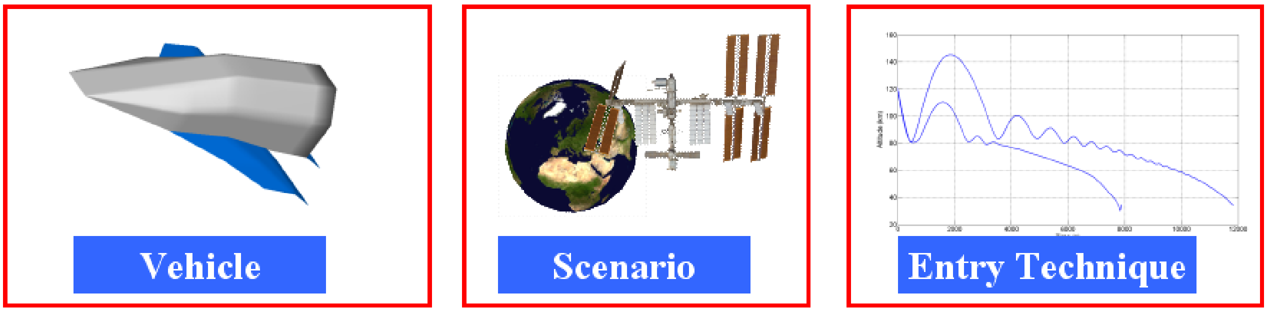


Figure 4-3 2nd Milestone: Selected Scenario for detailed assessments

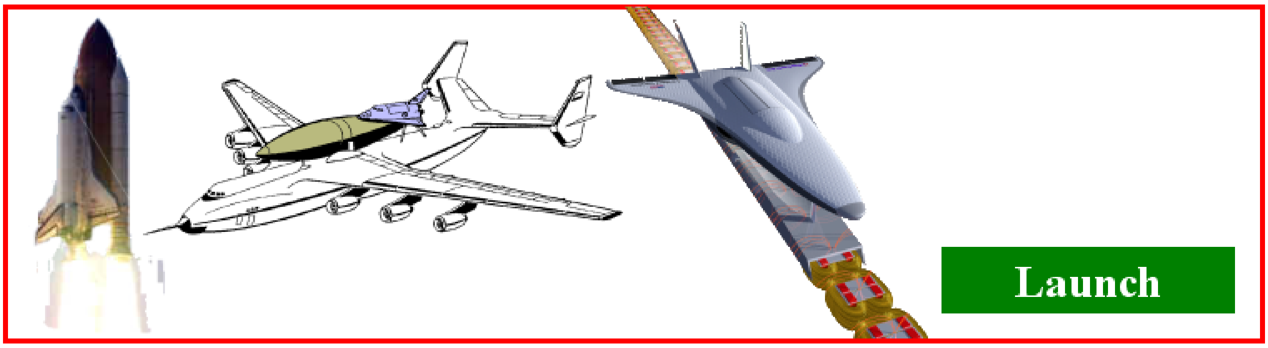


Figure 4-4 3rd Milestone: Trade-off of launch scenario

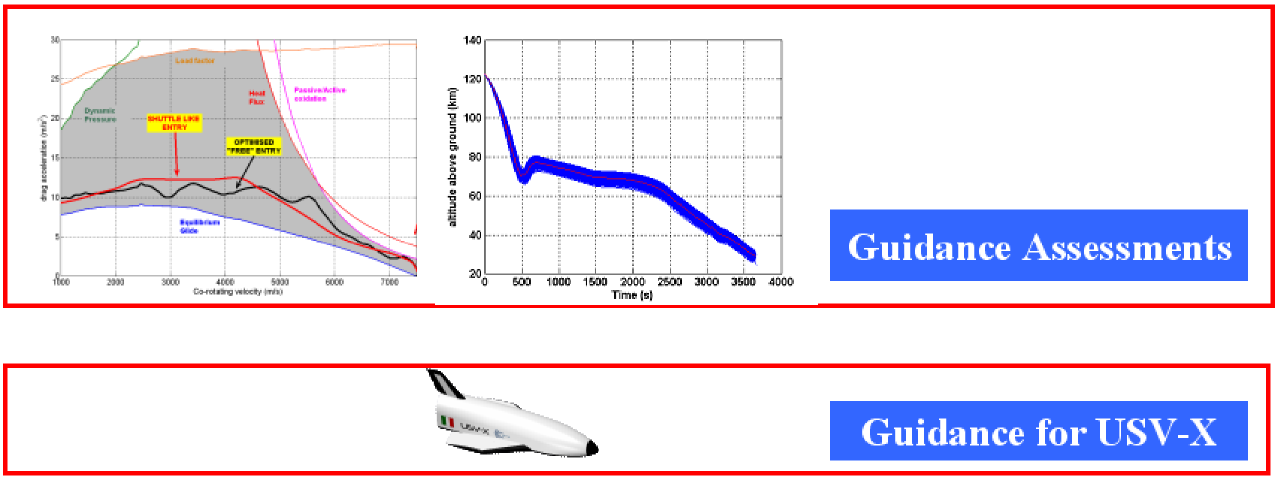


Figure 4-5 4th Milestone: Mission Performances evaluation

4.4. Mission Profile Summary

The summary of the proposed mission profile is presented in Figure 4-6.

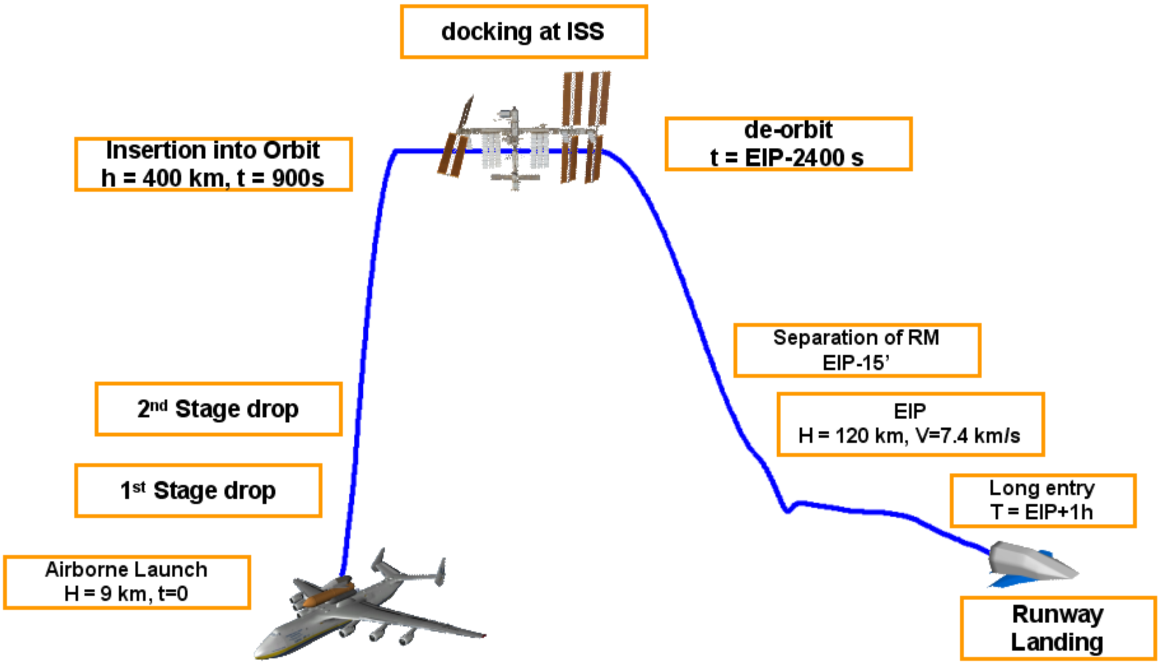


Figure 4-6 Summary of the proposed Mission Profile

5. SUMMARY OF TECHNICAL ACTIVITIES

5.1. Entry Strategies And Guidance Techniques For High L/D Vehicles

The objective of the planetary entry is to safely bring the spacecraft from orbital conditions to rest on the planet surface, dissipating the excess of energy it has at the EIP. Aerodynamic drag and lift are thus used to successfully steer the vehicle to the desired landing site. Table 5-1 shows the advantages and the drawback of using high L/D to perform an entry mission.

Table 5-1. advantages and drawbacks of high L/D entries

Advantages	Drawbacks
Lower g-loads	Reduced volumetric efficiency
Crew comfort (volumes)	Landing Site flexibility (runway)
Higher Cross range	Higher Heat Load
Re-planning capability	Complex TPS (localized heat)
Higher range	Complex GNC
Recovery (Horizontal landing)	Longer re-reentry duration
Reusability (TPS,..)	Non compatible with ballistic entry mode
Better Trajectory control	

Several entry strategies are compatible with the high L/D entry:

- Direct entry: the vehicle enters the atmosphere and decelerates with either a continuous loss of altitude or with moderate rebounds within the sensible atmosphere. Depending on the range flown, it can be a short entry, below half an hour, or a long entry flight (between 1 and 2 hours)
- Skip Entry: the vehicle enters the atmosphere and after an initial breaking performs one or several skip-outs. Depending on the number and intensity of the rebound we can have single skip entry, multi-skip or aerocapture depending on the mission objective: targeting, minimization of loads, …

The feasibility of an entry strategy is not assured and must be evaluated taking into account the characteristics of the considered vehicle. For example, for sharp ledge vehicle such as waveriders, high thermal load must be avoided, and then only the low stresses softer techniques must be taken into considerations.

Complementary to the entry strategy, the guidance technique determines the tactic the vehicle uses to fly within the entry corridor, defined once the mission and the vehicle have been defined. This technique directly influences the design of the reference trajectory. Several solutions have been considered:

- Free profile: a constrained optimisation problem is solved and a completely free entry trajectory is generated driven only by the form of the defined cost function. Existence of the solution is assured, but controllability is not, and this technique cannot be used for on-board replanning due to the excessive computational load.
- Fixed-shape profile: the shape of the trajectory in the corridor state-space is previously defined, and the solution is tuned to match current initial and final condition. Easy and fast, this technique assures controllability, while the existence of the solution should be verifies for each case. Complete on-board replanning is perfectly achievable[1 2 3 4].

- Feedback-like: the reference entry trajectory is generated imposing its dynamics, that is, a direct relation between the control variable and the trajectory parameters permits shaping of the trajectory as desired. As simple and fat as the previous technique, equally it assures controllability, because a control function is implicitly being considered planning the trajectory. Again, existence of a solution is not assure[5,6].
- Flight command law: a command law is directly used. Existence of the solution is not assured. Its complexity depends on the complexity of the adopted command law. A few examples are available with very simple laws: constant bank, or linear bank[5].

Given the available entry strategies and guidance techniques, the mission scenarios and the characteristics of each vehicle, a 4D matrix can be filled whose components are presented in Table 5-2. Every matrix element must be evaluated and its entry performance shall be considered to select the best solutions to design the guidance system for the selected vehicle.

Table 5-2. 4D matrix for the definition of the high lift entry concept

Strategy	
Direct entry	Short duration
	Long duration
Skip Entry	Single skip
	Multi Skip
	Aerocapture

Scenario
LEO
Beyond LEO

Vehicle Family
Lifting Body
Winged Body
Sharp LE

Guidance technique
Free profiles
Fixed Shape
Feedback-like
Flight Commands

5.2. Candidate Vehicles And Configuration

In the context of this investigation, the applicability of high lift entry approach to both Low Earth Orbit (ISS like) and beyond LEO scenario (high speed return from Low Lunar Orbit, LLO) is appraised.

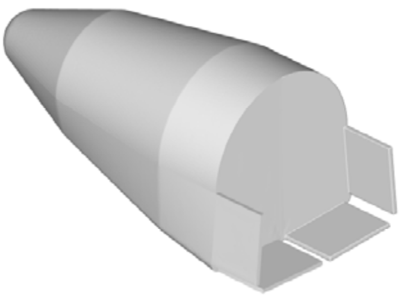


Fig. 5-1. Lifting Body vehicle

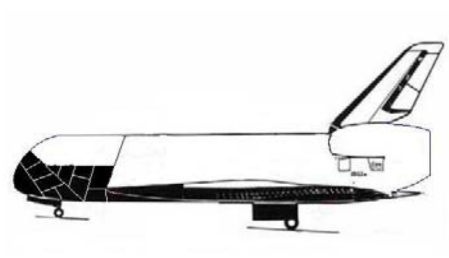


Fig. 5-2. candidate winged body vehicle

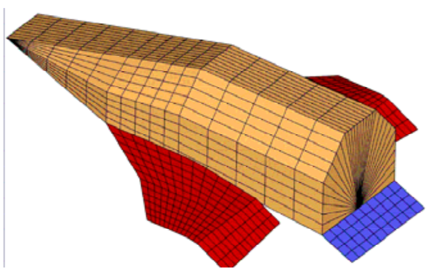


Fig. 5-3. advanced concept (sharp leading edge)

Three different candidate vehicles have been considered: lifting body, winged body, and an advanced concept sharp-edged body. Similar sizes and volumes have been proposed to ensure fair comparison between options. In the frame of the CIRA USV programme, the USV-X vehicle has been designed to provide a high light to drag ratio during the hypersonic flight. This unmmaned demonstrator is also considered due to its applicability in terms of high-lift entry techniques, in particular the so-called long entry flight.

A lifting body (LB, Fig. 5-1) vehicle allows a maximum L/D of 1.2 in hypersonic, and provides good stability down to low supersonic. Its suitability for human mission is guaranteed by the limited load factor during entry, and thermal loads are not an issue due to the lack of sharp edges in the vehicle geometry. The selected concept is the Klipper derived Lifting body concept analyzed in the frame of several ESA studies for both transportation to LEO and LLO.

A winged body vehicle (Fig. 5-2) that is a scaled version of the Space Shuttle enhances the maximum achievable L/D up to 2 in hypersonics, especially if an alternative trim solution – High Lift Shuttle Orbiter, HLSO – is considered with reduced angle-of-attack. Moreover, this vehicle has been proven suitable for human space flight in more than 120 flights, with excellent results in terms of crew comfort and performances. Of course, due to the blunt nose and particularly the wing leading edge, thermal stresses are higher than in the case of the lifting body, especially in the high speed lunar return scenario. Detailed aerodynamics is available coming from the Shuttle Orbiter program.

The advanced concept sharp-edged vehicle (Door Stopper vehicle, DS6) is derived combining a waverider concept with volumetric efficiency requirements. Fig. 5-3 represents the resulted vehicle.

The DS concept performance are incomparable with respect to the others vehicles. It enables L/D of 3.5 in hypersonic and limits load factor to values of the order of 1g. Moreover, as a mjor difference with respect to blunt concepts, the shock position almost independent of the Angle of Attack (AoA) and gas effects.

For all of the 3 concepts, realistic mass budgets have been proposed based on the system architecture for each of them in order to guarantee the feasibility of the concept and to avoid the use of desirable but unrealistically low wing loadings (m/C_D).

5.3. System Architectures And Budgets

The trade off among the considered vehicles was performed from a system standpoint considering both the compatibility for crew support provisions (volume availability, compatibility with flights having a maximum duration of about two weeks) and the technologic challenges given by the different architectures.

The LB resulted as the most affordable concept in terms of crew comfort and technology demand, requiring no particular effort for its realization and being practically the only vehicle for which a realization process could be feasible immediately. But it was also the vehicle less attractive from the re-usability outlook, not to say about the ground infrastructure and the launch needs.

The winged body resulted immediately only apparently an easy exercise, in fact the downscaling process from the NSTS required to drastically modify the vehicle architecture with wide implementation of hot structures instead of simpler protected structures in particular for the wings, and tails. On the other hand the reusability could have resulted largely improved and the launch policy with its related ground segment is potentially open to more practical solutions than the use of an expendable launcher.

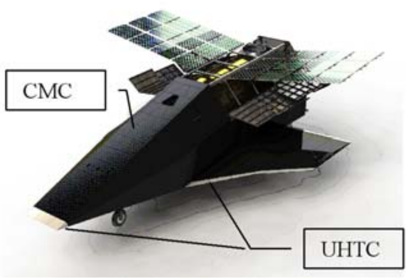


Fig. 5-4. The DS architecture with cargo bay doors open and solar arrays deployed

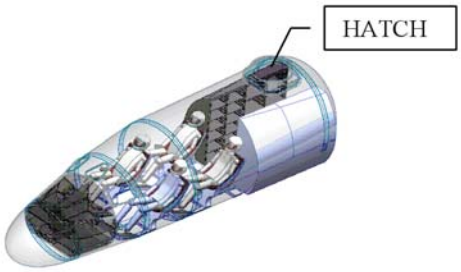


Fig. 5-5. The crew compartment

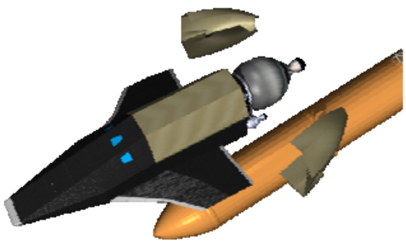


Fig. 5-6. The DS once reached LEO

The DS with its compromise among the diverging requirements coming from the adoption of hypersonic profiles and the need of hosting a reasonable crew compartment, resulted as affected by the need of hot structures as the winged vehicle, but the possibility of modifying the shape on purpose (not allowed simply scaling the shape of the NSTS) was found as a positive contribution to the overall system feasibility.

In extreme synthesis the conclusion of the trade of was that a vehicle to be done today could have been the only LB, while for a future vehicle the best solution seemed to be the DS with its high technological challenges.

The activity of refinement for the DS architecture, combined with the launchability and guidance analysis performed in an integrated way within all the different companies involved into the design team, leaded to the definition of a vehicle compatible with a crew of 4 astronauts to be air–launched with an AN-225 stacked with a first stage consisting in two RSB's and a second cryogenic stage plus an orbital/de-orbiting module.

A mass estimation of all the elements considering affordable shapes and manufacturing processes allowed the identification of an overall mass figure compatible with a LEO mission.

The areas with the lower maturity level encountered during the definition of the DS architecture are:

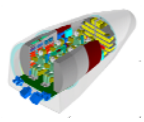
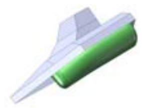
- UHTC – essential for the concept realization because unavoidable in all sharp edges – recommended also a development of very high emissivity coating
- Hot Window technology – not essential but highly recommended contributing to the safety chain
- Warm Mechanisms (aerodynamic surfaces, landing gear, cargo doors and hatch)
- HIgh Performance EXtreme Internal Insulation (HIPEX) withstanding Temp up to 2000ºC
- The carrier, An 225 – essential but available in a single unit.

Concerning the supporting infrastructure, apart a massive GSE (Ground Support Equipment) allowing the crew boarding when DS docked to the An 225, some development will be required for a FSE (Flight Support Equipment) maintaining the cryogenic condition of the second stage from the fuel boarding up to the beginning of the DS separation sequence.

The safety of all operation was taken care and phase-by-phase escape provisions were implemented into the architecture in order to provide the system with the required safety level.

The summary of the study on architectures, other than the comparison among the performances of the different concepts is hereafter summarized:

Table 5-3 summary of study architectures

	Lifting Body 	Shuttle Like 	DS-6 crew of 6 	DS 6 crew of 4 
Inhabitable volume	27	28	25	17
m^3/crew member	4,5	4,67	4,16	4,25
Able to agile atmospheric entry	No	No	YES	YES
Based on already qualified European technologies	YES (Partly for a Moon Mission)	Partly	Partly	Partly
Able to support a LEO mission	YES	YES	YES	YES
Able to support a Moon Mission	YES (changes in TPS)	No	No	No
Launcher available	YES (with modifications)	No	No	YES (with modifications)

5.4. Aerodynamics And Aerothermodynamics

Waverider configuration is the natural candidate as “Advanced Concept”. It is well known that relatively practicable shapes provide a max. L/D in the order of L/D = 10. The high L/D is the main advantage of these vehicles but the drawbacks are a complex shape and a relatively small usable volume.

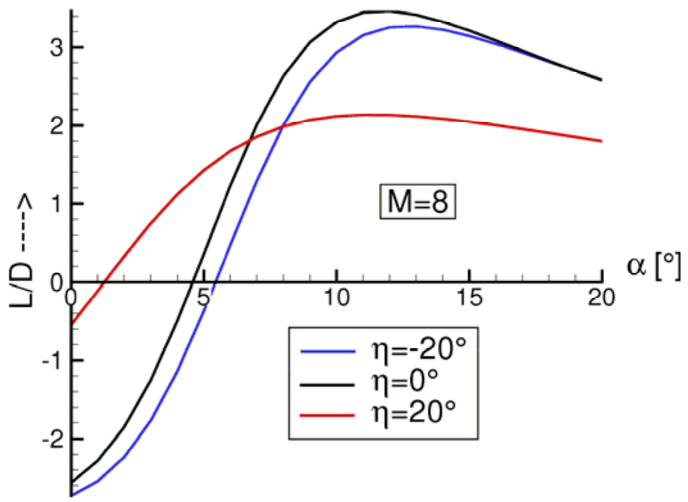


Fig. 5-7. hypersonic Lift-to-Drag ratio of the DS6 vehicle

In order to be compatible with the volumetric requirements imposed by a crew transportation vehicle and due to the fact that waveriders are anyway wings with a supersonic leading edge it is decided to consider a facetted wing-body vehicle with sharp supersonic leading edges. The resulting configuration is shown in Fig. 5-3, which includes wing and body flaps to ensure the aerodynamic controllability. Facetted layout is geometrically simple and enables sensitive adaptation to mission requirements

In order to allow Flying Qualities assessments comparable to the rest of candidates, the vehicle aerodynamics has been characterized in detail including longitudinal and lateral directional coefficients, elevator efficiencies, viscous effects and rarefied flown aerodynamics. The lift-to-drag ratio in hypersonics for several elevator deflections is shown in Fig. 5-7.

The aerothermal environment of the candidate vehicles has been characterized. It is particularly important for the sharp leading edge concept, as high temperatures are expected in localized areas (nose and wing leading edges). Ultra High Temperature Ceramics (UHTC) materials are proposed for the sharp leading concept due to the ability to maintain its properties (multi use) up to 2550 K, the high conductivity that alleviates the temperature in the sharp zones by transferring the heat towards the inner structure (hot structure) and the maintenance of the aerodynamic shape that guarantees the aerodynamic efficiency.

The analysis of the vehicle trajectories has shown that adiabatic wall temperatures below 3000 K are feasible, which means that accounting for the conduction effects the expected peak temperature would be bellow 2500 K. Given the optimized entry trajectories for each candidate vehicle, the aerothermodynamic analysis has been performed considering different TPS materials and thickness. An example is presented in Fig. 5-8 considering Zirconium Diboride based material at stagnation point for different swept angles (nose and wings) for the DS concept.

A verification of the vehicle aerodynamics and aerothermodynamics was conducted by coupling the trajectory and CFD codes. An example of coupled calculations is presented in Fig. 5-9, which includes an assessment of the impact of viscous effects.

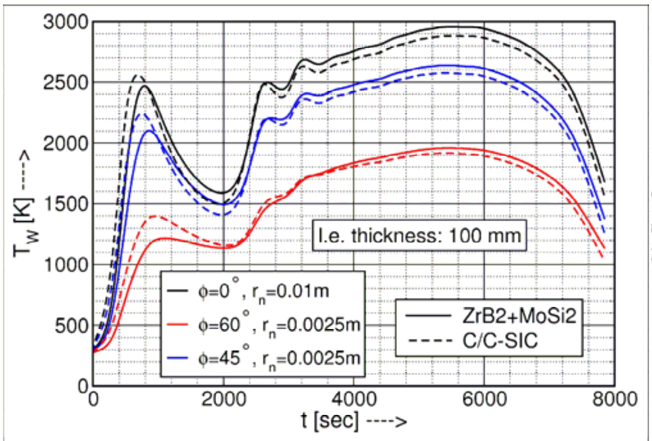


Fig. 5-8. Effect of materials and swept angles on adiabatic wall temperatures

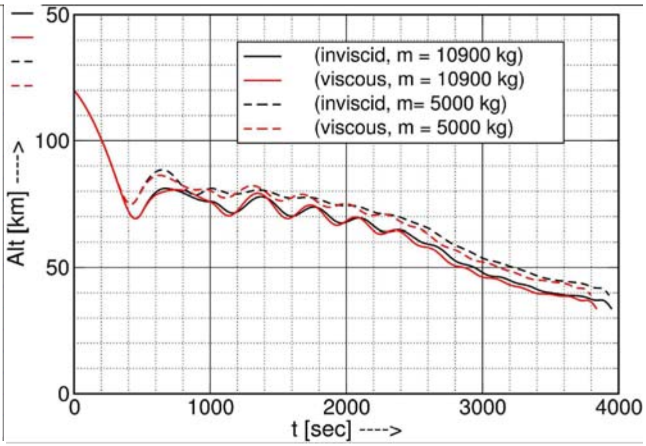


Fig. 5-9. coupled trajectory and calculations

5.5. Re-Entry Analyses

This section deals with the estimation of the preliminary vehicle performances during the atmospheric entry phase for the 3 vehicle candidates performing both LEO and Beyond LEO return missions. Different flying qualities are considered as criteria for a critical comparison of the different vehicle candidates and mission scenarios. The analysis is based on the evaluation of the entry corridor and of the envelope of performances resulting from the corridor limits. The corridor obtained is the result of the following constraints:

- Path constraints (Dynamic pressure, load factor, heat flux, wall temperature)
- Stability constraints (Longitudinal and lateral-directional)
- Performances (Minimum L/D ratio)
- Trimmability (Trim condition within the corridor)

The trim condition depends on the vehicle aerodynamics and on the Centre Of Gravity (CoG location). All the vehicles considered are provided with aerodynamic movable surfaces so the complete trim is a function of the deflection angle (can be variable along the flight, it is a law with the Mach number) and of the CoG location (almost fixed along the flight). Different CoG locations and different deflection laws are evaluated for each vehicle and the feasible ones (those compatible with the constraints set) are selected as potential candidates. The region of feasible CoG, called the Feasible Domain, FD in presented in Fig. 5-10 for the 3 candidate vehicles.

The envelope of performances is the result of the variability of the flying qualities and path constraints for the selected candidate solutions within the CoG envelope. This analysis provides a complete overview of the vehicle limits and allows the designer to clearly identify critical flight conditions, maximum and minimum performances expected, best and the worst design solutions. Fig. 5-11 shows the envelope of performances for some figures of merit (adiabatic wall temperature, lateral-directional stability, L/D and load factor) for the CoG domain of the DS6 concept in case of LEO return.

An optimum CoG location and an optimum trim AoA (through an optimum aerodynamic surface deflection law) can be selected based on all the performances and constraint limits

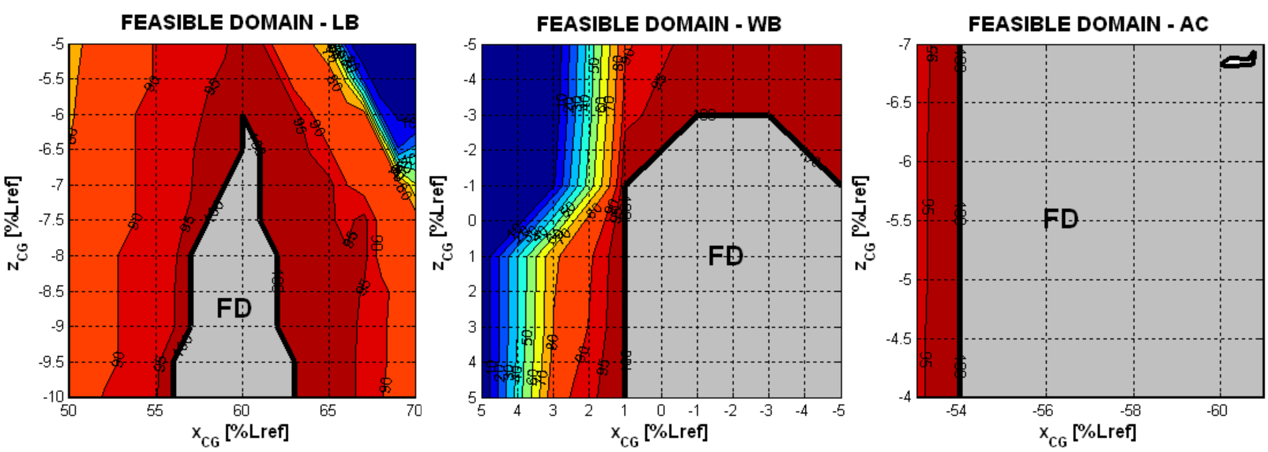


Fig. 5-10. Feasible Domain (FD) for Lifting Body (LB), Winged Body (WB) and Advanced Concept (AC)

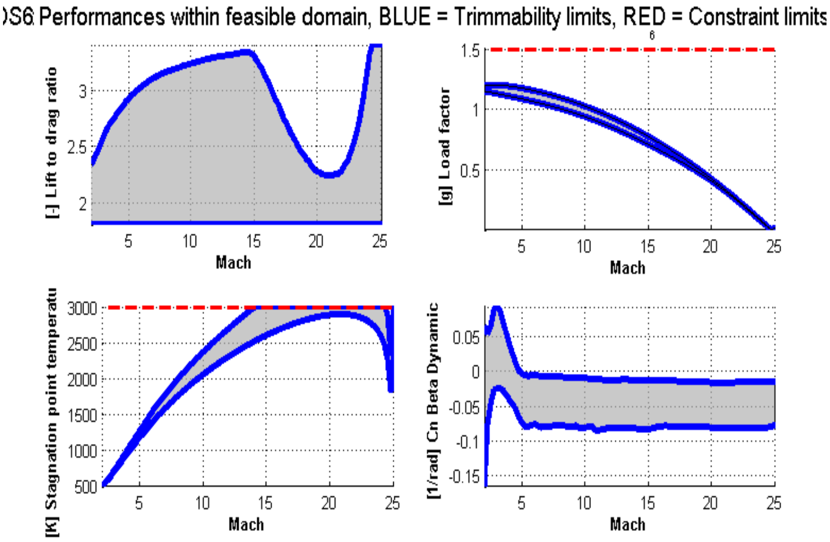


Fig. 5-11. Envelope of performances for the Advanced Concept (Grey region: Corridor, Red: Constraints)

Fig. 5-12 shows the angle of attack corridor and trim line for a particular configuration of the DS vehicle. In this case, the demanding thermal constraints in the nose require an AoA modulation. For the High Lift Shuttle Orbiter concept, a feasible trim line at low angle of attack has been identified providing L/D close to 2 and meeting all constraints.

The main results obtained are summarized in Table 5-4:

- The DS6 provides the best L/D performances
- Heat fluxes and temperatures are the highest for the DS6 (due to the sharp leading edge) and for the other vehicles in missions beyond LEO.
- Beyond LEO is not feasible for a sharp leading edge concept.
- Loads factor is low, guaranteeing a comfortable flight
- A Stability Augmentation System is required for the winged body and the DS6 (on longitudinal motion, elevators would compensate instability; on lateral motion a vertical tail is recommended)
- The flight time is expected to be higher for the DS6

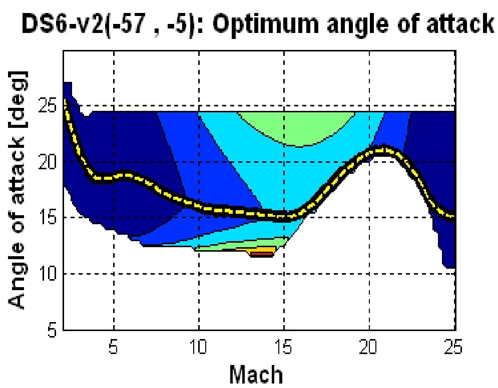


Fig. 5-12. Optimum trim for the optimum COG for the Advanced Concept

One of the main results of the analyses run is that a very strong correlation is detected between the L/D ratio (to be maximized as a project objective) and the thermal loads (heat flux and stagnation point temperature). In the case of the DS6, the maximum L/D (> 3, Fig. 5-11) is achieved when the vehicle flies in the region of low AoA values (around 15º) while the thermal constraints limits the feasible region to the higher AoA region. A trade-off is necessary: in the region of the peak temperature the AoA is increased (around 20º); the counterpart is that the L/D drops to about 2 for Mach close to 20.

The sensitivity to the entry mass has also been assessed and the main result is that feasible solutions exist for the DS6 vehicle up to an entry mass of about 15 tons.

Table 5-4 Comparison of different mission and vehicle options

		AVERAGE PERFORMANCES					
MISSION	VEHICLE	L/D	Thermal Loads	Mech. Loads	Stability	Flight time	CoG offset
LEO	LB	1.2	low	moderate	good	low	challenging, 9% z
	WB	2	low	low	SAS	low	good, 3%
	AC	3.5	high	low	SAS	mid / high	backwards, 60% x
BEYOND LEO	LB	1.2	high	moderate	good	mid / high	challenging, 9% z
	WB	2	high	low	SAS	mid / high	good, 3%

From these analyses it is concluded that the DS6 vehicle is a very good candidate for the achievement of the project objectives but it presents a challenging solution form the thermal loads and controllability points of view.

All the results of the entry corridor analyses provide fundamental feedbacks to the vehicle design (aerodynamics, layout, CoG, movable surfaces) and are the first step to the definition of the reference entry trajectory (that can be defined only if an entry corridor exists).

Feasible entry trajectories for the 3 candidate vehicles returning from LEO and Moon using different entry techniques have been generated using optimization. The selected algorithm to solve the Full Optimal Control Problem is the Gradient Restoration. For the particular case of the DS6 concept, the long entry with different durations, the skip and multiskip trajectory have been assessed as shown in Fig. 5-12. The calculated trajectories verify the envelope of performances predicted in the Feasible Domain analyses. Multi-skip trajectories are feasible but they lead to entry times higher than 7 hours, which are not compatible with human transportation requirements in case of contingency scenarios.

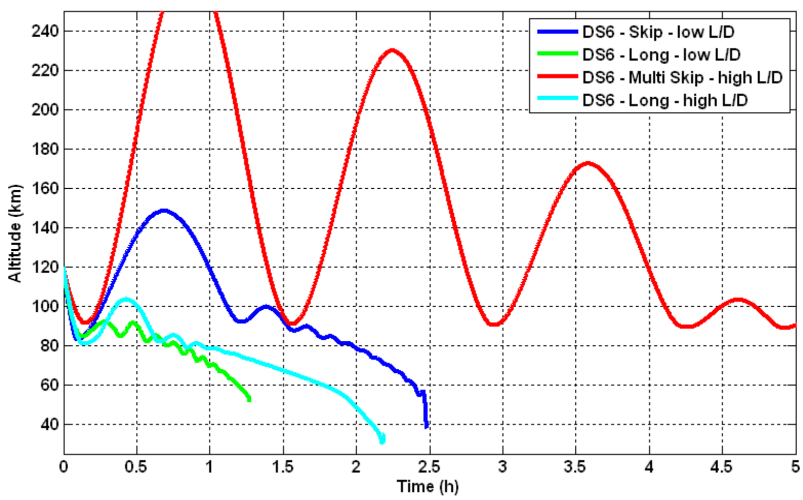


Fig. 5-13. Optimum entry trajectories performing different entry techniques: long entry, skip entry and multi-skip.

5.6. Launch Scenario

The launch scenario for the 3 concepts has been trade-off in order to complete the mission and system feasibility. Several launch options have been considered: airborne launch (captive on top o a mother aircraft), Rail Guided Sled Launch and conventional vertical ground launch. Any of the 3 options requires a relevant amount of new development. The airborne launch is the most appealing concept due to the operational flexibility as well as the advantages in terms of abort scenarios.

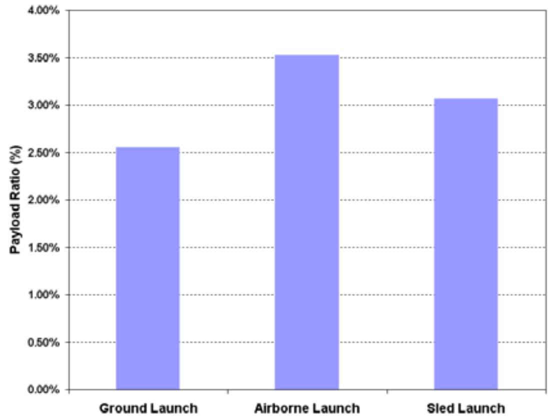


Fig. 5-14. payload ratios for the candidate launch options from the optimization process

Ascent optimization for LEO injection comprising trajectory, staging and propulsion plant optimization has been extensively used to assess the different launch architectures and launchable mass. For this optimization, a Full Optimal Control Problem (optimal control profiles and parameters) has been formulated. The selected algorithm is the Gradient Restoration. Realistic assumptions for the Isp based on actual state-of-art for both the solid and liquid stages have been assumed. The resulting payload ratios are presented in Fig. 5-14, which shows the advantages from a performance standpoint of the airborne concept due to the lower drag losses. The required propulsion for the ground vertical launch can be performed with existing launchers, while for a sled launch system, the take-off masses and the associated ground infrastructure seems quite challenging.

Fig. 5-15. sketch of the DS6 airborne launch architecture

The main limitation of the airborne concept comes from the compatibility with existing carriers. It limits the payload mass that can be inserted in orbit. For a mission to the International Space Station (ISS) it has been proven that a DS concept with 4 crew members is compatible with the Antonov AN-225 with good margins with respect to maximum payload capability of the carrier. The launch architecture is based on two solid boosters, one liquid propulsion stage and an independent resource module (RM) for the orbital maneuvering tasks. A sketch of the launch configuration is presented in Fig. 5-15. The 6 crew member version to LEO (11 Tons mass) can be only launched from a ground based system.

5.7. Guidance Technique Assessment

A comparative analysis has been carried out to define the most important characteristics of the considered guidance techniques. The main objectives of the guidance technique trade off are:

- To select the most promising guidance technique given the candidate combination of vehicle, mission, and entry strategy.
- To assess the controllability associated to each guidance technique and identify potential drawbacks for the implementation in a real guidance system.

Consequently, the selected guidance technique is applied to the actual scenario to verify the correctness of the trade off results and to in general assess the performance of the selected guidance solution, including actual solutions like the Space Shuttle and the Soyuz vehicle.

In the presented analysis three study cases referring to the free profile, fixed shape, and command law guidance techniques have been analyzed. To allow comparison between the different proposed solutions, a common scenario has been defined. In this case, the following scenario was selected to be representative of the most promising high-lift scenario solution, identified taking into account the results of the entry analysis reported in previous sections:

- The Door Stopper considered as the candidate re-entry vehicle with the configuration of 4 crew members
- Return from ISS considered as the candidate mission Direct long entry considered as the candidate.

A pre-existent guidance method[7] has been selected to track the reference drag profile, properly generated using the different guidance techniques. For the selected guidance, targeting of the landing site is not activated, i.e. the arrival point at the end of the simulated trajectory is not previously selected. Moreover, no adaptation of the existent algorithm to the tested reference profiles has been carried out. Different reference profiles have been generated using the different techniques to fly a feasible trajectory within the entry corridor. The reference profiles have been chosen to be as more representative as possible of the characteristics of the relative guidance technique. The entry trajectories are then simulated tracking the reference profiles with the selected guidance method running close-loop guidance simulations in a high-fidelity simulation environment.

The resulted trajectories are thus compared and analyzed in order to identify the more appropriate technique with respect to the mission constraints, namely thermal loads, and the controllability properties of the reference profile given the selected guidance method. In the following the results obtained for each case are presented and discussed. Fig. 5-16 presents the reference profiles (black line) and the controlled trajectories (green line) with respect to the entry corridor in the drag-velocity plane for the three study cases. For the free profile study case 1, the heat flux constraint has not been considered in order to design a reference profile that could seriously challenge the guidance method. For the fixed shape study case 2, the reference profile has been generated similar to the solution adopted by Space shuttle. For the command law study case 3, the reference profile has been generated forcing a constant bank equal to 45 deg. In all cases the selected method is able to correctly track the reference profiles, even in presence of such a challenging profile as in study case 1.

Fig. 5-17 shows the bank angle profile commanded by the guidance method for the three study cases. Focusing on the longitudinal command (i.e. not considering the sign of the bank angle) it is possible to see how in the study case 1 the bank magnitude is almost always limited between 30 and 60 deg, with the presence of some peaks where the bank is saturated at zero. In the study case 2 the bank magnitude presents a more regular profile; almost no oscillations are present and considerably less control action is required to track the reference profile. In the study case 3, the bank angle is almost constant during the whole entry and control effort is considerably reduced.

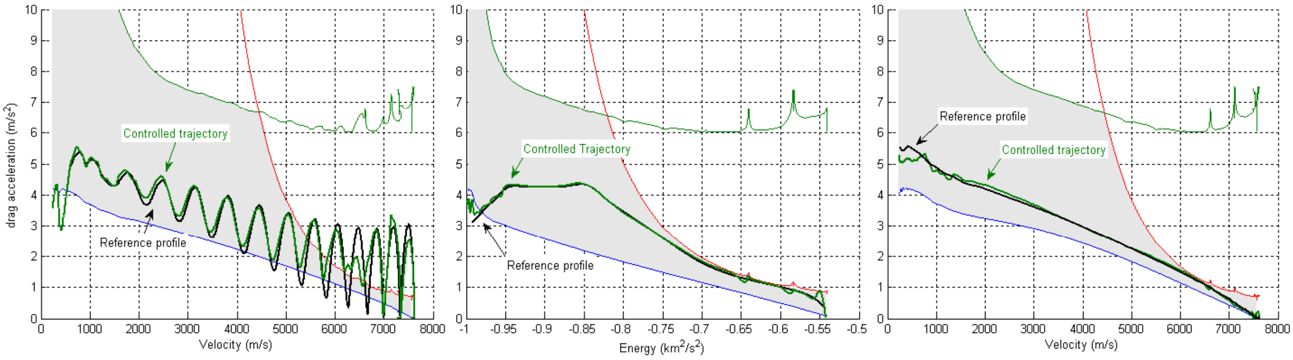


Fig. 5-16. Reference and controlled drag profiles for the study case 1 (left), 2 (center), and 3 (right).

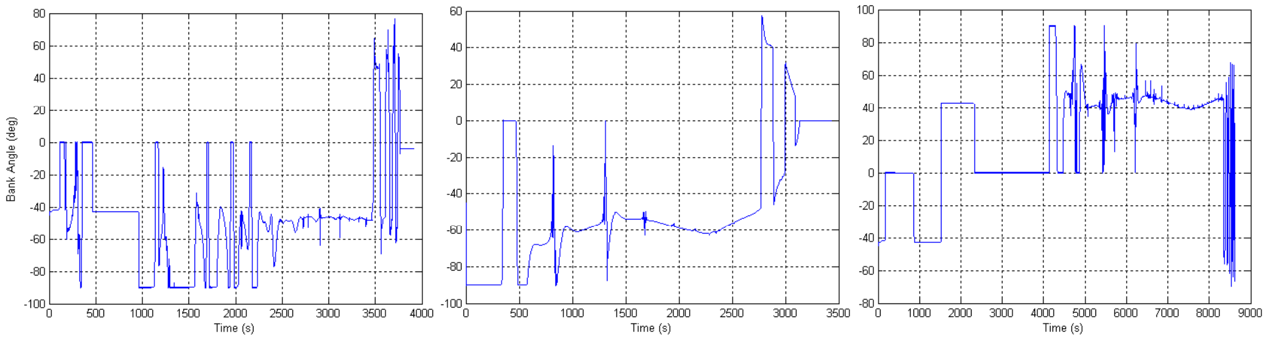


Fig. 5-17. Commanded bank angle profiles for the study case 1 (left), 2 (center), and 3 (right).

The controllability assessment has been successfully carried out for the free-profile technique, even if the control effort is higher than in the other cases. Anyhow, the main drawback associated to the implementation of this guidance technique is related to the complexity of storing, managing, and updating (through trajectory generation) a complex profile. The fixed-shape and the command law techniques leave higher margins in terms of control capability to be used in presence of dispersions.

Study case 3 resulted in a too long entry (almost three hours) for human transportation standards. To reduce the entry duration a more complex solution (e.g. combined constant or linear segments) could be adopted, because a constant bank solution with an increase of the reference value to 50 deg is not feasible: the entry corridor is no more defined in the medium hypersonic region.

The previous analysis and considerations allowed identifying the fixed shape (Shuttle-like) guidance technique as a reliable solution to be used with the selected scenario. This selection should assure easy controllability, acceptable results and good reproduction of the desired behavior (long entry with an high lift vehicle from LEO).

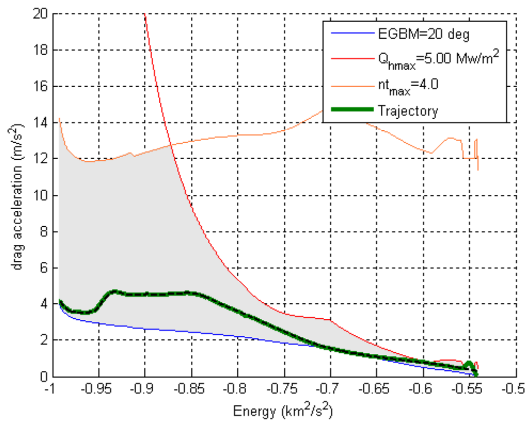


Fig. 5-18. Reference and controlled drag profile, reference scenario

In the next paragraphs, the performance assessment of the selected candidate solution (DS vehicle returning from ISS with a long entry flying a fixed-shaped type trajectory) is presented. With respect to the scenario defined for the guidance technique trade off, the vehicle and mission definition is refined taking into account the final solution identified by the mission analysis, aerothermodynamics, and system activities design loop. The selected guidance method is slightly tuned toward the definition of an operational guidance function that copes with the characteristics of the entry vehicle, trajectory, and mission performances defined by the final solution. Fig. 5-19 illustrates the reference drag profile designed using the fixed-shape technique in order to fly a long entry trajectory from an initial orbit representative of ISS towards the landing site.

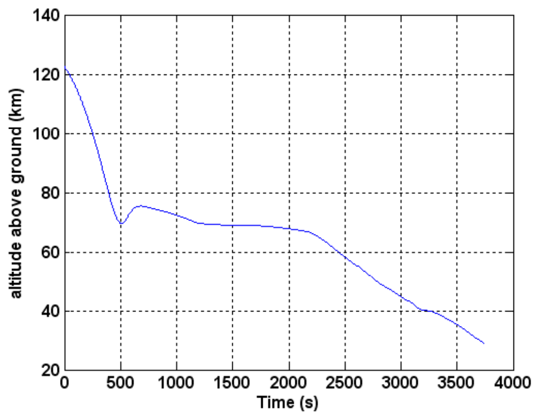


Fig. 5-19. Long entry altitude profile, reference scenario

The case under analysis corresponds to a configuration of 4 crew members to the ISS, with a mass around 9 Tons. The selected landing site is the Moron Air Base, near Sevilla (Spain), which is attractive due to its vicinity to the European west coast. The nominal trajectory has been obtained tracking the reference drag profile in nominal conditions. Fig. 5-18 shows the nominal altitude profile, and Fig. 5-20 presents the associated ground track. The nominal trajectory copes with the mission requirements of avoiding dense populated areas and preserving the integrity of the candidate TPS material by maintaining the wall temperature at stagnation point below 2500 K. Thanks to the high-lift capability, the DS vehicle flies during the entry almost 18000 km downrange and over 6000 km in total crossrange.

The L/D is constantly maintained around 2.8, with peaks at 3.2 in hypersonic regime. The total load factor is very low (maximum total load factor < 1.6 g), as expected.

The performance assessment has been carried out by running a Monte Carlo campaign testing the guidance function performance in close-loop presence of high-fidelity dispersions in the entry conditions, mass characteristics, aerodynamics, and environment. The obtained results confirm the correctness of the solution. The vehicle always performs the long entry as desired. The final dispersion at Mach 2 is ±8 km for the 99% of the cases, and 90% confidence level perfectly controllable during transonic and subsonic flight. All the entry trajectories satisfy the mission requirements and constraints. Fig. 5-21 shows the main MC results. The predicted wall temperature dispersion is low and the target of 2500 K, accounting for conduction cooling effects, is feasible.

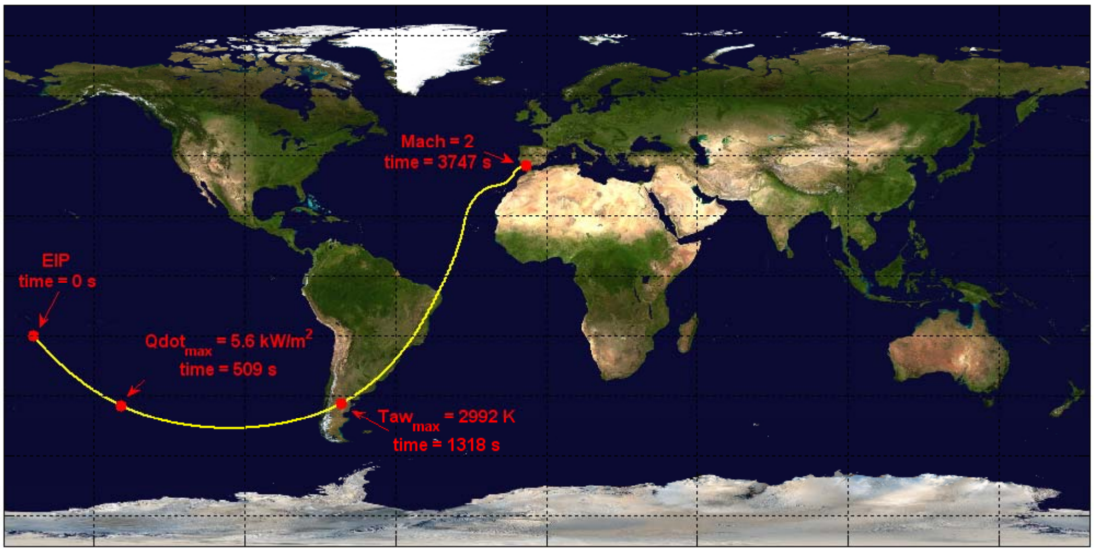


Fig. 5-20. Ground track and re-entry events, reference scenario

Therefore, the selected guidance technique and trajectory control method has show good performances in nominal conditions and in the presence of perturbations. The algorithm has low complexity in terms of CPU loading and memory requirements, which makes it suitable for on-board implementation. Several areas of improvement have been identified as a result of the high-lift characteristics of the vehicle. In mainly affects the lateral logic and the angle of attack modulation strategy during the flight. On-board replanning is enabled by the high-lift performance of the vehicle.

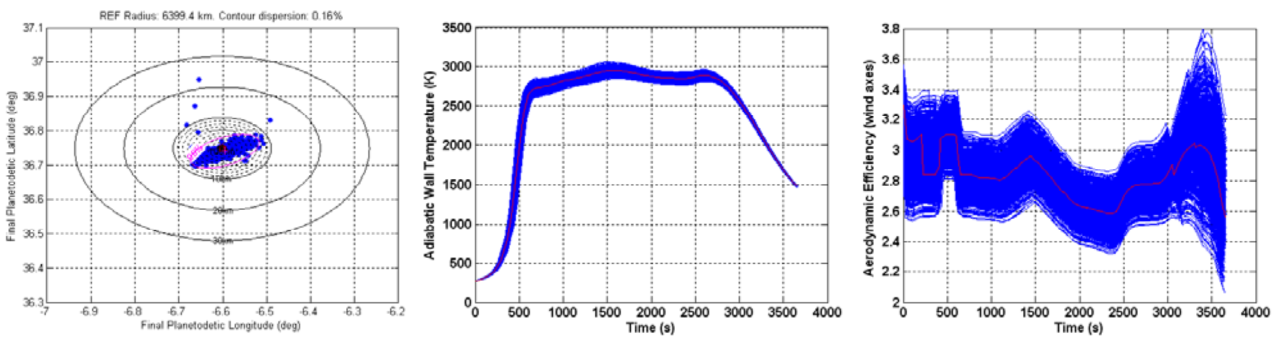


Fig. 5-21. Performance assessment results: accuracy at Mach 2 (left), adiabatic wall temperature dispersion (centre), and aerodynamic efficiency dispersion (right).

5.8. Guidance Of The USV-X Vehicle

During the investigations performed by CIRA aiming to design and develop a modern flying test-bed several aspects concerning the design of a high lift entry vehicle have been examined. The CIRA USV-X concept, represented in Fig. 5-22, is a wing-body configuration equipped with a delta wing and one vertical tail. The vehicle configuration design is compliant with the system requirement to fly as long as possible, in the highest sensible atmosphere layers with a shallow angle of attack, compatibly with the thermal constraints and the usage of both conventional and advanced (like UHTC) thermal protection systems. In these conditions, the vehicle guarantees L/D up to 1.8-2.

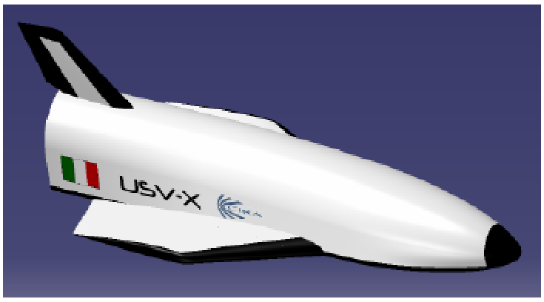


Fig. 5-22. CIRA's USV-X vehicle concept

A proper mission profile is then been defined in order to identify the best conditions to be complaining with the system requirements based on long entry flight in order to maximize the time available for experiments. As illustrated in Fig. 5-12, a long entry profile has thus been designed, to allow flight for almost 4000 s, considerably more than current performance of operation winged vehicles (i.e. the Space Shuttle). The reference mission presents a smooth altitude profile, with quite long gliding at very high altitude permitted by the high-lift properties of the vehicle, assured by the smooth reference AoA profile. Moreover, the reference mission profile presents very low mechanical loads. In addition a wide initial condition range, in terms of admissible velocity-FPA couples has been found, and trim and static margin performances identified the Mach-AoA envelope corresponding to the whole initial conditions range. For this complete mission profile, an innovative guidance strategy has been selected and designed.

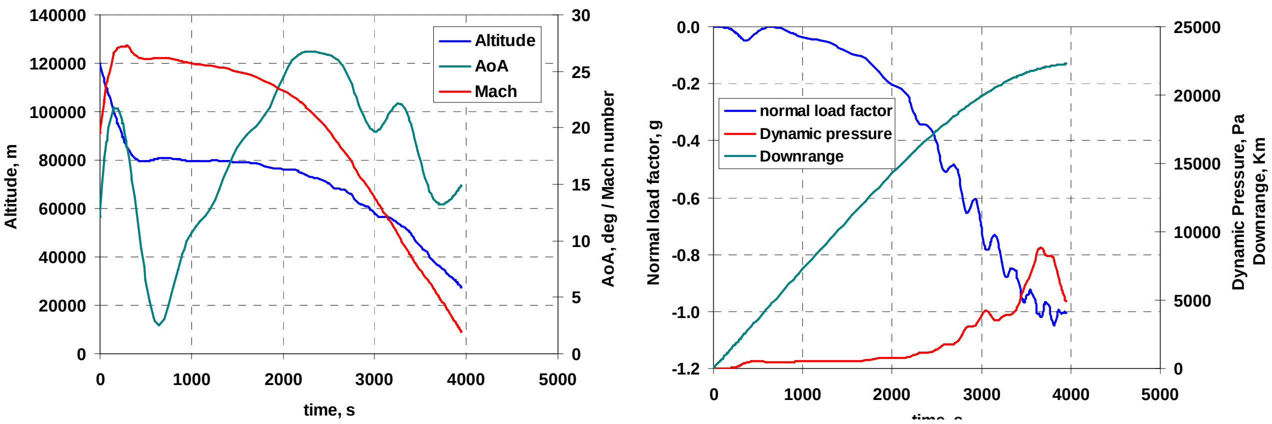


Fig. 5-23. USV-X concept expected mission profile.

The guidance method consists in direct tracking of the reference heat flux throughout control of the angle-of-attack. Lateral guidance is currently not considered. The trajectory control system relies on an adaptive model-following (AMF) concept based on the Lyapunov strategy, which turned out to be very useful and effective to deal with the control of uncertain time-varying systems. In order to prove guidance technique performance, robustness and effectiveness, a reduced number of relevant entry off-nominal scenarios have been defined with reference to the entry condition envelope, and variable aerodynamic and environment uncertainties. For what concerns the use of the proposed technique for a reentry guidance, since it allows achieving a satisfactory tracking of the reference heat flux, thus guaranteeing the flown trajectory to be compliant with the stringent trajectory requirements, mainly related to the thermal constraints and moreover its performances are almost insensitive to the system's uncertainties.

The only uncertainties that significantly affect the performances of the proposed controller are the ones related to the atmospheric uncertainties, mainly due to the fact that the controller does not take advantage of any direct measure of the heat flux or air density, so atmospheric uncertainties imply a measurement error of the heat flux that is the tracked variable. In any case, current practice in re-entry guidance (that uses a fixed AoA profile) are always affected by this kind of uncertainty because they shall account for dispersion of trajectory variables that influence the actual heat flux (velocity and altitude for instance) and thus they must constrain the mission entry corridor to a great extent depending on the predicted uncertainties. On the contrary, the proposed approach allows guaranteeing satisfactory tracking of the reference heat flux provided that a direct measure of the heat flux is available.

6. CONCLUSIONS

The study has shown the potential feasibility of a Space Transportation System based on an advanced Entry Vehicle providing high lift over drag ratios. The study has covered both Flight Mechanics and System aspects, showing that a close interaction between Flight Mechanics, Aerothermodynamics and System brings much consolidated and feasible results.

A scaling and reconfiguration of the Shuttle Orbiter has been carried out showing the possibility of exploiting its complete lifting capability. The Door Stopper concept has been created in the frame of this study and offers the advantages of a new concept and the flexibility of the adaptation of the shape and size to the specific mission requirements. These advanced entry concepts rely of the availability and maturity of UHTC materials.

The high-lift scenario has been at first completed by selecting the most appropriate guidance technique with respect to the candidate vehicle, mission, and entry strategy. To do the trade off throughout simulated trajectories, a candidate pre-existent guidance method was selected. Then, the identified guidance function has been adapted to the operational scenario, and the performance assessment of the complete solution has been carried out considering dispersions. The performance assessment results matched the partial results obtained by the entry analysis and the guidance technique trade off, confirming the validity of the identified solution.

A detailed step towards a new direction has been fulfilled. The consideration of advanced concept for Human Transportation rather than iterating on the classical solutions may bring new perspectives to exploration in the medium term.

The DS6 is a very good candidate vehicle for the achievement of the study objectives. Further steps need to be taken to consolidate the concept in all directions, covering on one side the evolution of the design on consolidated mission and system requirements and on the other the consideration of cost, safety, commercial, programmatic and synergies with other initiatives.