23-29 June 2007
Bordeaux, France, EU

Short Course on Controlled Entry and Descent into Planetary Atmospheres

LECTURE 1

SEPARATION AND ARRIVAL

IPPW-5
5th International
Planetary Probe Workshop

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DEIMOS Space S.L.

Contents

- Introduction to EDLS
- Release Scenarios
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- Propulsion
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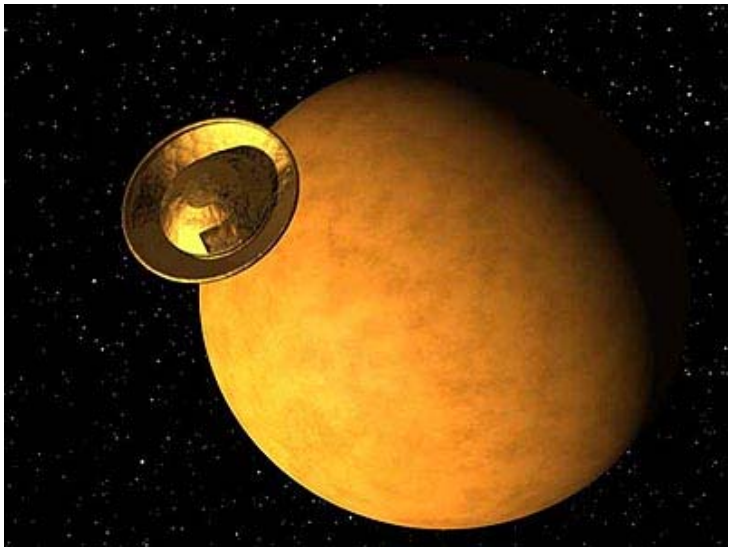
- GNC needs
- Pre-entry instrumentation



Credits: NASA (ESA website)

Introduction to EDLS 1/3

- **Definition**
  - EDL: Mission segment where final approach to the target planetary body occurs.
- **Objective**:
  - To safely bring the spacecraft from orbital conditions to rest on the planet surface
- **Scope of the lecture**
  - Planetary Atmospheres, apart from Earth

Mission Analysis

EDL vs EDLS

System components

Introduction to EDLS 2/3

- Energy management
  - High Energy to be dissipated

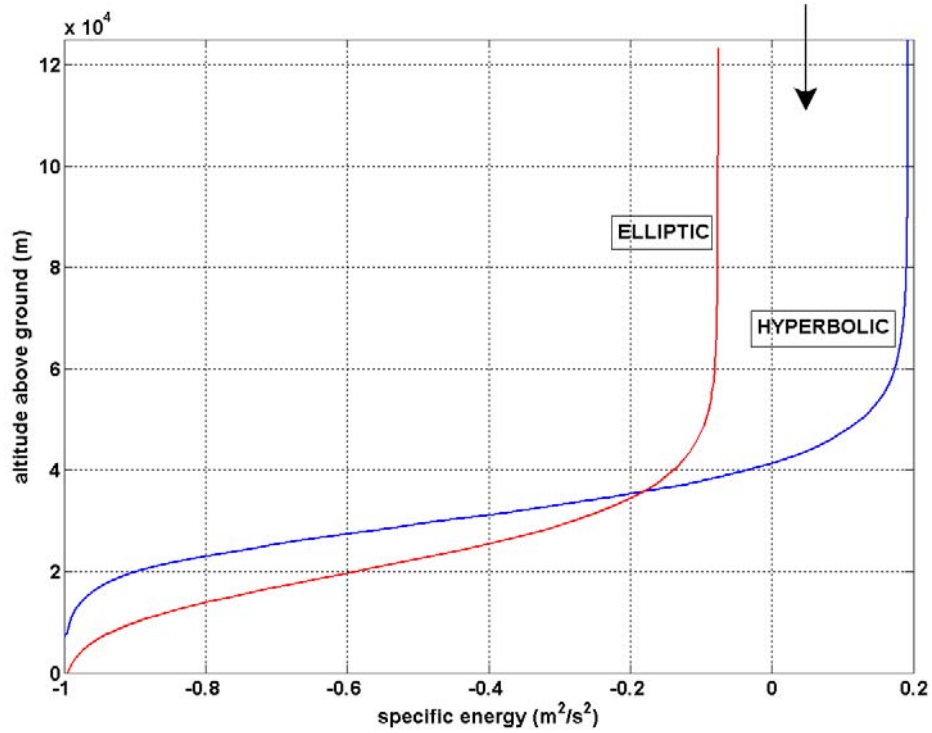
$$\varepsilon = \frac{v^2}{2} - \frac{\mu}{r}$$

  - Atmosphere used as energy sink

"free" braking

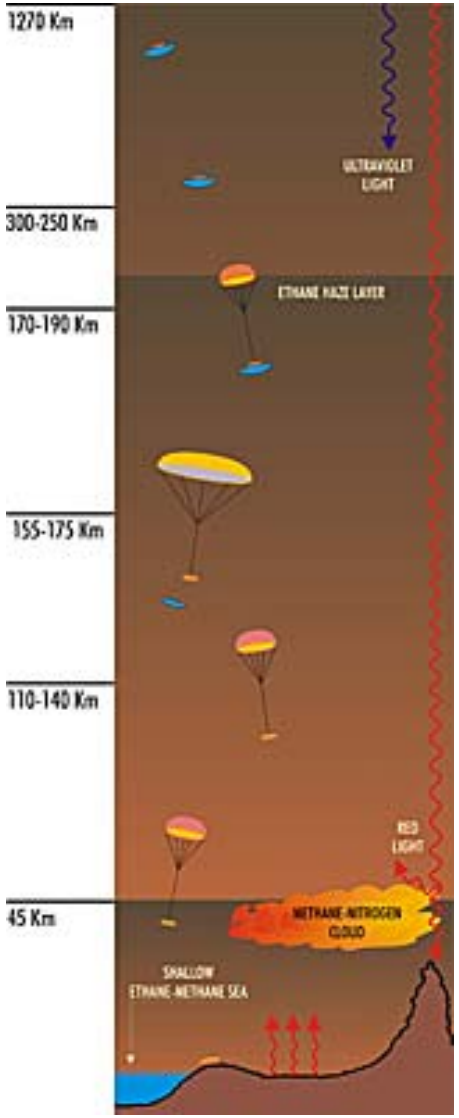
vs

propulsive descent



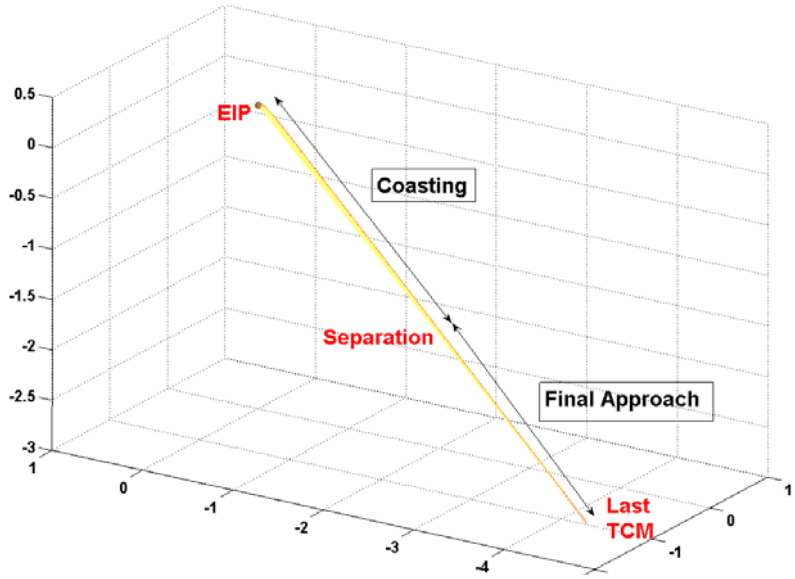
Introduction to EDLS 3/3

- EDL Phases
  - Exo-Atmospheric Phase
    - Orbital flight from last manoeuvre to the Entry Interface Point (EIP)
  - Entry
    - Hypersonic to supersonic flight of the aeroshell
  - Descent
    - Flight with an additional braking device deployed
  - Landing
    - Final braking for touchdown

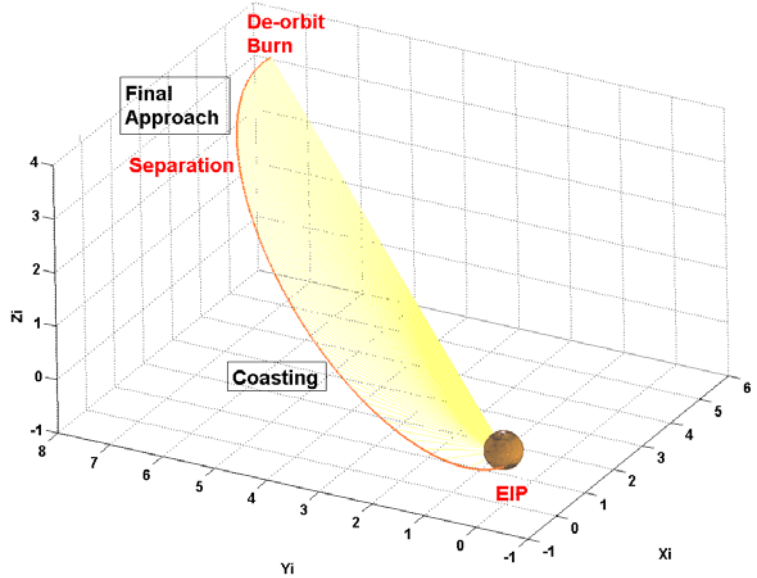


Release Scenarios 1/4

- The final targeting of the planet can be performed:
  - From the arrival Hyperbola
  - From a elliptic orbit



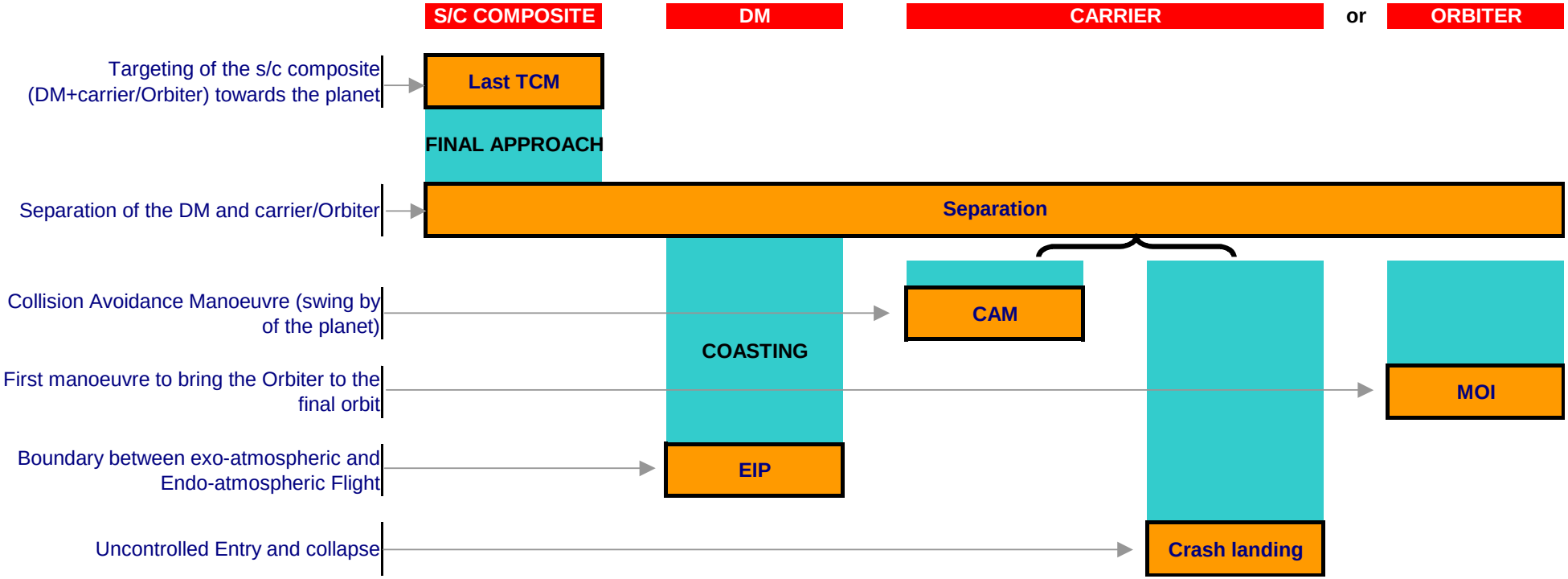
- Sub Phases
  - Final approach
  - Coasting



Release Scenarios 2/4

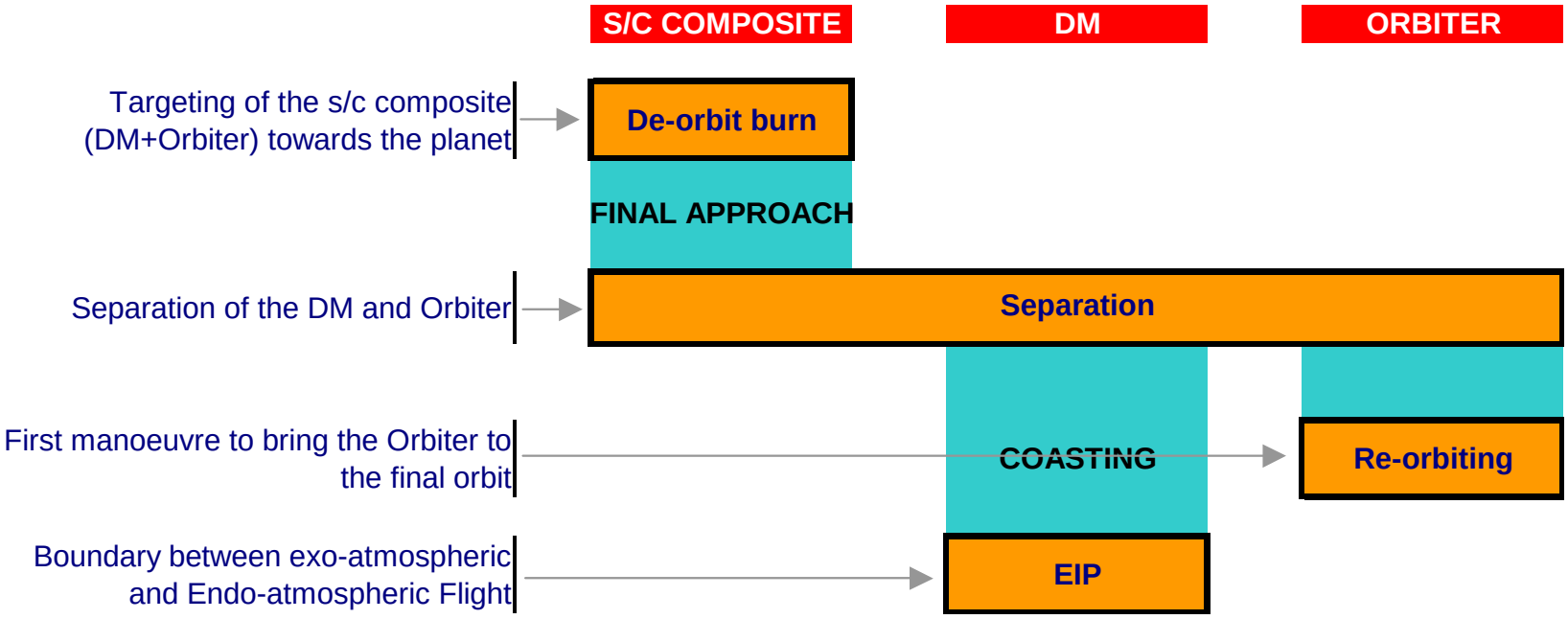
- Hyperbolic Release Sequence. Drivers:
  - Distance to planet at Last TCM (Δv)
  - Contingency (TCM and separation)
  - CAM / MOI budget
  - Power needs during coasting (batteries)

Planet	R_s, $\times 10^6$ km
Mercury	0.111
Venus	0.616
Earth	0.924
Mars	0.577
Jupiter	48.157
Saturn	54.796
Uranus	51.954
Neptune	80.196
Pluto	3.400
Moon	0.0662



Release Scenarios 3/4

- Elliptic Release Sequence. Drivers:
  - Parking orbit sets phase duration
  - Contingency (de-orbit and separation)
  - Re-orbiting budget
  - Power needs during coasting (batteries)



Release Scenarios 4/4

Criteria	Best Concept		Comments
	Hyperb.	Elliptic	
Heat Flux and load factor		✓	Loads increase with the entry velocity
Descent System Deployment Conditions *(ballistic entry)*	✓		Higher breaking capability in altitude
Dispersions at Entry		✓	Advanced navigation concepts needed to reduce dispersions in case of hyperbolic entry. For elliptic, precise OD is easily attained due to the fast dynamics
Landing accuracy *(ballistic entry)*		✓	For the same dispersions at entry, hyperbolic is more sensitive to fpa, aerodynamics and position uncertainties
Release planning		✓	On orbit waiting for optimum entry conditions
Release flexibility		✓	Maximum flexibility in case of circular orbits
Orbiter Δv	✓		Lower, as the MOI is performed without DM
Mass margins		✓	Higher Ballistic Coefficient allowed
Carrier mission	✓		No need for MOI

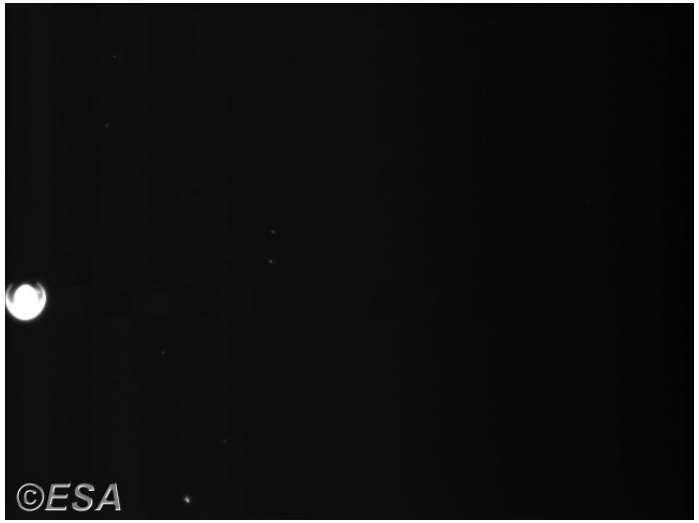
Separation Manoeuvre 1/3

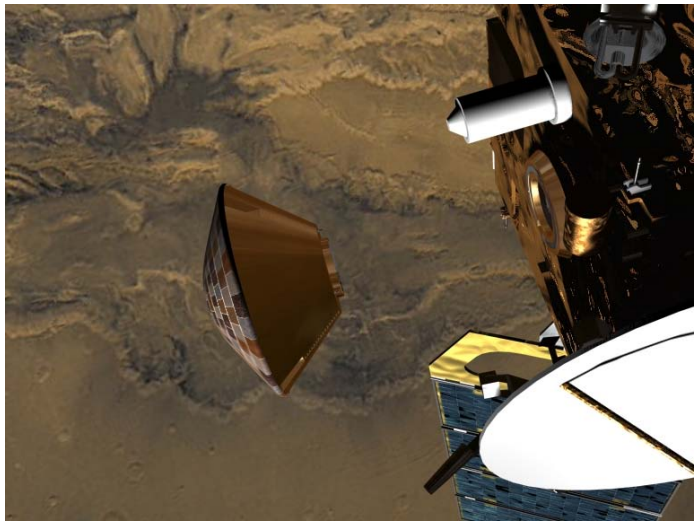
- Separation manoeuvre has a limited impact on trajectory dispersion due to its small size
  - Ex: Mars Express-Beagle2

    $\Delta V_{Beagle2}$=0.3 m/s , 4.5% error (3σ) $\rightarrow$ <1 km dispersion per day of coasting
- Manoeuvre errors:
  - Trajectory: ΔV magnitude & direction
  - Attitude: probe CoG Misalignment
- Mechanism
  - Non-propulsive manoeuvre carried out
    - separation nuts
    - push off springs

Separation Manoeuvre 2/3

- Hyperbolic release
  - The driver for the propagation of the dispersions is the timing of the last trajectory correction (TCM)
  - From the radius of influence to the planet:
    - Dispersion on position reduces
    - Dispersion on velocity increases
- Elliptic release
  - The parking orbit apoapse (orbit period) drives the propagation of the dispersions
- Schedule
  - Later as possible to benefit from carrier/orbiter functionality
  - Contingency margin if foreseen (Operations)

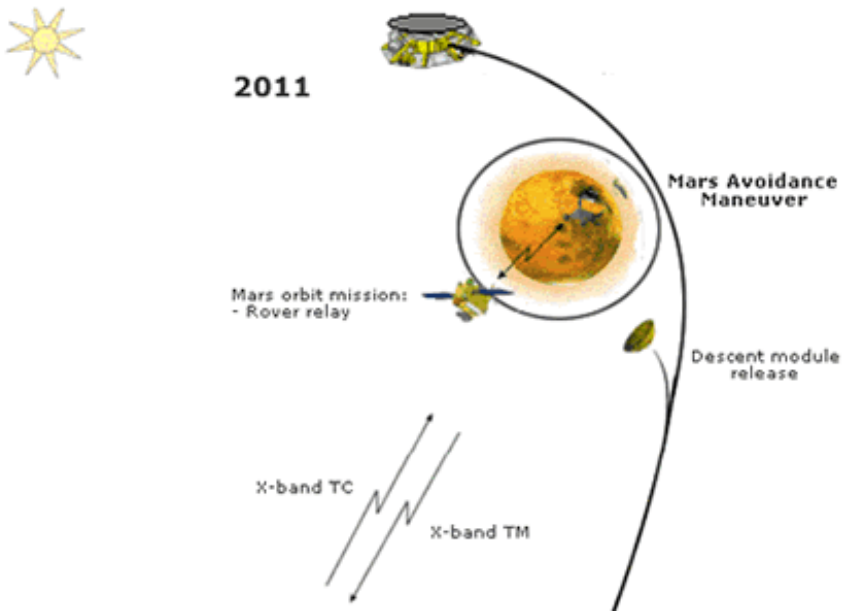


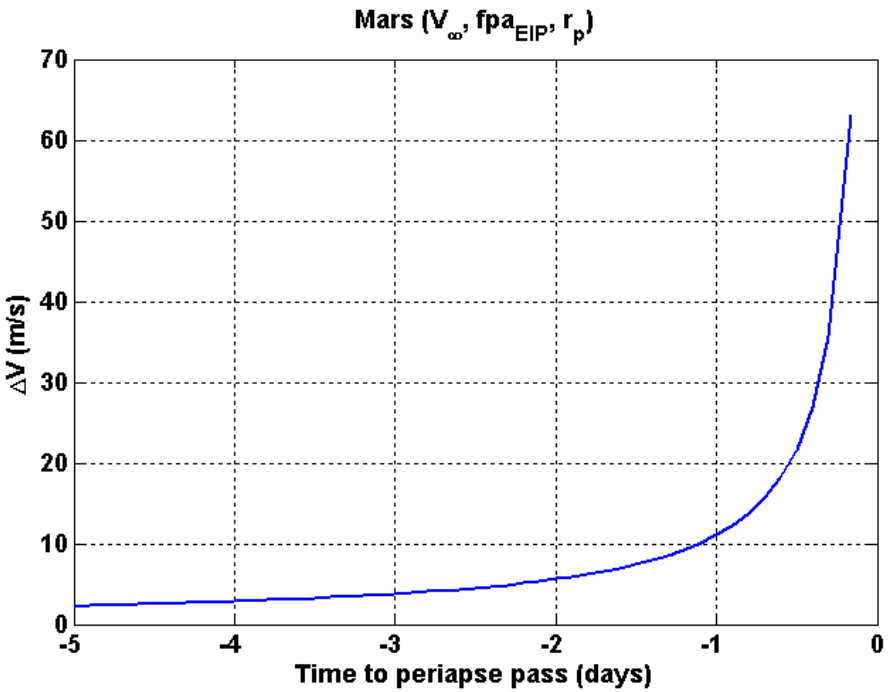


All rights reserved Beagle 2

Separation Manoeuvre 3/3

- Carrier Collision avoidance Manoeuvre
  - Must follow Planetary Protection Rules
  - Scheduled just after separation
  - The closer to the planet, the higher the Δv $\leftrightarrow$ trade-off with separation





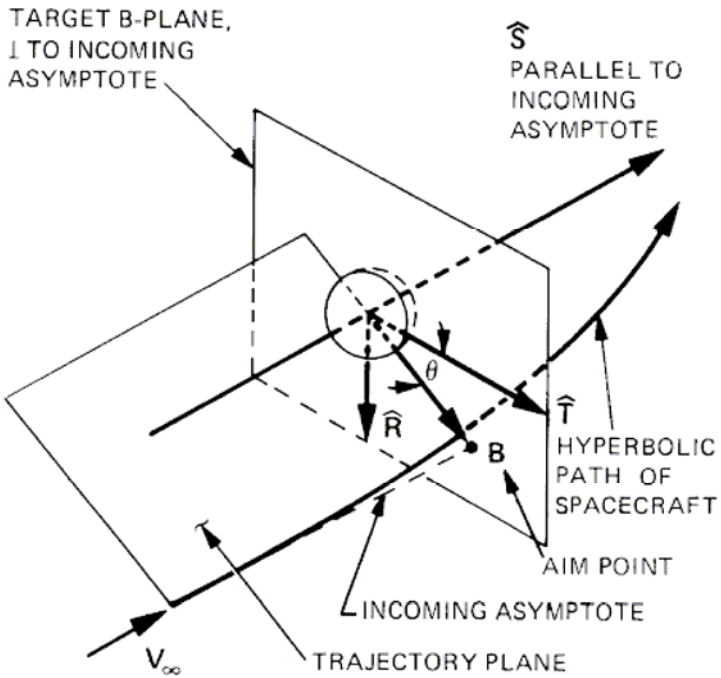
Targeting 1/3

- Objective:
  - To reach a target flight path angle at a given EIP location (latitude, longitude)
- Hyperbolic Release:
  - Based on the B-plane

$$\vec{v}_\infty, (\varphi, \gamma)_{EIP} \rightarrow \theta$$

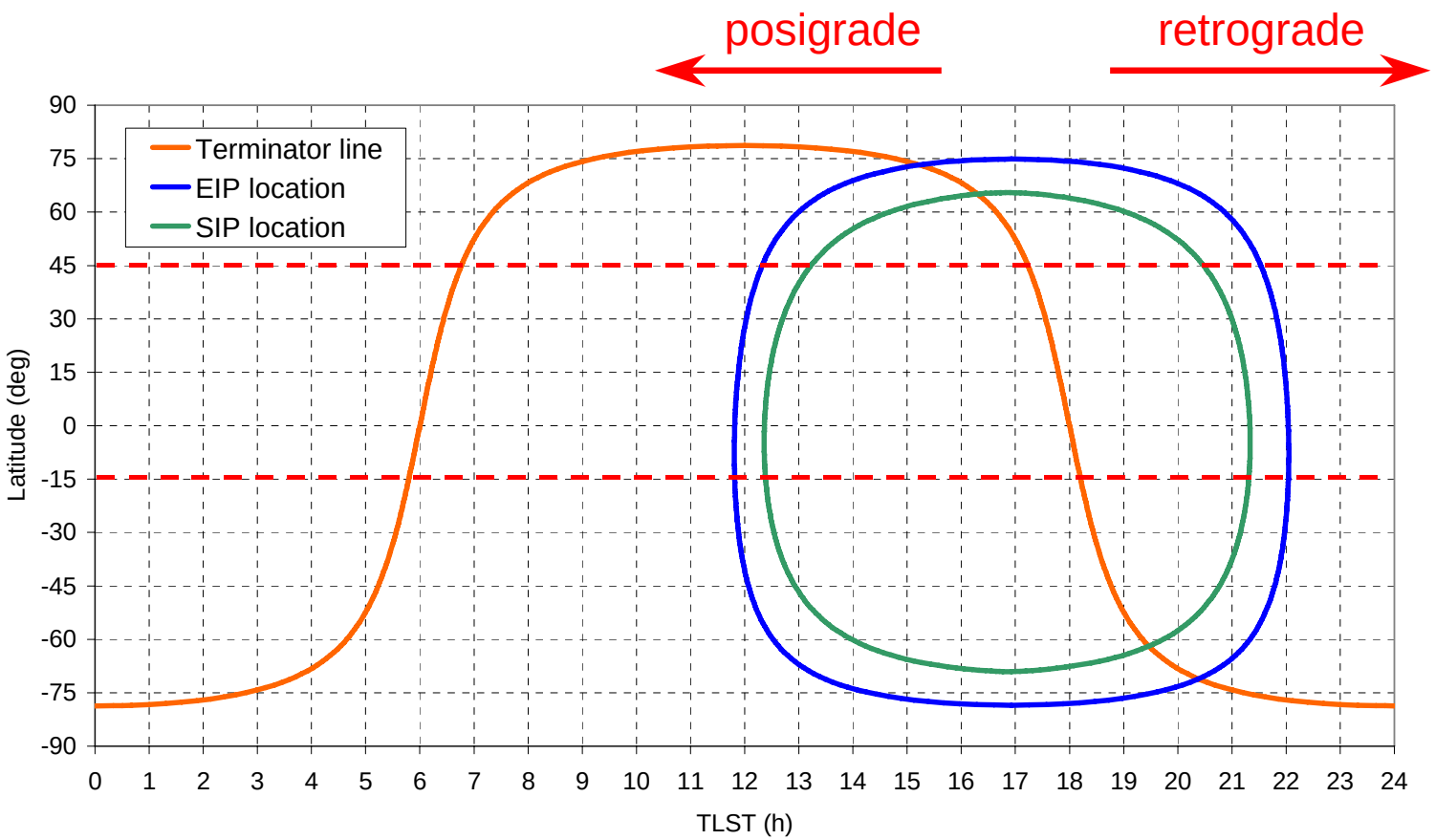
$\theta \rightarrow$ orb. Elements at EIP

  - 2 Solutions: pro & retrograde
  - Target of longitude
    - Arrival date adjustment



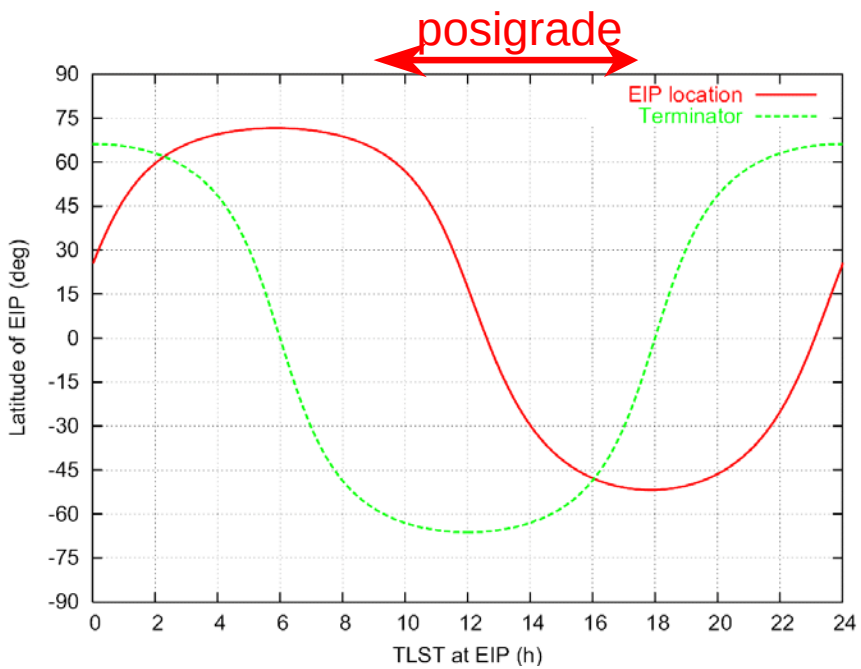
Targeting 2/3

- Hyperbolic Release Targeting:
  - Mars, direct Entry, -15º deg fpa at EIP



Targeting 3/3

- Elliptic Release Targeting:
  - From final orbit (HEO, circular)
    - Transfer from orbit to EIP (fixed inclination)
  - From parking orbit
    - Connected to arrival hyperbola: B-plane targeting
    - It fixed inclination and argument of pericenter of the parking orbit



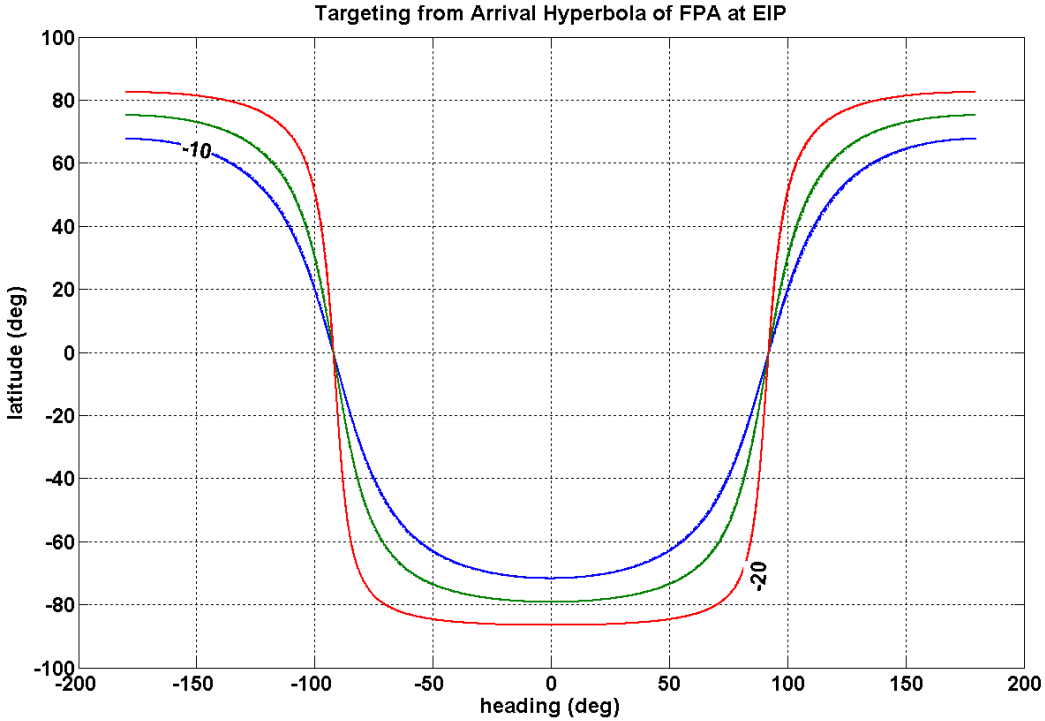
Propulsion

- Propulsion needs during EDL:
  - Perform last TCM (hyperbolic release)
  - Perform de-orbit burn (elliptic release)
  - Attitude control during coasting
  - Entry G&C
    - Ex: Reaction Control System (RCS) for bank control
  - Descent G&C
    - Ex: lateral velocity controller
  - Landing G&C
    - Braking towards zero vertical and lateral speed

Constraints on entry location 1/4

- Entry Interface Window combines
  - Exo-atmospheric constraints
  - Endo-atmospheric constraints

- Exo-atmospheric constraints
  - Targeting capabilities of the arrival orbit: φ, γ
  - Entry conditions window: V, χ, LT



Constraints on entry location 2/4

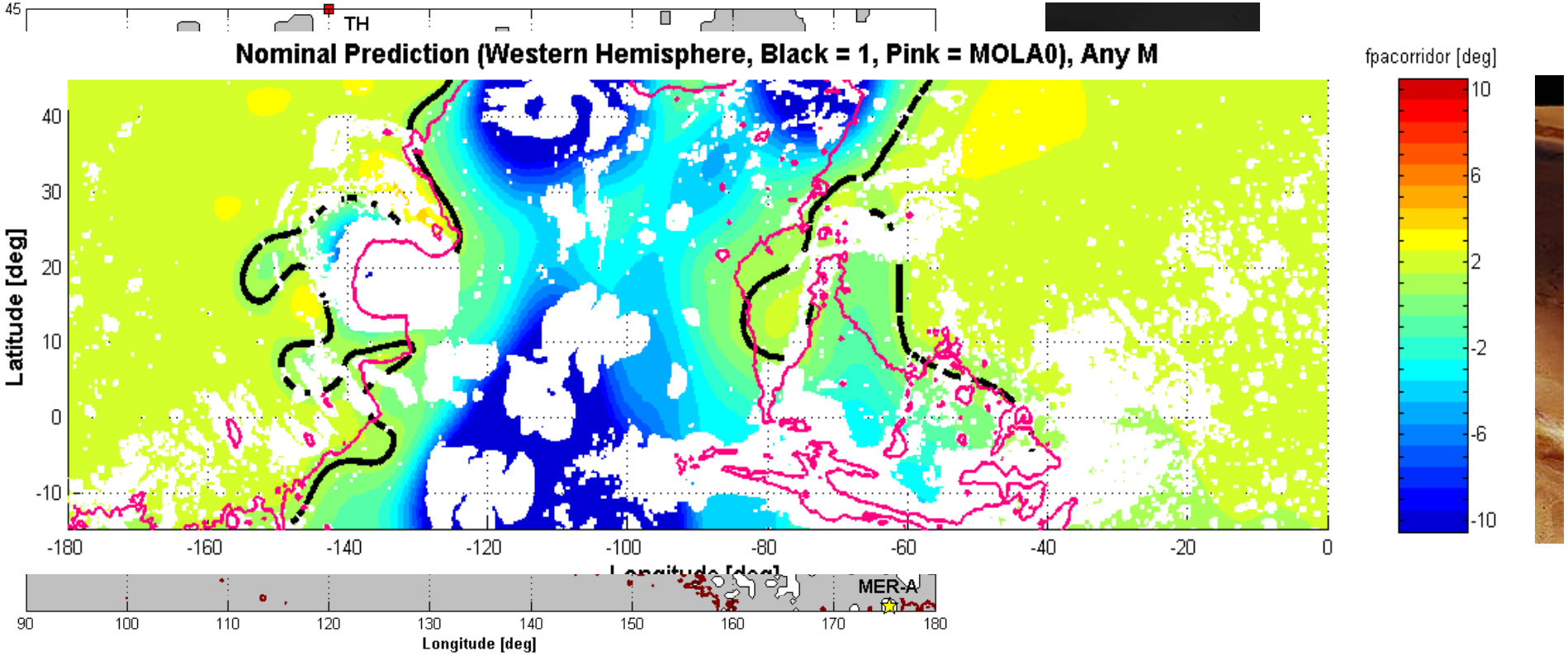
- Endo-atmospheric constraints
  - Scientific Constraints (SC):
    - landing areas of interest
  - Engineering Constrains (EC):
    - terrain filtering
  - Global Entry Corridor (GEC):
    - capability of the probe of reaching a landing site

      (Conceived by DEIMOS Space)

Constraints on entry location 3/4

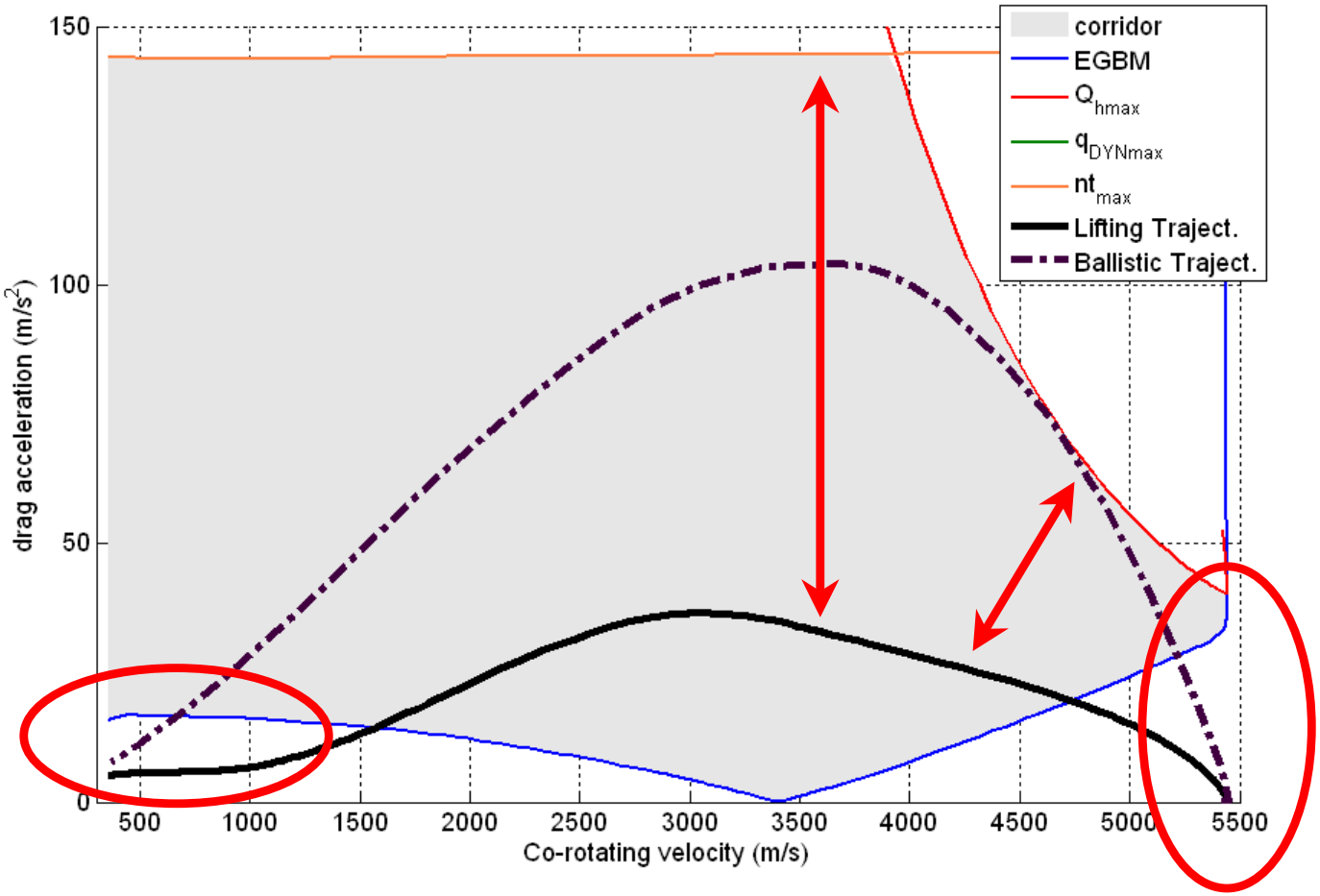
- Landing Site Selection

Scientific Constraints | **Engineering Constraints** | **Global Entry Corridor**



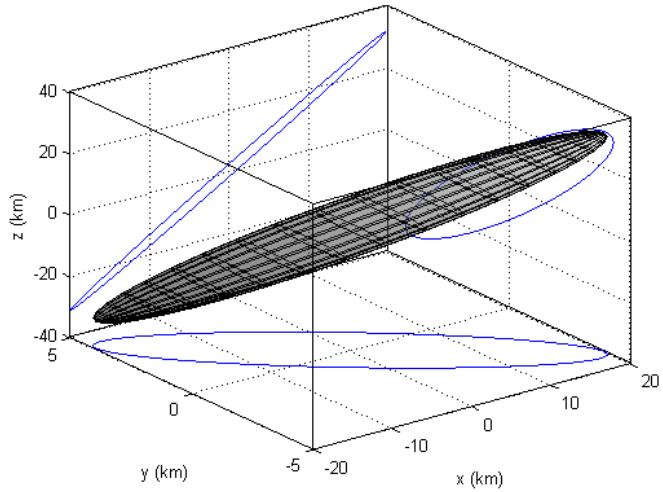
Constraints on entry location 4/4

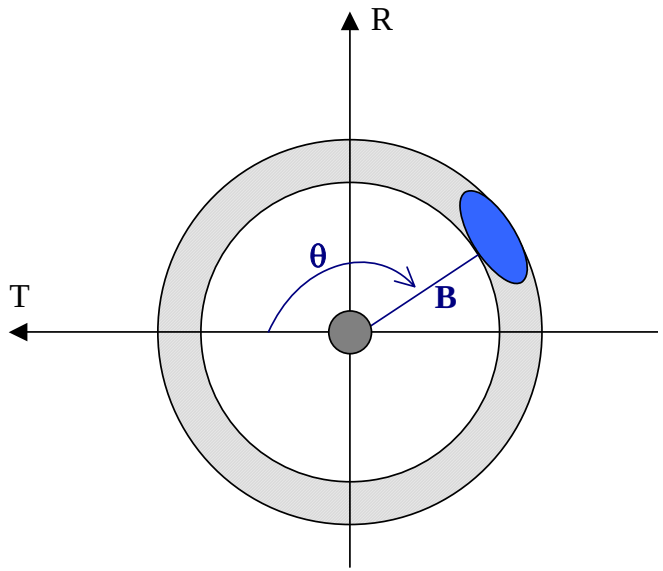
- Controlled Entry: Corridor for low L/D



Entry State Determination 1/2

- Probe state at entry results from:
  - Propagation of the uncertainties after the last manoeuvre (TCM/de-orbit)
  - Knowledge of the uncertainties from Navigation solution
- Navigation solution
  - Combines dynamical model & measurements to provide an estimation of the s/c state
  - From Ground OD or o/b filter
- Hyperbolic release:
  - Mapping of dispersions between Entry and Arrival through the B-plane





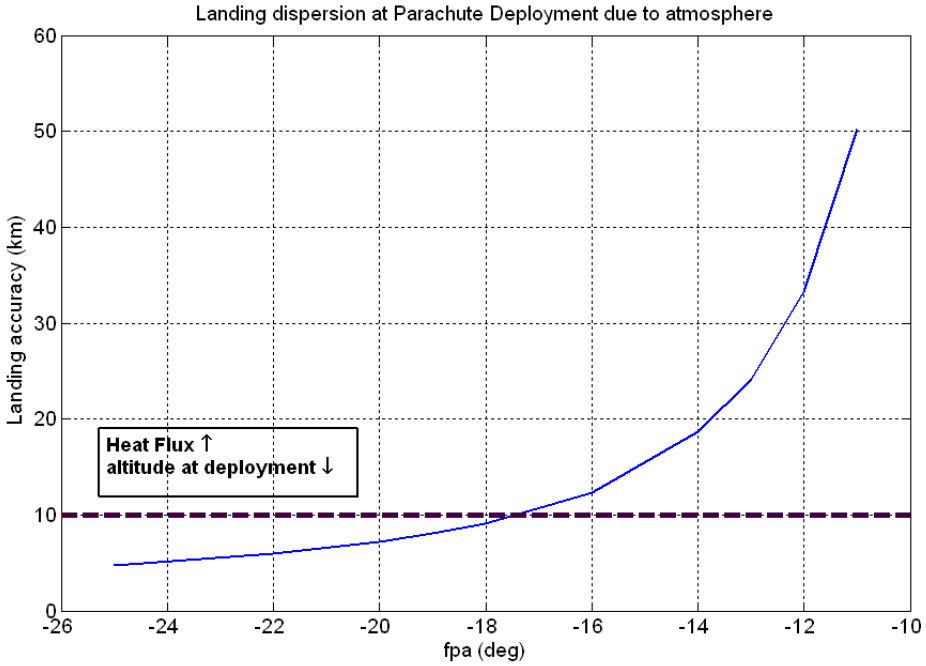
Entry state determination 2/2

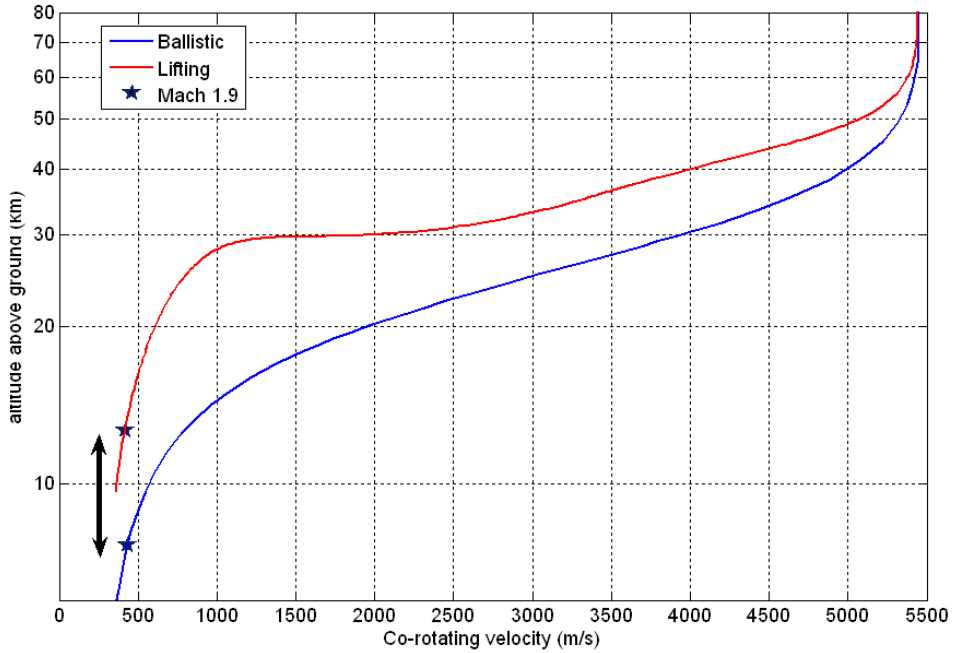
- Navigation performances are mainly affected by:
  - Presence of solar conjunctions close to arrival (to be avoided)
  - Earth-Planet distance (to be minimised)
  - Passes by equatorial zero-declination (to be avoided)

- Navigation options are:
  - Radio-tracking with two-way range and Doppler
  - ΔDOR
  - Same beam interferometry between arriving S/C and orbiting S/C at Mars
  - radio-link with an orbiting S/C
  - Camera relative measurements

Controlled entry & descent 1/2

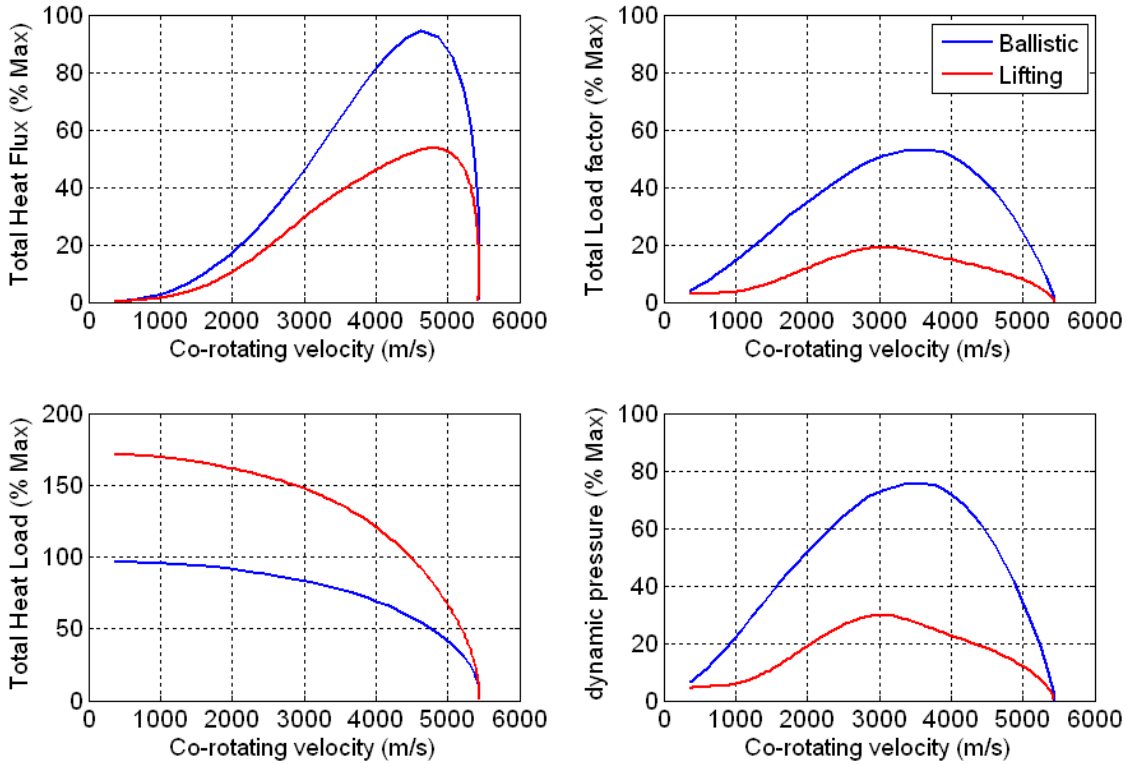
- Science drivers for controlled entry and descent.
  - Landing accuracy
    - accurate landing < 10 km (3σ) → L/D > 0.2
    - pinpoint landing < 1 km (3σ)
  - Landing site altitude
    - Upland sites in thin atmospheres





Controlled entry & descent 2/2

- Impact on Thermo mechanical design
  - Reduce mechanical loads
  - Different TPS design

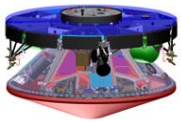


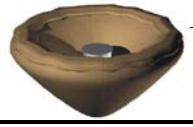
EDL Architectures 1/7

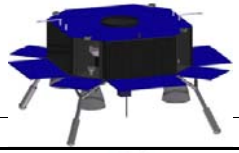
- EDL components aimed at reducing energy down to surface contact
- Most of energy removed during Entry Phase
- Depending on the Mission Requirements & Constraints, not all of the EDLS components need to be present
  Ex: Beagle2 had no propulsive braking
- Heritage is an strong argument for architecture selection (Space Qualification and testing)
  – Ex: DBG parachute, 70º cone angle aeroshell…

EDL Architectures 2/7

- Major EDL components

Phase	Element	Example
Exo-atmospheric	Carrier+DM	
	Orbiter+DM	
Entry	Rigid aeroshell	
	Inflatable Braking Device (IBD)	

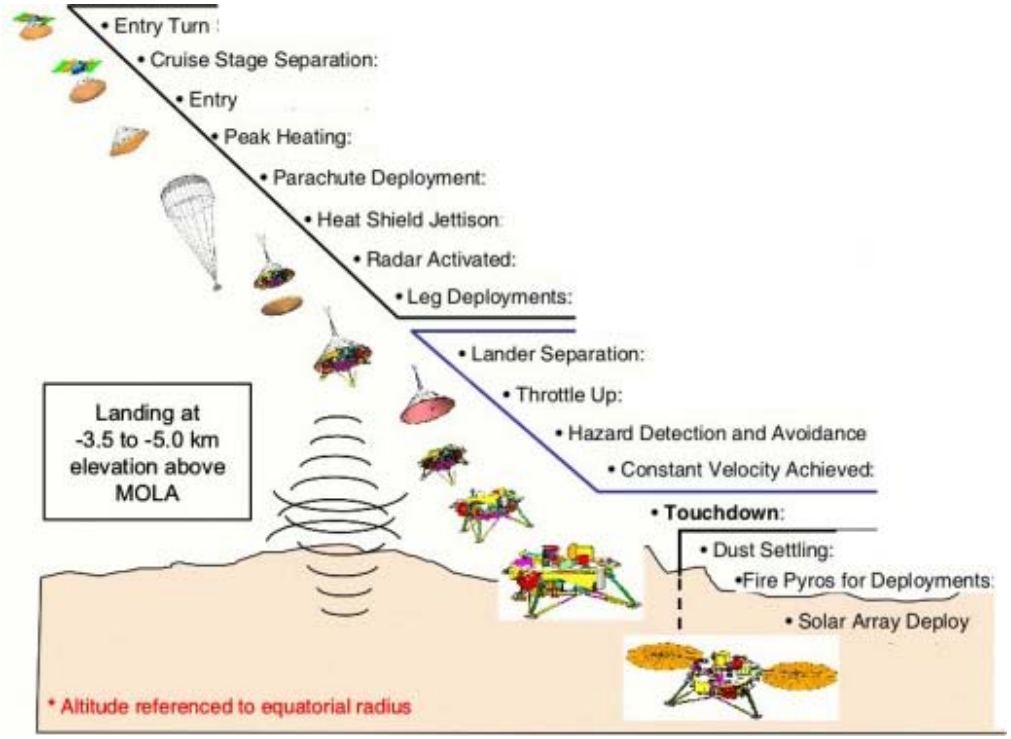
Phase	Element	Example
Descent	Supersonic Parachute	
	Subsonic Parachute	
	IBD	
	Propulsion	

Phase	Element	Example
Landing	Legs	
	Non Vented Airbag	
	Vented Airbag	
	Propulsion	
	Sky Crane	
	Penetrator	

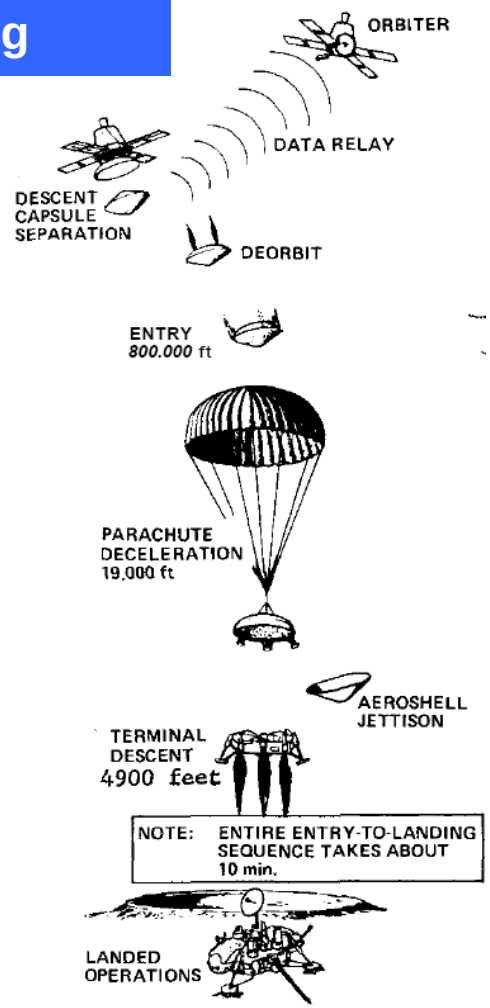
EDL Architectures 3/7

- Sequences

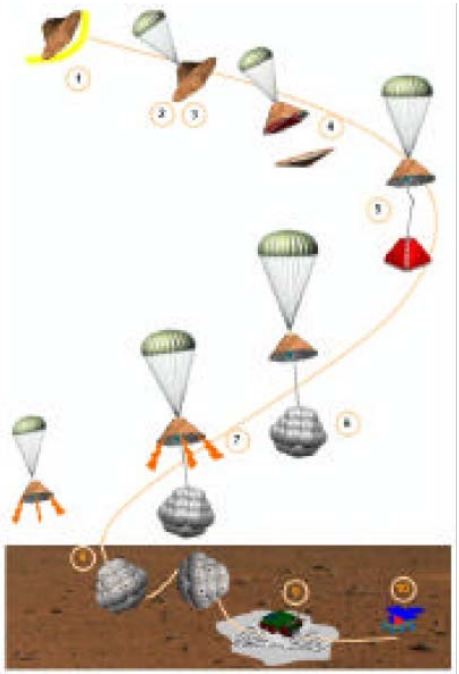
Phoenix



Viking



EDL Architectures 4/7

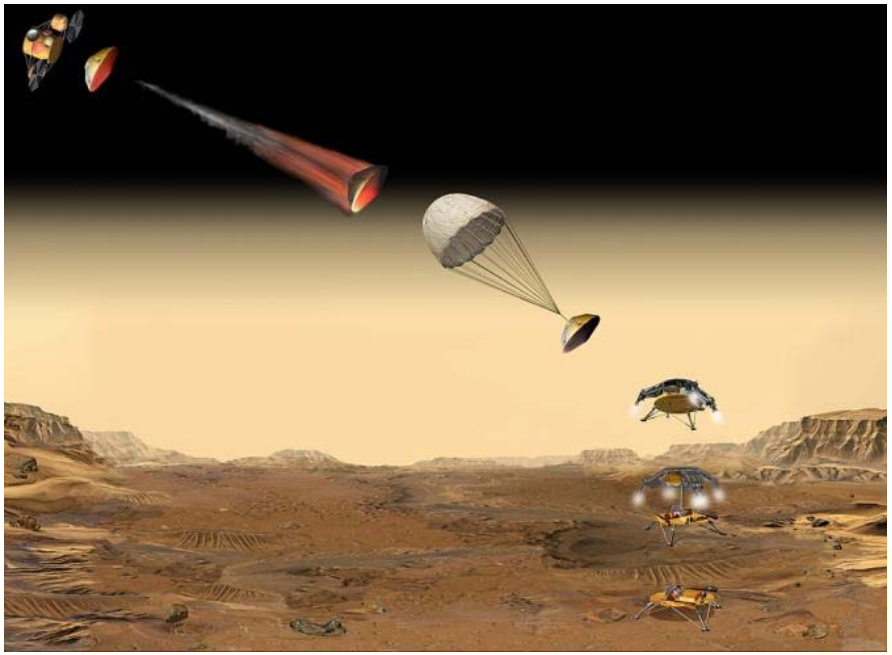


MPF & MER A-B

Mars 96

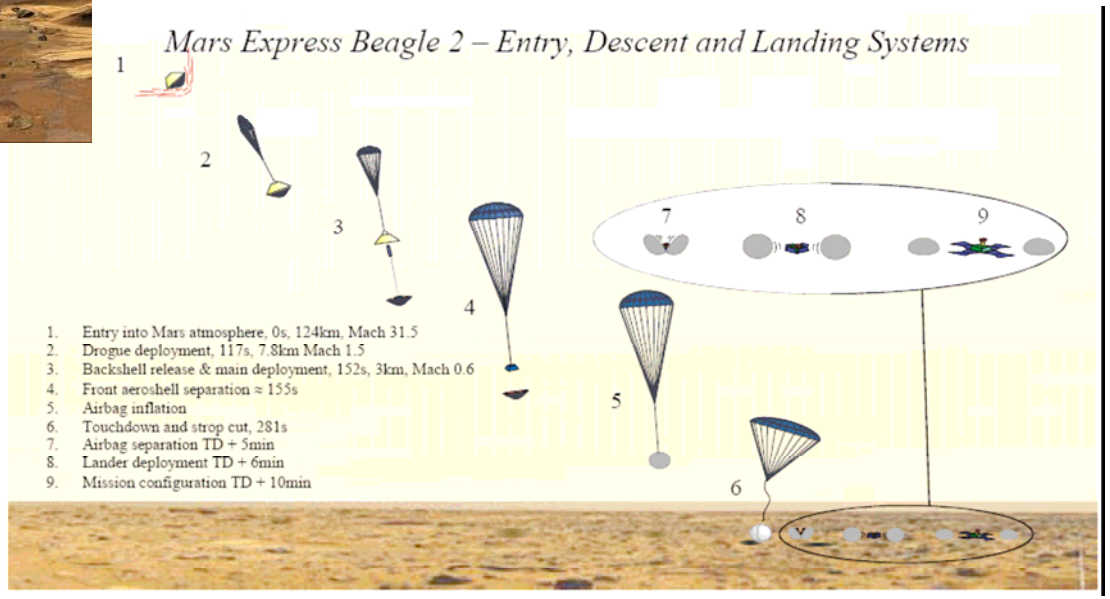
MSL

EDL Architectures 5/7



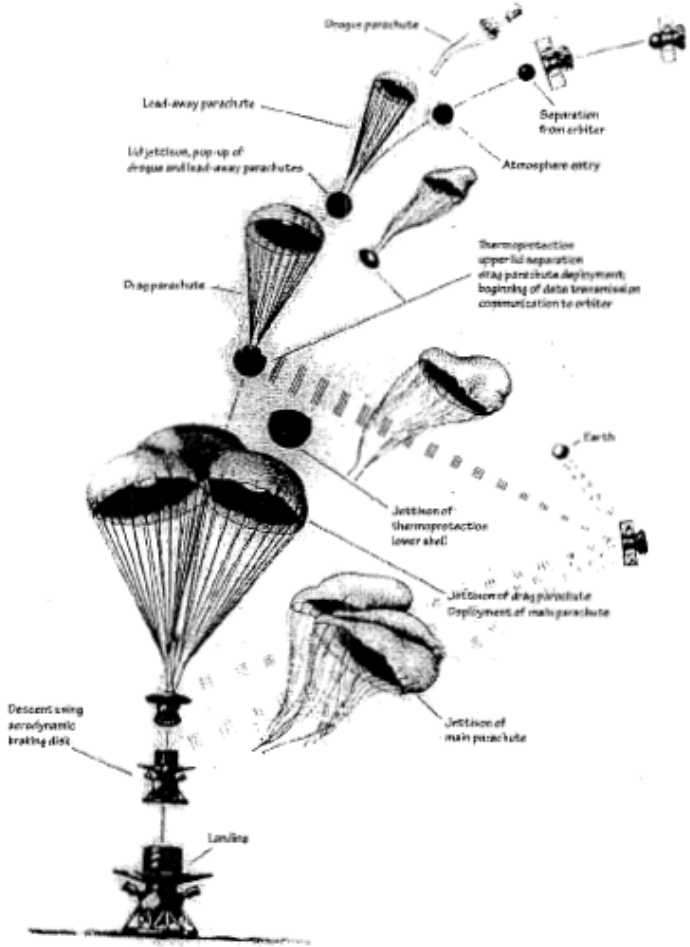
MSR

Beagle2

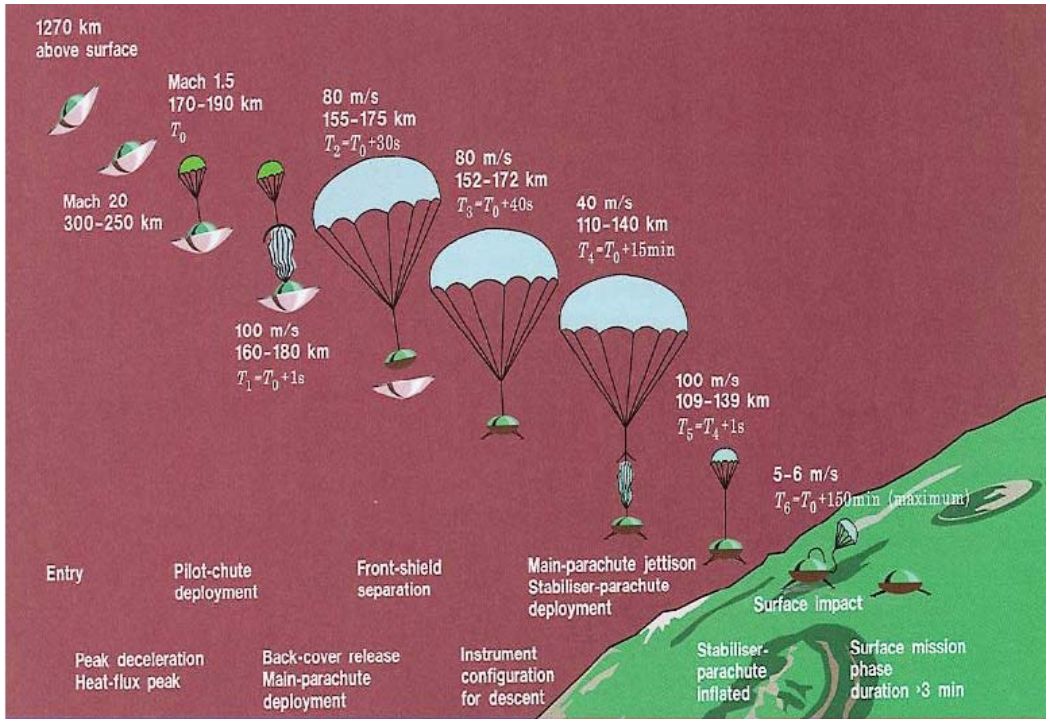


EDL Architectures 6/7

Venera 9-10



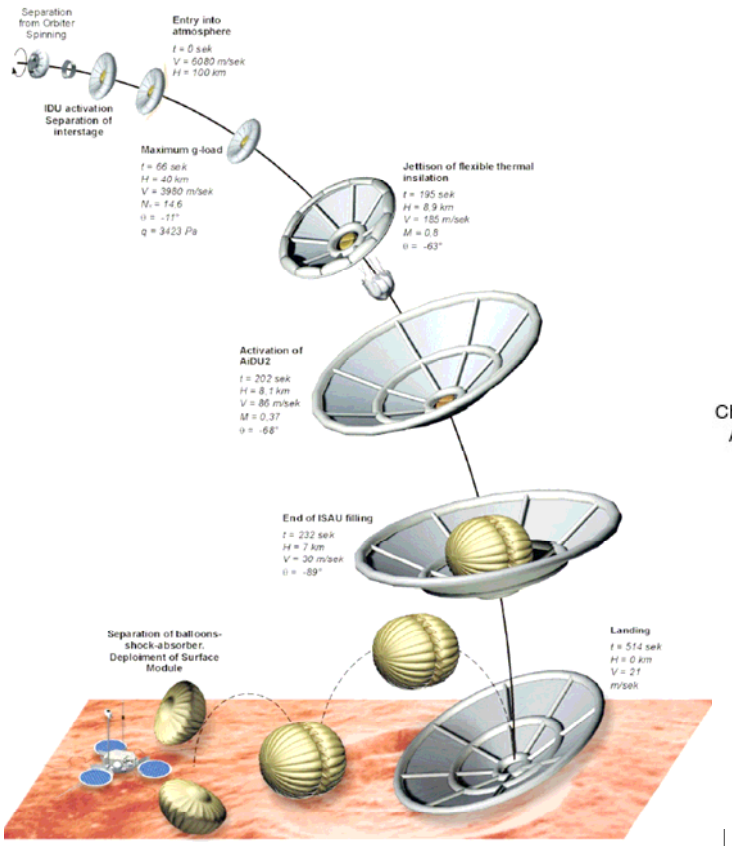
Huygens



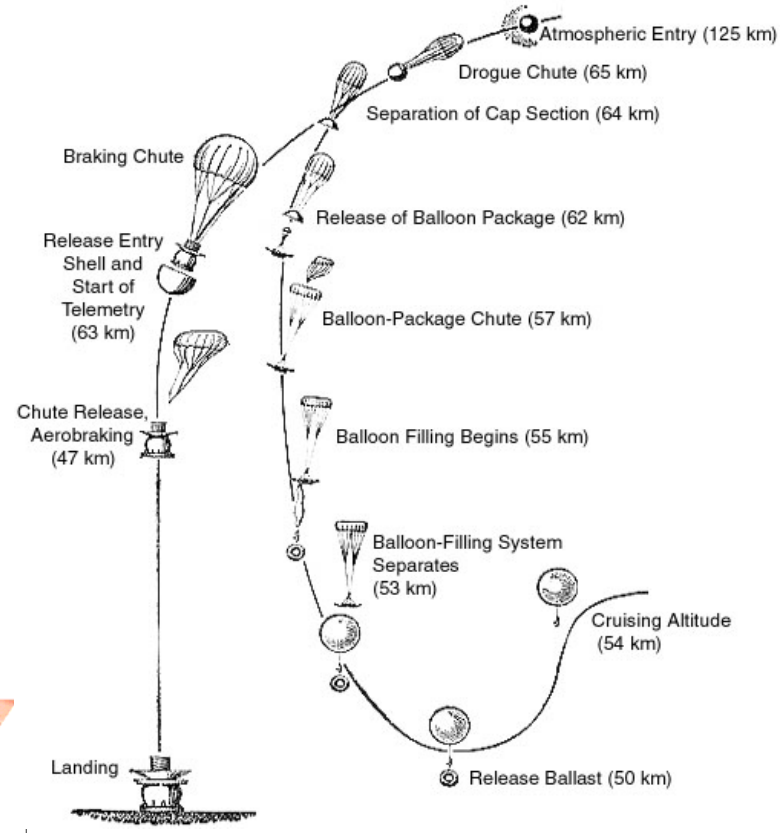
EDL Architectures 7/7

Mars 96

Netlander (initial)



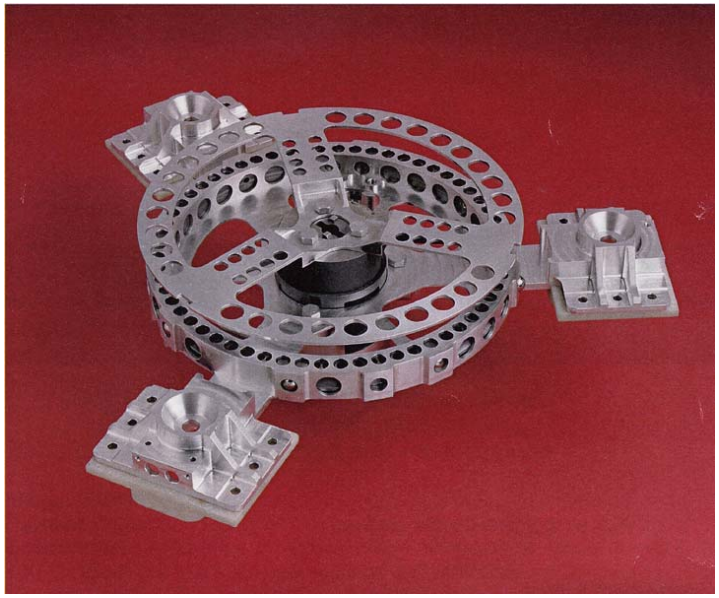
Vega 1-2



Spin-up and eject 1/2

- Spin used for passive stabilisation of the probe during exo/endo-atmospheric flight (poinsot motion)

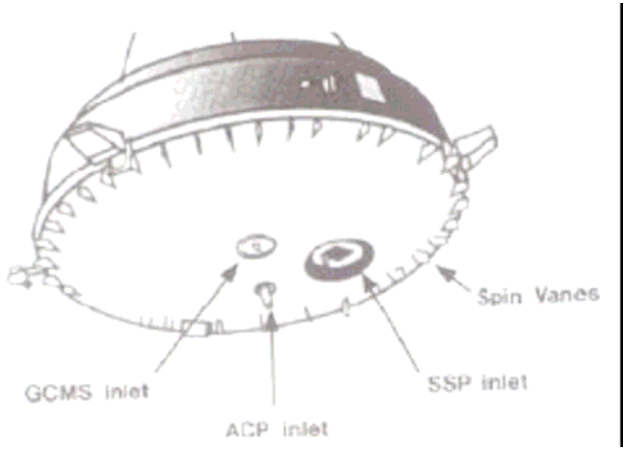
- Spin-up options
  - Before separation
  - Heritage of cruise spin
  - At separation

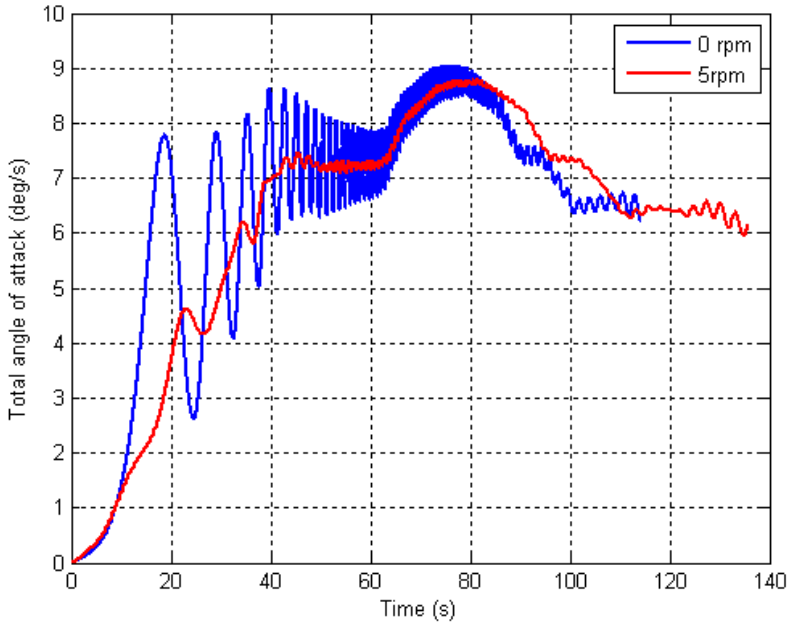


All rights reserved Beagle 2

Spin-up and eject 2/2

- Spin causes nutation due to non diagonal inertia tensor (gyroscopic effect)
  - Major contributor to AoA dispersion at Entry
  - High RPM causes AoA stiffness
  - Swivel required to decouple probe spin from parachute
  - Spin vanes used to control spin rate profile during Entry
- Controlled Entry
  - Spin Complicates GNC
  - Alternative: De-spin before entry





GNC needs 1/2

- GNC comprises
  - Trajectory Control
  - Attitude Control
  - Events detection and triggering
- No fully uncontrolled entry exist
  - Events detection & triggering at least
- *Ballistic* & *Controlled* entry usually refers to the Exo and Entry arcs
- GNC solution drivers:
  - Mission Requirements & Constraints
  - Heritage
  - Technology maturity

GNC needs 2/2

EDL Phase	GNC needs	GNC Means		
		Guidance	Navigation	Control
Exo-atmospheric	Attitude Stabilisation Attitude Control State Determination		Inertial Navigation Relative Navigation based on other s/c	Spin 3-axis control
Entry	Guidance Attitude Tracking Attitude Stabilisation Events detection State Determination	Guidance Controller		Weathercock effect Spin Roll control 3-axis Control
Descent	Guidance Wind / Lateral velocity compensation Events detection State Determination	Guided Parachute	Inertial Navigation Relative Navigation based on relative sensors (Lidar, radar Doppler, altimeter, camera…)	Controlled Parachute Lateral velocity control
Landing	Hazard Avoidance Pinpoint targeting Retargeting Impact velocity control (vertical & horizontal) Angular rates control Events detection State Determination	Landing Piloting Function Target guidance g-turn		3-axis control

Pre-entry instrumentation

- Pre-entry sensors (carrier/orbiter excluded)
  - Accelerometers
    - Rough Trajectory State Estimation
  - Gyroscopes
    - Rough Attitude State estimation
  - Star / Sun sensor
    - Accurate Attitude State estimation
  - Cameras
    - Optical Navigation (landmarks, celestial bodies)
  - 2-way range & Doppler
    - Navigation with respect to an Orbiter (accurate)
  - Timers
    - Event detection and triggering

Summary and Conclusions

- Ballistic entry is the initial window for exploration
- Controlled entry is an step forward towards detailed knowledge
- High degree of autonomy needed in all phases, involving advanced concepts on navigation and control.
- During separation and Arrival, navigation is the main challenge to allow precision landing, in particular for hyperbolic release
- Role of the separation and Arrival in the EDL design:
  - To provide the targeting function
  - To characterise the dispersions at the beginning of the atmospheric flight