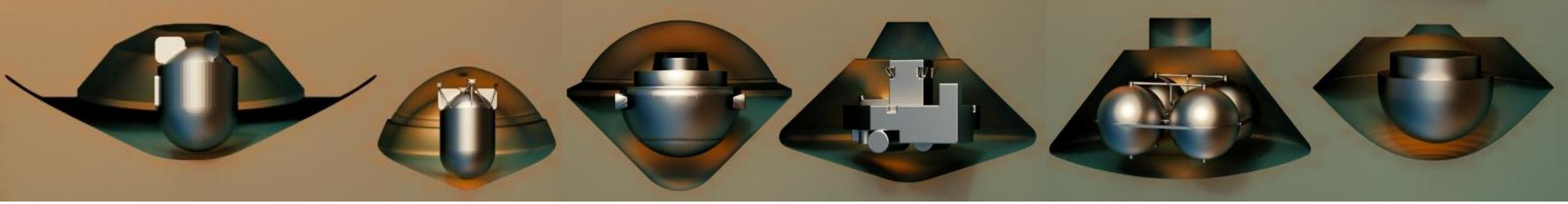

Entry, Descent, and Landing Systems Short Course

Subject: Guidance & Control

Author: Rodrigo Haya
Murray Kerr
Davide Bonetti (presenter)
DEIMOS Space S.L.U.

elecnor deimos

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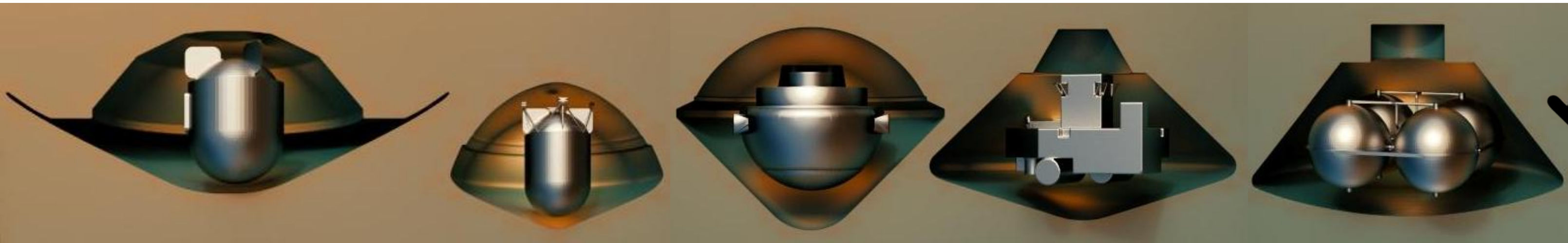


Table of Contents

Introduction

Motivation

- The general objective of the EDL GNC system is to safely bring the spacecraft from orbital conditions to rest on the planet surface following the designed mission profile.

- GNC for a planetary probe present many commonalities, but also key differences with respect to Earth re-entry.

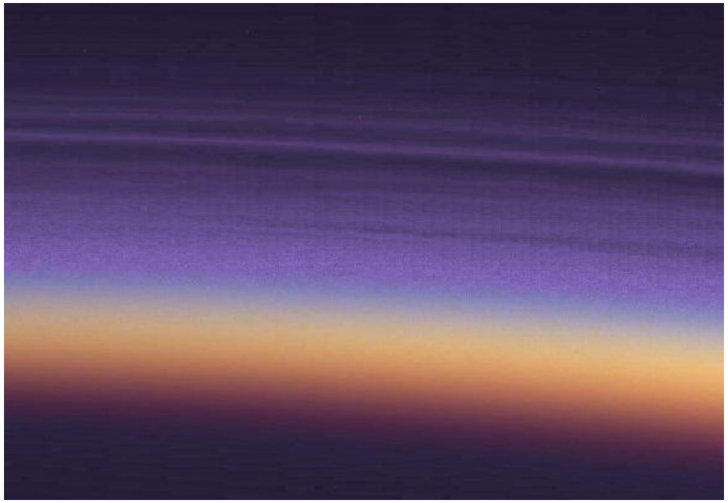
Objective

- To provide an overview of the GNC design for planetary entry missions

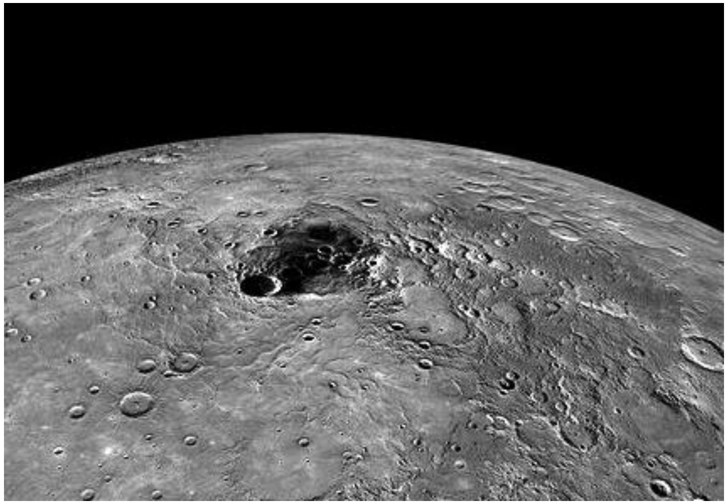
GNC REQUIREMENTS

GNC EDL Scenarios

- GNC Planetary Scenarios
  - Atmospheric
    - Landing probe (ex: rover)
    - Flying probe (ex: aerobot)
  - Airless bodies
    - Minor bodies (ex: NEO)
    - Major bodies (ex: Moon)



Titan Atmosphere (Cassini/Hyugens)
Credits: NASA/ESA



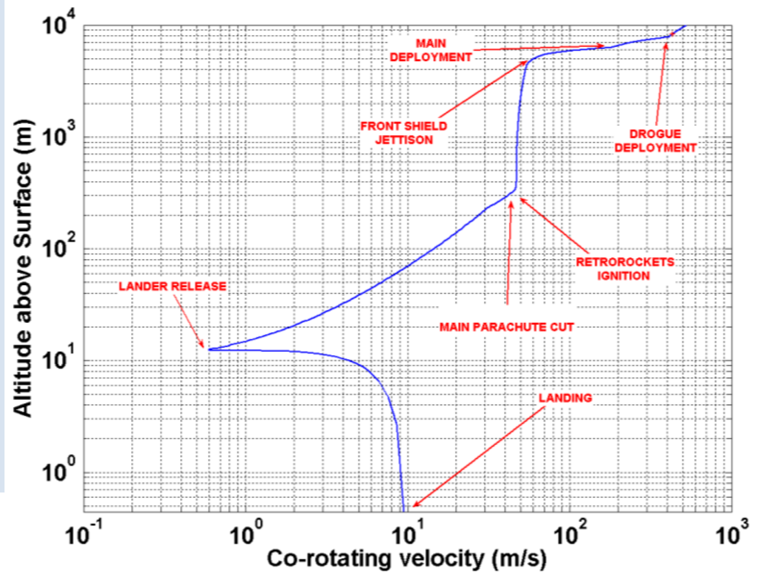
Mercury (MESSENGER)
Credits: NASA

GNC EDL Phases

- Atmospheric EDL
  - 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
  - Flight phase
    - Sustained flight (aerobots)
  - Landing
    - Final braking for touchdown

Atmospheric

2-stages ExoMars (2007)

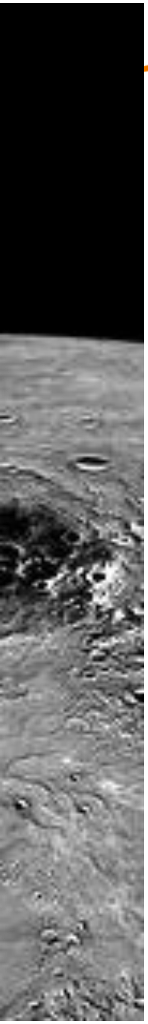


Titan Atmosphere (Cassini/Hyugens)

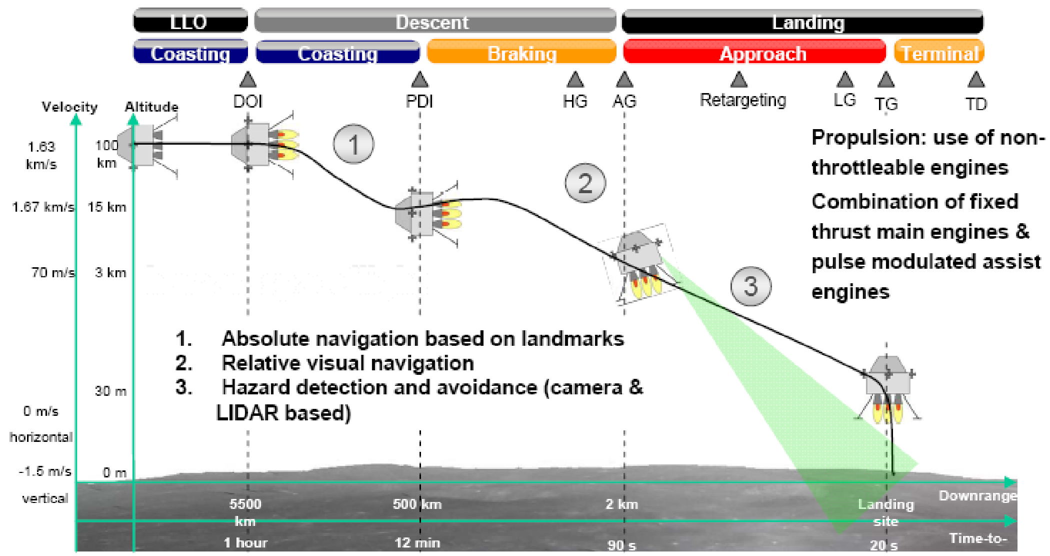
Credits: NASA/ESA

GNC EDL Phases

- Non-Atmospheric EDL
  - Descent: Coasting
    - e.g. elliptic orbit with perigee consistent with final landing phases
  - Descent: Braking
    - Main Δ V
  - Landing Approach
    - Final horizontal ΔV
    - LS observations
    - HDA & landing site retargetings
  - Landing: Terminal
    - Final vertical ΔV
    - Soft touchdown



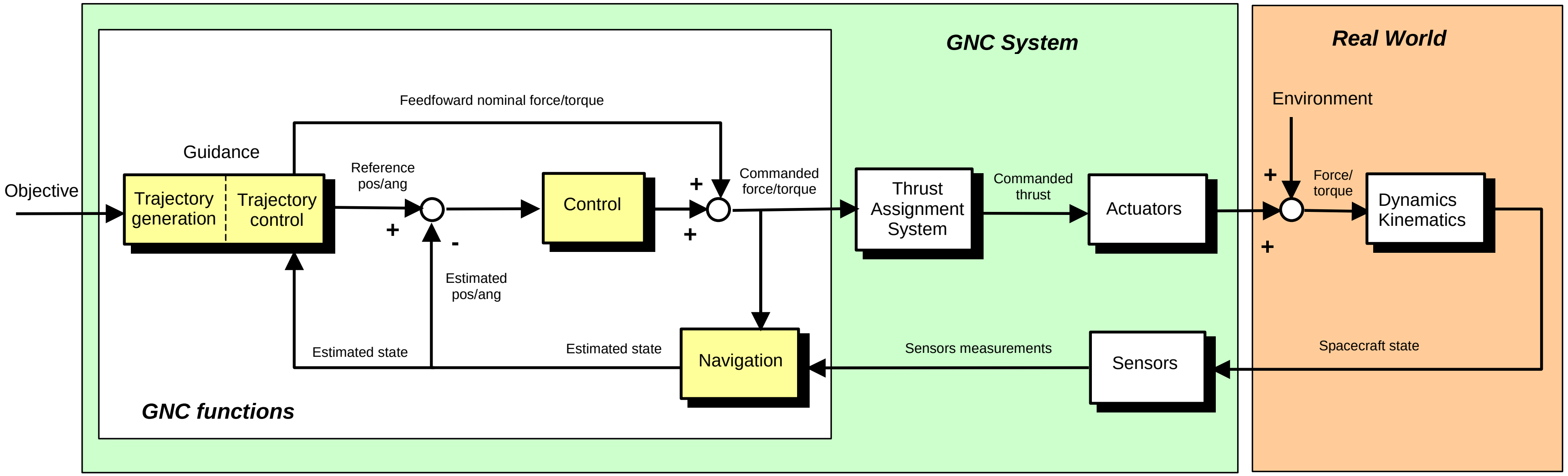
Mercury (MESSENGER)
Credits: NASA



Lunar Lander
Credits: ESA

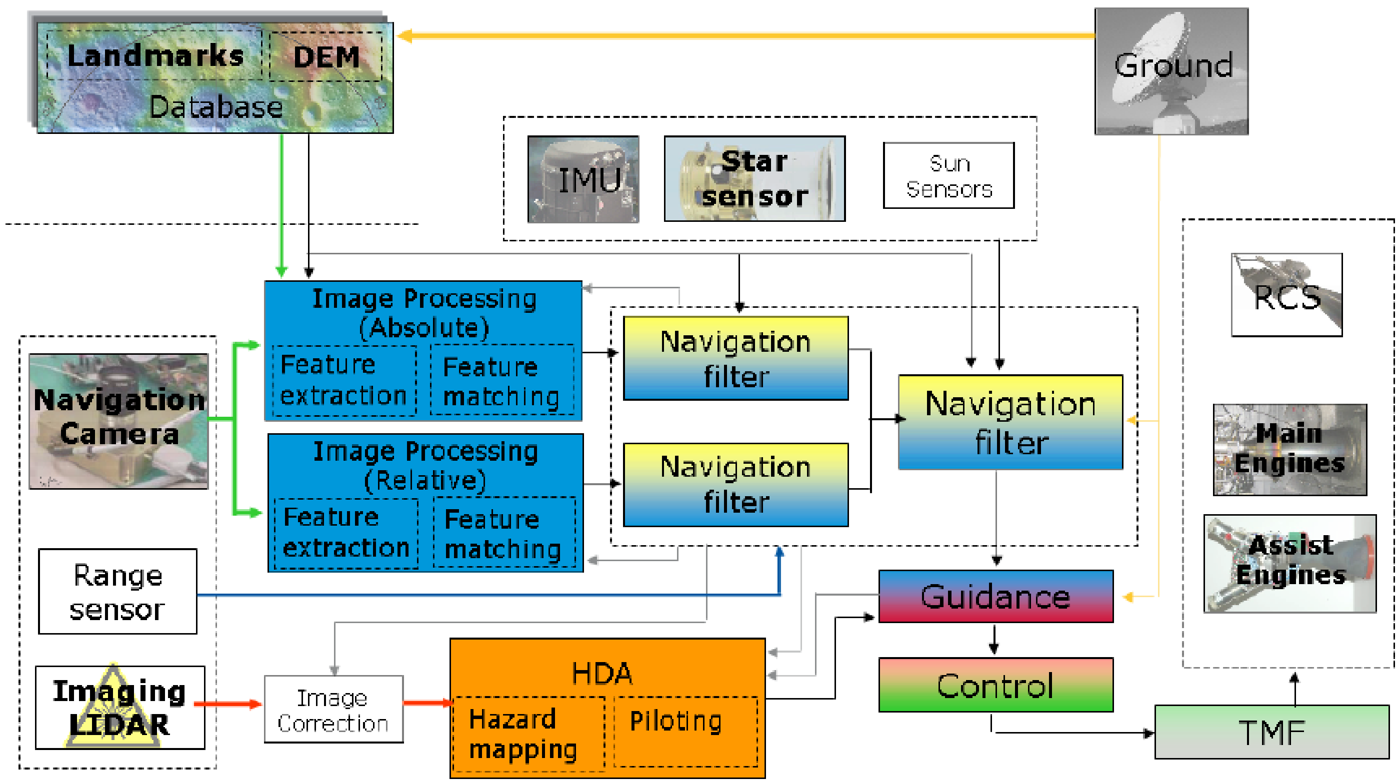
GNC Overview

- Generic components
  - G-N-C
    - Actuator management; sensor filtering
  - Modes Management (MVM, FM)



GNC Overview

- Example of EDL GNC sub-system functions



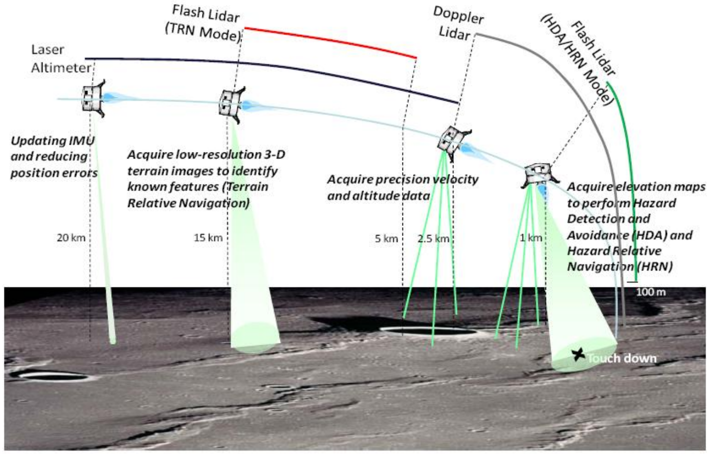
Lunar Lander

Credits: ESA

GUIDANCE

Guidance Tasks

- Generate o/b trajectory (trajectory generation)
- Tracking of reference trajectory (trajectory control)
- Targeting of final conditions
- Re-planning and re-targeting
- Stabilization (response against traj perturbations)



Planetary Lander Credits: NASA

Guidance means

- Thrust (rockets)
- Engine (aerobots)
- Aerodynamic angles

Mission /Study	Algorithm	Longitudinal Control (Bank Angle Modulation)	Lateral Control	Reference Profile	Replanning
MSL (NASA)	Entry Terminal Point Controller	$L/D = fnc(DR, D, \dot{h})$	Crossrange threshold	$DR(V), D(V)$ $\dot{h}(V)$	No
MREP - HP (ESA)	MSTS+	$L/D = fnc(D, \dot{h}, \int D)$	Azimuth error threshold	$D(e)$	Update of Dref wrt DR error

Example of Guidance Methods (Mars Entry)

Guidance Requirements

- Desired Trajectory Dynamics (ω_n, ζ)
- Targeting accuracy, Pointing needs
- Simplicity, Robustness, Low consumptions

NAVIGATION

Navigation Tasks

- Estimate state

Navigation means

- Sensors
  - Inertial (IMU: Accelerometer, Gyro)
  - Relative (Radar, Camera, Doppler, Sun…)
  - Hybrid solutions

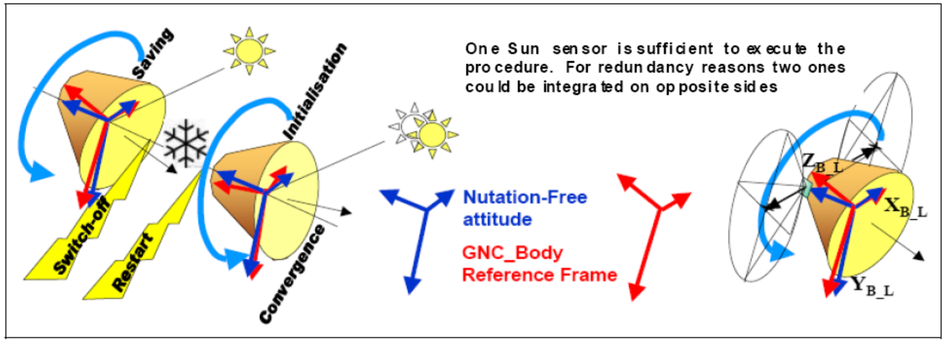
Navigation Requirements

- Accuracy
- Autonomy
- Initialization
- Redundancy

Hybernation (Exomars: ~10h, MREP - SL: ~10 days) and IMU initialization before Entry

Relative Navigation Concept	Advantages	Disadvantages
RA only navigation	· Simple	· Coarse accuracies
RA plus inertial navigation	· Improved accuracy with respect to RDA only	· Subject to inertial attitude navigation performances
Vision based navigation	· Provides position, velocity and orientation wrt to ground · High performance estimation of lateral velocity wrt to ground	· Complex · Adequate illumination conditions required
RA + inertial + VBN	Robust, high accuracy	Complex

Example of Relative Navigation Trade-offs (Mars Descent) MREP – SL (ESA)

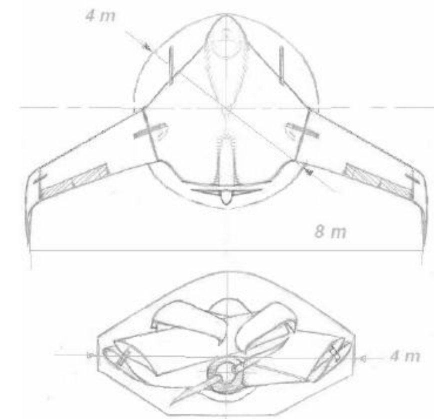


Credits: TASI

CONTROL

Control Tasks

- Tracking of guidance commands
- Stabilization (response against perturbations like turbulence)
- Actuator management and commanding
- Failure tolerance



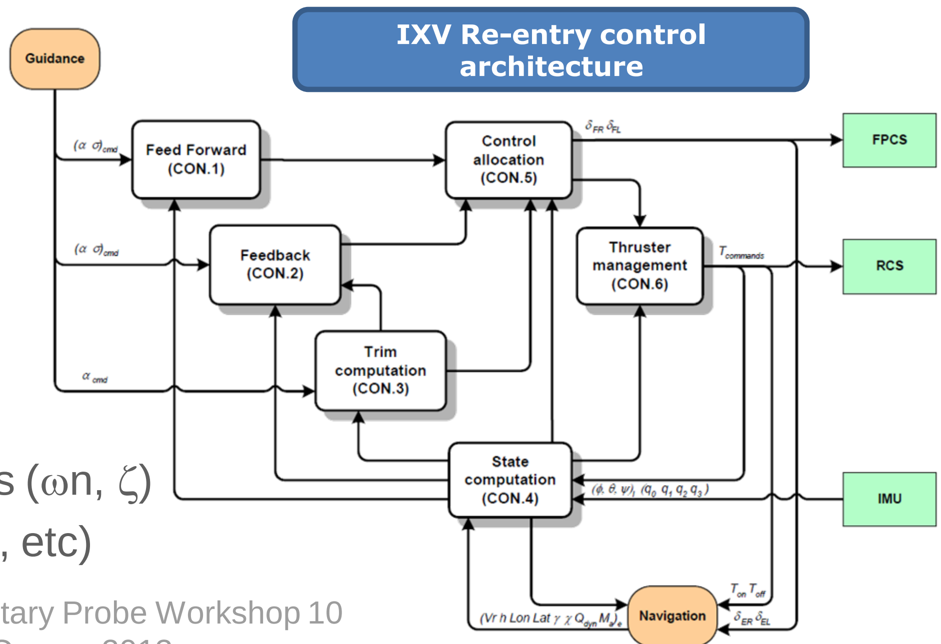
BWB configuration for Titan UAV PERIGEO, Credits: SCR, AERNNOVA, DEIMOS

Control means

- RCS
- Main engines (pulseable, throtable, etc)
- Active aerodynamic surfaces

Control Requirements

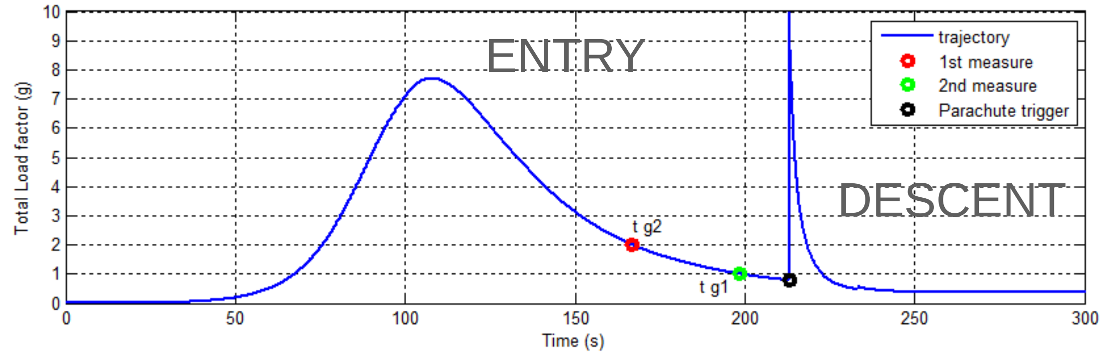
- Actuators limits (deflection, rates) and max thrust
- Desired Trajectory and attitude Dynamics (ωn, ζ)
- Robustness (MCI, AEDB, Atm, Actuation, etc)



MODES

Tasks

- Events detection
- Events triggering
- Modes Management (MVM)
- Failure modes management (HMS)



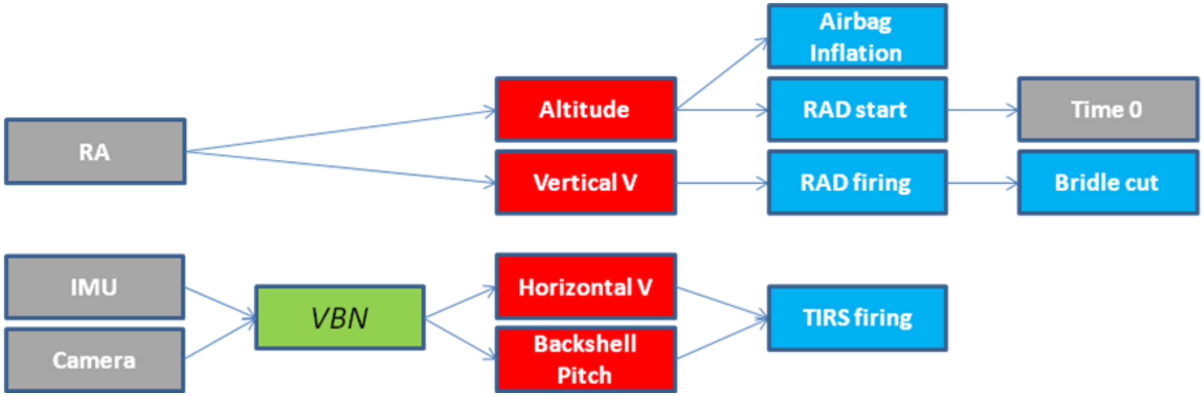
Example of load-factor-based algorithm to trigger a parachute opening

Means

- Sensors

Requirements

- Accuracy
- Autonomy



Example of sensors, measured state and events triggering
Mars, powered descent sequence MREP – SL (ESA)
MER-like (RAD+TIRS)

GNC NEEDS

EDL Phase	GNC needs	GNC Means		
		Guidance	Navigation	Control
Exo-atmospheric	Attitude Stabilisation Attitude Control State Determination	Delta V commanding and pointing	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

EDL GNC drivers

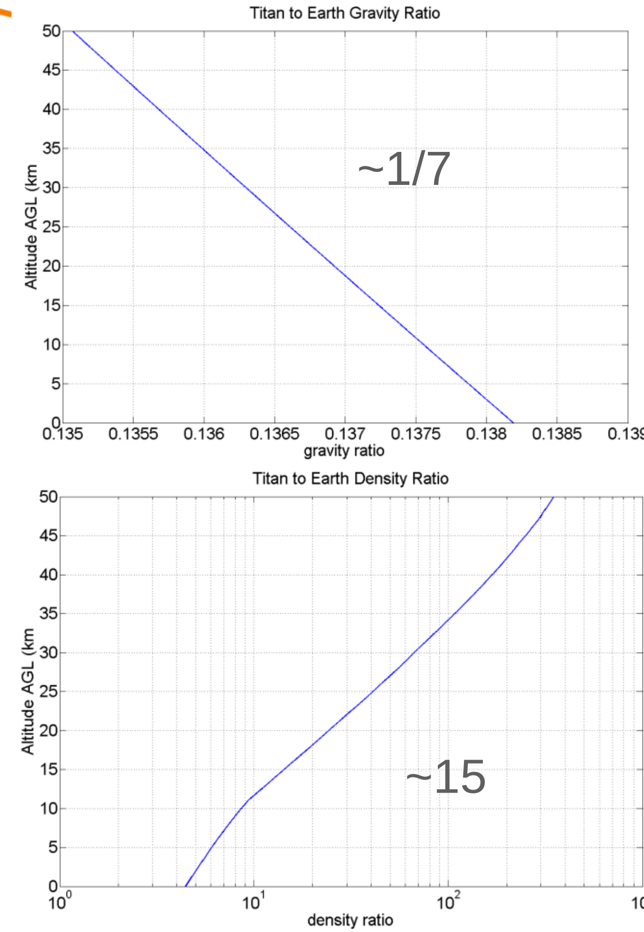
- Needs for GNC depends on the mission requirements: from fully ballistic to fully guided and controlled probes.
  - Keep it simple but safe: add complexity only if needed

- GNC specific requirements for planetary probes
  - Target body: Titan, Mars, Venus, Jupiter, asteroids, Moon..
  - Environment knowledge
  - Vehicle: capsule, lifting body, aerobot
  - Entry strategy: ballistic, controlled…
  - Autonomy
  - …

Target body

- **No/tiny atmosphere: asteroids, Moon, Europa**
  - No “free” deceleration
  - Lower trajectory and attitude disturbances
  - Easier safe modes
- **Low density: Mars**
  - Limited “flyability”
  - Breaking as main EDL task
- **High density: Titan, Venus**
  - Enables sustained flight missions (endurance)

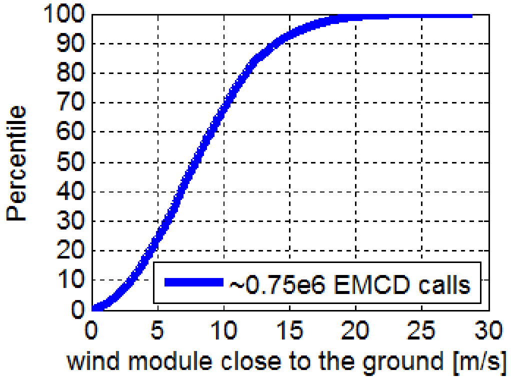
Titan Balloon Concept
Credits: NASA/JPL, Caltech



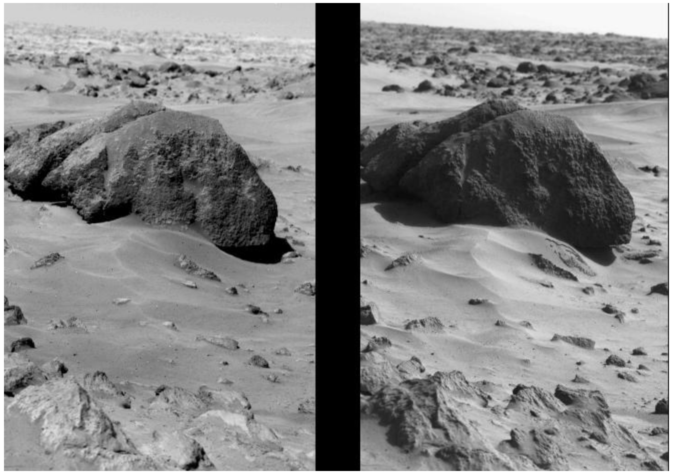
Titan / Earth Environment (gravity, density)

Environment

- Limited Knowledge drives robustness requirement
  - Atmosphere
  - Terrain
- Mitigation:
  - Remote sensing (atmosphere & terrain)
  - Hazard Detection and Avoidance (landing)

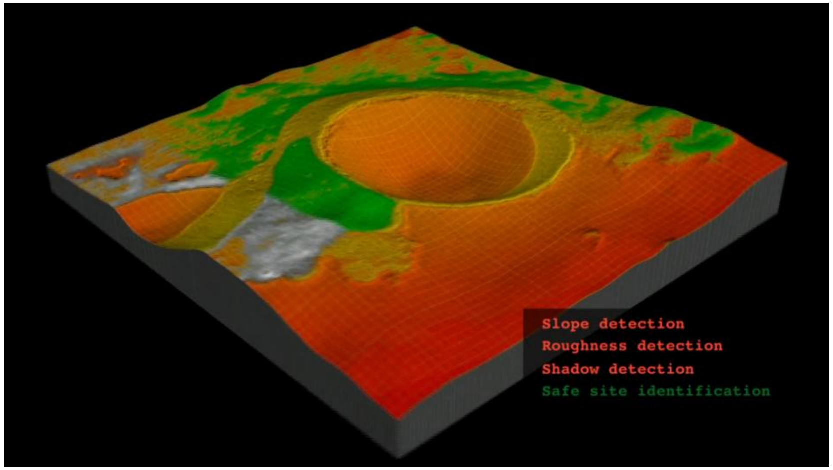


Mars Winds close to ground
(post-process of EMCD calls)



Viking "Big Joe" boulder and surface changes with time

Credits: NASA

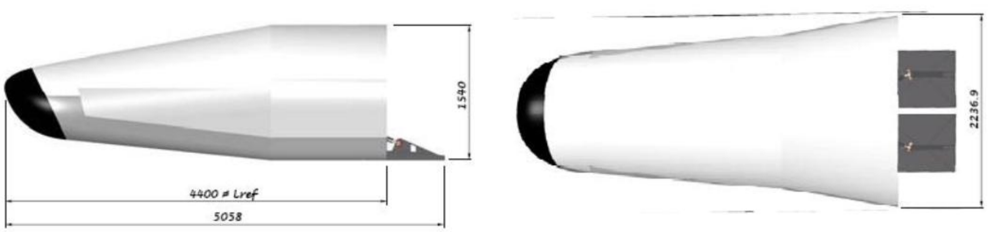


HDA (Lunar Lander, ESA)

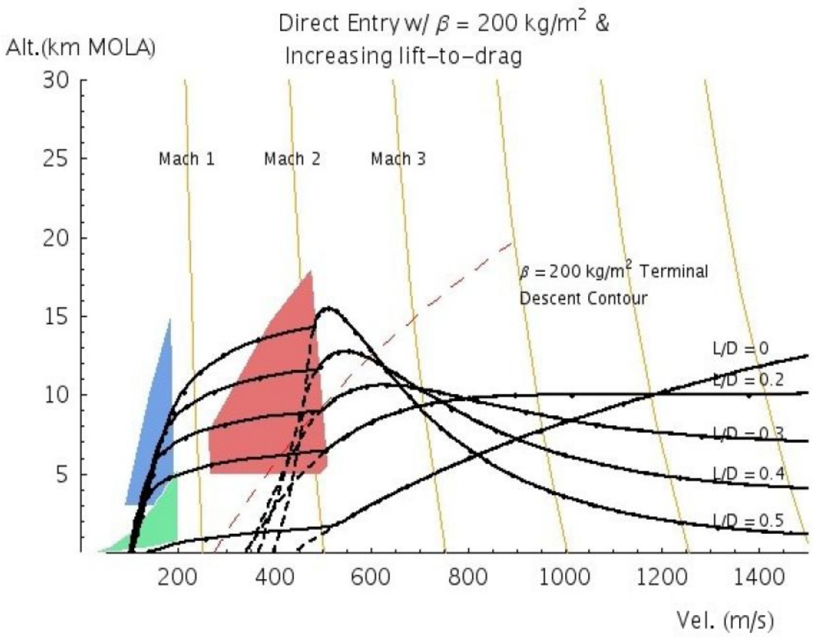
Credits: ESA

Vehicles

- Atmospheric: shape is relevant for GNC
  - Capsules (limited authority)
    - Ballistic (L/D=0)
    - Lifting (low L/D)
  - Lifting bodies
  - Aerobots (balloons, airplanes)
  - Parachutes and parafoils
- Non-atmospheric
  - Landing modules



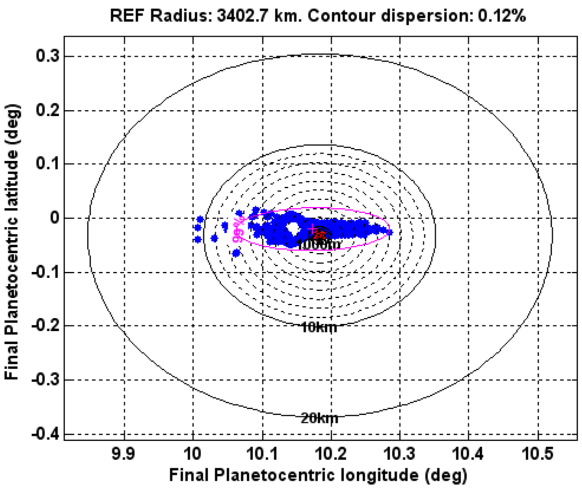
Intermediate eXperimental Vehicle (IXV, ESA)
Lifting body GNC Technology Demonstrator (Earth)
Credits: ESA



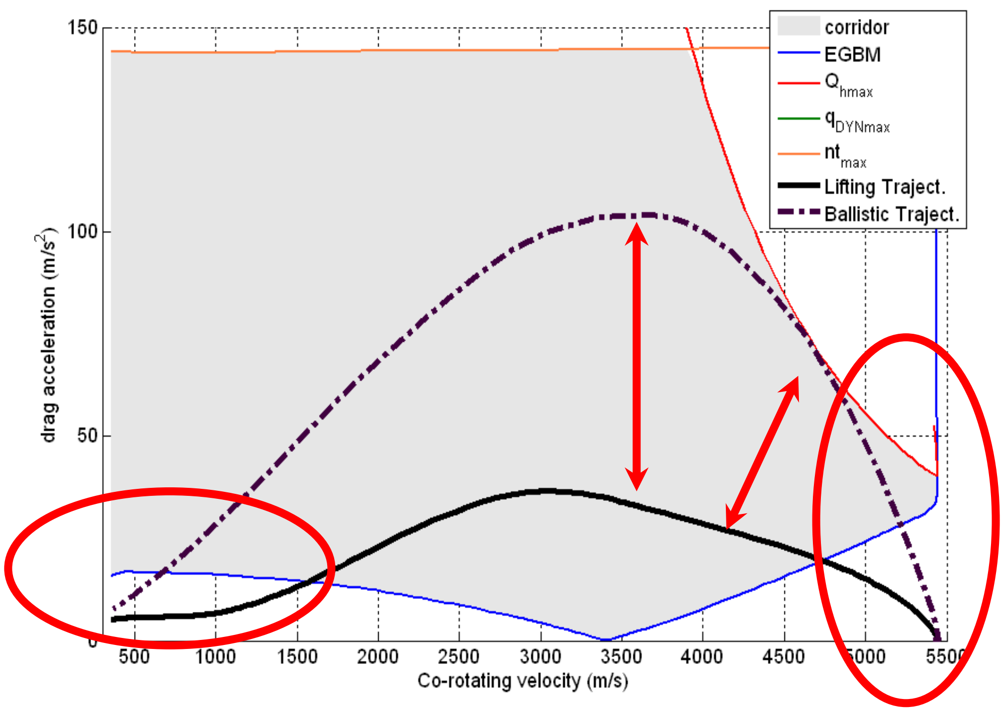
Impact of L/D on Mars Entry and Descent
Credits: R.D. Braun, R.M. Manning

ATM Entry Strategy

- Controlled or ballistic: accuracy, complexity and robustness trade-off
- Release strategy drives GNC requirement during coasting phase. (ex: hybernation)
  - Release from Elliptic
  - Hyperbolic arrival



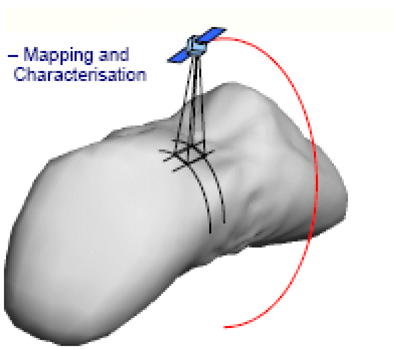
Accuracy at end of Controlled Entry, Mars MREP – HP



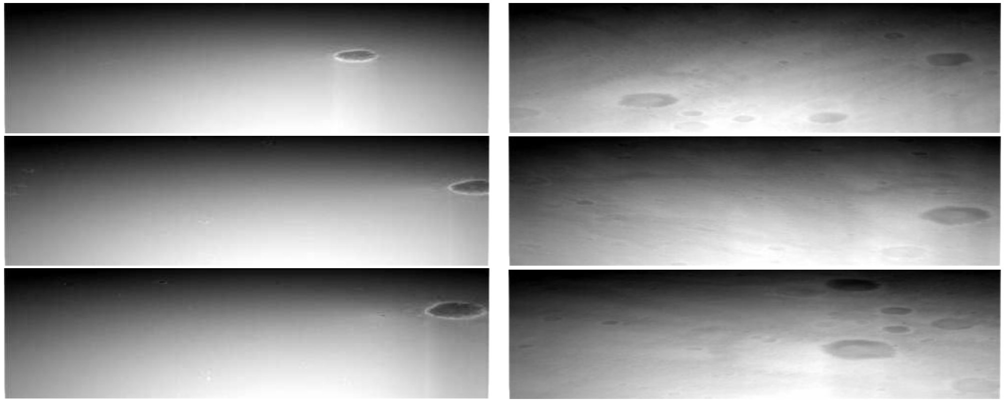
Entry corridor: drag acceleration for ballistic or lifting entry (Mars)

Autonomy

- Large distances does not allow remote commanding in the vicinity of the target body
- After last TCM, GNC must be autonomous
  - Reflected in the modes management (MVM) and the failure management (FDIR)
  - o/b processing
  - o/b sensors
  - Target mapping
  - Robustness



FIRE TIRS!



MER DIMES: Opportunity (left) – Spirit (right)
Used by GNC in combination with other sensors (IMU, RA) to take the correct decision on firing TIRS

Credits: NASA

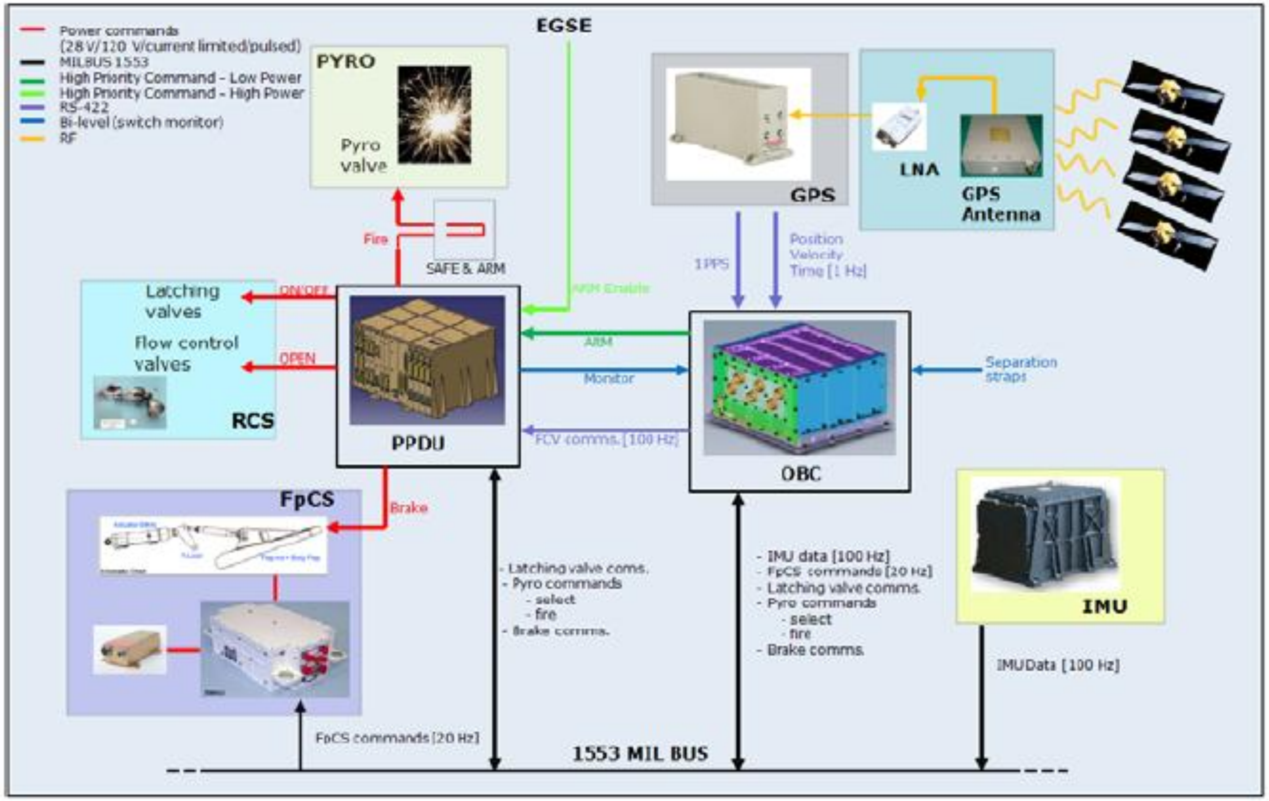
System Aspects

- GNC closely relates with Mission and System
  - Mission
    - Provides “flyability” of the proposed mission scenario
  - System
    - Mass, volume, power and fuel budgets
    - Control surfaces deflection ranges (not so common…)
    - Thrust authority and budget
  - Avionics
    - Data (DHU) and CPU budget
  - Cost

GNC ARCHITECTURE SOLUTIONS

ARCHITECTURE

- Avionics & hardware
- Actuators
- Sensors
- OBC
- Power
- Data exchange



Overview of IXV Avionics Hardware and Interfaces
Credits: ESA, TAS, Alenia SIA

ARCHITECTURE

- ESA MREP-SL: Small Mars Landers (Network of 3)

EDL Elements

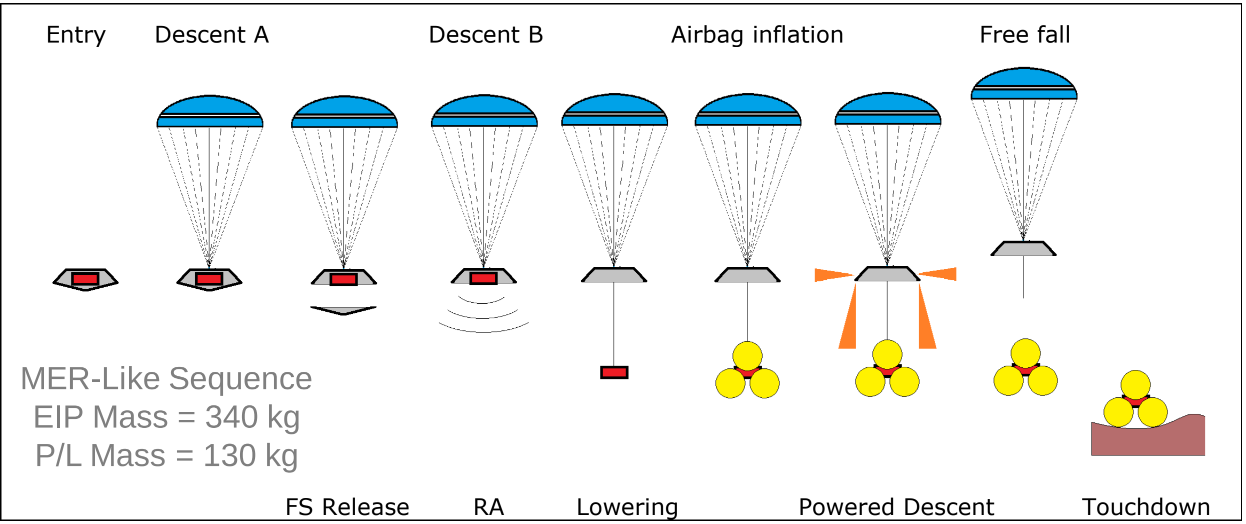
Sub-system	Type
Aeroshell	70º sphere-cone
Entry	Ballistic (no guidance needed)
Descent	1 stage (DGB)
Retro-rockets	Solid (Vertical & Horizontal)
Lowering	Yes, from backshell
Landing	Non vented airbags

Sensors

Sub-system	Phases
Sun Sensor	Coasting
Radar Altimeter	Descent & Landing
IMU	All
Vision Based Navigation	Descent

Actuators

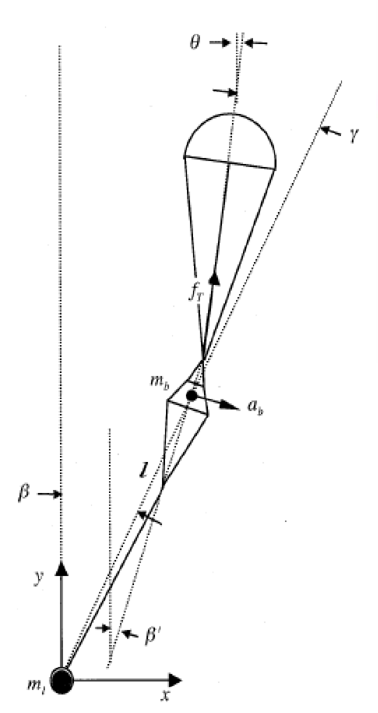
	Sub-element	Units	Value
RAD	Nominal thrust, one rocket	N	2200
	Number of thrusters		3
	Specific impulse	s	270
	Total impulse	Ns	10120
	Rockets burnout	s	4.6
	Fuel mass rate	Kg/s	0.83088
	Case diameter	m	0.12
	Case length	m	0.50
	Canted noozle	deg	17
	Off-vertical angle (mounting)	deg	28
TIRS	Nominal Thrust, one rocket	N	800
	Number of thrusters		3
	Specific impulse	s	270
	Total impulse	Ns	400
	Rockets burnout	s	0.5
	Fuel mass rate	Kg/s	0.30203
	Case diameter	m	0.07
	Case length	m	0.12
	Off-vertical angle (mounting)	deg	90



Landing Accuracy not a main concern!

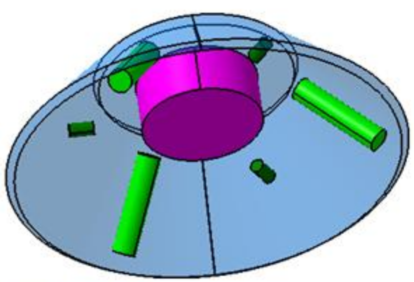
ARCHITECTURE

- ESA MREP-SL: Controlled versus uncontrolled descent under parachutes



Credits: NASA/JPL

Credits: TESSELLA



RAD & TIRS thrusters, bottom view

- **Powered descent phase objective**: reduce the lander speed from parachute terminal velocity to impact velocities sustainable by the landing system (i.e. non vented airbags).

Vertical and Horizontal impact velocity components:

- **Vertical impact V**: parachute terminal velocity + free fall
- **Horizontal impact V**: is the result of several contributors:
  - sustained winds: act drifting parachute and payload
  - wind gusts: act changing the attitude of the backshell. Vertical retrorockets (if present) can introduce a lateral ΔV to the lander (if the backshell is not aligned with the local vertical).
  - relative motion of the payload under the backshell (at bridle distance)
  - non-verticalized trajectories (shallow trajectories)
  - Terrain slope

Vertical and Horizontal V can be reduced by retrorockets.

MER implemented solid retro-rockets, so there was no throttle control. All depended on the sequence of events: smart triggerings had to be carefully tuned to achieve satisfactory performances.

Liquid retrorockets add flexibility but also complexity.

ARCHITECTURE

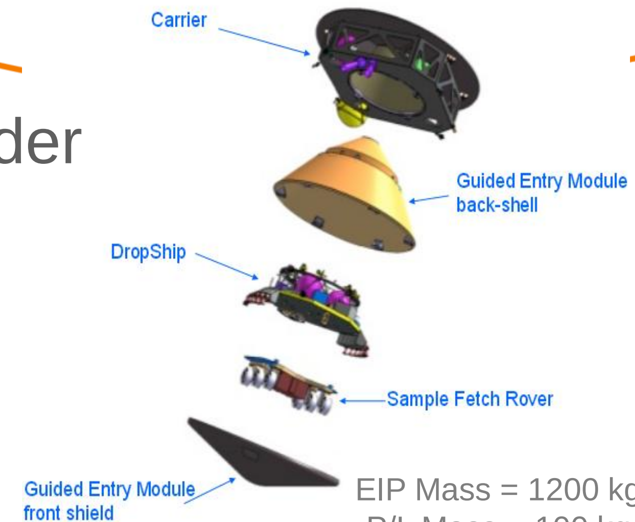
- ESA MREP: High Precision Mars Lander

EDL Elements

Sub-system	Type
Aeroshell	70º sphere-cone
Entry	Guided (L/D 0.2-0.25)
Descent	1 stage (DGB)
Lowering	Yes, from DropShip (after a free-fall phase)
Retro-rockets	Liquid (Vertical & Horizontal)
Landing	Soft touchdown (rover wheels)

Sensors

Sub-system	Phases
Sun Sensor	Coasting
Radar Altimeter	Descent & Landing
IMU	All
Vision Based Navigation	Descent



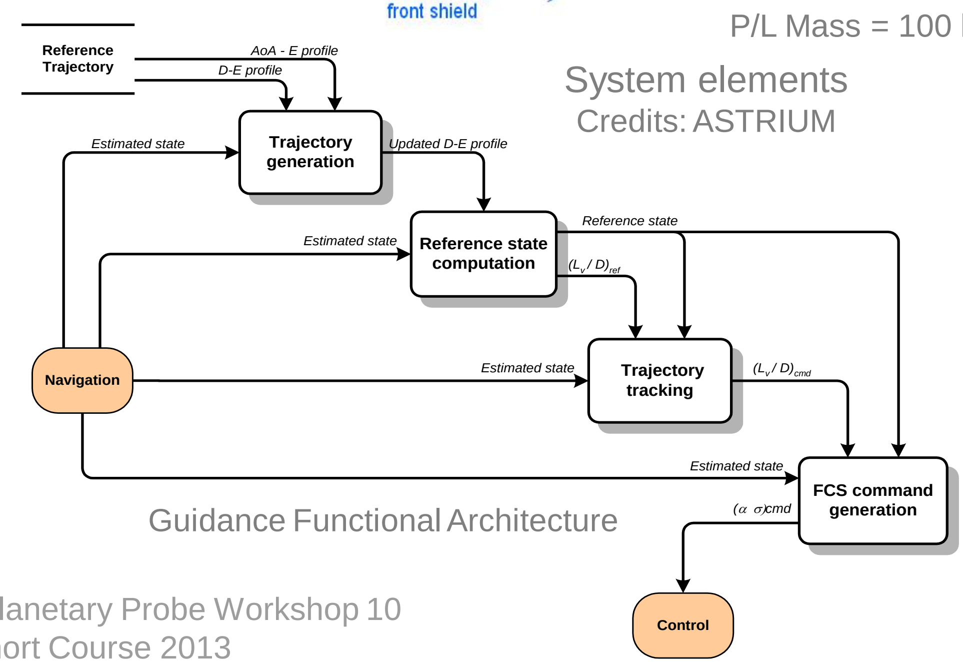
EIP Mass = 1200 kg
P/L Mass = 100 kg

System elements
Credits: ASTRIUM

Landing Accuracy is a main concern!
Guidance is critical: so far, only MSL implemented it for planetary entry probes

Dispersion taken into account	Miss-range error at chute deployment (km)				Altitude error at parachute deployment (km)			
	downrange		crossrange					
	mean	sigma	mean	sigma	mean	sigma	min	max
EIP + MCI	2.15	0.89	0.76	0.93	-0.38	0.31	-0.62	0.85
Atmosphere	2.19	0.74	0.67	0.80	-0.42	0.91	-2.27	2.01
Winds	2.13	1.13	0.40	1.57	-0.37	0.17	-0.57	0.55
Aerodynamics	2.04	0.28	0.30	0.69	-0.38	0.37	-0.86	1.07
All dispersions	**2.27**	**1.61**	**1.03**	**1.58**	**-0.31**	**0.92**	**-2.35**	**2.08**

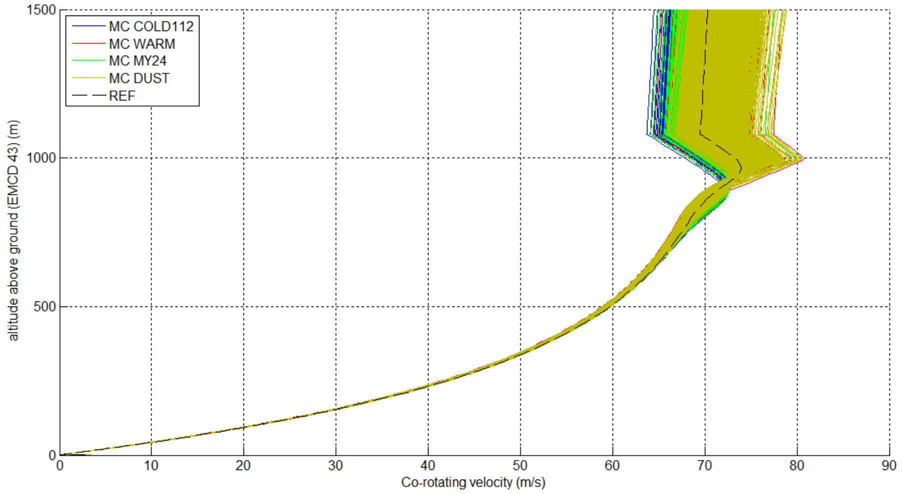
MSTS+ Entry Guidance performances (<10 km range)

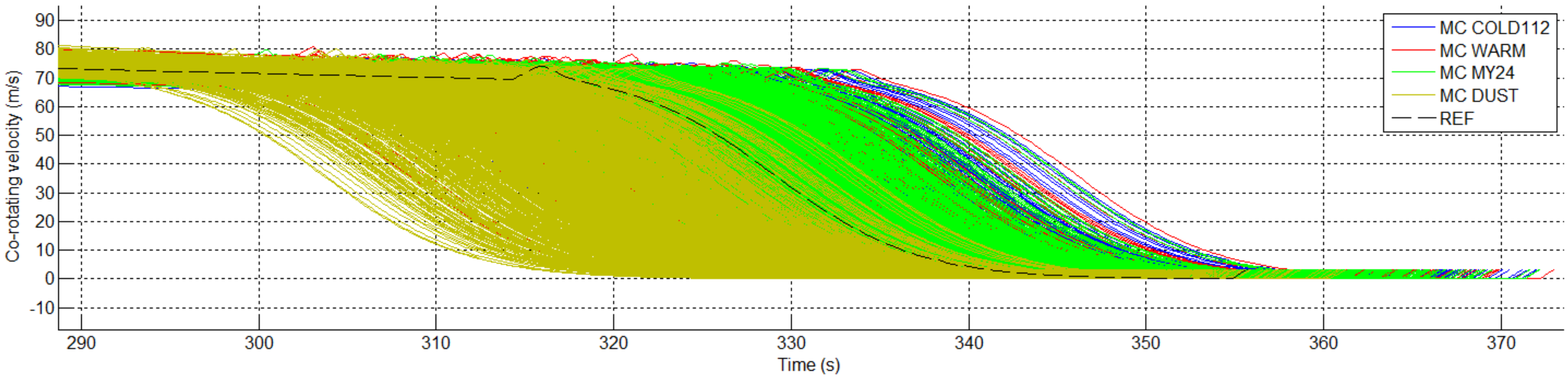


Guidance Functional Architecture

ARCHITECTURE

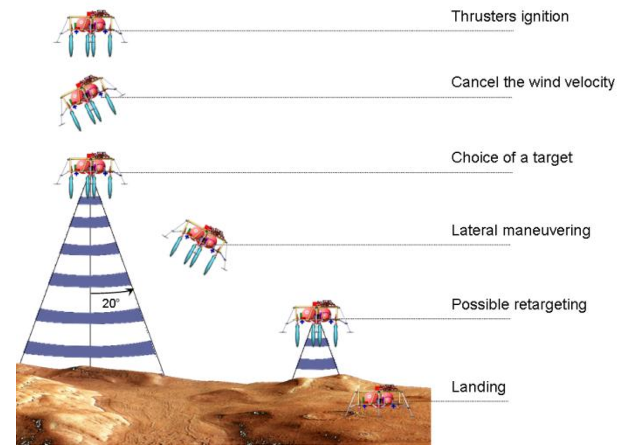
- Exomars: g-turn Landing Guidance (retros phase)
- Simple but robust landing guidance solution
- T is opposite to V
- Act on the Thrust/Weight
  - Variable T/W
  - Fixed T/W

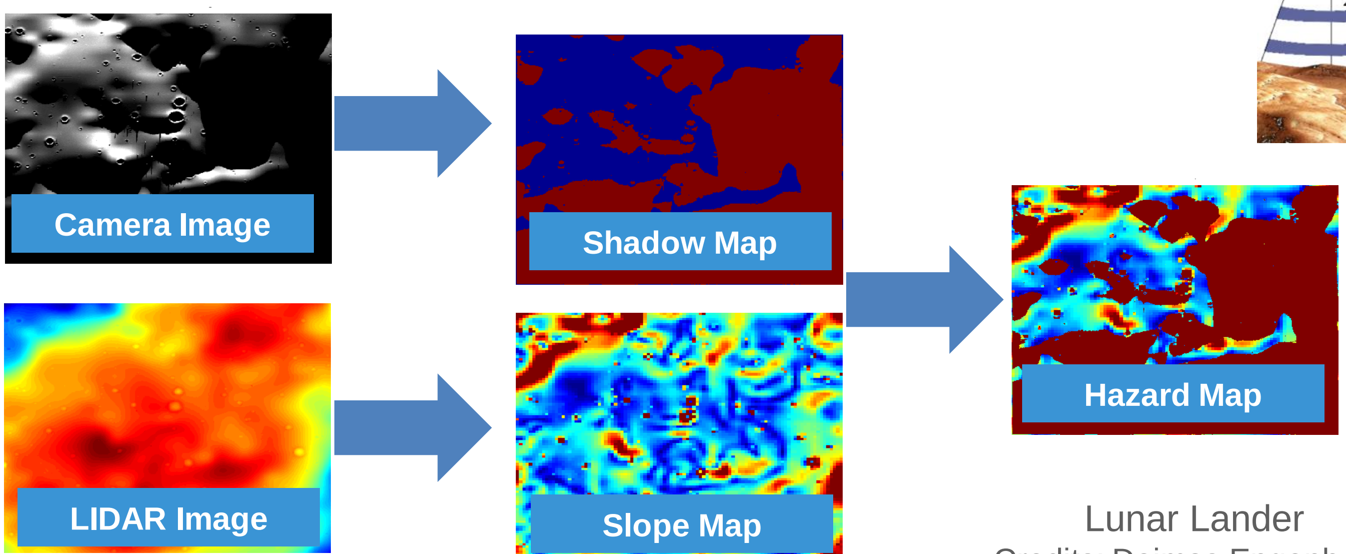




ARCHITECTURE

- Lunar lander: Hazard mapping & detection
  - Provides robustness to unknown terrain
  - Allows for autonomous landing site changes
  - Facilitates safe landing



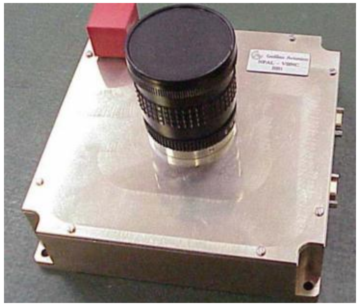


Lunar Lander
Credits: Deimos Engenharia

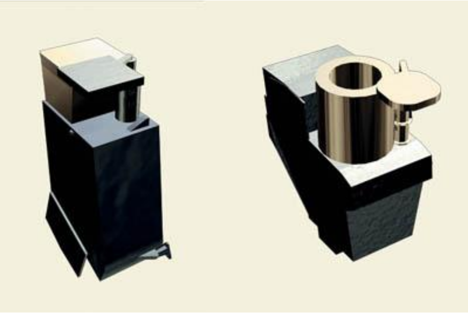
SENSORS AND ACTUATORS

Sensors

- 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



NPAL WAC
Credits: Astrium, Galileo Avionica



NAC
Credits: OSIRIS

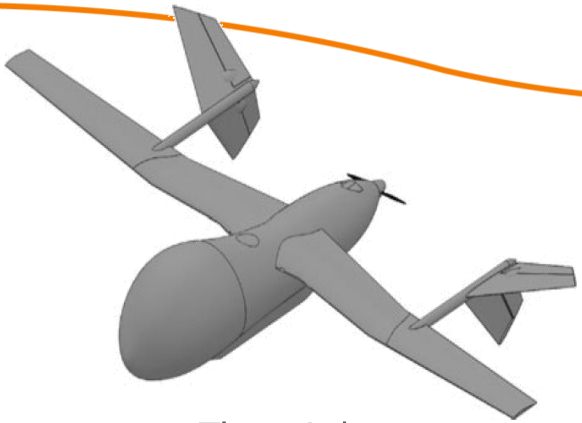
Sensors

- EDL sensors (beyond pre-Entry)
  - IMU is the "minimum"
  - Large dynamic range: velocity, altitude and illumination
  - Calibration is necessary for accurate performance (IMU, Camera)

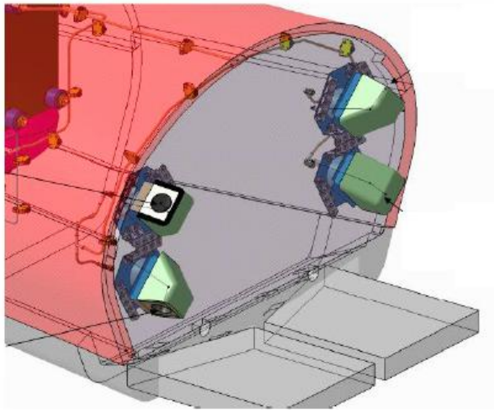
	Atmospheric			Non Atmospheric	
	Entry	Descent	Landing	Descent	Landing
IMU (acc & gyros)	■	■	■	■	■
Camera			■	■	■
3D LIDAR			■		■
Range sensor		■		■	■
FADS	■	■	■		
Star-Tracker				■	

Actuators

- Aerodynamic Surfaces
- Rockets
  - Solid
  - Liquid
    - Monopropellant
    - Bi-propellant
- Engine



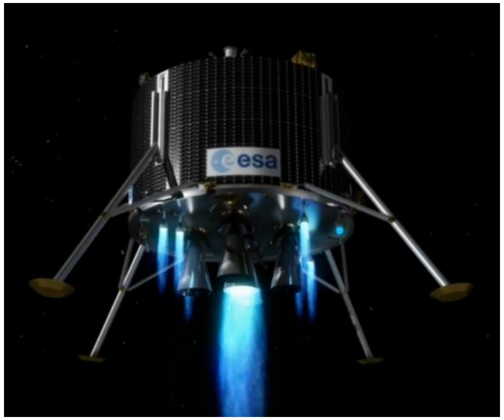
Titan: Aviatr
Credits: W. Barnes



IXV
Credits: ESA, TASI

7.7 kN Solid Thruster (STAR 8)
Credits: ATK

400N Hydrazine Thruster
Credits: Astrium



Lunar Lander Terminal Descent
Credits: ESA

CONCLUSIONS

CONCLUSIONS

- Guidance, Navigation and Control is an integral part of the EDL concept and solution
- Planetary Entry GNC solutions are characterized by high levels of autonomy.
- Need for GNC is driven by the Robustness-Complexity-Performance trade-off
- Strong heritage from Earth lessons learned.
- GNC complexity increases as far as the EDL environment is better known
- Increased autonomy and performance will require inclusion of FDIR function.

Thank you!