Mission Design for Mars Pinpoint Landing with Retropropulsion

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Agenda

- Background
- Motivation
- Trajectory Design
  - Mars Pinpoint Landing - Overview
  - Interplanetary Flight
  - Atmospheric Flight: Entry and Retropropulsive Phases
- Results in the scope of ANPLE
- Conclusions

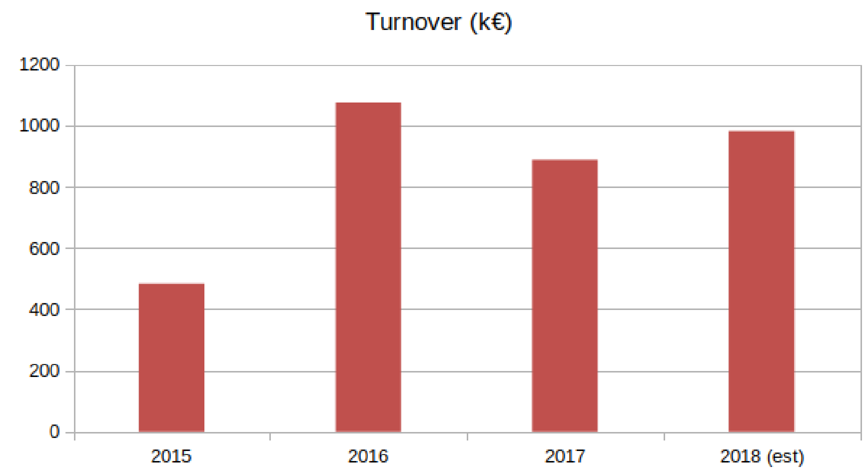
Company Profile

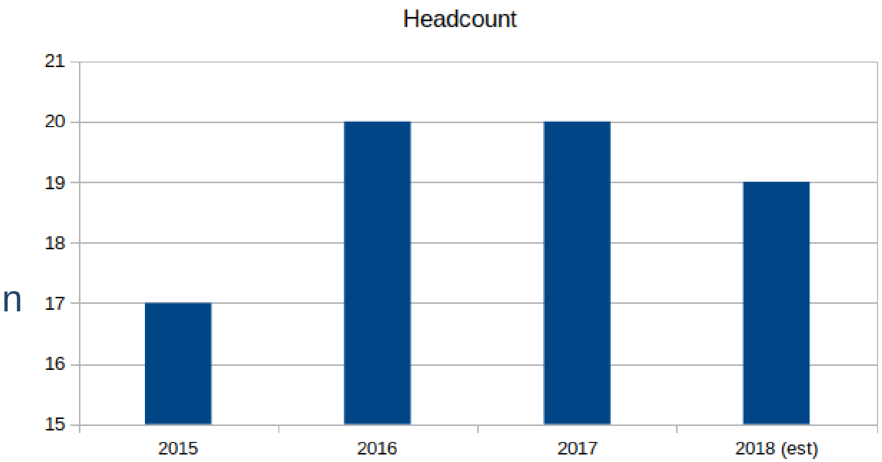
Spin.Works, S.A.

- **Based in Lisbon, Portugal**
- **Founded in 2006**
- **Aerospace and Defence Company**

- **Space**
  - Mechanisms
  - Guidance, Navigation and Control
  - Machine Vision

- **Unmanned Systems**
  - End-to-End Vehicle and System Design
  - Avionics and Flight Control Systems
  - Imaging and Data Services

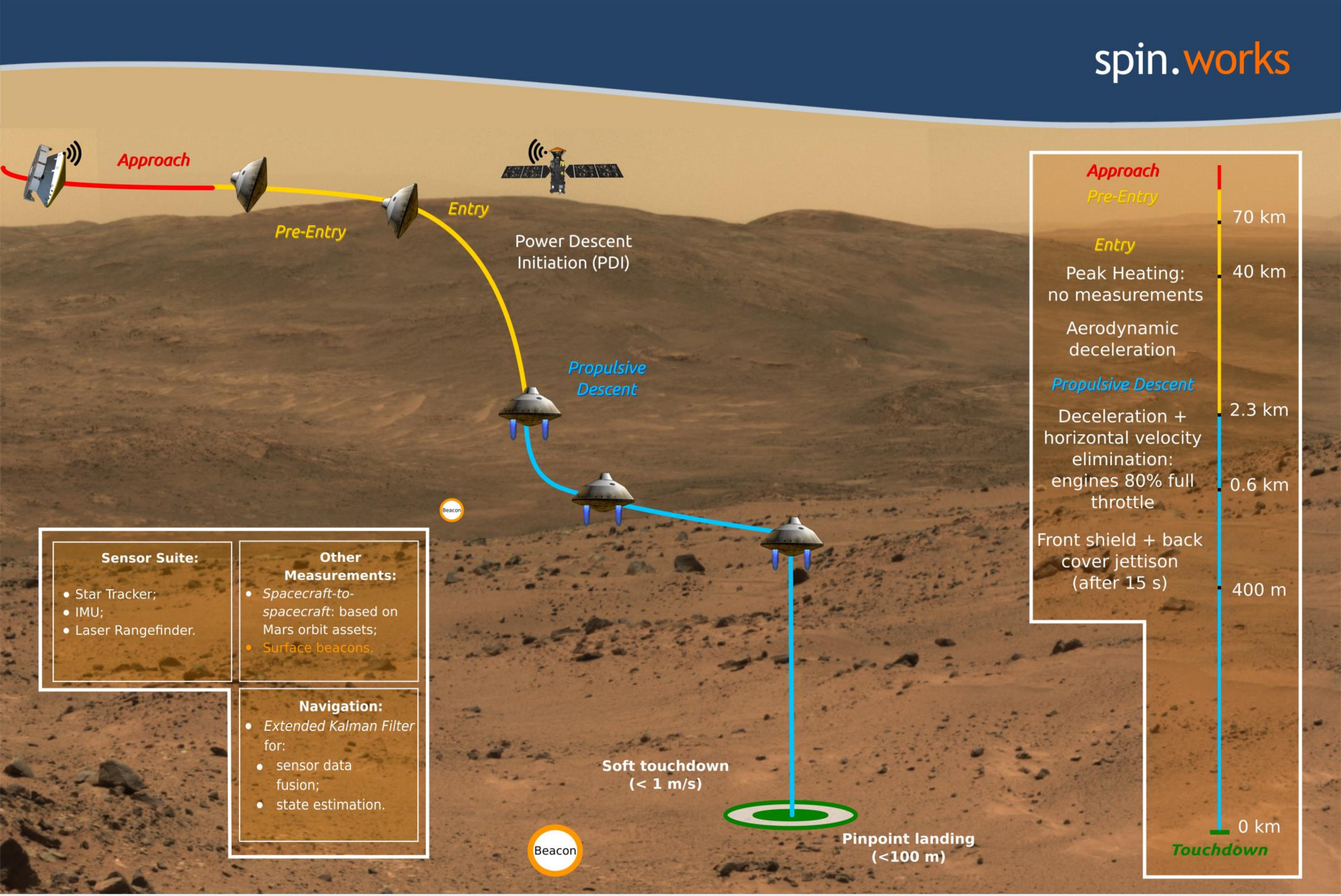




ANPLE (ongoing ESA activity) - End Goals

- Investigate navigation techniques applicable to a Safe, Precise Mars EDL mission:
  - **Trajectory Design:** Direct Entry from Interplanetary Transfer
  - **Orbit determination + control:** included in design cycle (reference timelines for sensor use and clear separation between ground + onboard functions)
  - **GNC:** 6DOF system applicable to all mission phases from entry interface to touchdown
  - **HDA:** No HDA assumed for the retropropulsive mission (beacons only), where landing target is assumed to be pre-prepared
  - **Validation:** via MC sims, targeting <<100m landing accuracy (using beacons)

- Assess effects of evolving Avionics + GN&C technologies
  - **Design to Real-time Implementation:** considers real, existing, available sensors + processing units, assesses computational costs, data acquisition + processing timing constraints, storage, etc. While considering incremental upgrades with new technologies as per current tech. dev. timelines
  - **Performance, constraints and limitations** of **navigation solution:** beacons-only solutions for absolute navigation (aided by ΔDOR, IMU calibration phase prior to entry, radar altimeter for descent and landing)
  - Designed for straightforward **Processor-in-the-loop compatibility**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Approach
Pre-Entry
Entry
Power Descent
Initiation (PDI)
Propulsive
Descent
Beacon
Sensor Suite:
• Star Tracker;
• IMU;
• Laser Rangefinder.
Other
Measurements:
• *Spacecraft-to-spacecraft*: based on Mars orbit assets;
• Surface beacons.
Navigation:
• *Extended Kalman Filter* for:
• sensor data fusion;
• state estimation.
Soft touchdown
(< 1 m/s)
Beacon
Pinpoint landing
(<100 m)
Approach
Pre-Entry
70 km
Entry
40 km
Peak Heating:
no measurements
Aerodynamic
deceleration
Propulsive Descent
2.3 km
Deceleration +
horizontal velocity
elimination:
engines 80% full
throttle
0.6 km
Front shield + back
cover jettison
(after 15 s)
400 m
0 km
Touchdown

Trajectory Design

-Interplanetary Transfer:

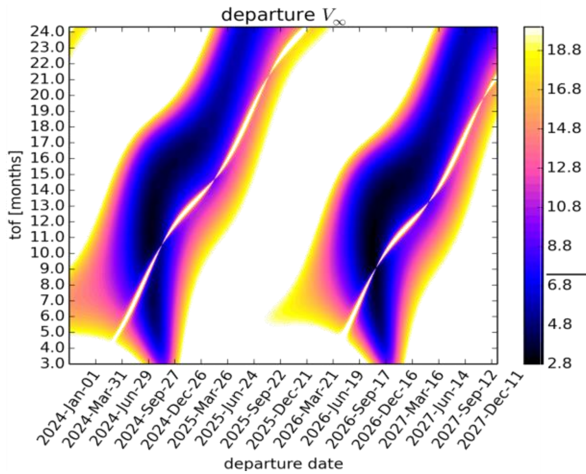
- Earth-Mars launch window in 2024
- Entry aim point calculated for ballistic atmospheric segment
- Orbit Determination assumes range, range-rate, ΔDOR

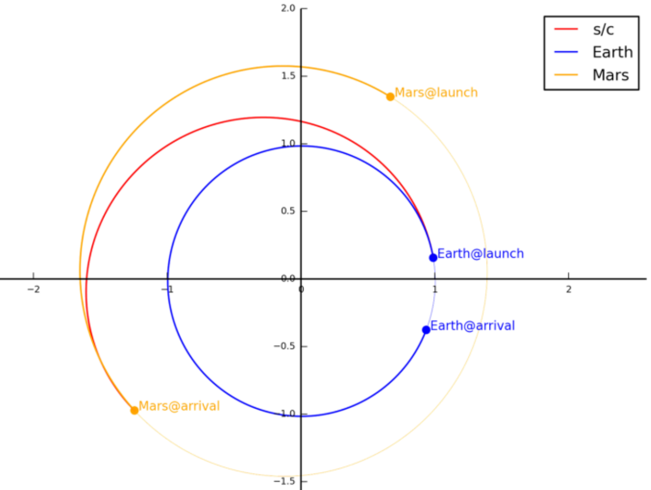
-Entry Point:

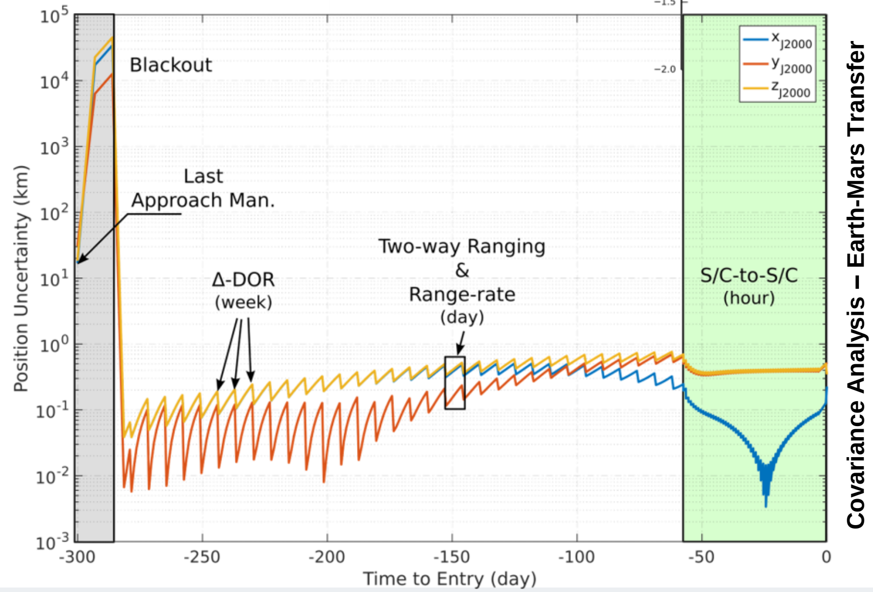
- Flight path angle calculated for a 10-g peak deceleration, acceptable heat flux
- MSL-like guidance and control assumed

-Atmospheric segment:

- Targeted landing site: Exomars 2016 LS
- Atmospheric segment includes entry, TAEM and (nominally optimal) retropropulsive descent
- Mass loss events modelled (TPS, back cover ejection, continuous mass flow associated to thrust)

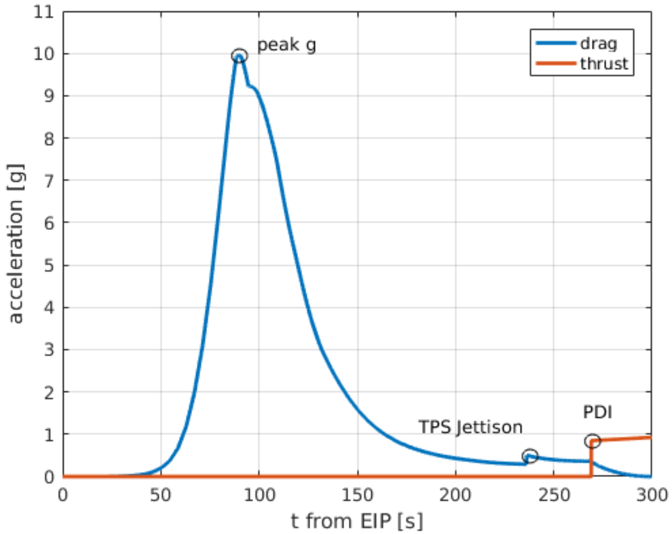






Trajectory Design Assumptions

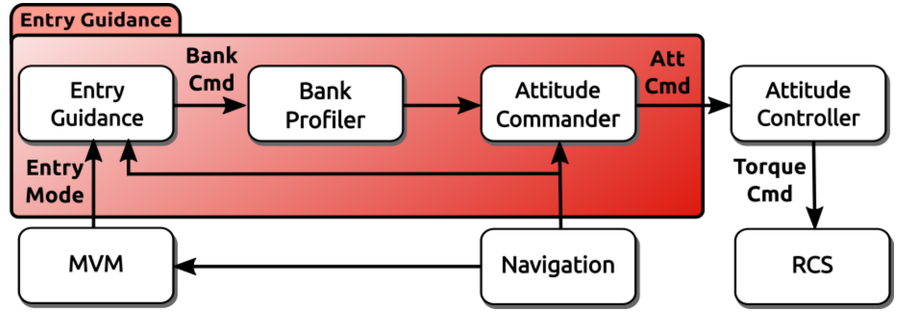
- **Entry Phase:** MSL-like guidance and control
  - Range control + heading alignment + transition to TAEM
- **Descent:** Shuttle TAEM-like
  - Energy management indicates required length of segment
  - Polynomial segments lengthen/shorten path to achieve desirable conditions (alt, lat, long) at ignition
- **Powered Descent:** Retropropulsive
  - **Nominal ignition conditions: optimal**
    - 2.3km altitude, 220-230m/s
  - **Calculated ("actual") ignition conditions**
    - onboard assessment from alt-vel estimates
    - linear Apollo-like descent acceleration profile assumed ($1.2<T/W_v<1.8$)
    - alternative implementation: convex optimization with line search for optimal ignition time ($T/W_v<1.8$)
  - **Terminal Descent**
    - Pure vertical descent from 10m

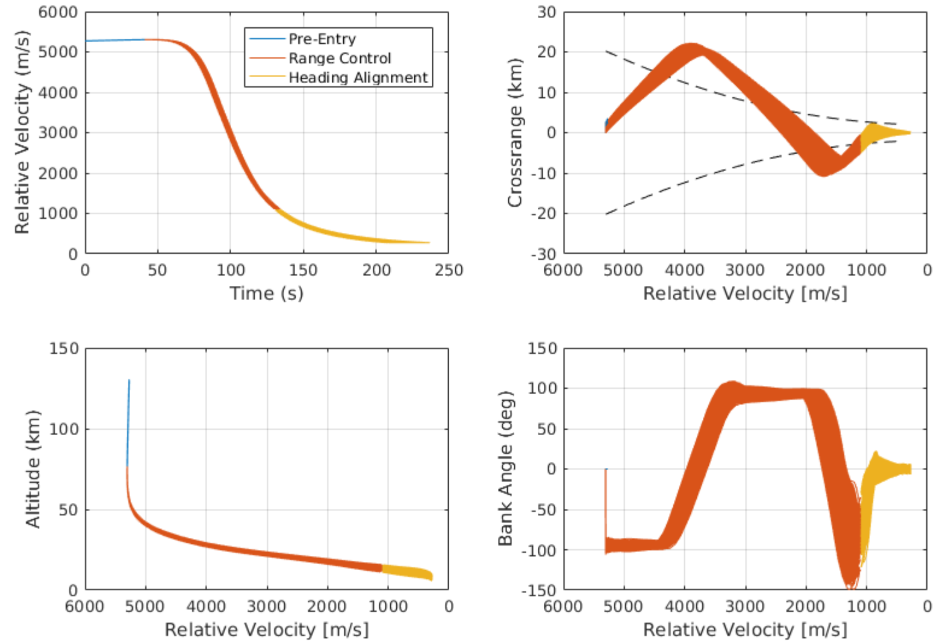


S/C Parameters (similar to Exomars EDM)	
Mass	600 kg
β	93 kg/m^2
Max. Thrust	3.5 kN
I_{sp}	311 s
Entry Point Conditions	
Epoch	31/08/2025
Latitude	-22.545 deg
Longitude	331,241 deg
γ	-15.1 deg
Speed	5271.95 m/s

Entry Trajectory Design Process

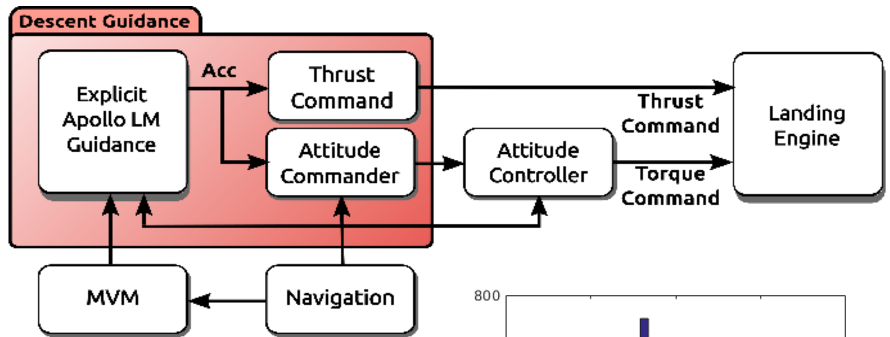
- **Optimized Trajectory** with MSL-like guidance in-the-loop:
  - **Range Control** phase: bank continuously tracks velocity-referenced range-to-target, to minimize PDI dispersions;
  - **Heading Alignment** phase: bank used to align capsule velocity with target direction;
  - **Final entry position** such that remaining atmospheric flight leads to target LS
- **Reference bank magnitude** chosen to maximize control margins
  - nominal trajectory w/ two bank reversals
- **Bank Profiler**: shapes slew manoeuvres, forces limited angular rates+accelerations in phase transitions & bank reversals.

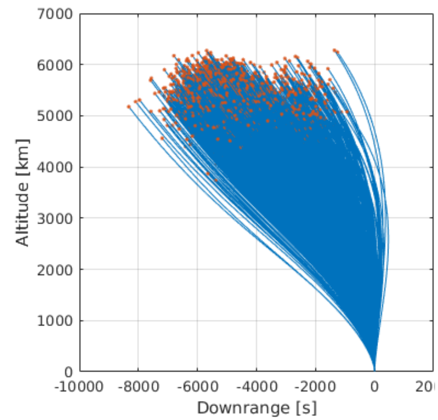




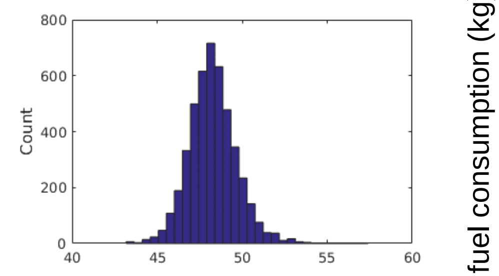
Retropropulsion Phase Design Process

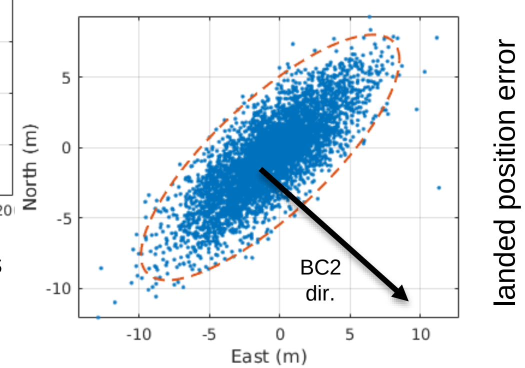
- **Baseline trajectory**: optimized for T/W=1.8
- **Actual (simulated) descent trajectory generation**:
  - Alternative 1: **Apollo Lunar Powered Descent**
    - **two-point boundary value-based** acc. profiles;
    - **single arc** drives capsule from final entry points to target landing site;
    - **linear acceleration profile** in **z-axis** for hor. position control authority ($1.2<T/W_v<1.8$).
    - acceleration profile determines predicted altitude loss and the **PDI trigger**.
  - Alternative 2: **RT Fuel-Optimal Guidance**
    - Pinpoint landing problem posed as **convex, second-order cone problem**
    - **Line search** determines fuel-optimal powered descent duration → ignition time
    - Descent trajectory **re-adjusted in-the-loop@10Hz**



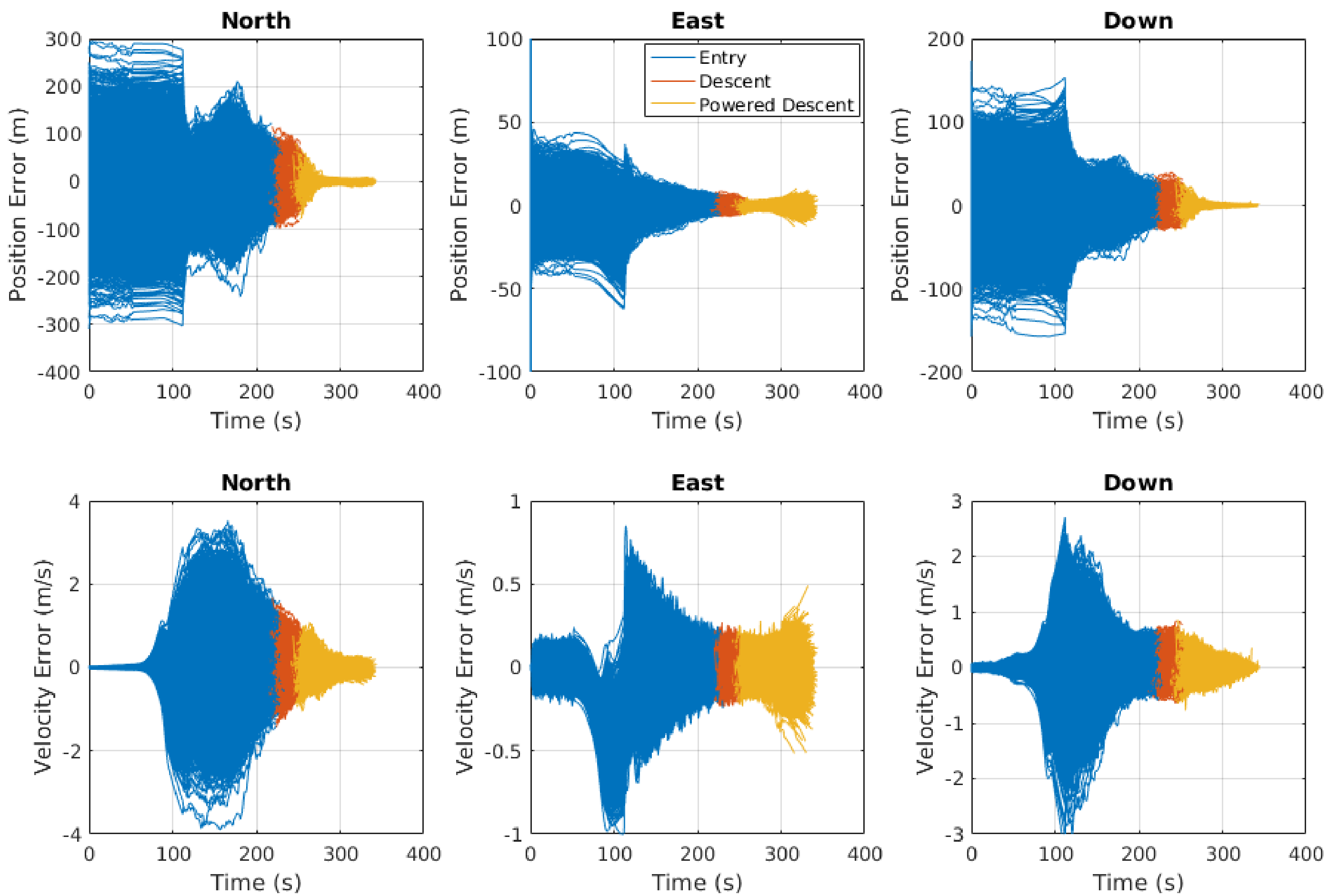


1500 descent trajectories (Apollo PDG)





Dispersed Trajectories - State Knowledge (full GNC-in-the-Loop)



Summary & Conclusions

- A **complete mission design cycle** was performed, including the **interplanetary transfer**, **approach**, **entry**, and **propulsive-only descent** and **landing phases** of a Mars EDL mission
- A **covariance analysis** was **used in support of the mission design tasks**, to identify acceptable initial knowledge/dispersions for pinpoint landing, as well as suitable sensor suite (from a list of existing sensors & processing units).
- MSL-like **guidance algorithm** used **in-the-loop** for **entry phase** trajectory design
  - Selection of flight path angle and reference bank angle (extract maximum margin)
  - Iterative entry point selection refinement
  - Maximum reference trajectory feasibility
- **Fuel-optimal guidance** assumed for reference **retropropulsive trajectory design**
  - For a **T/W of 1.8** and an **Exomars-like system, ignition** occurs at **2.3km alt.** and **M=1.1**
- **An End-to-End Trajectory Design has been performed in support of Safe, Pinpoint Mars Landing with Retropropulsion**