Interplanetary Path Early Design Tools at ASTRIUM Space Transportation

Nathalie DELATTRE
ASTRIUM Space Transportation
Interplanetary missions
Prime approach: ASTRIUM-ST has developed tools for all phases

Mission can only be considered end-to-end, and together with global design
Interplanetary trajectory legs definition

ASTRIUM-ST is improving its tools for simplified interplanetary trajectory analysis for phase 0/A projects

- **WINLAUNCH**: simplified interplanetary trajectory optimisation tool based on patched conic
  - Find the best way to reach a planet B leaving from a planet A according to various criterions and constraints (ΔV budget, $V_\infty$ restrictions, dates and duration)
  - Find various different “ways” to fulfil the mission (determination of the strategy of flybys)
  - Presently no trajectory integration: Lambert transfers calculation
  - No need to be initialised
Interplanetary trajectory legs definition (2)

Using a progressive approach, ASTRIUM-ST has also developed tools to determine the interplanetary mission opportunities and calculate precise optimised trajectories

- A **Patched-Conic** method provides the mission opportunities + initial trajectory

- The **Multi-Conic** method refines the trajectory

- An integration using **Encke’s Method** gives an accurate final trajectory.
Interplanetary trajectory legs definition (3)

These methods and tools have been used for several mission analysis:

- NASA’s Galileo mission (including 3 flybys)
- Mars Sample Return and Manned missions
- Venus Sample Return mission
- Europa Sample Return mission (including one aerogravity assist maneuver)
Interplanetary trajectory definition (4)

Based on its experience on reentry vehicles, ASTRIUM-ST has developed mission analysis tools and guidance algorithms for various aeroassist manoeuvres used in interplanetary missions.

- Aerocapture
- Aerobraking
- Aerogravity Assist
Example of ATPE

Objectives

- Interplanetary travel legs definition
- Reference trajectories/profiles for all aeroassist manoeuvres
- GNC specification
Interplanetary Travel Legs: General Methodology

Analysis using the patched-conic method: simple and accurate enough:

- Interplanetary trajectories divided into hyperbolas around the planets and ellipses around the Sun, joint at the planet’s sphere of influence.
- The method can be used by:
  - Grid search
  - Coupled with an optimization tool
For each interplanetary travel leg in each mission:

• Departure infinite velocities are determined as a function of departure date and the travel time.

• The departure date is chosen by finding the minimum infinite velocity (in case of a direct launch) or the minimum $\Delta V$ (in case of departure from an orbit).

• The arrival conditions are given only in terms of infinite velocity components. It is assumed that the arrival periapsis can be adjusted at low cost by the mid-course corrections.
Mars Sample Return Mission

Earth–Mars Window: Departure Infinite Velocity

Mars–Earth Window: Required ΔV from a 500 km/500 km/50 orbit

Chosen points
**example of earth-mars-earth flight**

**Earth - Mars**

- Departure date: 11.08.2005
- Departure $V_\infty$: 3942 m/s
- Departure mass: 2473 kg
- Trip duration: 197 days
- Midcourse corr.: 50 m/s
- Arrival date: 24.02.2006
- Arrival $V_\infty$: 3134 m/s
- Arrival mass: 2434 kg

**Mars - Earth**

- Departure date: 20.07.2007
- Departure $V_\infty$: 3211 m/s
- Departure $\Delta V$: 2379 m/s
- Departure mass: 434 kg
- Trip duration: 284 days
- Midcourse corr.: 50 m/s
- Arrival date: 29.04.2008
- Arrival $V_\infty$: 3055 m/s
- Arrival mass: 200 kg
Methodology for transfers with aerogravity assist

• The patched conic method has been adapted to simulate the aerodynamically-assisted flyby

• The maneuver is simulated by a $\Delta V$ upon arrival to the planetary atmosphere.

• The optimization tool finds the optimal departure, arrival and aerogravity assist dates in order to maximize the final mass.

• The maneuver conditions (position and $\Delta V$) are also optimized.
**Earth - Mars**

- **Departure date**: 24.01.2012
- **Departure** $V_\infty$: 3490 m/s
- **Departure mass**: 9183 kg
- **Trip duration**: 420 days
- **Midcourse corr.**: 50 m/s
- **Arrival date**: 19.03.2013
- **Arrival** $V_\infty$: 7726 m/s
- **Arrival mass**: 9038 kg

**Mars - Jupiter**

- **Departure date**: 19.03.2013
- **Departure** $V_\infty$: 7457 m/s
- **Departure mass**: 4038 kg
- **Trip duration**: 570 days
- **Aerogravity corr.**: 100 m/s
- **Midcourse corr.**: 50 m/s
- **Arrival date**: 10.11.2014
- **Arrival** $V_\infty$: 8846 m/s
- **Arrival mass**: 3849 kg

**Aerogravity Assist Maneuver**

- **Departure** $V_\infty$: 7457 m/s
- **Arrival** $V_\infty$: 7726 m/s
- **Propulsive $\Delta V$**: 0 m/s
Reference Profiles: Aerocapture Maneuvers

The reference (nominal) profiles were built to be used by the guidance algorithm. The principles are the following:

- Constant bank angle of 90° all along the maneuver (maximize controllability margins).
- Given the arrival infinite velocity, the arrival periapsis is adapted to reach the desired apoapsis.
- The constant bank angle leads to inclination errors, which will be corrected by the lateral guidance.
Reference Profiles: Aerogravity Assist Maneuvers

The reference (nominal) profile was built to be used by the guidance algorithm. The principles are the following:

- Constant bank angle all along the maneuver with one roll reversal.
- Given the arrival infinite velocity, the arrival periapsis and the date of the roll reversal are adapted to reach the desired exit conditions (infinite velocity).
- The value of the bank angle is the third parameter to adapt to reach the desired exit conditions (3 components of the infinite velocity).
## Reference Profiles: Aerogravity Assist on Mars

<table>
<thead>
<tr>
<th></th>
<th>Entry Interface</th>
<th>Aerogravity assist Manoeuvre</th>
<th>Exit Interface</th>
<th>Departure Infinite Velocity (m/s)</th>
<th>Arrive Infinite Velocity (m/s)</th>
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<tbody>
<tr>
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<td>7726.0</td>
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<td>Duration (s)</td>
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Reference Profiles: Aerobraking Maneuvers

The reference (nominal) profile was built to be used by the guidance algorithm. The principles are the following:

- The goal is to reach the parking orbit in the minimum time possible.
- At each apoapsis, a propulsive maneuver is performed to adapt the periapsis, in order to reach the nominal maximum heat flux.
- The heat flux is calculated based on the exponential atmospheric model.
GNC Specification: Aerocapture (AC) & Aerogravity Assist Maneuvers (AGA)

Maximum allowable errors at atmospheric entry interface (1σ):
  • Velocity: 0.13 m/s (AC) and 0.52 m/s (AGA)
  • Latitude: 0.01° (AC) and 0.04° (AGA)
  • Flight path angle and azimuth: 0.043° (AC) and 0.172° (AGA)

Navigation precision requirement during the atmospheric phase (1σ):
  • Altitude: 0.667 km (AC) and 2.7 km (AGA)
  • Latitude: 0.01° (AC) and 0.04° (AGA)
  • Velocity: 0.4 m/s (AC) and 1.6 m/s (AGA)
  • Flight path angle and azimuth: 0.03° (AC) and 0.12° (AGA)
  • Drag acceleration: 0.1 m/s² (AC) and (AGA)
Perspectives and conclusions

- These tools have been developed for phase 0/A exploration missions studies (scenario and budget assessment)

- For interplanetary missions, additional efforts need to be done in the area of:
  - Low thrust manoeuvres during interplanetary travel leg
  - Flight strategy related with Weak Stability Points

Prospective reflexion on-going for both of these subjects, but no satisfactory legacy tools library available up to now to solve these types of problems.