REENTRY TRAJECTORIES FOR SPACE VEHICLES

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SPACE VEHICLE REENTRY

natural reentries

deorbit ΔV

orbital arc

E point: (Z=120 km)

initial orbit

atmospheric arc

Terre

atmosphere

ORBITAL ARC

ATMOSPHERIC ARC

DEORBIT MANEUVER

controlled reentries
SPACE VEHICLE REENTRY: DEORBITATION

Initial orbit → Terre → atmosphere → orbital arc → atmospheric arc → E point: (Z=120 km) → deorbit ΔV

Natural reentries

DEORBIT MANEUVER

Controlled reentries

ORBITAL ARC

ATMOSPHERIC ARC
DEORBITATION: POSITION-VELOCITY PARAMETERS

To fully define the center of mass motion, we need 6 parameters:
\[ x, y, z, v_x, v_y, v_z \]

Orbital motion study leads to choose other set of parameters “speaking for themselves” as:
\[ a, e, i, \omega, \Omega, v \]

“Classical” flight dynamics will use:
\[ Z, \text{lat}, \text{lon}, V, \gamma, \chi \]

- \( Z \): Topocentric or geodetic altitude (or \( r \): radius)
- \( \text{lat} \): Topocentric or geodetic latitude
- \( \text{lon} \): Longitude / Greenwich
- \( V \): Velocity module
- \( \gamma \): Flight Path Angle
- \( \chi \): Velocity Azimuth
DEORBITATION: MANEUVER PARAMETERS

INTENSITY

- If impulsive maneuver:
  - $\Delta V$ : velocity increment (m/s)
- else:
  - $F$ : thrust level (Newton)
  - $I_{sp}$ : specific impulse (s)
  
  $F = q \cdot g_0 \cdot I_{sp}$ with $q = -\frac{dm}{dt}$

DIRECTION

- $\omega'$ : angle between thrust direction and orbital plane
- $\omega$ : angle between projection of thrust direction on the orbital plane and velocity (or horizontal)
DEORBITATION : IMPULSIVE ASSUMPTION (1/5)

PARAMETERS :

- Before maneuver : \([ r_s, \alpha_s, \beta_s, V_s, \gamma_s, \psi_s ]\)
- Maneuver : \([ \Delta V, \omega, \omega' ]\)
- After maneuver : \([ r_0, \alpha_0, \beta_0, V_0, \gamma_0, \psi_0 ]\)
- At \(Z = 120\)km : \([ r_e, \alpha_e, \beta_e, V_e, \gamma_e, \psi_e ]\)

FIRST SIMPLIFICATIONS :

- Reference relative to initial conditions : \(\alpha_s = 0, \beta_s = 0\) et \(\psi_s = 0\)
- Impulsive assumption : \(r_0 = r_s, \alpha_0 = \alpha_s\) et \(\beta_0 = \beta_s\)
- Keplerian orbit : \(\psi_0 = \psi_e = \psi\)
- By definition : \(r_e = r_T + 120\) km

KEEPING PARAMETERS :

\[ [ r_s, V_s, \gamma_s ], [ \Delta V, \omega, \omega' ] \]
\[ [ V_0, \gamma_0, \psi ] , [ \alpha_e, \beta_e, V_e, \gamma_e ] \]
DEORBITATION: IMPULSIVE ASSUMPTION (2/5)

- **MOTION EQUATIONS:**
  - vectorial relation:
    \[ \Delta \tilde{V} = \tilde{V}_0 - \tilde{V}_S \]
    \[
    \begin{align*}
    \Delta V \sin(\omega') &= V_0 \cos(\gamma_0) \sin(\psi) \\
    \Delta V \cos(\omega') \cos(\omega - \gamma_s) &= V_0 \cos(\gamma_0) \cos(\psi) - V_s \cos(\gamma_s) \\
    \Delta V \cos(\omega') \sin(\omega - \gamma_s) &= -V_0 \sin(\gamma_0) + V_s \cos(\gamma_s)
    \end{align*}
    \]
  - Conservation of the total energy on the orbital arc:
    \[ V_e^2 = V_0^2 + 2\mu \left( \frac{1}{r_e} - \frac{1}{r_0} \right) \]
  - Conservation of the kinetic moment on the orbital arc:
    \[ r_0 V_0 \cos(\gamma_0) = r_e V_e \cos(\gamma_e) \]
  - Relation on the longitudinal range \( \alpha_e \) (implicit equation):
    \[
    \frac{\mu(1-\cos(\alpha_e))}{r_0 V_0^2 \cos(\gamma_0)} - \frac{r_0}{r_e} \frac{\cos(\alpha_e + \gamma_e)}{\cos(\gamma_0)} = 0
    \]
  - Relation on the cross range \( \beta_e \) (spherical trigonometry):
    \[ \sin(\beta_e) = \sin(\alpha_e) \sin(\psi) \]
Influence of the\( \omega \) parameter
\( \gamma = -1.3 \text{ deg} ; \omega' = 0 \text{ deg} \)
Influence of the $\omega'$ parameter
($\gamma e = -1.3$ deg ; $\omega = 180$ deg)
DEORBITATION: IMPULSIVE ASSUMPTION (5/5)

- **Initial values (γₐ = -1.3 deg):**
  - \( h_s = 300 \text{ km} \)
  - \( V_s = 7.725761 \text{ km/s} \)
  - \( \gamma_s = 0. \text{ deg} \)
  - \( \Delta V = 89.275 \text{ m/s} \)
  - \( \omega = 180. \text{ deg} \)
  - \( \omega' = 0. \text{ deg} \)

- **Dispersions on initial values:**
  - \( d(h_s) = 10. \text{ m} \)
  - \( d(V_s) = 0.02 \text{ m/s} \)
  - \( d(\gamma_s) = 0. \text{ deg} \)
  - \( d(\Delta V) = -1. \text{ m/s} \)
  - \( d(\omega) = 1. \text{ deg} \)
  - \( d(\omega') = 1. \text{ deg} \)

<table>
<thead>
<tr>
<th>( \delta Z_s ) [m]</th>
<th>( \delta V_s ) [m/s]</th>
<th>( \delta \gamma_s ) [deg]</th>
<th>( \delta \Delta V ) [m/s]</th>
<th>( \delta \omega ) [deg]</th>
<th>( \delta \omega' ) [deg]</th>
<th>Somme quadratique</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \delta V_e ) [m/s]</td>
<td>0.01</td>
<td>0.02</td>
<td>0.</td>
<td>0.87</td>
<td>0.</td>
<td>0.</td>
</tr>
<tr>
<td>( \delta \gamma_e ) [deg]</td>
<td>0.00012</td>
<td>0.00036</td>
<td>0.</td>
<td>-0.016</td>
<td>0.</td>
<td>0.</td>
</tr>
<tr>
<td>( \delta X_e ) [km]</td>
<td>0.94</td>
<td>1.77</td>
<td>0.72</td>
<td>-79.1</td>
<td>-56.4</td>
<td>0.</td>
</tr>
<tr>
<td>( \delta Y_e ) [km]</td>
<td>0.</td>
<td>0.</td>
<td>0.</td>
<td>0.</td>
<td>0.</td>
<td>1.3</td>
</tr>
</tbody>
</table>
When the « thrust / mass » ratio is low and involves longer maneuvers durations (order of magnitude comparable to orbital period).

**Hermes or ATV example:**

- \( F = 800 \text{ to } 1600 \text{ N} \) (\( I_{sp} \approx 310 \text{ s} \))
- mass \( \approx 20 \text{ tons} \)

By integration of the equation \( F = qg_0I_{sp} \), we obtain: \[ \Delta t = \frac{mg_0I_{sp}}{F} (1 - e^{-\Delta V/g_0I_{sp}}) \]

=> up to \( \Delta t > 1000 \text{ s} \) for orbital periods of about 5500 s

**Problems linked to these durations:**

- greater needed \( \Delta V \) (thus higher ergols consumption)
- precision at \( Z=120 \text{ km} \) (in position and velocity)
- Cases of impossibility to obtain aimed conditions at \( Z=120 \text{ km} \)
DEORBITATION: CONTINUOUS THRUST (2/11)

γ_e EVOLUTION FOR AN AIMED PERIGEE ALTITUDE OF 0 KM

\[ γ_e \] [deg] vs Altitude of the initial circular orbit [km]
DEORBITATION: CONTINUOUS THRUST (3/11)

THRUPT DURATION
($H_{\text{per}} = 0 \text{ km} ; F = 1600 \text{ N} ; Isp = 310 \text{ s} ; m = 20 \text{ t})$

![Graph showing the relationship between altitude of the initial circular orbit and thrust duration](image)
DEORBITATION: CONTINUOUS THRUST (4/11)

DIFFERENCE ON $\Delta V$

(Hper = 0 km; $F = 1600$ N; $Isp = 310$ s; $m = 20$ t)

$\Delta V$ [m/s]

Altitude of the initial circular orbit [km]
DIFFERENCE ON ERGOLS CONSUMPTION
(Hper = 0 km ; F = 1600 N ; Isp = 310 s ; m = 20 t)
DEORBITION :
CONTINUOUS THRUST (6/11)

DIFFERENCE ON TIME REMAINING AFTER END OF BOOST
(Hper = 0 km ; F = 1600 N ; Isp = 310 s ; m = 20 t)

![Graph showing difference in time remaining after end of boost](image-url)
DEORBITATION: CONTINUOUS THRUST (7/11)

Thrust direction optimization and/or several maneuvers

$\Delta V_{imp}$

initial orbit

$Z = 120 \text{ km}$

Thrust duration

$\gamma_0$
TWO MANEUVERS STRATEGIES:

- 2 braking $\Delta V$

- 1 accelerating $\Delta V$ and 1 braking $\Delta V$
DEORBITATION: CONTINUOUS THRUST (9/11)

■ ADVANTAGES:

- duration of each boost is shorter (divided by about two in case of two breaking ΔV’s)
- ergols consumption is lower (5 to 10 %)
- Time between end of last maneuver and Z=120 km is longer => opportunities recovery (for low initial altitudes)
- Computation of the second maneuver can be done w.r.t the first one (dispersions issued from its realization can be taken into account)

■ DRAWBACKS:

- Longer duration of the deorbit phase
- Intermediate elliptic orbit:
  - Lower perigee (atmospheric drag)
  - Drift of the apsides line versus the landing site longitude
DEORBITATION: CONTINUOUS THRUST (10/11)

DIFFERENCE ON $\Delta V$
(Hper = 0 km; $F = 1600$ N; $I_{sp} = 310$ s; $m = 20$ t)

![Graph showing the difference on $\Delta V$ versus altitude of the initial circular orbit. The graph compares the effects of 1 maneuver, 2 braking maneuvers, and impulsive thrust.](image)
DEORBITATION: CONTINUOUS THRUST (11/11)

DIFFERENCE ON TIME REMAINING AFTER END OF BOOST
(Hper = 0 km ; F = 1600 N ; Isp = 310 s ; m = 20 t)

- 1 maneuver
- 2 braking maneuvers
- Impulsive thrust

Altitude of the initial circular orbit [km]
T120 [mn]
No specific MIR engines were available, so it was chosen to use engines of a Progress vehicle previously docked. MIR mass (about 130/140 tons) and thrust acceleration produced by this Progress vehicle engines did not allow to carry out the deorbitation only with one maneuver.

Originally, it was foreseen to execute up to 4 maneuvers distributed on several days but uncertainties on AOCS at those unusual very low orbits lead to envisage the following strategy:

- 2 initial maneuvers of about 10 m/s each on daily orbits 15/16 to prepare for the third and final impulse (i.e. semi major axis sufficiently high to stay 24 hours in orbit and a well phased apsides line).
- Those maneuvers executed using the 8 Progress attitude control engines
- A final maneuver of about 25 m/s executed in two sub phases:
  - First with the main engine + the attitude control engines
  - Then, only with the attitude control engines
Also due to uncertainties on the AOCS, it has been chosen to keep an inertial attitude including during the boosts. In order not to be too far from the optimal attitude (opposite to velocity), a pitch angle was computed in to have the direction almost aligned on the velocity/horizontal line at the middle of the boost (+ a 4 deg bias due to position of the center of gravity).

Then, for so critical maneuvers, it was absolutely required to have a maximum of visibility from the ground:

- Maneuvers were foreseen on daily orbit numbers 15, 16 and 02 to get also visibility on orbits 13, 14 and 01 (orbits with large visibilities with Russian ground stations)
- A particular constraint was applied on the end of the two first maneuvers to be in visibility of the Petropavlovsk (PPK) ground station for a complete passage (to get a full diagnostic in case of problems occur on the attitude control).
MIR de-orbiting (3/3)
Vehicle constraints:
- Maneuver can only be executed when Sun pointed (or anti Sun pointed) because only Sun sensors were operational (but not Earth sensors).
- Maneuver has to be programmed between time when satellite was entering in eclipse + 10 mn and time when it was exiting + 20 mn because of thermal constraints on propulsive engines.
- Maneuver has to occur above 150 km of altitude (AOCS constraints)

« Flight dynamics » constraints
- To get thrust direction as close as possible to the orbital plane (for a best thrust efficiency)
- To align thrust direction as close as possible to the velocity axis (for a best efficiency on the semi-major)
- To set the maneuver as close as possible to the apogee
- To control perigee positioning to be phased with the landing site
Command: 1443.385 s (127.19 m/s) on 10th Dec 2002 / 00:42:21
ATV De-orbiting (1/3)

Main ATV vehicle constraints:

- The duration of the maneuvers must not exceed 30 minutes.
  => influence on the amount of maneuvers since ATV has a low thrust/mass ratio.
- The perigee altitude of the intermediary orbits must not be lower than 200 km at 3σ in order not to degrade the solar arrays.
- The delay between the end of the last deorbitation maneuver and 120 km altitude must be typically 20 min (10 min for the tumbling acquisition and typically 10 min more for on-board operational verifications after tumbling acquisition).

Main ATV mission constraints:

- Before the maneuvers, minimum 3h00 (2 orbits) must be scheduled in order to perform orbit determination, maneuver computation and on-board loading.
- A back-up deorbitation orbit is required a day (thus 2 opportunities per day).
- A back-up day must be foreseen. It means that it must be possible to deorbit on the same orbit numbers one day later.
The deorbitation sequence consists in transferring the ATV from an orbital point to a ground point by decreasing its perigee altitude through two maneuvers.

- **The first maneuver** will have two objectives:
  - The first one is to put the ATV from a circular orbit to an elliptical orbit with the required apside line orientation (phasing with the entry point).
  - The second objective is to decrease the perigee altitude.

- **The second maneuver** is then located at the apogee of the intermediary orbit and decrease the perigee altitude up to 0 km.
ATV De-orbiting (3/3)

- “Generic” nominal reentry:
  - The ATV has waited for the entry opportunity docked to the ISS.
  - As soon as ATV is in visibility of the Russian ground stations, de-docking is performed.
  - Several orbits later, the deorbit sequence starts

- Jules Verne mission:
  - Dedocking three weeks before the reentry (5th September)
  - Rephasing in order to get visibility from ISS during the reentry
    => Additional maneuvers
  - Reentry observation with airborne means ... night time observation
    => Orbit number and reentry epoch modification
ATV REENTRY (altitude profile)

29/09/08 10:00:24 (UTC)  
\( \Delta V = -29.85 \text{ m/s (388.3 s)} \)

29/09/08 12:58:18 (UTC)  
\( \Delta V = -70.1 \text{ m/s (896.65 s)} \)

~ 13:31:34 (UTC)  
Z ~ 120 km

~ 13:36:19 (UTC)  
Explosion (Z ~75 km)

~ 13:43:09 (UTC)  
first impacts

South Pacific Ocean
ATV REENTRY (ground track)

nominal impact point (mean fragment)
lat = -39.98°
lon = 207.82°

10⁻² area
ATV REENTRY : fragmentation
SPACE VEHICLE REENTRY: ATMOSPHERIC ARC

- **Orbital Arc**
- **Atmospheric Arc**
- **Initial Orbit**
- **E point: (Z=120 km)**
- **Deorbit ΔV**

**Natural reentries**

**Controlled reentries**

**DEORBIT MANEUVER**

**ORBITAL ARC**

**ATMOSPHERIC ARC**
ATMOSPHERIC ARC : ATTITUDE

- Attitude parameters: $\alpha, \beta, \mu, p, q, r$

- $\alpha$: angle of attack
- $\beta$: slip side angle
- $\mu$: bank angle
- $p$: roll rate
- $q$: pitch rate
- $r$: yaw rate
ATMOSPHERIC ARC : FORCES

- **Main forces:**
  - Gravitational forces (central term + J2 term)
  - Aerodynamic forces (drag + lift [assumption $\beta = 0$])

**Weight** = $-mg \left[ (\sin \gamma) \vec{i}' + (\cos \gamma) \vec{j}' \right]$

**Drag** = $-\left( \frac{1}{2} \rho SC_{x_{aero}} V^2 \right) \vec{i}'$

**Lift** = $\left( \frac{1}{2} \rho SC_{z_{aero}} V^2 \right) \left[ (\cos \mu) \vec{j}' + (\sin \mu) \vec{k}' \right]$
ATMOSPHERIC ARC : EQUATIONS

- **Assumptions**: no side slip angle ($\beta = 0$) ; central term of geopotential ($J_2 = 0$)

- **Derivation of position**: $\frac{dr}{dt}$
  
  \[
  \frac{dr}{dt} = V \sin(\gamma) \quad \frac{d(\text{lat})}{dt} = \frac{V}{r} \cos(\gamma) \cos(\chi) \quad \frac{d(\text{lon})}{dt} = \frac{V}{r} \cos(\gamma) \frac{\sin(\chi)}{\cos(\text{lat})}
  \]

- **Derivation of velocity**: $dV/dt$

  \[
  \frac{dV}{dt} = -g \sin(\gamma) - \frac{1}{2} \rho \frac{\text{SC}_x}{m} V^2 + \text{terme en } \omega_E^2
  \]

  \[
  \frac{d\gamma}{dt} = -\frac{g}{V} \cos(\gamma) + \frac{1}{2} \rho \frac{\text{SC}_z}{m} V \cos(\mu) + \frac{V}{r} \cos(\gamma) + 2\omega \cos(\text{lat}) \sin(\chi) + \text{terme en } \omega_E^2
  \]

  \[
  \frac{d\chi}{dt} = \frac{1}{2} \rho \frac{\text{SC}_z}{m} V^2 \sin(\mu) + \frac{V}{r} \cos(\gamma) \tan(\text{lat}) \sin(\chi) + 2\omega_E (\sin(\text{lat}) - \tan(\gamma) \cos(\text{lat}) \cos(\chi)) + \text{terme en } \omega_E^2
  \]
ATMOSPHERIC ARC: SIMPLIFYING ASSUMPTIONS

- **FIRST REBOUND ASSUMPTION:**
  - no side slip angle ($\beta = 0$)
  - central term of geopotential ($J_2 = 0$)
  - Fixed Earth frame ($\omega_E = 0$)
  - small $\gamma$ (sin $\gamma = \gamma$ and cos $\gamma = 1$)
  - ($V^2/r - g$) small vs lift term

- **EQUILIBRIUM ASSUMPTION:**
  - no side slip angle ($\beta = 0$)
  - central term of geopotential ($J_2 = 0$)
  - Fixed Earth frame ($\omega_E = 0$)
  - small $\gamma$ (sin $\gamma = 0$ and cos $\gamma = 1$)
  - $d\gamma/dt$ small vs other terms of the equation $d\gamma/dt = ...$

\[ V^2 = V_e^2 e^{-\frac{2CD}{cL \cos(\mu)}(\gamma - \gamma_e)} \]
\[ \gamma^2 = \gamma_e^2 - \frac{SC_L \cos(\mu)}{\beta m}(\rho - \rho_e) \]
ATMOSPHERIC ARC : EQUILIBRIUM ASSUMPTION

\[
\frac{dV}{dt} = g \frac{V^2 - 1}{(L/D) \cos(\mu)} \quad \text{avec} \quad V = \frac{V}{\sqrt{g r_T}} \quad \text{et} \quad L/D = \frac{C_Z}{C_X} \quad \text{deceleration is inversely proportional to } L/D
\]

\[
\gamma = \frac{2C_X}{\beta r_T C_Z \cos(\mu) V^2} \quad \text{avec} \quad \rho = \rho_0 e^{-\beta(z-z_0)}
\]

\[
\frac{X - X_e}{r_T} = \frac{1}{2} \frac{L}{D} \cos(\mu) \log\left(\frac{1 - V^2}{1 - V_e^2}\right) \quad \text{Longitudinal range is proportional to } L/D
\]

\[
\frac{Y - Y_e}{r_T} = \frac{1}{2} \left(\frac{L}{D}\right)^2 \sin(\mu) \cos(\mu) \left[\log\left(\frac{1 - V^2}{1 - V_e^2}\right) - V_e \log\left(\frac{1 - V}{1 + V} \cdot \frac{1 + V_e}{1 - V_e}\right)\right] \quad \text{Cross range is proportional to square of } L/D
\]

\[
\Psi = \frac{\pi}{2} - \chi = \frac{L}{D} \sin(\mu) \log\left(\frac{V}{V_e}\right)
\]

\[
t - t_e = \frac{1}{2} \sqrt{r_T L} D \cos(\mu) \left[\log\left(\frac{1 - V}{1 + V} \cdot \frac{1 + V_e}{1 - V_e}\right)\right]
\]
ATMOSPHERIC ARC: ANALYTIC / NUMERICAL COMPARISON

- First rebound assumption
- Equilibrium assumption
- Numerical simulation

- SCx / m = 0.005 m²/kg
- L/D = 0.2
- γe = -5 deg
ATMOSPHERIC ARC: NUMERICAL INTEGRATION

- **ANALYTICAL MODELS LIMITATIONS:**
  - Low precision of atmospheric models
  - Fixed Earth frame hypothesis
  - Aerodynamic coefficients variations along the flight:
    - Depends on the Mach, Reynolds or Knudsen number
    - Depends on angle of attack (AoA)
    - Depends on altitude …
  - Variations on attitude angles (command laws)

- **STRONGLY NON LINEAR MOTION => NUMERICAL INTEGRATION:**
  - Varied atmospheric models: US76, GRAM, CIRA, MSIS + Martian models …
  - More precise aerodynamic data bases (for example, dependence on Mach, altitude, AOA, side slip angle, etc)
  - More sophisticated guidance laws and more realistic attitude motion (6 degrees of freedom motion)
ATMOSPHERIC ARC : METHODOLOGY

- **Objective**: to find guidance laws during hypersonic phase in order to maximize cross range and minimize heat quantity while respecting varied mechanical and/or thermal constraints.

- **Methodology**:

  1. Flight domain determination
  2. Optimization under constraints
  3. Simplified laws
  4. Guidance
  5. Dispersion studies
ATMOSPHERIC ARC : GNC/NGC definitions

Measurements → NAVIGATION

θ, dθ/dt + other estimated parameters

X, dX/dt, θ, dθ/dt
other estimated parameters

GUIDANCE

commanded α, β, μ

CONTROL

Actuator commands
ATMOSPHERIC ARC : EXAMPLES

- « THEORETICAL » STUDY OF INHABITED CAPSULES
- GEMINI CAPSULES GUIDANCE
- SOYUZ GUIDANCE
- L/D HYPersonic GUIDANCE
- ARD MISSION
ATMOSPHERIC ARC :
INHABITED CAPSULE (1/6)

HYPOTHESES:

- initial circular equatorial orbit; altitude = 400 km
- impulsive $\Delta V$
- standard US76 atmosphere
- two types of vehicles:

<table>
<thead>
<tr>
<th></th>
<th>« type A »</th>
<th>« type B »</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass</td>
<td>5.5 t</td>
<td>8 t</td>
</tr>
<tr>
<td>Sref</td>
<td>13.2 m²</td>
<td>22.9 m²</td>
</tr>
<tr>
<td>L/D max</td>
<td>0.295</td>
<td>0.633</td>
</tr>
</tbody>
</table>
ATMOSPHERIC ARC: INHABITED CAPSULE (2/6)

- COMMAND LAWS:

<table>
<thead>
<tr>
<th>« type A »</th>
<th>AoA</th>
<th>Bank angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mach &gt; 27</td>
<td>145 deg</td>
<td>90 deg</td>
</tr>
<tr>
<td>23.7 &lt; Mach &lt; 27</td>
<td>145 deg</td>
<td>90 -&gt; 45 deg</td>
</tr>
<tr>
<td>15 &lt; Mach &lt; 23.7</td>
<td>145 deg</td>
<td>45 -&gt; 12 deg</td>
</tr>
<tr>
<td>1 &lt; Mach &lt; 15</td>
<td>145 deg</td>
<td>12 deg</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>« type B »</th>
<th>AoA</th>
<th>Bank angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mach &gt; 27</td>
<td>130 deg</td>
<td>90 deg</td>
</tr>
<tr>
<td>22.5 &lt; Mach &lt; 27</td>
<td>130 deg</td>
<td>90 -&gt; 45 deg</td>
</tr>
<tr>
<td>15 &lt; Mach &lt; 23.7</td>
<td>130 deg</td>
<td>45 -&gt; 12 deg</td>
</tr>
<tr>
<td>1 &lt; Mach &lt; 22.5</td>
<td>130 deg</td>
<td>45 -&gt; 5 deg</td>
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</table>
ATMOSPHERIC ARC: INHABITED CAPSULE (3/6)

BANK ANGLE COMMAND LAWS

-90 -80 -70 -60 -50 -40 -30 -20 -10 0 20 40 60 80 100 120 140 160
0 200 400 600 800 1000 1200 1400 1600

Bank Angle [deg]

Initial ground track

Initial ground track

µ=90 deg

Cross Range

Cross Range

"Type A"

"Type B"
## ATMOSPHERIC ARC: INHABITED CAPSULE (4/6)

### TRAJECTORIES:

<table>
<thead>
<tr>
<th></th>
<th>« type A »</th>
<th>« type B »</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ΔV</strong></td>
<td>97.8 m/s</td>
<td>98 m/s</td>
</tr>
<tr>
<td><strong>AoA</strong></td>
<td>145 deg</td>
<td>130 deg</td>
</tr>
<tr>
<td><strong>Cross range</strong></td>
<td>108 km</td>
<td>519 km</td>
</tr>
<tr>
<td><strong>Longitudinal range</strong></td>
<td>5850 km</td>
<td>8180 km</td>
</tr>
<tr>
<td><strong>nmax</strong></td>
<td>2.52 g</td>
<td>1.58 g</td>
</tr>
<tr>
<td><strong>P_{dyn max}</strong></td>
<td>9.39 kPa</td>
<td>7.61 kPa</td>
</tr>
<tr>
<td><strong>Φ_{ref max}</strong></td>
<td>581.66 kW/m²</td>
<td>513.77 kW/m²</td>
</tr>
<tr>
<td><strong>Heat quantity</strong></td>
<td>254.34 MJ/ m²</td>
<td>390.92 MJ/ m²</td>
</tr>
</tbody>
</table>
ATMOSPHERIC ARC: INHABITED CAPSULE (5/6)

CONSTRAINTS

Load factor [g]

- Type A
- Type B

Reference heat flux [kW/m²]

- Type A
- Type B

Time [sec]
ATMOSPHERIC ARC:
INHABITED CAPSULE (6/6)

- **ORBITAL DISPERSIONS**:  
  - \( \delta(\Delta V) \) of +/- 1 m/s

- **ATMOSPHERIC DISPERSIONS**:  
  - \( \Delta T \) of +/- 20 K on US76 atmosphere

- **DISPERSIONS AERODYNAMIQUES**:  
  - +/- 10% on \( C_x \)
  - +/- 10% on \( L/D \) (\( C_z/C_x \))

<table>
<thead>
<tr>
<th></th>
<th>« type A »</th>
<th>« type B »</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross range error</td>
<td>-26 / +31 km</td>
<td>-126.5 / +151.5 km</td>
</tr>
<tr>
<td>Longitudinal range error</td>
<td>-505 / +587 km</td>
<td>-668.5 / +800 km</td>
</tr>
<tr>
<td>( n_{\text{max}} )</td>
<td>2.69 g</td>
<td>1.69 g</td>
</tr>
<tr>
<td>( \Phi_{\text{ref max}} )</td>
<td>605.7 kW/m²</td>
<td>536 kW/m²</td>
</tr>
<tr>
<td>( P_{\text{dyn max}} )</td>
<td>10.11 kPa</td>
<td>8.39 kPa</td>
</tr>
</tbody>
</table>
ATMOSPHERIC ARC: GEMINI CAPSULES GUIDANCE

- Ballistic trajectories
- Lifting trajectory
- Constant bank angle guidance (Gemini V, VI-A, VII)
- Half lifting trajectory
- Full lifting trajectory
- Roll guidance (Gemini III, IV, VII, IX-A, X, XI, XII)
- Guidance initialization
- Maneuver capacities
ATMOSPHERIC ARC : SOYUZ CAPSULES GUIDANCE

DEORBITATION PARAMETERS:
- $\Delta V = 115.2 \text{ m/s}$
- Duration $\sim 4 \text{ mn}$
- LANDING AREAS:
  - KAZAKHSTAN (ARKALYK, DZHEKAZGAN)
  - RAAN longitude:
    - $20^\circ$ East to $55^\circ$ West
- OPPORTUNITIES PER DAY: 3 to 4
Flight domain:

- Thermal limit
- Load factor limit
- Dynamic pressure limit
- Equilibrium glide

Equations:

- \((V, Z) \rightarrow \text{Mach} \rightarrow \alpha\)
- \((\alpha, \text{Mach}, Z) \rightarrow C_x\)
- \(Z \rightarrow \rho\)
- \((\rho, C_x, V) \rightarrow D\)
**Optimization / reference profile**

- **Load factor limit**
- **Dynamic pressure limit**
- **Thermal limit**
- **Margins**
- **Equilibrium glide**
- **Iso-D**
- **Linear D**
- **Linear Vz**
- **Iso-T**

---

ATMOSPHERIC ARC: L/D HYPERSONIC GUIDANCE (2/9)
If neglecting terms due to Earth rotation and considering $\gamma \approx 0$:

$$\frac{dV}{dt} \approx -\frac{1}{2} \frac{SC_x}{\rho m} V^2$$

A way to interact on drag deceleration is to modify $C_x$

$$C_x = f(\alpha, \text{Mach} = \frac{V}{V_{son}})$$

By modifying AoA, deceleration is then instantaneously modified

Problems:
- instability
- controllability
- influence on thermal protection surfaces
Another way to interact on drag deceleration is to use bank angle variations

\[ \dot{\gamma} = \frac{V^2_{abs}}{r} - g + \frac{1}{2} \rho \frac{SC}{m} V^2 \cos(\mu) \]

\( \mu \) makes \( \dot{\gamma} / dt \) varying

\( \dot{\gamma} / dt \) makes \( \gamma \) varying then \( V_z = dZ/dt = V \sin(\gamma) \)

\( dZ / dt \) makes \( Z \) varying then \( \rho \) and thus \( D = f(\rho) \)

Most of the time, we will keep relatively simple angle of attack profiles and will compute bank angle variations to follow a drag deceleration profile
lateral guidance:

- Projection of the relative velocity on the local horizontal plane
- "great circle" arc
- Current point
- Landing runway
- : roll-reversals

ATMOSPHERIC ARC: L/D HYPERSONIC GUIDANCE (5/9)
ATMOSPHERIC ARC:
L/D HYPersonic Guidance (6/9)

ANGLE OF ATTACK

SIDE SLIP ANGLE

BANK ANGLE

Commanded vs. Real Values

Reference Angle vs. Real Angle

Commanded vs. Real Side Slip Angle

Commanded vs. Real Bank Angle
ATMOSPHERIC ARC:
L/D HYPersonic Guidance (7/9)

DRAG DECELERATION

- DREF
- DCOM
- Dreal

Total velocity (m/s)

D (m/s^2)

0 1000 2000 3000 4000 5000 6000 7000 8000 9000

0 1 2 3 4 5 6 7 8
ATMOSPHERIC ARC: L/D HYPERSONIC GUIDANCE (9/9)

GROUND TRACK

1st roll-reversal
2nd roll-reversal
End of Black-Out
1st bank maneuver
Beginning of Black-Out
Z = 120 km

longitude (deg)
latitude (deg)

Service Manoeuvres Orbitales (DCT/SB/MO)
4th International Conference on Astrodynamics Tools and Techniques – 30 April 2010
Characteristics
- mass: 2716 kg
- reference surface: 6.158 m²
- APOLLO shape
- Angle of Attack: about 160 deg.

Control:
- via 7 hydrazine thrusters

On-board navigation
- IMU
- GPS

Atmospheric guidance (Apollo/Shuttle derived)
- reference drag deceleration profile
- longitudinal range
- roll-reversals for lateral guidance
ATMOSPHERIC ARC : ARD MISSION (3/4)

T.U. 21/10/1998 17h 12mn 56s  Date/H0 +00h 35mn 35s
dernier point de la traj. reelle: lat= -1.84 deg; lon= 31.77 deg; alt= 660.86 km; orig= GPS; date/H0= +00h 28mn 52s
dernier point de la traj. reelle: ecart en distance traj. estimee/traj. reelle= 0.61 km

FIN VISIBILITE LIBREVILLE

ARD  53.8  -3.9  779.2  VISIBILITES(site)
Good precision on orbit based on GPS PVT measurements

Very good representation of the simulations of orbital arcs and especially atmospheric arc (with guidance)

Good consideration of wind profiles obtained at H0-30 mn

Final difference between real point (issued from GPS) and predicted one: 4.93 km
ARD : Air Range Instrumentation Aircraft