8th INTERNATIONAL PLANETARY PROBE WORKSHOP
Portsmouth, Virginia on June 6-10, 2011

Aerobraking Pericentre Control Strategies

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Context and activity summary

- Context and objective
  - ESA Technology Research Programme / MREP
  - Investigation of AB strategies aimed to increase level of autonomy in such operations

- Key issue is the definition of control strategy to fulfill aerobraking corridor conditions:
  - When and where applying a correction burn
  - How to compute a correction burn size
  - 1D versus 2D Corridor definition and control variables

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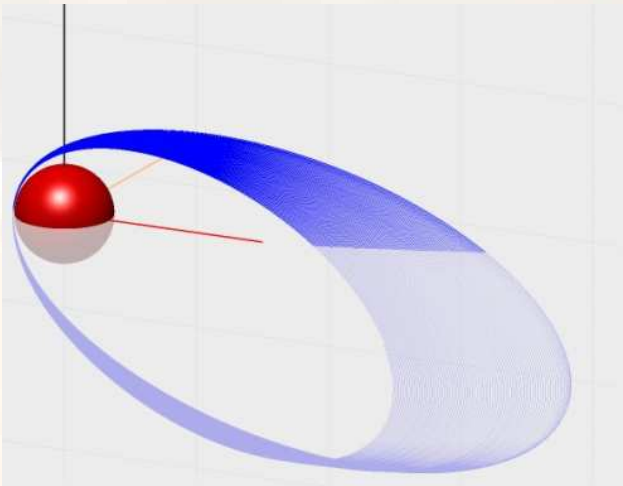
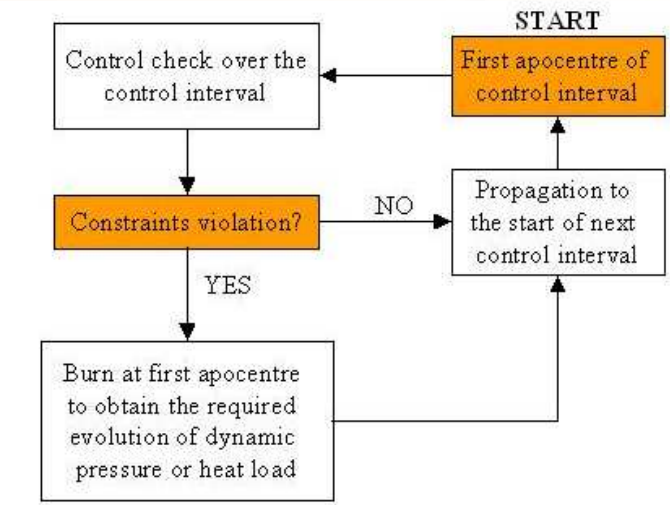
Context and activity summary

- Corridor Upper boundary definition:
  - Natural definition of upper boundary constraint
  - Functional definition of corridor upper boundaries
  - Simplified Solar Array Model (assumptions and equations)



- Lower boundary definition:
  - Minimum peak dynamic pressure

- Examples of control corridor applications:
  - Aerobraking on Mars (**MSRO**): 1-D and 2-D corridor
  - Aerobraking on Venus(**Magellan-like**): 2-D corridor
  - Aerobraking on Titan (**TSSM**): 1-D corridor



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The Aerobraking Control Corridor

- Two boundaries
  - **Upper boundary** to **prevent damage** of **S/C structures**
  - **Lower boundary** to **guarantee** a **minimum apocentre reduction** per pass
- Definition of the corridor requires:
  - Choice of the control variables:
    - **Peak dynamic pressure** or **heat flux** for each drag pass
    - **Peak solar array temperature** for each drag pass
    - **Heat load** throughout each drag pass (integrated heat flux)
  - Choice of the control domain:
    - **1-D**: Variable corridor based on **peak heat flux** or **dynamic pressure**
    - **2-D**: Fixed corridor in **Peak Heat Flux Vs Heat Load** plane
  - **Upper boundary constraint specification** (e.g. maximum array temperature)
  - **Lower boundary constraint specification** (e.g. maximum AB duration)

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How to fulfill the corridor conditions (1)

- Correction Manoeuvres (ABMs) applied at apocentre to counteract natural evolution of control variables
  - Pericentre density varies significantly from orbit to orbit due to altitude and longitude changes
  - DeltaV cost of a given pericentre altitude change is **lowes**t at **apocentre**
- Definition of the "*control interval*" as:
  - **Minimum Time Interval** between successive ABM decisions
- Every "*control interval*":
  - **Orbit** is **predicted** to check the evolution of the control variables
  - If control variables step out of the corridor, an ABM is applied at the first apocentre of the control interval
  - ABM computed so as **to maximize** the apocentre altitude reduction, while **respecting** the upper boundary constraint

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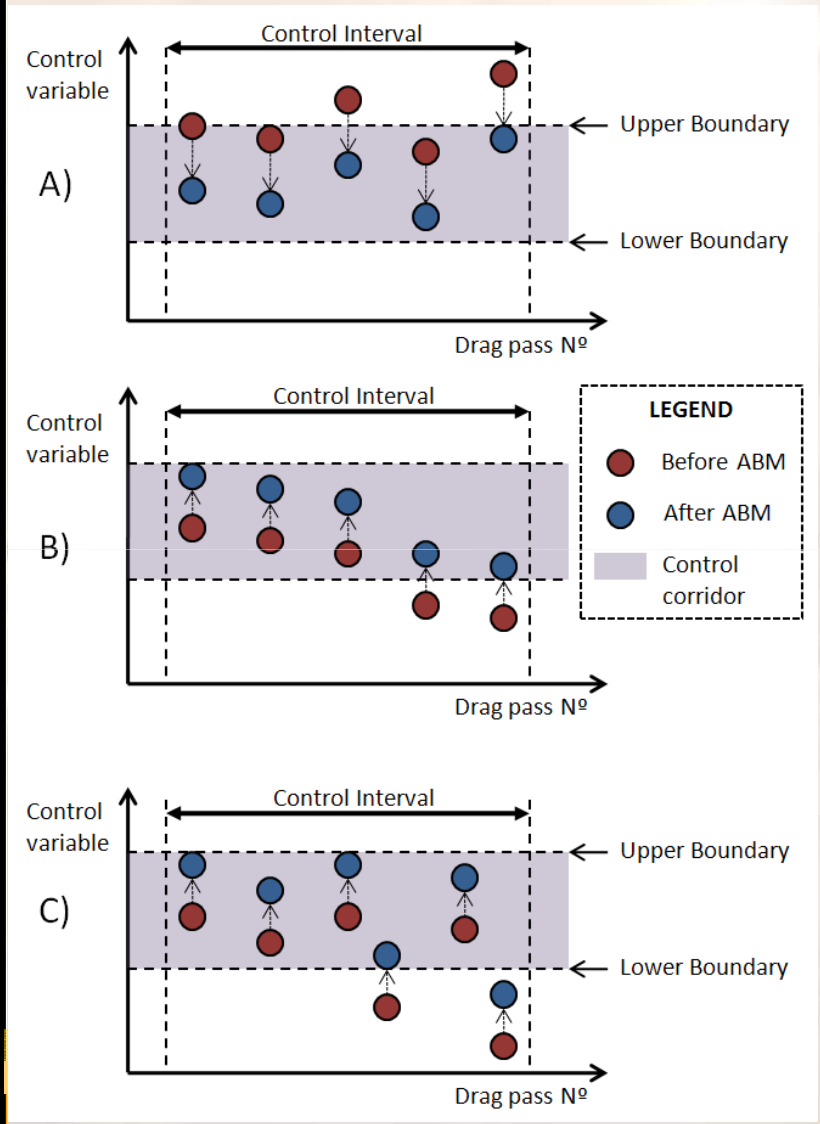
How to fulfil the corridor conditions (2)



The **ABM effect** is always that of **shifting** the **highest predicted control variable** to the **corridor upper boundary**

Case A): Upper boundary violation

Case B): Lower boundary violation

Case C): Lower boundary violation with a natural dispersion higher than the corridor width

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Corridor Upper Boundary (1)

- Typically, the most critical structure is the solar array:
- Natural definition of the upper boundary:
  - **Locus of points** (in terms of the control variables) yielding a **maximum allowable array temperature** (taking into account a **safety margin**)
- Solar array peak temperature as control variable:
  - Non-trivial prediction (very accurate thermal model)
  - Complex to measure during mission operations
- Surrogate variables are preferred due to their easier predictability:
  - **Peak Dynamic Pressure**: $p_{dyn\,peak} = \max\left(1/2 \cdot \rho \cdot V_{atm}{}^{2}\right)_{drag\,pass}$
  - **Peak Heat Flux**: $\Phi_{peak} = \max\left(1/2 \cdot \rho \cdot V_{atm}{}^{3}\right)_{drag\,pass}$
  - **Heat Load** per pass: $\Delta Q = \int_{drag\ pass} \Phi(t)dt$

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Corridor Upper Boundary (2)

- Main factors affecting the peak array temperature are:
  - **Peak heat flux**
  - **Duration** of the **pass** or **orbit geometry**
  - **Integrated heat flux** or **heat load**
- According to the choice of independent variables, two corridor approaches can be defined:

1-D CORRIDOR APPROACH

$$T_{peak} = f\left(\Phi_{peak}, orbit\ geometry\right)$$

$$T_{peak} = T_{\max}$$

and inverting

$$\Phi_{peak\ upper\ boundary} = g\left(T_{\max}, orbit\ geometry\right)$$

Orbit geometry can be expressed as a function of apocentre altitude

2-D CORRIDOR APPROACH

$$T_{peak} = T_{peak}\left(\Phi_{peak}, \Delta Q\right)$$

$$T_{peak} = T_{\max}$$

$$T_{peak}\left(\Phi_{peak}, \Delta Q\right) = T_{\max}$$

ΔQ takes into account the effects of the density profile, thus making 2-D corridors more efficient

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Simplified Thermal Model

- Assumptions:
  - **Conservative assumptions** to simulate **Worst Case**
  - **Single Node Thermal Model**: no thermal gradient
  - **Solar Array thermally decoupled** from the S/C body
  - Convective heat flux coefficient equal to 1
  - **Normal incidence** of incoming fluxes (solar flux Φ_{Sun}, planetary albedo and infrared radiation Φ_{Planet})
  - **Solar flux** applied to most absorbing array surface, albedo and IR radiation applied to back and front surfaces
- Array temperature equation:
  - **Balance** between **incoming fluxes** (from **radiation** and **convective flux**) and **outgoing radiative flux**

$$mC_p\dot{T} = \Phi_{convective} + (\alpha_1 + \alpha_2)\cdot\Phi_{Planet} + \max(\alpha_1, \alpha_2)\cdot\Phi_{Sun} - \sigma\cdot(\varepsilon_1 + \varepsilon_2)\cdot T^4$$

- Initial temperature at drag pass start:
  - **Equilibrium temperature (dT/dt=0)** under environmental fluxes only (**$\Phi_{convective}$=0**)

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Corridor Lower Boundary

- Lower boundary purpose:
  - **Ensure** that the apocentre reduction does not take too long to be accomplished
- How to achieve this?
  - Several approaches: guarantee a **minimum drag deltaV**, **apocentre altitude reduction** or **drag peak deceleration**
  - **Peak dynamic pressure** is **proportional** to the **drag peak deceleration** and hence is a good candidate for the lower boundary definition
- Definition of lower boundary:
  - **Locus of points** (in terms of the control variables) yielding a **minimum allowed peak dynamic pressure**

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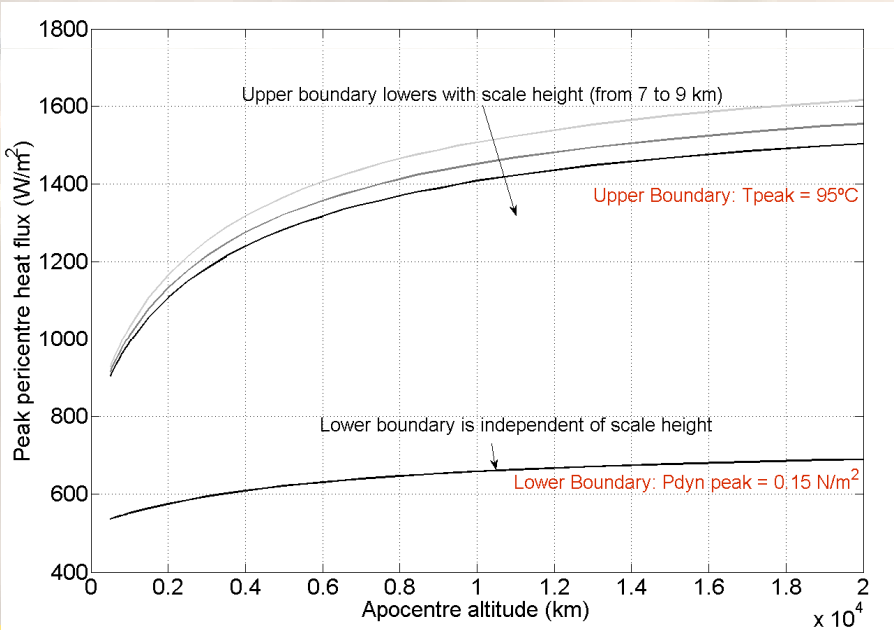
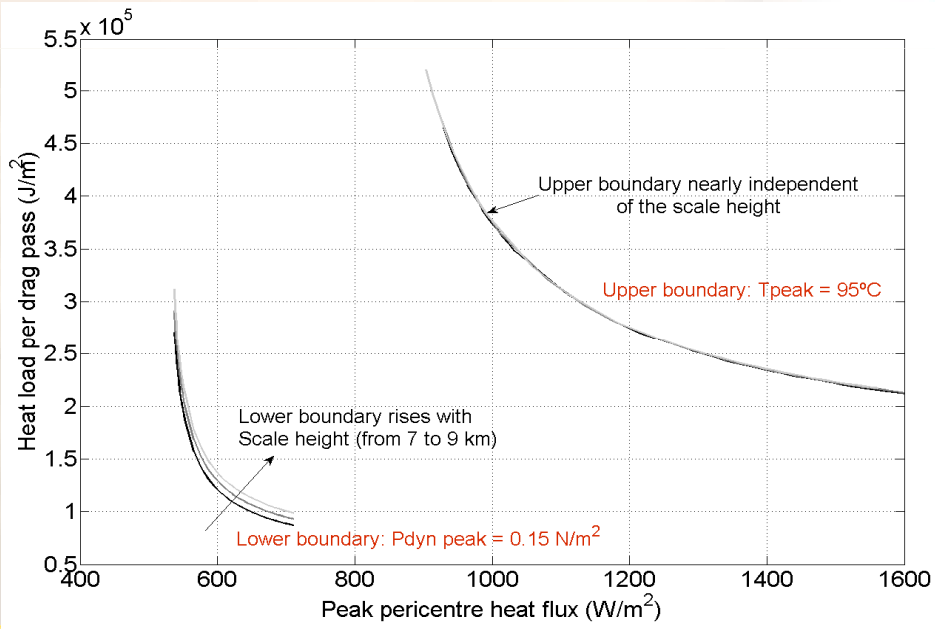
Application: Aerobraking on Mars

- 1-D corridor upper boundary depends slightly on the atmospheric scale height:
  - **Scale Height:** Vertical distance over which the density changes by a factor of *e*
  - Conservative scale height value (**9km**) assumed in simulations
  - **1-D upper corridor** is more conservative

1-D CORRIDOR



2-D CORRIDOR



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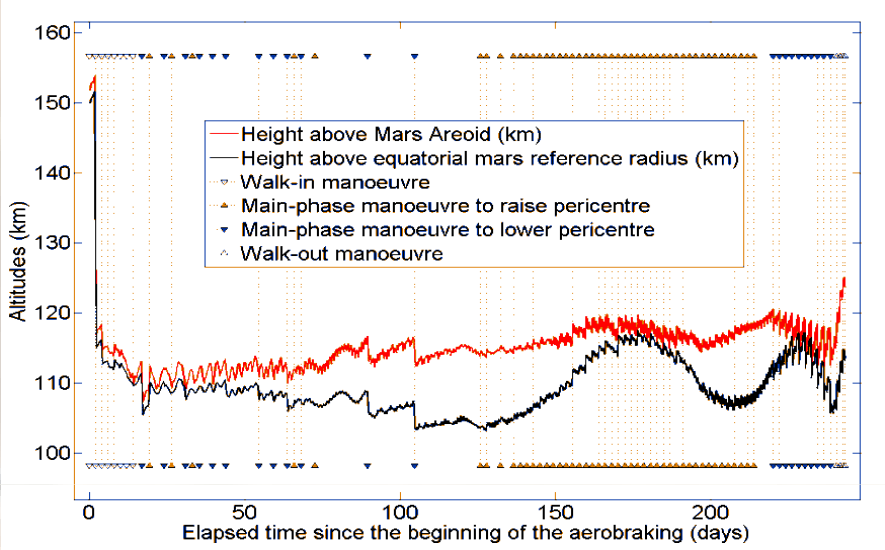
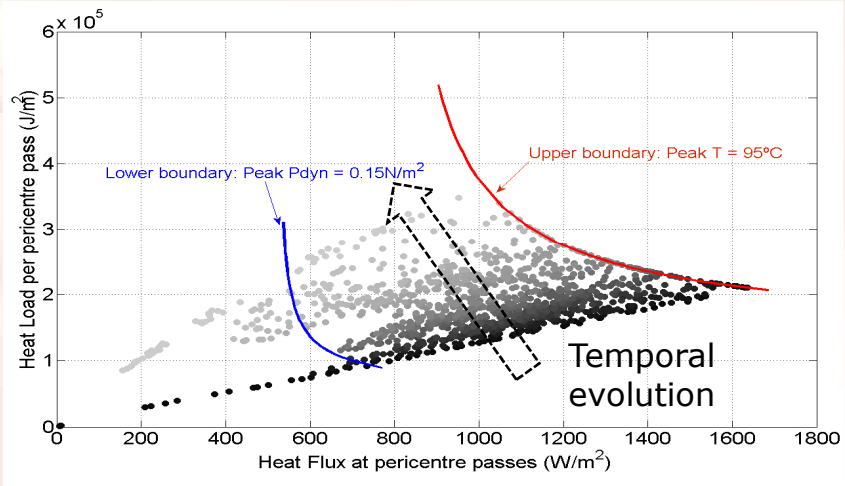
Aerobraking on Mars: 2-D corridor simulation

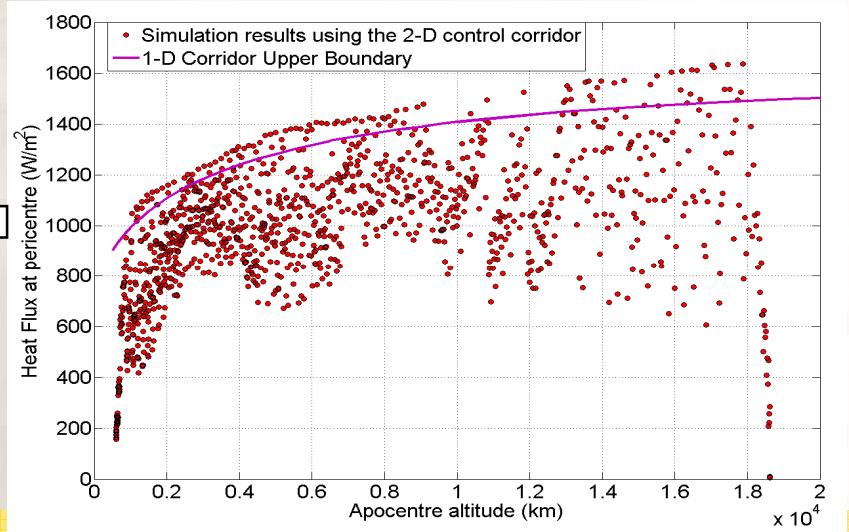
PERICENTRE ALTITUDE EVOLUTION



CONTROL VARIABLES EVOLUTION



HEAT FLUX VS APOCENTRE ALTITUDE



Comparison between peak heat flux values attained with the 2-D corridor control and the 1-D corridor upper boundary underlines the <u>higher efficiency of the 2-D approach</u>

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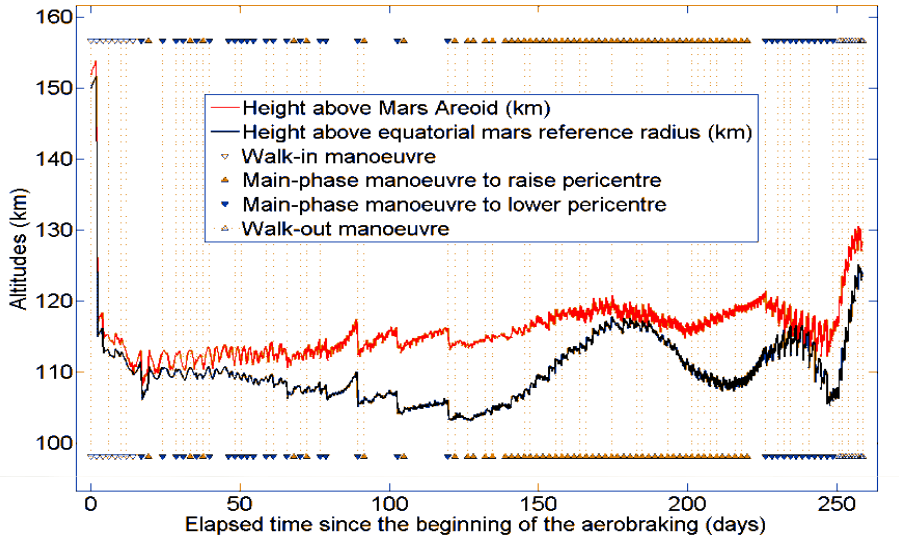
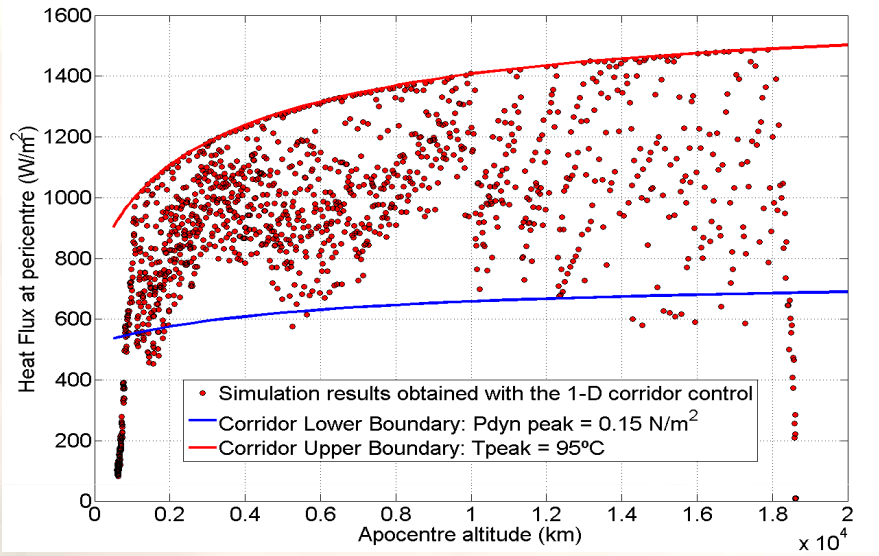
Aerobraking on Mars: 1-D corridor simulation

PERICENTRE ALTITUDE EVOLUTION

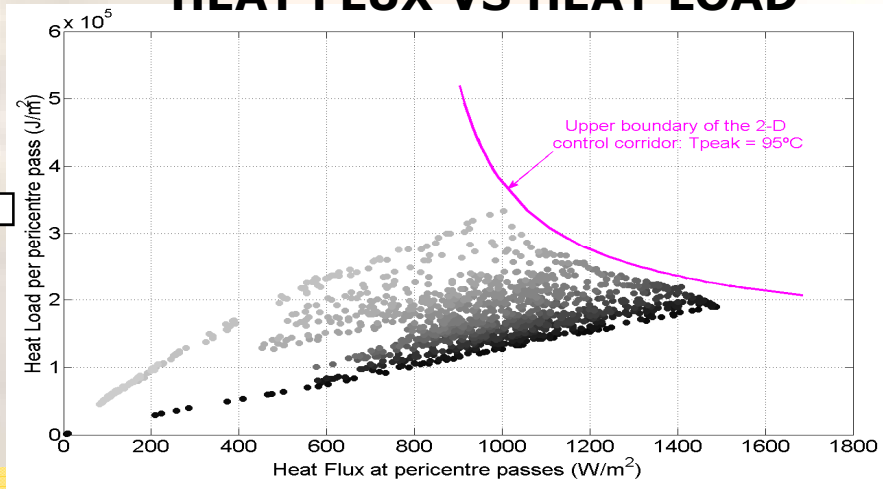


CONTROL VARIABLE EVOLUTION



Evolution in the heat flux/ heat load plane is more conservative with respect to the 2-D corridor. This translates into an overall longer aerobraking duration (15 days)

HEAT FLUX VS HEAT LOAD



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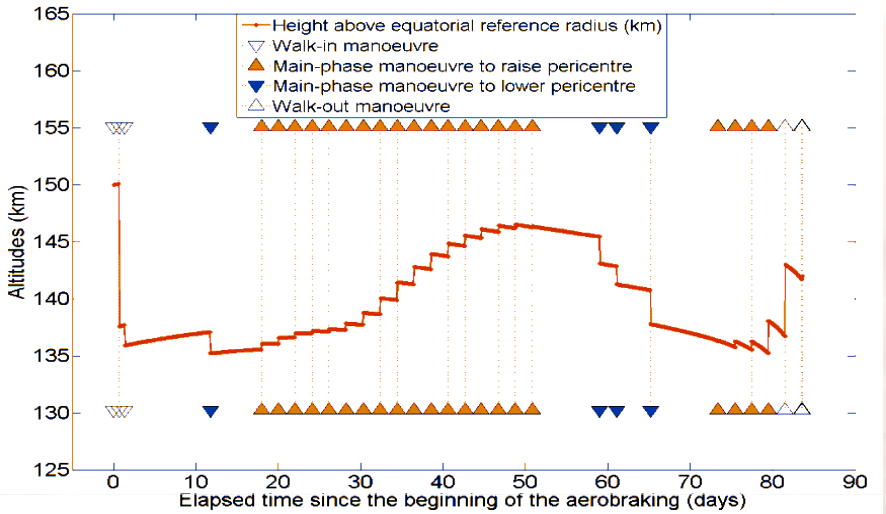
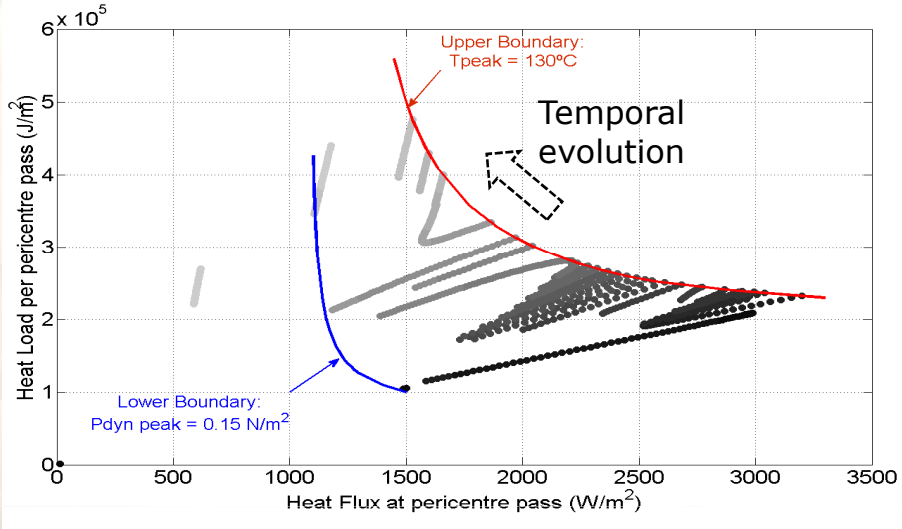
Application: Aerobraking on Venus

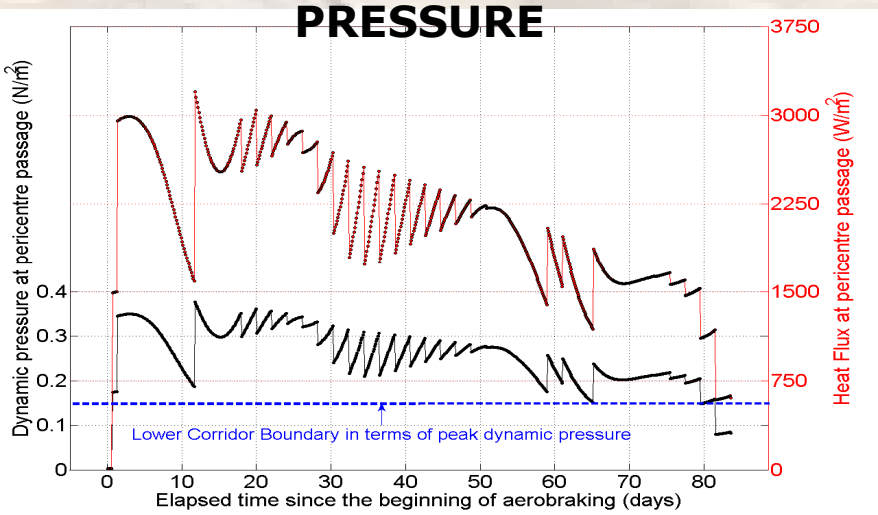
PERICENTRE ALTITUDE EVOLUTION



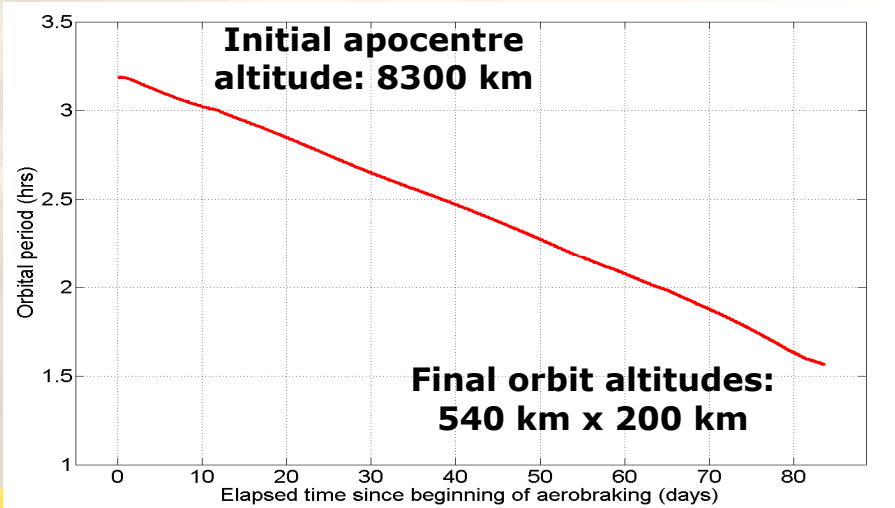
CONTROL VARIABLES EVOLUTION



PEAK HEAT FLUX AND DYNAMIC PRESSURE



ORBITAL PERIOD EVOLUTION



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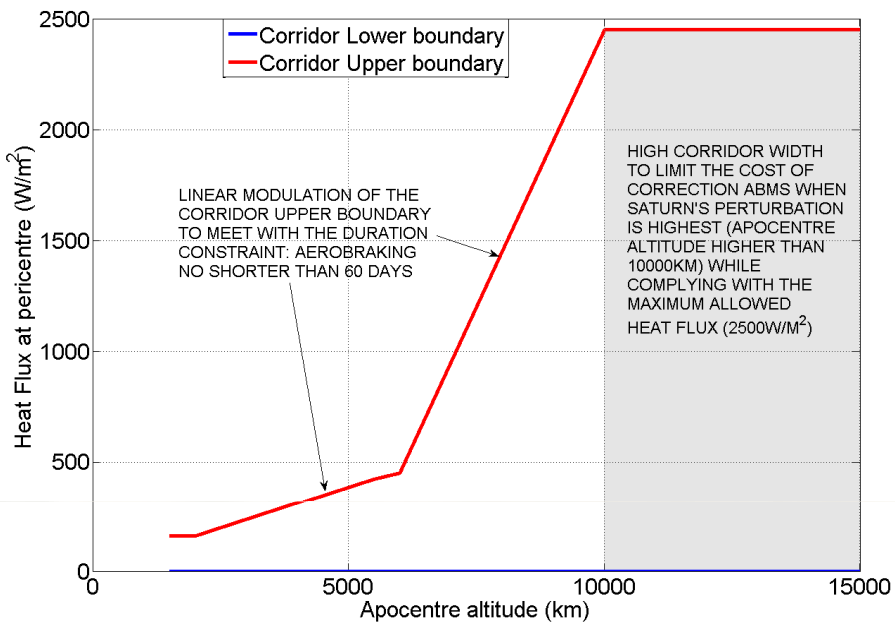
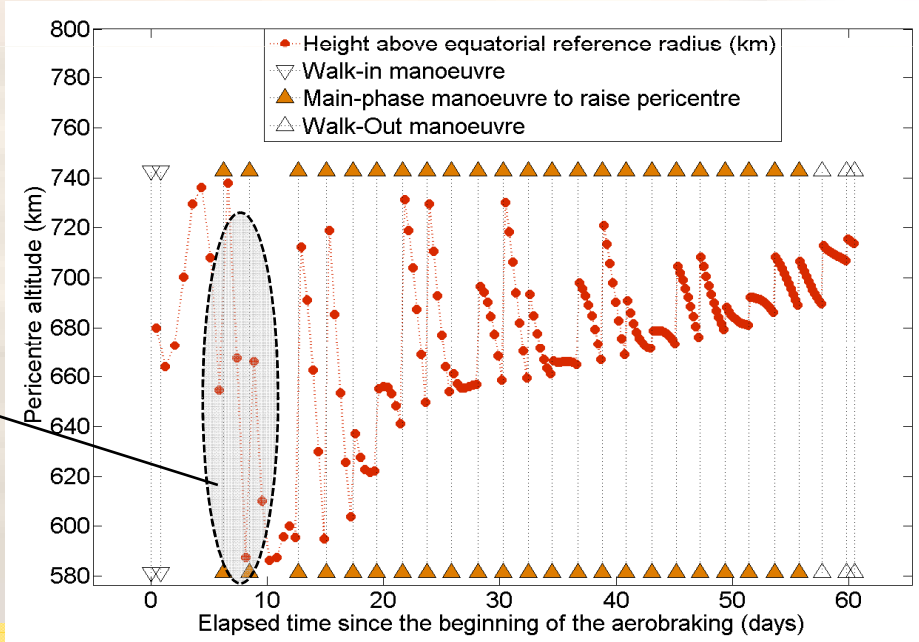
Aerobraking on Titan: 1-D Corridor Sim. (1)

1-D CONTROL CORRIDOR



- **Different high level constraint:**
  - Minimum duration of **60 days** (**Science phase**)
  - Maximum heat flux of **2500W/m²** (High Gain Antenna constraint)
  - **Saturn's gravity perturbation** suggests that corridor width be the widest at high apocentre altitudes

PERICENTRE ALTITUDE EVOLUTION



Saturn's Third Body gravity induces orbit to orbit changes of pericentre altitude of **up to 80 km**

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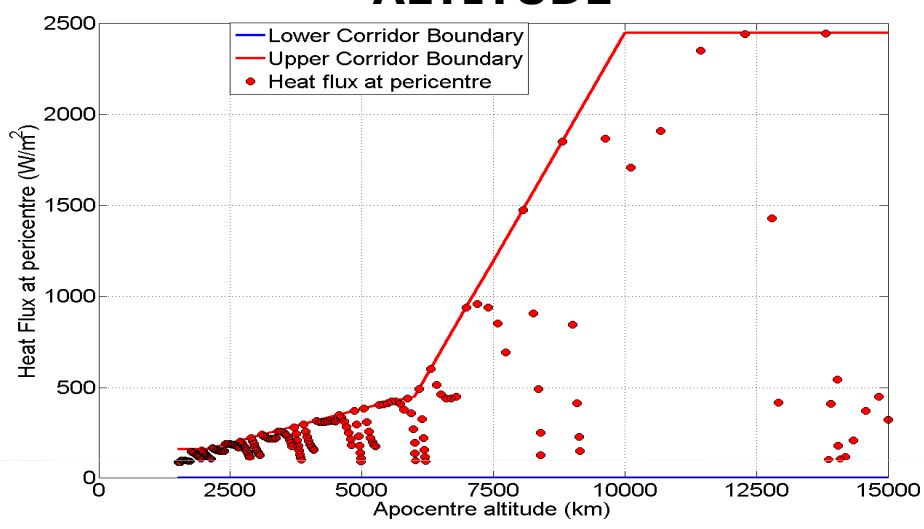
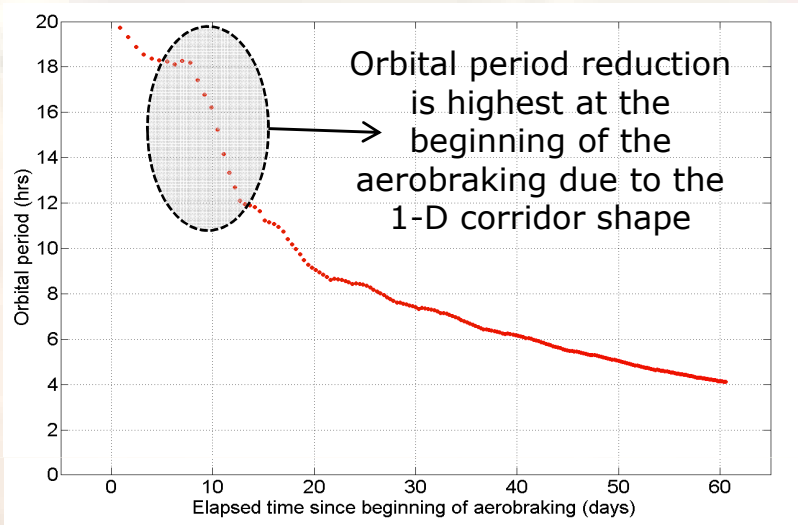
Aerobraking on Titan: 1-D Corridor Sim. (2)

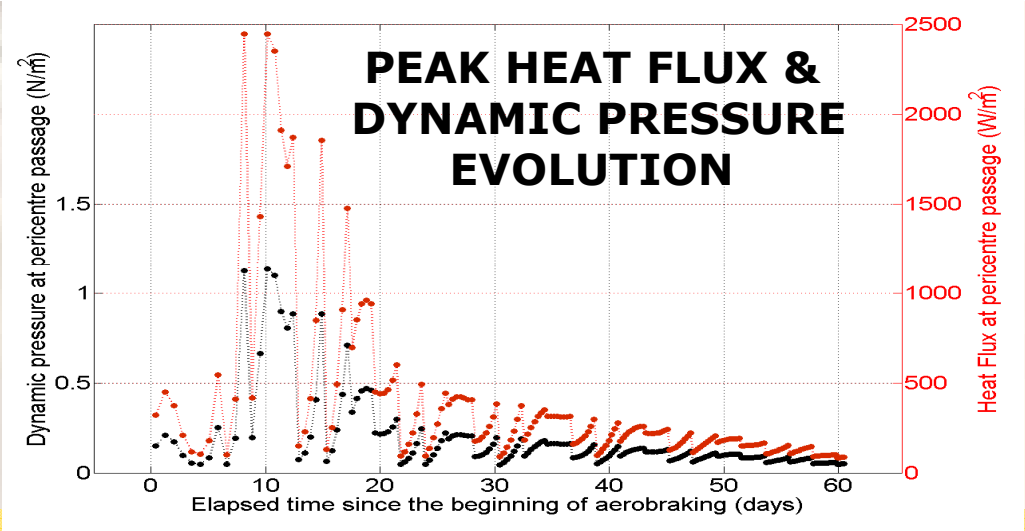
PEAK HEAT FLUX VS APOCENTRE ALTITUDE



ORBITAL PERIOD EVOLUTION



PEAK HEAT FLUX & DYNAMIC PRESSURE EVOLUTION



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Conclusions

- New approach to control corridor correction ABMs:
  - Selection of surrogate variables: peak heat flux or dynamic pressure (**1-D**), peak heat flux and heat load (**2-D**)
  - Prediction of surrogate control variables throughout a selectable interval of time, named "***control interval***"
  - **ABM size** computed so as to yield the highest apocentre altitude reduction while complying with structural constraints (applicable to both onboard and ground architectures)
- 1-D and 2-D corridor definition:
  - Simplified and conservative **solar array model**
  - **Corridor algorithms** to compute both boundaries for each apocentre altitude contained in the aerobraking range
- Examples of application on Mars, Venus and Titan:
  - Mars simulation has showed the **higher efficiency** of **2-D** corridor
  - Proved applicability of the corridor concept to Venus Environment
  - Titan simulation has showed the **versatility** of **1-D corridors**

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