National Aeronautics and Space Administration

Mars Optimal Aerobrake Maneuver Estimation

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Introduction

- Development of an innovative maneuver planning tool for GSFC
  - tooL for maneUver Planning Analysis and Navigation - LUPAN
  - Expands from maneuver design to aerobrake and formation flying
- The tool used for maneuver analysis is presented
- The MAVEN previous Deep Dip Campaign is analyzed
- Comparison between LUPAN and a high-fidelity propagation
- Comparison between LUPAN and an optimal high-fidelity solution

LUPAN Outline

tooL for maneUver Planning Analysis and Navigation - LUPAN

- LUPAN automatically calculates:
  - The best maneuver points
  - The trade between maneuver points and number of maneuvers
  - The error associated with early of late execution
- LUPAN requires only a reference orbit to represent the regime
  - Ephemerids and State Transition Matrix
  - The tool works in low, mid and high fidelity
- LUPAN calculates the best target point
  - Can be adjusted according to point stability, arrival time, ephemerids, position, velocity, inclination coverage, and density
- LUPAN is self contained and robust to different cases
  - All it is needed is the reference trajectory

Finding ΔV to change final periapsis (1/4)

- We use the state transition matrix (STM) of the high fidelity flow to find the required Δv to change the final periapsis.
- If $x_f = \phi_{t_f}(t_0, x_0)$ is the satellites state at time starting at (t_0, x_0) and the STM at (t_f, x_f) is $\Phi_{tf} = D\phi_{t_f}(t_0, x_0)$, then

$$\phi_{t_f}(t_0, x_0 + \delta x_0) \approx \phi_{t_f}(t_0, x_0) + \Phi_{tf}\delta x_0 \approx x_f + \delta x_f \qquad (1)$$

- If we consider $x = [R \;\; V]^T$ from (1) we have

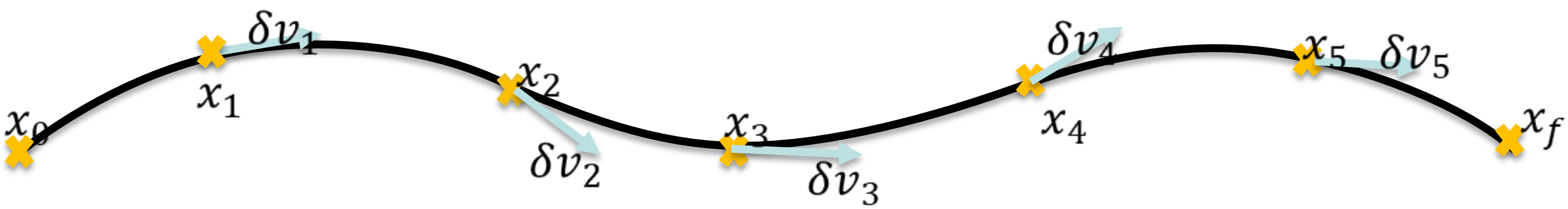
$$\begin{bmatrix} \delta R_f \\ \delta V_f \end{bmatrix} = \begin{bmatrix} \Phi_{RR} & \Phi_{RV} \\ \Phi_{VR} & \Phi_{VV} \end{bmatrix} \begin{bmatrix} \delta R_0 \\ \delta V_0 \end{bmatrix}.$$

- So if we do a Δv at t_0 we have the $\delta R_f = \Phi_{RV}\, \Delta v$. We can use equation to find the required Δv to reach a specific displacement δR_f from the final state x_f:

$$\Delta v = (\Phi_{RV})^{-1}\delta R_f$$

Finding ΔV to change final periapsis (2/4)

- If we have more than one Δv through the full trajectory:



- If there are n different Δv's along the trajectory, the final displacement δR_f can be approximated by $\delta R_f = \Phi_{RV}^1 \Delta v_1 + \Phi_{RV}^2 \Delta v_2 + \cdots + \Phi_{RV}^n \Delta v_n = M\,\Delta V,$ where $M = [\Phi_{RV}^1 \quad \cdots \quad \Phi_{RV}^n]$ and $\Delta V = [\Delta v_1 \quad \cdots \quad \Delta v_n]^T$.
- To find the required ΔV to reach δR_f we need to solve $\delta R_f = M\,\Delta V$. As we have more equations than unknowns, we find the ΔV such that $||\Delta V||$ is minimum:

$$\Delta V = M^t (M M^t)^{-1} \delta R_f$$

Finding ΔV to change final periapsis (3/4)

- Instead of using the "classical STM" we consider the periapsis Poincaré map and the Poincaré STM to find the required Δv to change the periapsis.
  - The periapsis map $P(x) = \phi_{t(x)}(t_0, x)$ is a map that takes any initial state x_0 to the final state $x_f = P(x_0)$ such that x_f is a periapsis (i.e. $\langle r_f, v_f \rangle = 0$).
  - We can numerically compute $P(x)$ and $\Pi(x) = D\phi_{t(x)}(t_0, x)$ (the periapsis map STM) from the original STM (Φ_{tf}).
  - As before we can find the required Δv to reach x_f by

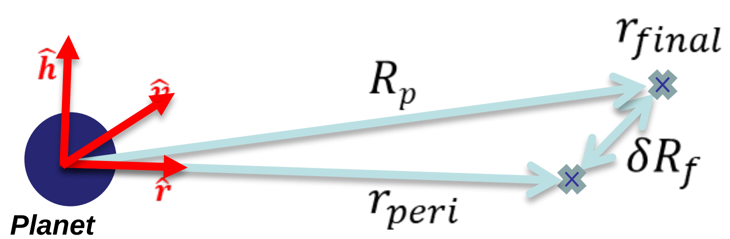
$$\Delta v = (\Pi_{RV})^{-1} \delta R_f$$

We note that the Periapsis map ensures that $x_{new} = (x_f + \delta R_f)$ is also a periapsis.

Finding ΔV to change final periapsis (4/4)

- We parametrize the desired change of periapsis by two angles (az, el) and a distance, R_p, as follows,

$$\delta R_f(az, el, R_p) = R_p\left(\cos(el)\cos(az)\,\hat{\boldsymbol{r}} + cos(el)\sin(az)\,\hat{\boldsymbol{v}} + \sin(el)\,\hat{\boldsymbol{h}}\right) - r_{peri}$$



Ref. Frame

$$\hat{\boldsymbol{r}} = \frac{r_{peri}}{\|r_{peri}\|}$$
$$\hat{\boldsymbol{v}} = \frac{v_{peri}}{\|v_{peri}\|}$$
$$\hat{\boldsymbol{h}} = \hat{\boldsymbol{r}} \times \hat{\boldsymbol{v}}$$

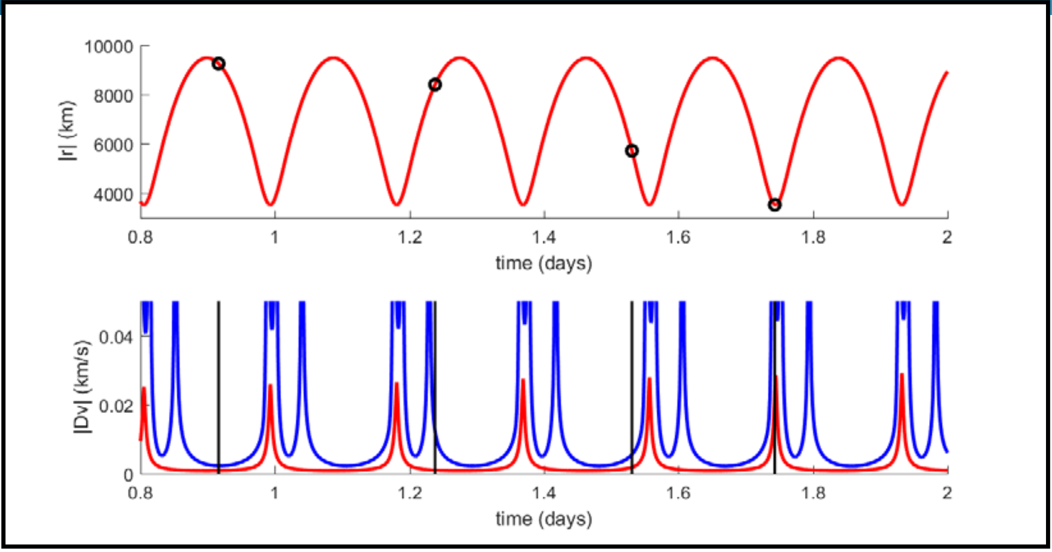
For a specific R_p (desired density height) using $\Delta v = (\Pi_{RV})^{-1}\delta R_f$ we solve such that Δv is minimum for all $(az, el) \in [\theta_{min} \quad \theta_{max}]^2$. *(Note: we have used SNOPT for this computation)*

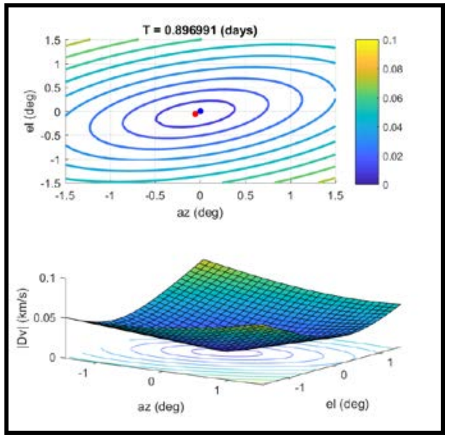
Single ΔV analysis

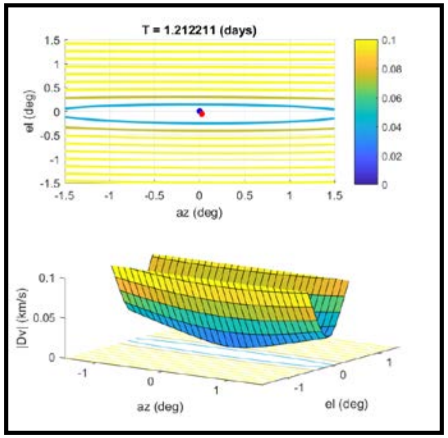
Computation of ΔV required to change the periapsis.

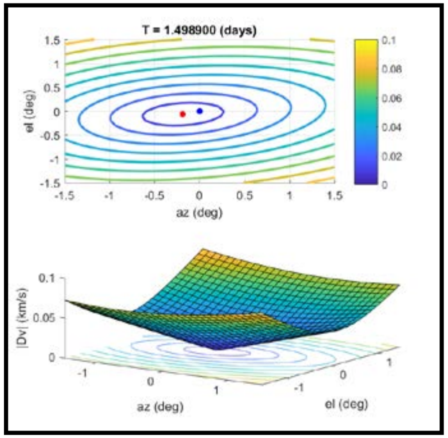
Recall Inverse of Poincaré map:

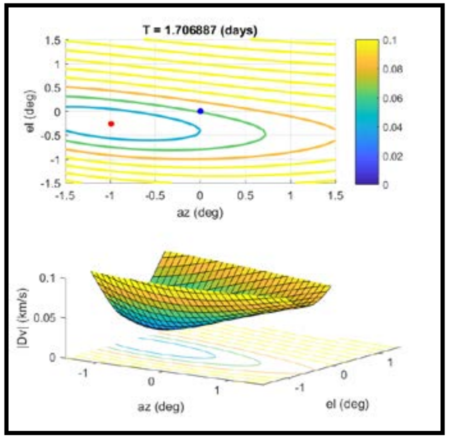
$$\Delta v = (\Pi_{RV})^{-1}\delta R_f(az, el)$$





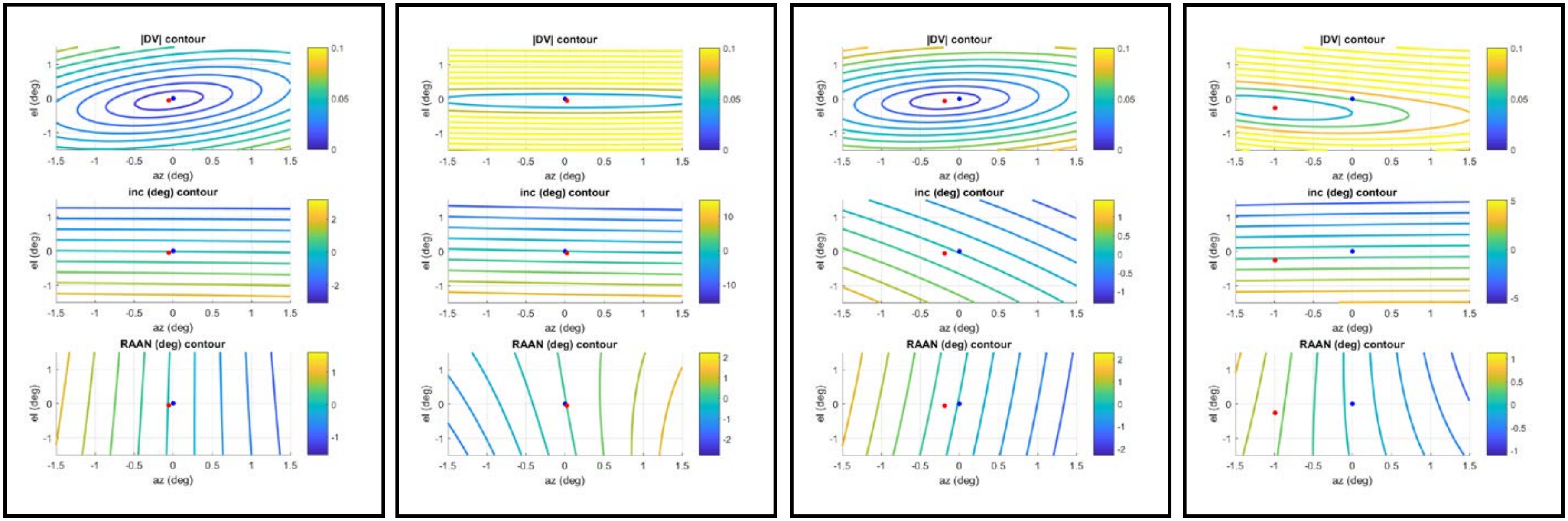






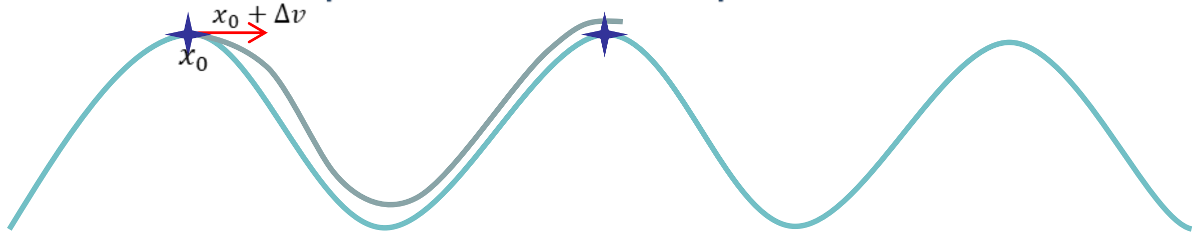
Final Inclination and RAAN change

Inclination and RAAN w.r.t. changes in az and el for a single Δv maneuver.



Correcting the Events Epoch

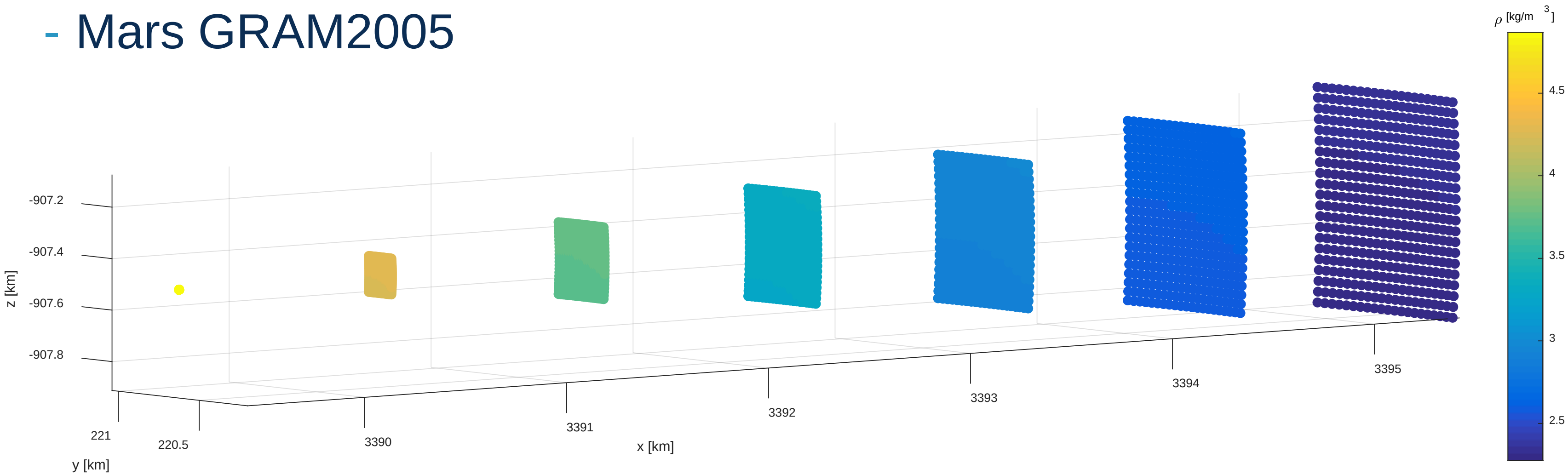
- After a Δv maneuver, the time of the following apses changes. We use a first order approximation to estimate these new times, to ensure that all the maneuvers are performed at the apsis.



- If $t(x_0)$ is the apsis passage time of an initial state $x_0 = (r_0, v_0)$, then after a Δv maneuver $t(x_0 + h) = t(x_0) + Dt(x_0)h$, where $h = (0, \Delta v)$.
- We can extend this approach to get the apses time for multiple Δv.

Density Corridor Evaluation

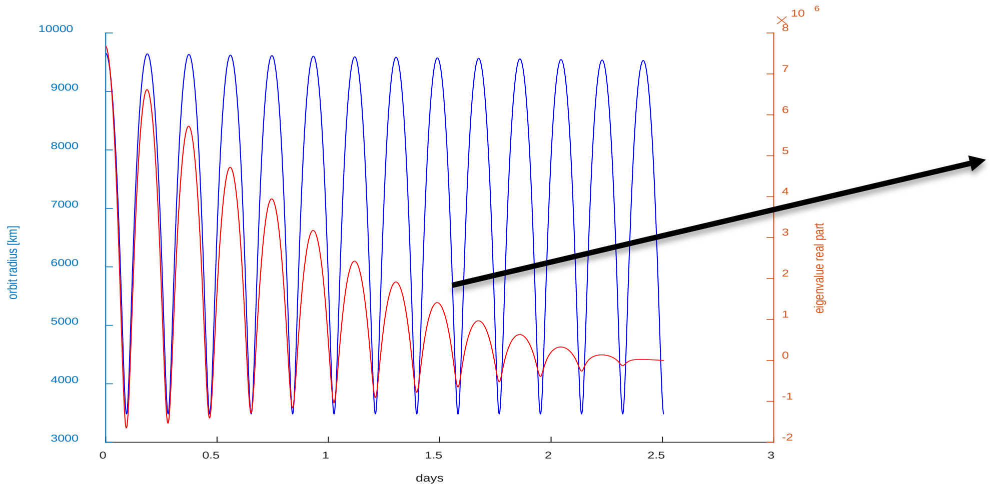
- The change in the periapsis magnitude can be selected by analyzing the density corridor.
- Inputs:
  - Epoch of the periapsis
  - Mars GRAM2005



Running LUPAN (1/5)

From the reference orbit and its STM, LUPAN calculates:

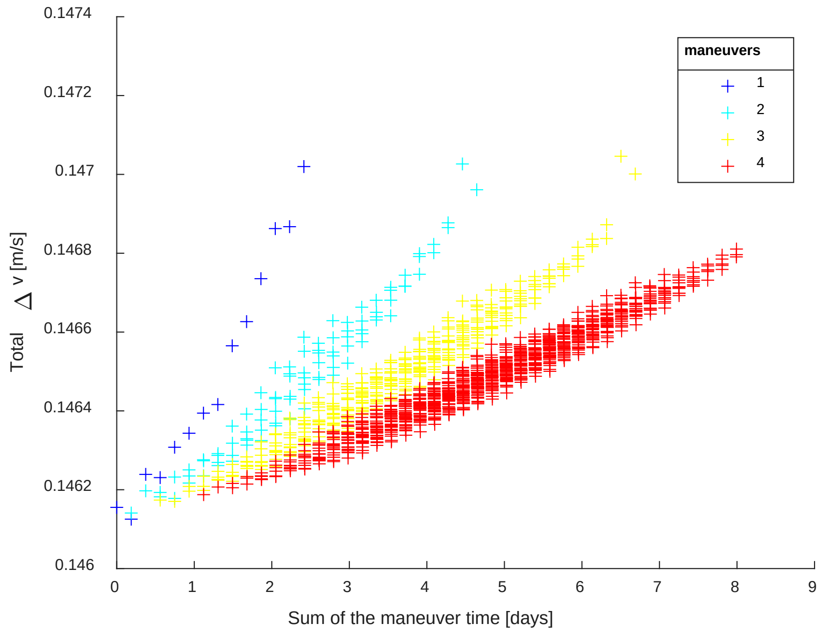
- The sensitivity of the orbit. In the case of MAVEN, how changes in the velocity throughout the orbit impact the last periapsis.



The eigenvalue tells us how stable each trajectory point is with respect to a change in the last periapsis.
Note how the best points align with the apoapsis, which is a known result.

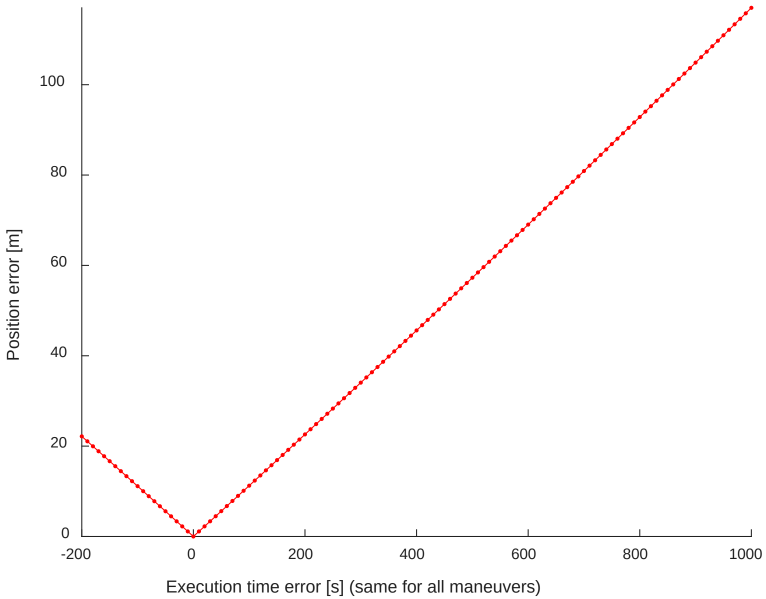
Running LUPAN (2/5)

- It calculates the Poincaré section to the periapsis
- It calculates the "point 2 go" based in a gradient search for the minimum Δv point for the selected density range
- It performs a trade study between all the possible maneuver points and a user set number of maximum impulses
  - In here we use 4 max impulses as an example
  - Calculation can be made using core parallelization
- It outputs the correct epoch for Δv's and final point
  - Correction based on the orbital change made by the Δv

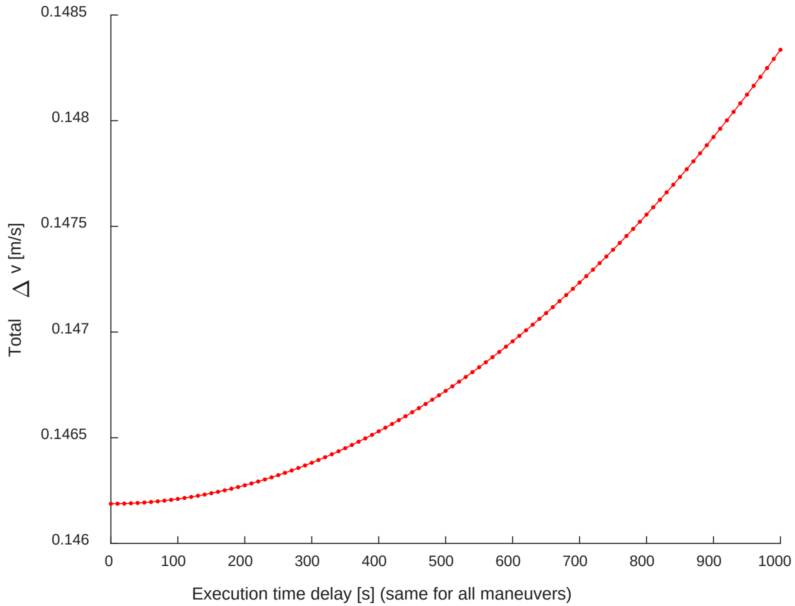


Running LUPAN (3/5)

- It calculates the error due to a delayed execution time.

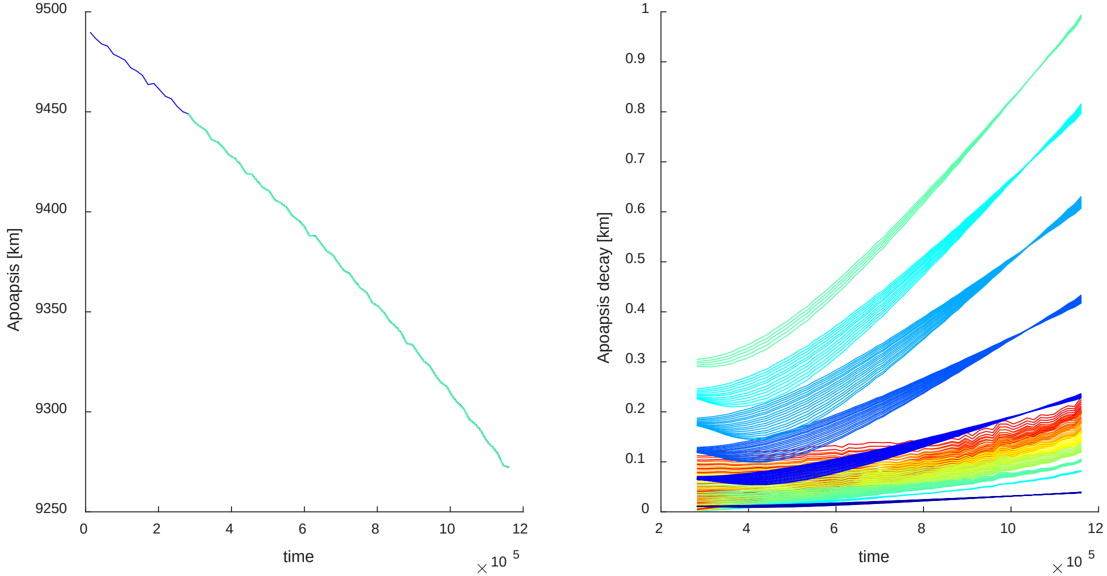


- It calculates the Δv change due to a delayed execution time.



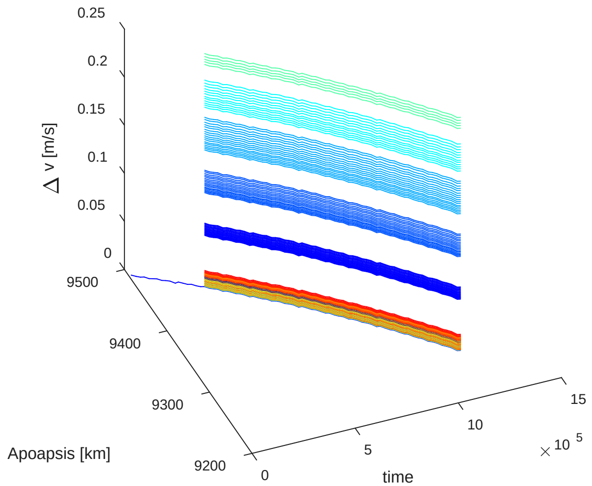
Running LUPAN (4/5)

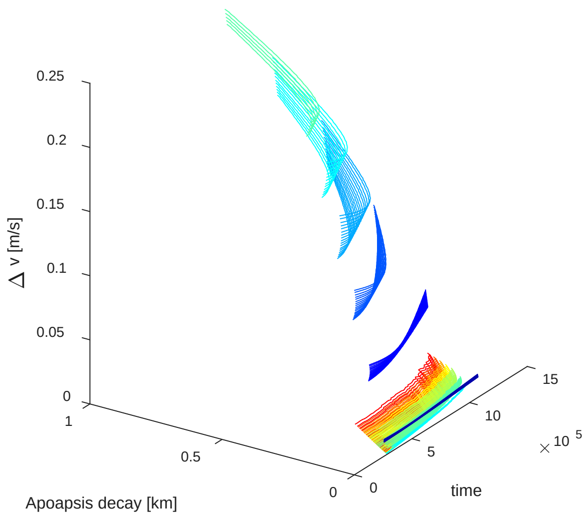
- It calculates the apoapsis decay and required Δv
  - Select the periapsis to be raised or lowered
  - Select allowed time for maneuvers



Running LUPAN (5/5)

- It calculates the apoapsis decay and required Δv
  - Select the periapsis to be raised or lowered
  - Select allowed time for maneuvers (vector of UTC dates)





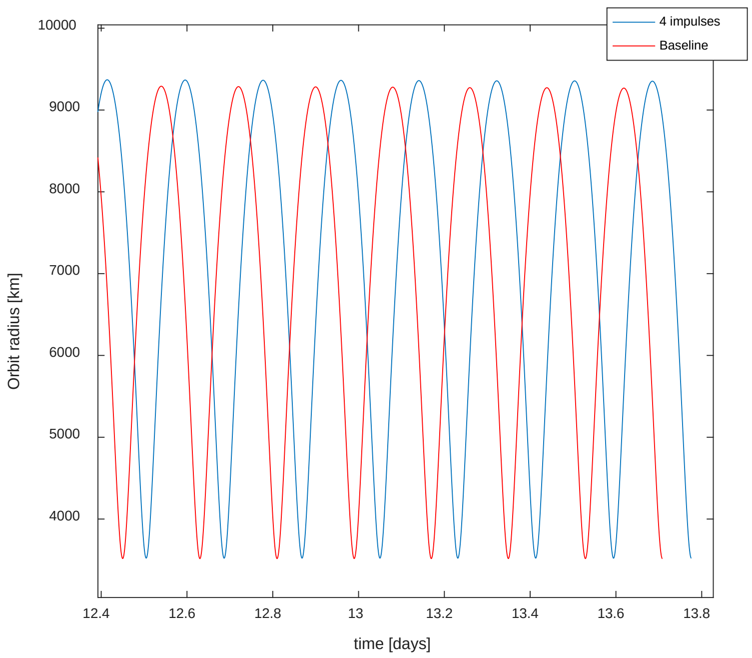
GMAT High-Fidelity Comparison

- Simulation of the best 4 impulses solution provided by LUPAN.

Maneuver time from epoch (s)	ΔVx (m/s)	ΔVy (m/s)	ΔVz (m/s)	|ΔV| (m/s)
12386	-7.441385e-03	4.886937e-02	-0.200887443	0.2068800
28310	-8.068770e-03	4.848910e-02	-0.200164796	0.2061122
44231	-8.561318e-03	4.807098e-02	-0.199550315	0.2054372
60154	-9.156516e-03	4.759759e-02	-0.198963444	0.2047824
			Total (m/s)	**0.8232118**

Targeted: 5.6547 km
Reached: 5.2973 km

Error:
0.35645 km



GMAT High-Fidelity Comparison

- Optimal solution for the selected case

	GMAT	LUPAN	Difference
Δv1 [m/s] **Epoch [s]**	0.22054542788488 12386.219041077	0.206880049824896 12386.219041077	**0.013665378059984** **0**
Δv2 [m/s] **Epoch [s]**	0.218581170914821 28310.327776596	0.206112213017252 28310.327776596	**0.012468957897569** **0**
Δv3 [m/s] **Epoch [s]**	0.2190760067401324 4231.304811217	0.205437202179435 44231.304811217	**0.013638804560697** **0**
Δv4 [m/s] **Epoch [s]**	0.218043174217973 60161.5791768390	0.204782384591256 60153.524327365	**0.013260789626717** **8.0523332962257**
Total Δv [m/s]	0.87624577975781	0.82321184961284	**0.053033930144965**
Periapsis altitude [km] **Epoch [s]**	3521.38636457079 1190515.17876381	3521.3882602503 1192750.25269757	**2.46145424 meters** **37.2512322 minutes**

LUPAN correctly calculates the maneuvers with 10^{-2} m/s precision

General optimizers had difficulty in find the maneuver epochs

LUPAN calculates the maneuvers' epoch to a high degree

Conclusions

- Results show an average of 0.081% error per orbit on the altitude prediction with an accumulated 6% error over 74 orbital revolutions with an analysis on the execution error is presented.
- An aerobrake campaign for MAVEN has been analyzed as an example to show the versatility of the approach. A trade study between 1, 2, 3, and 4 impulsive maneuvers was analyzed for a reference trajectory of 14 days around Mars.
- The method developed for this study has shown to reasonably predict the optimal aerobrake maneuvers (time, direction and magnitude) when compared to a direct optimization method with high-fidelity orbital perturbations.
- Its software implementation permits orders-magnitude faster calculation, allowing it to be used in large searches, such as grid and Monte Carlo.