Dynamical study of the aerobraking technique in the atmosphere of Mars

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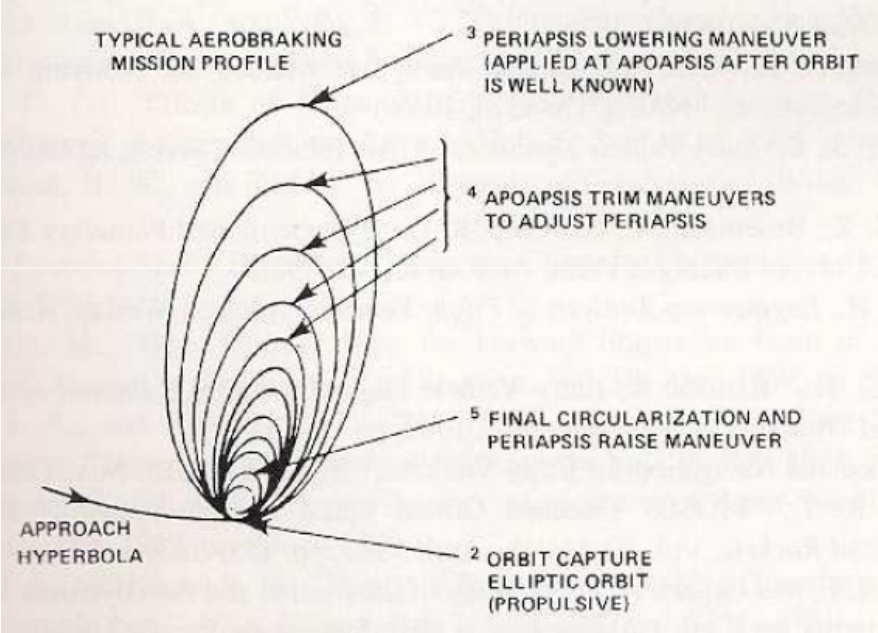
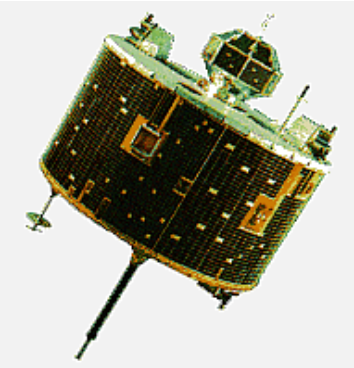
AEROBRAKING SCENARIO



1) Capture to high apocenter orbit.
2) Lower pericenter to the upper atmosphere.
3) Perform aerobraking to lower apocenter.
4) Monitor change in orbit and adjust pericenter via small apocenter maneuvers, to target nominal aerodynamic deceleration expected.
5) Perform small pericenter altitude maintenance maneuvers, if it is requiered.
6) Raise pericenter via small prograde maneuver at apocentre.

AEROASSISTED MANEUVERS IN THE PAST

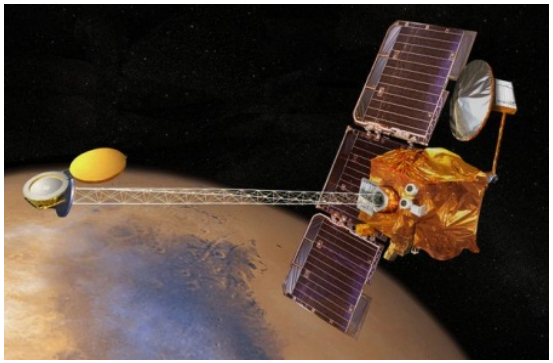
Hiten (Earth)



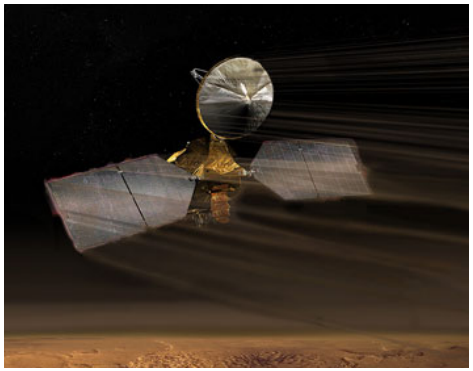
Magellan (Venus)

Mars Global Surveyor

Mars Odyssey



Mars Reconnaisance Orbiter



USE AND ADVANTAGES OF AEROASSISTED MANEUVERS

- Proven technique for reducing speed.
- MGS, Odyssey & MRO used aerobraking at Mars.
- Technically more complicated, longer and operationally more demanding than a fully chemical orbit insertion.
- However, aerobraking strategy is implemented because it allows for large Δv and propellant budget savings for the science orbit acquisition.
- Its use is becoming more and more common and has evolved into the concept of aerocapture (design of missions to the outer planets that can only be achieved with this technique)

Scope of the present investigation

- Time to maneuver completion.
- Orbital elements evolution under typical aerobraking scenarios.

The dynamical model includes:

- Central body gravitational attraction.
- Atmospheric drag and atmospheric density model.
- Third body gravitational effect of Sun and Jupiter.
- Radiation pressure: direct solar, albedo, and planetary thermal.

Dynamical model: Gravity field

$$V(r,\varphi,\lambda)=GM/r\sum_{n=0}^{\infty}(a/r)^n\sum_{m=0}^{n}P_{nm}(\sin\varphi)(C_{nm}\cos m\lambda+S_{nm}\sin m\lambda)$$

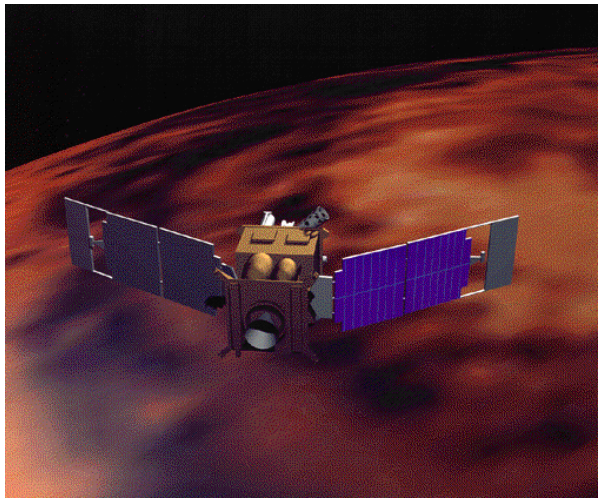
- Stokes coefficients model from MRO Gravity / Radio Science Field Investigation (Doppler shift data) [Zuber et al., 2007][Konopliv et al., 2011]
- Complete to degree and order 95.
- Singularity of acceleration at the poles eliminated by Pines formulation of V and its gradients:

$$V(P)=V(s,t,u,r)=\sum_{n=0}^{N}\rho_n\sum_{m=0}^{n}D_{nm}(s,t)H_{nm}(u)$$

Dynamical model: Atmospheric drag

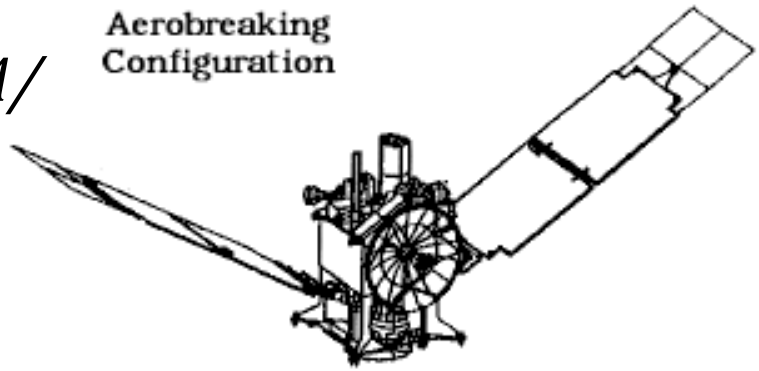
- Acceleration produced by drag:

$$\boldsymbol{a_{AD}} = -1/2 \; C_D \, A/m \; \rho \, |v_{rel}| \, \boldsymbol{v_{rel}} / |v_{rel}| .$$



- Lift is not considered for this study.
- Drag coefficient C_D and the ratio A/m are those of Mars Global Surveyor:

$$C_D = 2{,}0, \quad A/m = 2 \cdot 10^{-2}$$



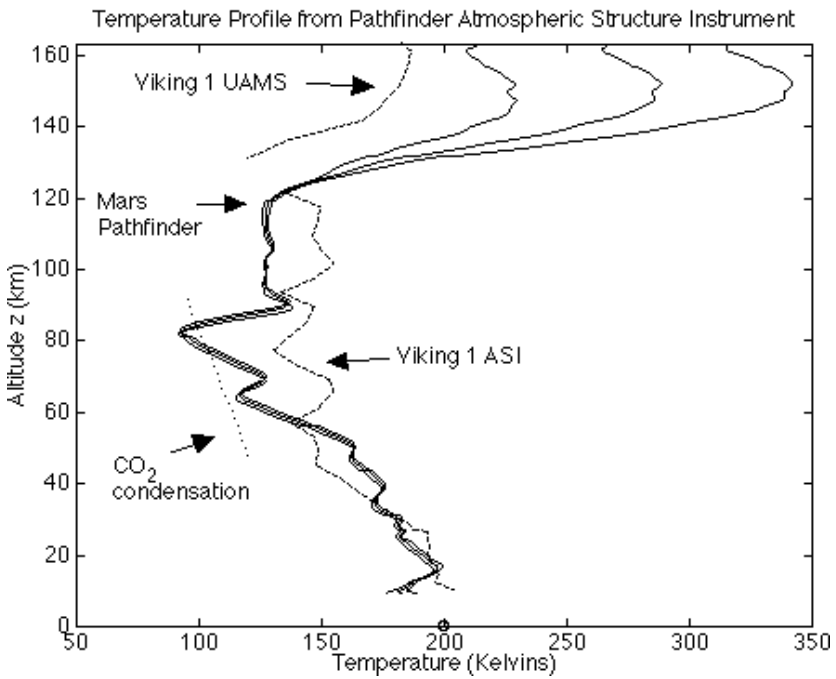
MODEL ATMOSPHERE

$$T = -23{,}4 - 0{,}00222h \qquad [°]$$

$$p = 0{,}699 \cdot e^{\uparrow} - 0{,}00009 \cdot h \qquad [KPa]$$

$$\rho = p/[0{,}1921 \cdot (T + 273{,}1)] \qquad [kg/m^{\uparrow}3\ ]$$

- This model T [Mars atmosphere model, Glenn Research Center] is valid for h < 81 km.
- At higher h, T is modeled using linear expressions based on the temperature profile measured by Mars Pathfinder.
- From 120 km we use six different temperature profiles.



Dynamical model: Radiation pressure

- Acceleration due to radiation pressure:

$$\boldsymbol{a}_{RP} = -p_R\, C_R\, A\, \boldsymbol{r}/m \quad |r|$$

- Solar direct contribution.
- Planetary thermal (IR) radiation: although Mars has little greenhouse effect, we have simplified treatment by assuming that the atmosphere radiates uniformly.
- Albedo radiation.

$$C_R = 1{,}5 \qquad a_{albedo} = 0{,}25$$

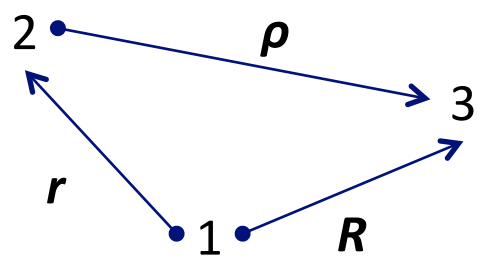
$$A/m = 2 \cdot 10^{-2}$$

DYNAMICAL MODEL: THIRD-BODY PERTURBATIONS

- Model used to calculate the acceleration produced by the third body:

$$\boldsymbol{a}_{TB} = \mu' \left(\boldsymbol{\rho}/\rho^3 - \boldsymbol{R}/R^3 \right)$$

- μ' = gravitational parameter of the third body
- $\boldsymbol{\rho}$ and $\boldsymbol{R}$:



- We have considered Jupiter and the Sun

SCOPE OF THE PRESENT INVESTIGATION

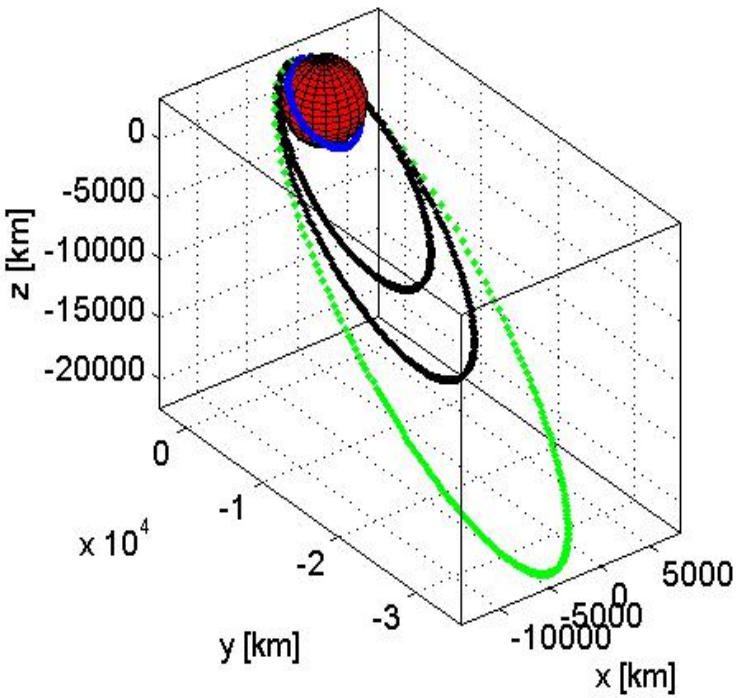
In particular, we have investigated the influence of:

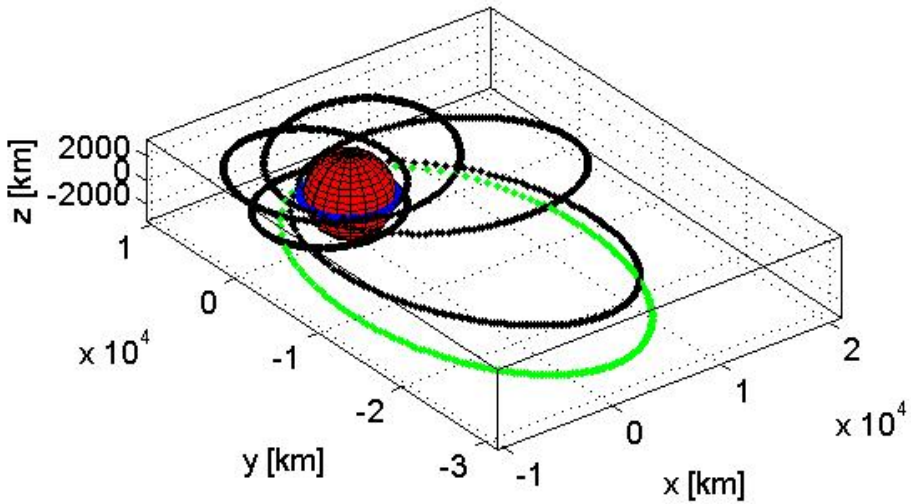
- The choice of the limit density on the computation of the atmospheric drag.
- The final eccentricity on the outcome of the simulations.
- The orbital perturbations and their mutual interactions on the total maneuver time, from entry to final circularization.

Finally, we have estimated the propellant savings in a typical mission as an alternative to the direct insertion into the final, circular orbit.

SIMULATIONS

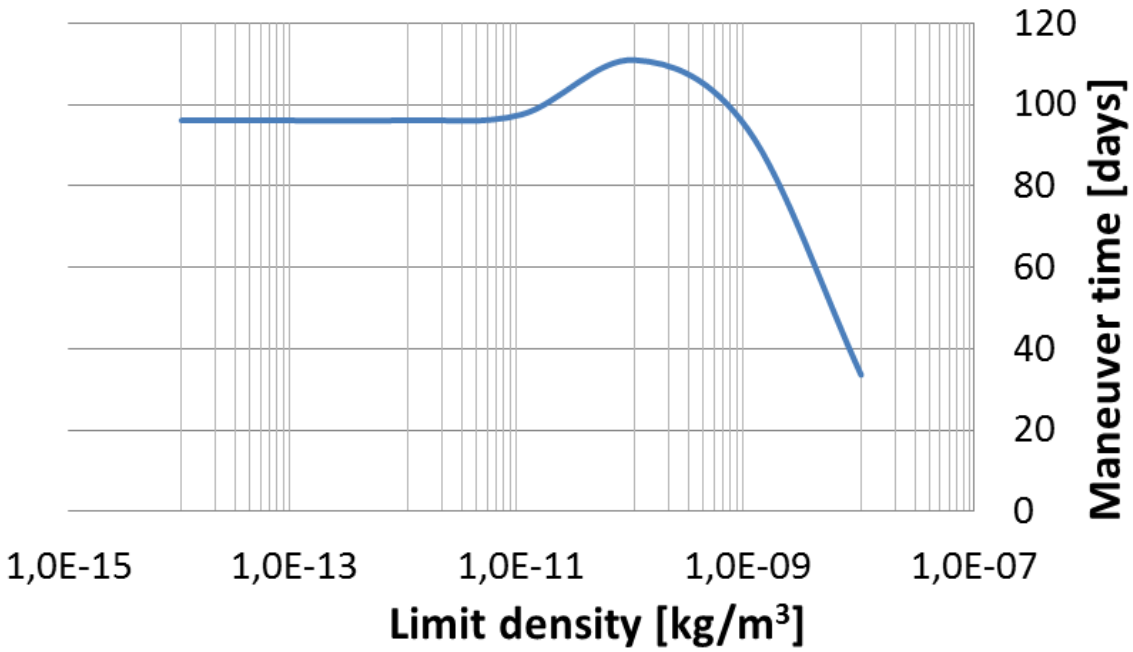
We have simulated several sets of initial conditions (orbital parameters) both in the equatorial plane and with inclination:



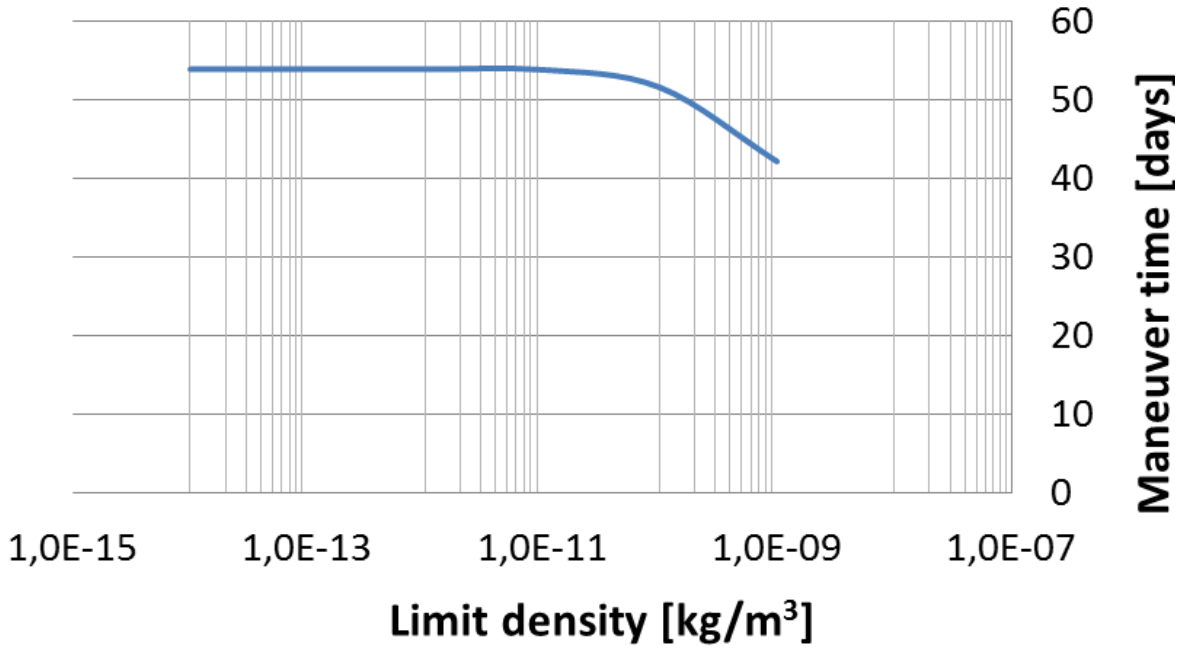


LIMIT DENSITY

An important simulation parameter is the limit density: we integrate the trajectory without considering the effect of drag for all heights above that associated to the limit density.



Pericenter height [km]	145
Inclination [°]	0
Initial eccentricity	0,8
Final eccentricity	$10\uparrow-2$

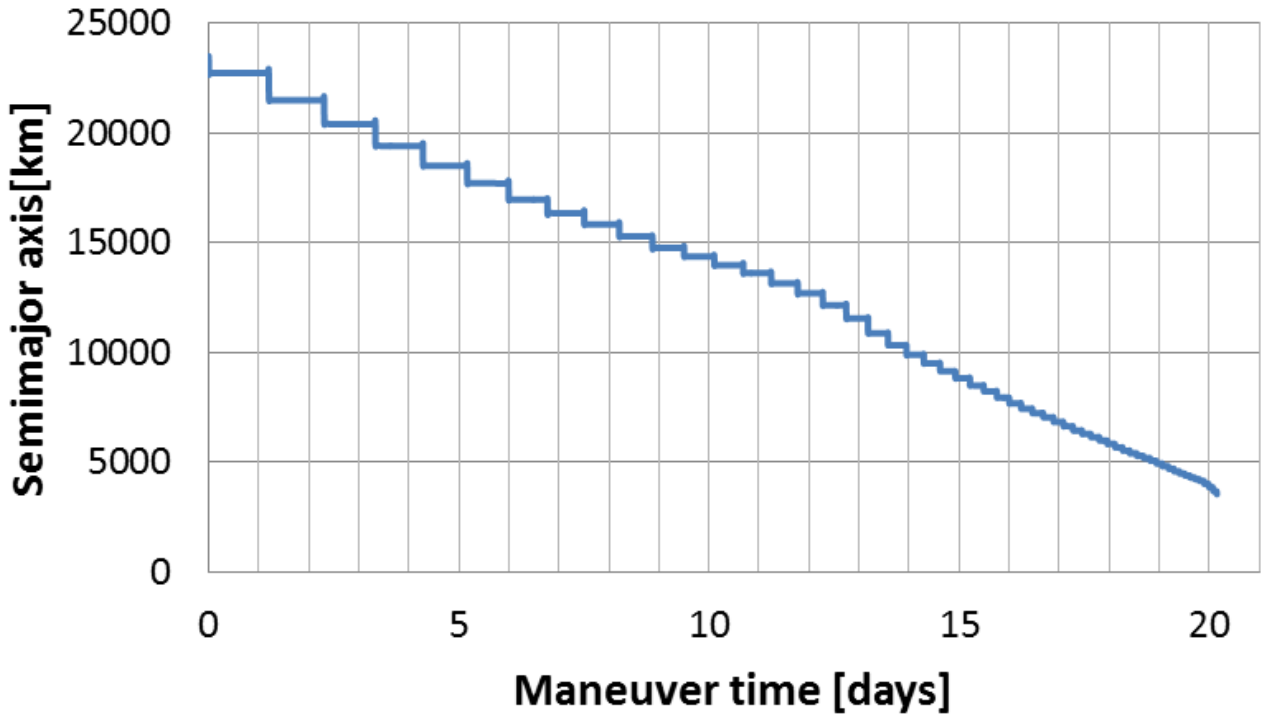


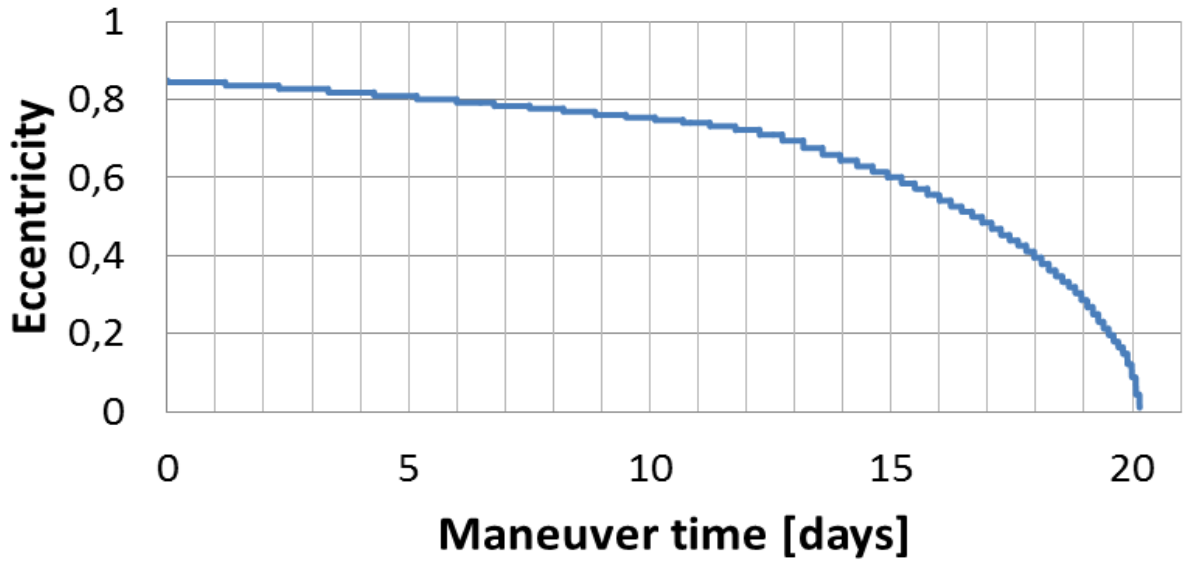
Pericenter height [km]	140
Inclination [°]	0
Initial eccentricity	0,8
Final eccentricity	10^{-2}

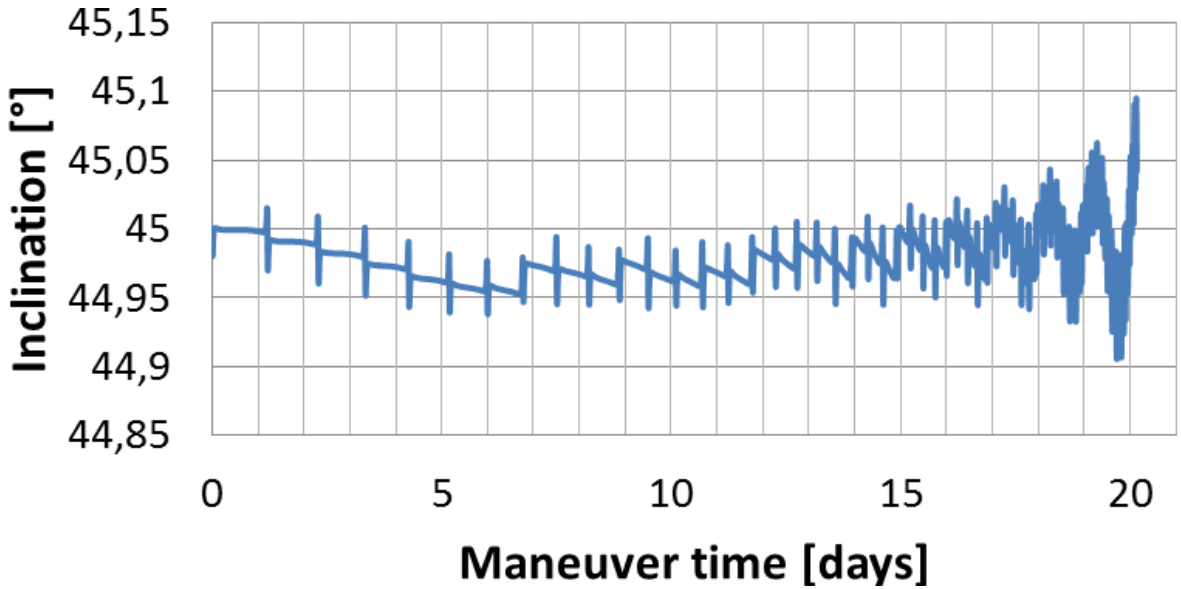
- For $\rho \leq 10^{-11}$ kg/m^3 the time to circularization is unaffected and stays constant for a given set of initial conditions.

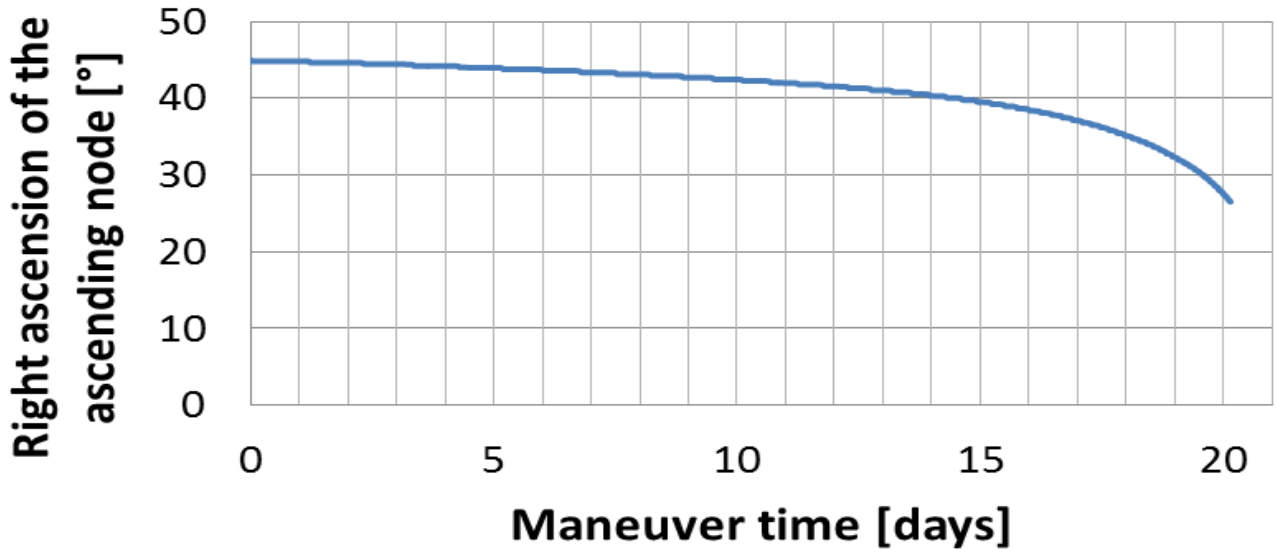
EVOLUTION OF THE ORBITAL ELEMENTS

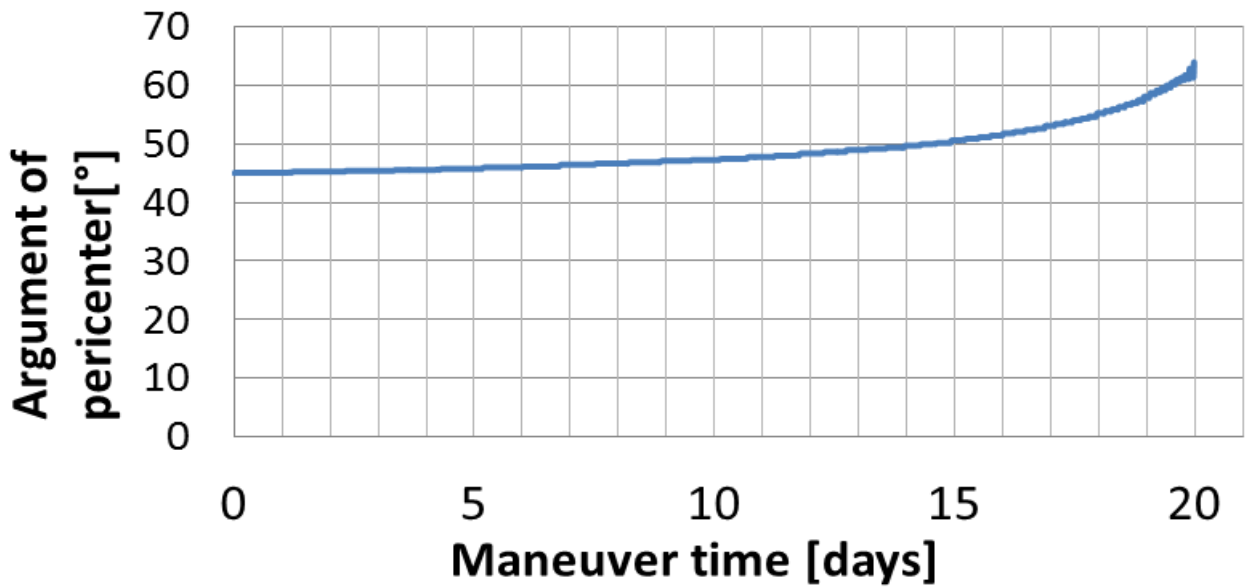
The orbital elements evolve and exhibit oscillations, result of the composition of different sources of excitation which affect the orbit on different time scales.




Eccentricity
1
0,8
0,6
0,4
0,2
0
0
5
10
15
20
Maneuver time [days]

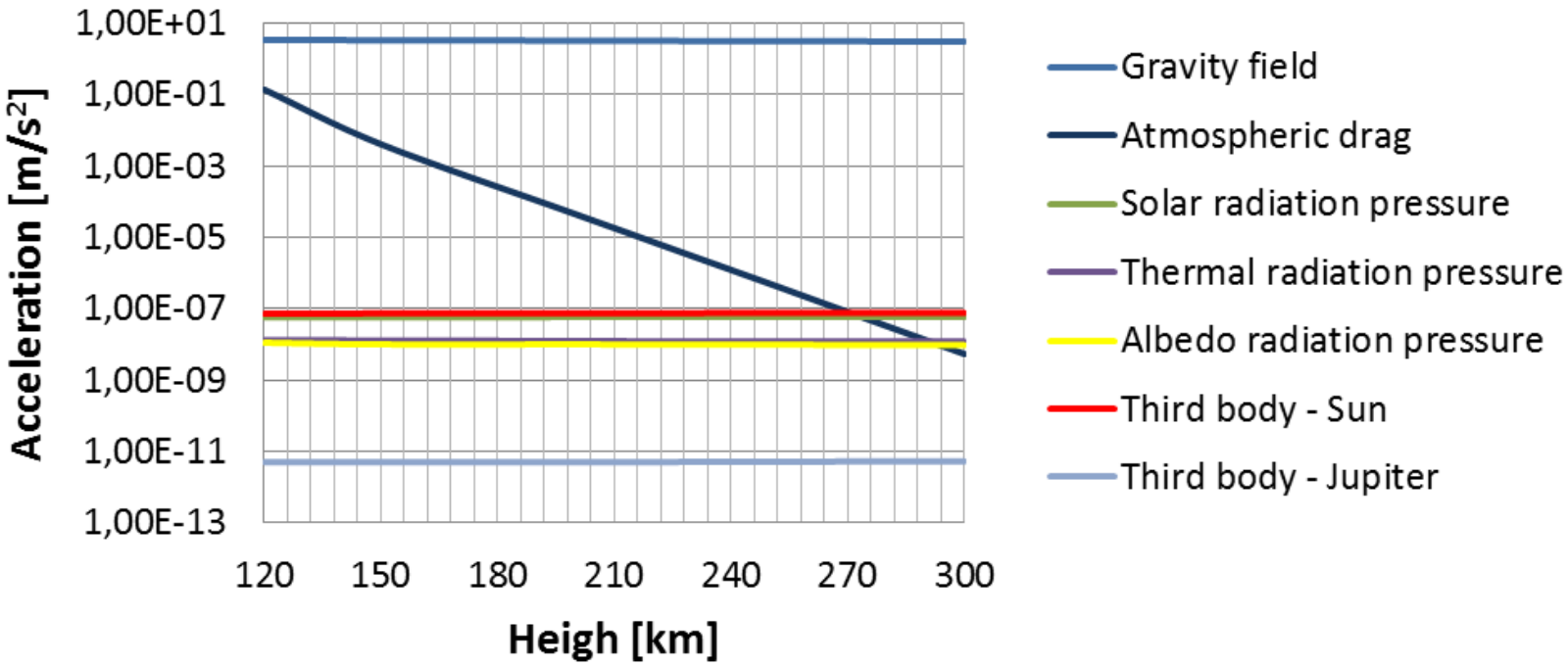

Inclination [°]
45,15
45,1
45,05
45
44,95
44,9
44,85
0
5
10
15
20
Maneuver time [days]

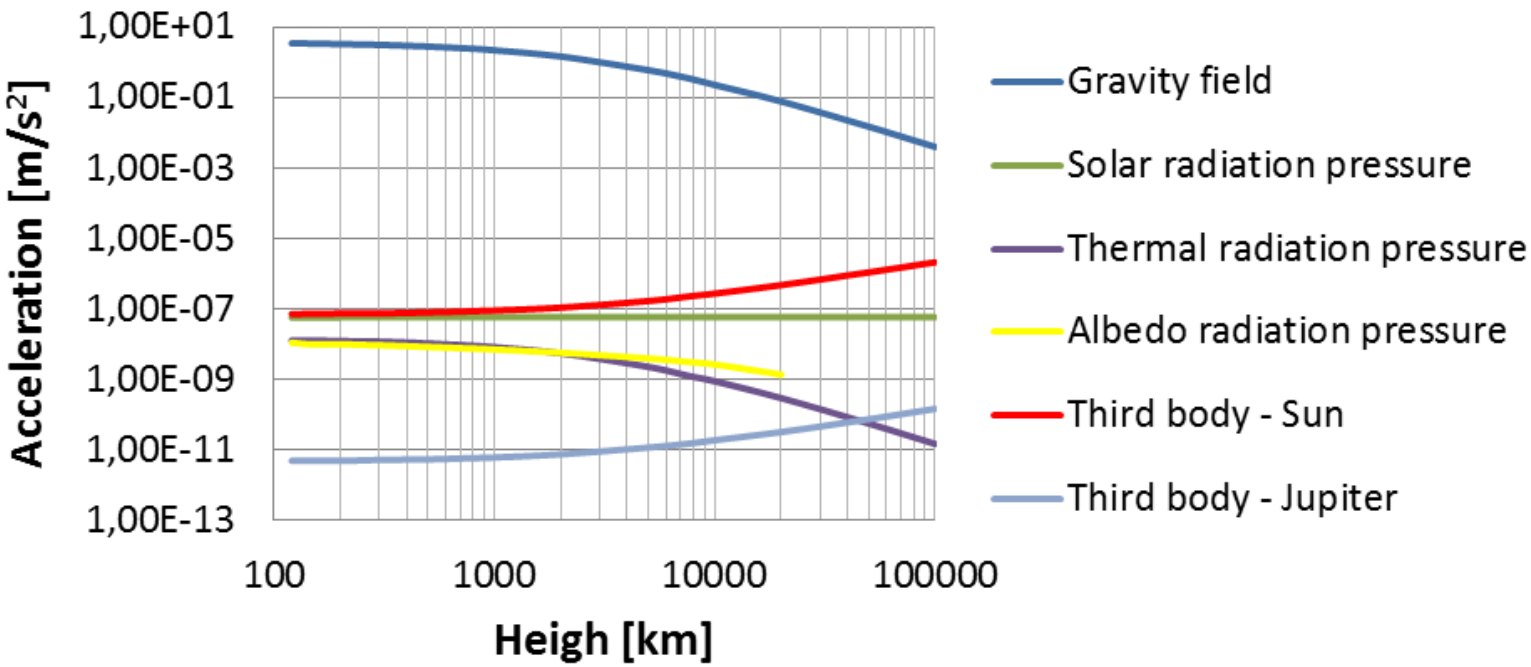

Right ascension of the ascending node [°]
50
40
30
20
10
0
0
5
10
15
20
Maneuver time [days]


Argument of pericenter[°]
70
60
50
40
30
20
10
0
0
5
10
15
20
Maneuver time [days]

EFFECT OF THE ORBITAL PERTURBATIONS

- It is important to know the behavior of each perturbation separately.
- We studied them as functions of altitude above the surface.





- Thermal and albedo radiation pressures and Jupiter's third body effects are small.
- However, the longer the maneuver the more important these perturbations become, up to the point in which they are no longer negligible and cannot be excluded from the computations.

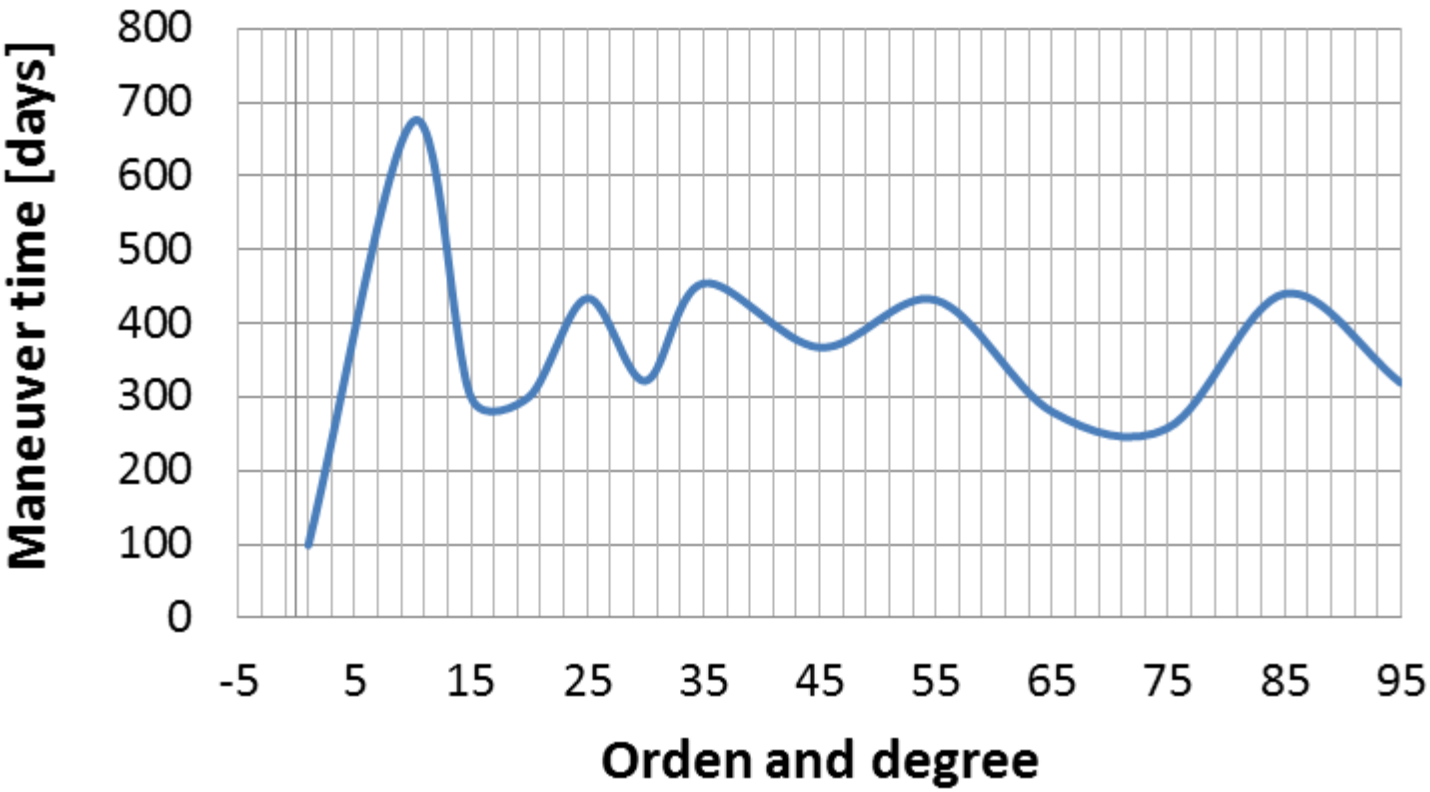
- Several simulations of the same initial conditions under different combinations of the dynamical perturbations:

Orbital perturbations	Atmospheric model	Gravitational model	Maneuver time [days]
Activated	Exponential	Complete	108,9
Activated	Exponential	Keplerian	69,32
Activated	Complete	Keplerian	98,8
Deactivated	Exponential	Keplerian	71,24
Deactivated	Complete	Keplerian	113,28
Deactivated	Exponential	Complete	60,52
Deactivated	Complete	Complete	169,59
Activated	*Complete*	*Complete*	**319,18**

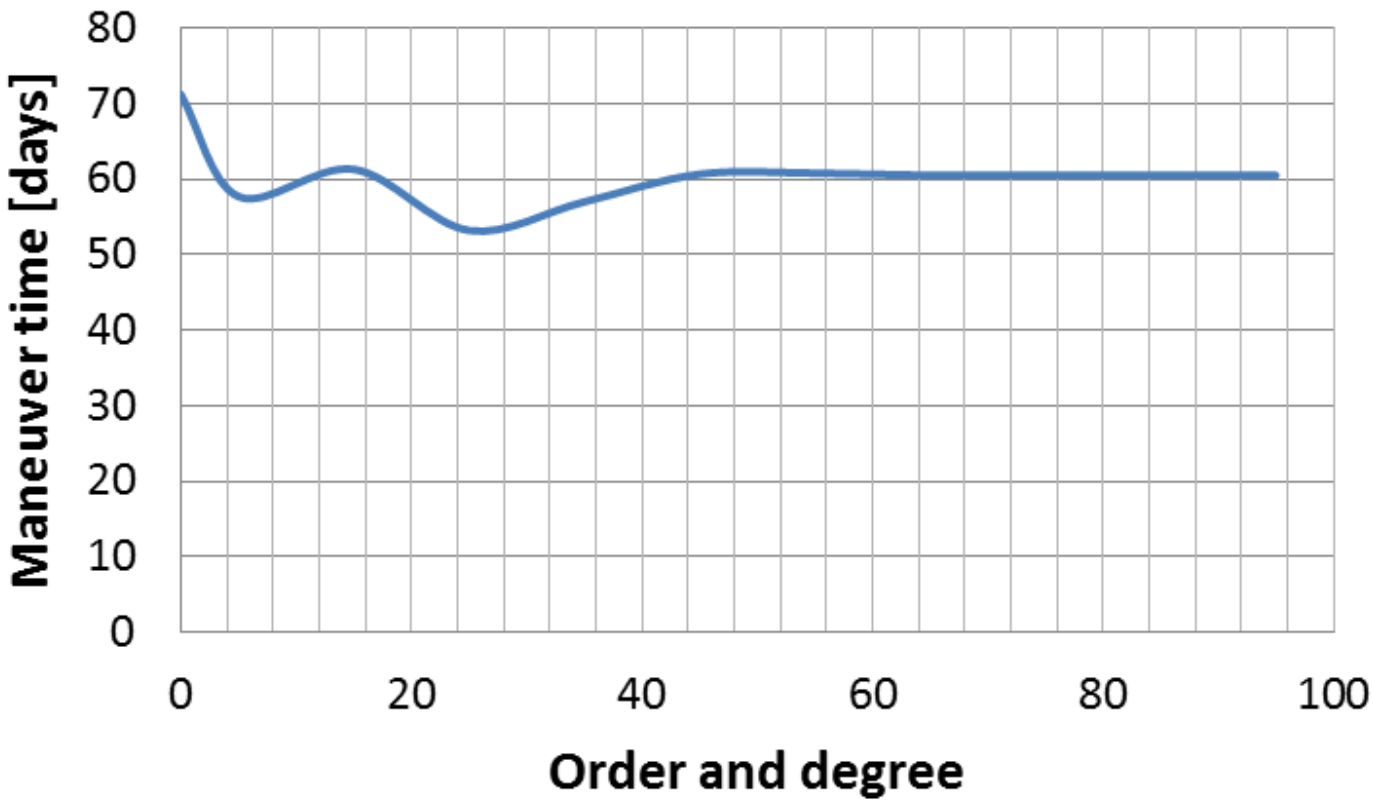
- A comparison of maneuver time for simulations with a complete gravitational model (95 x95), a complete atmosphere model and one perturbation deactivated:

Perturbation deactivated	Maneuver time [days]
Third body – Jupiter	256,1
Third body - Sun	75,93
Thermal radiation pressure	272,8
Albedo radiation pressure	375,7
Solar radiation pressure	91,2
All perturbation activated	**319,18**

- Comparison of maneuver time of simulations with the full perturbation model and increasing resolution of the gravity field:

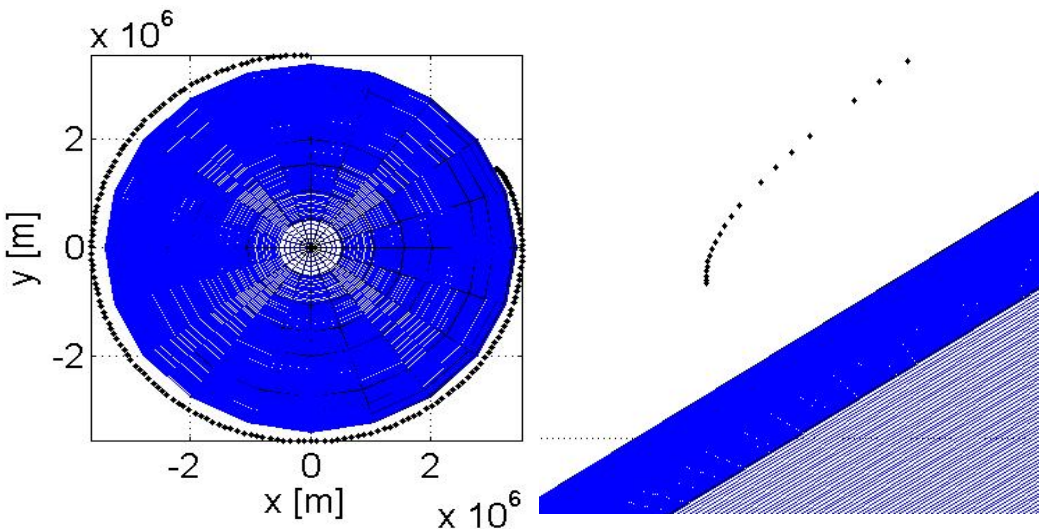


- Comparison of maneuver time of simulations with perturbation deactivated, exponential atmosphere and increasing resolution of the gravity field:



Effect of the limit eccentricity

- Choosing too low a value of the limit eccentricity makes the simulation fail.
- It is important to perform a tradeoff analysis to select this value.



Pericenter height [km]	135
Inclination [°]	0
Initial eccentricity	0,8
Final eccentricity	$1{,}0991 \cdot 10^{-2}$

PROPELLANT SAVINGS

- The difference in Δv between a direct insertion into a circular orbit, with pericenter altitude of $140\ km$, and insertion into an orbit for aerobraking maneuver with pericenter altitude of $140\ km$ and eccentricity of $0{,}8$, is about $1{,}3\ km/s$.

$$m_{propellant} = m_{spacecraft} \cdot \left(1 - e^{-\Delta v / I_{SP} \cdot g}\right) \approx 350\ kg$$

- This value is obtained by considering I_{SP} of $315\ s$, typical of chemical bipropellant engines.

CONCLUSIONS

- If the limit density is lower than 10^{-11} kg/m^3, we are neglecting important atmospheric layers which would significantly affect the orbital evolution.
- Thermal and albedo radiation pressures and Jupiter third body effects are small.
- We cannot oversimplify the model by reducing it to Keplerian central force field with a simple exponential atmosphere because the timescale of the maneuver is large and all perturbations act significantly
- Tradeoff analysis to select the value of the limit eccentricity.
- Propellant savings allow reduced launch mass, which translate into savings in launch system costs.

THANK YOU FOR YOUR ATTENTION