POLITECNICO
MILANO 1863

6th International Conference on Astrodynamics Tools and Techniques

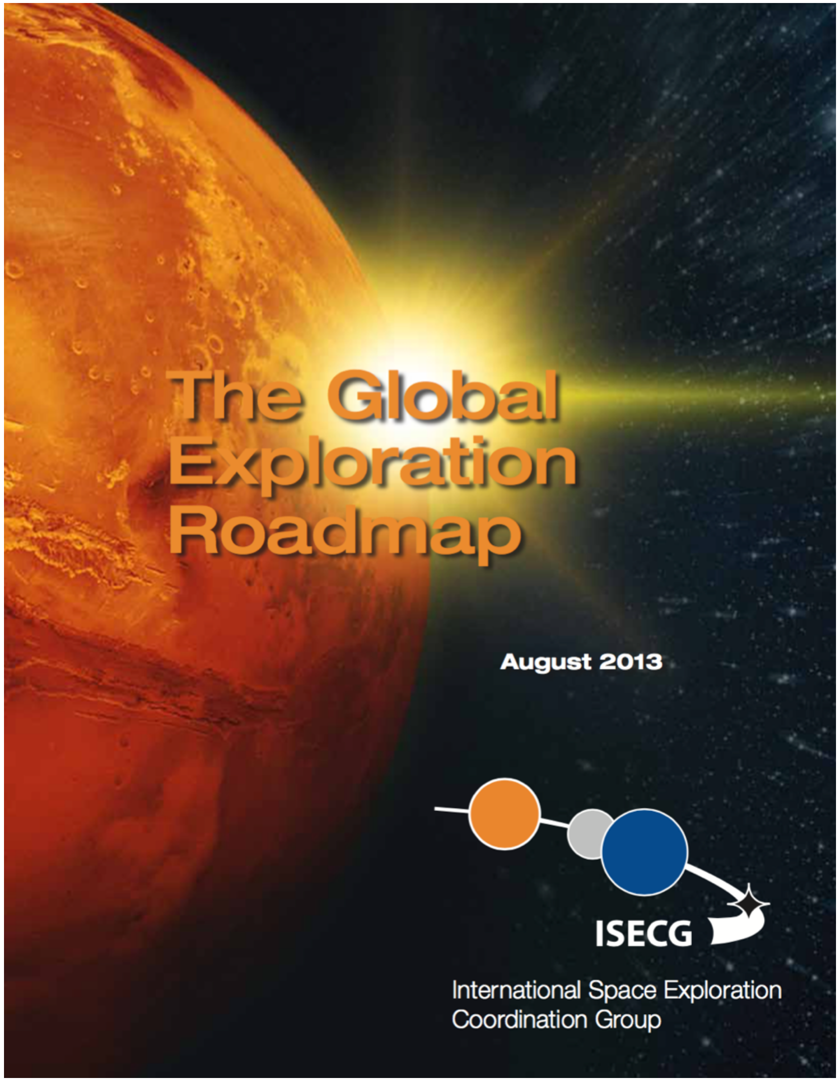
Dynamical Analysis of Rendezvous and Docking with Very Large Space Infrastructures in Non-Keplerian Orbits

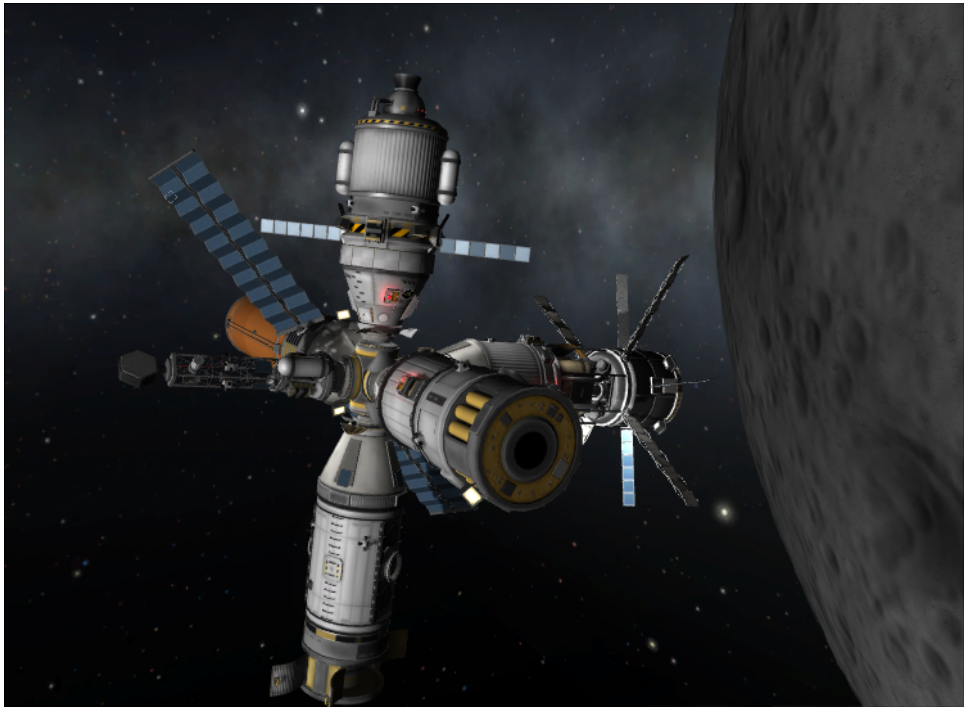
Andrea Colagrossi, Michèle Lavagna and Simone Rafano Carnà
Department of Aerospace Science and Technology

Darmstadt, 17th March 2016

Framework of Present Work

Framework of Present Work





Courtesy of International Space Exploration Group and Kerbal Space Program.

POLITECNICO
MILANO 1863

Scope of Present Work

Scope of Present Work

- Definition of a possible rendezvous scenario with a large space infrastructure in Non-Keplerian orbit
  - Dynamical Analysis performed with a simulation tool that includes a coupled orbit-attitude model in a Circular Restricted 3 Body Problem (CR3BP) environment and the flexibility of the structure
- Optimization of rendezvous manoeuvres: transfer and proximity phases
- Preliminary analysis on the effects of flexibility on the coupled dynamics in non-Keplerian orbit
- Preliminary implementation of an astrodynamics tool able to deal with flexible large structures in cis-lunar space

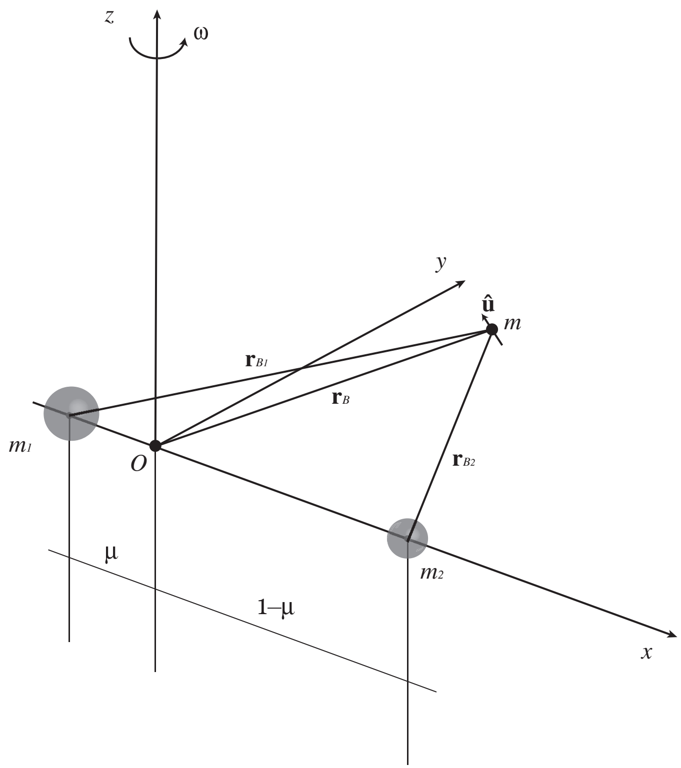
POLITECNICO MILANO 1863

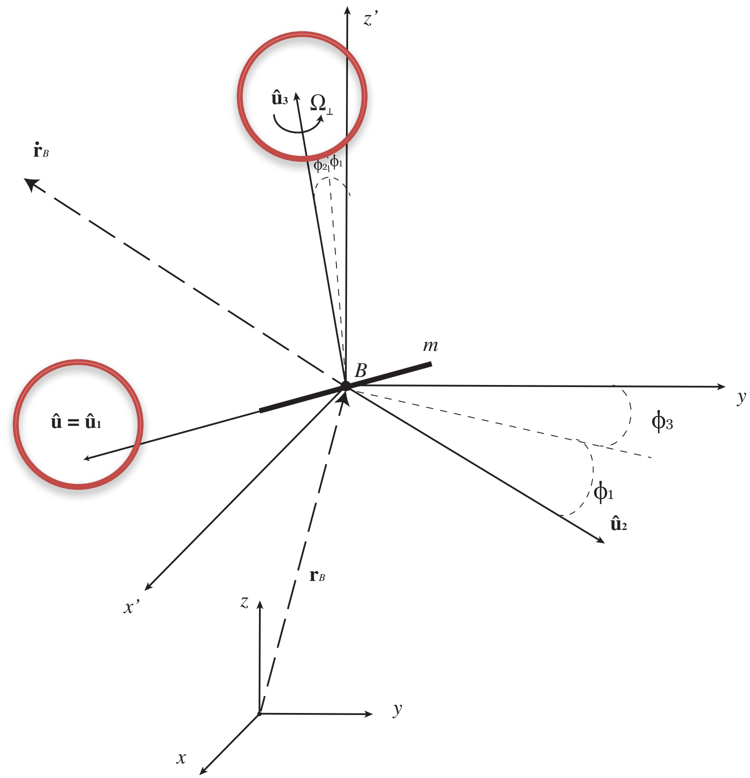
Theoretical Background

Dynamics in CR3BP

The simulation tool is developed exploiting a "Multi-Body-Friendly" approach; with the idea of further extensions and refinements.

Lagrangian Formulation in the Synodic Reference Frame





Dynamics in CR3BP

$$\mathcal{L} = \mathcal{T} - \mathcal{G}$$

$\mathcal{T}$ kinetic energy

$\mathcal{G}$ generalized potential

$$\mathcal{T} = \frac{1}{2} m \dot{\vec{r}}_B \cdot \dot{\vec{r}}_B + \frac{1}{2} \mathbf{\Omega} \cdot \mathbf{I}_B \cdot \mathbf{\Omega}$$

$$\mathcal{G} = V_{g_1} + V_{g_2} + V_i$$

Effect of finite dimension of the body

$$V_{g_i} = -\frac{G m_i m}{r_{B_i}} + \frac{G m_i}{r_{B_i}^3} \left[\frac{3}{2} (\hat{\mathbf{r}}_{B_i} \cdot \mathbf{I}_{B_i} \cdot \hat{\mathbf{r}}_{B_i}) - \mathrm{tr}(\mathbf{I}_B) \right]$$

$$V_i = \frac{m}{2} \mathbf{r}_B \cdot [\boldsymbol{\omega} \times (\boldsymbol{\omega} \times \mathbf{r}_B) + 2\boldsymbol{\omega} \times \dot{\mathbf{r}}_B] - \frac{1}{2} \boldsymbol{\omega} \cdot \mathbf{I}_B \cdot (\boldsymbol{\omega} + 2\mathbf{\Omega})$$

Influence of the Extended Body

The large space infrustructure has been modeled as a rigid rod of length, l , and non-dimensional length $\epsilon_0 = l/r_{12}$

The lagrangian function can be expressed as

$$\mathcal{L} = \mathcal{L}_0 + \epsilon_0^2 \mathcal{L}_2 + \epsilon_0^3 \mathcal{L}_3 + \dots$$

Reducing $\mathcal{L}$ to the main order, the size of the rod disappears from the problem

In this analysis $\mathcal{L}$ has been limited to the second order

The equations of motion are written in non-dimensional form (usual CR3BP non-dimensional formulation)

Equations of Motion

$$\frac{d}{d\tau}\left(\frac{\partial \mathcal{L}_0}{\partial \dot{x}}\right) - \frac{\partial \mathcal{L}_0}{\partial x} = \epsilon_0^2 \frac{\partial \mathcal{L}_2}{\partial x}$$

$$\frac{d}{d\tau}\left(\frac{\partial \mathcal{L}_0}{\partial \dot{y}}\right) - \frac{\partial \mathcal{L}_0}{\partial y} = \epsilon_0^2 \frac{\partial \mathcal{L}_2}{\partial y}$$

$$\frac{d}{d\tau}\left(\frac{\partial \mathcal{L}_0}{\partial \dot{z}}\right) - \frac{\partial \mathcal{L}_0}{\partial z} = \epsilon_0^2 \frac{\partial \mathcal{L}_2}{\partial z}$$

$$\frac{d}{d\tau}\left(\frac{\partial \mathcal{L}_2}{\partial \dot{\theta}}\right) - \frac{\partial \mathcal{L}_2}{\partial \theta} = 0$$

$$\frac{d}{d\tau}\left(\frac{\partial \mathcal{L}_2}{\partial \dot{\varphi}}\right) - \frac{\partial \mathcal{L}_2}{\partial \varphi} = 0,$$

More convenient to describe attitude motion with Newton-Euler formulation:
1-2-3 Euler angles are used

$$\frac{d\,\mathbf{h}_B}{dt} = \mathbf{m}_B$$

$$\mathbf{h}_B = I_B \Omega_\perp \hat{\mathbf{u}}_3$$

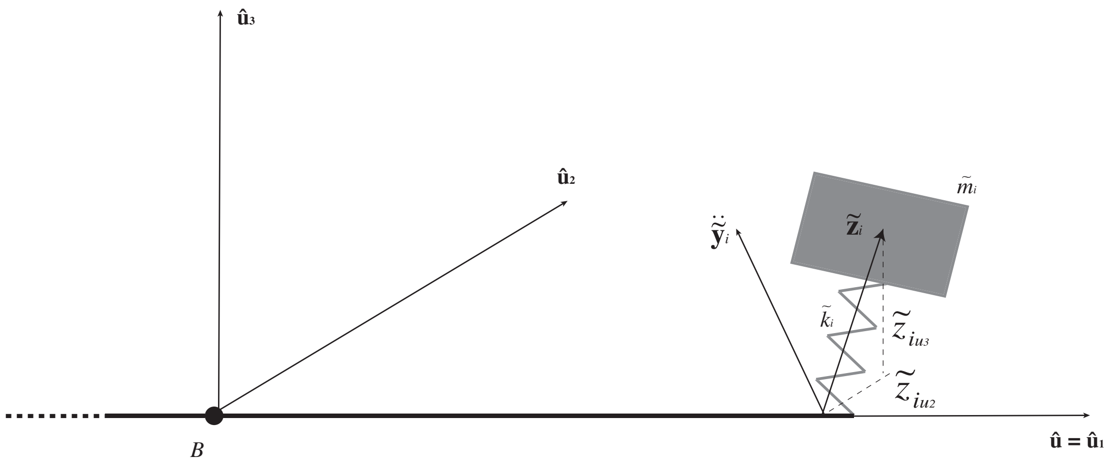
$$\Omega_\perp = |\hat{\mathbf{u}} \times \dot{\hat{\mathbf{u}}}| = |\dot{\hat{\mathbf{u}}}|$$

Flexible Dynamics

Flexibility is currently inserted in the model with a lumped parameters technique: spring-mass systems representing <u>pseudo-mode of vibrations</u>.

$$\tilde{m}_i(\ddot{\tilde{\mathbf{z}}}_i + \ddot{\tilde{\mathbf{y}}}_i) + \tilde{k}_i \tilde{\mathbf{z}}_i = 0$$

$$\tilde{k}_i = \tilde{\omega}_i^2 \tilde{m}_i$$



$\tilde{z}_{iu_1} = 0$: Spring-Mass constrained to be orthogonal to the rod

Torque exerted on the rod

$$\mathbf{m}_{B_{k\,i}} = l_i \hat{\mathbf{u}}_1 \times \tilde{k}_i \tilde{\mathbf{z}}_i$$

POLITECNICO
MILANO 1863

Rendezvous Definition

State of the Art

- Autonomous rendezvous in CR3BP is in a preliminary study phase
- Proposed strategies often exploit invariant manifolds: low-cost transfer capabilities
- Existing studies are focused on point-mass spacecrafts (Lizy-Destrex, Murakami et al., Ueda et al.)
- Possible rendezvous strategies (Koon et al).
  - HOI – Halo orbit insertion (Halo To Halo)
  - MOI – Stable manifold orbit insertion (Transfer to Halo)

Proposed Rendezvous Strategy

Departure: the chaser is injected in a unstable manifold of the parking orbit with a first manoeuvre, Δv_1.

Switching: the chaser is injected, Δv_2, in the stable manifold of the target's operational orbit. The injection point is at the intersection of unstable and stable manifolds.

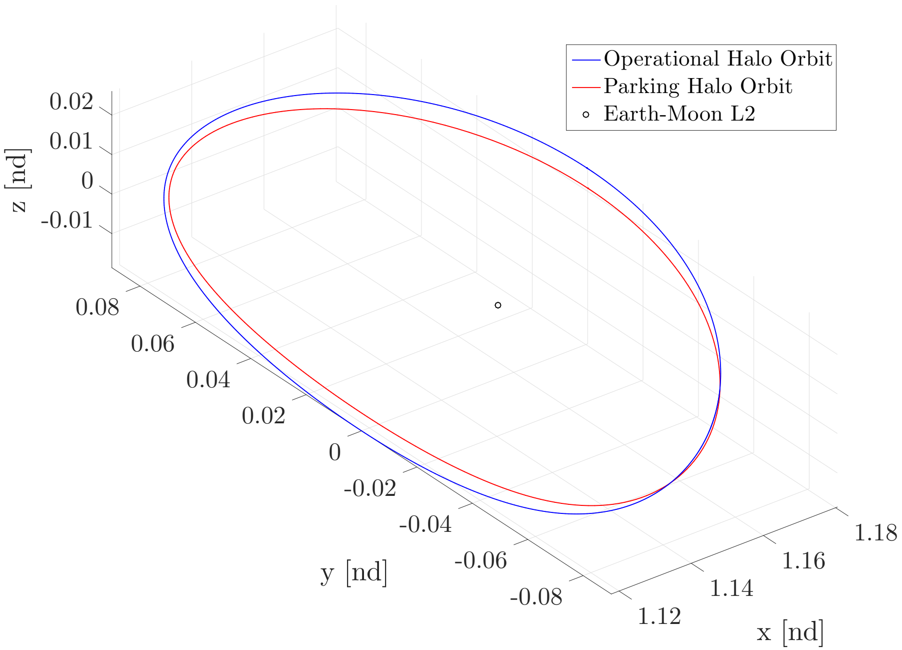
Approach: the chaser arrives in proximity of the target and it is moved very close to the operational Halo orbit, Δv_3.

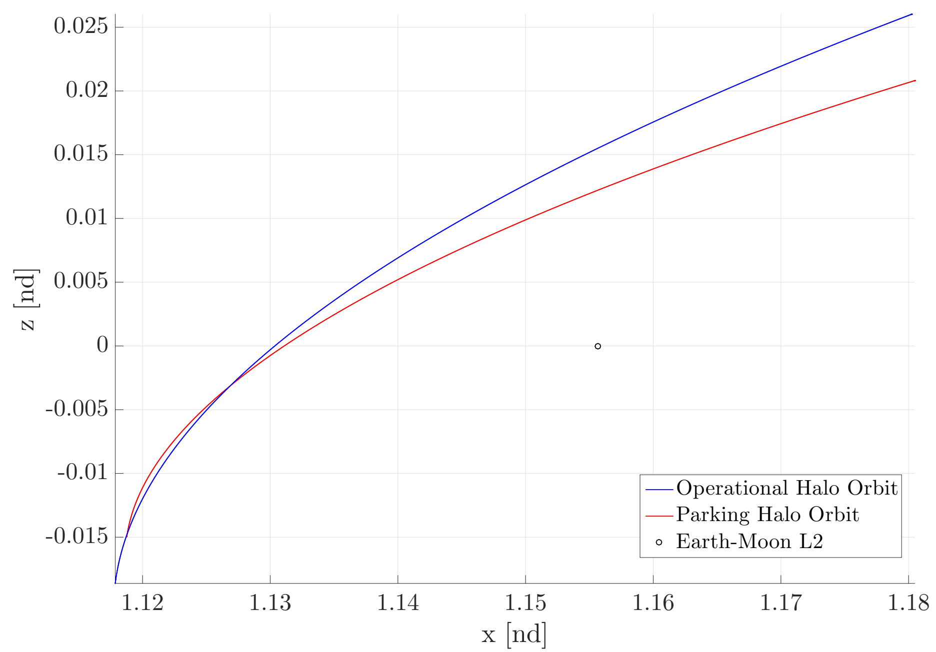
Closing: Δv_4 aligns the chaser with the docking axis of the space station.

Final approach: Δv_5 and Δv_{51} progressively reduce the relative distance between chaser and target. The chaser is maintained aligned with the the docking axis of the target, which is rotating.

Mating: a continuous Δv_6 reduces to zero the relative distance between the two spacecrafts and brings the chaser at the docking port

Operational and Parking Halo Orbit





Orbit	A_z [km]	T [D]	C [-]
Operational Halo	10000	14.808	3.149
Parking Halo	8000	14.813	3.150

Rendezvous Scenario

- Intersection between manifolds (switching point) is assumed to be in the space between Moon and Earth: $x_{sp} = 1 - \mu$
  - The position of the switching point is a free parameter in the rendezvous optimization tool
  - The region where the algorithm look for the switching point is an input from the user
  - Hypothetical mission with a cyclic chaser between parking and operational Halo orbit. (Possibility to ecounter a cargo coming from Earth, Moon or LLO)
- Chaser is a point mass
- Target (space station) is an extended body

	m_T [kg]	l_T [m]
Target	300000	100

POLITECNICO
MILANO 1863

Rendezvous Simulation

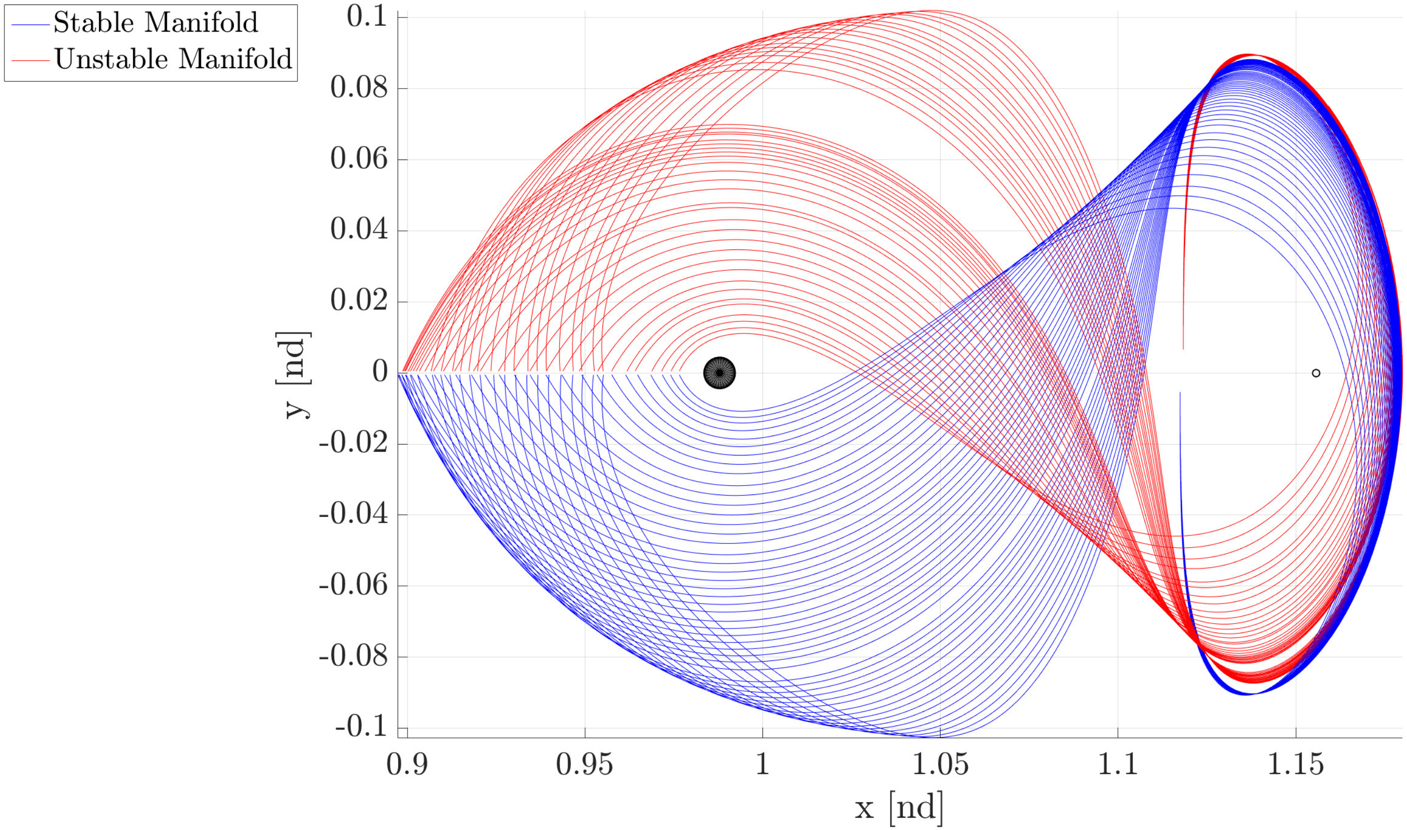
Heteroclinic Transfer

Target and chaser are approximately phased

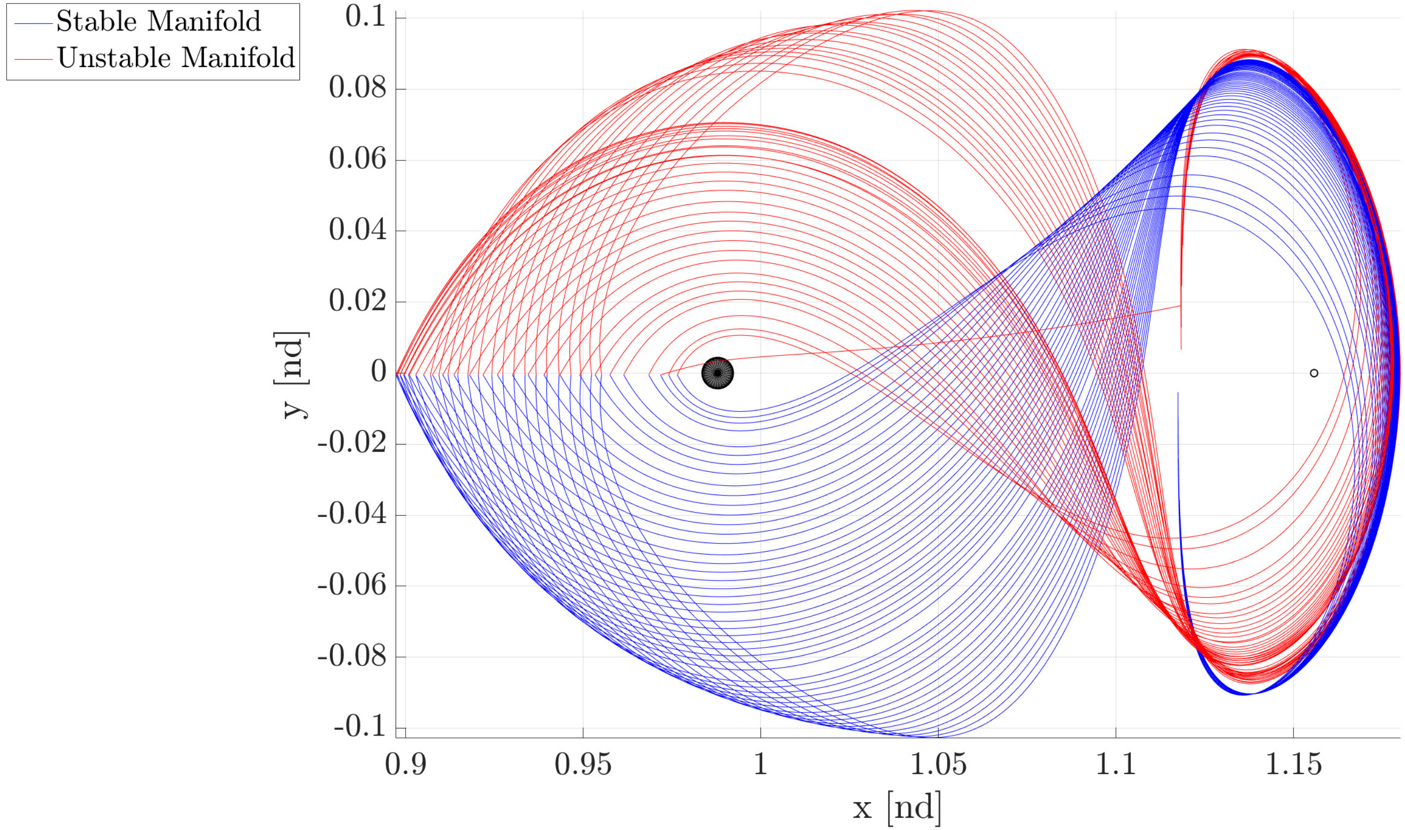
- This condition can be always obtained with a preliminary phasing manoeuvre
- Proximity operations are able to correct errors in phasing

- Invariant manifolds are computed
- Intersection are analysed on a Poincarè section → Sub-Optimal Transfers
- Sub-Optimal transfers are corrected and position continuity along the transfer is enforced
- Best Sub-Optimal transfer is a first guess for the optimization algorithm
- Optimization process varies state vector at the beginning of the transfer → min ($\Delta v_{transfer}$) → Optimal transfer

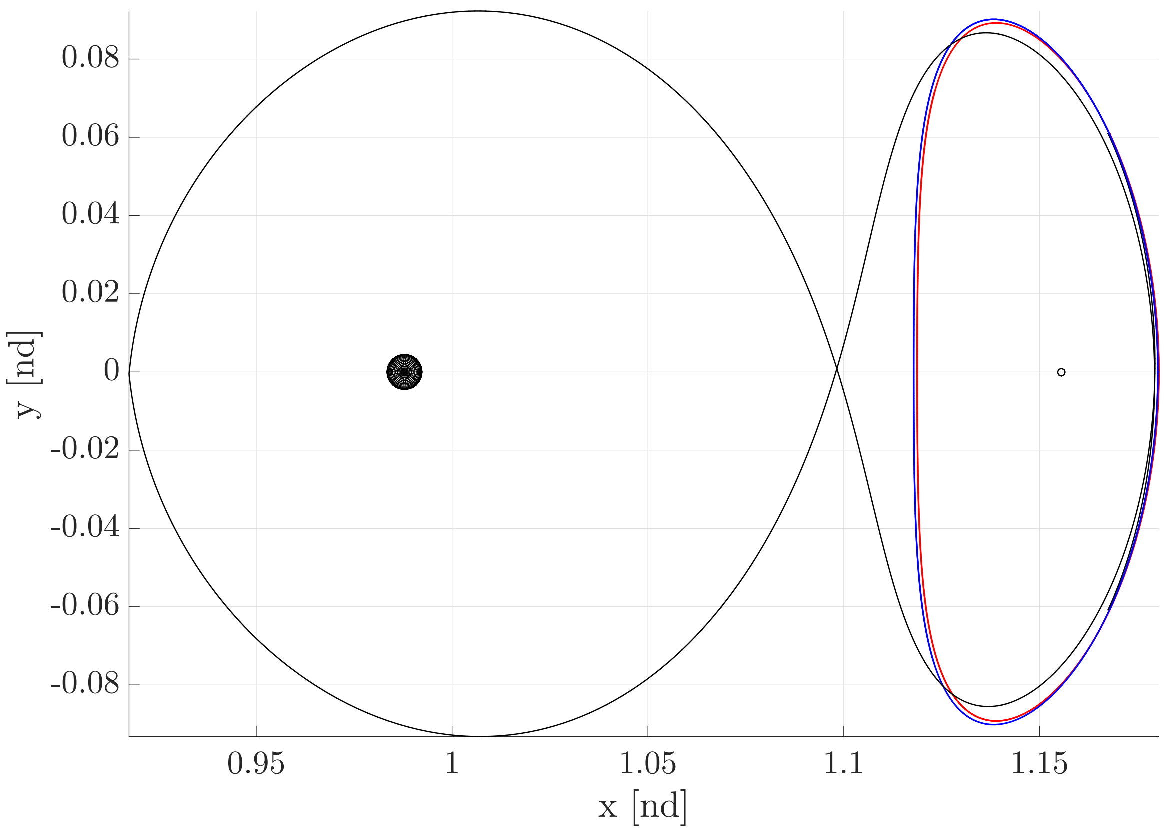
Heteroclinic Transfer



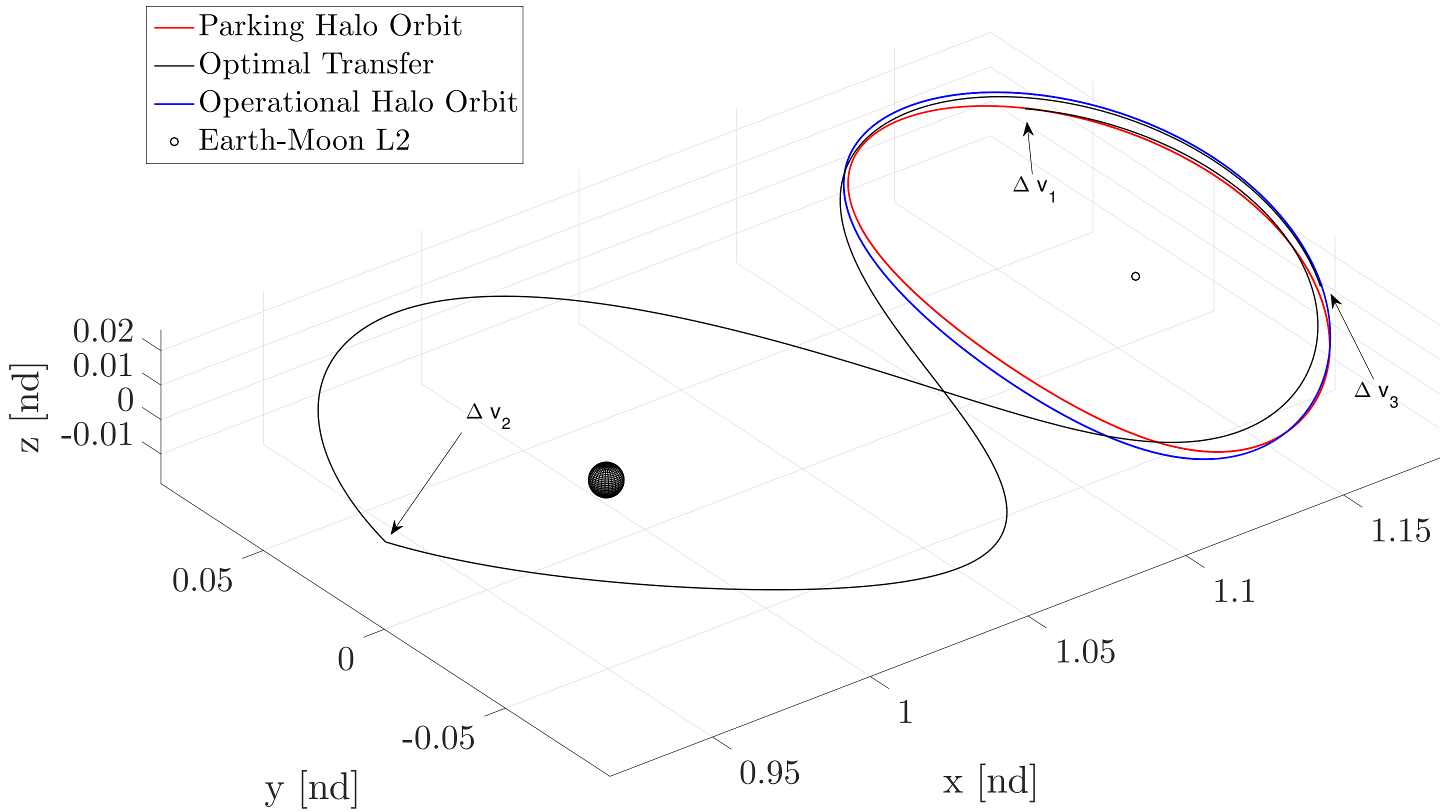
Heteroclinic Transfer



Heteroclinic Transfer



Heteroclinic Transfer



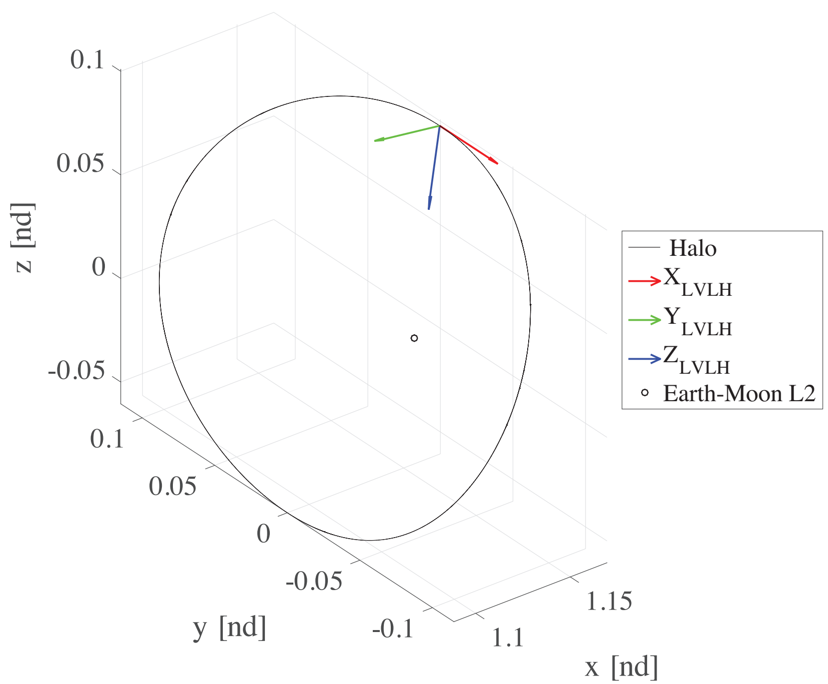
$t_{transfer}$ [d]	Δv_1 [m/s]	Δv_2 [m/s]	Δv_3 [m/s]	$\Delta v_{transfer}$ [m/s]
26.14	5.49	152.29	0.51	**158.29**

Proximity Operations

The transfer is assumed to be concluded when:

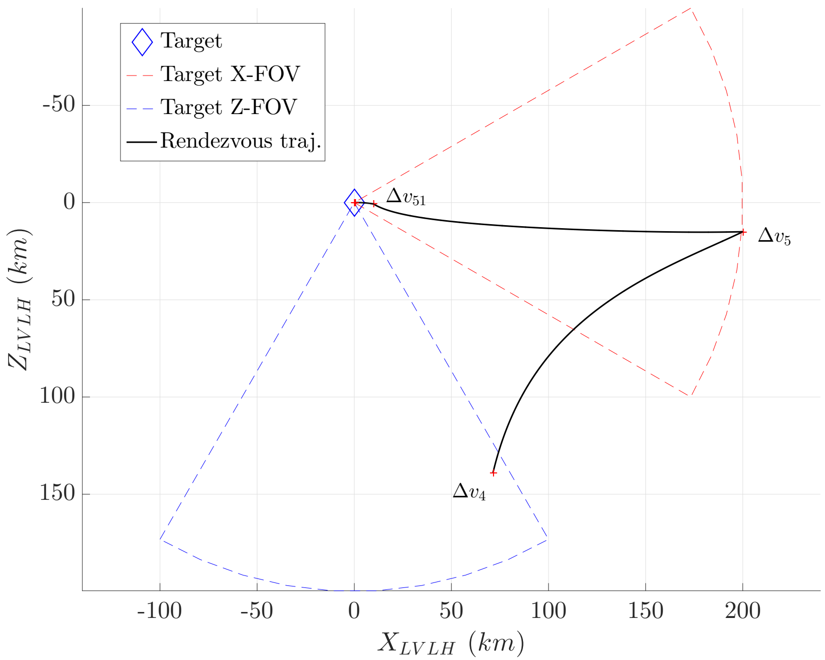
- Relative distance is ~10^2 km
- Chaser in view along Z_{LVLH}

Proximity operations are analysed in EML2-LVLH frame

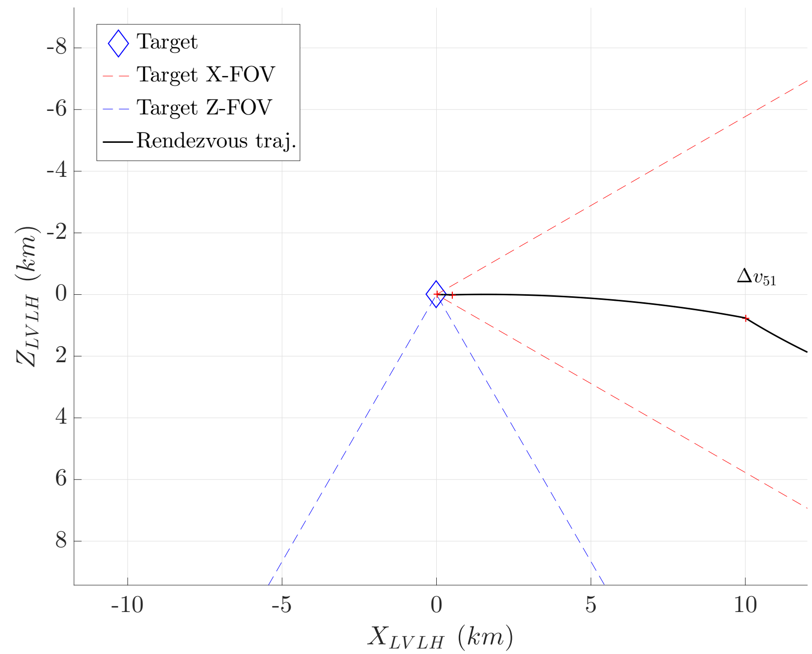


Proximity Operations

Closing Phase

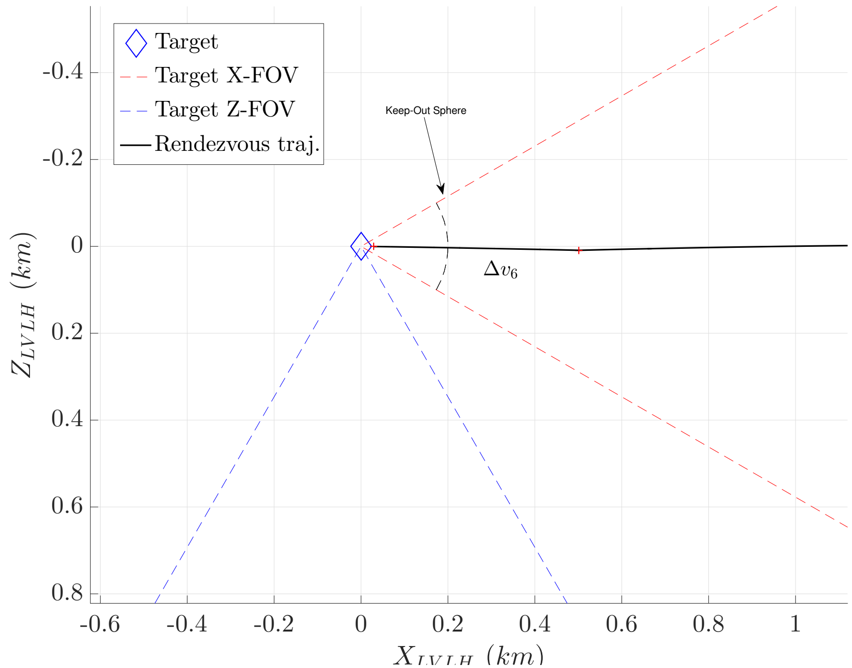


Final Approach Phase



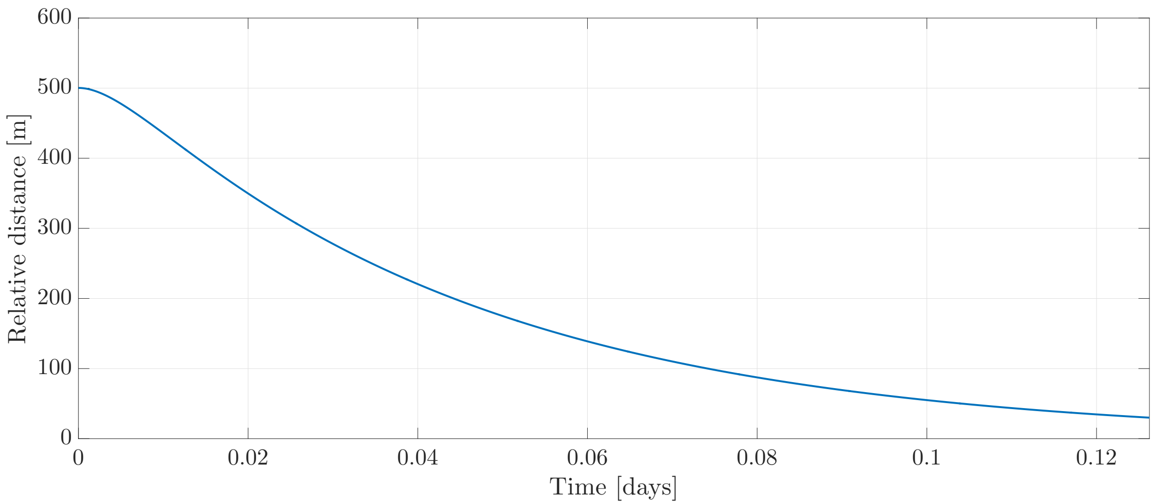
$t_{proximity}$ [d]	Δv_4 [m/s]	Δv_5 [m/s]	Δv_{51} [m/s]
3.23	1.27	3.41	2.52

Mating Phase



Continuous thrust before docking

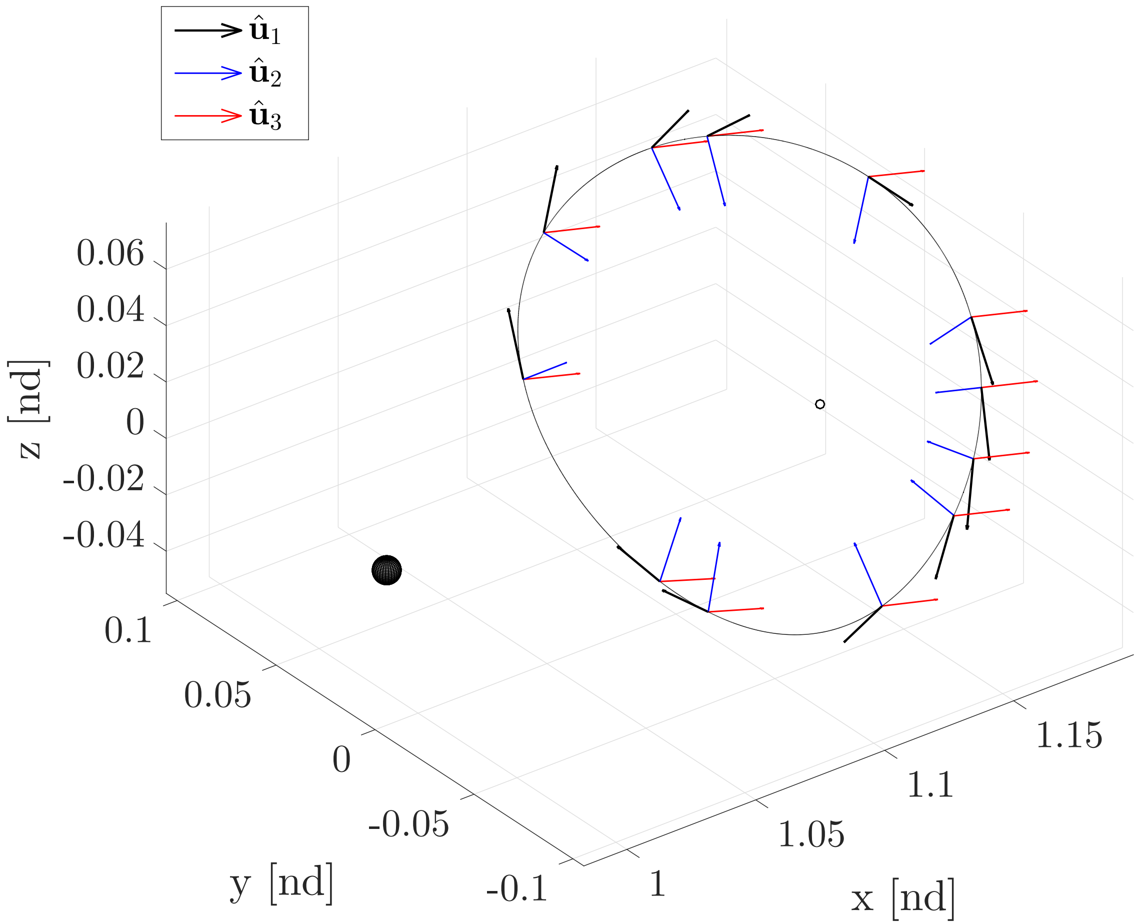
LQR trajectory on linearised CR3BP: target dynamics is computed with the flexible orbit-attitude model



t_{mating} [h]	Δv_6 [m/s]
~3	0.44

Flexible Orbit-Attitude Analysis

Orbit-Attitude Motion



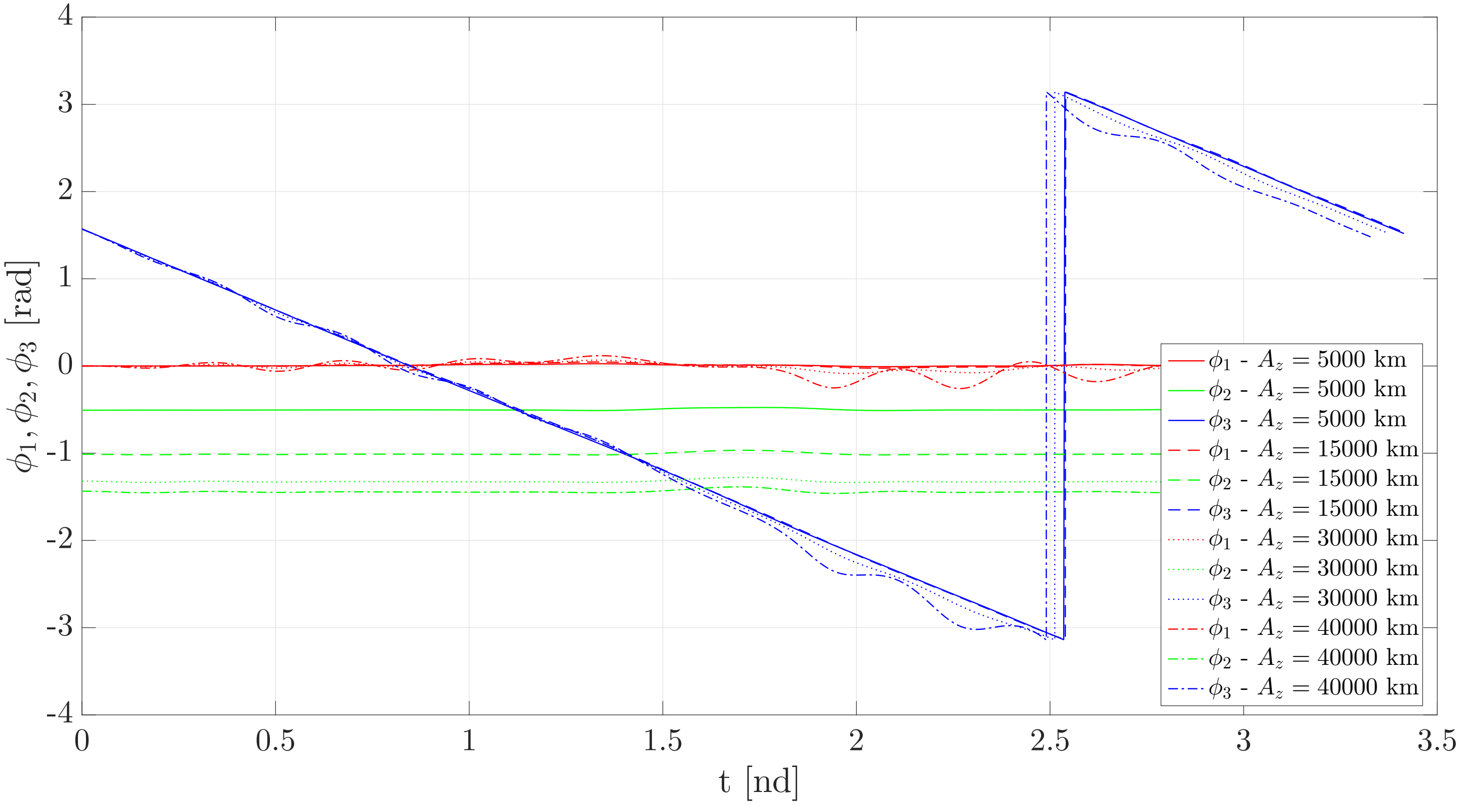
<u>Quasi-periodic attitude motion</u>: almost 1 rotation in the first orbital period

Attitude dynamics (in terms of stability of the periodic motion) is very sensitive to orbital dynamics

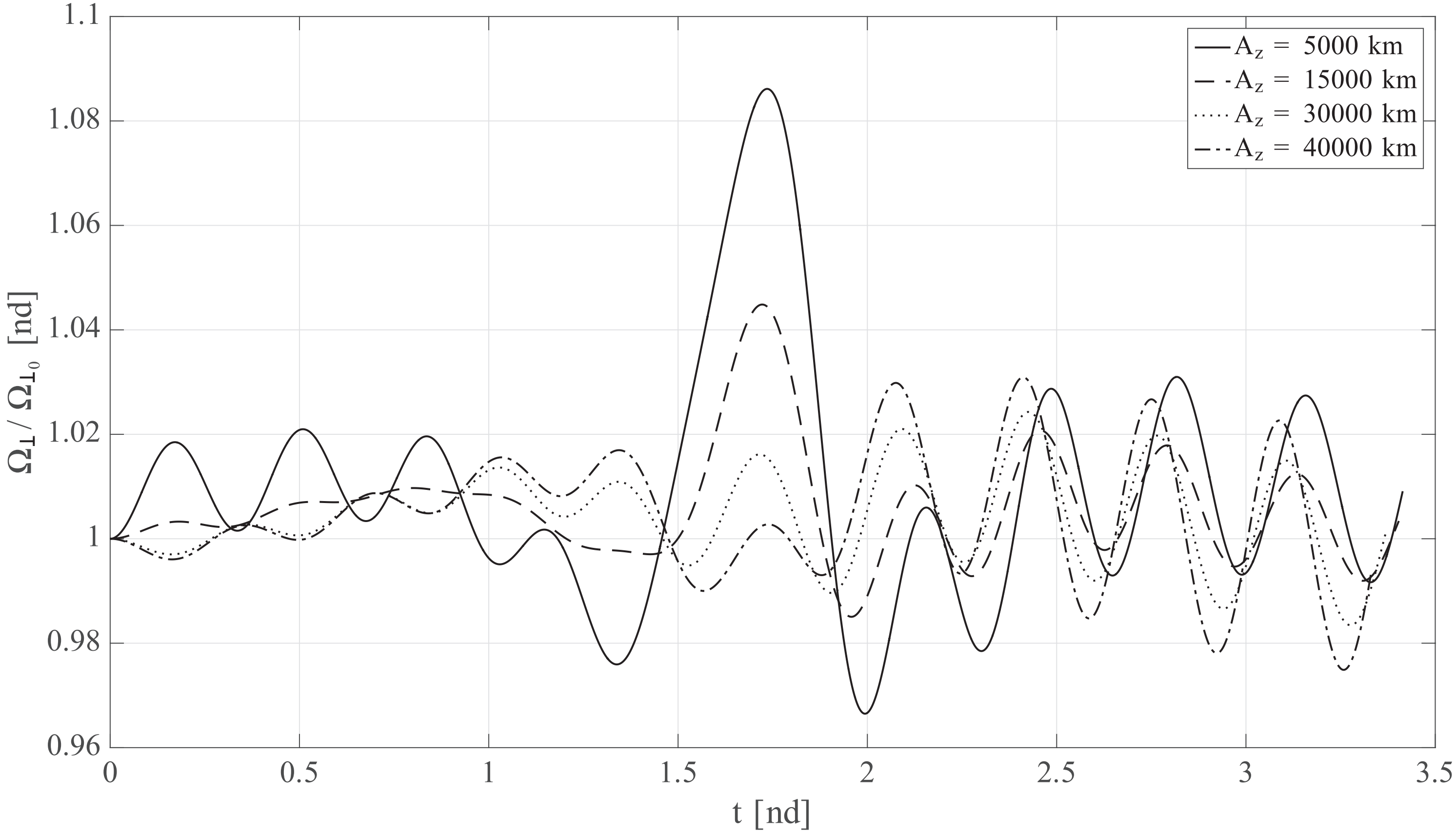
Orbit-Attitude Dynamics Effect on Flexible Dynamics

Influence of the orbital frequency on flexible (spring-mass) frequencies.

- Spring-Mass have $\widetilde{\omega} = 50\ [-]$
- Halo orbits with $A_z = 5000, 15000, 30000, 40000 [\mathrm{km}]$



Orbit-Attitude Dynamics Effect on Flexible Dynamics



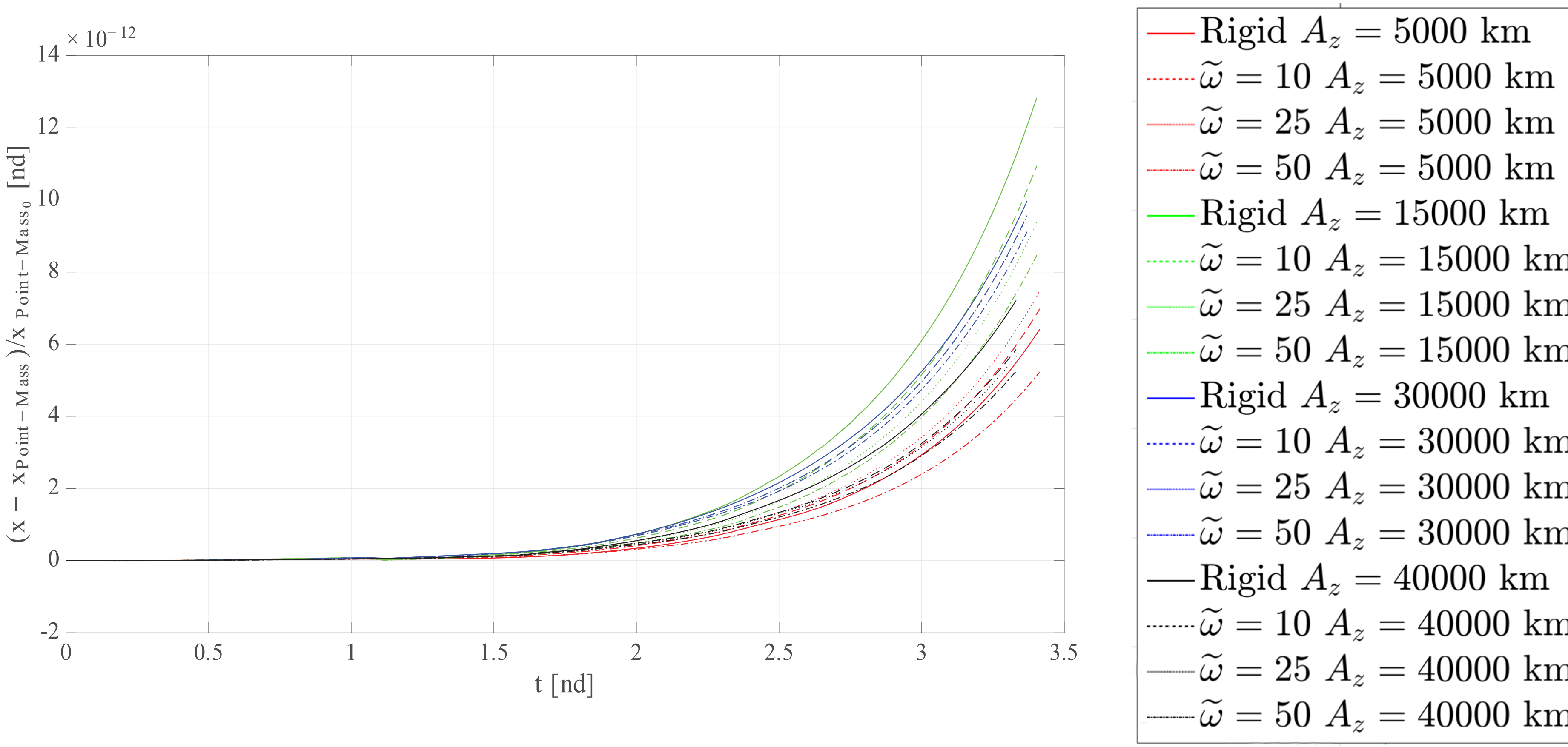
Orbits with large A_z have particular influence on orientation angles, while the others strongly act on $\Omega_\perp$

Colagrossi, Lavagna and Rafano Carnà

Natural Frequencies Effect on Orbit-Attitude Dynamics

Same Halo orbits of the previous analysis but different $\widetilde{\omega}$

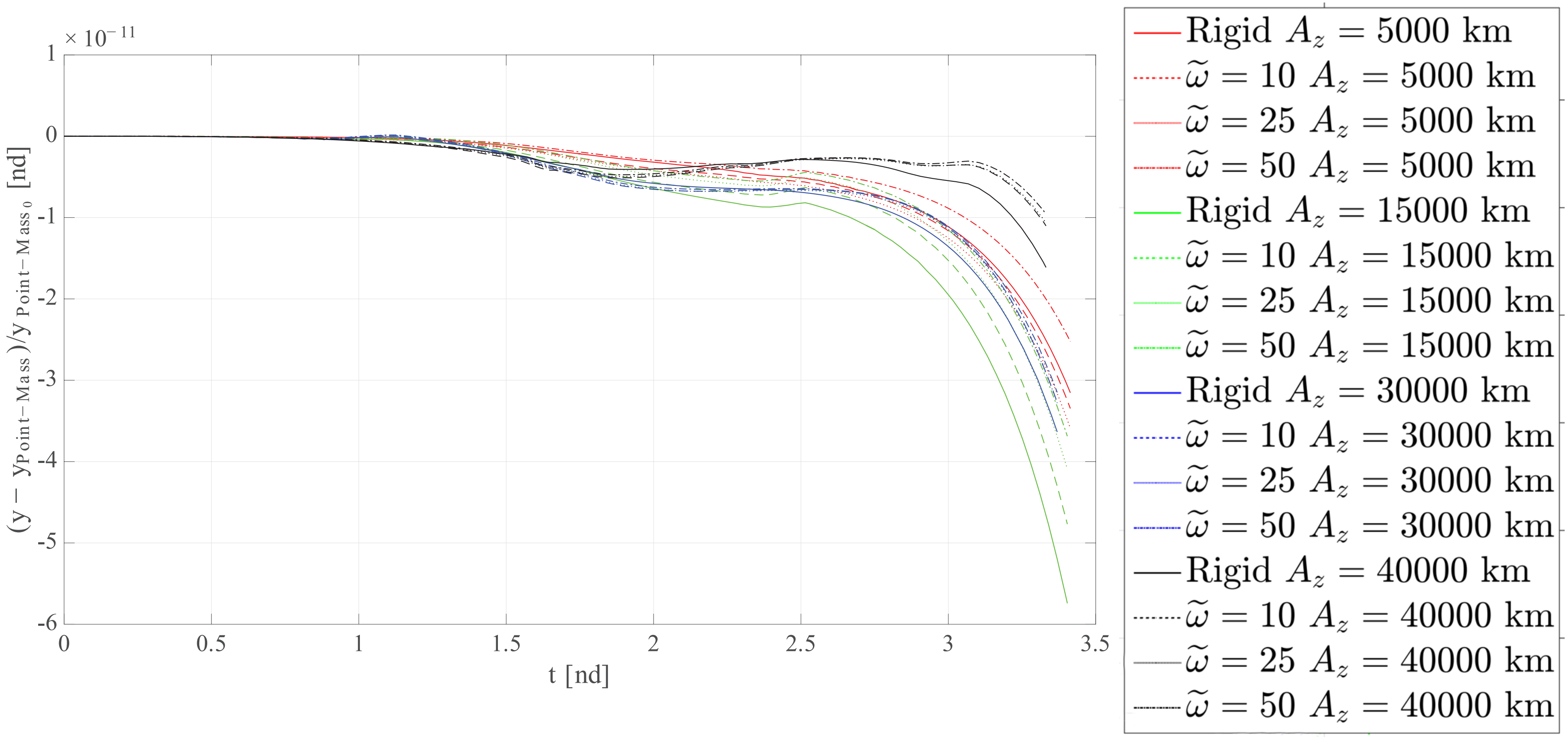
- Error with respect to point-mass dynamics



Natural Frequencies Effect on Orbit-Attitude Dynamics

Same Halo orbits of the previous analysis but different $\widetilde{\omega}$

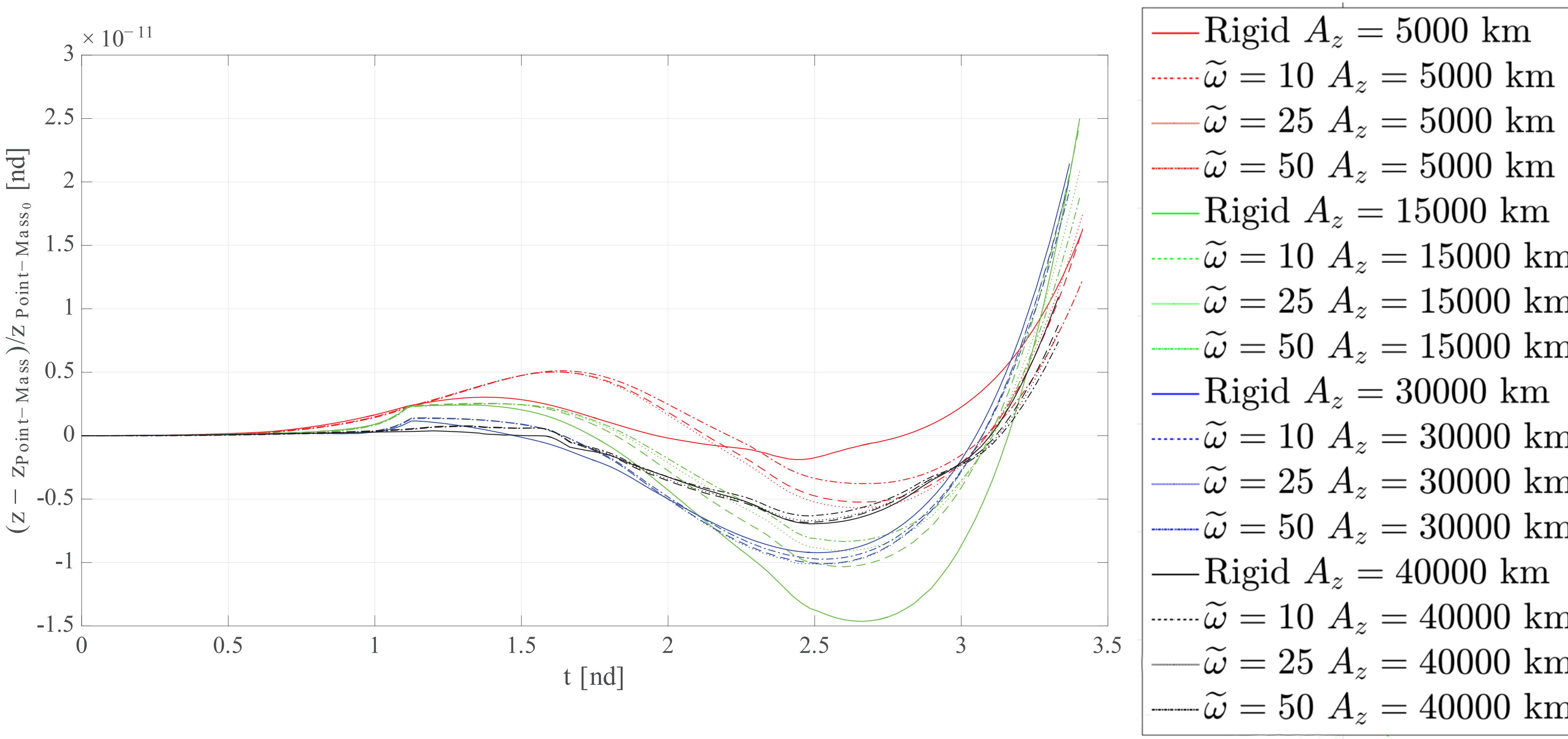
- Error with respect to point-mass dynamics



Natural Frequencies Effect on Orbit-Attitude Dynamics

Same Halo orbits of the previous analysis but different $\widetilde{\omega}$

- Error with respect to point-mass dynamics



Concluding Remarks

Concluding Remarks

- The effects of flexibility on orbit-attitude dynamics (and viceversa) must be analysed isolating each single effect
  - Outline meaningful trends and particular coupling effects
- The effects of flexible orbit-attitude dynamics cannot be neglected
  - In particular for attitude stability and proximity operations
- Rendezvous with a large and flexible space infrastructure in Non-Keplerian orbit deserves particular attention
  - Refined models must be used to simulate the dynamics
- Cyclic mission with a passage on the Earth side of the Moon is feasible in terms of needed Δv

Future Works

- Enhance the flexibility modelling approach
  - Distributed parameters technique
  - Refined lumped parameters approach will be compared with distributed parameters technique
  - Assess the fidelity of the structural model
- Increase the fidelity of simulations
  - Disturbing phenomena will be included (SRP, 4^{th} body …)
- Add more structural elements to the large flexible body
  - Multi-body approach

POLITECNICO MILANO 1863

6th International Conference on Astrodynamics Tools and Techniques

Dynamical Analysis of Rendezvous and Docking with Very Large Space Infrastructures in Non-Keplerian Orbits

Andrea Colagrossi, Michèle Lavagna and Simone Rafano Carnà
Department of Aerospace Science and Technology