Numerical Modeling of the Dynamics of a Tether Stack in Towed Active Debris Removal

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Agenda

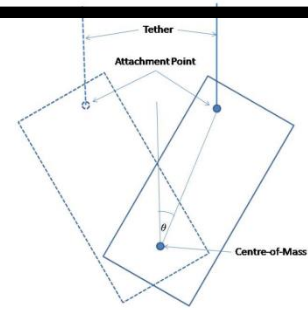
- BOUNCED study
- Description of the deorbiting mission
- How do we model it ?
- Validation & Results
- Modeling capabilities

« BOUNCED » STUDY

- **BO**dies **U**nder **C**onnected **E**lastic **D**ynamics
  - ESA GSP Activity
  - Clean Space Initiative
  - Support to Active Debris Removal Concepts
    - Harpoon/Net
    - Spacecraft Requires Towing using a Tether
    - What do we know about fundamental tether dynamics?
    - What happens if control is lost?
  - <u>Elastic</u> tether:
    - Interests

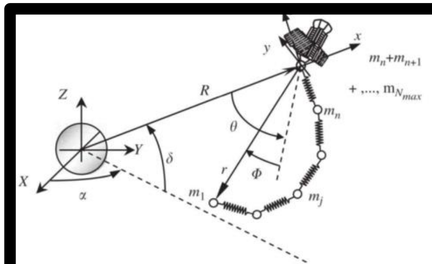
« BOUNCED »

Tether rupture



Rotation model

Systems



Bead model

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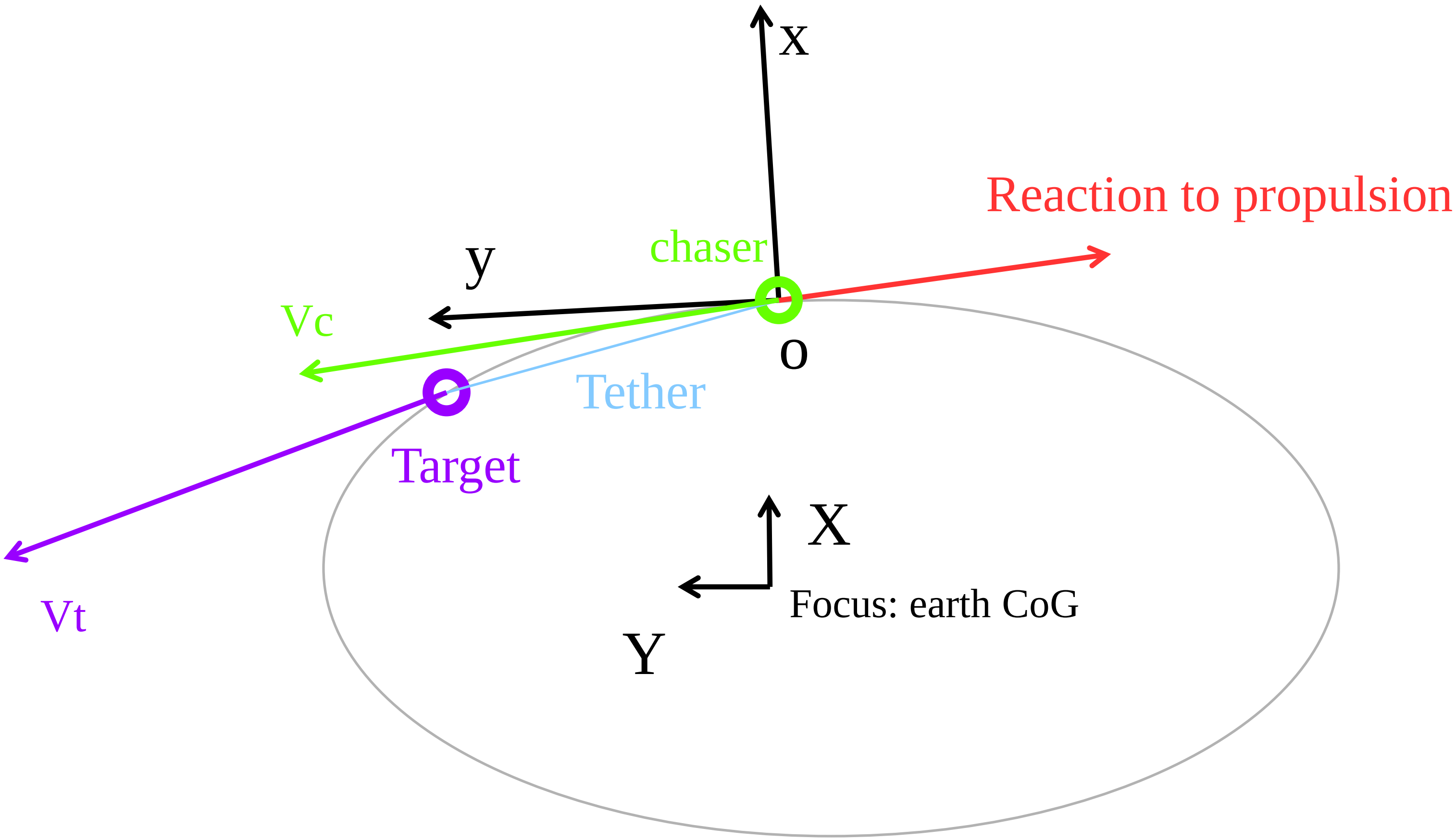
Analytic bead model

Numeric bead model

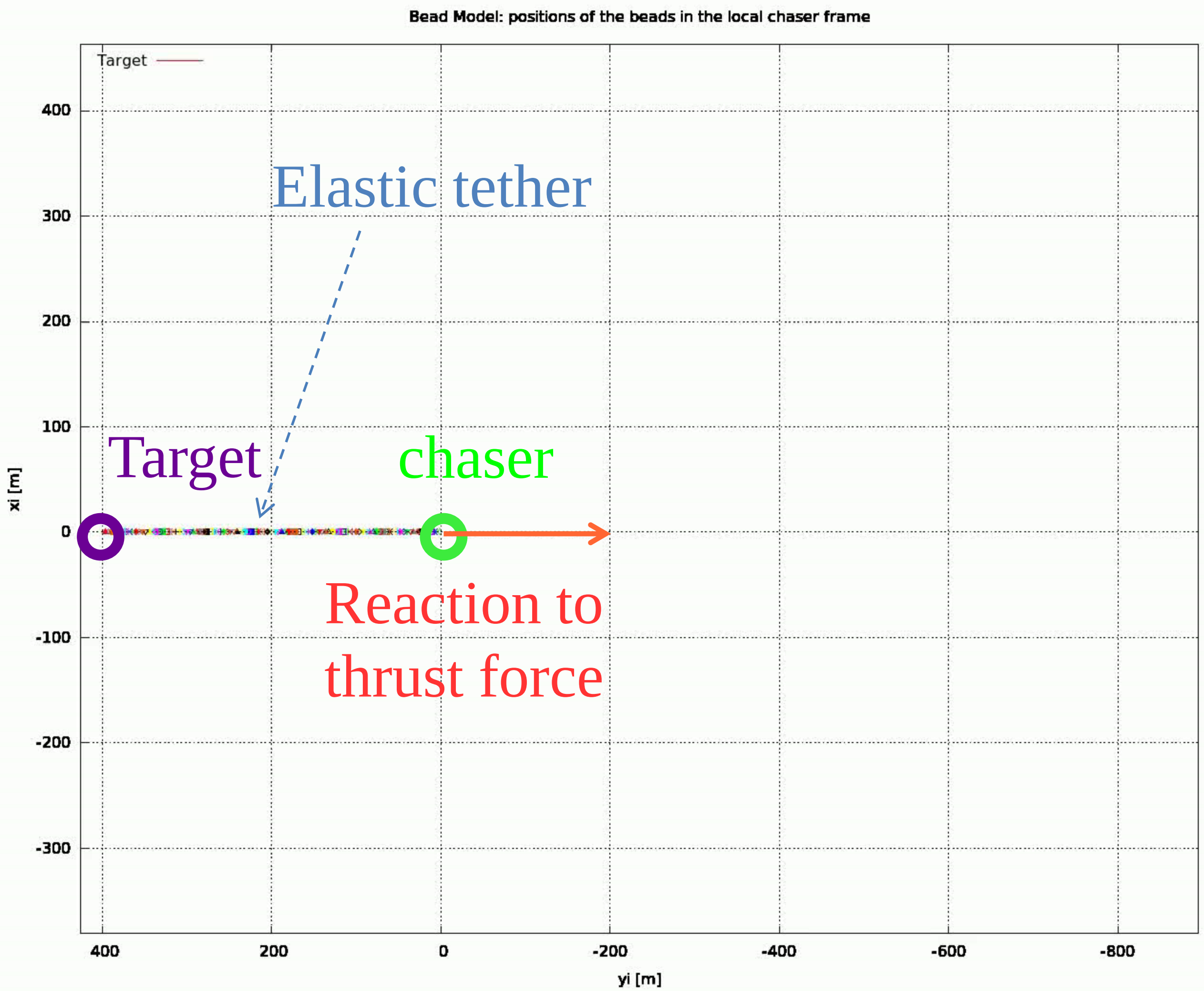
This presentation

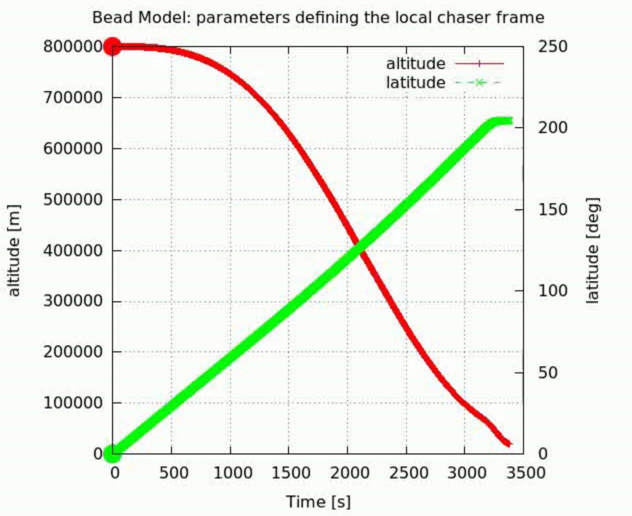
Description of problem:
Target orbiting around the earth to be demised

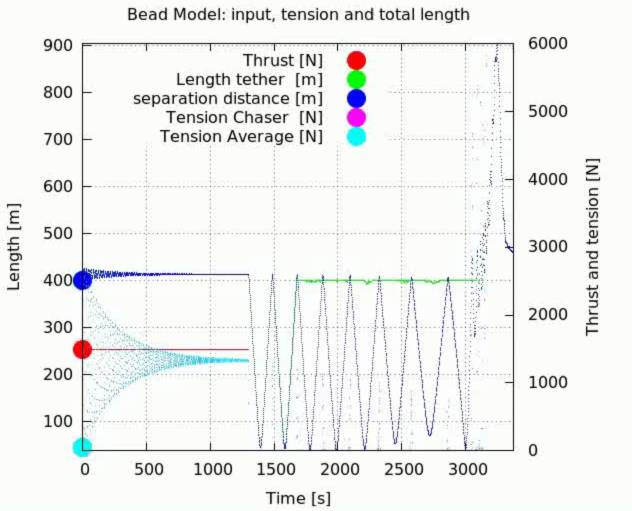


Different regimes covered by BOUNCED

What are we modeling ? (1/2)

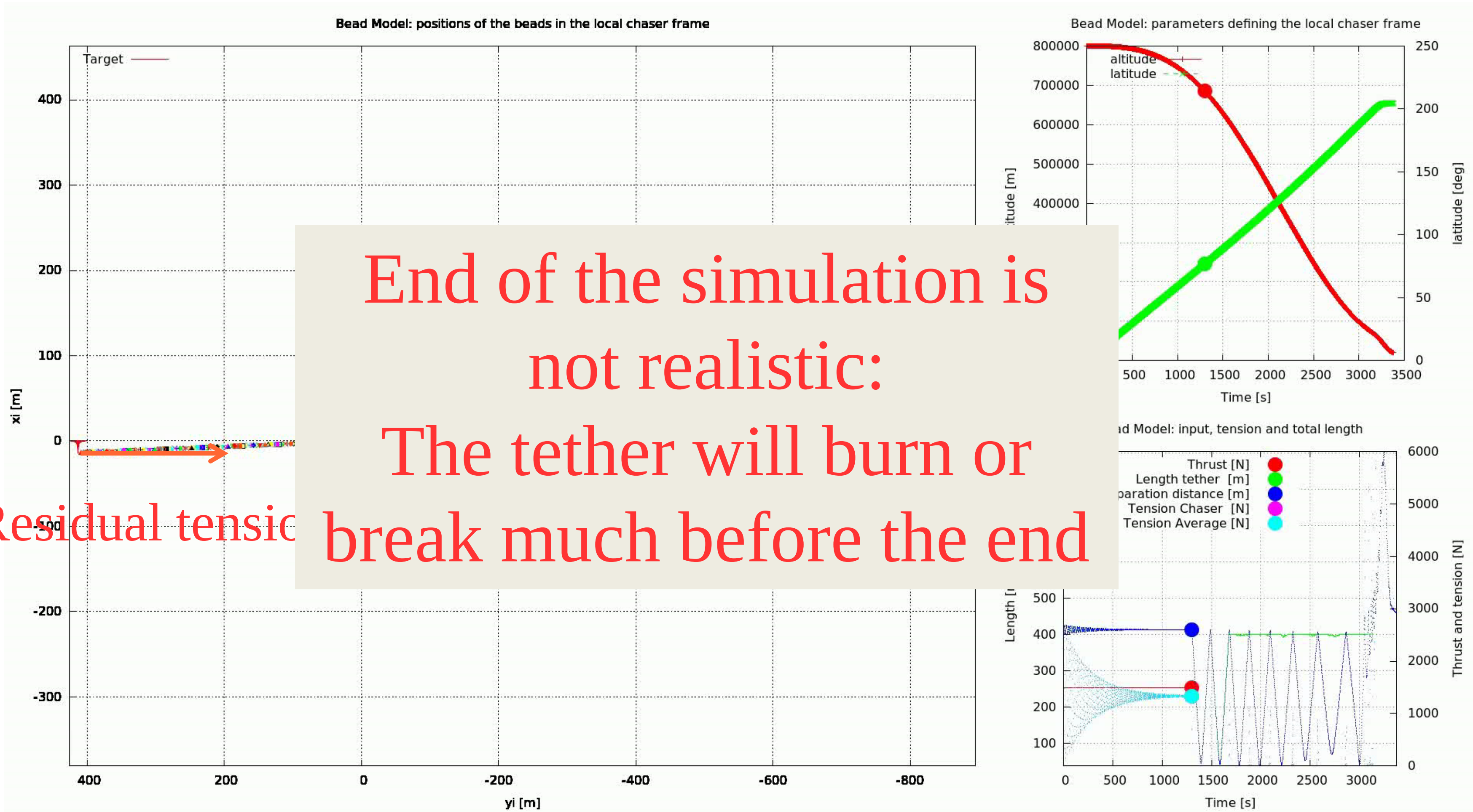






Burn Phase

What are we modeling ? (2/2)



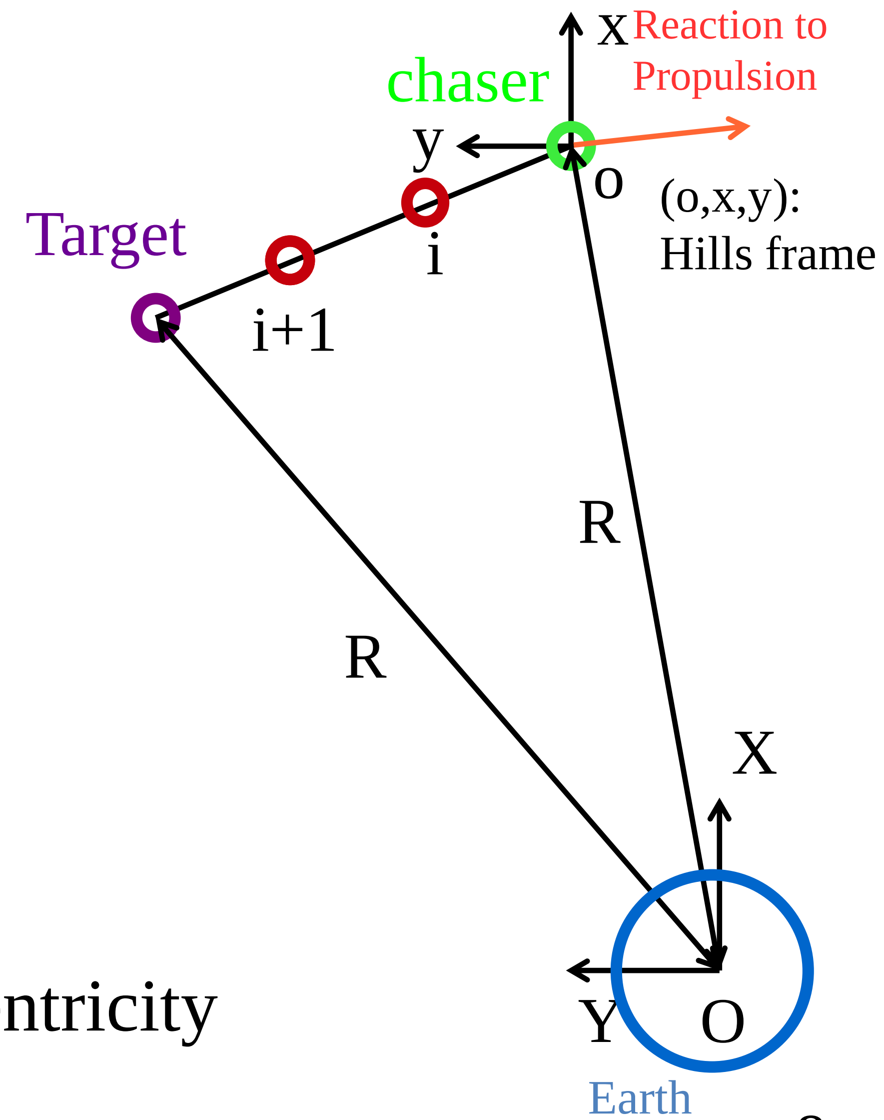
Residual tensio

End of the simulation is not realistic:
The tether will burn or break much before the end

Relative orbital motion, retention & early atmosphere interaction

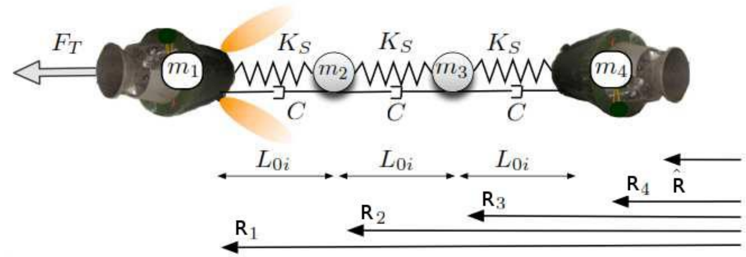
Bead Model: external forces and propulsion

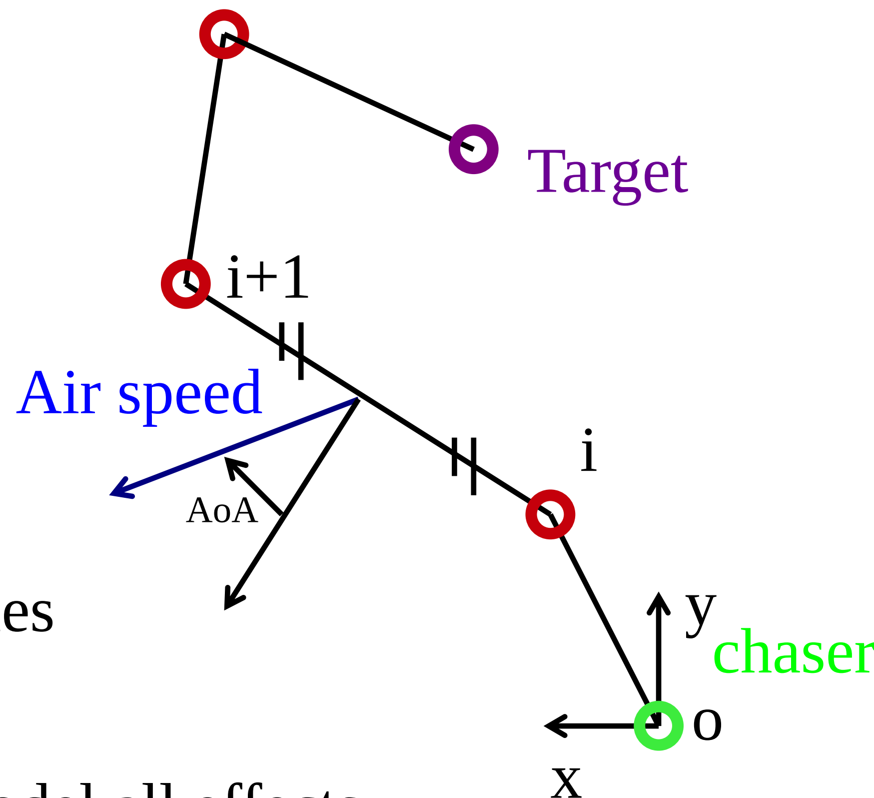
- N beads:
  - (1) Chaser
  - (1) Target
  - (N – 2) Elastic tether
- External forces:
  - Gravitation
  - Inertia
  - Simple aerodynamics
- Propulsion force
- 2D effects and orbital eccentricity



Bead Model: tether modeling

- Beads connection modeling:
  - Spring
  - Damper
- Parameters of the tether:
  - E : Young module
  - L : Length
  - Ks : Elasticity
  - C : Damping
  - m^i : Bead masses
  - N beads => Mods/frequencies
  - Drag coefficients



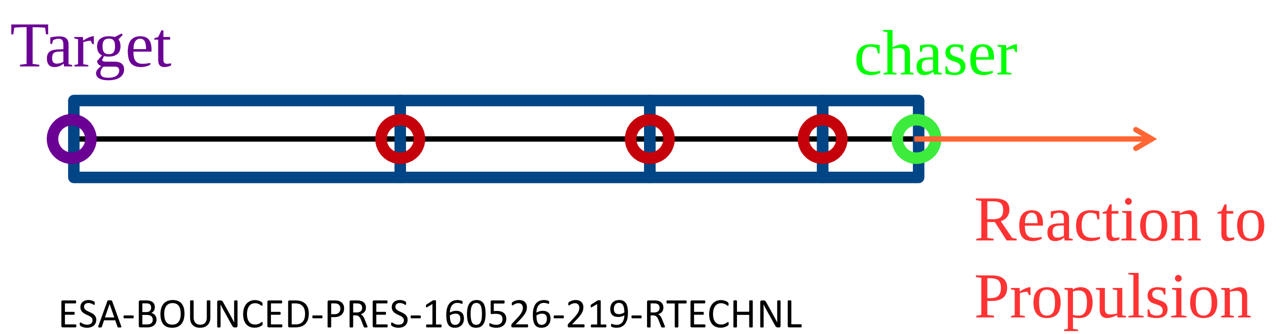


=> **Numerical bead model**: can model all effects

Analytical model

- Combination of 2 analytical models
- Main differences with numeric model:
  - Burn and retention phases:
    - 1D bead model
    - No external forces
  - Orbital phases:
    - No force apply on the tether beads (target and chaser only).
    - Low eccentricity approximation

1D bead model with identical tether sections



Resolution

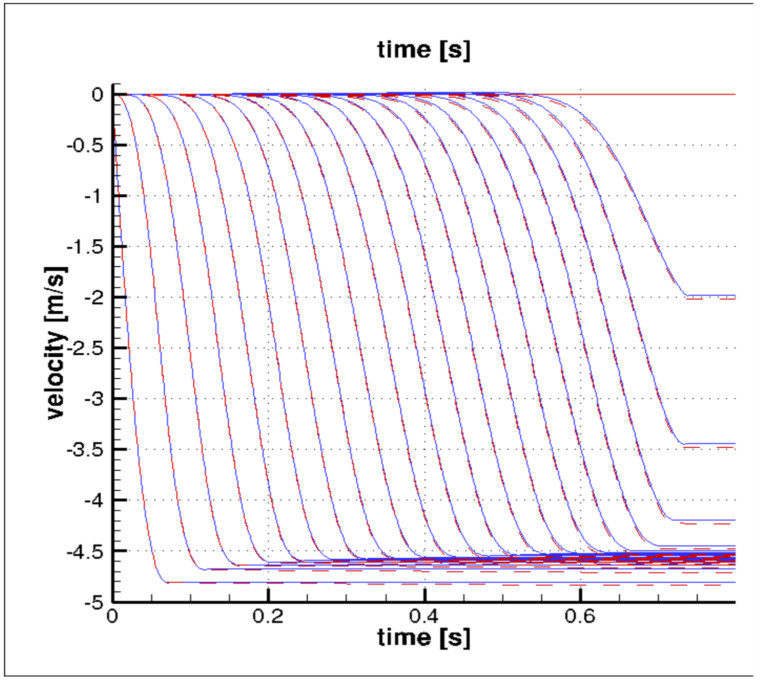
- Analytic model:
  - Combination of 2 analytical models:
    - Tension phases: symmetric tridiagonal system
    - Orbital phases: Hills's equations
- Numeric model:
  - Implemented in Java
  - Equations solved by a numerical integrator

Validation

- Numeric model validated using:
  - Analytic model
  - Experimental data
- Cross validation between
  - Analytic model
  - Numeric model
- Different parameters

⇒ **What have we learned from the cross comparison (parameter study) ?**

⇒ **What can be done with the analytic model ?**

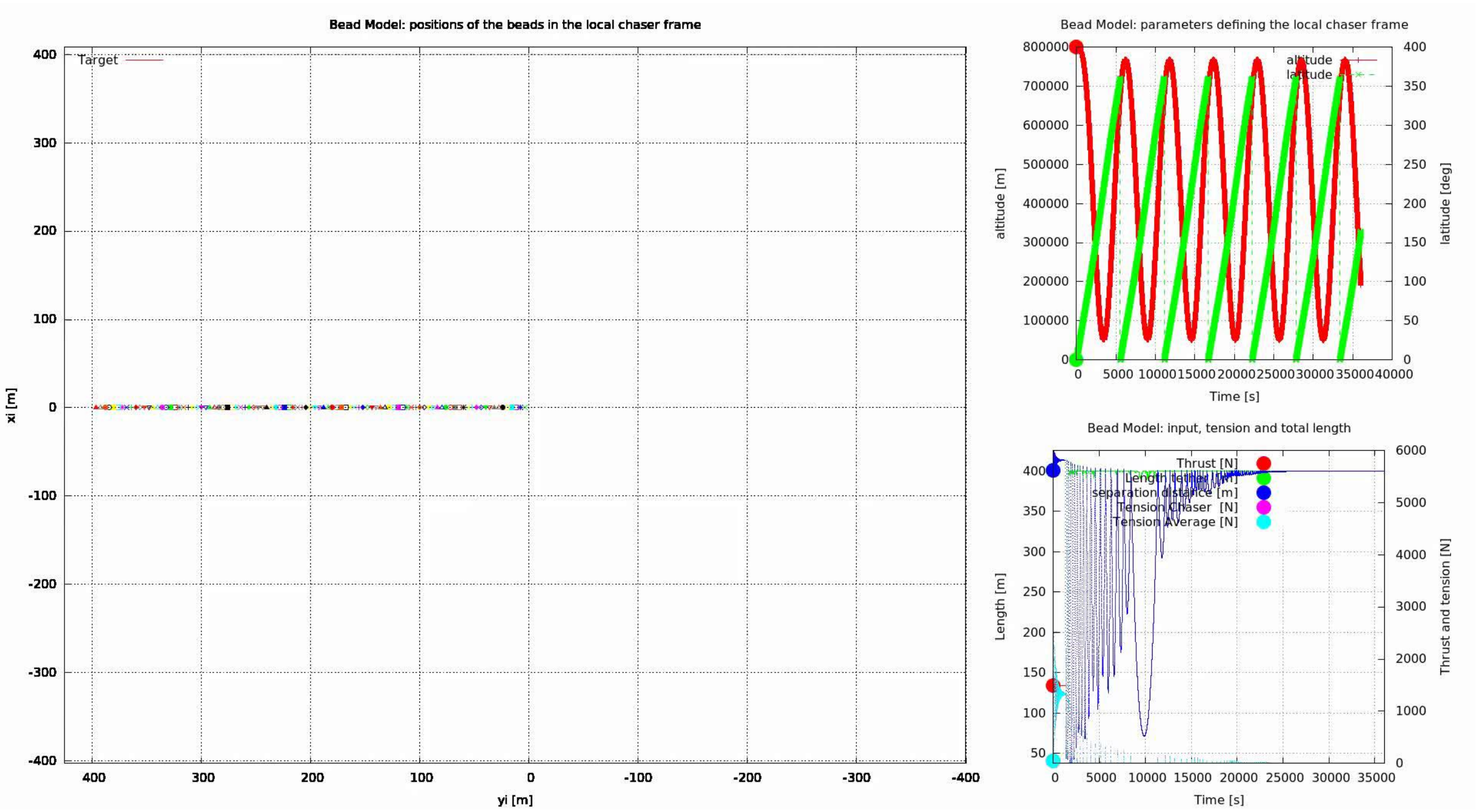


<u>Example of comparison:</u>

Velocities of the beads after breaking of the tether: 1D model (red) vs 2D at 800km (blue)

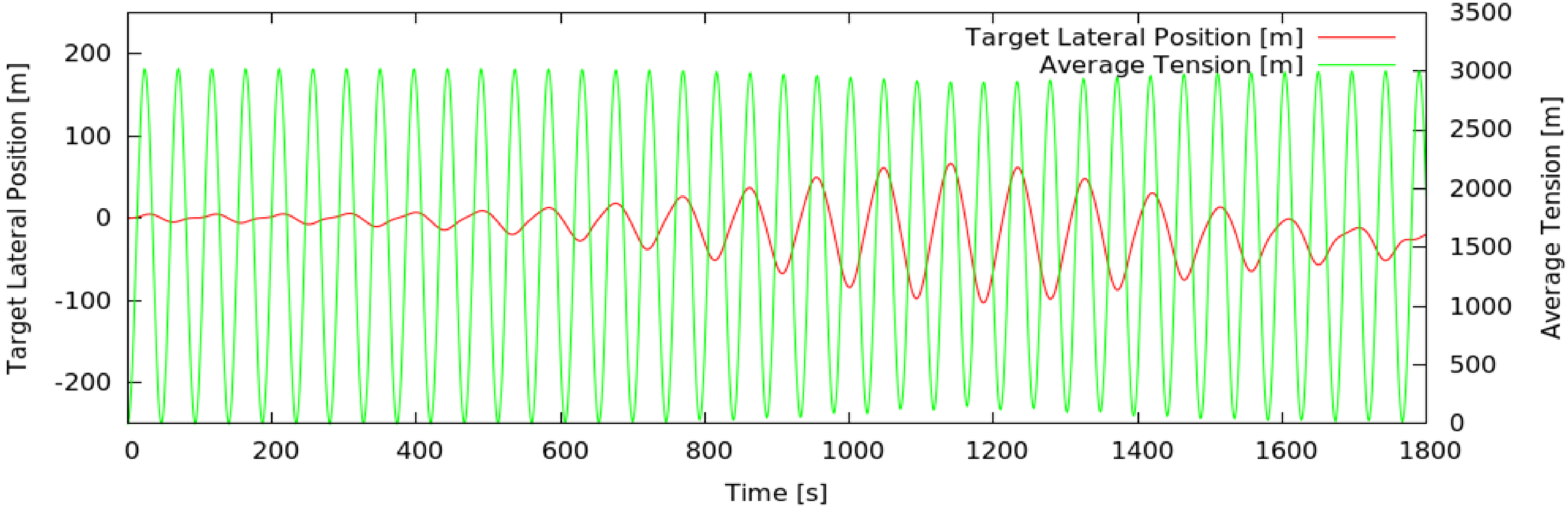
Results: Description of the motion without atmospheric drag (e.g. to mimic propulsion failure)

- Coriolis forces are dominant => 1st pass misses suggests others miss
- System evolves to a gravity gradient stabilized oscillating state



Results: 2D lateral motion characterization - Burn phase

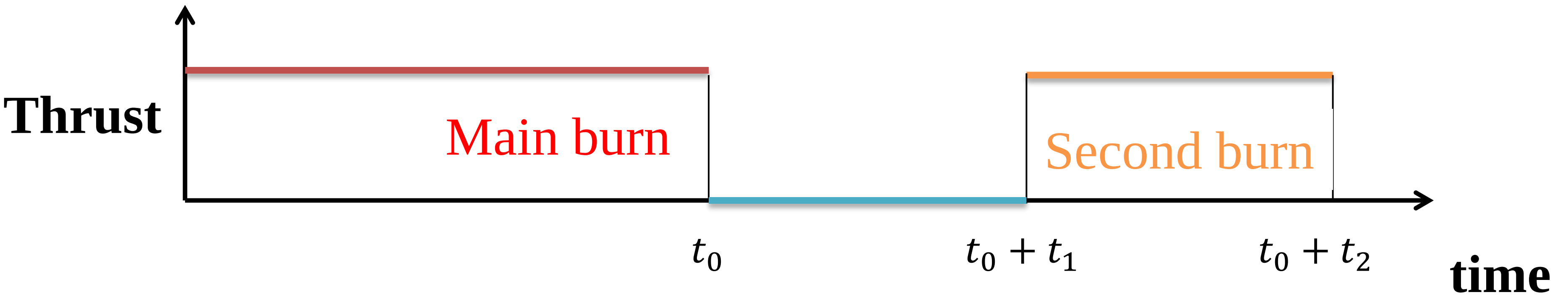
- Lateral 2D motion observed in numerical model
- The lateral motion is due to thrust not exactly in orbit direction.
- Frequency can be approximated by a pendulum analogy
- Minimum acceptable frequency can be predicted for the system
  - Analytic formula validated through numerical experiment.
- Limiting case shown: lateral and longitudinal oscillations synchronize



- Pretension and tether damping have limited impact on mitigation

Results: Input shaping to mitigate lose of control

- **Stored elastic energy => Post burn relative velocity** significant
- A **second burn** (Bang-off-bang) is used to mitigate the velocity
- **<u>Objective</u>: null relative velocity at the end of the second burn**

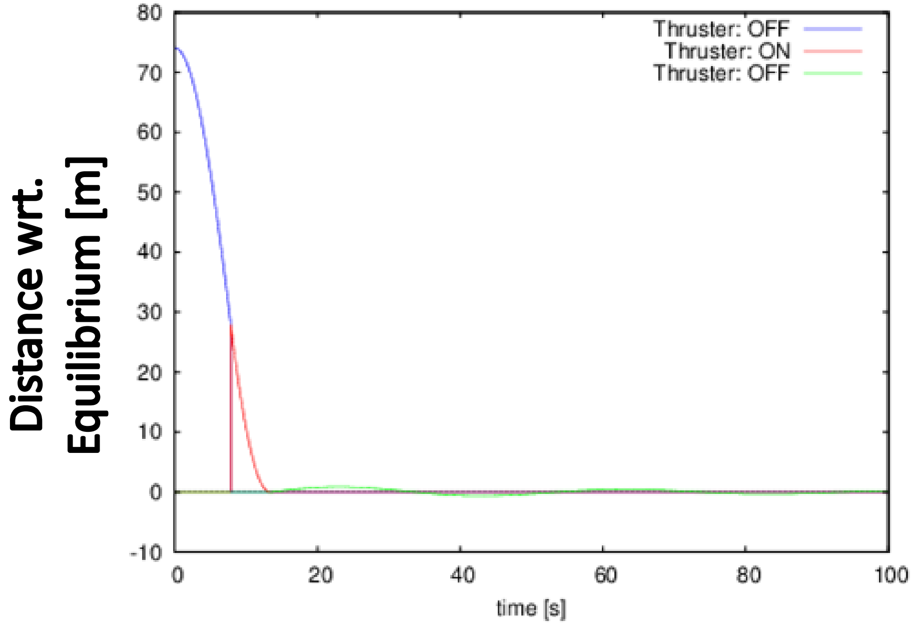


- Exact solution for undamped system **(C=0)** :
  - **Derived from the 1D analytical model** assuming:
    - <u>End of main burn: Tether system is **fully damped**</u>
- Solution for damped system **(C!=0) :**
  - Based on exact solution for undamped system
  - Corrected with a term taking into account the damping (**C**)

Results: Input shaping to mitigate lose of control

- Solution <u>with damping</u> gives a good solution
- Numerical simulation validates the analytical solution:

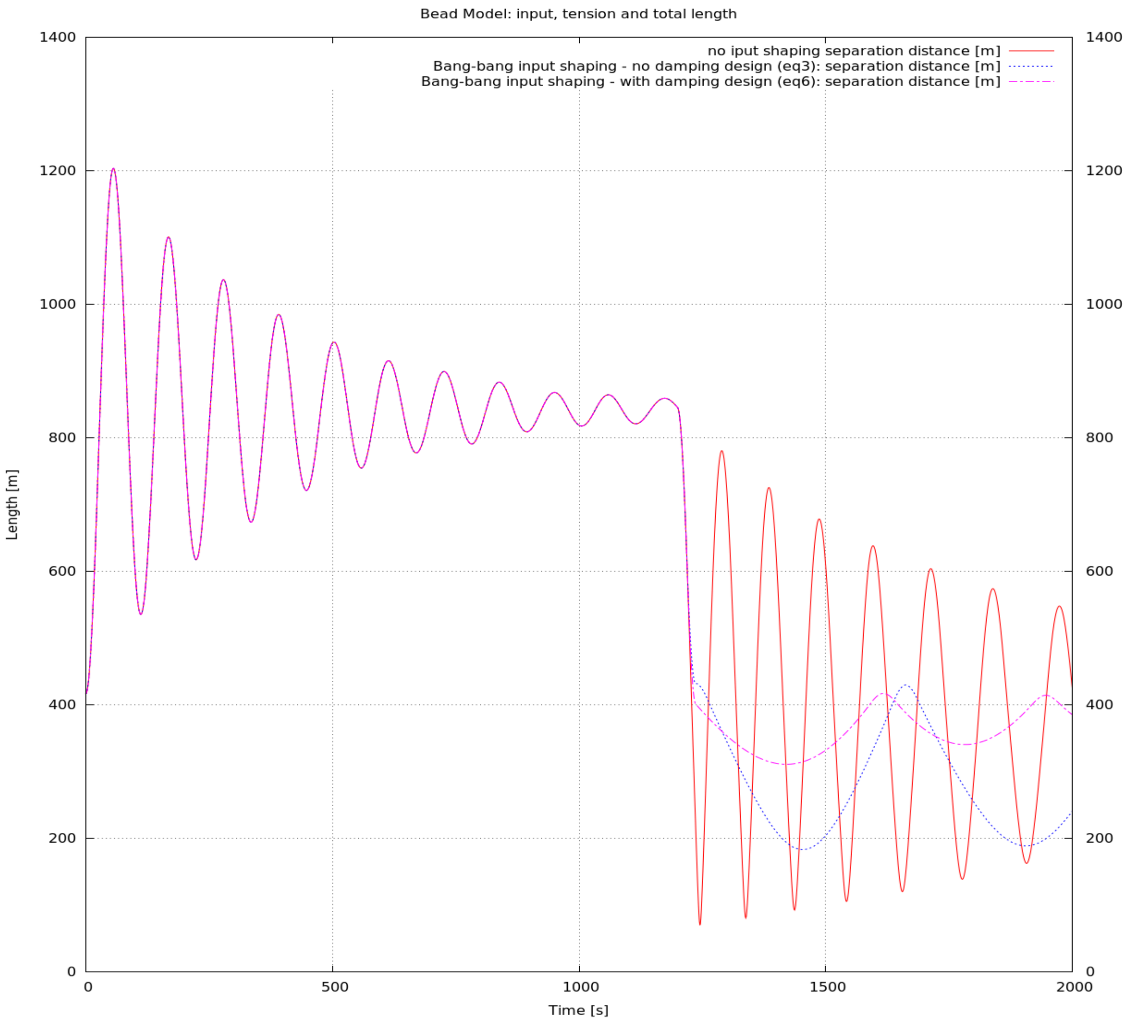
  - Simulation starts at the end of the main burn (time=0)



10% damping ratio system: Bang-off-bang using the damped scheme

NB: Solution (in green) are not representative of the system as soon as the distance is negative.

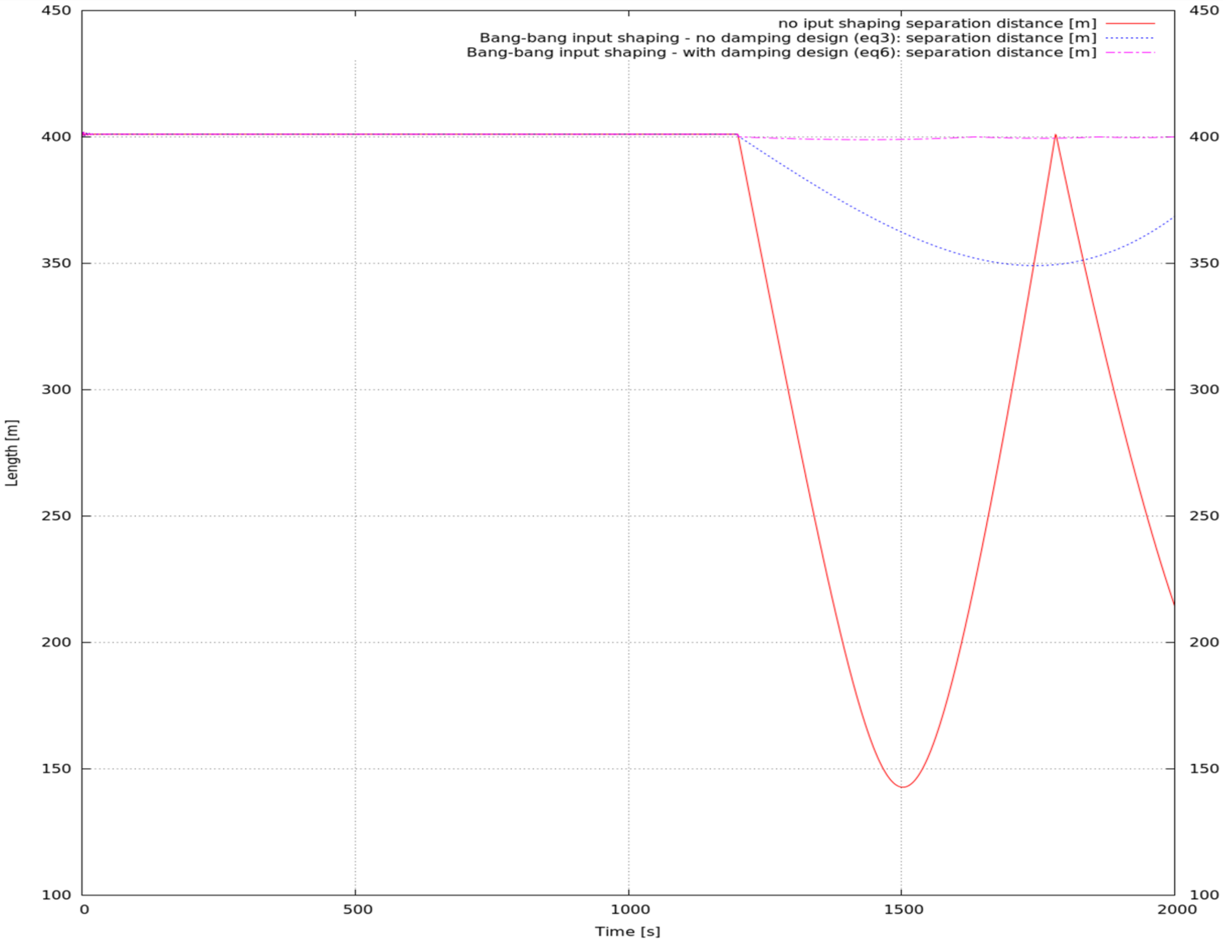
Results: Input shaping applied to Rubber



Separation distance vs time

- Oscillations not fully damped at the end of the main burn
- => Timing for input shaping not appropriate

Results: Input shaping applied to Dyneema



Separation distance vs time

⇒ Timing for input shaping gives good results for:

- ⇒ Dyneema
- ⇒ Also with Kevlar & Steel

⇒ Propulsion system should be able to set on/off <u>faster</u> than 1/6th of the period associated with the 1st mod of the tethered system

Modeling capabilities for elastic tether dynamics

Modeling	Analytic model	Numeric model
Retention phases	Error introduced by relative velocity mirrored after retention	Modeled, but rotation model also is an important aspect .
Slacking during burn phase	Not needed if enough pretension (50 N is OK) or damping	Snatch loads modeled when part of tether are slacked
Propellant mass	Not needed if oscillations damped at the end of burn	Time dependent propellant mass loss modeled
Lateral 2D motion	Not needed if tether not too elastic	Predict oscillations. Validate analytical formula for prediction of large lateral oscillations
Orbit eccentricity	Low eccentricity. Do not capture orbital dynamics precisely. But relatively good approximation for a few retention cycles	Modeled.
Multiple burn	No, but theory used to define times: off-on-off	Use to simulate mitigation of relative velocity at the end of burn
Multiple material tether	Limited: dashpot constant over stiffness ratio identical for each tether section	Difficult: time consuming
Multiple frequencies captured	Many beads: fast (seconds)	Many beads: slow (hours)

Thank you for your attention

Questions ?

Back up slides

Baseline data

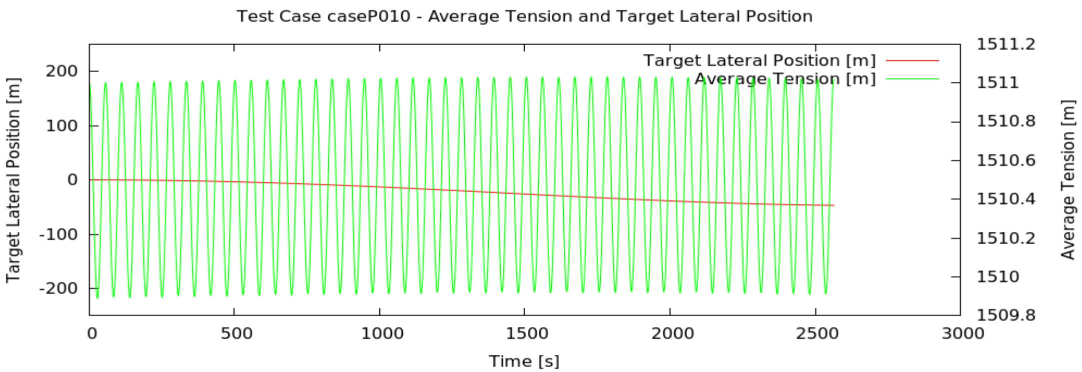
Quantity	Value	Unit
Mass target	8000	[kg]
Mass chaser	1000	[kg]
N	2	[-]
rho	5000	[kg/m^3]
E	1e9	[Pa]
A	5.e-6	[m^2]
L	400	[m]
pretension	0	[N]
Burn Time	1200	[s]
Thrust Force	1700	[N]
Altitude	800	[km]
vx	0	[m/s]

Results: 2D lateral motion, pretension effect

- Lateral motion depends on: $\left|F_{pretension} - T_{avg}\right|$
- Average tether tension: $T_{avg} = F\dfrac{m_t}{m_c + m_t}$
- Impact negligible with a pretension of 50 [N]

$$F_{pretension} = 0[N]$$

$$F_{pretension} = T_{avg} = 1511[N]$$



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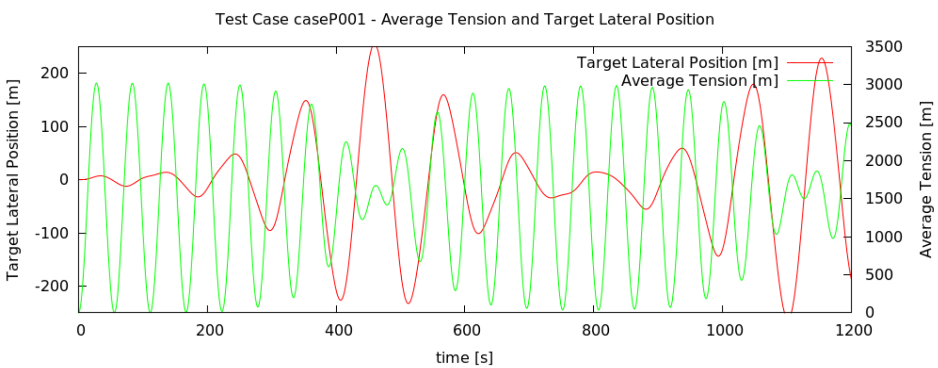
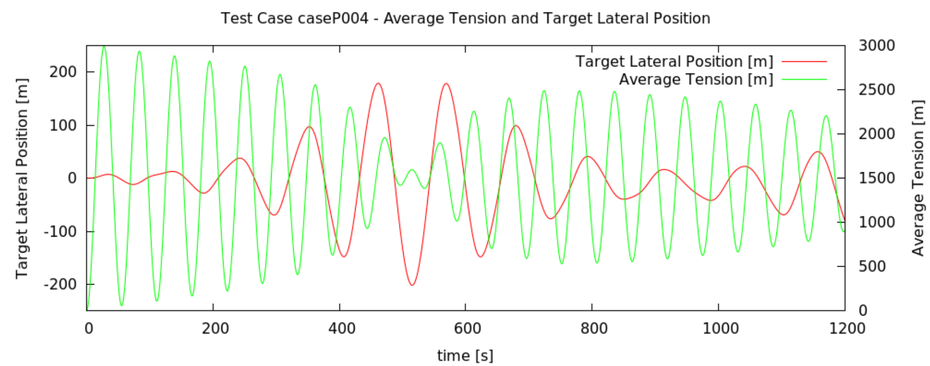
Results: 2D lateral motion, damping effect

- Lateral/longitudinal coupling not altered by damping
- Longitudinal oscillations damped → Lateral oscillations damped until a certain point
- Simulations carried out with “p”=2:

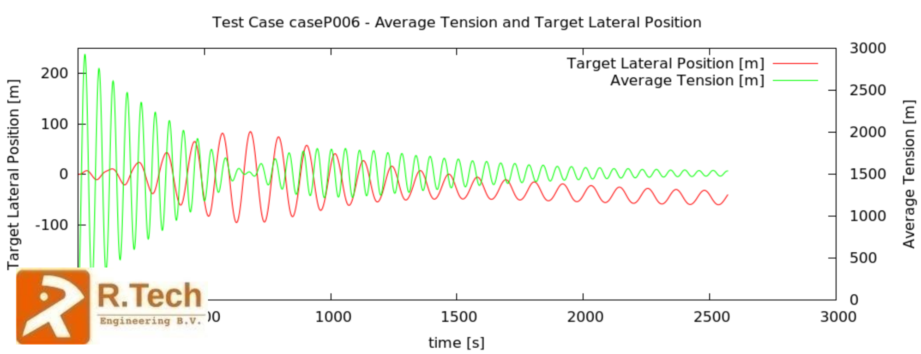


$\xi = 0\,\%$

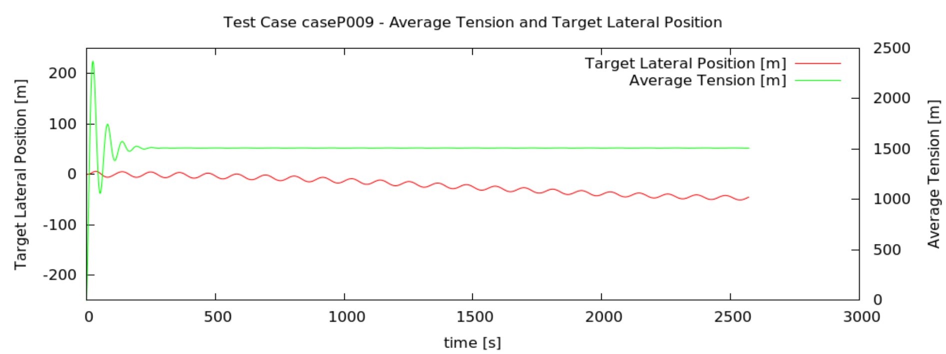


$\xi = 6\,\%$

$\xi = 20\,\%$



$\xi = 200\,\%$



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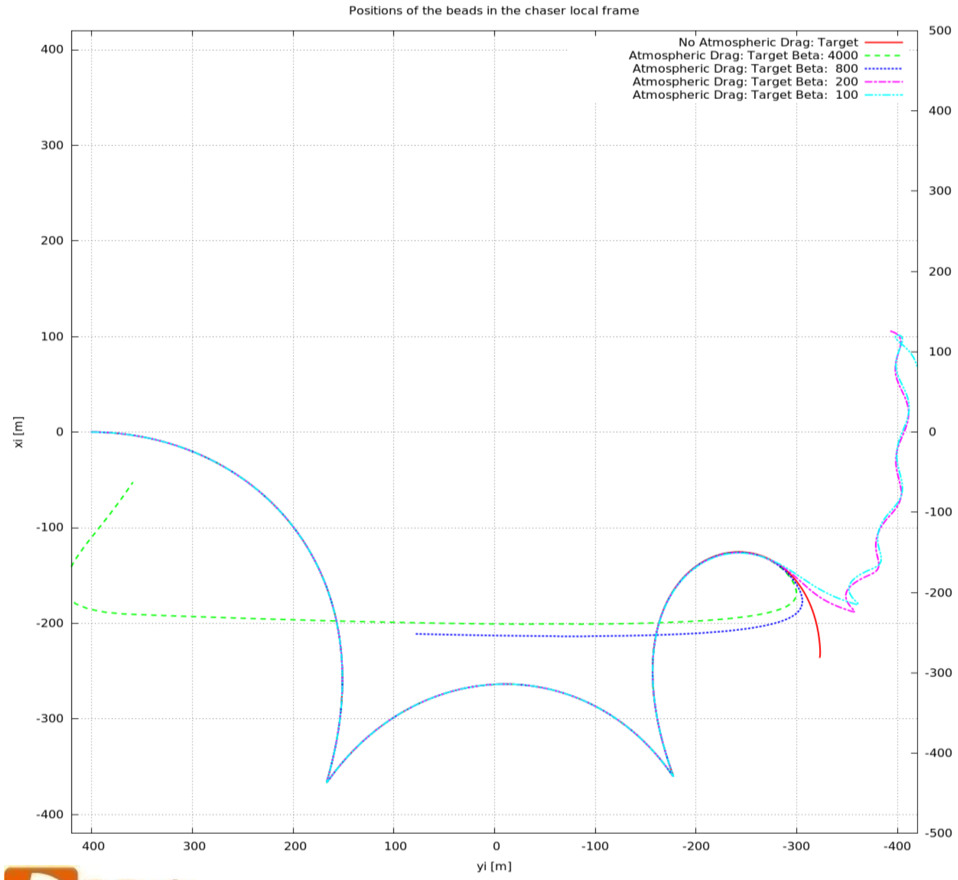
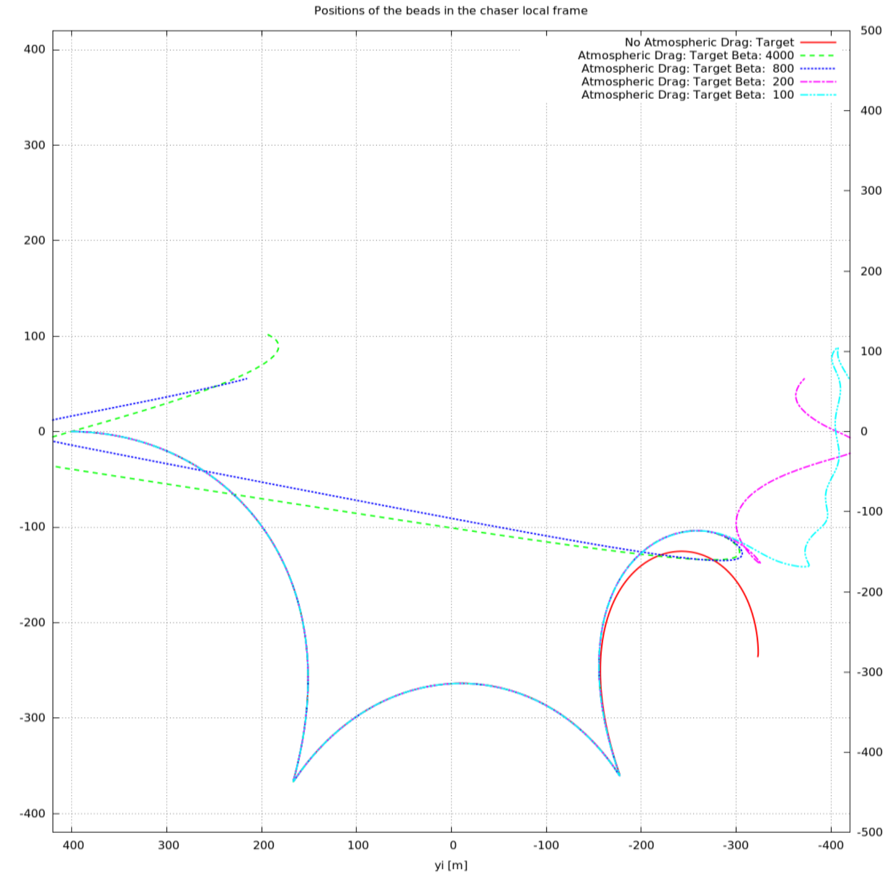
Atmosphere drag: low post burn velocity

- Post burn relative velocity: -0.5 [m/s]
- Chaser Ballistic coefficient: 500 [kg/m2]



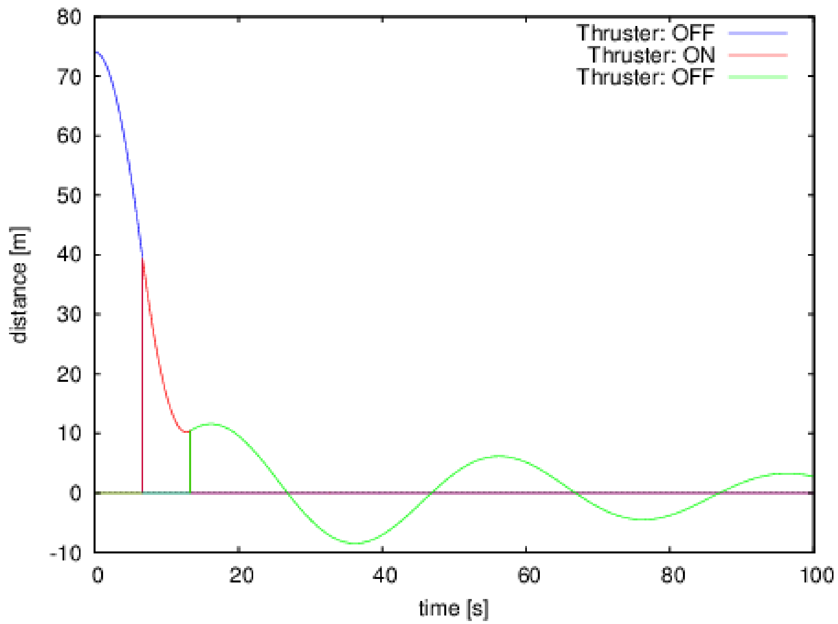
No tether drag



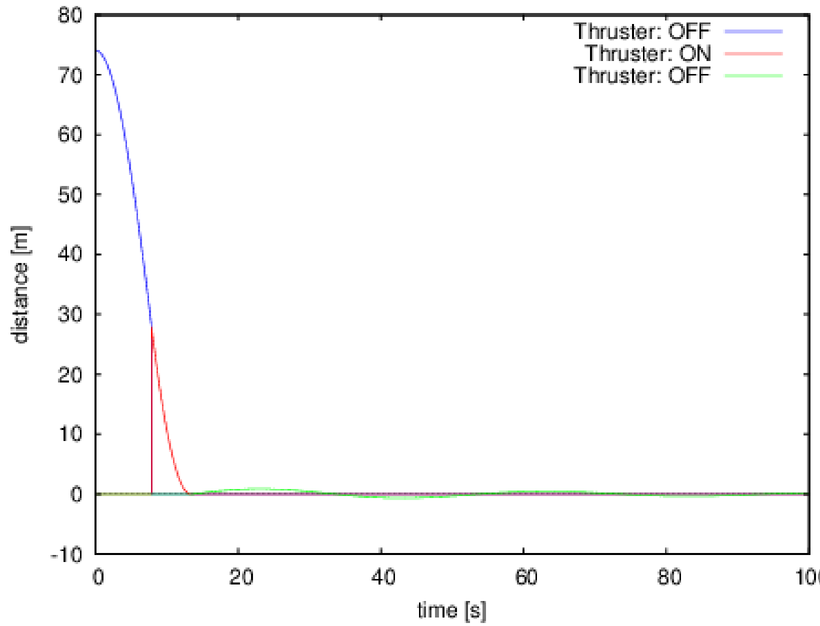
Tether drag inclusive

Results: Input shaping to mitigate lose of control

- Analytical solution <u>with damping</u> gives a good approximation
- Numerical simulation validate the analytical solution:
  - Simulation starts at the end of the main burn (time=0)



10% damping ratio system: Bang-off-bang using the undamped scheme



10% damping ratio system: Bang-off-bang using the damped scheme

NB: Solution (in green) are not representative of the system as soon as the distance is negative.

Energy

Energies: definitions

Potential of gravitation: $V_g = \sum_{i=0}^{N-1} -m_i \frac{GM_{Earth}}{R_i}$

Elasticity energy: $V_e = \frac{1}{2}\sum_{i=0}^{N-1} k_i\left(|\ \mathbf{R_{i+1}} - \mathbf{R_i}\ | - L_i^{eq}\right)^2$

Kinetic energy: $K_T = \frac{1}{2}\sum_{i=0}^{N-1} m_i|\ \dot{\mathbf{R}}_{\mathbf{i+1}} - \dot{\mathbf{R}}_{\mathbf{i}}\ |^2$

The total energy: $U = K_T + V_g + V_e$

Kinetic energy Center of gravity: $K_{CoG} = \frac{1}{2}\frac{\left(\sum_{i=0}^{N-1} m_i \dot{\mathbf{R}}_{\mathbf{i}}\right)^2}{\sum_{i=0}^{N-1} m_i}$

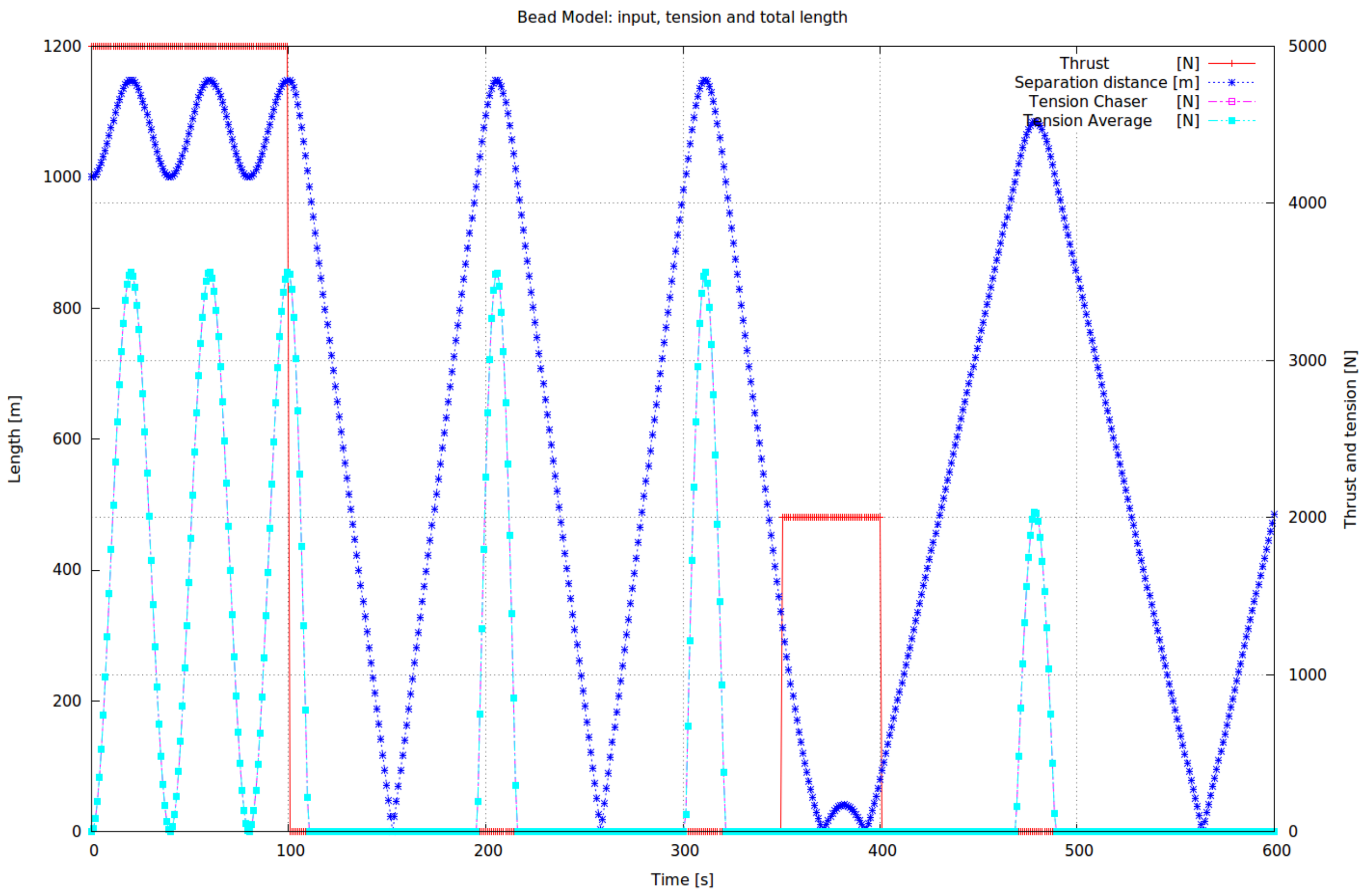
Difference of Kinetic Energy: $K_{int} = K_T - K_{CoG}$

The total energy: $U = U_{int} + U_{CoG}$

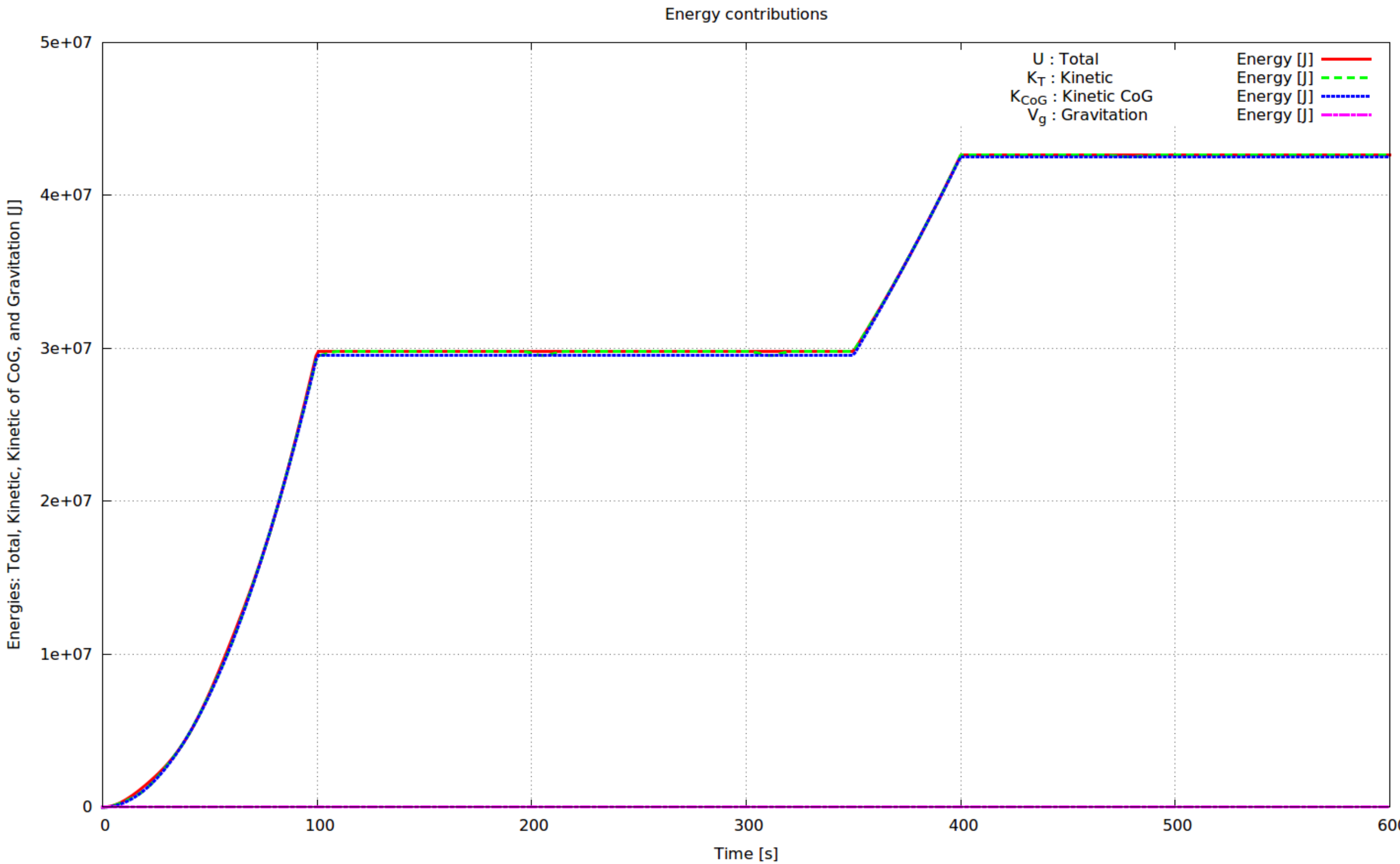
“Internal energy” : $U_{int} = K_{int} + V_e$

“Energy of the center of gravity”: $U_{CoG} = K_{CoG} + V_g$

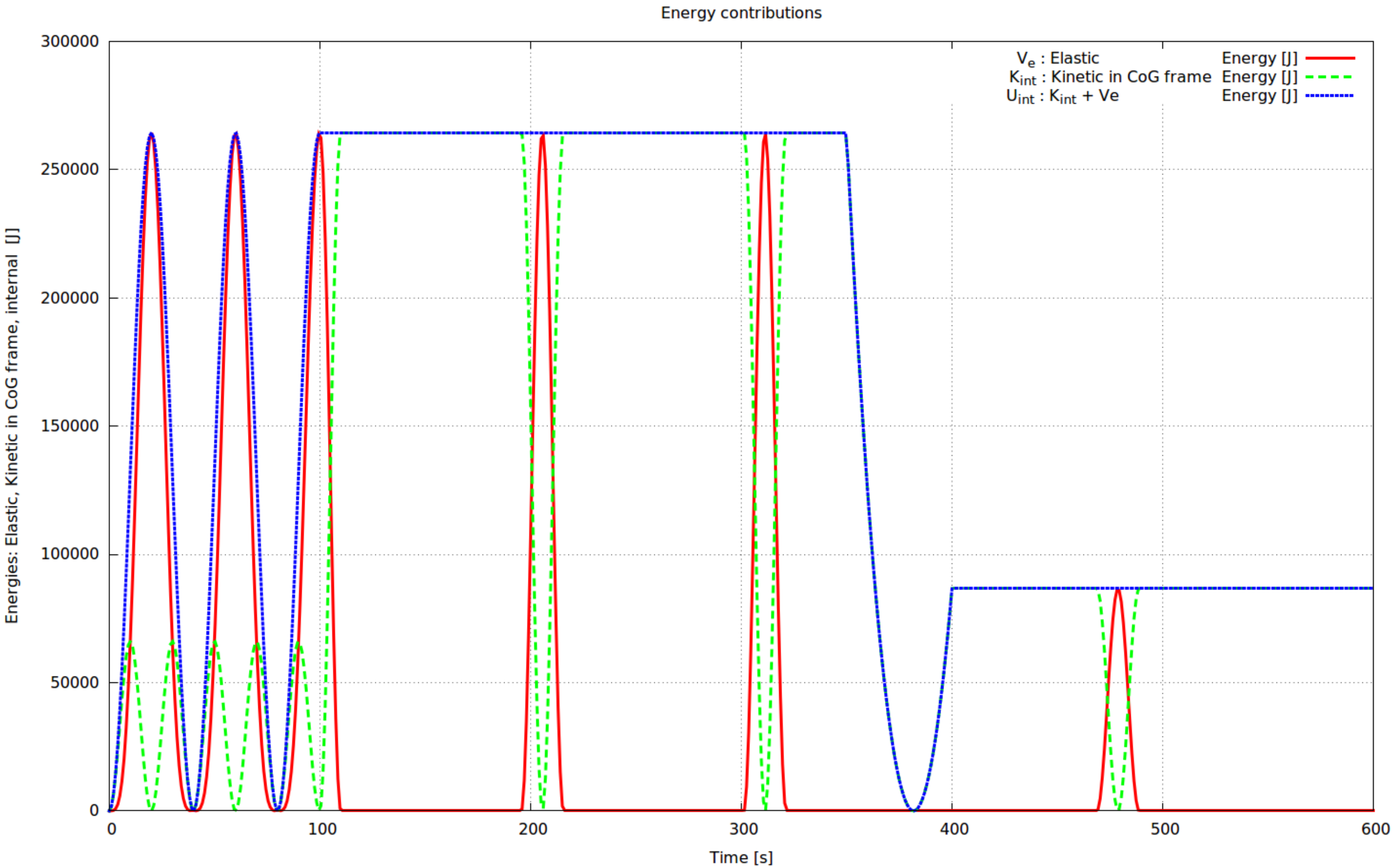
Energies: 1D example



Energies:


Energy contributions
U : Total
K_T : Kinetic
K_{CoG} : Kinetic CoG
V_g : Gravitation
Energy [J]
Energy [J]
Energy [J]
Energy [J]
5e+07
4e+07
3e+07
2e+07
1e+07
0
0
100
200
300
400
500
600
Time [s]
Energies: Total, Kinetic, Kinetic of CoG, and Gravitation [J]

Energies: without damping



Energies: with damping