Gravitational-magnetic tug

Combined gravitational and magnetic interactions for asteroid deflection

Renato Cirelli[1], Juan Luis Gonzalo[2] and Camilla Colombo[3]
Department of Aerospace Science and Technology, Politecnico di Milano, Italy
1 MSc Student, renato.cirelli@mail.polimi.it
2 Postdoctoral research fellow, juanluis.gonzalo@polimi.it
3 Associate professor, camilla.colombo@polimi.it

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INTRODUCTION

Near Earth Objects (NEOs) pose a great threat to our planet not only due to the direct consequences of a possible impact, but rather because of the long-term climatic effects it would induce.

Many **deflection strategies**, based on either impacting the NEO or gently pushing it for a long time, have been proposed to **reduce** its **impact probability** or to avoid its passage into an Earth's gravitational keyhole that would lead to a future impact.

Among these, the **Gravitational Tug (GT)** technique is the most straightforward Low Thrust Action (LTA) option in case of high warning time, contained asteroid mass and small targeted deflection at Minimum Orbit Intersection Distance (MOID). However, the GT often requires a Spacecraft (SC) with **limited thrust** capabilities to **non-inertial hover close to** the **target**. This may increase the **mission risk** and **reduces** the linear momentum transfer **efficiency** between NEO and SC.

The GT may be enhanced by the introduction of the NEO-SC's **magnetic interaction** that operates in **synergy with** the objects' **mutual gravitational attraction**, aiming to improve performance and operational conditions.

GOALS

Taking a classical GT as reference, the study [1] goals are

1. evaluate the possible improvements in deflection at MOID, introduced by the **simultaneous use** of the **gravitational** and the **magnetic interactions** between a NEO (target), with known natural global magnetisation state, and a SC (chaser), equipped with an onboard magnetic field generator and characterised by a **limited propulsive** and **power** generation **performances**.
2. estimate the **SC requirements** (e.g., generated magnetic dipole, allocated power mass) to maintain the tug for a specified time.

ASSUMPTIONS

The analysis is carried out considering two targets in course of impact with planet Earth (i.e., Braille and virtual* Apophis), and assuming:

- **Target** with spherical shape, uniform constant density, uniform constant **global magnetization state**, generic **tumbling state** about an inertially fixed rotational axis.
- **Chaser** with spherical shape, known mass at interception epoch, equipped with a power generation subsystem (PGS) and a propulsive subsystem (PS) composed by ion engines with **fixed performances** and adapted **canted geometry**, and equipped with a **Superconductive Magnets Subsystem (SMS)** capable of generating a magnetic dipole moment in any direction of space, regardless its attitude.
- Maximum **SC**'s **thrust proportional to** its **power mass**.
- Mutual magnetic interaction approximated by the **far-field equations** (free-free dipoles magnetic interactions [2]).
- **Target at** geometric **MOID** condition at the same time as Earth.
- The **tug** happens **from interception** epoch **until MOID** epoch.
- Interplanetary transfer to the target is not considered.
- **Reference GT** performing a **tangential LTA on** the **target**.

* It is assumed a specific magnetic dipole equal to the one of Braille.

REFERENCES

[1] R. Cirelli, "Gravitational-magnetic tug: an investigation on combined gravitational and magnetic interaction for asteroid deflection and control", 2021, Master's Thesis, School of Industrial and Information Engineering, Department of Aerospace Science and Technology, Politecnico di Milano, Italy.
[2] E. Fabacher, S. Lizy-Destrez, D. Alazard, F. Ankersen, "Guidance and navigation for electromagnetic formation flight orbit modification", EuroGNC, 13 April 2015 - 15 April 2015 (Toulouse, France).
[3] J. P. Sanchez, C. Colombo, M. Vasile, and G. Radice, "Multicriteria Comparison Among Several Mitigation Strategies for Dangerous Near-Earth Objects," *Journal of Guidance, Control, and Dynamics*, vol. 32, no. 1, Art. no. 1, Jan. 2009.

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METHOD AND RESULTS

I - MAGNETIC LTA STATIC ANALYSIS

- Target-chaser **relative distance sensitivity** to select a test target and compare the magnetic and gravitational LTAs.
- Target-chaser **relative orientation sensitivity** to evaluate the maximum and minimum magnetic LTAs, a selected **Dipole Control Laws** (DCLs)
  - **Target-pointing DCL**
    Magnetic interaction always pointing to the target.
  - **B-field aligned DCL**
    Magnetic interaction is such that the magnetic torque disturbance on the chaser is absent.

II – GRAVITATIONAL MAGNETIC TUG (GMT)

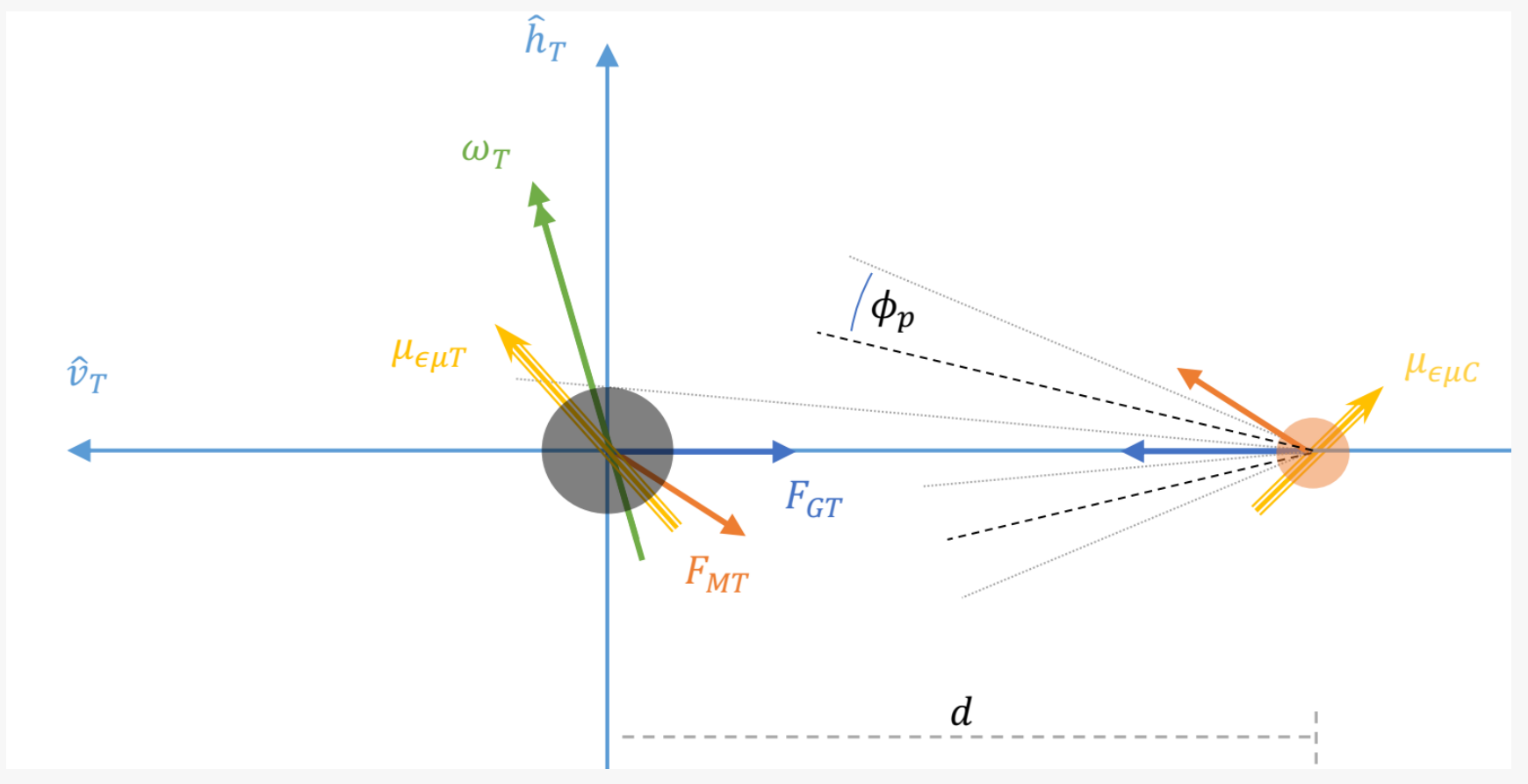
GMT designed assuming the **worst target-chaser relative orientation** possible (target's dipole orthogonal to target's orbital plane) that leads to the **most demanding magnetic dipole** generated by the chaser.

- **Fixed relative hovering distance** [3] that satisfies non impingement and tug maintainability for a given total tugging time, assuming a **tugging mode** (TM)
  - **TM1**
    Magnetic interaction ν times the gravitational one, at interception epoch, and **fuel mass consumption compensation** during the tug.
  - **TM2**
    Magnetic interaction ν times the gravitational one for the entire duration of the tug.
  - **TM3**
    Magnetic interaction ν times the gravitational one, at interception epoch, and **constant magnetic dipole** for the entire duration of the tug.
- SC **power mass allocation** between thrust and magnetic dipole generations.
- **GMT-GT performance comparison** propagating using Gauss' planetary equations.
- **GMT sensitivity analysis** with respect to a selected group of model parameters (e.g., magnetic amplification factor ν, power mass repartition, chaser's PS and PGS efficiencies).

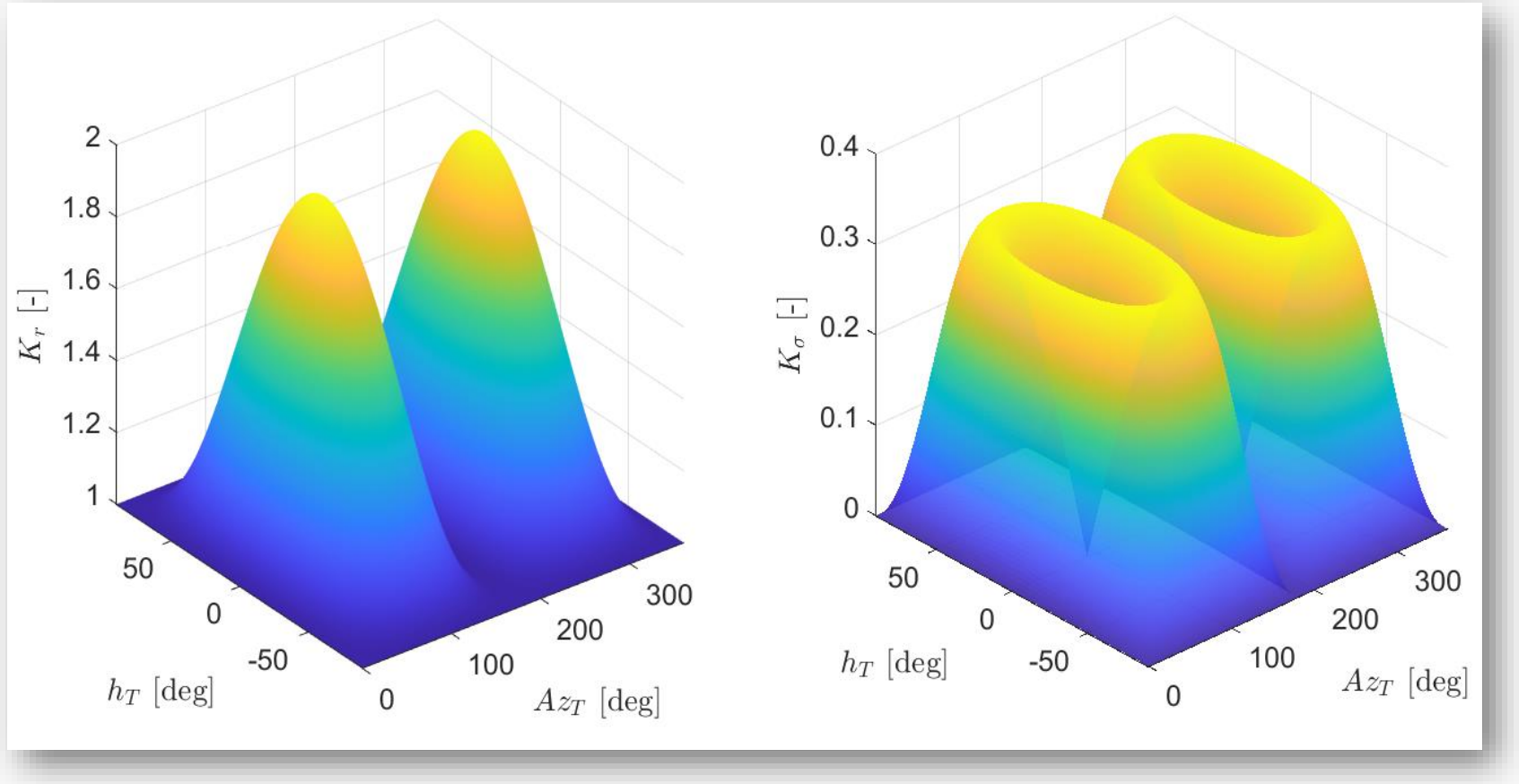
III - RELATIVE TARGET-CHASER DYNAMICS

Dynamics written in nominal target's Local Vertical Local Horizontal (LVLH) frame, using GMT-TM3 on virtual target, assuming **an initial target's tumbling state**, and a **chaser designed for nominal** interaction **condition**.

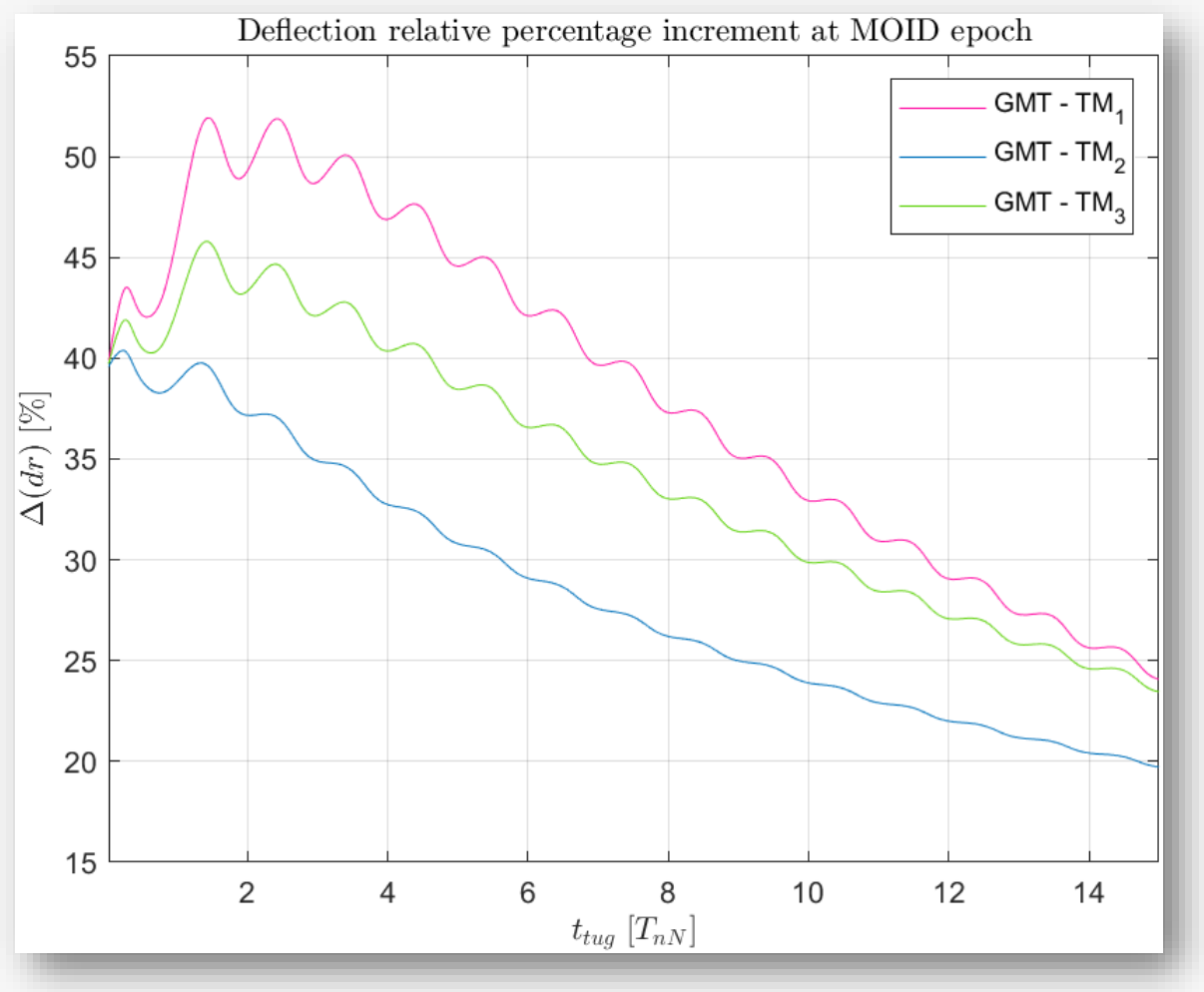
- **Shifted** maintainable **hovering distance** due to fixed chaser's performance.
- Chaser's **AOCS workload** with proposed DCLs.
- GMT performance evaluation **with/without** SC's magnetic **dipole. magnitude modulation.**
- GMT performance **sensitivity to** the **target's magnetic dipole evolution** (i.e., Azimuth, elevation) in the target's NTH frame.



GMT represented in the target's Normal Tangential (NTH) frame.



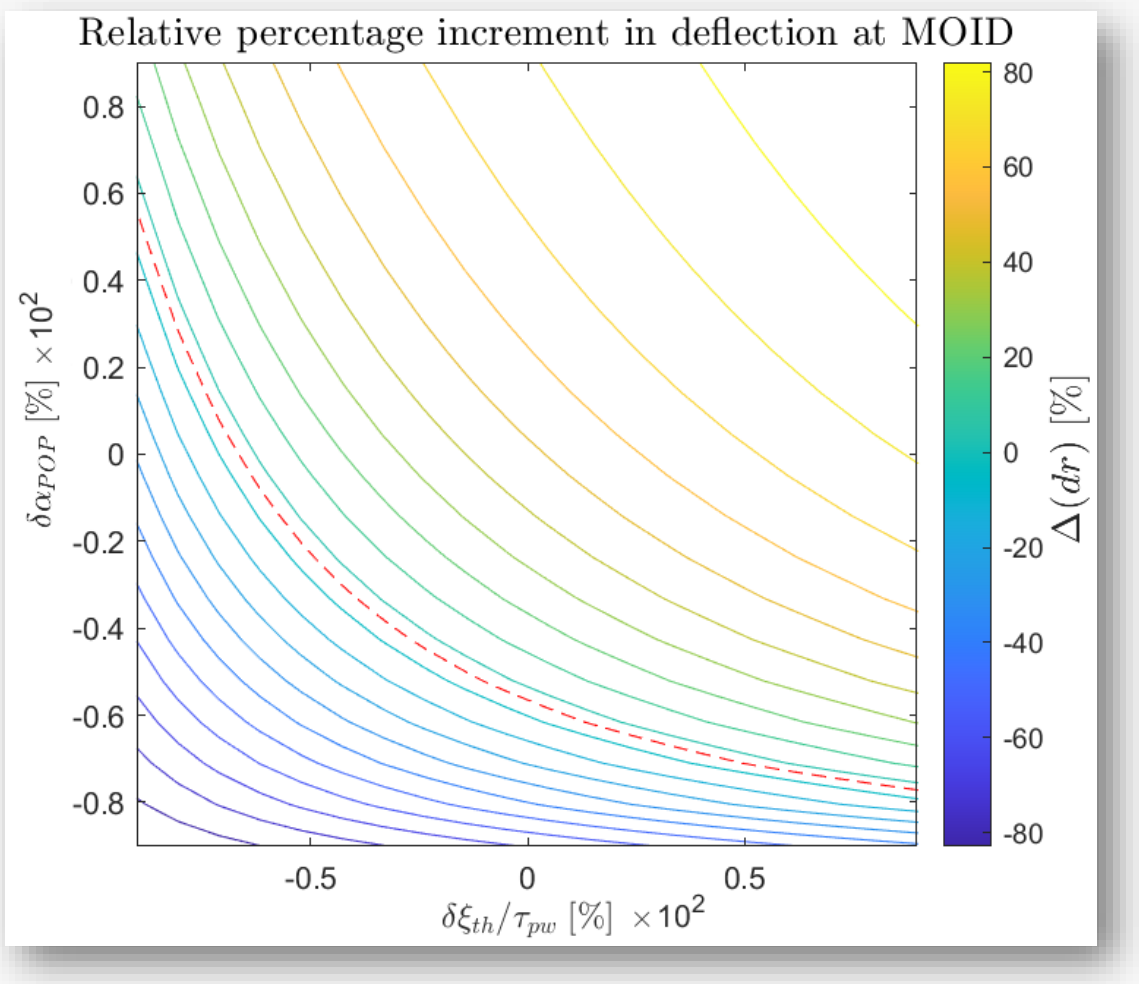
Normalized radial and transversal magnetic LTA components using B-field aligned DCL as a function of the target's dipole orientation (i.e., Azimuth, elevation) in the target's NTH frame.



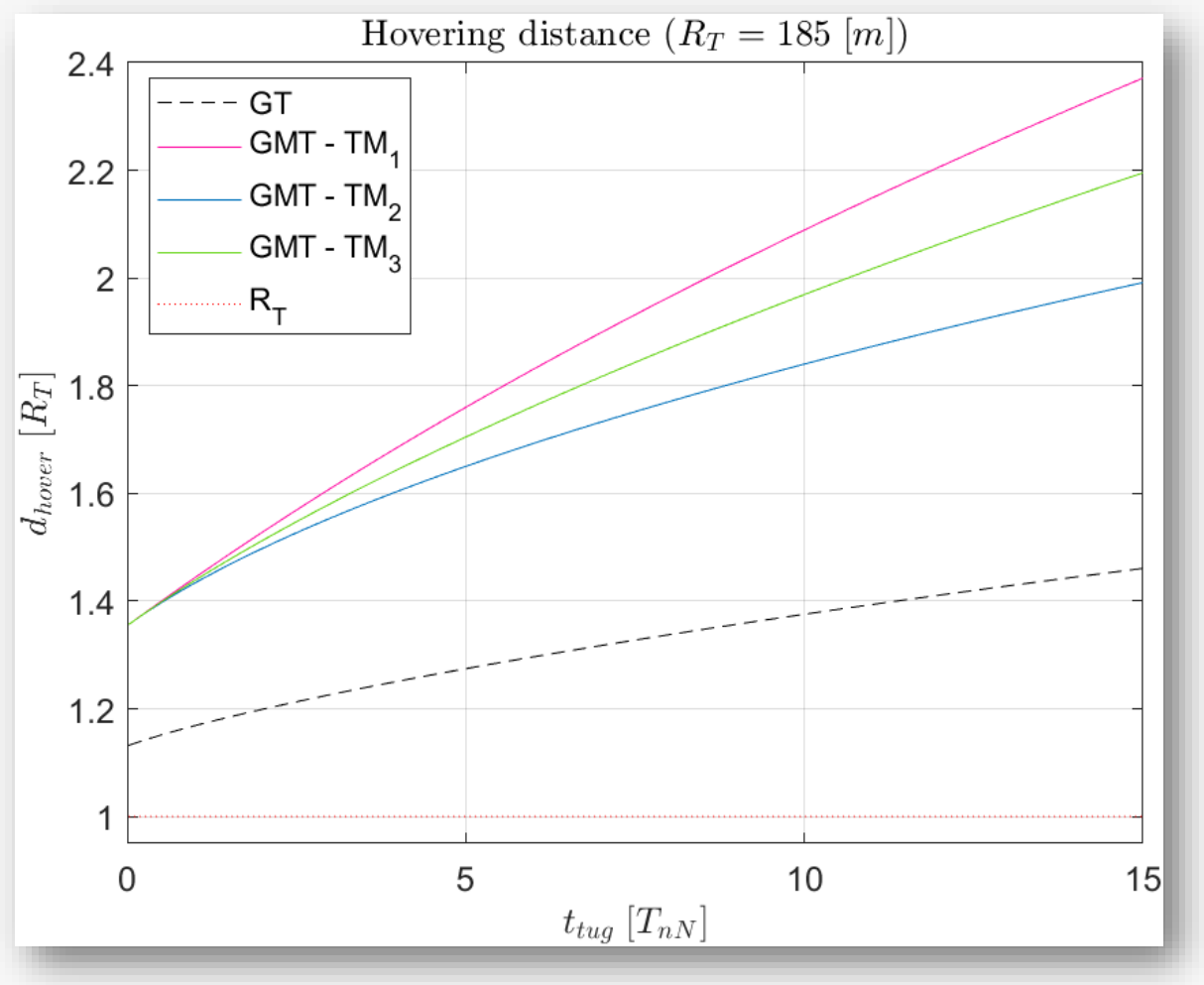
Virtual target deflection percentage increment # using GMT with respect GT, evaluated at nominal MOID epoch.

Tugging Mode	TM1	TM2	TM3
Magnetic fuel mass compensation	✓		
Magnetic amplification	✓	✓	✓
Constant dipole magnitude			✓

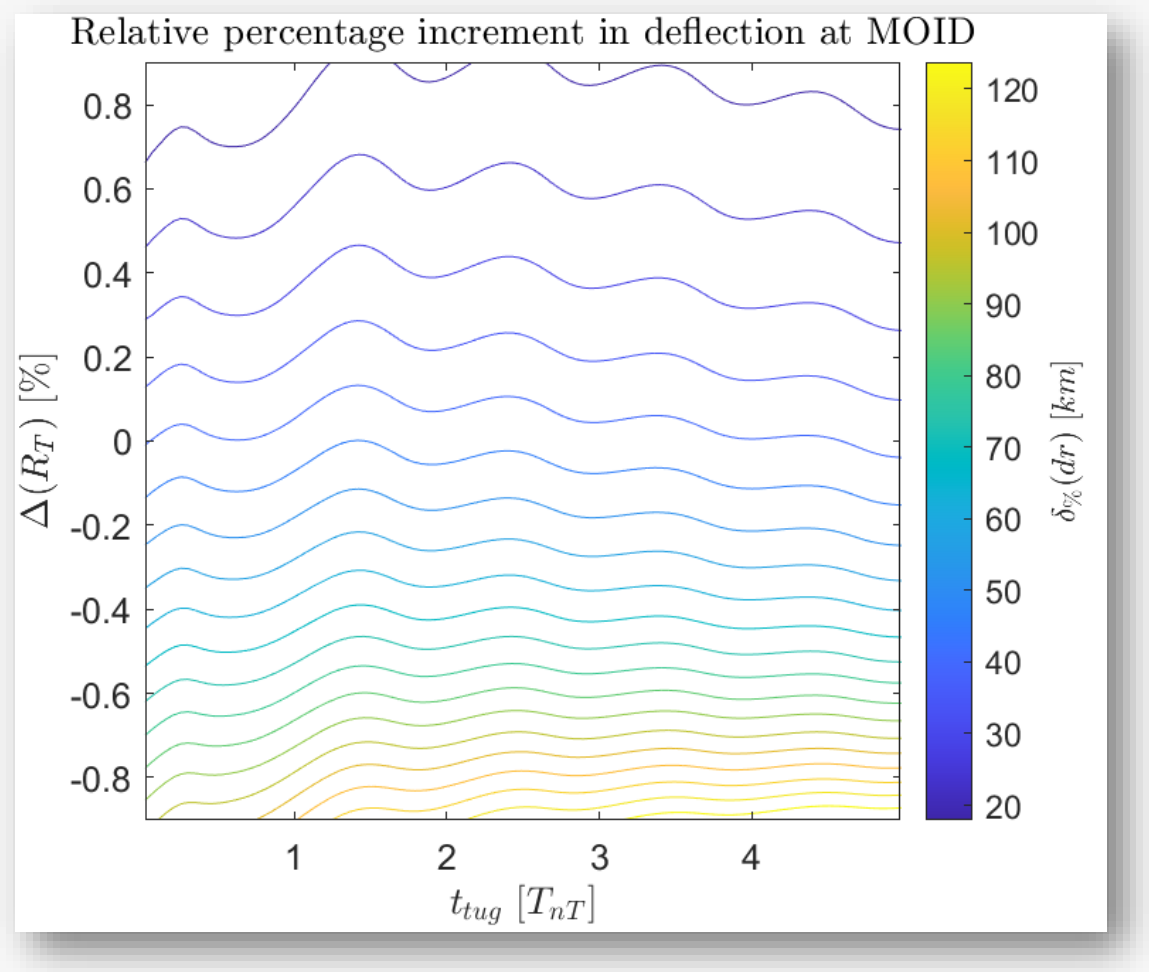
Tugging modes summary



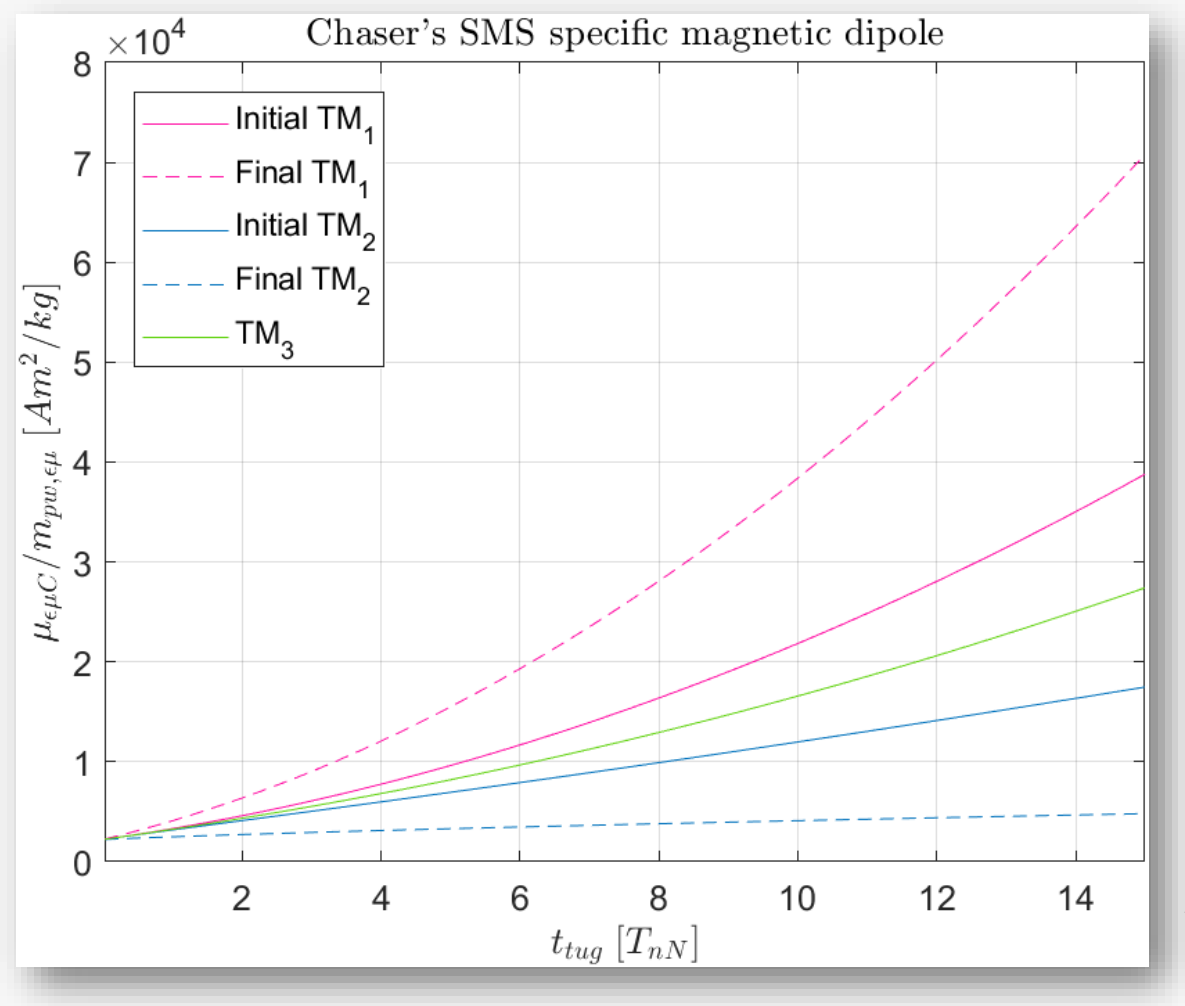
GMT performance*# sensitivity to the power mass repartition and to the ratio of PS and PGS efficiencies. Evaluated at optimal total tugging time.



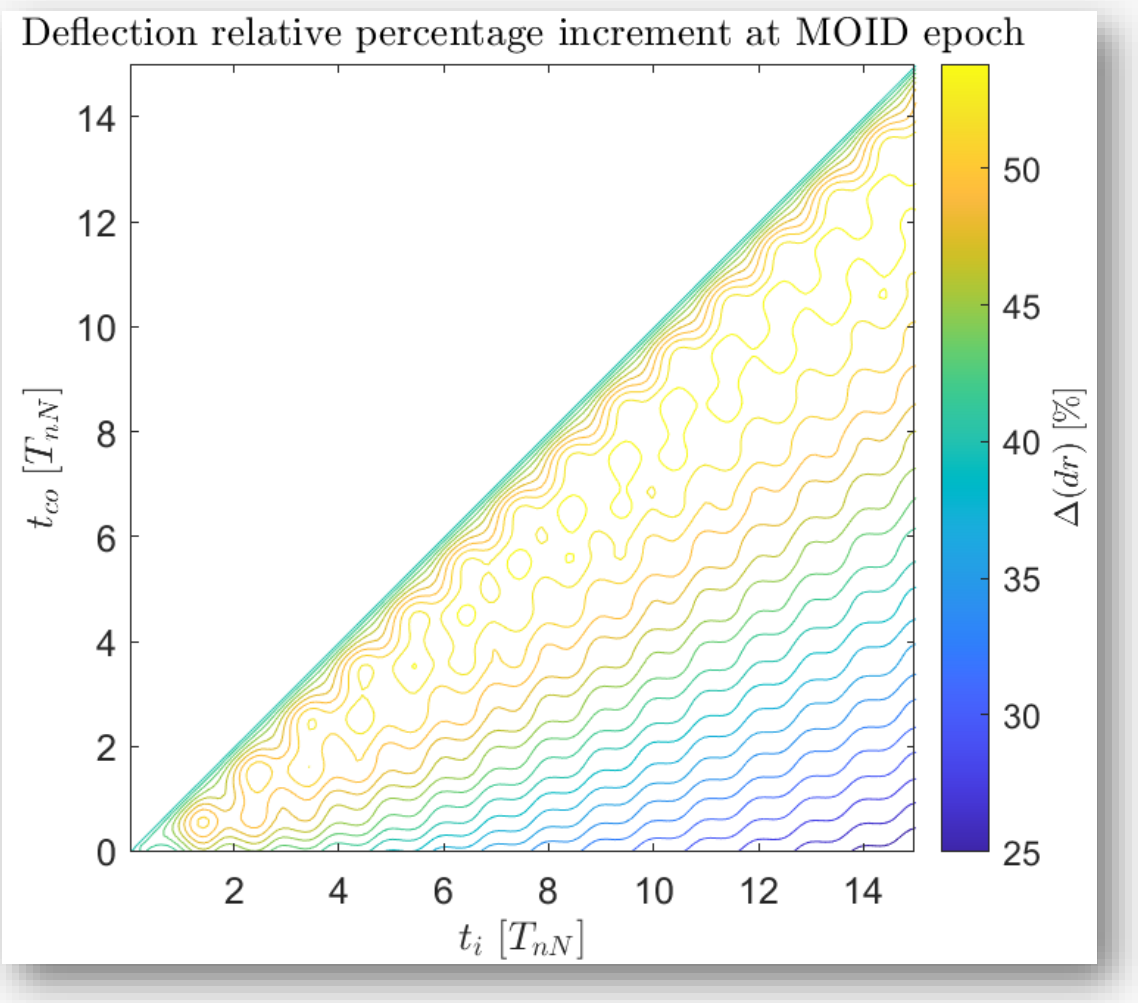
Hovering distances# as a function of the total tugging time.



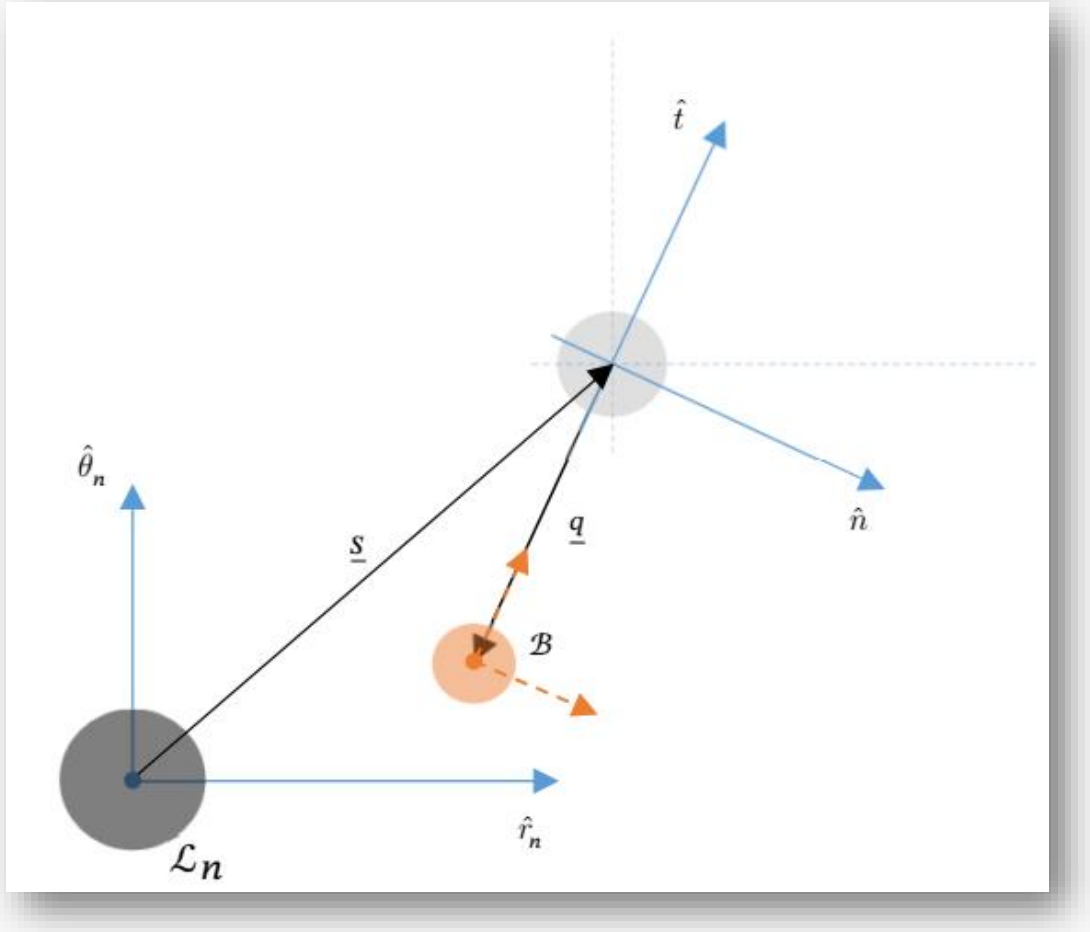
GMT performance*# sensitivity to the target's equivalent radius and total tugging time. Evaluated at constant target's density.



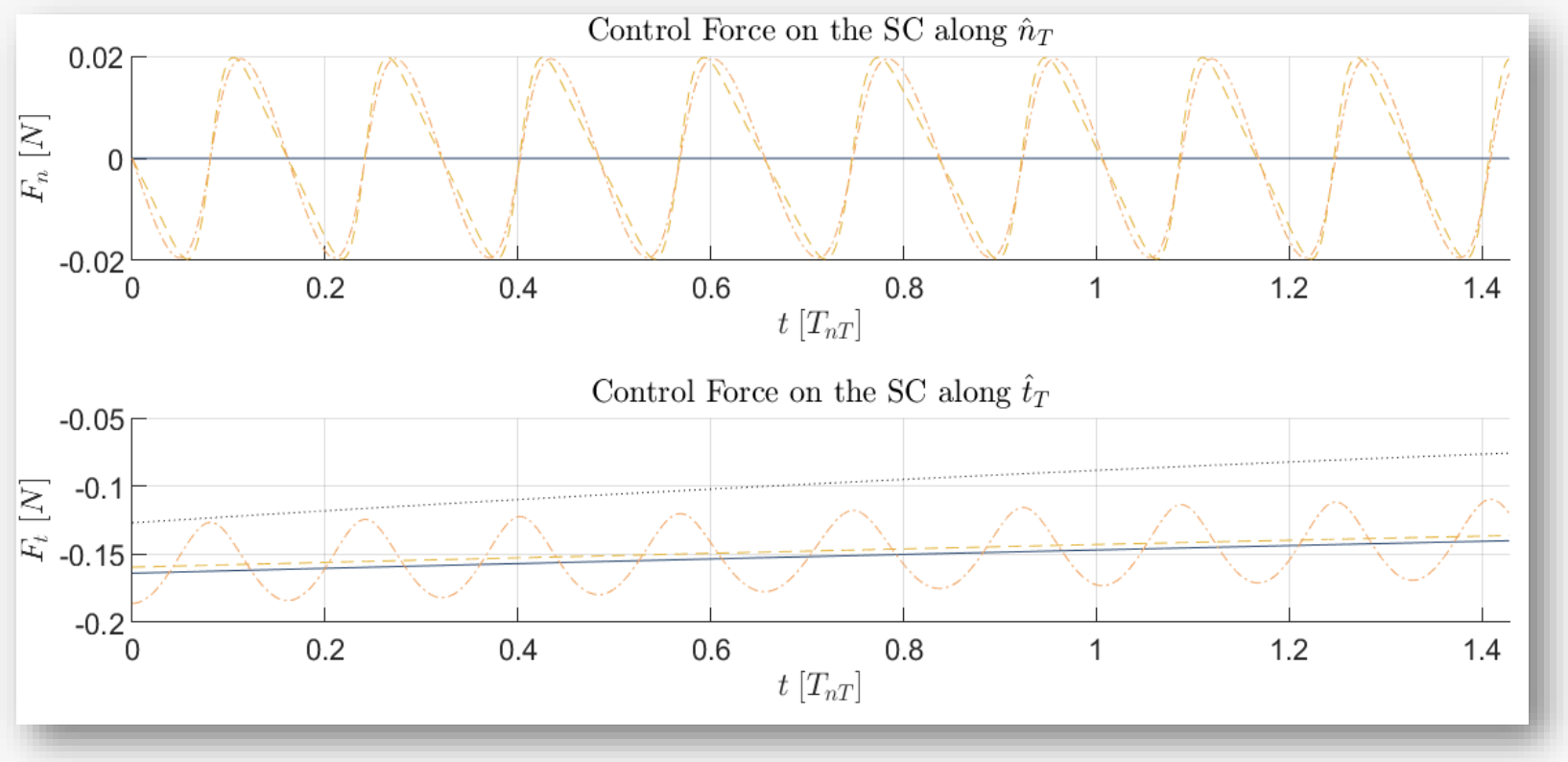
Initial and final chaser's SMS efficiency for the proposed GMT tugging modes #



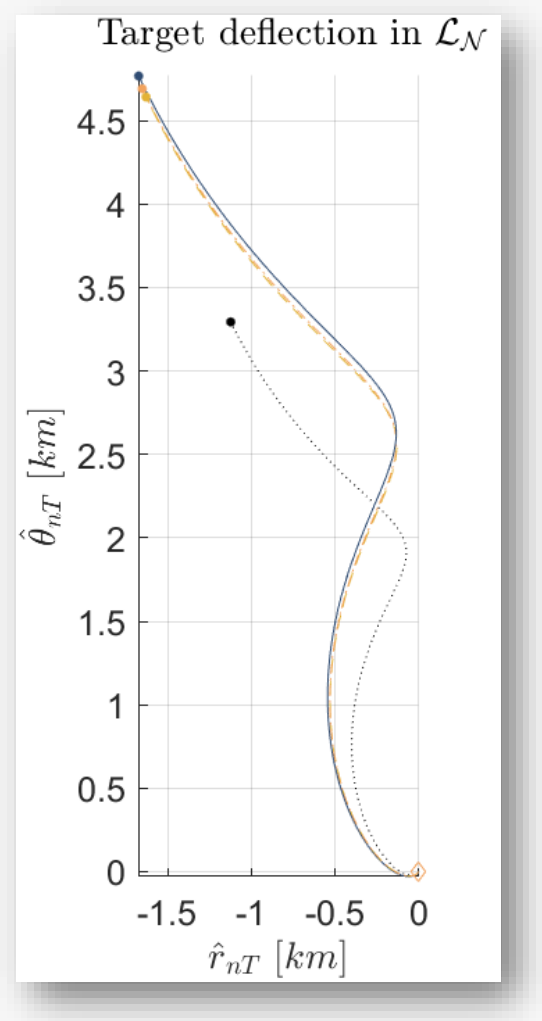
GMT performance*# sensitivity to interception and cut-off epochs prior to MOID condition.



SC (red sphere) performing a non-inertial hover seen in the NTH frame of the target (light grey sphere) and target's deflection seen in the LVLH frame of the nominal target (dark grey sphere).



Chaser's ideal control force* in target's NTH frame, with null target's dipole elevation (i.e., dipole contained in the orbital plane of the target) and using B-field aligned DCL.



GMT deflection*§ seen in the nominal target's LVLH frame.

NOTES: results for virtual target. #In design conditions *Adopting TM3 §Adopting the B-field aligned DCL.

CONCLUSIONS

- A chaser adopting **GMT** may achieve a **higher deflection** than the one obtained with a classical GT, for fixed chaser's mass at interception and fixed performance.
- **GMT** allows a **farther hovering distance**, resulting in **safer** operational conditions, and **longer maintainable total tugging times**.
- SMS shall be able to operate with the allocated power mass, integrable in the chaser's structure and it shall generate a **magnetic dipole higher than** the one achieved by the most performant **nowadays technology**.
- The **GMT performance** is **highly affected by** the **evolution of** the **target's dipole orientation**. However, for both DCLs, it **remains greater than** the **GT** one, when evaluated for the nominal total tugging time.
- The **relative hovering distance shift** is decreasing the fuel mass consumption, allowing to **maintain the tug for** a **total tugging time greater than** the **nominal** one. This leads to better performance, when the GMT operates on a thrusting arc close to interception and far from MOID epoch.
- **B-field aligned DCL** grants the **highest magnetic torque on** the **target** and the **lowest AOCS workload** during operations. Possibility to control its attitude while tugging.