# Scalable Multi-Spacecraft Hybrid Electromagnetic Strategies for Non-Contact Asteroid Deflection


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## Introduction

- **Risk:** Near-Earth asteroids threaten Earth; kinetic and nuclear options risk fragmentation or complex operations.
- **EM Deflection:** Charge spacecraft + asteroid to apply Coulomb, magnetic & Lorentz forces without contact.
- **Swarms:** Multi-spacecraft formations reduce per-craft $\Delta$v and power needs.
- **Case Studies:** Kete simulations for Apophis & 2025 HX quantify $\Delta$v, station-keeping and TRL readiness.

## Key Contributions

- Modeling of electrostatic, magnetostatic, and electromagnetic forces for asteroid deflection.
- Side-by-side numerical simulation of five primary and three hybrid methods using the open-source Kete toolkit.
- Analysis of cumulative $\Delta$v vs. engagement time for asteroids of very different mass regimes (Apophis vs. 2025 HX).
- Scalability study: multi-spacecraft formations to boost net deflection and reduce per-craft requirements.
- Feasibility assessment and subsystem TRLs.

## Methodology

1. **Force Modeling:** Coulomb, magnetostatic, and Lorentz forces (Eqs. 1–3).
2. **Simulation Framework:** Extend Kete with custom force-model classes and PD station-keeping controllers.
3. **Case Studies:** Parameterize for 99942 Apophis and 2025 HX; set standoff = 100 m, $\Delta t$ = 3 min.
4. **Hybrid Architectures:** Combine Gravity Tractor (GT), Electrostatic Tractor (ET), and Ion-Beam Shepherd (IB) in three hybrid modes.
5. **Performance Metrics:** Track cumulative $\Delta$v, separation error, and agility of station-keeping.

## Force Models

Coulomb force:

$$\mathbf{F}_{\mathrm{E}} = k_e \frac{q_S\, q_A}{r^2}\,\hat{r} \tag{1}$$

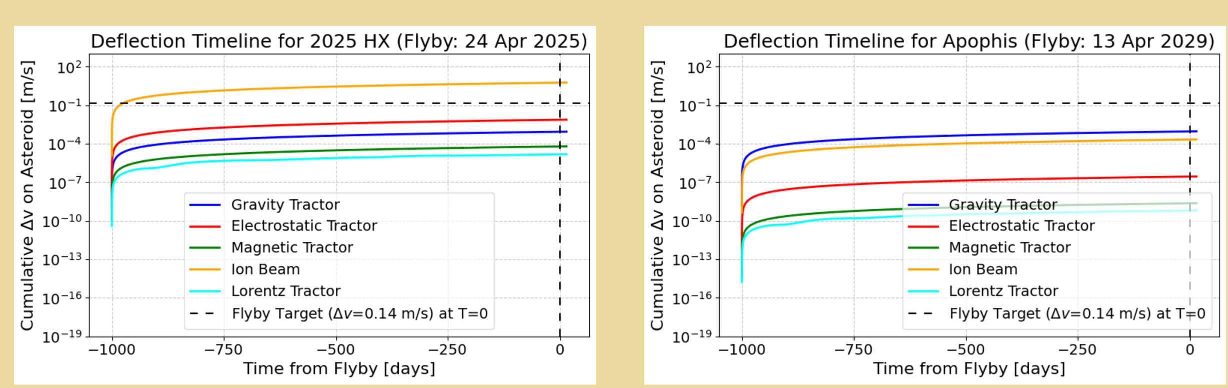
Magnetostatic (dipole–dipole):

$$\mathbf{F}_M = \frac{3\mu_0}{4\pi r^4}\Big[(\mathbf{m}_1\cdot\hat{\mathbf{r}})\,\mathbf{m}_2 + (\mathbf{m}_2\cdot\hat{\mathbf{r}})\,\mathbf{m}_1 + (\mathbf{m}_1\cdot\mathbf{m}_2)\,\hat{\mathbf{r}} - 5\,(\mathbf{m}_1\cdot\hat{\mathbf{r}})(\mathbf{m}_2\cdot\hat{\mathbf{r}})\,\hat{\mathbf{r}}\Big] \tag{2}$$

Lorentz Force:

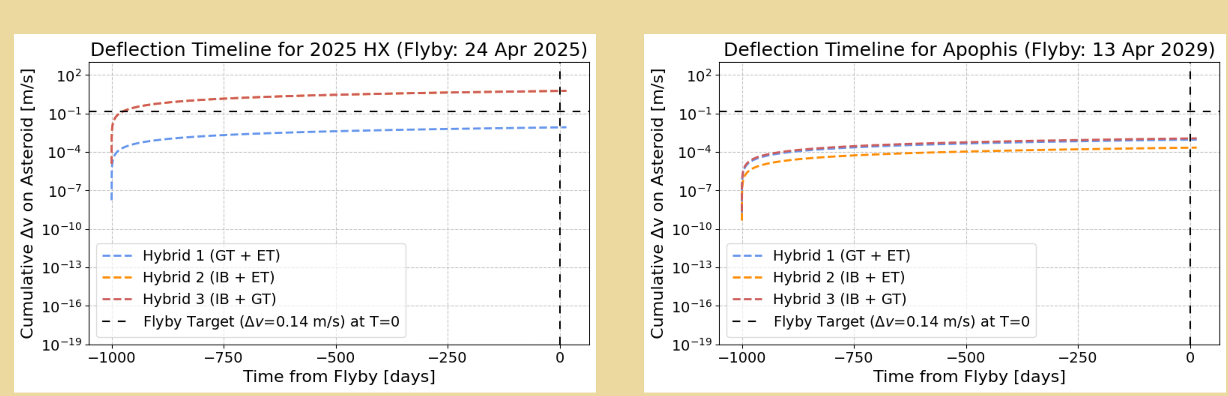
$$\mathbf{F}_L = q(\mathbf{E} + \mathbf{v}\times\mathbf{B}) \tag{3}$$

## Results for Single Spacecraft




(a) 2025 HX (b) 99942 Apophis

Figure 1: Cumulative $\Delta$v imparted by five primary deflection methods for two different asteroids.




(a) 2025 HX (b) 99942 Apophis

Figure 2: Cumulative $\Delta$v imparted by three hybrid deflection methods for two different asteroids.

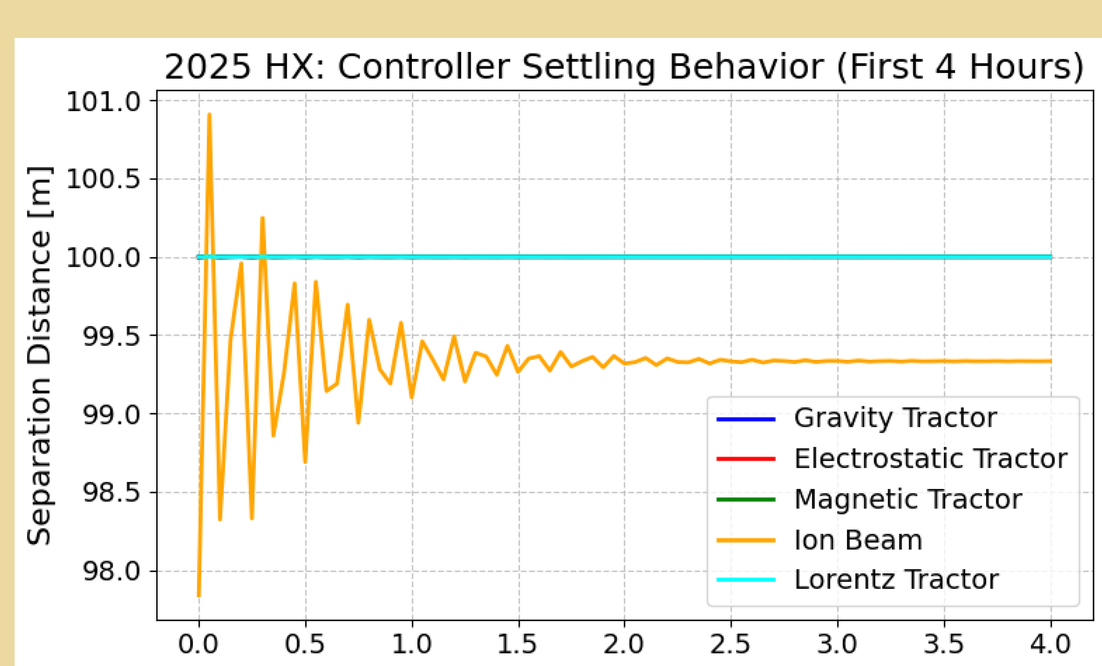



Figure 3: Transient separation response under PD control ($K_p$=0.0001, $K_d$=0.001).

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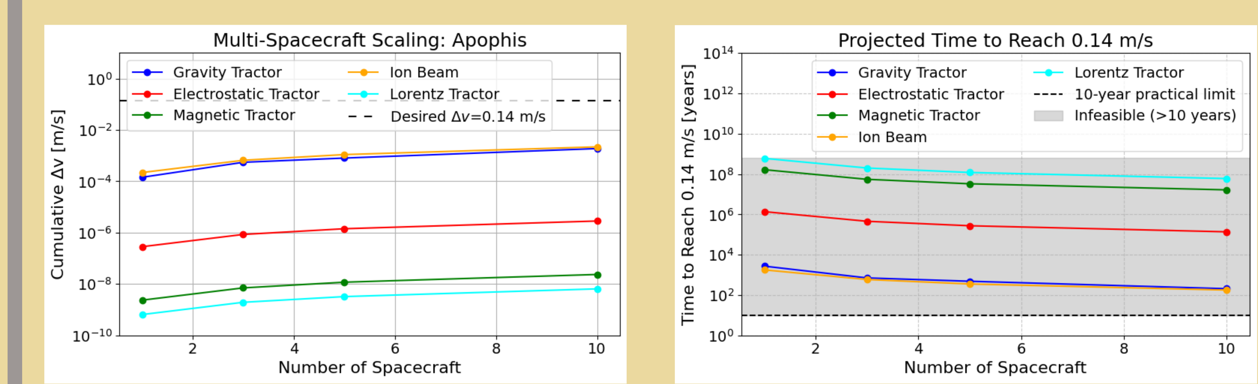
## Results for Multi-Spacecraft




(a) (b)

Figure 4: (a) Cumulative $\Delta$v over a 3-year mission vs. fleet size and (b) extrapolated time to reach $\Delta$v = 0.14 m/s vs. fleet size. Dashed line = 10-year feasibility; shaded area = beyond the practical timeline.

## Feasibility & Technology Readiness

- **Conductivity & Electrostatics:** High-conductivity (M/C-types) → strong Coulomb forces; low-conductivity (S-types) → limited charge unless seeded.
- **Magnetic Susceptibility & MT:** Paramagnetic (olivine-rich) asteroids couple to magnetic tractors; diamagnetic regolith yields near-zero force.
- **Surface Cohesion & IBS:** Fine, loose regolith (high sputter yield) → efficient ion-beam thrust; solid rock/porous interiors → reduced efficacy.
- **Mass Density & GT:** Deflection $\propto$ target mass; denser bodies demand more station-keeping thrust; porous C-types require less.
- **Mechanical Strength & Kinetic Impactors:** β-factor rises with porosity/regolith cover; coherent silicates produce lower ejecta mass.

## Conclusions

- Ion-beam shepherds deliver the highest $\Delta$v among all non-contact methods.
- Electrostatic tractors show significant promise.
- Ion-Gravity (IB+GT) hybrids yield synergistic gains for mid-mass targets.
- Electromagnetic methods, though at lower TRLs, bring flexibility, reusability, and minimal fragmentation.
- Next steps: address plasma interactions, charge leakage, spacecraft attitude dynamics, and multi-craft coordination.

## References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