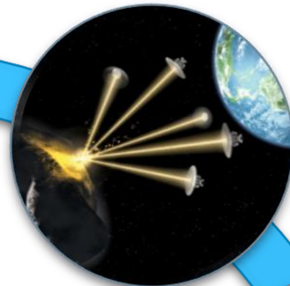
TASK 5.2 – UPDATE FEBRUARY 2023

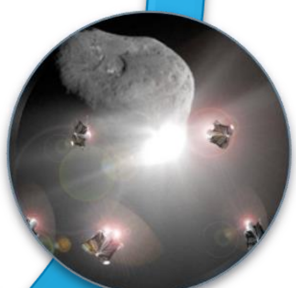
Massimiliano Vasile

Agenda



Task 5.2

Deflection Decision Support System



NEO Related Activities

Future Activities

Task 5.2

- Activities on Task 5.2 supported by Stardust-R
  - Development of an Intelligent Decision Support System (IDSS) for the selection of deflection action.
  - Extended uncertainty models for all deflection methods in the current IDSS
- NEO Related Activities
  - Landing dynamics and control of Juventas and Milani on Dimorphos
  - Close flyby of impact crater
  - Optical close proximity navigation

Intelligent Decision Support System (IDSS)

Yirui Wang, Massimiliano Vasile, Intelligent selection of NEO deflection strategies under uncertainty, Advances in Space Research, 2022.

Scope

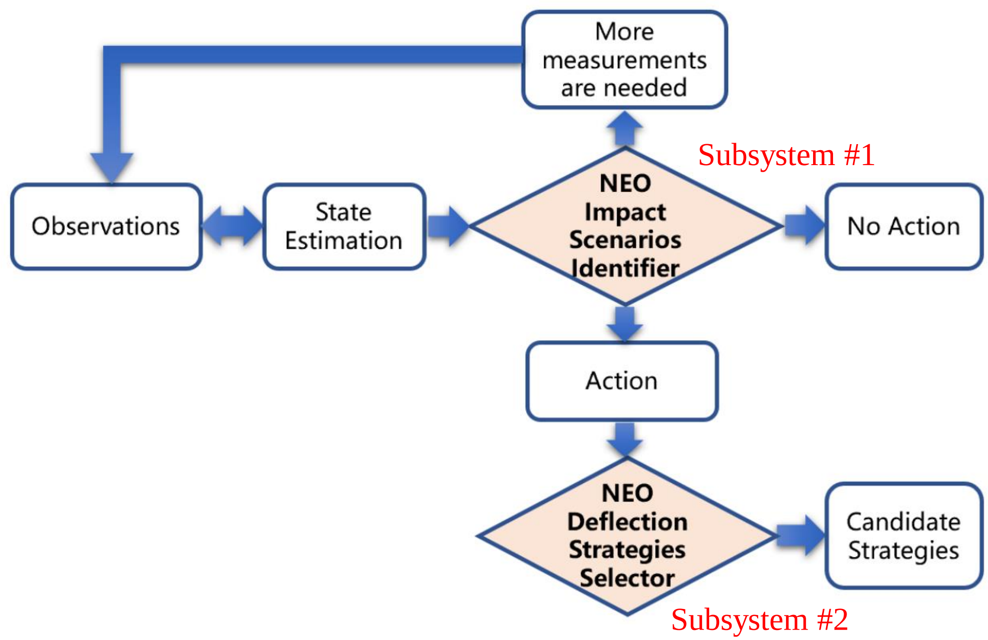
- First estimation of deflection technology to be employed
- Recommendation on optimal action in response to a threat scenario

Input:

- Warning time
- Orbital Elements of the NEO
- Diameter of the NEO
- Uncertainty of Orbital Elements
- Uncertainty of Diameter

Output:

- If the NEO is dangerous enough to implement deflection?
- Which deflection strategy is most efficient and reliable?



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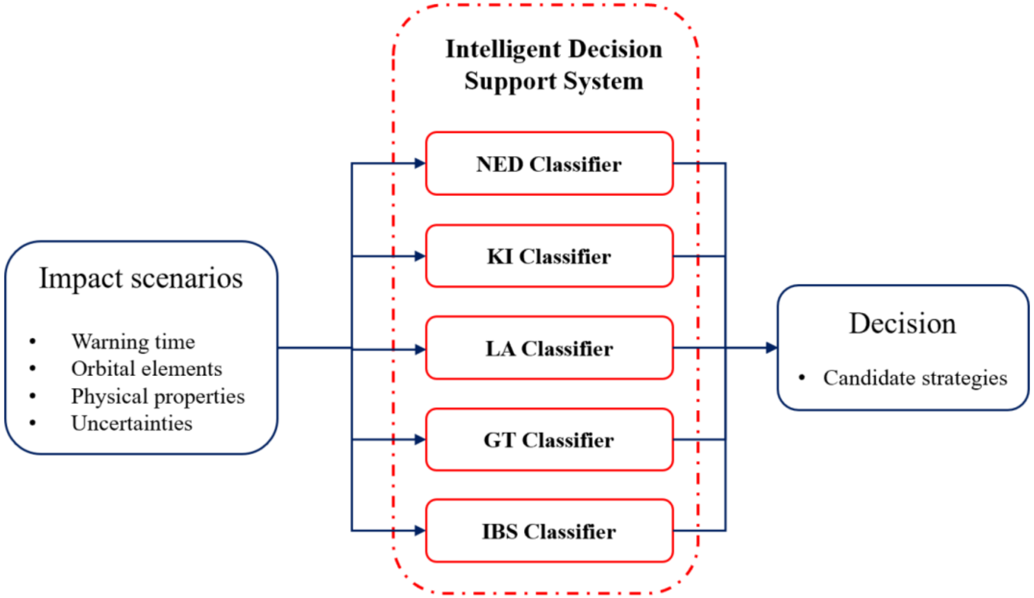
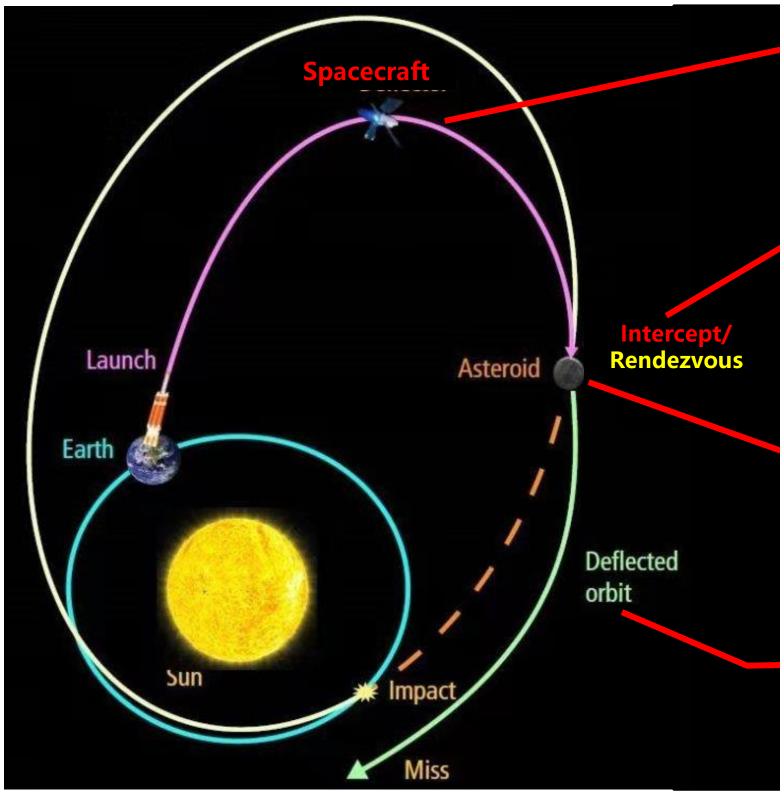


Generation of mission scenarios



Transfer trajectory
- Impulsive
- Low-Thrust

Deflection mechanism
- Impulsive methods
- Slow-push methods

Uncertainties
- Ephemeris uncertainty
- Physical uncertainty

Post-deflection trajectory
- Numerical model
- Analytical model

Constraints
- Warning time
- Launch window
- Launch performance
- Spacecraft system

$$f(\boldsymbol{d},\boldsymbol{u}) = P'_c$$

$$\min_{d\in D}\max_{u\in U} f(\boldsymbol{d},\boldsymbol{u})$$

Optimisation Algorithm
- MP-AIDEA
- SQP
- ...

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Generation of mission scenarios

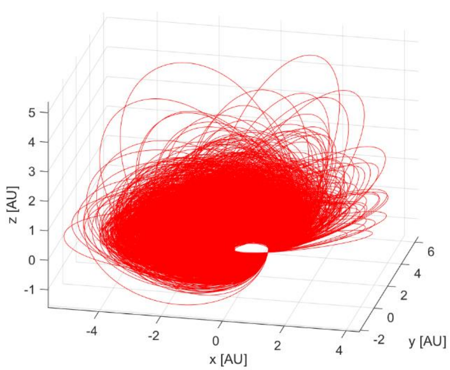
- Download NEO database from JPL Small-Body Database Browser
- Fix $a, e, incl$ and modify the rest of orbital elements

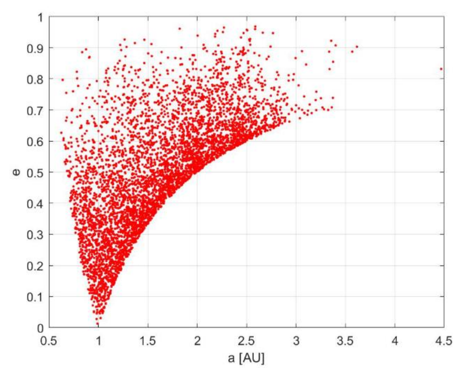
$$\begin{cases} \Omega = 0 \\ 1AU = \dfrac{a(1-e^2)}{1+ecos\omega} \\ \theta = 2\pi - \omega \end{cases}$$

s.t. $a(1-e) < 1AU$ and $a(1+e) > 1AU$

- Simulate uncertainties into the orbit and the diameter of the NEO

Parameters	Uncertainty Interval (Source1)	Uncertainty Interval (Source2)
σ_a (AU)	[1e-10, 1e-6]	[1e-6, 1e-1]
σ_e	[1e-8, 1e-6]	[1e-4, 1e-2]
σ_i (deg)	[1e-6, 1e-4]	[1e-3, 1e-1]
σ_Ω(deg)	[1e-5, 1e-3]	[1e-3, 1e-1]
σ_w (deg)	[1e-5, 1e-3]	[1e-3, 1e0]
σ_M (deg)	[1e-5, 1e-3]	[1e-2, 1e0]
σ_H	[0.1, 0.5]	[0.5, 0.8]





15,000 virtual impact scenarios

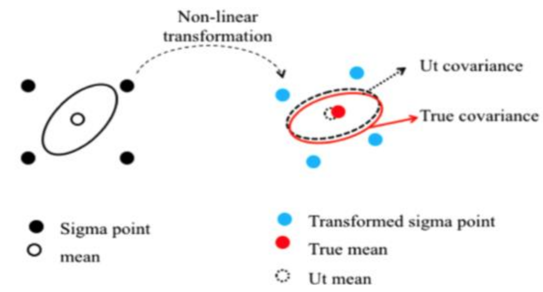
Uncertainty treatment and Impact Probability

Uncertainty treatment and Impact Probability

- **Uncertainty quantification and propagation**

Dempster-Shafer theory of evidence (DSt) is used to model epistemic uncertainty; the Unscented Transformation (UT) is used for uncertainty propagation.

$$\tilde{\boldsymbol{æ}} \approx \boldsymbol{æ} + \Delta\boldsymbol{æ}\left(\boldsymbol{\lambda}_{\boldsymbol{æ}}\right), \quad \boldsymbol{\lambda}_{\boldsymbol{æ}} = [\boldsymbol{\mu}_{\boldsymbol{æ}}^T, \boldsymbol{\sigma}_{\boldsymbol{æ}}^T]$$
$$\tilde{H} \approx H + \Delta H\left(\lambda_H\right), \quad \lambda_H = [\mu_H^T, \sigma_H^T]$$



Visualization of UT (Sanseverino, 2014)

- **Impact Probability**

Simple projection of the ellipsoid of uncertainty on the impact plane. Only first two statistical moment are considered.

$$P_c\left(\boldsymbol{x}_{\xi\zeta}; \boldsymbol{\mu}_{\xi\zeta}, \boldsymbol{\Sigma}_{\xi\zeta}\right) = \frac{1}{2\pi\sqrt{\left|\boldsymbol{\Sigma}_{\xi\zeta}\right|}} \iint_{\mathcal{B}((0,0),R)} e^{-\frac{1}{2}\left[\left(x_{\xi\zeta}-\mu_{\xi\zeta}\right)^{\mathsf{T}} \Sigma_{\xi\zeta}^{-1}\left(x_{\xi\zeta}-\mu_{\xi\zeta}\right)\right]} d\xi\, d\zeta$$

Uncertainty on deflection action

- **Kinetic Impactor**

$$\delta \boldsymbol{v}_{NEO} = \beta \frac{m_{sc}}{m_{sc} + m_{NEO}} (\boldsymbol{v}_{sc} - \boldsymbol{v}_{NEO})$$

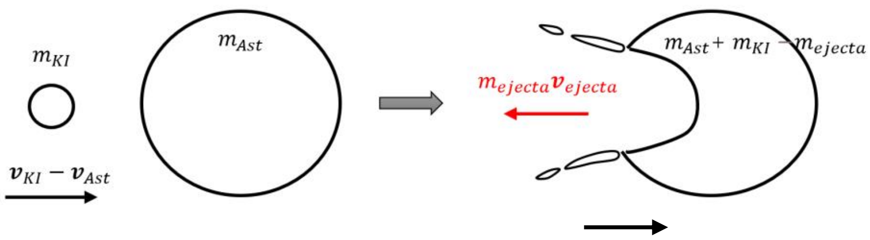


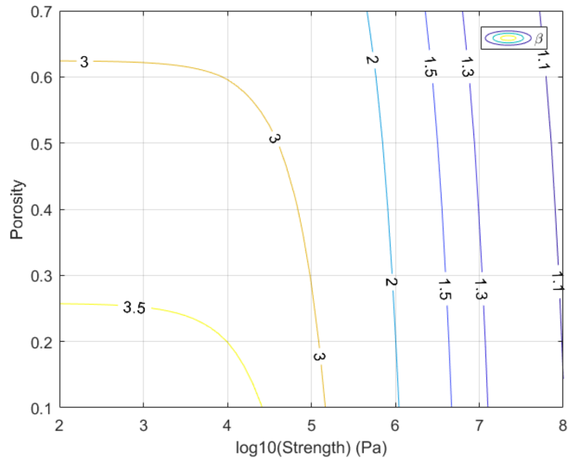
Image credit: inspired by HERA workshop

$$\beta = 1 + 0.741(Y + \epsilon)^{-0.527} v_{sc}^{0.314} (1 - \Phi)^{0.326}$$

- **Uncertainty factors:** diameter, density, strength, porosity,

Uncertainty modelled with a simple parametric family of Gaussians with epistemic parameter

```
Vsc = 4.55 km/s
Y = [1e-4, 100] MPa
Phi = [0.1, 0.7]
```



KI mission

$$\begin{cases} \boldsymbol{d} = [JD_{depart}, ToF]^T \\ \boldsymbol{u} = [\mu_D, \sigma_D, \mu_\rho, \sigma_\rho, \mu_Y, \sigma_Y, \mu_\Phi, \sigma_\Phi]^T \end{cases}$$

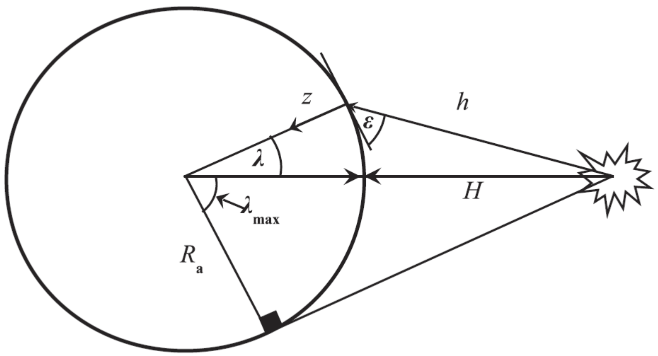
Uncertainty on deflection action

- **Nuclear Explosion**

$$\delta v = \delta v_{radiation} + \delta v_{debris}$$

Energy fraction f_i over all the products of a nuclear explosion.

Source	1-X-ray	2-Neutrons	3-Gamma rays	4-Debris	5-Others
Fission	0.7	0.01	0.02	0.2	0.07
Fusion	0.55	0.2	0.01	0.2	0.04



$$\delta v_{radiation} = \frac{\pi R_A^2}{M_A} \int_0^{\lambda_{max}} \times \int_0^{z_{max}(\lambda)} \rho_A \bar{v}(\lambda, z)\, dz \quad \sin\lambda \cos\lambda \, d\lambda$$

$$\bar{v}(\lambda, z) = \sqrt{2(E(\lambda, z) - E_v)}$$

One can now integrate over the surface area and over the thickness the total energy per type of radiation and get the total momentum per each type of radiation

- **Uncertainty factors:** diameter, density, strength, porosity, Enthalpy

Uncertainty modelled with a simple parametric family of Gaussians with epistemic parameter

- **NED mission**

$$\begin{cases} \boldsymbol{d} = [JD_{depart}, ToF]^T \\ \boldsymbol{u} = [\mu_D, \sigma_D, \mu_\rho, \sigma_\rho, \mu_Y, \sigma_Y, \mu_\Phi, \sigma_\Phi, \mu_{E_v}, \sigma_{E_v}]^T \end{cases}$$

Probability of deflection

☐ Input & Output

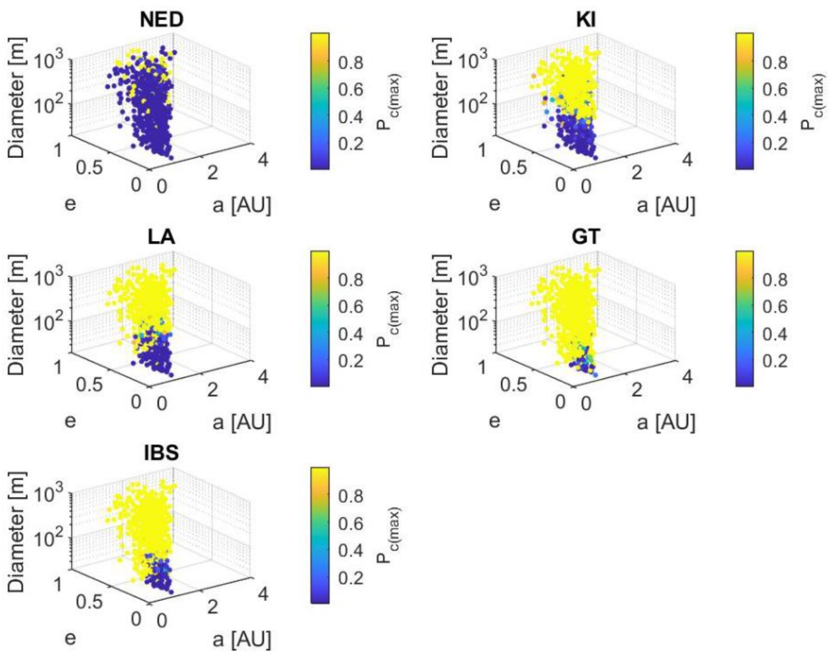
- Input: warning time, orbital elements, diameter and corresponding uncertainties
- Output: the most efficient deflection strategy that offers the highest probability of success

☐ Data-set

- Only short warning time (<10years) are considered at the current stage
- Robust optimization for five methods: NED, KI, LA, GT, IBS.
- Label the successful deflection

(worst) P_c after deflection $\leq P_0$(1e-2)

Sub-classifier	Class	Criteria
NED Classifier	successful	$P_c' \leq P_0$
	failed	$P_c' > P_0$
KI Classifier	successful	$P_c' \leq P_0$
	failed	$P_c' > P_0$
...	...	...



NEO Related Activities - Conferences

Stardust-Reloaded conference on asteroids and space debris November 2022

- May 2023 – Meeting on Planetary Defence organised in collaboration with the Royal Astronomical Society:
  - **Impact Earth! Protecting the UK and Further Afield from Impacts by Near Earth Objects**

  https://ras.ac.uk/events-and-meetings/ras-meetings/impact-earth-protecting-uk-and-further-afield-impacts-near-earth

NEO Related Activities

STARCON2 – 2nd Stardust Conference on **asteroids and space debris** held at ESTEC 7-11 November 2022 co-organized with ESA (Detlef)

357 registered participants, 181 in person attendees, 135 speakers, 34 countries

Recorded talks and presentations are now available on the Stardust-R website

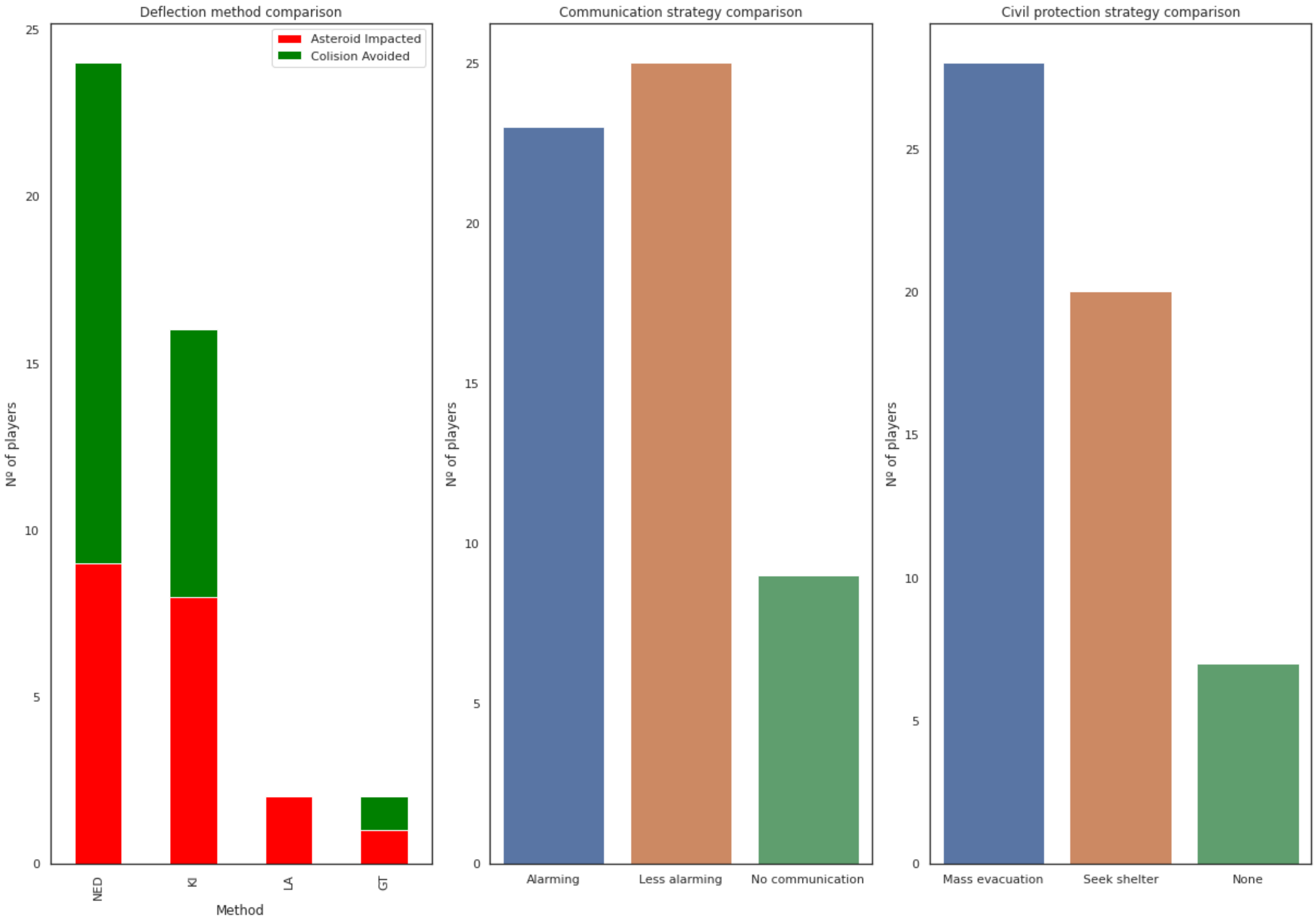
NEO Related Activities – Impact Game

Created a game app on how to react to an incoming asteroid.

Based on the type of asteroid, probability of impact, expected damage and warning time the attendees were asked to decide:

1. Whether to deflect, launch a reconnaissance mission, go for civil protection
2. Which deflection approach
3. How to communicate the threat to the public
4. Which form of civil protection to use

NEO Related Activities – Impact Game



NEO Related Activities - Hera

Landing dynamics and control of Juventas and Milani on Dimorphos

Close flyby of impact crater on Dimorphos

Optical-based NEO close proximity navigation

Aurelio Kaluthantrige & Iosto Fodde

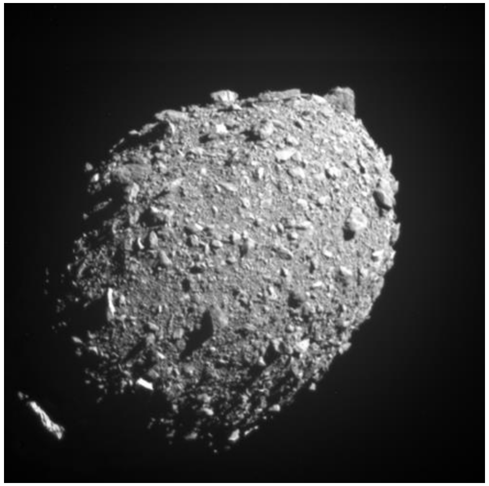
Dr. Jinglang Feng

Dr. Jesús Gil-Fernández – ESA

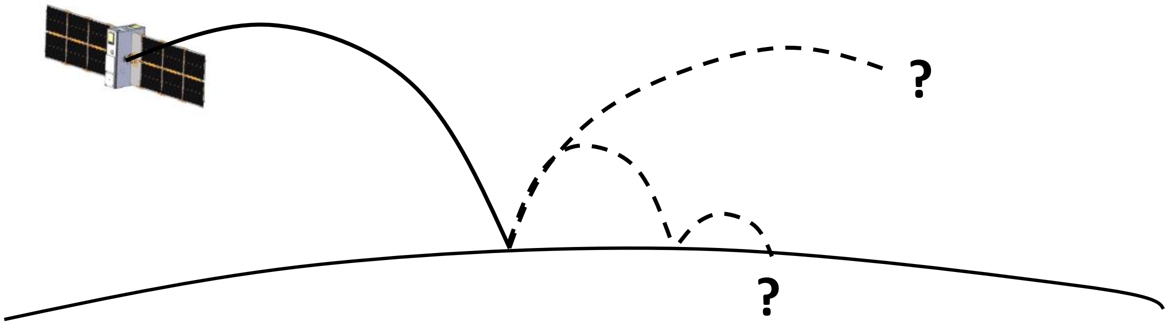
Prof. Massimiliano Vasile

Analysis of Landing Dynamics

Fodde, I., Feng, J., and Vasile, M., "Robust Trajectory Design for Ballistic Landings on Dimorphos." AIAA Science and Technology Forum and Exposition, AIAA SciTech Forum 2022, 2022. https://doi.org/10.2514/6.2022-1476, URL, https://arc.aiaa.org/doi/10.2514/6.2022-1476



- EoL: Juventas and Milani perform ballistic landing onto Dimorphos, i.e. no active control during descent.
- Very sensitive to uncertainties in the deployment and surface conditions (material type, rocks, craters).
  - Example: Philae bouncing on 67P.
- Find optimal landing conditions that give highest chance of settling on surface.
  - Use Pseudo-diffusion indicator.
  - Measures sensitivity to uncertainties.



Analysis of Landing Dynamics

Fodde, I., Feng, J., & Vasile, M. (2022). "Landing area analysis for ballistic landing trajectories on the secondary of a binary asteroid". Paper presented at AAS/AIAA Astrodynamics Specialist Conference 2022, Charlotte, United States.

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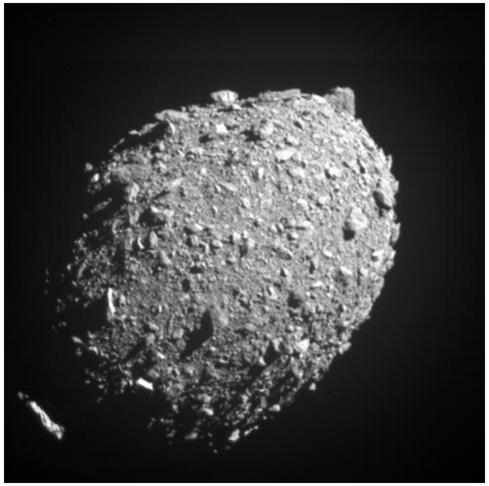
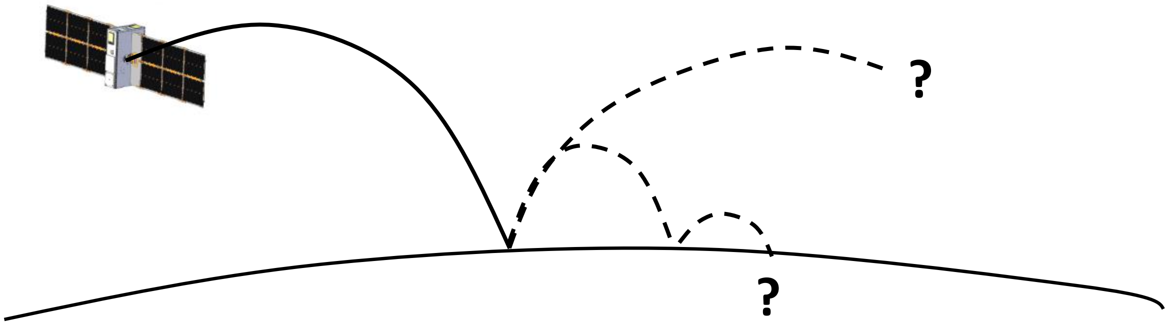


- 1. The Hera GNC team: to inform them of the desired landing conditions to keep the spacecraft on the surface of Dimorphos, which they can use for their trajectory design of the landing maneuver.
- 2. The Hera Scientific Working Group: to reconstruct what happens with the spacecraft during landing based on the IMU and gravimeter measurements (e.g. investigate the mismatch between the modelled bouncing and true bouncing).



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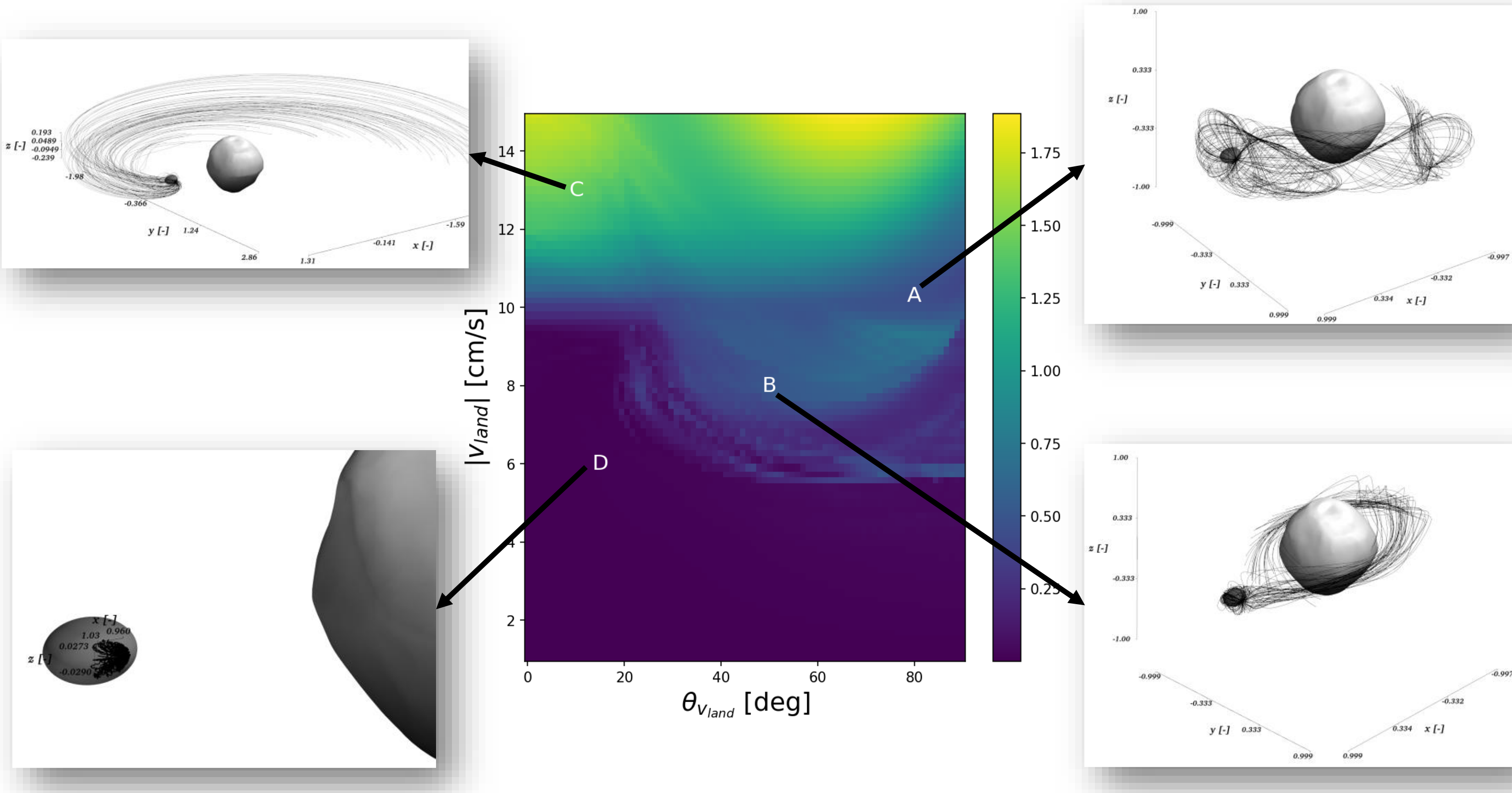
Analysis of Practical Stability Regions Around Dydimos

Fodde, I., Feng, J., Gil-Fernández, J., & Vasile, M. (2022). "Binary asteroid landing trajectory design from a self-stabilized terminator orbit considering parametric uncertainties". Paper presented at 73rd International Astronautical Congress 2022, Paris, France.



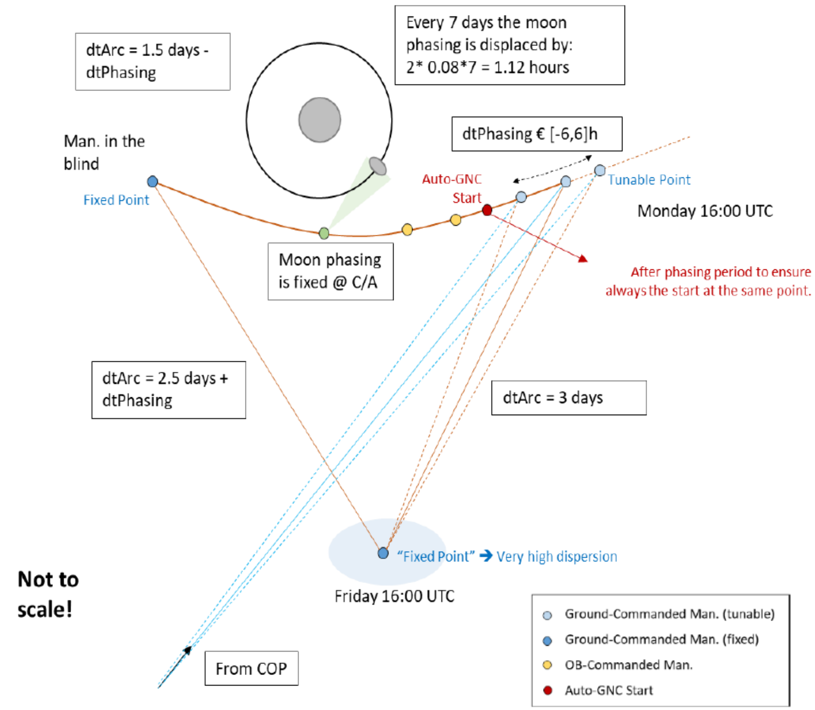
Robust design of Very-Close Fly-By (VCFB)

Greco, C., Campagnola, S., & Vasile, M. (2022). Robust space trajectory design using belief optimal control. Journal of Guidance, Control and Dynamics, 45(6), 1060-1077

- Goal: image the DART impact crater with sub 10 cm/pixel resolution under proper lighting conditions.

- Very demanding constraints:
  - Low probability of impact.
  - Robust against missed thrust events and uncertainties in thruster performance.

- Solution:
  - Robust optimization (optimize trajectory while considering uncertainties).
  - Autonomous trajectory control.



Credit: GMV

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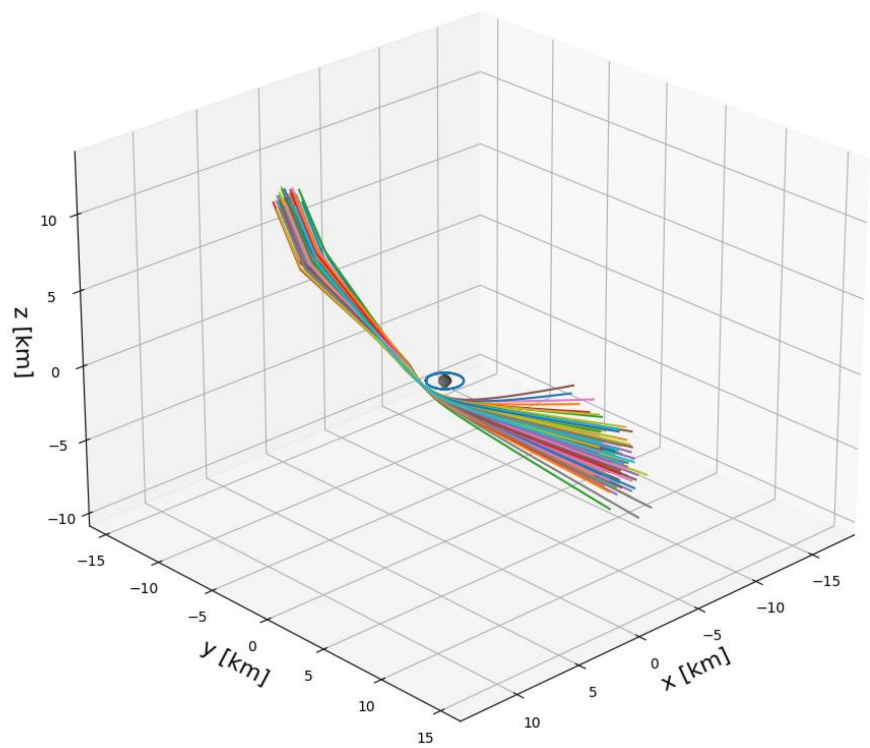
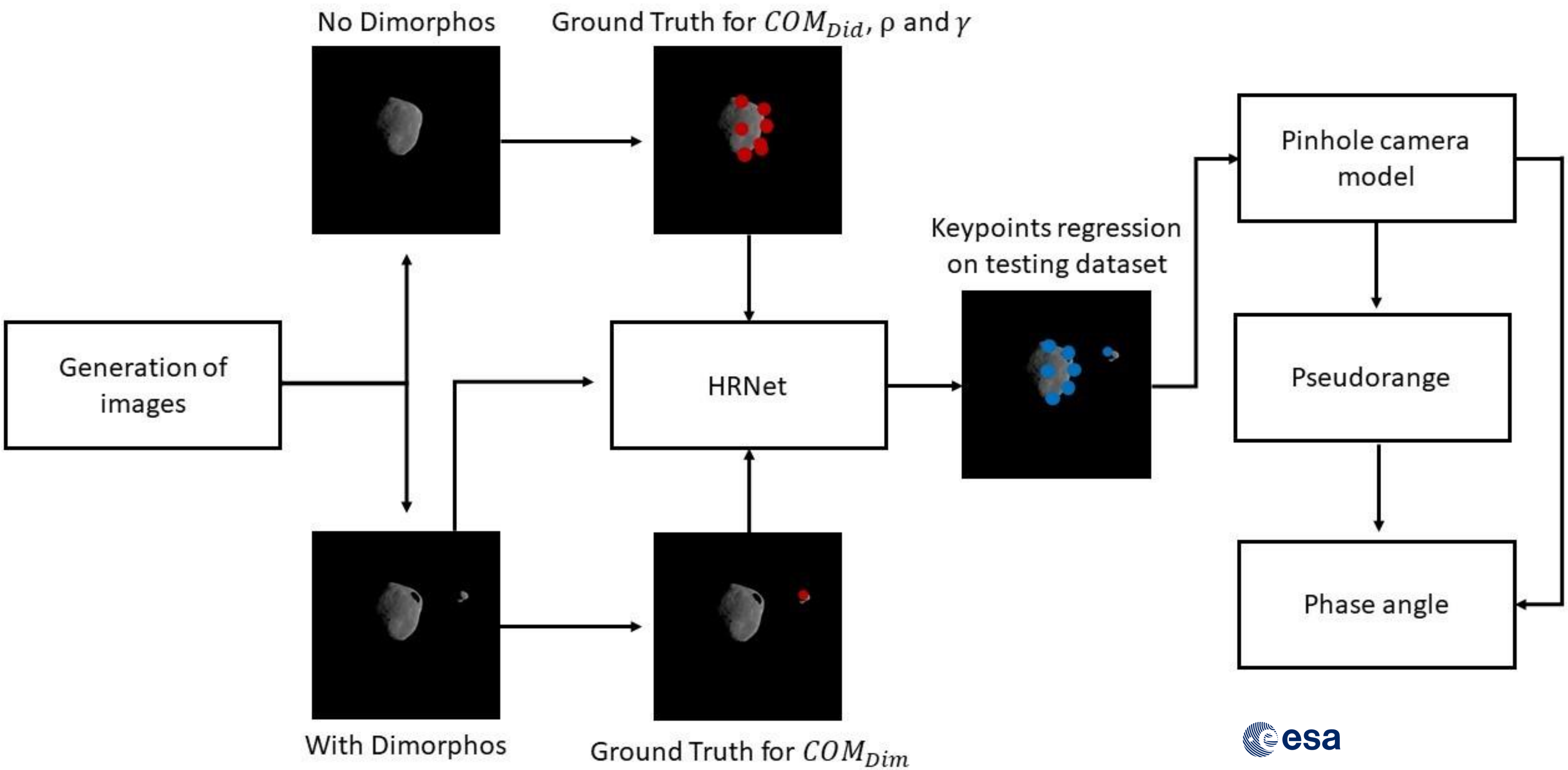


- Robust trajectory: minimize dispersion at close approach.
  - Constraints: PoI < 0.1 percent, velocity always larger than escape velocity.
- Additionally: add autonomous trajectory control.
  - Need to include navigation system to estimate state.
  - Bring trajectory to desired close approach position.
- Design using novel uncertainty propagation technique (GIPA) combined with trajectory optimization.

AI-based Navigation System

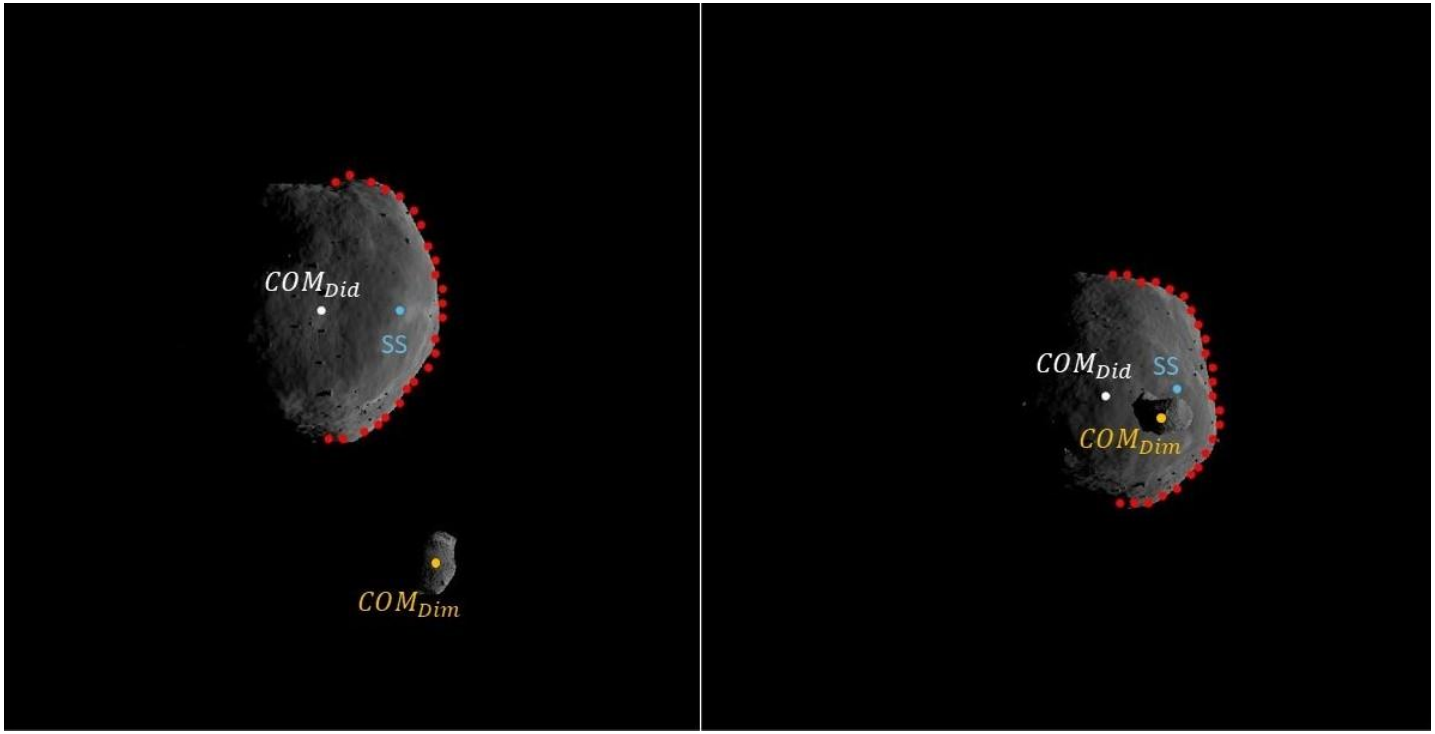
Proof of concept for future autonomous missions to asteroids.

Using Hera as a test-bed



Automatic Centroiding and Pose Estimation

Example of close approach navigation with synthetic images and closed loop pose estimation.



Future Activities

- Horizon Europe proposal NEO-DATA led by the University of Belgrade submitted.
  - Focus on modelling of asteroids and deflection actions based on observation and mission data
  - Data as a service available to the scientific community for validation and model development
- Future Leaders Fellowship on the modelling of the ejecta – Dr Stefania Soldini, University of Liverpool
- Stardust-Next proposal in preparation

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