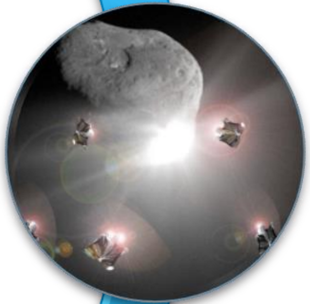
TASK 5.2 MITIGATION MISSION TYPES AND TECHNOLOGIES TO BE CONSIDERED

Massimiliano Vasile

Agenda

Results from NEOShield



Results from Stardust

Future Perspective

RESULTS FROM NEOSHIELD

Summary of results based on D7.5.1 Trade Offs of Viable Alternative Mitigation Concepts.

Deflection concepts:

- Kinetic impactor
- Nuclear blast (including human mission option)
- Gravity tractor (including multi-spacecraft option)
- Ion beaming
- Laser ablation
- Electrostatic tractor

RESULTS FROM NEOSHIELD

Main assumption of the trade-off:

- Reference mission scenario with asteroid 2011 AG5
- Both keyhole and direct deflection scenarios
- Single Falcon Heavy launch with C3=6km/s^2
- Transfer time 2-3 years and Δv budget of 3km/s (Isp=3100s for slow push)
- Launcher separation mass is 12500kg
- Laser ablation model based on (Vasile et al. 2012 LightTough^2 ESA study)
- Minimum distance from the Earth as quantity of interest

- Scoring from 0 to 3 based on performance, deflection precision, mission readiness, mission risk, politics, cost.

RESULTS FROM NEOSHIELD

Direct deflection weighted scoring

Option	Diameter (m)	Asteroid Density (g/cm^3)	Asteroid Mass (kg)	Mitigation-to-Impact (years)	2040 Baseline Best Choice	2040 Best Score	2040 Baseline Backup Choice	2040 Backup Score	2040 Score Margin
1	50	1	6.5E+07	20	1000kT Nuclear Blast (Stand-Off)	1.975	Kinetic Impactor from Escape Orbit	1.958	0.018
2	50	1	6.5E+07	15	Ion-Beam Shepherd	2.483	1000kT Nuclear Blast (Stand-Off)	2.375	0.108
3	50	1	6.5E+07	10	Ion-Beam Shepherd	2.483	Laser Ablation	2.470	0.013
4	50	1	6.5E+07	5	Laser Ablation	2.533	Ion-Beam Shepherd	2.483	0.050
5	50	1	6.5E+07	1	1000kT Nuclear Blast (Stand-Off)	2.375	Kinetic Impactor from Escape Orbit	2.358	0.018
6	100	2	1.0E+09	20	Kinetic Impactor from Escape Orbit	2.020	1000kT Nuclear Blast (Stand-Off)	1.975	0.045
7	100	2	1.0E+09	15	Kinetic Impactor from Escape Orbit	2.420	Ion-Beam Shepherd	2.383	0.037
8	100	2	1.0E+09	10	Laser Ablation	2.470	Kinetic Impactor from Escape Orbit	2.420	0.050
9	100	2	1.0E+09	5	Kinetic Impactor from Escape Orbit	2.420	1000kT Nuclear Blast (Stand-Off)	2.375	0.045
10	100	2	1.0E+09	1	1000kT Nuclear Blast (Stand-Off)	2.375	100kT Nuclear Blast (Surface)	2.313	0.063
11	156	2	4.0E+09	20	Kinetic Impactor from Escape Orbit	2.295	1000kT Nuclear Blast (Stand-Off)	1.975	0.320
12	156	2	4.0E+09	15	Kinetic Impactor from Escape Orbit	2.595	1000kT Nuclear Blast (Stand-Off)	2.375	0.220
13	156	2	4.0E+09	10	Kinetic Impactor from Escape Orbit	2.595	1000kT Nuclear Blast (Stand-Off)	2.375	0.220
14	156	2	4.0E+09	5	Kinetic Impactor from Escape Orbit	2.495	1000kT Nuclear Blast (Stand-Off)	2.375	0.120
15	156	2	4.0E+09	1	100kT Nuclear Blast (Surface)	2.313	1000kT Nuclear Blast (Stand-Off)	2.275	0.037
16	200	2	8.4E+09	20	Kinetic Impactor from Escape Orbit	2.195	1000kT Nuclear Blast (Stand-Off)	1.975	0.220
17	200	2	8.4E+09	15	Kinetic Impactor from Escape Orbit	2.495	1000kT Nuclear Blast (Stand-Off)	2.375	0.120
18	200	2	8.4E+09	10	Kinetic Impactor from Escape Orbit	2.495	1000kT Nuclear Blast (Stand-Off)	2.375	0.120
19	200	2	8.4E+09	5	1000kT Nuclear Blast (Stand-Off)	2.375	100kT Nuclear Blast (Surface)	2.313	0.063
20	200	2	8.4E+09	1	100kT Nuclear Blast (Surface)	2.313	1000kT Nuclear Blast (Stand-Off)	2.175	0.137

RESULTS FROM NEOSHIELD

Keyhole deflection weighted scoring

Option	Asteroid Diameter (m)	Asteroid Density (g/cm^3)	Asteroid Mass (kg)	Mitigation-to-Keyhole (years)	2040 Baseline Best Choice	2040 Best Score	2040 Baseline Backup Choice	2040 Backup Score	2040 Score Margin
1	50	1	6.5E+07	20	1000kT Nuclear Blast (Stand-Off)	1.800	Kinetic Impactor from Escape Orbit	1.780	0.020
2	50	1	6.5E+07	15	Ion-Beam Shepherd	2.600	1000kT Nuclear Blast (Stand-Off)	2.100	0.500
3	50	1	6.5E+07	10	Ion-Beam Shepherd	2.600	Laser Ablation	2.590	0.010
4	50	1	6.5E+07	5	Laser Ablation	2.640	Multiple Gravity Tractors	2.620	0.020
5	50	1	6.5E+07	1	Ion-Beam Shepherd	2.650	Laser Ablation	2.640	0.010
6	100	2	1.0E+09	20	Kinetic Impactor from Escape Orbit	1.830	1000kT Nuclear Blast (Stand-Off)	1.800	0.030
7	100	2	1.0E+09	15	Ion-Beam Shepherd	2.600	Multiple Gravity Tractors	2.570	0.030
8	100	2	1.0E+09	10	Multiple Gravity Tractors	2.620	Gravity Tractor	2.610	0.010
9	100	2	1.0E+09	5	Laser Ablation	2.640	Multiple Gravity Tractors	2.620	0.020
10	100	2	1.0E+09	1	Ion-Beam Shepherd	2.550	Laser Ablation	2.540	0.010
11	156	2	4.0E+09	20	Kinetic Impactor from Escape Orbit	2.040	1000kT Nuclear Blast (Stand-Off)	1.800	0.240
12	156	2	4.0E+09	15	Ion-Beam Shepherd	2.600	Multiple Gravity Tractors	2.570	0.030
13	156	2	4.0E+09	10	Multiple Gravity Tractors	2.620	Gravity Tractor	2.610	0.010
14	156	2	4.0E+09	5	Laser Ablation	2.640	Gravity Tractor	2.610	0.030
15	156	2	4.0E+09	1	Kinetic Impactor from Escape Orbit	2.340	1000kT Nuclear Blast (Stand-Off)	2.100	0.240
16	200	2	8.4E+09	20	Kinetic Impactor from Escape Orbit	2.040	1000kT Nuclear Blast (Stand-Off)	1.800	0.240
17	200	2	8.4E+09	15	Ion-Beam Shepherd	2.600	Gravity Tractor	2.560	0.040
18	200	2	8.4E+09	10	Gravity Tractor	2.610	Ion-Beam Shepherd	2.600	0.010
19	200	2	8.4E+09	5	Laser Ablation	2.640	Gravity Tractor	2.510	0.130
20	200	2	8.4E+09	1	Kinetic Impactor from Escape Orbit	2.240	1000kT Nuclear Blast (Stand-Off)	2.100	0.140

RECENT RESULTS FROM STARDUST

Updated comparison of deflection methods

- Methods: kinetic impactor, laser ablation, gravity tractor, ion beaming
- Revised model of laser ablation
- In-line vs Halo GT analysis
- Use of current NEO distribution model
- Inclusion of launch and mission scenario
- Inclusion of system design consideration
- Globally optimised solutions

Collaboration with Japan on electrostatic tractor

Collaboration with JPL on post-close encounter impact probability

KINETIC IMPACTOR

Basic momentum transfer equation:

$$\delta v = \beta \frac{m_{s/c}}{m_{AST}} \delta v_{s/c}$$

Mass of the spacecraft at the end of the transfer

Enhancement factor equal to 1

Bi-impulsive transfer maximising the final miss distance

ASTRODYNAMICS CONSIDERATIONS

3D analytical formulas based on Vasile and Colombo, JGCD 2008.

Coordinates on the b-plane of the MOID $\mathbf{x}_b = [\xi \;\; \eta \;\; \zeta]^T$

$$\mathbf{x}_b(t_{MOID}) = \mathbf{BAG}\delta\mathbf{v}$$

B is projecting the deflection on the b-plane, where the deflection is:

$$\delta\mathbf{r}(t_{MOID}) = \mathbf{A}\delta æ$$

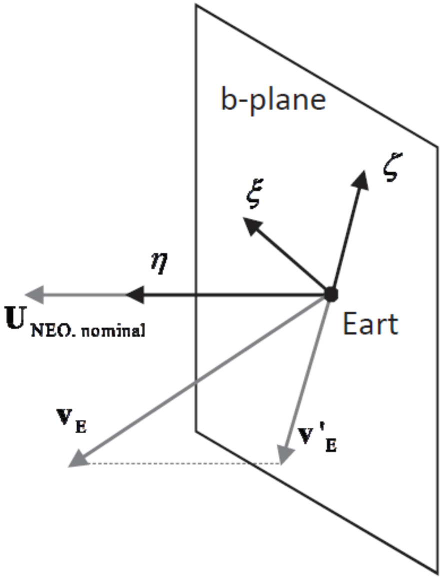
with the variation of the orbital parameters post deflection

$$\delta æ = [\delta a, \delta e, \delta I, \delta\omega, \delta\Omega, \delta M]^T$$

$$\delta æ = \mathbf{G}\delta\mathbf{v}$$

Quantity of interest is the impact parameter:

$$b = \sqrt{\xi^2 + \zeta^2}$$



.

ASTRODYNAMICS CONSIDERATIONS

Formulas provide an analytical relationship between the deflection impulse and the resulting variated position of the asteroid at the MOID.

Importance of the geometric variation:

- For short warning times the time component becomes irrelevant (tangential deflection suboptimal)
- For deep crossers there is a substantial normal δv component
- For shallow crossers simple time delays are not accounted for in the in the 1D formulation

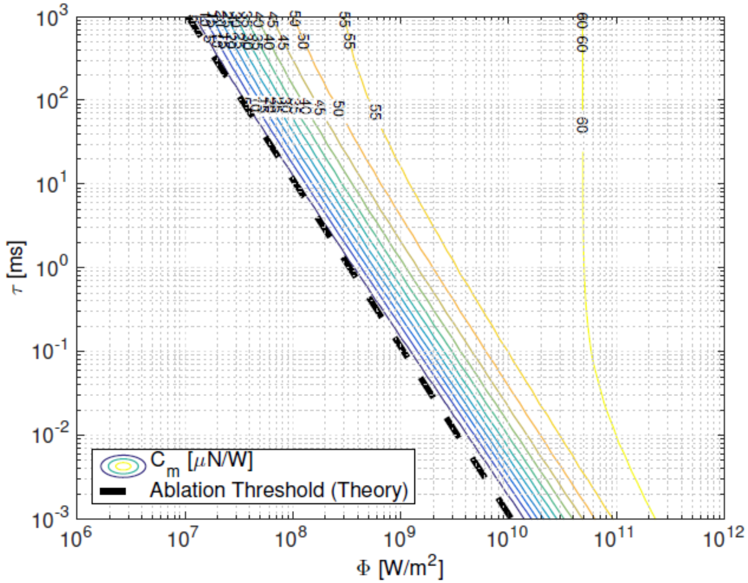
REVISED LASER ABLATION

Continuous wave solution with a momentum coupling C_m in excess of 50 μN/W, 2.5 times higher than the value used in NEOShield (Thiry and Vasile, ASR, 2016) where the thrust on the asteroid is:

$$F_{\mathrm{LS}} = \eta_{LS} C_m P_{in}$$

With h_{LS} the efficiency of the laser and P_{in} the input power.

Analysis for pulsed lasers solutions (much longer shooting distance and lower contamination) (Phipps 2011)

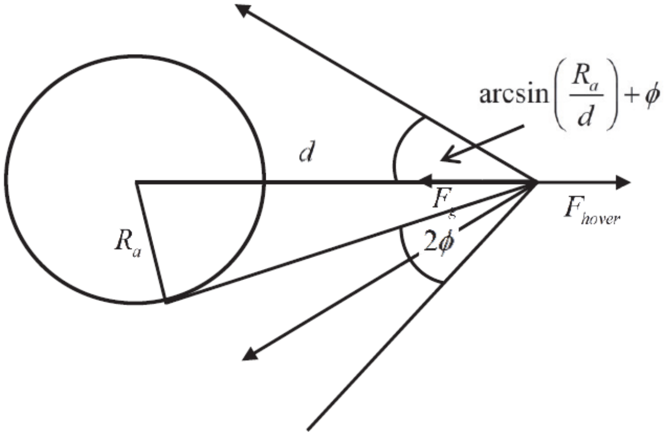


GRAVITY TRACTOR: IN-LINE VS HALO

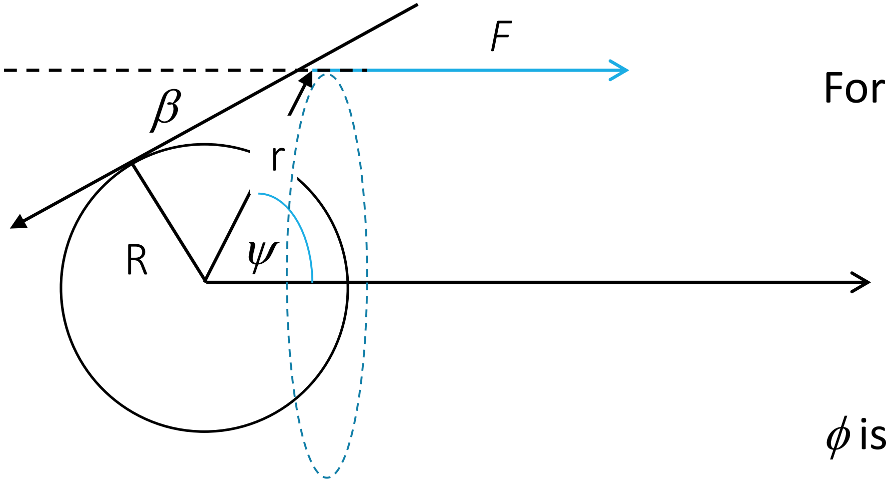
(VASILE AND MINISCI, AIAA, 2016)

In-line configuration:

$$a_{gtug}(t) = \frac{G m_S(t)}{d^2}$$



Halo configuration:



For the same tugging acceleration:

$$m_H = m_S \cos\alpha$$

$$\alpha = \arcsin\left(\frac{R_a}{d}\right)+\phi$$

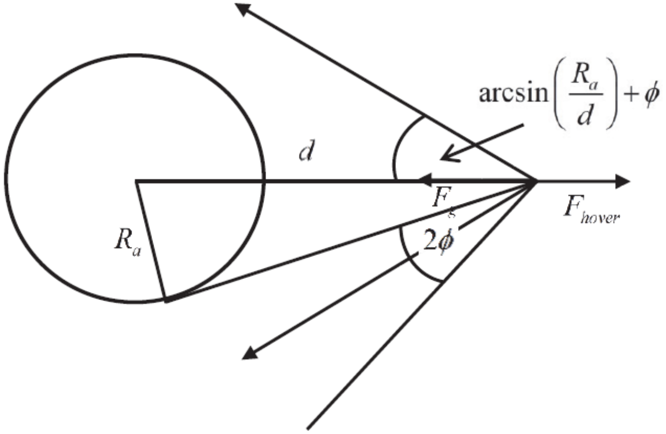
ϕ is the beam divergence angle

GRAVITY TRACTOR: IN-LINE VS HALO

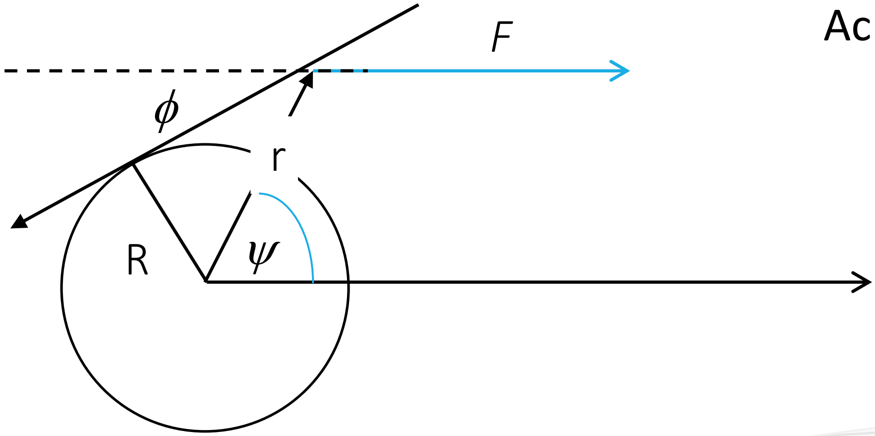
(VASILE AND MINISCI, AIAA, 2016)

In-line configuration:

$$a_{gtug}(t) = \frac{G m_S(t)}{d^2}$$



Halo configuration:



Achievable tugging acceleration:

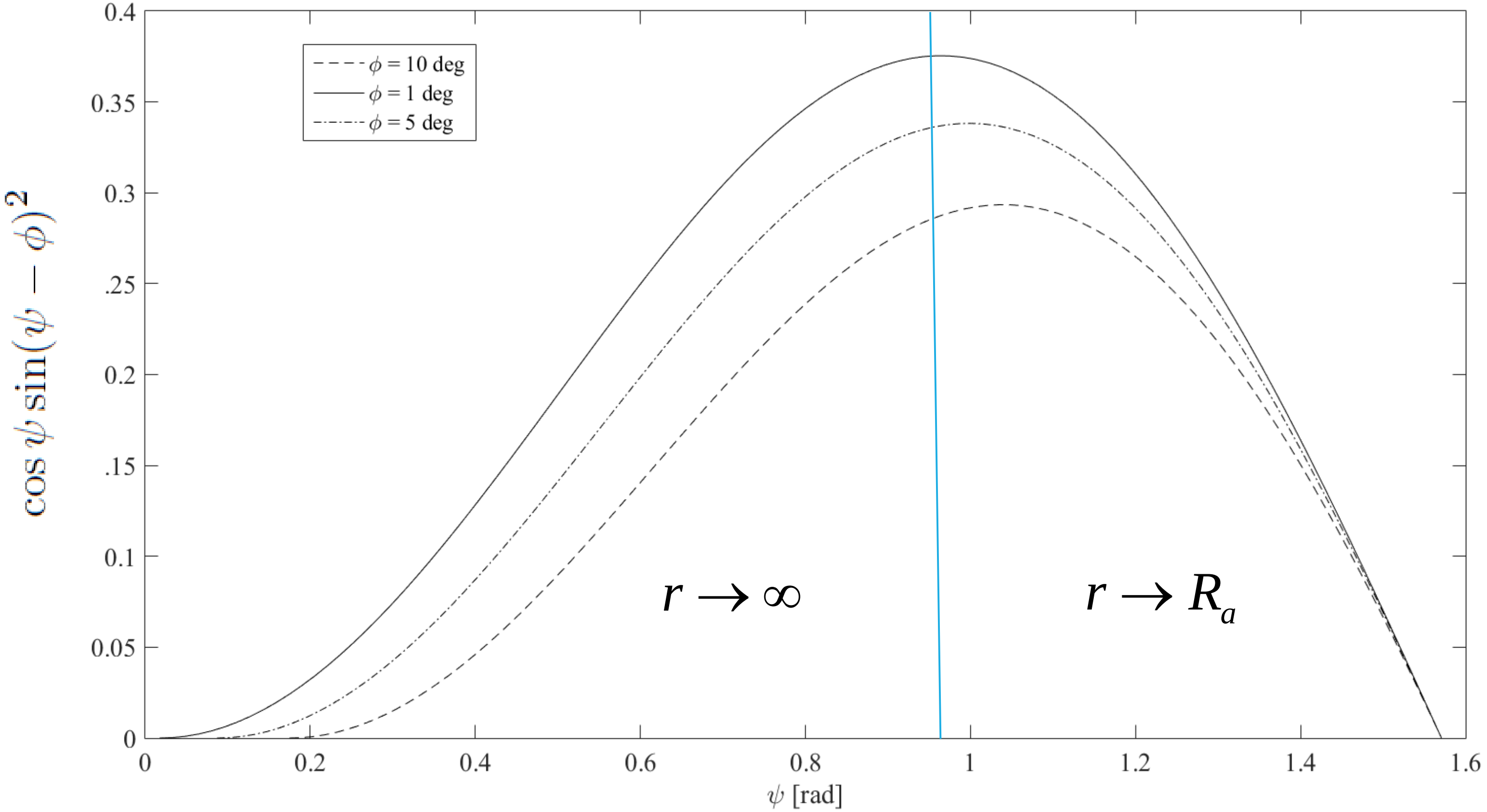
$$a_H = \frac{G m_H(t)}{R_a^2} \cos\psi \sin(\psi - \phi)^2$$

$$\phi < \psi \leq \frac{\pi}{2}$$

GRAVITY TRACTOR: IN-LINE VS HALO

(VASILE AND MINISCI, AIAA, 2016)

Halo configuration: $a_H = \dfrac{G m_H(t)}{R_a^2} \cos\psi \sin(\psi - \phi)^2$

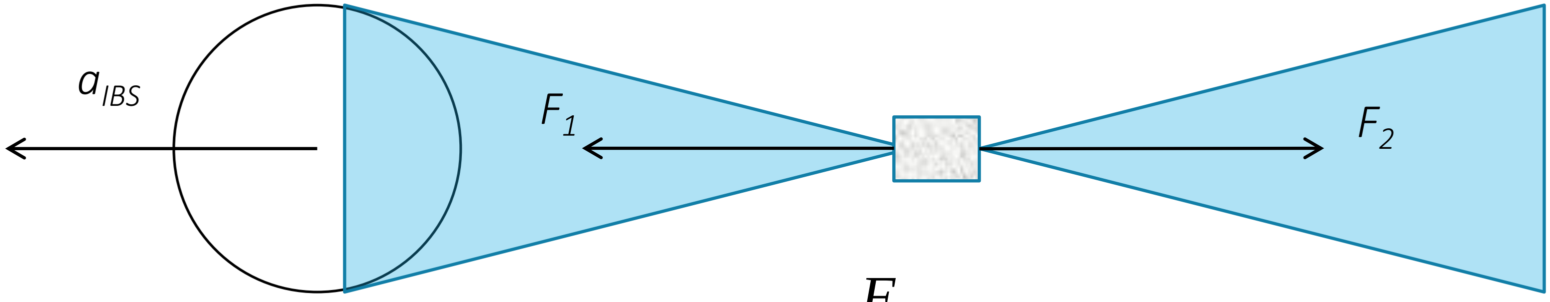


ION BEAMING

(BOMBARDELLI ET AL. 2011)

Very simple basic model:

- No back-sputtering
- Momentum coupling efficiency equal to 1
- No tugging effect



$$a_{IBS} = -\frac{F_2}{M_a}$$

TRANSFER AND SYSTEM DEFINITION

(THIRY AND VASILE, IAC, 2016)

Maximum launch mass with Delta IV Heavy, 10000kg @ C_3=0 km^2/s^2

Simple 2-impulse transfer for kinetic impactor

C_3=0 km^2/s^2 and low thrust transfer for laser, ion beaming and GT

System mass estimation including transfer propellant and major subsystems

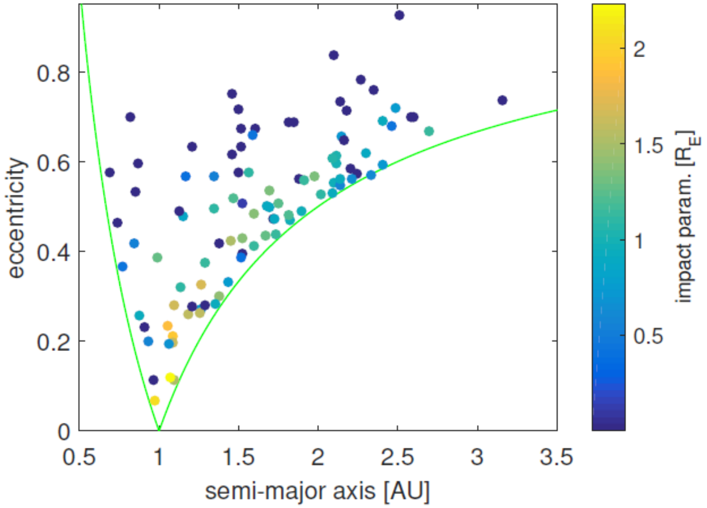
Residual mass allocated to deflection system (laser+optics+radiators, secondary ion engine+propellant, propellant)

Asteroid mass: 4x10^{9}kg

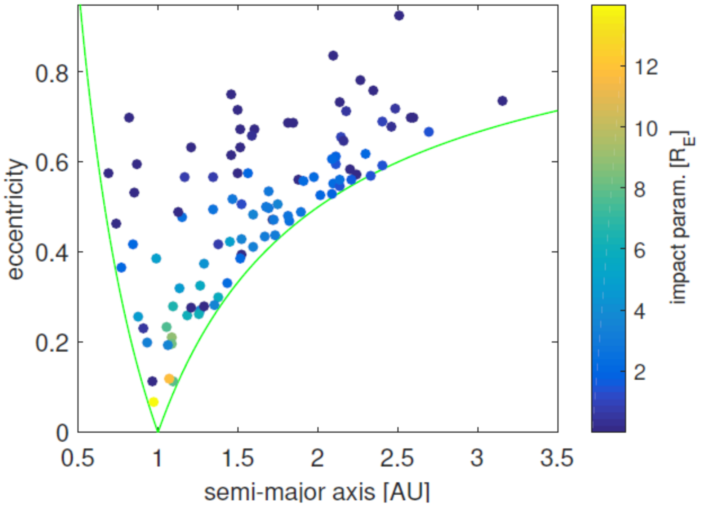
100 samples from current NEO population

MISS DISTANCE IN A GIVEN TIME

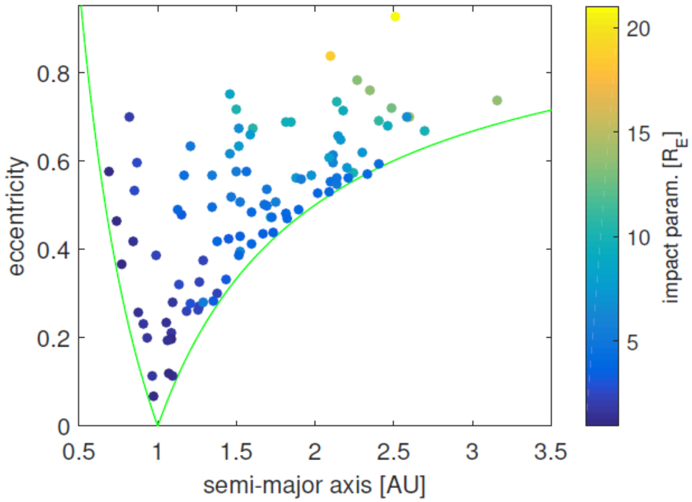
(THIRY AND VASILE, IAC, 2016)



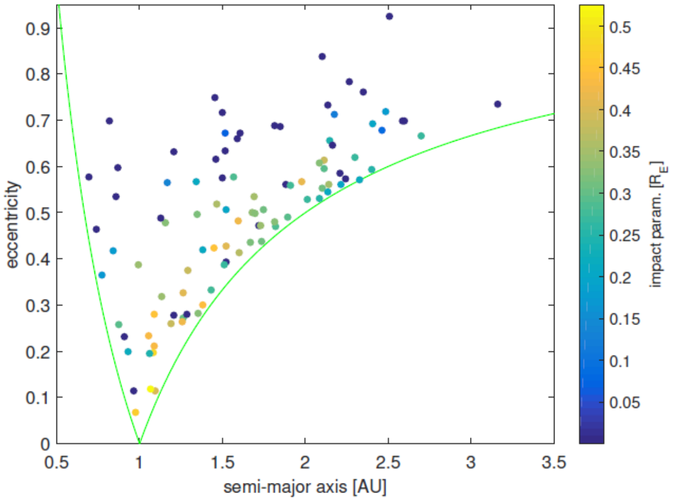
(b) Ion Beam Shepherd



(c) Laser Ablation System

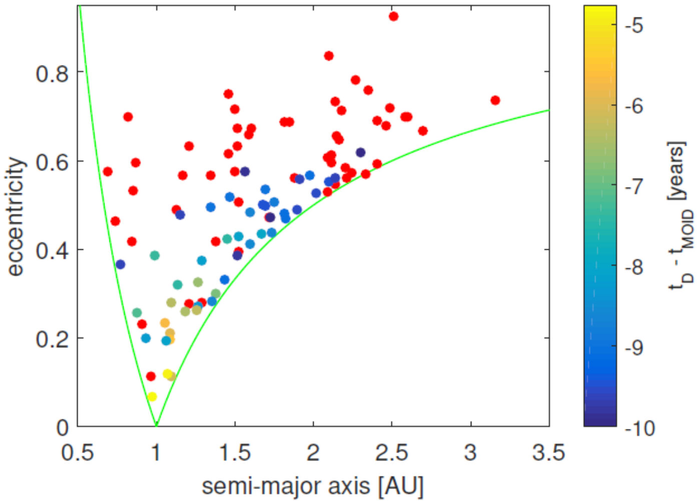


(a) Kinetic Impactor

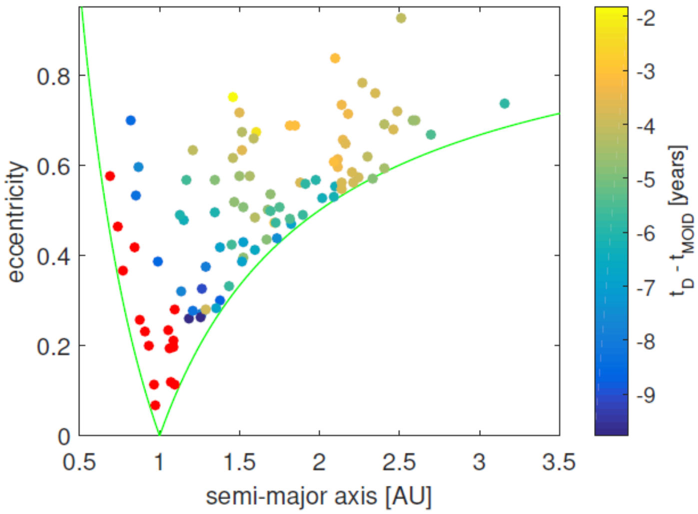


WARNING TIME GIVEN THE MISS DISTANCE

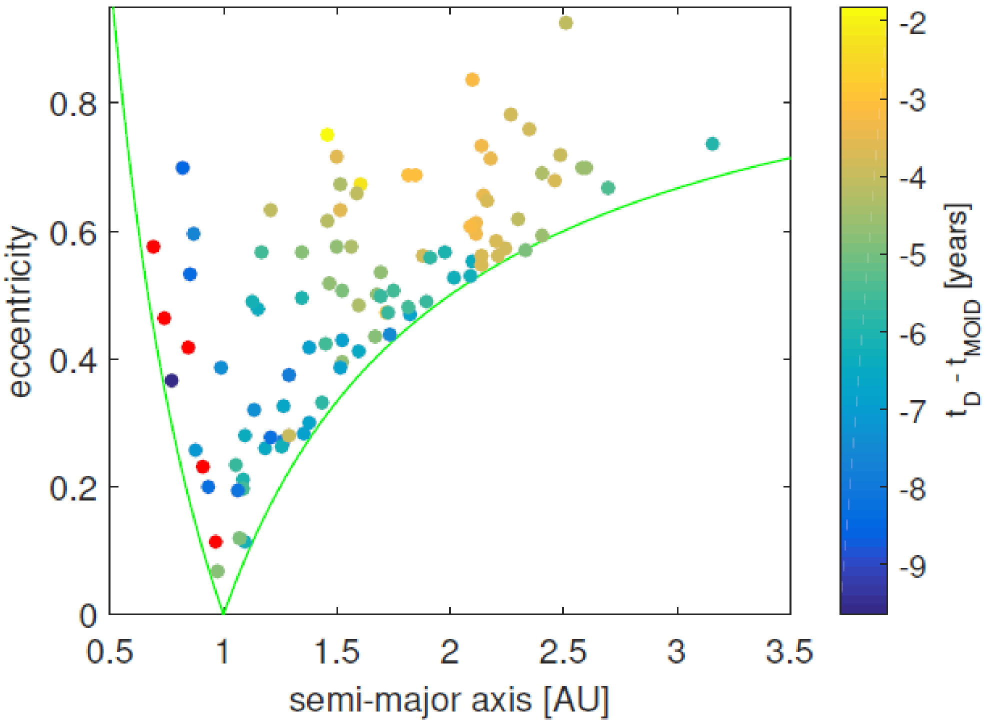
(THIRY AND VASILE, IAC, 2016)



(b) Laser Ablation



(a) Kinetic Impactor



(c) Kinetic Impactor and Laser Ablation

SOME CONCLUSIONS

- For a fixed distance, halo configuration more effective and efficient though with lower maximum tugging force
- Laser and kinetic impactor appear to be complementary, covering different regions of the NEO distribution
- Kinetic impactor more appropriate for deep crossers
- Low semimajor axis and high eccentricity region more problematic
- Ion beaming significantly less effective though better than the GT on the tested sample

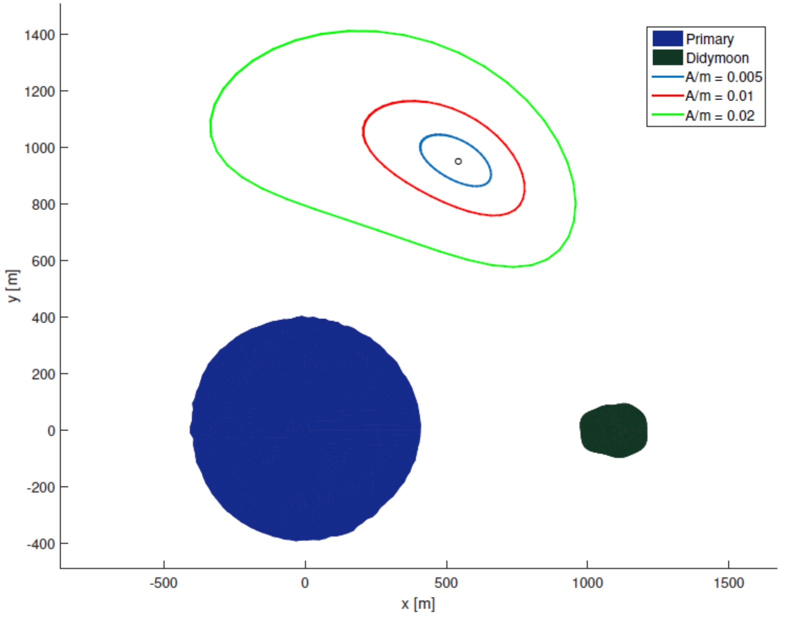
AIDA-LIKE LASER ABLATION DEMONSTRATOR

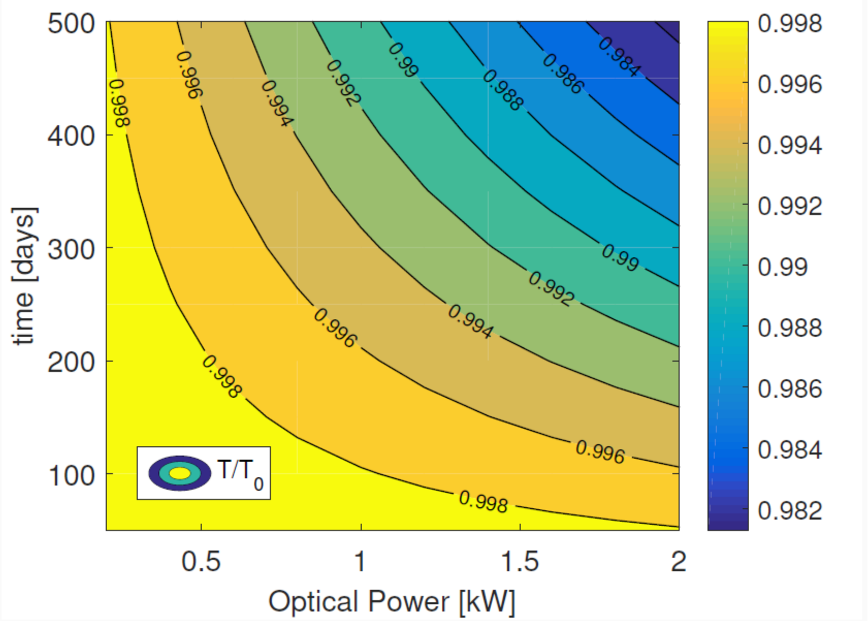
(THIRY AND VASILE, 2016)

Spin up of the secondary of the Didymos system using laser technology.

0.2-0.6% reduction of orbital period in 150-350 days with 1kW (AIDA expects 0.6%).

Single spacecraft can perform the deflection, measure the change in orbital period and analyse the subsurface material.





FUTURE PERSPECTIVE

Actions to be completed:

- Evaluation of kinetic impactor with low-thrust propulsion – theoretical treatment partially complete
- Improved characterisation of ion beaming
- Uncertainty in post deflection impact probability – critical to evaluate deflection method applicability, TRL and required precursor missions
- Uncertainty in post-close encounter impact probability – work in progress in collaboration with JPL
- Inclusion of the electrostatic tractor and other variants of the GT in the comparison

FUTURE PERSPECTIVE

Stardust2 proposal submitted to the EC in January 2017

Expected result of the evaluation in May 2017

Expected start of Stardust2, if successful Jan 2018

Key partners in the network relevant to SMPAG and IWAN:

- University of Arizona – OSIRIS-REX System Engineering Team
- ESA –SSA and ESOC MAS (Johan)
- Airbus DS – system engineering and test facilities
- TU Munich (Detlef) – ion beaming
- Observatoire de Paris – asteroid characterisation
- SpaceDyS and University of Pisa – asteroid impact monitoring
- University of Belgrade – small asteroid population model
- Deimos Space – asteroid landing

University of
Strathclyde
Glasgow