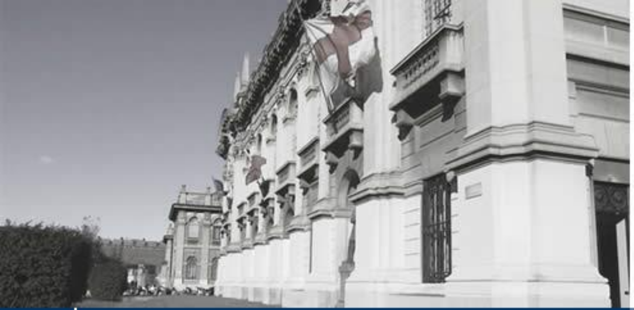

6th International Conference on Astrodynamics Tools and Techniques (ICATT)

Darmstadt 14 – 17 March 2016

POLITECNICO DI MILANO

Coupling High Fidelity Body Modeling with Non-Keplerian Dynamics to Design AIM-MASCOT-2 Landing Trajectories on Didymos Binary Asteroid

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Content

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- Dynamical environment around Didymos system
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  - Escape velocities in the three-body system
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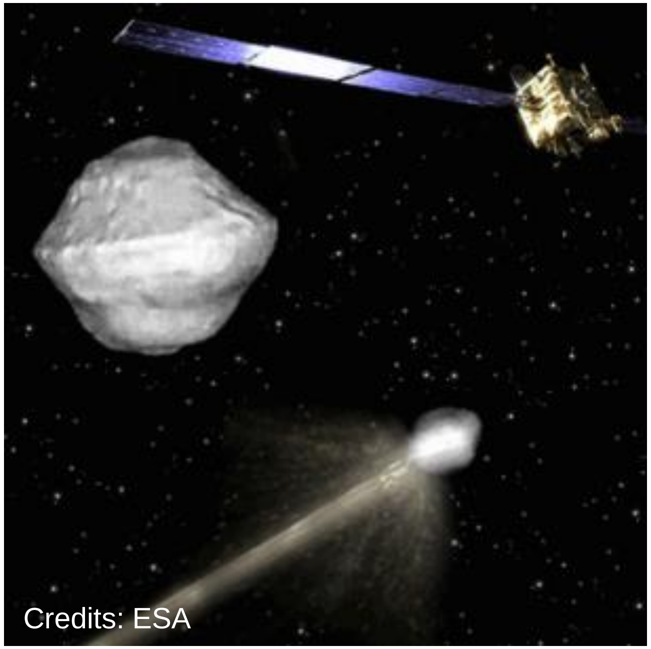
  - Landing dispersion at rest



65803 Didymos will transit near Earth (less than 0.1 AU) in late 2022

[Didymos = Didymain + Didymoon]

AIDA - Asteroid Impact & Deflection Assessment

AIM - Asteroid Impact Mission (ESA)
Goals:
- Study of binary system
- Deployment of a lander (MASCOT-2)
- Deployment of cubesats (COPINS)

DART - Double Asteroid Redirection Test (NASA)
Goals:
- High velocity kinetic impact

MASCOT-2 landing highlights

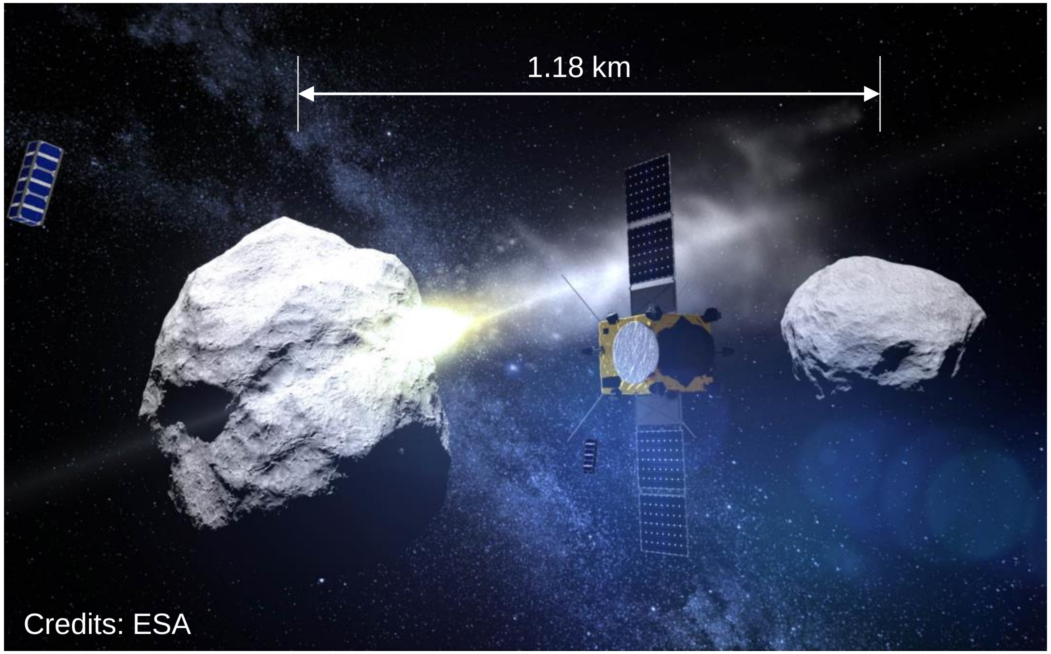
- MASCOT-2 shall land on the smaller asteroid (Didymoon)

- MASCOT-2 is a passive probe
  - No actuators for trajectory control
  - No actuators or devices for anchoring to the surface

- Extremely low gravity field on Didymoon’s surface
  - MASCOT-2 can bounce but it shall stay on the surface

- MASCOT-2 release point shall be safe from AIM spacecraft point of view

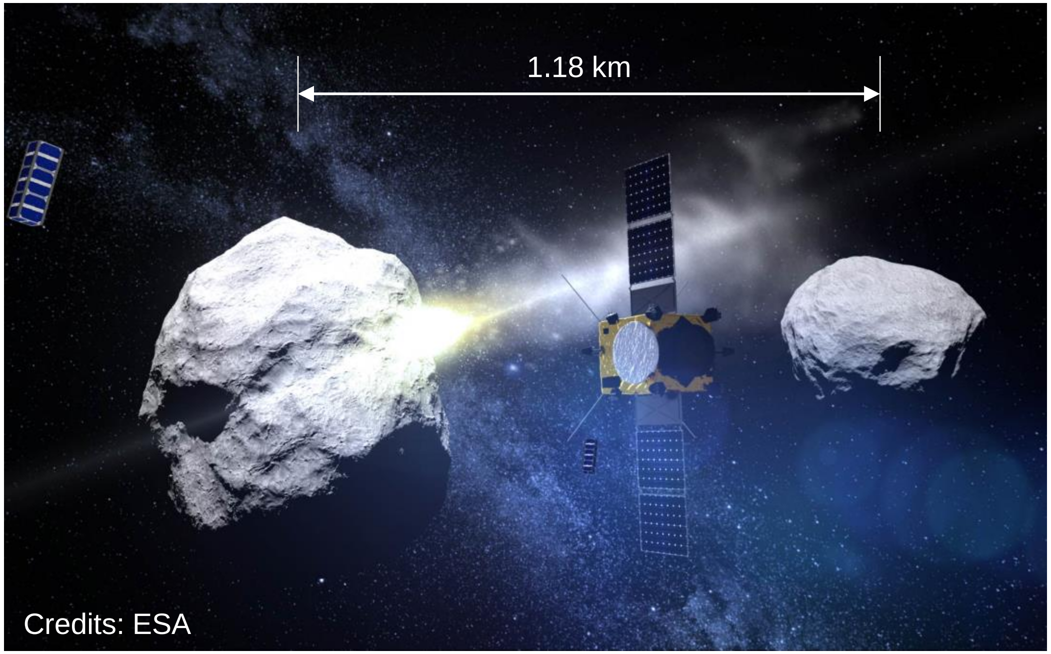
Didymos system



	Diameter [m]	Mass [kg]
Didymain	775	5.2 e11
Didymoon	163	4.8 e9

Two orders of magnitude lower than 67/P C-G (Rosetta/Philae)

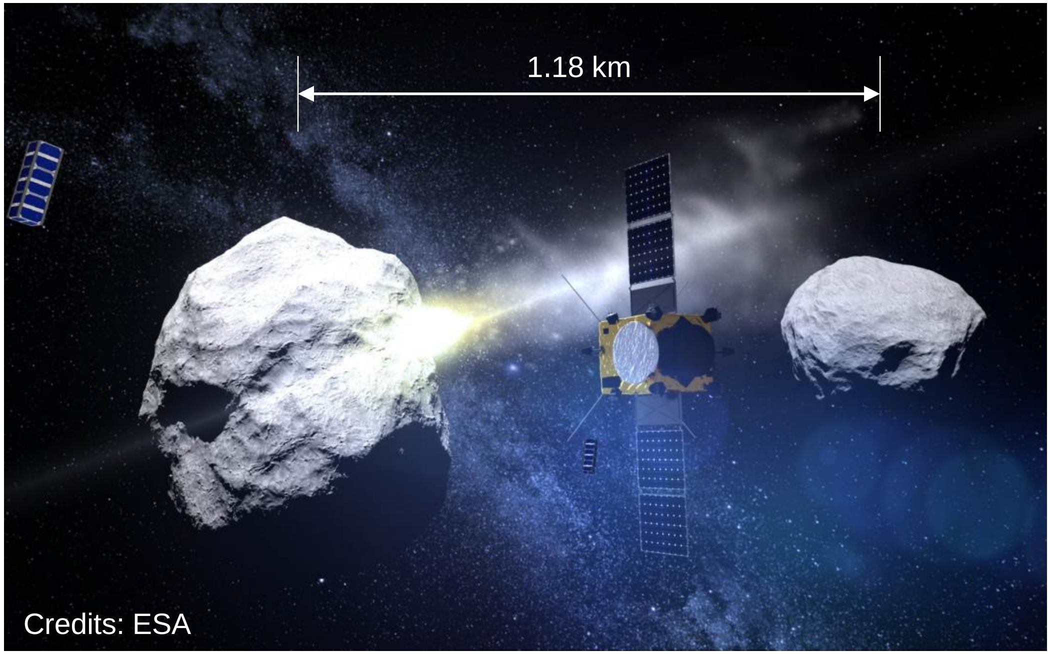
Didymos system



	Diameter [m]	Mass [kg]
Didymain	775	5.2 e11
Didymoon	163	4.8 e9

Four orders of magnitude lower than 67/P C-G (Rosetta/Philae) + Didymain's perturbation

Didymos system
Gravity model



MASCOT-2 dynamics

Three-body system

L*	1.18 km
μ	9.2 e-3
T	11.92 h

	Diameter [m]	**Mass [kg]**
Didymain	775	5.2 e11
Didymoon	163	4.8 e9

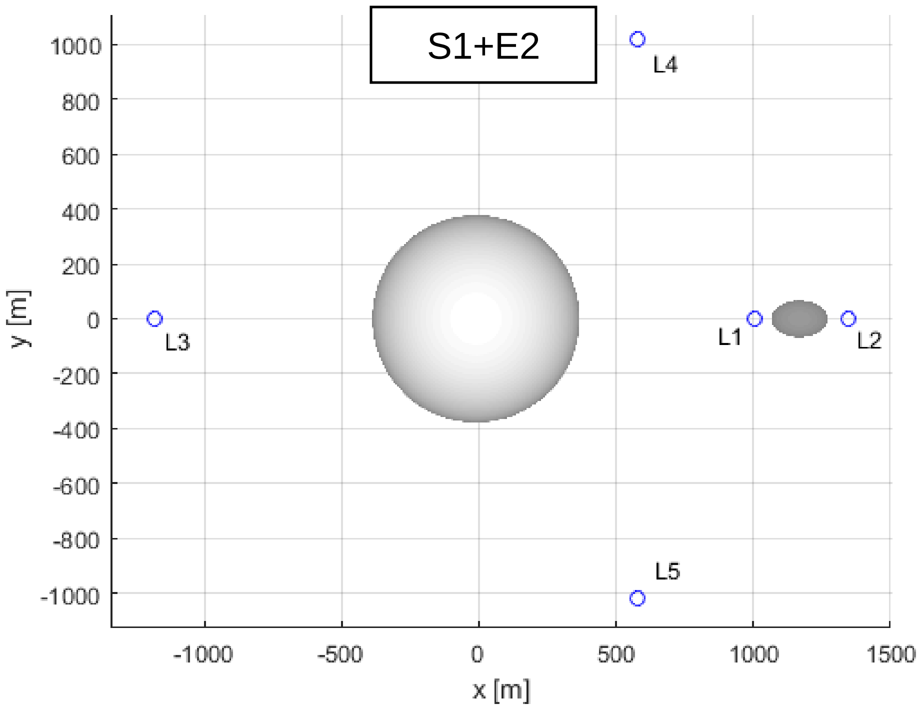
CR3BP to model the motion of the asteroids' center of mass

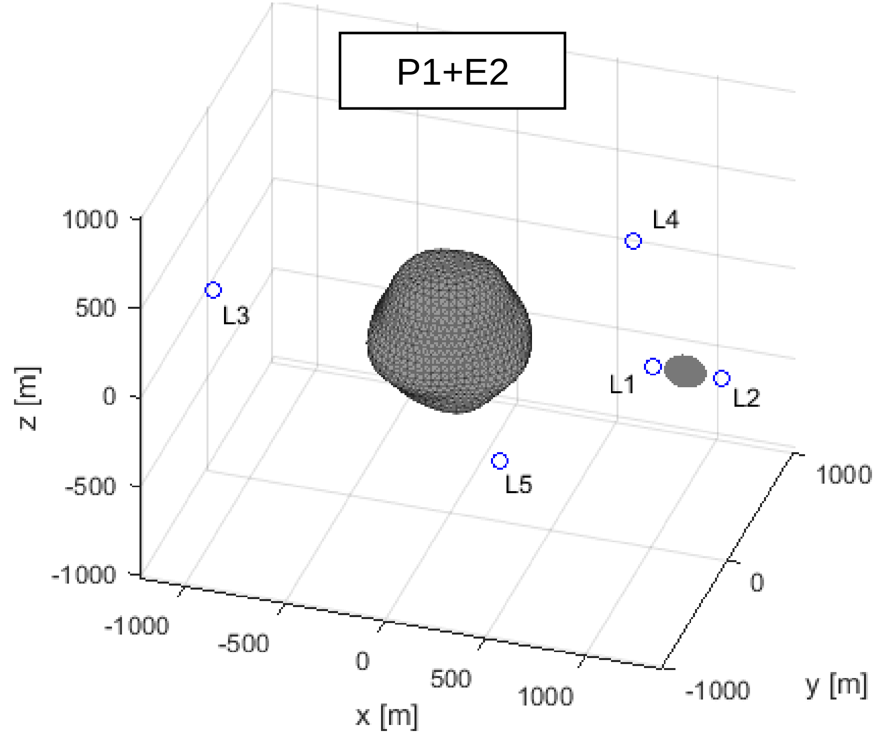
Didymos system
Gravity model

CR3BP to model the motion of the asteroids' center of mass

+

Gravity source	Dynamical model
Didymain (sphere) + Didymoon (sphere)	S1+S2 (CR3BP)
Didymain (sphere) + Didymoon (ellipsoid)	S1+E2
Didymain (polyhedron) + Didymoon (ellipsoid)	P1+E2





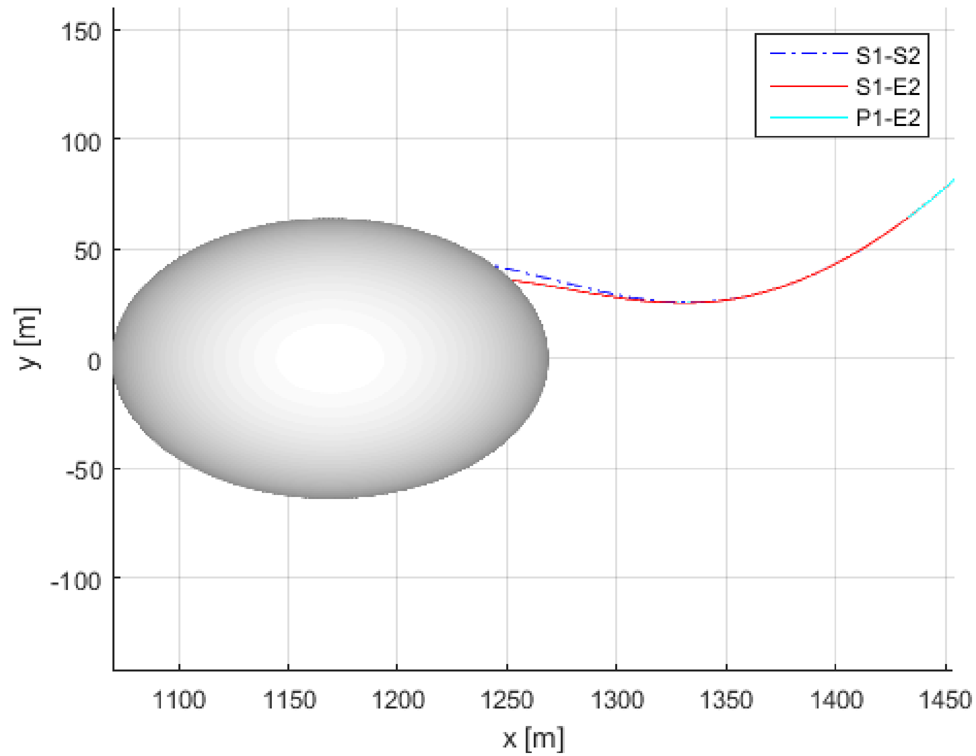
Didymos system
Dynamical perturbations

Relevant effects at 1 km	$[m/s^2]$
Acceleration due to Didymos system's gravity	e-5
Acceleration due to SRP on MASCOT-2 lander	e-8
Perturbation due to Sun's gravity (third body)	e-11
Perturbation due to Earth's gravity (third body)	e-13

Not relevant for MASCOT-2 scenario

Irregularities in Didymos gravity field are the most relevant perturbations

No relevant differences found between S1+E2 and P1+E2 modeling



MASCOT-2 landing design
Requirements

- MASCOT-2 shall land on the smaller asteroid (Didymoon)

- MASCOT-2 is a passive probe
  - No actuators for trajectory control
  - No actuators or devices for anchoring to the surface

- Extremely low gravity field on Didymoon's surface
  - MASCOT-2 can bounce but it shall stay on the surface

- MASCOT-2 release point shall be safe from AIM spacecraft point of view

Ballistic descent with no escape after bouncing → $v_{after_{TD}} < v_{esc}$

Escape velocity from Didymoon's surface

Theoretical limits

Dynamical model	v_{esc} [cm/s]
S2	7.70
S1+S2	4.95
S1+E2	4.58
P1+E2	4.57

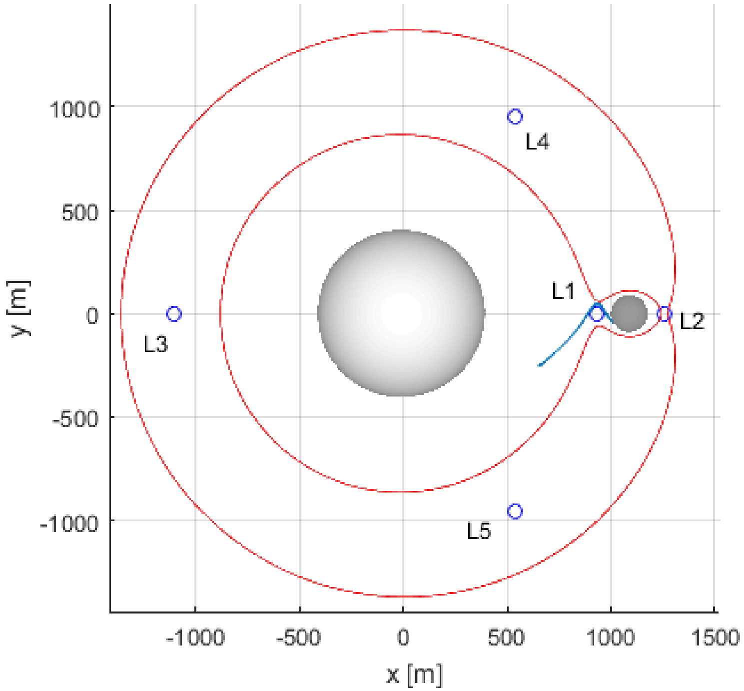
Values to escape Didymoon's SOI (or neighborhood)

It depends on latitude

they depend on latitude and longitude

The escape velocity is the touch down velocity for a pure ballistic landing from the SOI

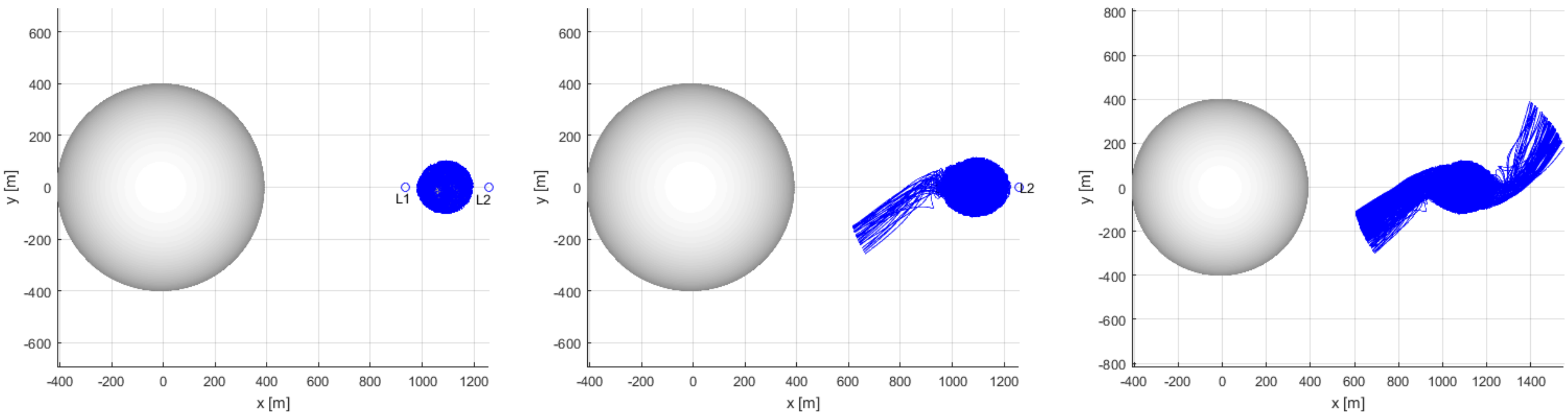
$$v_{TD} \geq v_{esc}$$



Minimum energy to land / escape: through L1 point

Touch-down velocity
Monte Carlo backwards integration

Energy



$v_{TD} < v_{L1}$ $v_{L1} < v_{TD} < v_{L2}$ $v_{TD} > v_{L2}$

	Minimum v_{td} [cm/s]	
	Through L1 neck (v_{L1})	**Through L2 neck (v_{L2})**
S1+S2	4.95	5.23
S1+E2	4.58	5.11
P1+E2	4.57	5.11

Requirements

- Ballistic descent with no escape after bouncing

$$v_{after_{TD}} < v_{esc}$$

- Safety: release far from Didymoon constraints the dynamics to

$$v_{TD} \geq v_{esc}$$

Design strategy

- Keep v_{TD} as low as possible

⇓

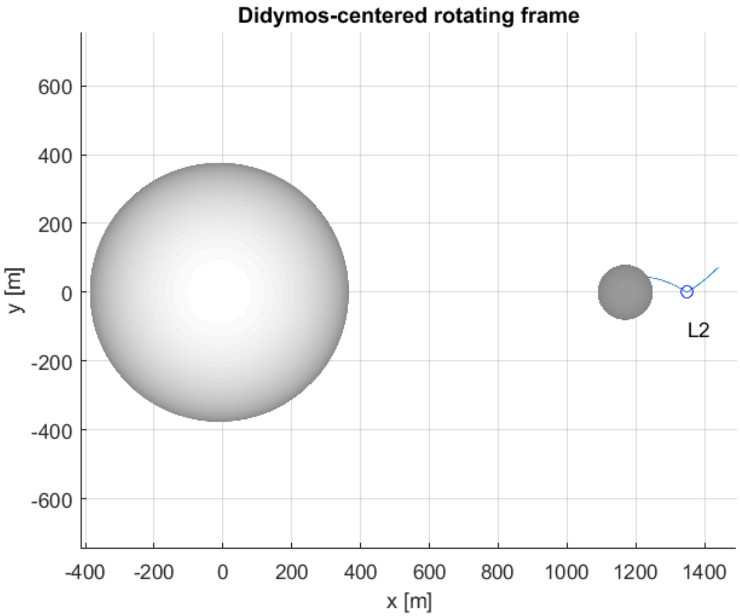
Trajectories with low v_{TD} are those passing through the L1 or L2 neck with low energy (L2 neck is considered for safer release)

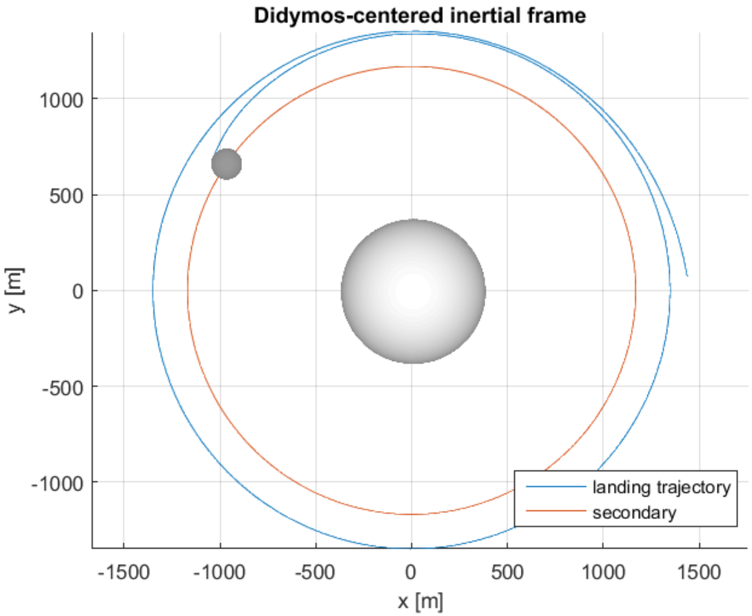
⇓

Manifolds associated to L2 point

MASCOT-2 landing design
Example of landing solution

Release from 200 m altitude



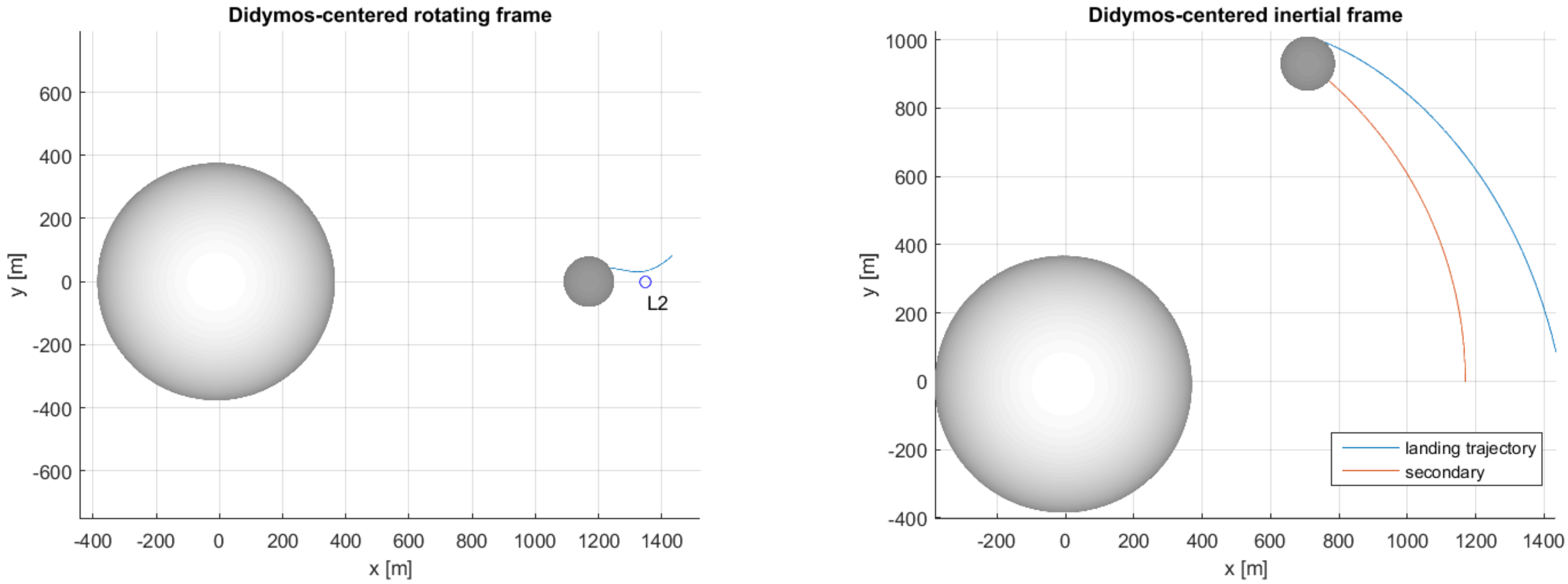


Manifold

- High time of flight
- Not robust after release dispersion

MASCOT-2 landing design
Example of landing solution

Release from 200 m altitude



Near the manifold

- Low time of flight
- Robust after release dispersion

MASCOT-2 landing design
Assumptions

BALLISTIC DESCENT: MASCOT-2 dispersion at release

- Navigation error
- Release mechanism error
  - 5 deg (1σ) half cone angle around nominal release direction
  - 0.5 cm/s (1σ) uncertainty in release velocity

BOUNCING DYNAMICS: velocity after touch down

- Direction according to soil inclination
  - Uniform distribution in azimuth
  - Gaussian distribution in elevation: 90 ± 70 deg (μ ± 3σ)
- Norm of velocity dumped according to the restitution coefficient

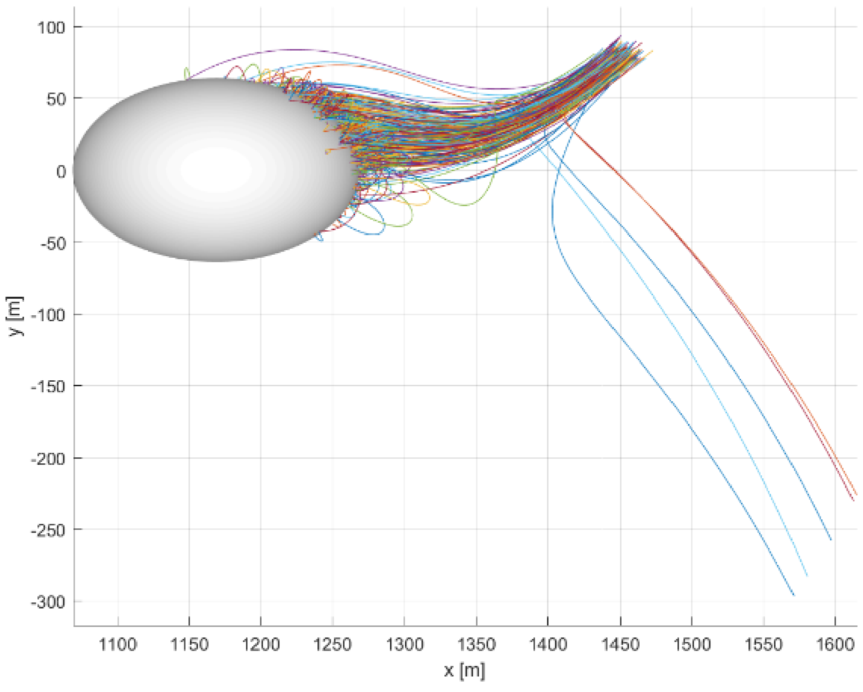
$$\eta = \frac{v_{afterTD}}{v_{beforeTD}} = 0.9 \cdot 0.6 = 0.54$$

0.9: asteroid's soil

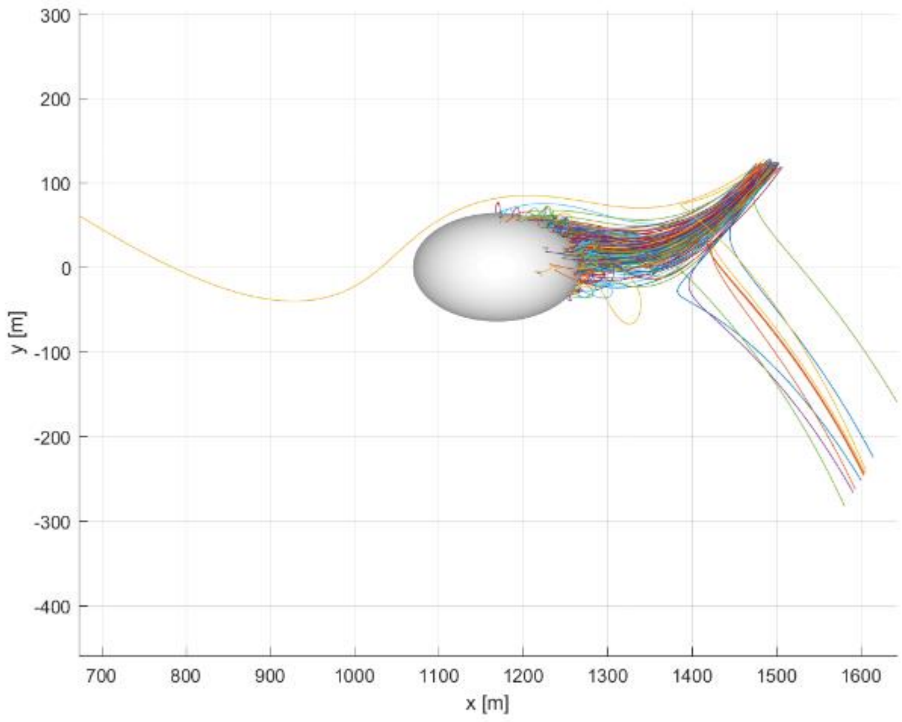
0.6: lander's structure

Escape probability

- From release up to escape or stay on Didymoon's surface
- Monte Carlo simulation (200000 cases for each release point)
- S1+E2 model used (equivalent to P1+E2)



Release from 200 m altitude



Release from 250 m altitude

MASCOT-2 landing design
Escape probability

- From release up to escape or stay on Didymoon's surface
- Monte Carlo simulation (200000 cases for each release point)
- S1+E2 model used (equivalent to P1+E2)

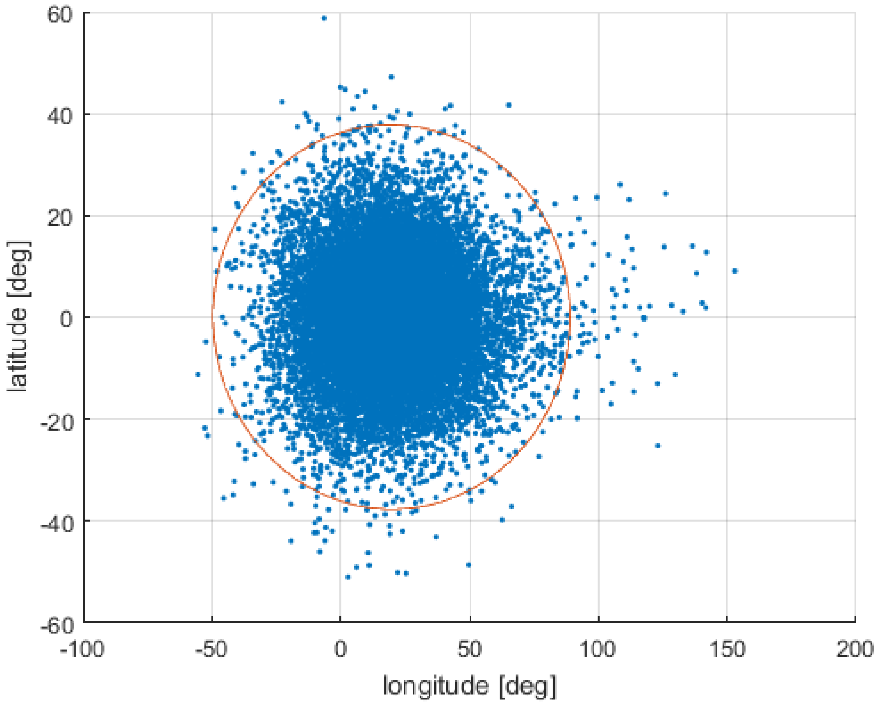
Release altitude [m]	Escaped trajectories [%]		
	After release	After touch down	TOT
100	1.14	0.00	1.14
150	1.26	0.00	1.27
200	3.18	0.01	3.19
250	5.79	0.04	5.83
300	6.03	0.32	6.35

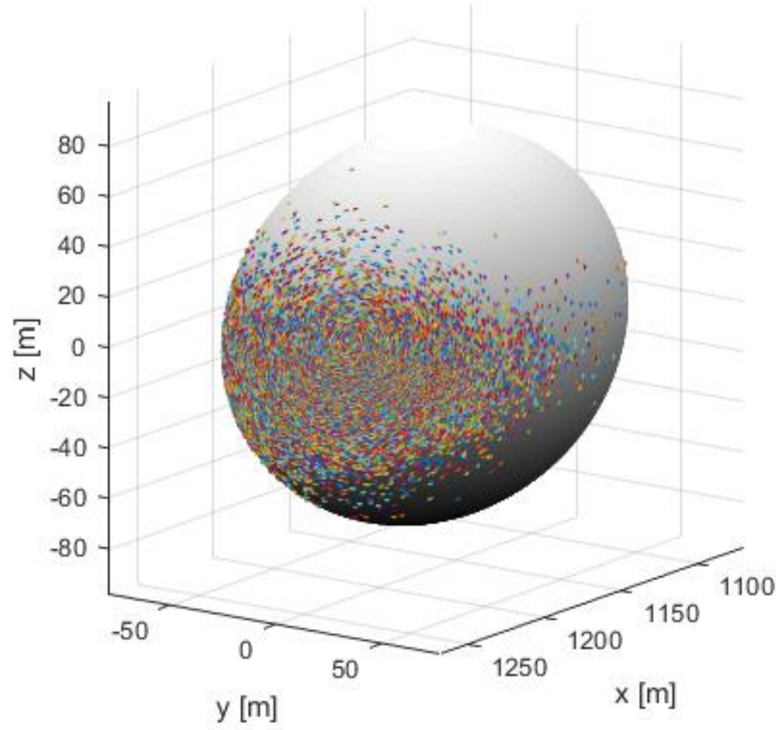
MASCOT-2 landing design
Landing dispersion at rest

- From release up to rest on Didymoon's surface: outgoing vertical velocity lower than 0.5 cm/s
- Monte Carlo simulation (200000 cases for each release point)
- S1+E2 model used (equivalent to P1+E2)

Release altitude [m]	**Dispersion at rest (μ ± 3σ)**		
	Latitude [deg]	**Longitude [deg]**	**Tof [h]**
100	0.2 ± 32.5	23.3 ± 87.9	1.81 ± 0.95
150	0.0 ± 31.5	20.1 ± 66.7	2.19 ± 1.06
200	0.1 ± 32.9	19.7 ± 60.5	2.50 ± 1.21
250	-0.1 ± 36.6	20.5 ± 64.8	2.77 ± 1.41
300	0.1 ± 44.3	19.5 ± 86.0	2.95 ± 1.35

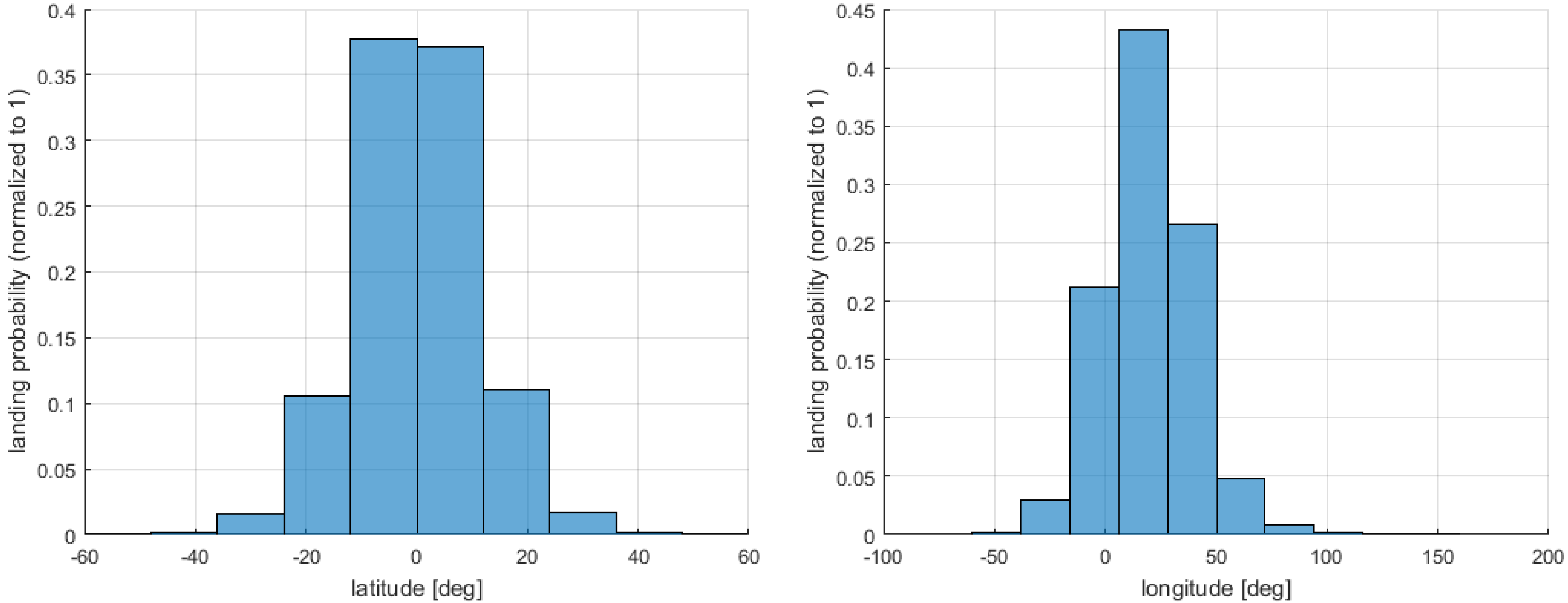
MASCOT-2 landing design
Landing dispersion at rest: release from 200 m





Release altitude [m]	Dispersion at rest (μ ± 3σ)		
	Latitude [deg]	Longitude [deg]	Tof [h]
200	0.1 ± 32.9	19.7 ± 60.5	2.50 ± 1.21

MASCOT-2 landing design
Landing dispersion at rest: release from 200 m



Release altitude [m]	Dispersion at rest (μ ± 3σ)		
	Latitude [deg]	**Longitude [deg]**	**Tof [h]**
200	0.1 ± 32.9	19.7 ± 60.5	2.50 ± 1.21

Summary

- The main perturbing action is due to the uncertainty on Didymos/Didymoon gravity field
- Higher successful landing probability for lower release points
- Landing dispersion at rest is confined within a certain latitude-longitude band
- Good results with current assumptions on release dispersion, soil uncertainty and restitution coefficient

Release altitude [m]	Successful probability [%]
100	98.86
150	98.73
200	96.81
250	94.17
300	93.65

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