Proximity Operations at Small Bodies

Findings of the ASTEX Study

Workshop on GNC for Small Body Missions
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Introduction

- What is ASTEX?
- Small body environment (physics, ...)
- Close proximity operations and study results
- Landing scenarios and results
- Conclusion

ASTEX Study

ASTEX

- Feasibility study funded by German space agency DLR
- Study team: MPS, DLR, Astrium, Astos

- Exploration mission to two near-Earth asteroids
- Targets should have different mineralogical constitution
- One asteroid should be a fragment of a differentiated object and the other one should be of primitive nature

- Evolved fragment: taxonomy E, V, M, S, A, Q, R
- Primitive: taxonomy C, D, P, B, F

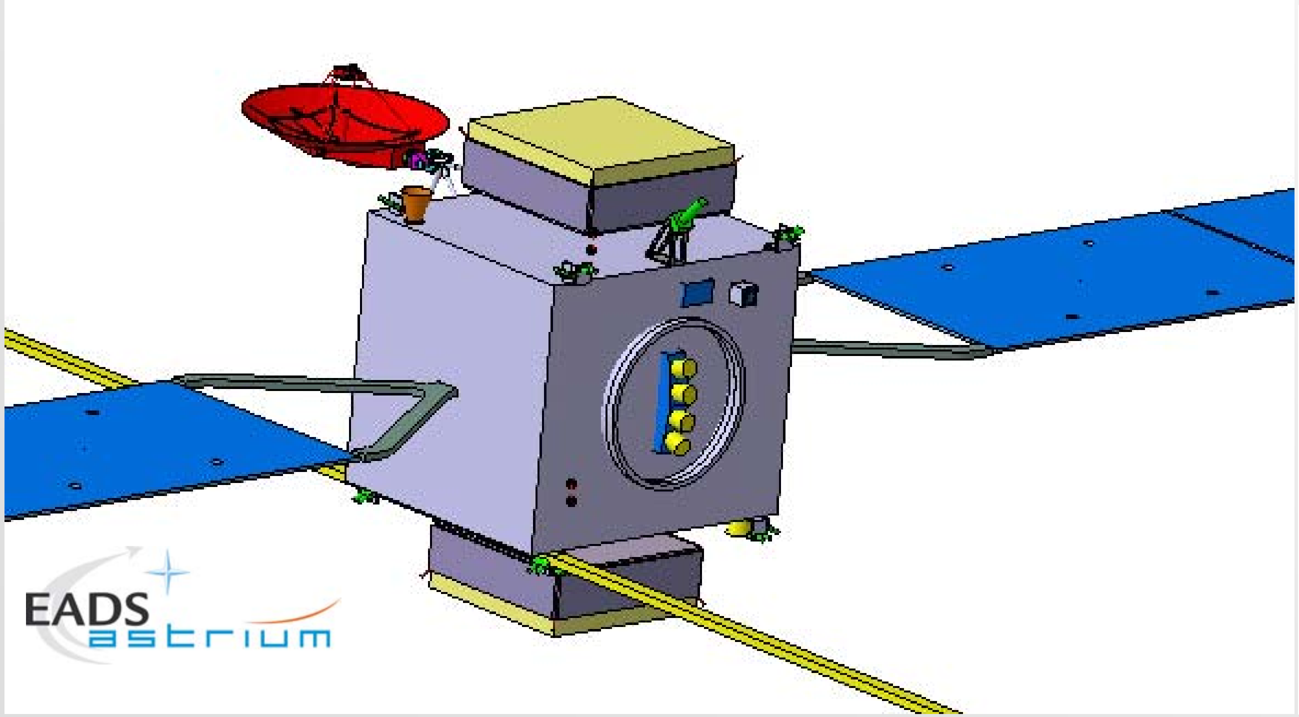
ASTEX Study

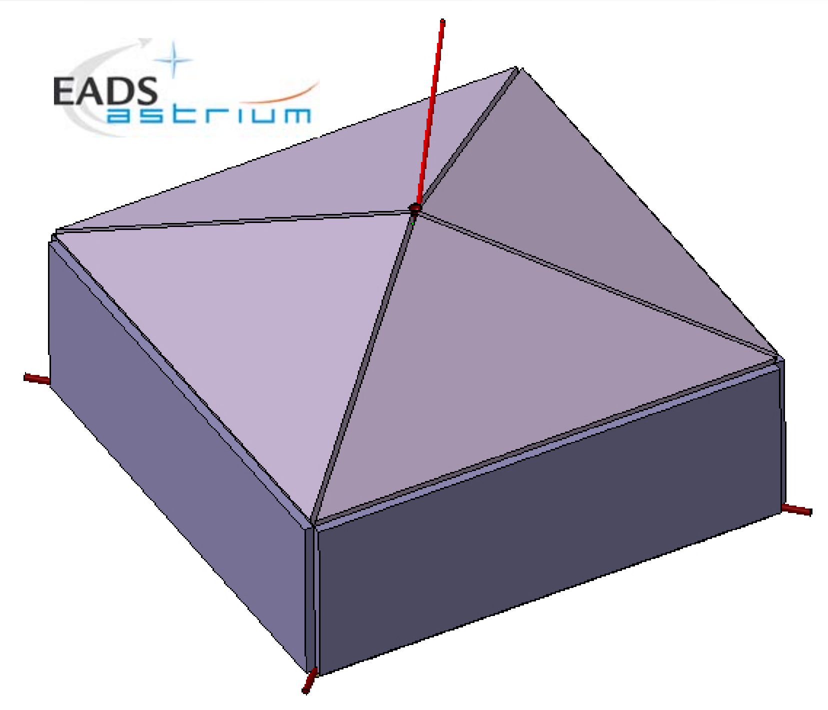
Immediate Scientific Goals

- Explore the origin and evolution history of NEAs
- Determination of the inner structure of NEAs
- Determination of the morphology, geology, chemistry, mineralogy as well as the age of the surface
- Search for bounded water
- Determination of physical parameters as size, shape, mass, density, rotation period, spin vector
- Determination of the physical properties of the surface (thermal conductivity, roughness, material strength)
- Establish the link between the asteroids and the meteorite class

ASTEX Study

- Spacecraft consists of one orbiter and two lander spacecrafts
- On each target asteroid one lander spacecraft is separated for in-situ asteroid surface investigations
- Launcher for about 1.6 t S/C wet mass

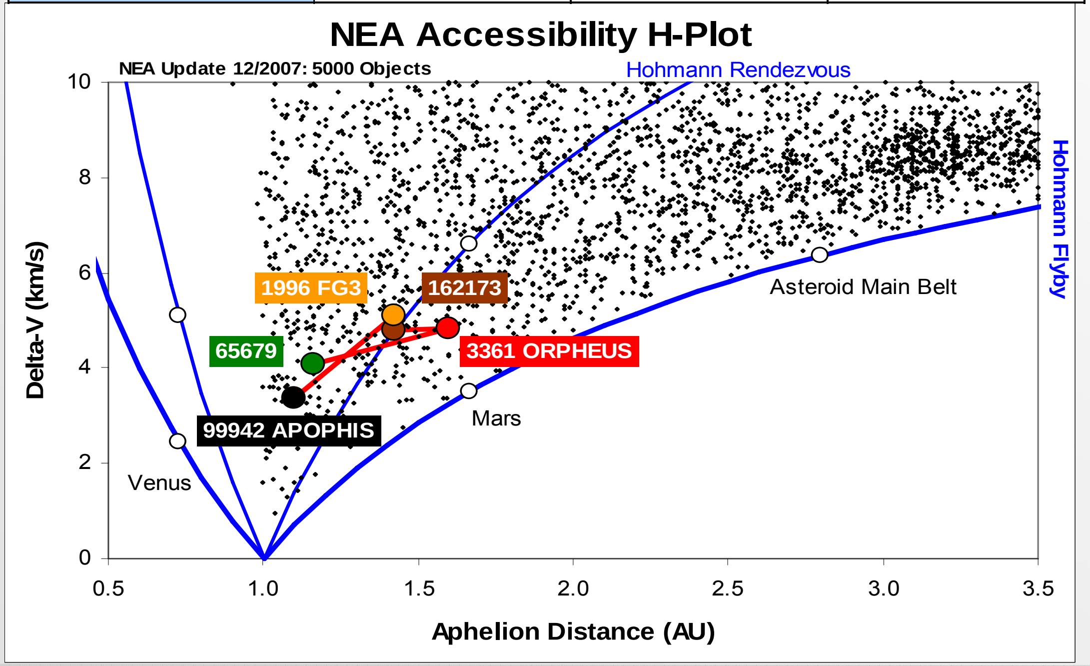




ASTEX Study

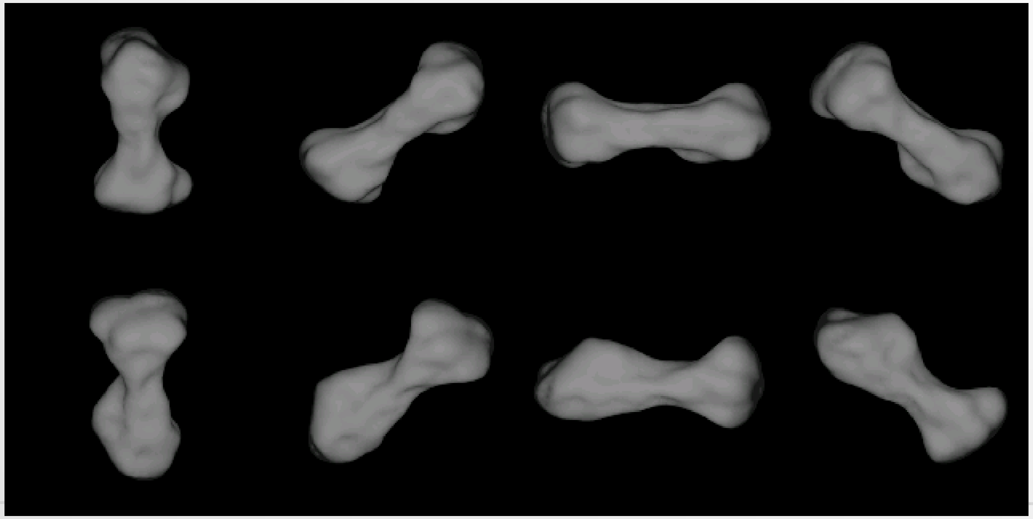
- Finally three target combinations have been selected
- Stay time at each target is 6 months
- Possible mission extension at second target

1st Target	99942 Apophis	162173 1999 JU3	65679 1989 UQ
2nd Target	1996 FG3	3361 Orpheus	3361 Orpheus
Taxonomy 1st	Sq	Cg	B
Taxonomy 2nd	C	S, V	S, V
Start Mission	20 May 2023	06 Dec 2020	01 Mar 2017
Arrival 1st	08 Jun 2027	30 Dec 2024	04 Jul 2021
Departure 1st	05 Dec 2027	28 Jun 2025	31 Dec 2021
Arrival 2nd	30 Dec 2031	16 Aug 2027	20 Aug 2024
End Mission	27 Jun 2032	12 Feb 2028	16 Feb 2025
Mission Duration	9.11 years	7.19 years	7.97 years
Delta-V Mission	9.114 km/s	8.833 km/s	10.090 km/s



Environment of Small Bodies

- In general: only few is known about physical characteristics of near-Earth asteroids
- Known: absolute magnitude H
- Asteroid size depends on H and albedo, last one often estimated
- Mass and gravitation depend on size and density
- Rotational parameters like spin axis orientation, precession, nutation are unknown
- Is target a binary? (15%-19% of all NEAs are expected binaries)
- Other possible inconveniences: dog-bone shape, contact binaries, rubble pile structure, ..?..



Proximity Operations

- Options of Proximity Operations at Small Bodies
  - Orbiting
    - Stable orbiting (i.e. thrust free)
    - Unstable orbiting (including periodic correction maneuvers)

  - Flyovers
    - High-altitude flyovers
    - Low-altitude flyovers

  - Hovering
    - Inertial hovering
    - Body-fixed hovering

  - Landing

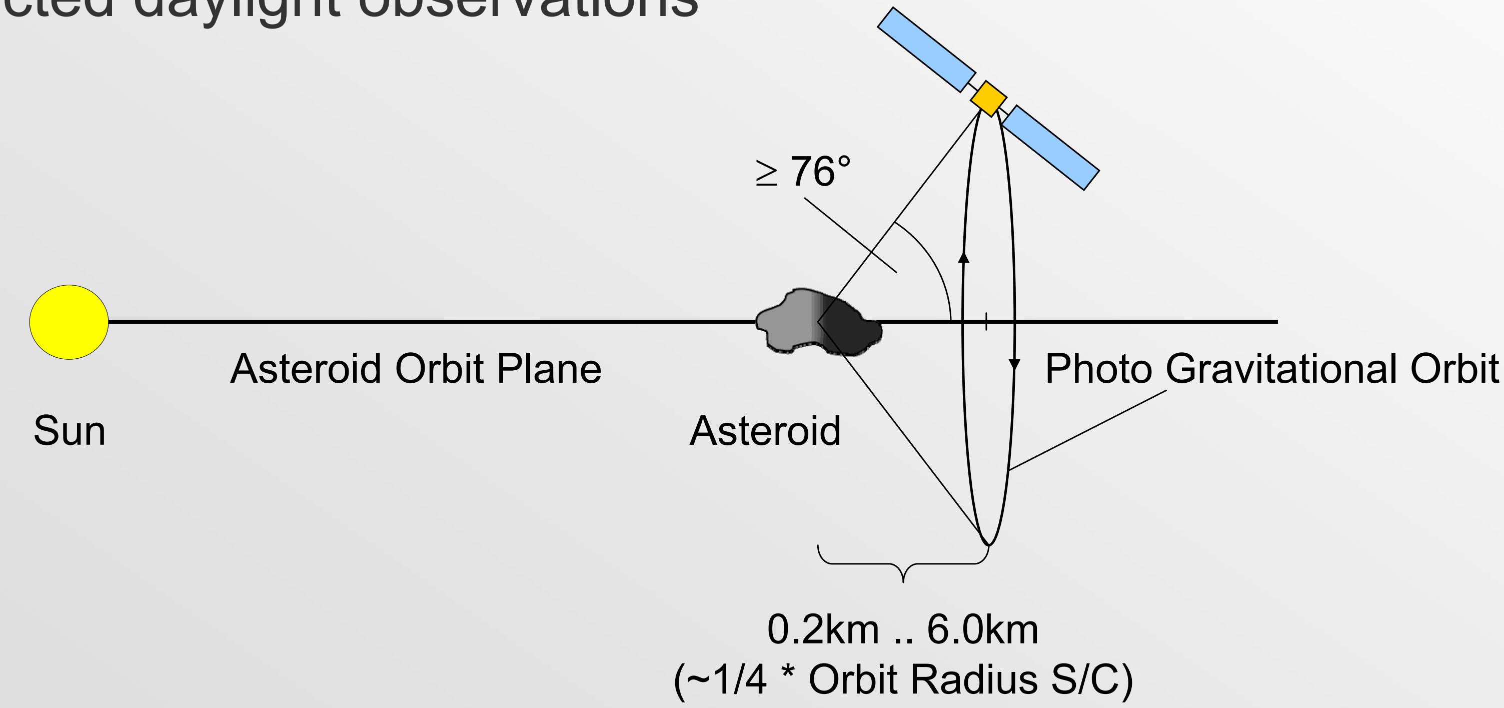
Orbiting

- Two Limiting Factors for Orbit Radius:
  - Lower bound: very inhomogeneous gravity field of asteroid
    (a lower orbit radius usually results in crash on the surface)
  - Upper bound: solar radiation pressure
    (a higher orbit radius results in escape from asteroid or crash on the surface)

➢Stable orbiting is feasible if lower bound < upper bound
(stable longterm orbiting, at least several weeks)

Orbiting

- Photo-Gravitational Orbit
  - Terminator orbit
  - Shifted away to the dark side of the asteroid due to SRP
  - Best option for stable orbiting
  - ➢Distance S/C to terminator plane is ~ 1/4 orbit radius
  - ➢Restricted daylight observations



Orbiting

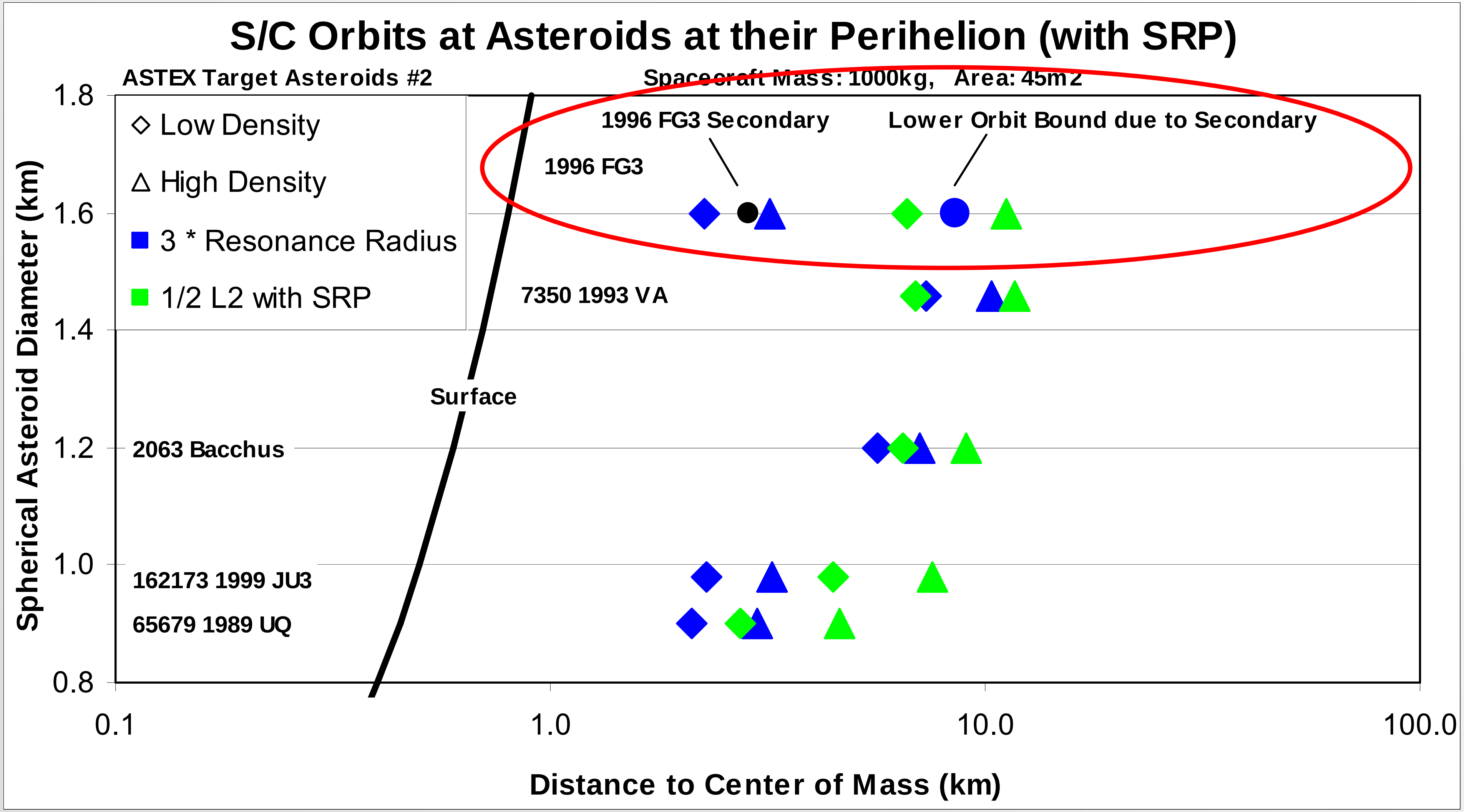
- Photo-Gravitational Orbit

Asteroid	Statement	Orbit Radius *	Orbit Period
2063 Bacchus	Stable orbiting is feasible	6 km - 19 km	80 h - 335 h
3361 Orpheus	Stable orbiting is feasible	1 km - 5 km	19 h - 200 h
7350 1993 VA	Stable orbiting for rotation period < 24 h	*unknown*	*unknown*
11500 1989 UR	No stable orbits	*none*	*none*
65679 1989 UQ	Stable orbiting is feasible	2 km - 8 km	40 h - 175 h
99942 Apophis	No stable orbits	*none*	*none*
101955 1999 RQ36	Stable orbiting is feasible	0.2 km - 1.0 km	11 h - 72 h
152560 1991 BN	Stable orbiting for rotation period < 12 h	*unknown*	*unknown*
162173 1999 JU3	Stable orbiting is feasible	2 km - 11 km	40 h - 250 h
1996 FG3	Stable orbiting is feasible	9 km - 23 km	90 h - 360 h

*** Hardly depends on asteroid's physical properties and distance to the Sun**

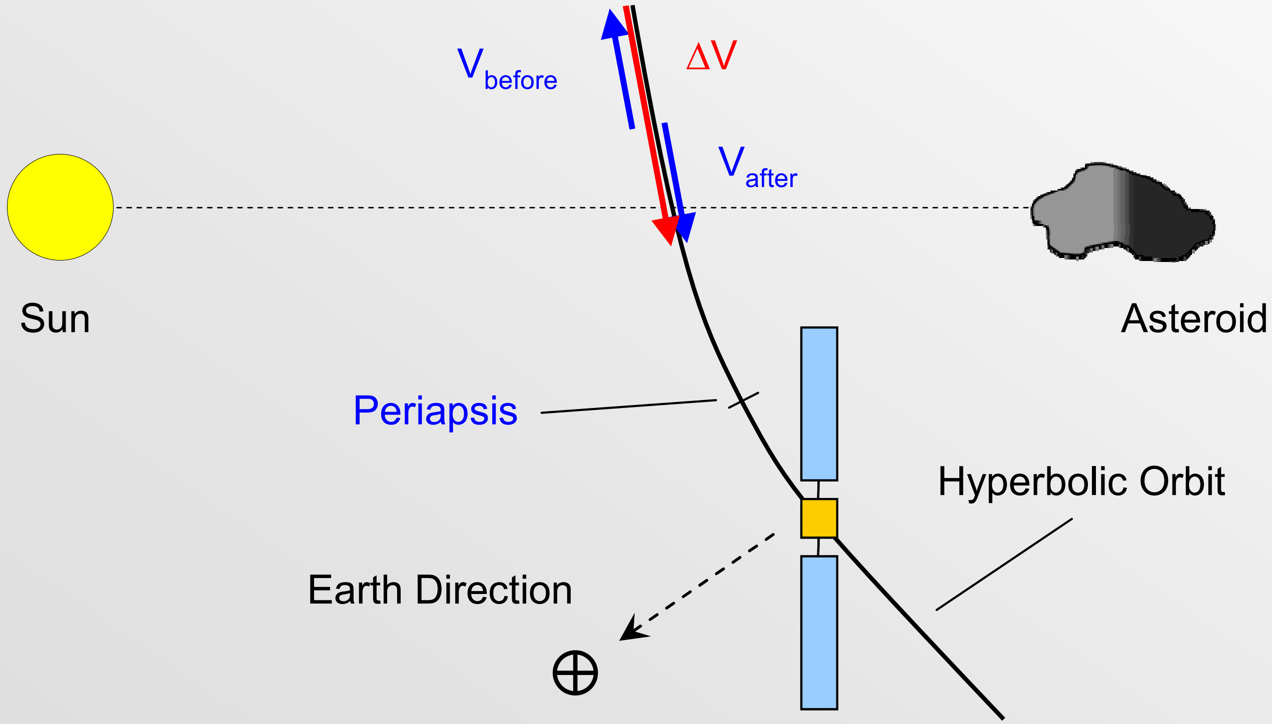
Orbiting

- Impact of a Binary



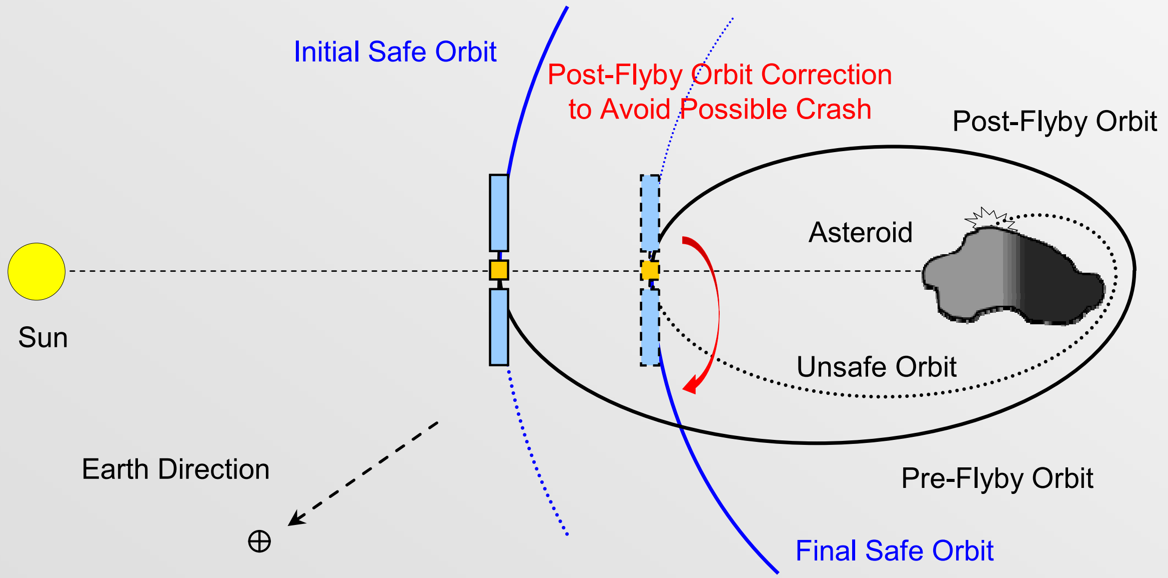
Flyovers

- High-Altitude Flyover
  - Asteroid flyby in higher altitudes (several kilometers)
  - E.g. wobbling on hyperbola
  - ➤ Purpose: e.g. first determination of gravity field (lower coefficients)



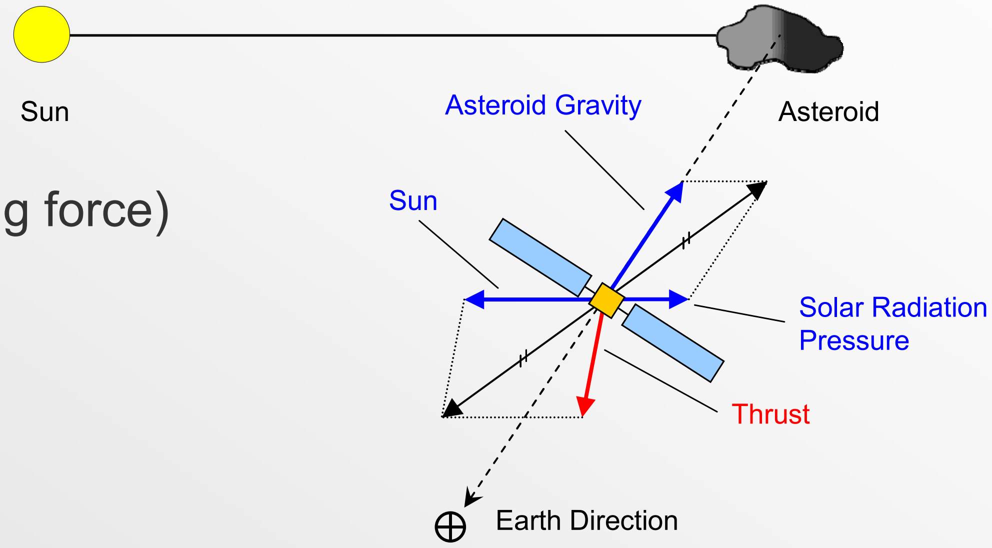
Flyovers

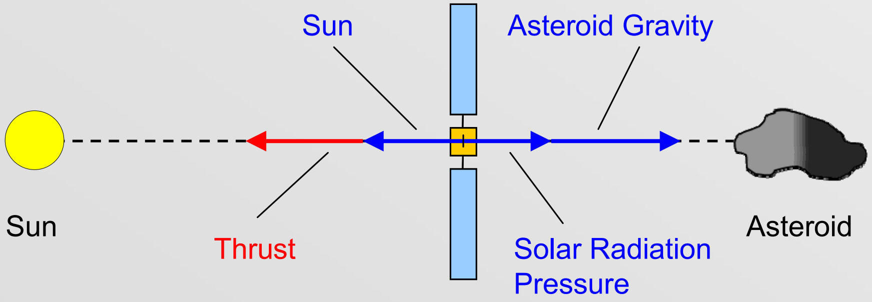
- Low-Altitude Flyover
  - Flyby in very low altitude (< few hundred of meters)
  - Precise determination of gravity field (higher order coefficients)
  - Detailed investigation of possible landing areas
  - Flyby orbit is disturbed by gravity field uncertainties
  - ➢Post-maneuver orbit correction essential



Hovering

- Inertial Hovering
  - Forces acting on the spacecraft
    - Sun gravity
    - Asteroid gravity
    - Solar radiation pressure
    - Thrust (to compensate resulting force)
  - Typical hovering positions
    - Earth-asteroid line (sub-Earth)
    - Sun-asteroid line (subsolar)





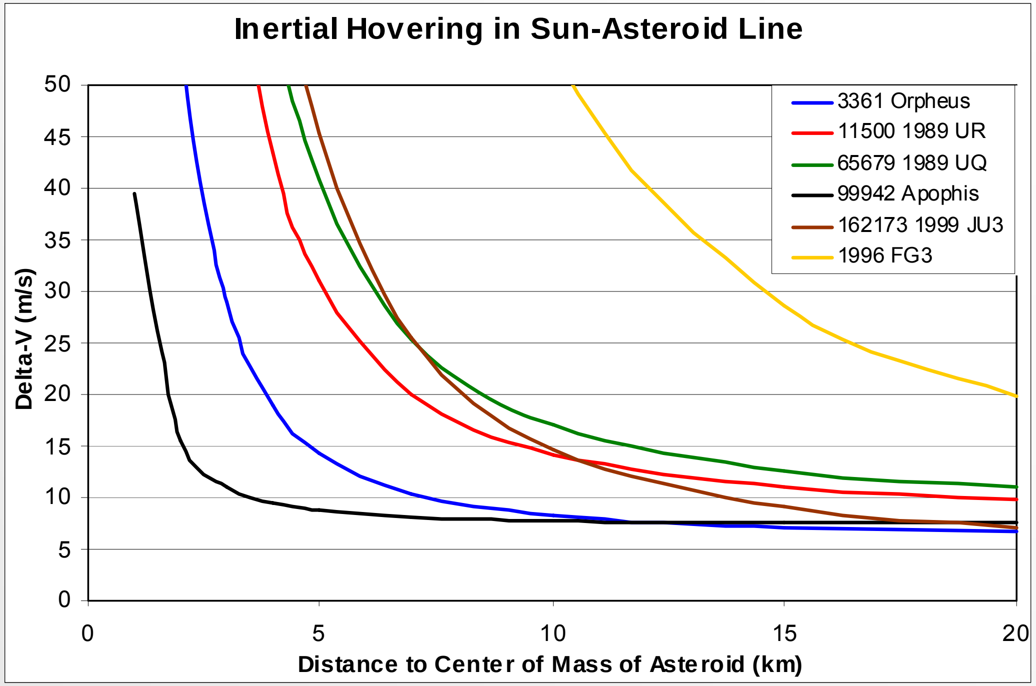
➢Possible restrictions in global mapping

➢Possible high propellant consumption

Hovering

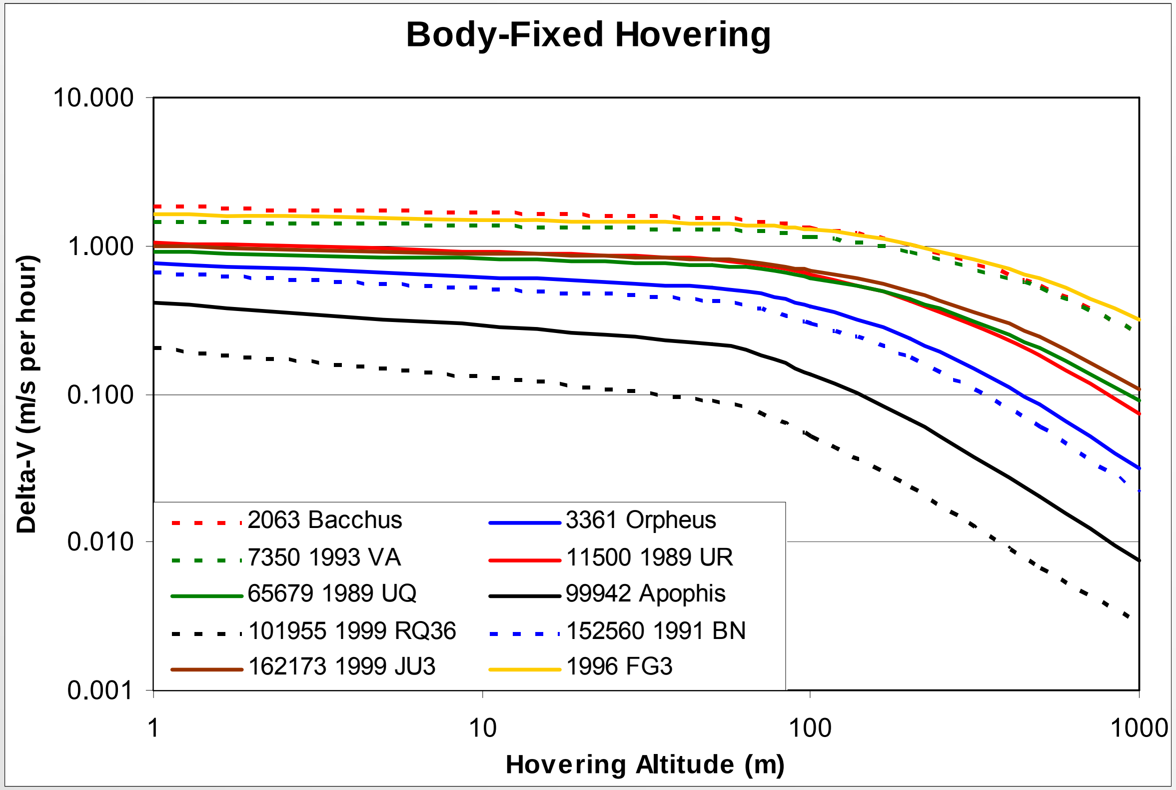
- Inertial Sub-Solar Hovering
  - Duration: 180 days

Asteroid	Delta-V Requirement in a Certain Sub-Solar Hovering Distance						
	1 km	3km	5 km	7 km	10 km	15 km	20 km
2063 Bacchus	2826 m/s	322 m/s	121 m/s	66 m/s	37 m/s	21 m/s	15 m/s
3361 Orpheus	210 m/s	29 m/s	14 m/s	10 m/s	8 m/s	7 m/s	7 m/s
7350 1993 VA	3370 m/s	380 m/s	141 m/s	75 m/s	40 m/s	21 m/s	14 m/s
11500 1989 UR	568 m/s	71 m/s	31 m/s	20 m/s	14 m/s	11 m/s	10 m/s
65679 1989 UQ	802 m/s	97 m/s	41 m/s	25 m/s	17 m/s	13 m/s	11 m/s
99942 Apophis	40 m/s	11 m/s	9 m/s	8 m/s	8 m/s	8 m/s	7 m/s
101955 1999 RQ36	14 m/s	6 m/s	6 m/s	5 m/s	5 m/s	5 m/s	5 m/s
152560 1991 BN	135 m/s	20 m/s	11 m/s	8 m/s	7 m/s	6 m/s	6 m/s
162173 1999 JU3	1028 m/s	118 m/s	45 m/s	25 m/s	15 m/s	9 m/s	7 m/s
1996 FG3	4461 m/s	504 m/s	187 m/s	100 m/s	53 m/s	29 m/s	20 m/s



Hovering

- Body-Fixed Hovering
  - Fixed S/C position wrt asteroid surface
    - S/C rotates with asteroid
    - Hovering in low altitudes (from 0.5 asteroid radius to several meters)
  - Very detailed investigation of landing areas
  - Possible starting point for landing approach or lander release



➢Very detailed knowledge of gravity field and shape required

➢Very expensive in sense of fuel consumption!

➢High GNC requirements

Landing Scenarios

- Different Types of Landing Scenarios:
  - Classical de-orbit maneuver
  - Fast de-orbit maneuver (continuous thrust)
  - Free-fall

- General Aspects
  - Needed: map of surface, gravity field model, spin vector
  - No thrust in surface direction during descent to avoid surface contermination

- Lander S/C
  - Mass: 100 kg
  - Propulsion system: cold gas (Isp 70 s)

Landing Scenarios

- Active and Passive Landing Possible
  - Critical S/C Issues
    - Descent time (up to several hours, battery capacity!) in case of lander S/C
    - Impact velocity
    - Rebounds
  - Disturbing Influences
    - Gravity field, shape and spin state
    - Small landing area (regolith pond)
  - ➢ Active Landing is First Choice
- Starting Point
  - Hovering position
  - Orbit

Landing Scenarios

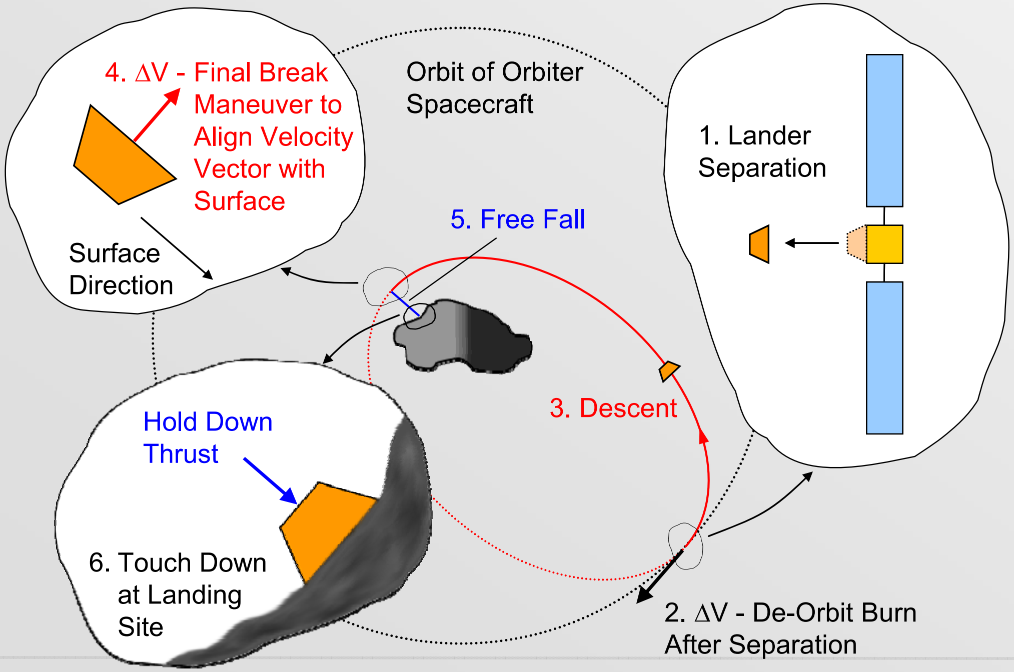
Classical De-Orbit

- Break maneuver to align S/C velocity with surface
- Hold-down thruster after landing to minimise hopping

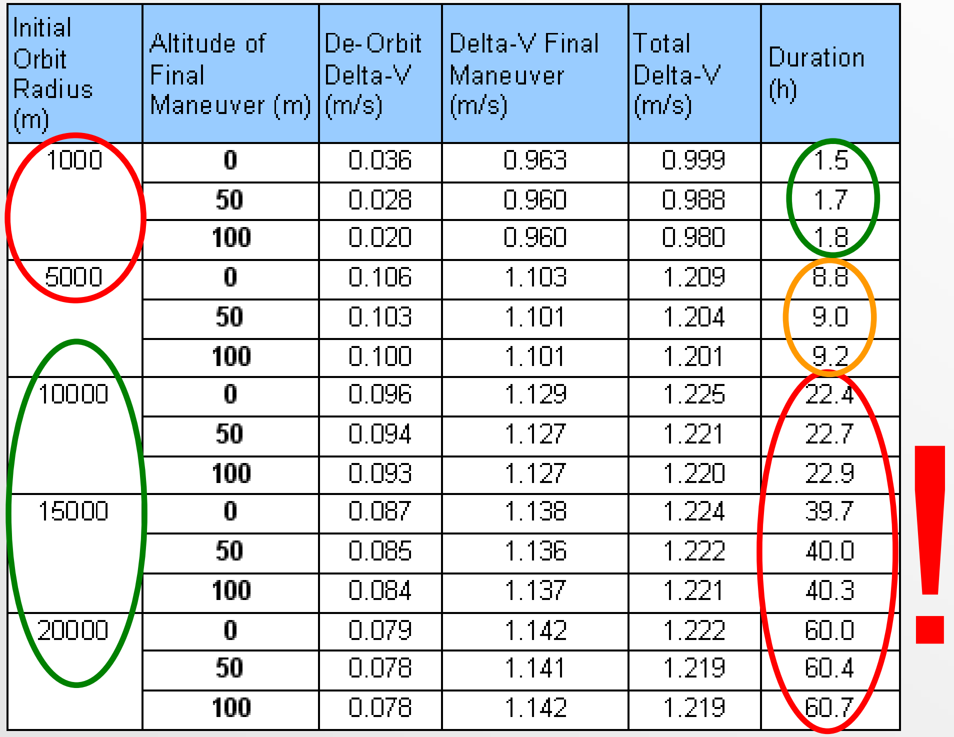
➢ De-orbiting from photo-gravitational orbit is unfavorable due to bad illumination conditions next to the terminator

➢ Only small impact of intial orbit radius

➢ Descent duration is mostly very critical



Example for 1996 FG3 (fast rotator):



Initial Orbit Radius (m)	Altitude of Final Maneuver (m)	De-Orbit Delta-V (m/s)	Delta-V Final Maneuver (m/s)	Total Delta-V (m/s)	Duration (h)
1000	**0**	0.036	0.963	0.999	1.5
	50	0.028	0.960	0.988	1.7
	100	0.020	0.960	0.980	1.8
5000	**0**	0.106	1.103	1.209	8.8
	50	0.103	1.101	1.204	9.0
	100	0.100	1.101	1.201	9.2
10000	**0**	0.096	1.129	1.225	22.4
	50	0.094	1.127	1.221	22.7
	100	0.093	1.127	1.220	22.9
15000	**0**	0.087	1.138	1.224	39.7
	50	0.085	1.136	1.222	40.0
	100	0.084	1.137	1.221	40.3
20000	**0**	0.079	1.142	1.222	60.0
	50	0.078	1.141	1.219	60.4
	100	0.078	1.142	1.219	60.7

!

Landing Scenarios

Alternatives for Classical De-Orbit?

- Thrusted descent: using continuous thrust
  - 10 N cold gas (hold-down thruster)
  - Example: initial orbit altitude of 15 km, landing site is at ~60° latitude
    - ~50 s thrusting time to accelerate S/C to 5 m/s radial velocity
    - Descent lasts less than 1 hour
    - Break maneuver starts in an altitude of ~100 m and ends in ~50 m (again ~50 s thrusting), → no relative motion wrt surface
    - Free-fall lasts ~10 min with an impact velocity of 0.14 m/s
    - Complete maneuver lasts ~ 1 hour, Δv ~10 m/s, propellant mass is 1.5 kg

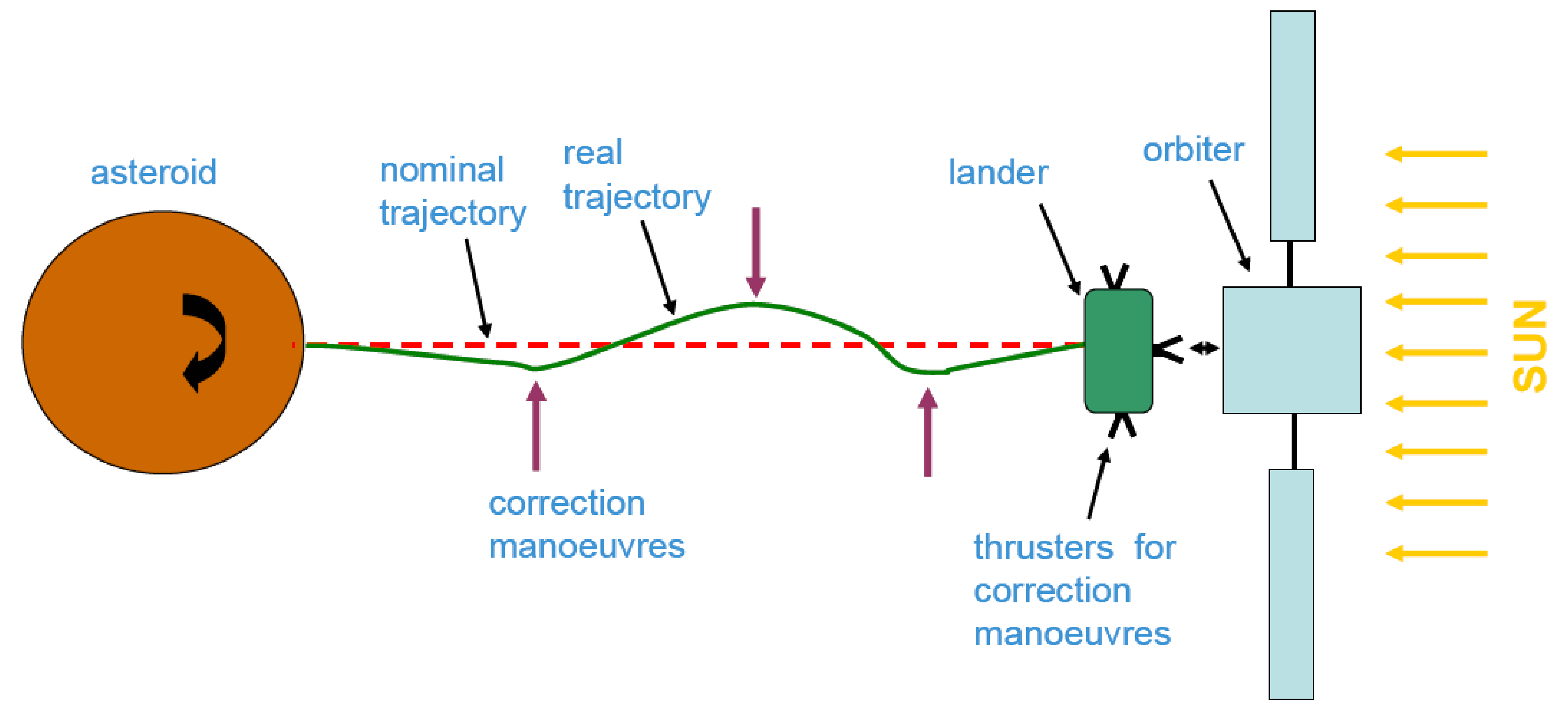
  - Critical: already small uncertainties in propulsion system may cause crash or loss of S/C

- Release from low-altitude hovering position

Landing Scenarios

Free-fall: controlled descent

- Radar ranger
- Guide camera
- Momentum wheel
- Thruster for orbit and attitude control



Landing Scenarios

- Fast rotation of small body increases landing uncertainty
- Rotation period P of few hours is critical as the landing site will only be illuminated ~1/2*P

➢ Illumination conditions next to terminator sufficient?

- Slow rotators are good for landing, but long rotation poriod means long nights with high power requirements for S/C and payload
  - ➢ Massive sizing factor for battery and mass of lander spacecraft

➢ Rotation period impacts selection of possible targets

Landing Scenarios

Hold-Down Strategies, Examples:

- Anchor
- Harpoon
- Thruster
- Glue
- None

➢ Most of these solutions are very complex with high risks or even not working for small asteroids

➢ Maybe none of the above is an appropriate solution for small asteroids

Conclusion

Main Open Issues

- How long does the characteriziation phase lasts?
- Impact of binary systems?
- Descent/target site navigation
- What precision can be achieved for landing?
- Minimising impact energy (absorption)
- How to hold-down the S/C effectively on very small bodies for robotic activities (digging, sampling, etc.)?