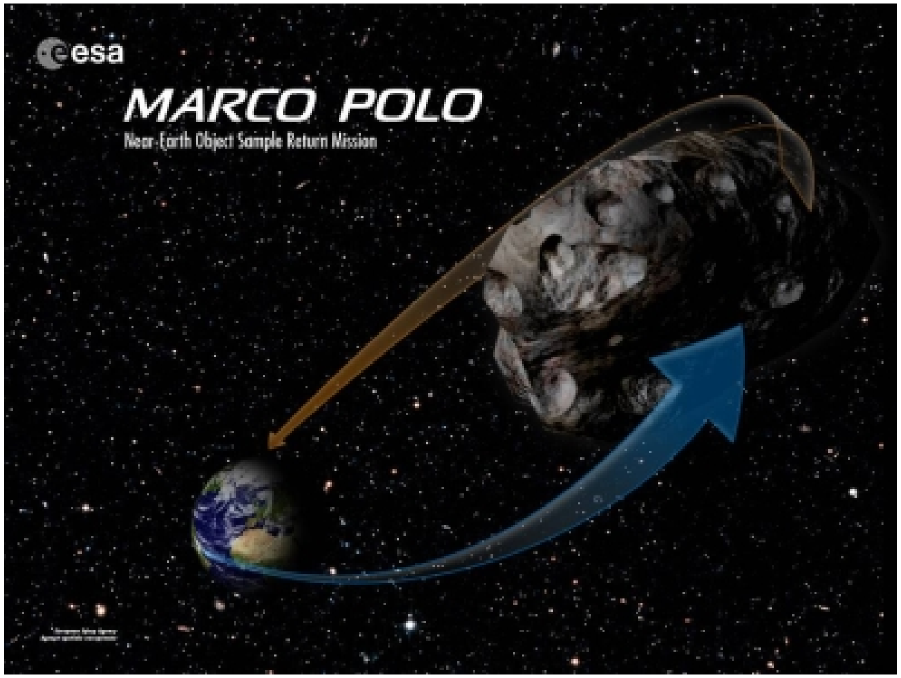
GNC aspects of the Marco Polo mission



The ESA Workshop on GNC for Small Body Missions

Presentation based on work conducted by Astrium Ltd, TAS-F and ESA CDF

Outline

- ☐ Cosmic Vision
- ☐ Marco Polo context
- ☐ Marco Polo science
- ☐ Small body environment
- ☐ Surface features
- ☐ Sampling strategies
- ☐ Landing accuracy
- ☐ Marco Polo JAXA/ESA mission baseline design
- ☐ ESA CDF study
  - Mission description
  - Descent and landing strategy

ESA Cosmic-Vision 1

- ❑ Future of the ESA Scientific programme 2017-2025+
- ❑ Cosmic Vision Call for Proposals in April 2007 for an M-class and L-class mission for launch in 2017/2018 led to 50 proposals
- ❑ 10 missions are now being studied in the frame of CV:

M: Cross-Scale

M: Euclid

M: Marco Polo

M: Plato

M: Solar Orbiter

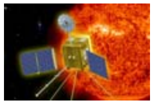
M: Spica

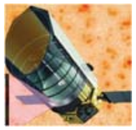
L: Laplace

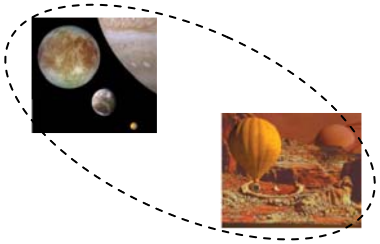
L: Tandem

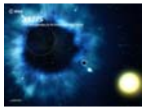
L: XEUS

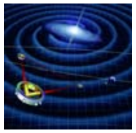
L: LISA





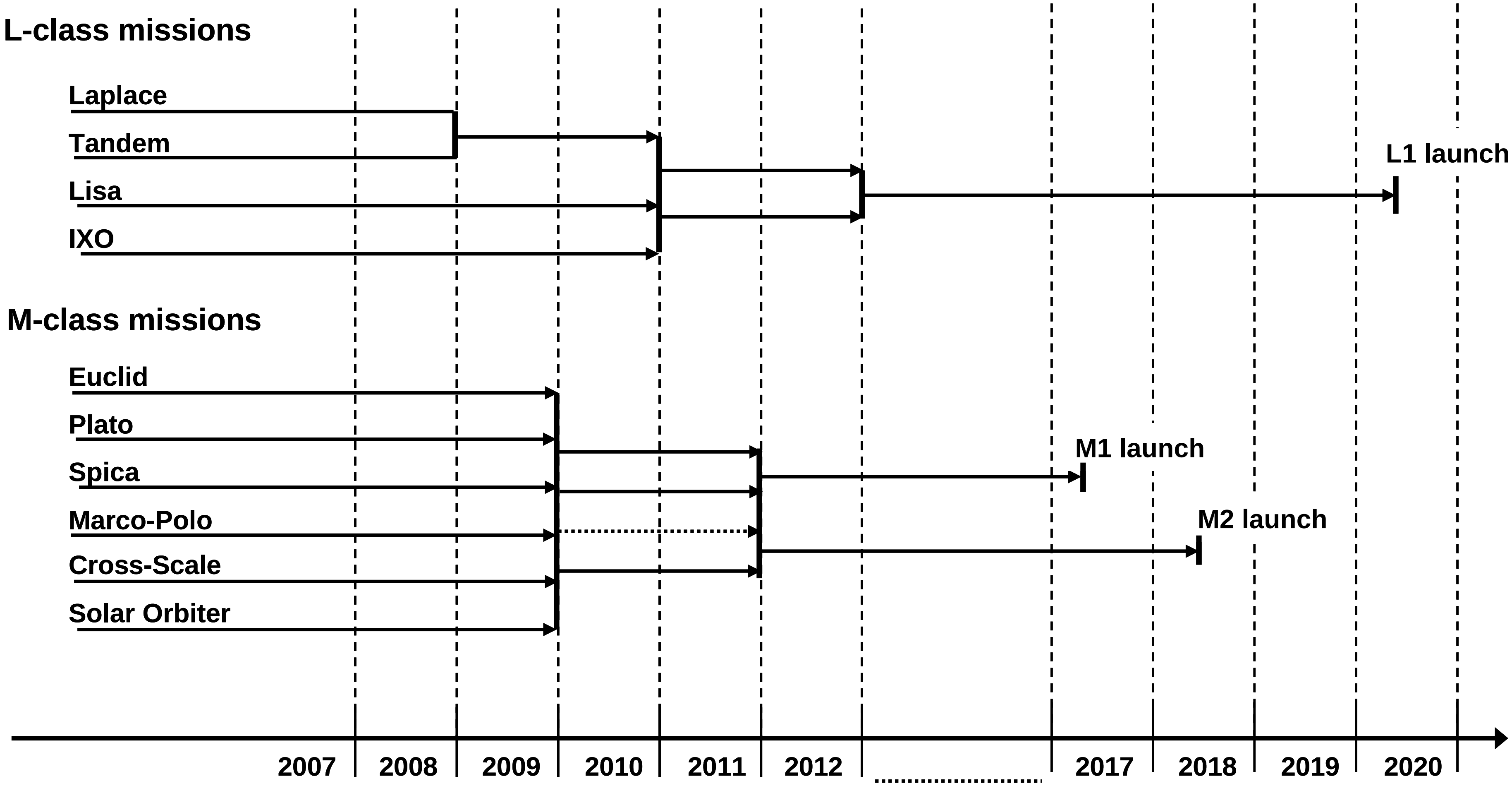






- ❑ Down selection of 3 (or 4) M missions to enter definition phase ~ end-2009
- ❑ 2 or more M-missions (~ 900 M€ budget) selected in 2011 for implementation

ESA Cosmic-Vision 2



L-class missions

Laplace

Tandem

Lisa

IXO

L1 launch

M-class missions

Euclid

Plato

Spica

Marco-Polo

Cross-Scale

Solar Orbiter

M1 launch

M2 launch

2007 2008 2009 2010 2011 2012 .... 2017 2018 2019 2020

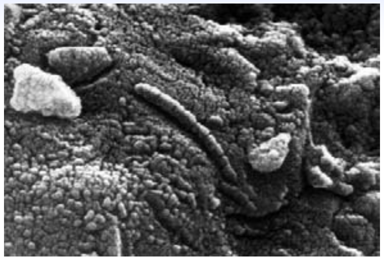
Marco Polo – context 1

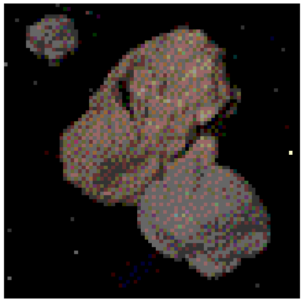
- ☐ NEO Sample return mission
- ☐ European Japanese team
- ☐ Lead proposers:
  - A. Barucci (LESIA, Paris Observatory)
  - M. Yoshikawa (JSPEC/JAXA)
- ☐ Various scenarios initially proposed
- ☐ GNC issues addressed in this presentation valid for all of them

Marco Polo – context 2

- ☐ **Baseline scenario:**
  - JAXA-provided main spacecraft:
    - ✓ Based on Hayabusa design
    - ✓ Enhanced ion engines and sampling operations
  - ESA contribution (TBC):
    - ✓ Re-entry capsule,
    - ✓ Mission/science operations,
    - ✓ Launch vehicle
- ☐ **ESA internally studied in CDF the full mission to better understand the challenges of all mission phases and support development phase**
  - Easily reachable target for case study purposes
  - Chemical mission
  - Using synergies with ongoing ESA exploration-related activities

Marco Polo - science





- ☐ Go to a D, T or C (incl. dormant comets) type NEO
- ☐ Return > 30 g sample (goal 100 g)
- ☐ Place sample in their global/local context
- ☐ Multiple sampling locations
- ☐ Avoid contamination of the sample
- ☐ Instruments: wide & narrow angle camera, Vis-NIR & mid-IR spectrometer, laser altimeter, neutral particle analyzer, radio science experiment

	Spatial resolution for imaging in the visual	Spatial resolution for VIS/IR spectrometer	Spatial resolution for mid-IR instrument
Global characterisation	**Order of dm**	**Order of m**	**Order of 10 m**
Local characterisation **x 5**	**Order of mm**	**Order of dm**	**Order of dm**
Context measurements	**Tens of µm**	**-**	**-**

Small body environment 1

- ☐ **Baseline scenario**
  - Wilson-Harrington, 2001 SG286, others TBC
- ☐ **Other asteroid options**
  - 1989 UQ, 1999JU3, 2001 SK162

Asteroid target	Eccentricity	Semi-major axis (AU)	Perihelion (AU)	Aphelion (AU)	Inclination (deg)
1999 JU3	0.19	1.19	0.96	1.42	5.88
2001 SK162	0.47	1.93	1.01	2.84	1.68
1989 UQ	0.26	0.92	0.67	1.16	1.29
2001 SG286	0.35	1.36	0.89	1.83	7.75
Wilson-Harrington	0.62	2.64	0.99	4.28	2.79

Asteroid	Number	Diameter (km), assumes p=0.06	Rotation period (hours)	Mass (kg) (assumed density =1300 kg/m^3)
1989 UQ	65679	0.76	7.7	3.0E+11
1999 JU3	162173	0.9	7.5	5.0E+11
2001 SG286		0.35	?	2.9E+10
2001 SK162	162998	1.52	68	2.4E+12
Wilson-Harrington		4	6.1	4.4E+13

NEO	μ_{NEO} (m^3/s^2)	g_{NEO} (μg_{Earth})	$R_{sphere\_influence}$ (km)	R_{Hill_sphere} (km)	V_{escape} (cm/s)	$V_{orbital}$ (cm/s)
1989 UQ	20	14	4	55	32	23
1999 JU3	33	17	5	65	38	27
2001 SG286	2	6	2	25	15	11
2001 SK162	160	28	10	110	65	46
Wilson-Harrington	2908	74	32	290	171	121

Small body environment 2

Parameters with strong influence on GNC system and proximity operations (incl. descent/landing/ascent):

- Asteroid orbital parameters (aphelion, perihelion) → sun gravity influence, solar radiation pressure
- Size (& mass)
  - ✓ e.g. risk to land/collect a sample on Eros/Phobos lower than on Itokawa-sized bodies
  - ✓ e.g. Orbit altitude, perfos of the characterization phase
- Spin rate and state
- Shape
- **Surface features**
- Soil properties to a certain extent (frictions at landing/sampling)
- Binaries:
  - ✓ Unknown until getting there: what are the limits compatible with "reasonable" mission design?
  - ✓ Can we still fulfil all science objectives, orbit strategies?

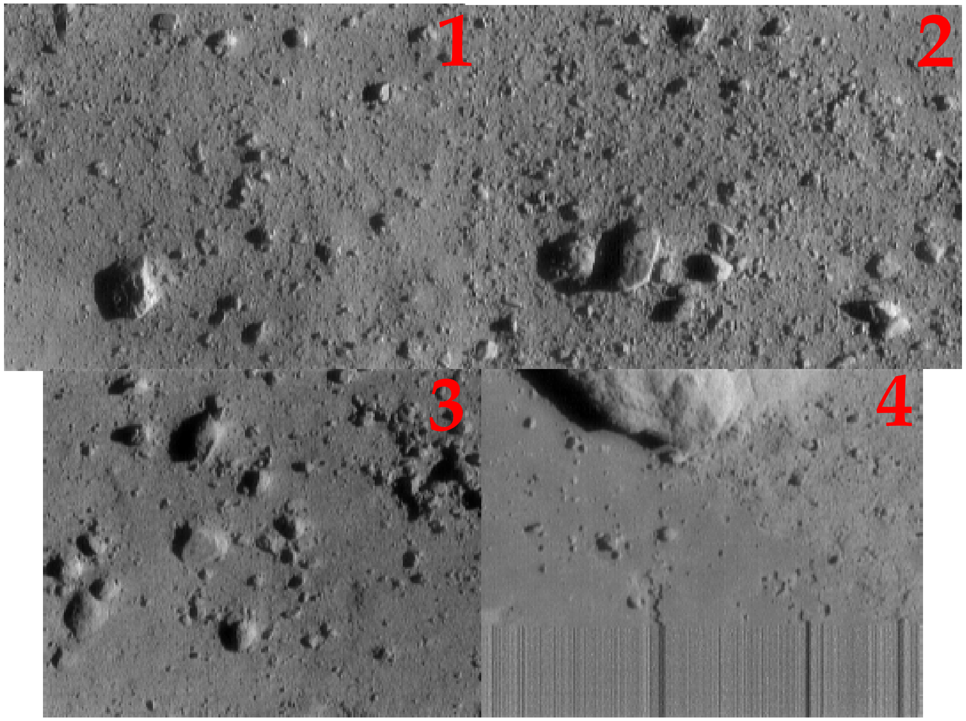
Surface features 1

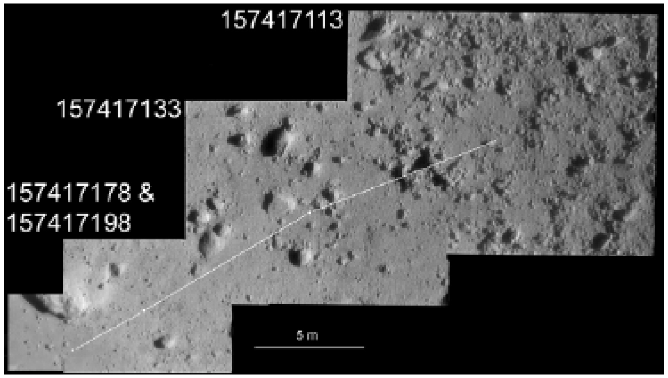
- What do we know?
- Boulder/rock distribution statistical approach similar to Moon/Mars missions not possible
- All bodies visited so far seem to differ from one another
- High resolution (cm - m) surface features only derived from previous missions:
  - Eros (20 km body)
  - Itokawa (200-500 m body)
- Strong impact on:
  - Sampling strategy (hover and go vs full landing?)
  - And thus on descent/touchdown/holding strategy

⇔ GNC

Surface features 2 - Eros

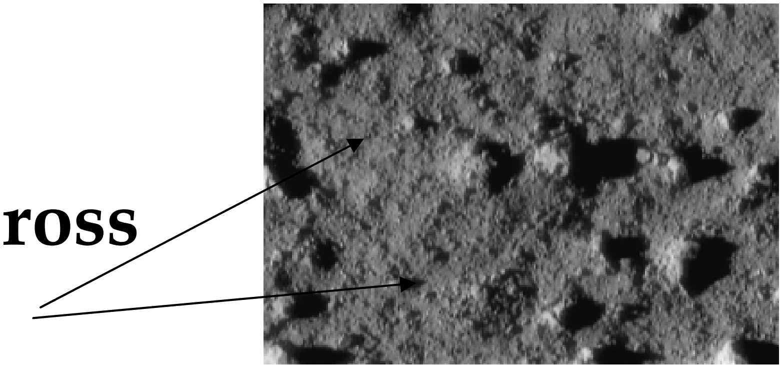
1. 54 m wide
2. 33 m wide
3. 12 m wide
4. 6 m wide (1 cm/pixel)



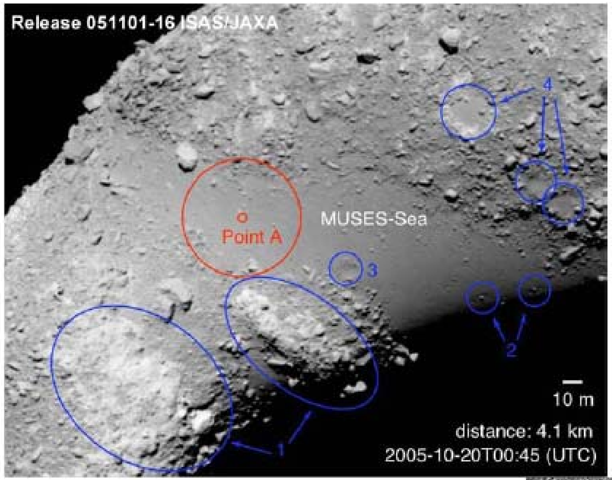


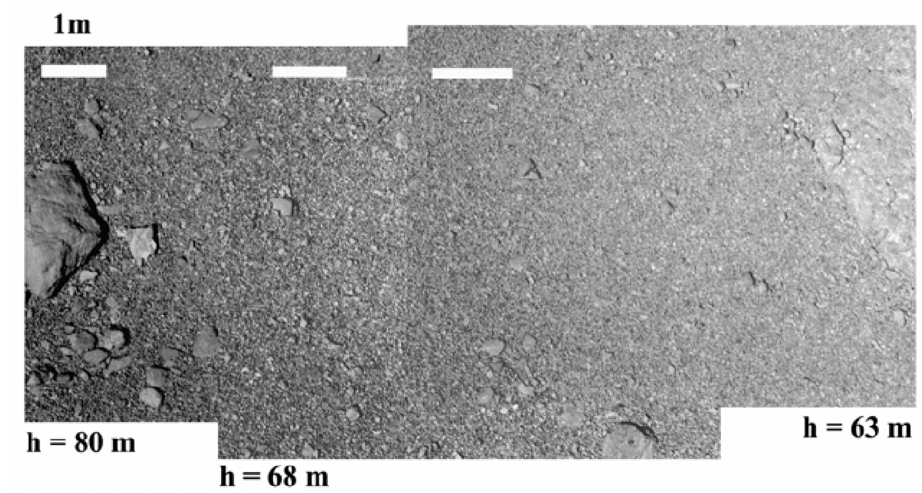
❑ 18 m across

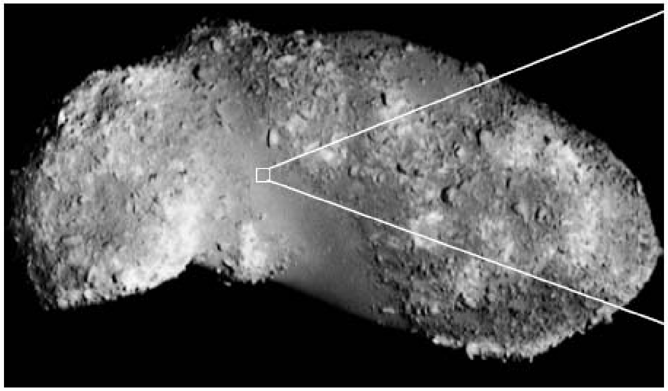
❑ Ponds

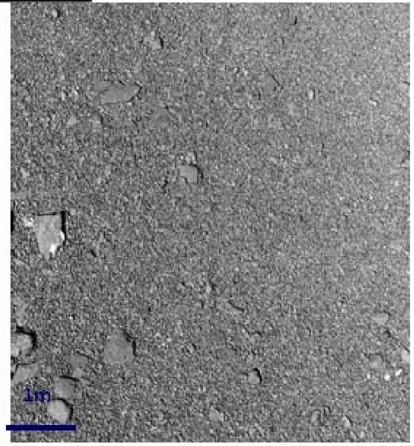


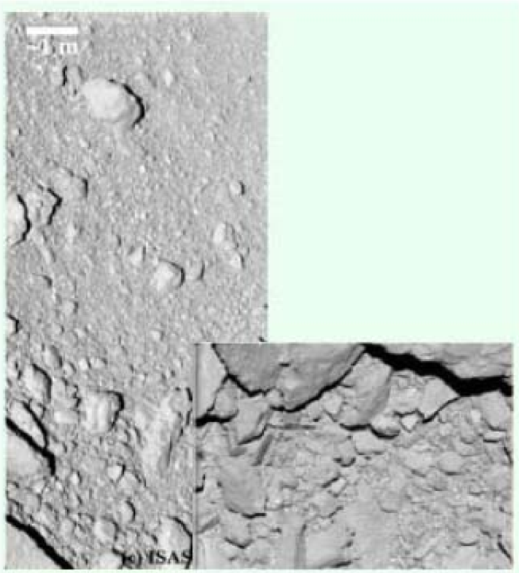
Surface features 3 - Itokawa







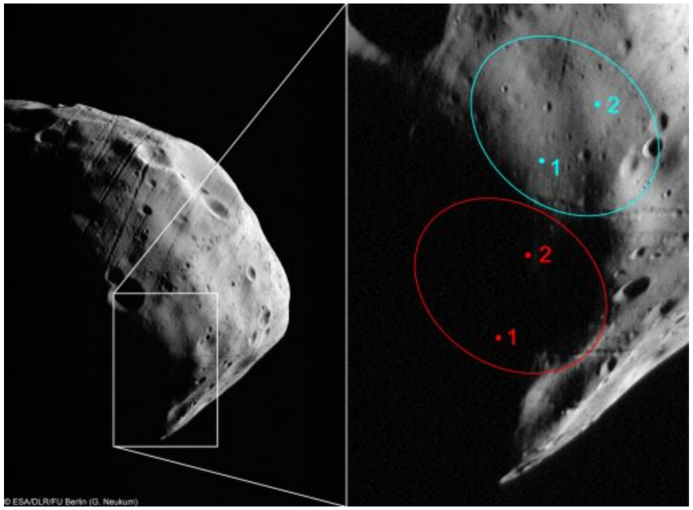




Surface features 4

❑ **What else can we do to increase our knowledge?**

- Mapping the surface features before target selection or mission design starts → not an option (except specific cases → Phobos, Deimos, Eros, Itokawa)



© ESA/DLR/FU Berlin (G. Neukum)

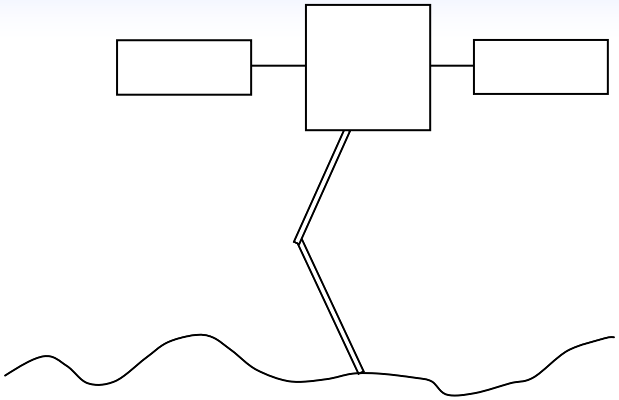
- Map the surface features from orbit at high resolution and target/land on safe areas (characterization phase)
  - ✓ Avoid the need for autonomous hazard-avoidance capability
  - ✓ Cannot totally remove the risk of not finding any hazard-free areas
  - ✓ However, it is reasonably safe to assume that at least a few small sites, large enough for a spacecraft, will be safe for landing (i.e. with only few small boulders)

Surface features 5

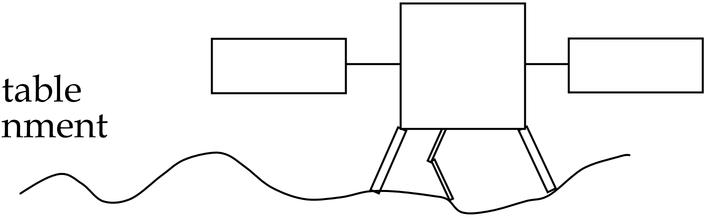
- ☐ **Design mitigation strategies:**
  - Far from the surface: Remote sampling via tether, lance, etc. High risk of the sample collection process + very low TRL + hard to meet sample mass requirements
  - Close to the surface: Large clearance below the S/C
    - ✓ Hover and go (allowing up to 5 m clearance). Cannot prevent large rock below the sampling device leading to sampling re-attempts, unless autonomous re-targeting of the sampling device is implemented
    - ✓ Short-term landing: For a simple and cost-efficient design a landing strategy allows up to ~ 50 cm clearance. Mission failure if landing near hazards > 50 cm
  - High navigation/landing accuracy seems to be a strong asset in all cases (also from a science viewpoint) but is a requirement for a landing approach (except if the surface has very large feature-less areas)

Sampling strategies

- ☐ **Hover and go**
  - Pros (e.g.):
    - ✓ no landing (better capability to cope with surface hazards)
  - Cons (e.g.):
    - ✓ Complex transfer of the collected sample
    - ✓ GNC-wise quite challenging (strongly depends on the sampling mechanism requirement)?



- ☐ **Landing**
  - Pros (e.g.):
    - ✓ Less challenging GNC-wise than hover & go (decoupling of the landing and sampling function)?
    - ✓ Better stability during sampling collection
    - ✓ "Simple" solutions for the sample transfer are possible
  - Cons (e.g.):
    - ✓ Requires a high landing accuracy to yield an acceptable mission success probability given uncertain environment
    - ✓ Cannot remove the risk of total mission failure if absolutely no safe area on the body



- ☐ **Touch and go can be coupled with above solutions**

Landing accuracy

- ☐ **Landing/touchdown accuracies (semi-major axis of landing/touchdown "ellipse") :**
  - Philae → > 100 m
  - Hayabusa → 30 m
  - Hayabusa 2 → 30 m (?)
  - OSIRIS (Previous Discovery programme study) → 25 m (TBC)
  - Marco Polo → target 2-3 m
  - Phobos-Grunt → ?
- ☐ **Large range of values**
- ☐ **Foreseen studies to increase knowledge and determine feasibility of high navigation accuracy**

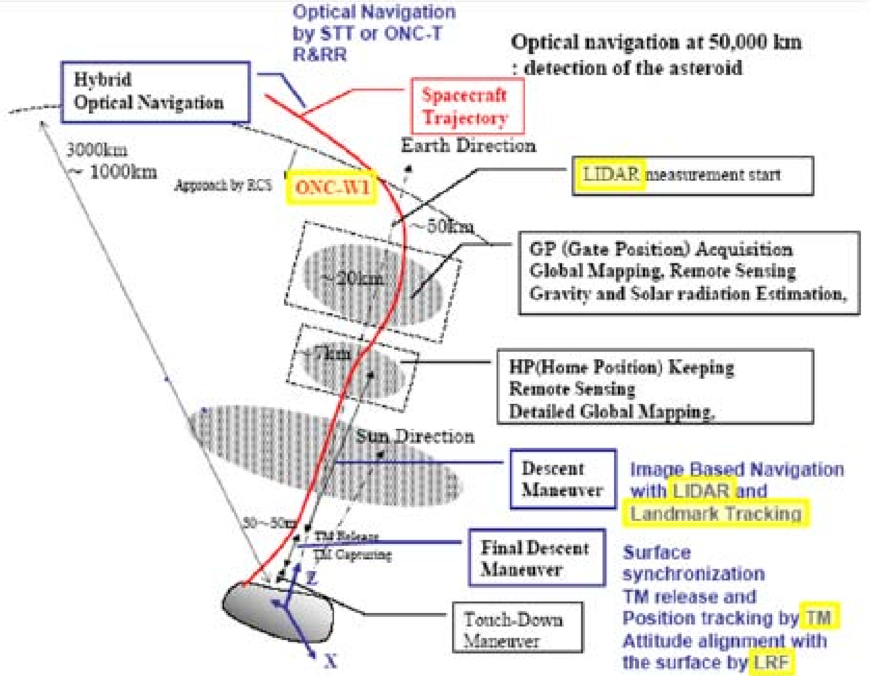
Marco Polo – Baseline scenario 1

Dates	Events	Notes
2018/04/25	Soyuz-Fregat 2-1b launch from Kourou	Inserted to interplanetary orbit for EDVEGA acceleration (Back-Up Window in '18/10)
2019/10/10	Earth gravity assist (Swing-by)	IES acceleration
2022/09/24	Rendezvous with W-H	At 1.04 AU after perihelion passage
2022/09-12	• Global characterization • Sampling/landing site selection • Touchdown rehearsals • Lander deployment and measurements • Touch-and-Go sampling • IES restart tests	Staying at the target during ~100 days
2023/01/01	Departure from W-H	IES operations restart at 1.7 AU
2026/10/01	Earth return and capsule retrieval	Re-entry velocity at ~ 14 km/s

Acknowledgment: JAXA

Marco Polo – Baseline scenario 2

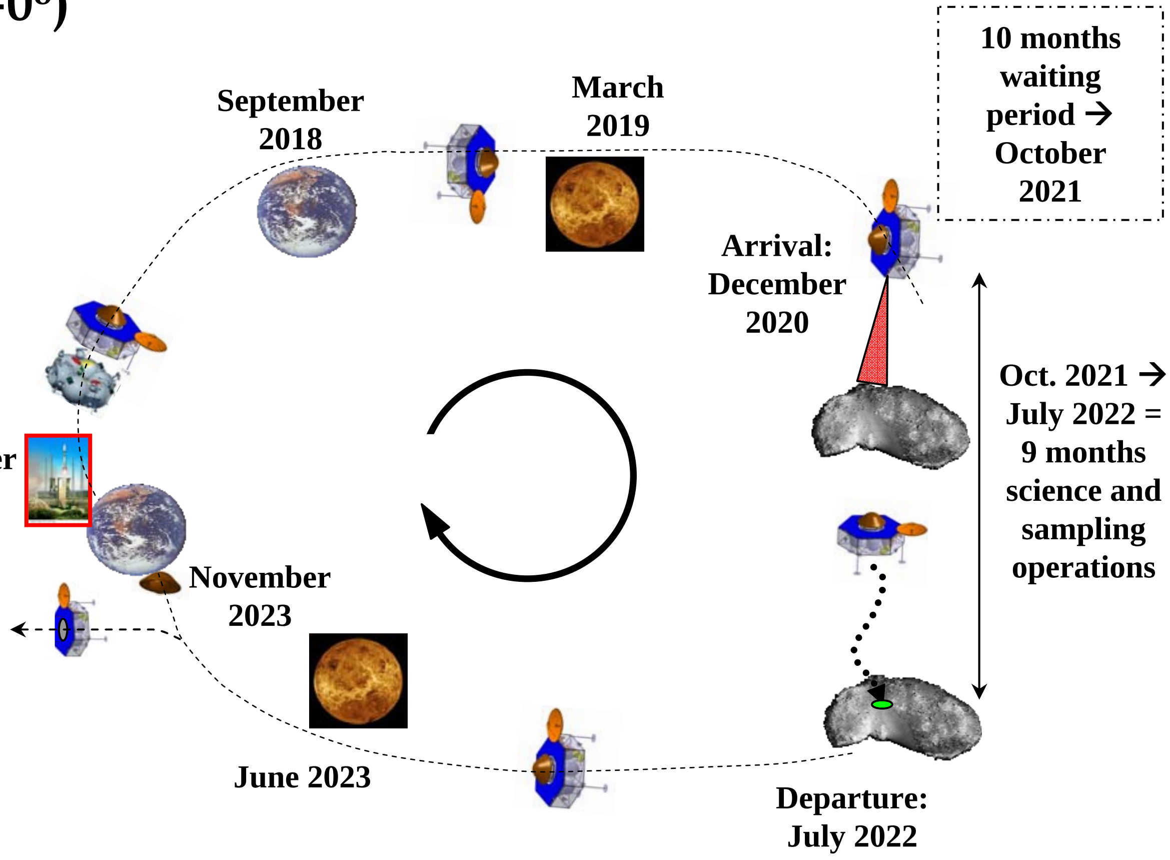
- ❑ Ion engine-based mission to Wilson-Harrington (TBC)
- ❑ Sampling approach based on combination of touch&go/hover&go
- ❑ For GNC aspects, see Dr. Kubota's presentation tomorrow



Acknowledgment: JAXA

Marco Polo – CDF 1

- Launch by Soyuz-Fregat 2-1b from Kourou on direct escape (V_{inf} = 3.49 km.s^{-1}, Dec=0°)
- 1566 kg launch mass capability
- Total mission $\Delta V \sim 1143$ m.s^{-1}
- Re-entry velocity ~ 11.8 km.s^{-1}
- Mission duration 6.2 years, incl. 1.6 years at NEO


September 2017

September 2018

March 2019

Arrival: December 2020

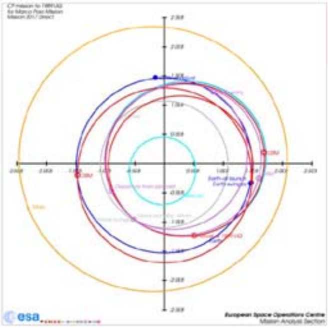
10 months waiting period → October 2021

Oct. 2021 → July 2022 = 9 months science and sampling operations

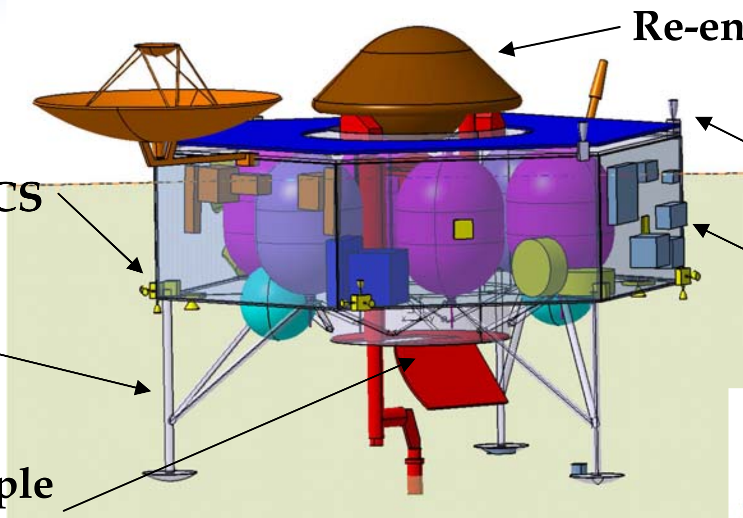
Departure: July 2022

June 2023

November 2023



Marco Polo – CDF 2



Re-entry capsule

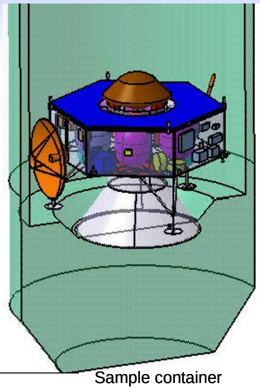
4 x 22N thrusters

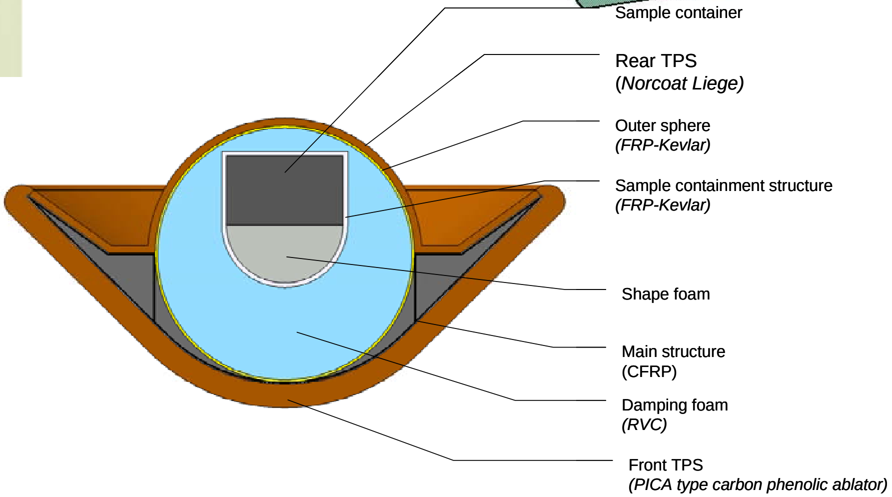
Science payload

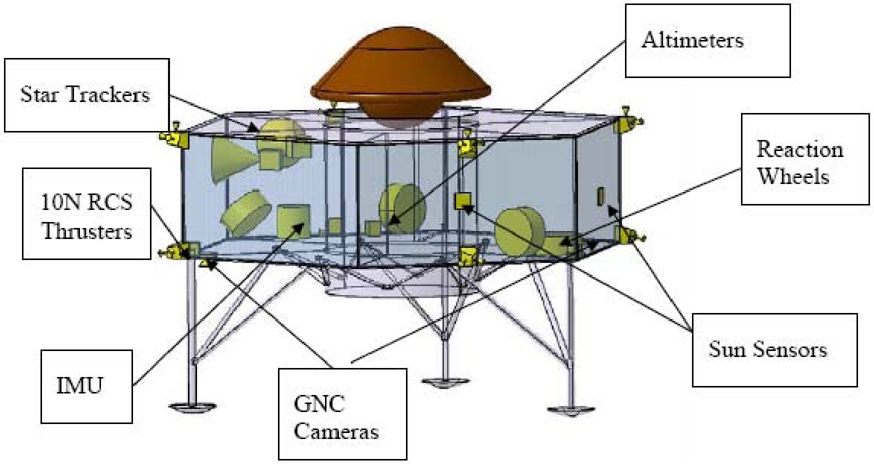
12 x 10 N RCS thrusters

3 landing legs

Central sample transfer system

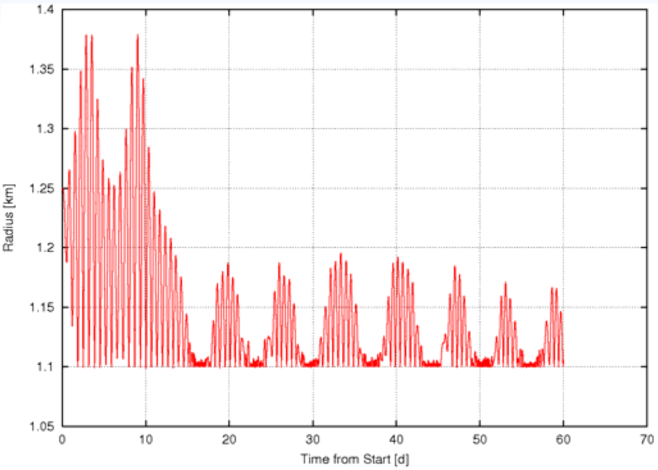






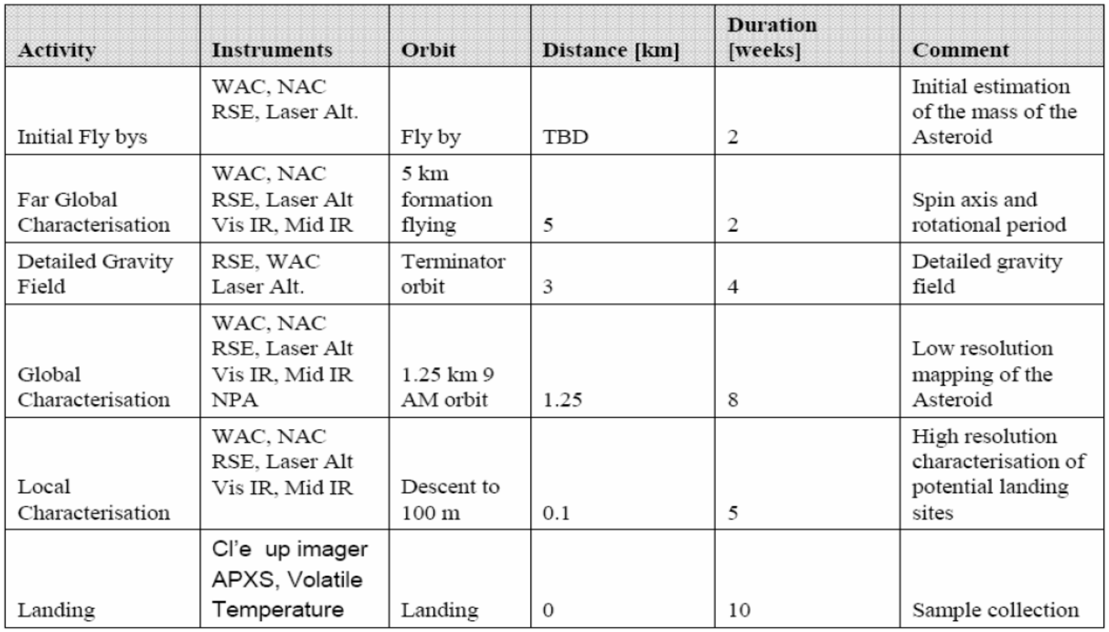
	Mass
Orbiter-lander dry mass incl. system margin	646 kg
Orbiter-lander wet mass	1191 kg
ERC	76 kg
Orbiter-lander propellant mass	545 kg
Launch mass	1267 kg
Launch mass incl. adapter	1312 kg
Launch vehicle performance	1566 kg
Below mass target by	- 254 kg

Marco Polo – CDF 3



Both uncontrolled (for radio science) and controlled orbits have been analyzed assuming:

- 1989 UQ physical properties (tumbling, 4:2:1 shape, ~ 760 m diameter, 7.7 h rotation, 1300 kg/m^3, etc.)
- Solar radiation pressure
- Sun's gravity influence (influence of planets' negligible)



Activity	Instruments	Orbit	Distance [km]	Duration [weeks]	Comment
Initial Fly bys	WAC, NAC RSE, Laser Alt.	Fly by	TBD	2	Initial estimation of the mass of the Asteroid
Far Global Characterisation	WAC, NAC RSE, Laser Alt Vis IR, Mid IR	5 km formation flying	5	2	Spin axis and rotational period
Detailed Gravity Field	RSE, WAC Laser Alt.	Terminator orbit	3	4	Detailed gravity field
Global Characterisation	WAC, NAC RSE, Laser Alt Vis IR, Mid IR NPA	1.25 km 9 AM orbit	1.25	8	Low resolution mapping of the Asteroid
Local Characterisation	WAC, NAC RSE, Laser Alt Vis IR, Mid IR	Descent to 100 m	0.1	5	High resolution characterisation of potential landing sites
Landing	Cl'e up imager APXS, Volatile Temperature	Landing	0	10	Sample collection

1 month

7 months

Marco Polo – CDF 4

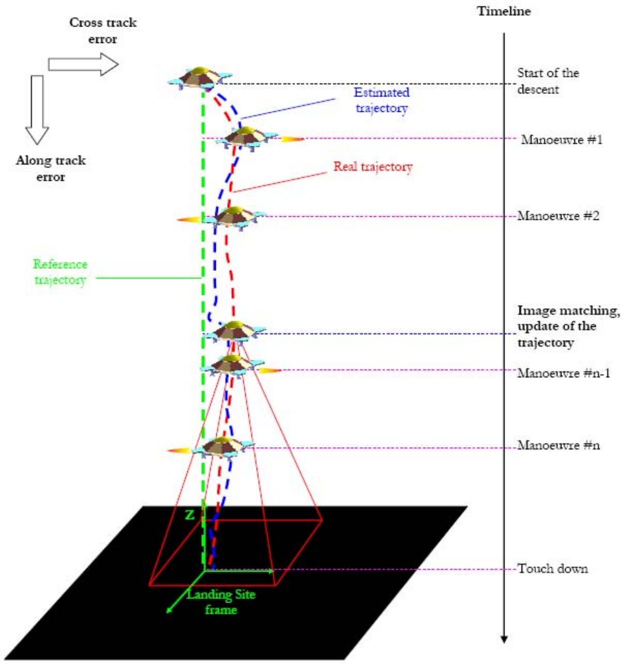


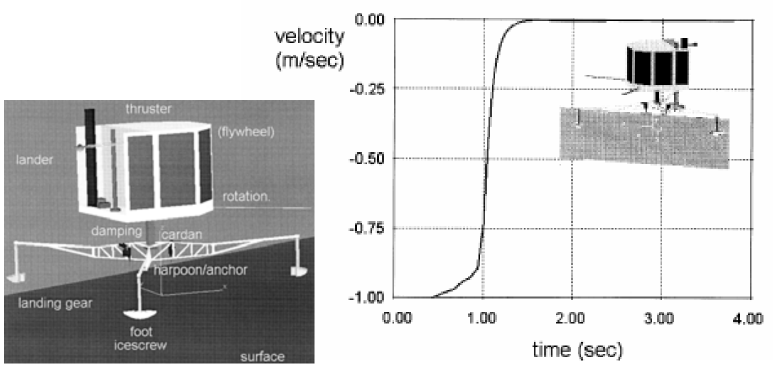
Image courtesy: Astrium Ltd

❑ Navigation strategy (vision-based)

- Get a good shape/gravity model and map hazards from orbit
- Descent down to 500 m
- “Go” decision → Autonomous + 90º slew
- Controlled descent (lateral)
- Landing conditions: $V_V < 20$ cm.s^{-1}, $V_H < 5$ cm.s^{-1}, $\theta < 10^{o}$
- Landing accuracy < 5 m → <u>safe site</u>
- Autonomous battery-powered descent, landing, sampling and ascent operations (~ 2 hours)

❑ Landing structure/mechanism

- Philae damping system or multistage crushable
- Much higher clearance requirement
- No anchoring



ESA CDF study example:
Descent and landing approach 1

- ☐ **Guidance**
  - pre-planned strategy (except FDIR) from Observation campaign
  - vertical descent – no retargeting
- ☐ **Navigation**
  - autonomous
  - vision-based + IMU + altimetric info
  - natural features tracking
  - use of target reference maps (known features) to increase accuracy
- ☐ **Control**
  - 3-axis control (limited rotational excursions)
  - stability needs (images acquisition, sampling…)
- ☐ **Try to maximally take advantage of extensive observation/characterization phase. Should allow several rehearsals (during local characterization?)**

ESA CDF study example: Descent and landing approach 2

- ☐ **GNC strategy**
  - Sequence ~ Hayabusa/Deimos SR-TRS/NEA SR-TRS
  - Pinpoint landing, no hazard avoidance
  - Landing accuracy target: a few meters
- ☐ **GNC Sensors**
  - IMU/WAC
  - Altimeter
- ☐ **Altimetric sensor trade-off**
  - LRF providing attitude info (short range)

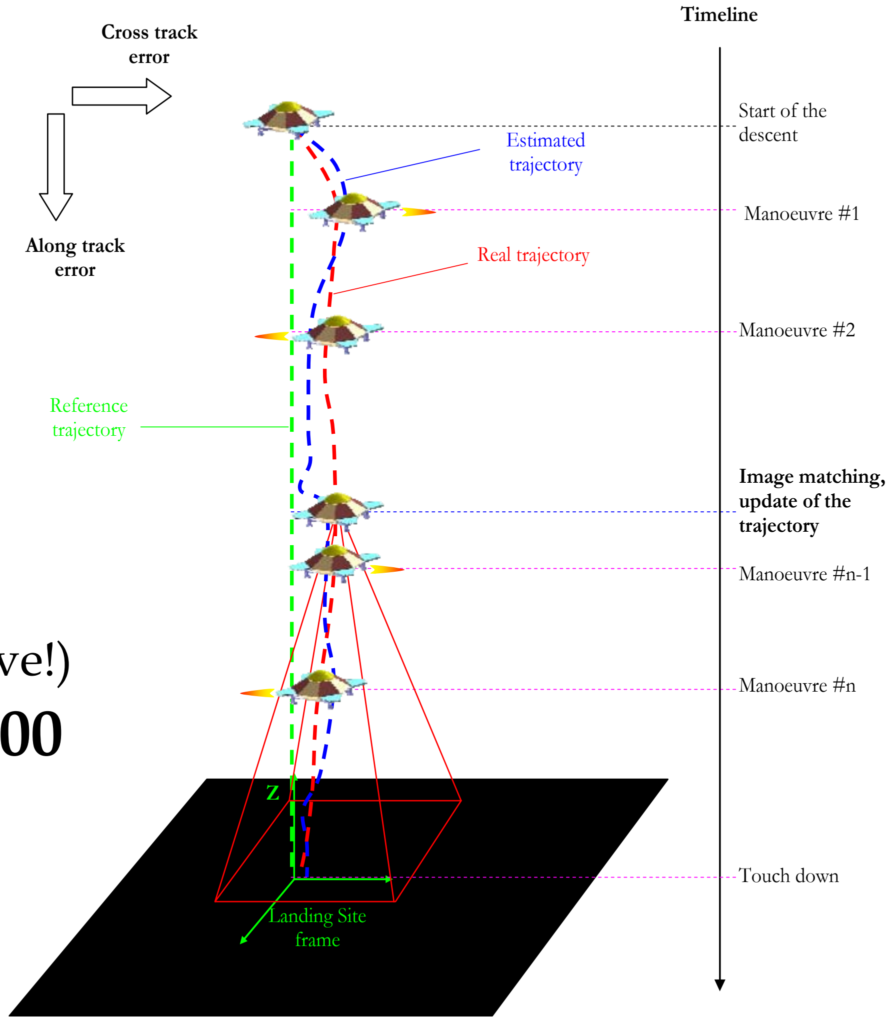
  versus
  - LIDAR (5km-7m range, heavy) or simply Beagle2 altimeter (700m range)
- ☐ **GNC actuators**
  - RW, RCS (THR number, thrust level and redundancy), …

ESA CDF study example: Descent and landing approach 3

- ☐ **Descent strategy (after extensive characterization and rehearsals)**
  - Initial altitude ~ few km
  - GO/no GO @ ~ 500m
  - Close approach/ranging @ ~100m
  - Maneuver for Z axis alignment with local vertical @ ~20m
  - Final descent
- ☐ **Requirements at touch down**
  - $V_{vertical} < 30$ cm/s , $V_{horiz} < 5$cm/s
  - 10° attitude wrt terrain local vertical
  - SRP considered & used during descent
  - Duration ~ 50′ (w/o ascent, TBC), ΔV ~ 2 m/s (incl. ascent,TBC)

ESA CDF study example: Descent and landing approach 4

- ❑ **From NEA-SR TRS (Astrium)**
- ❑ **Assumptions (1 σ when applicable)**
  - initial errors:
    - ✓30 / 4.5 m (along/cross track)
    - ✓20 / 2 mm/s (along/cross track)
  - 10% error on thrust magnitude
  - 0.1 pixel measurement error
  - VB measurement every 10s (no ALT)
  - 2 control maneuvers (timing is sensitive!)
- ❑ **Results at touch down (1 σ, 1000 runs)**
  - Cross-track position error: ~ 3 m
  - Cross-track velocity error: ~ 0.5 cm/s



Conclusions

- ☐ **Landing strategy only an option if high landing accuracy (few m) can be guaranteed**
  - Can we confidently design a mission with a few m accuracy for small bodies and with safe attitude at landing?
- ☐ **Touch and go and/or hover and go:**
  - Can we guarantee stability of the spacecraft over a few sec/min without dedicated landing system?
- ☐ **What are required sensors? A priori measurements? Processing/autonomy requirements? etc,**
- ☐ **What are the necessary development steps?**
- ☐ **If asteroid sample return missions are to happen in the near future, ESA is likely to be involved in the sampling operations**

→ Need to get ready