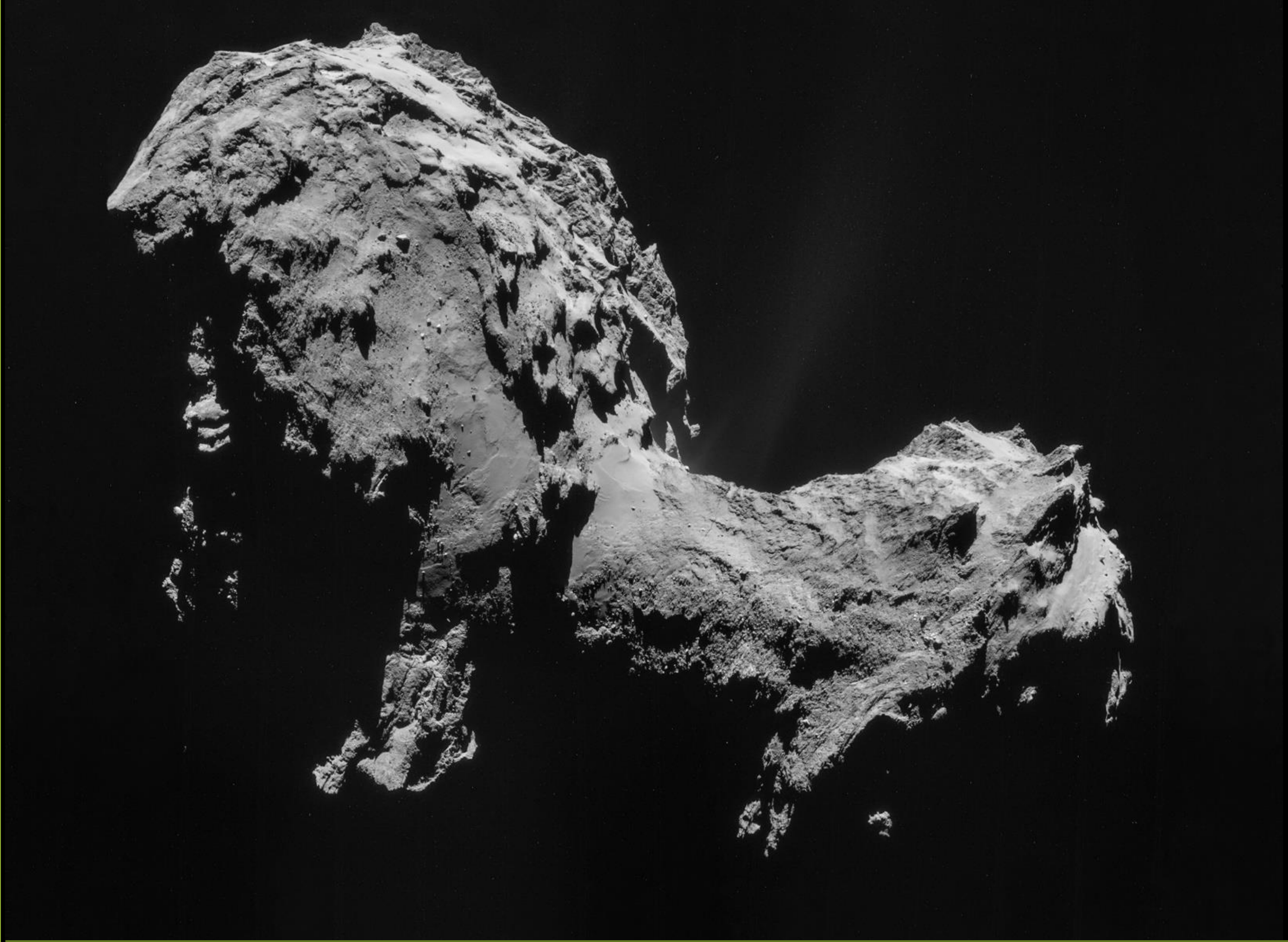


SMALL BODY LANDINGS

The journeys of the micro-lander »Philae« to comet 67P/C.-G. and »MASCOT« to asteroid 1999JU3/Ryugu

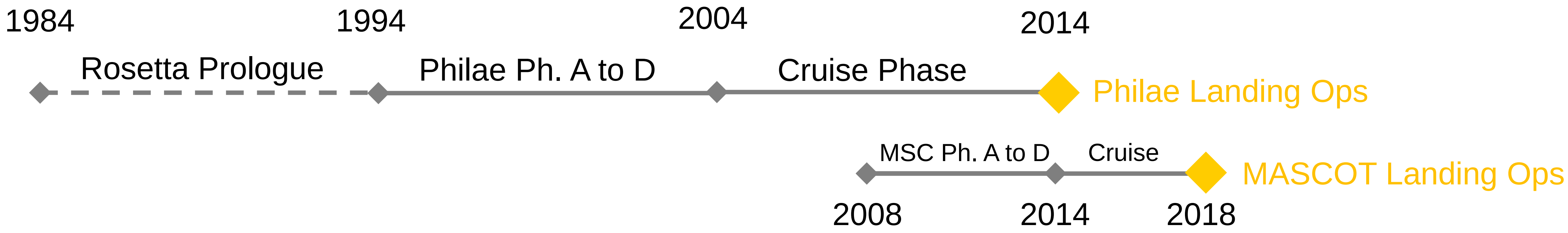
Lars Witte, Achim Block, Tra-Mi Ho, Stephan Ulamec

IPPW 2024 Short Course, 08. – 09. June 2024, Williamsburg, VA, USA

Overview

The exiting journeys of Philae and MASCOT in (each) three stages:

1. Development of the spacecraft: »Why does it look how it looks?«
2. Cruise phase activity and landing preparation
3. Sep., descend & landing: years of work culminate in few exciting hours!



PHILAE & 67P / „CHURY“

Prologue: The origins of Rosetta and Philae since 1984

- ESA „Cornerstone Missions“ laid down in the Horizon 2000 program in 1984
- Originally planned as joint ESA/NASA „Comet Nucleus Sample Return Mission“ (CNSR), but de-scoped
- Planning continued as European comet orbiter „Rosetta“ around 1992, NASA withdrawal in favor of Cassini-Mission
- Consensus among mission scientists that scientific objectives only achievable with a comet landing
- ESA endorsed the planning for a „Surface Science Package“

- Target comet: 46P/Wirtanen, Diameter ~1100m

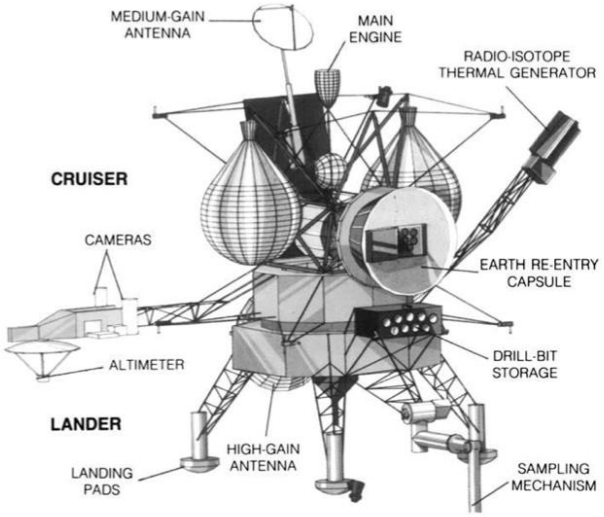


Image credit: NASA or ESA?

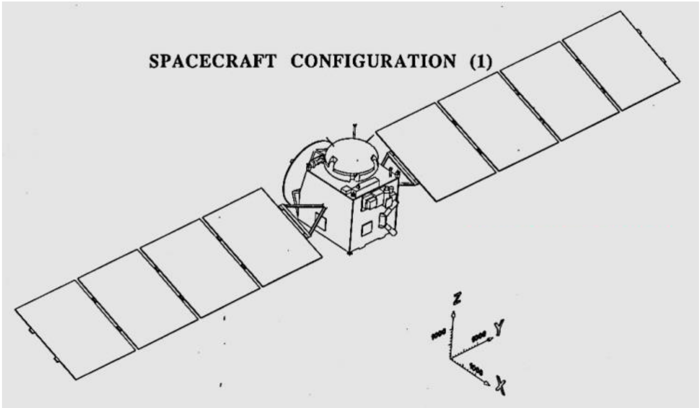
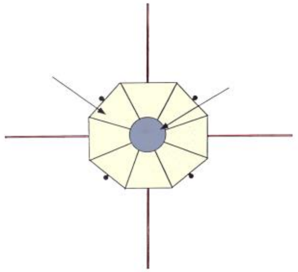


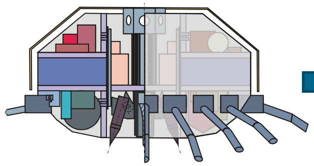
Image credit: ESA

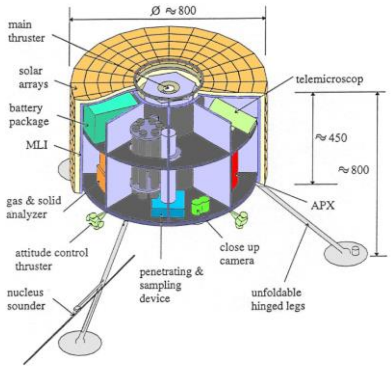
Early Development Phase since 1994

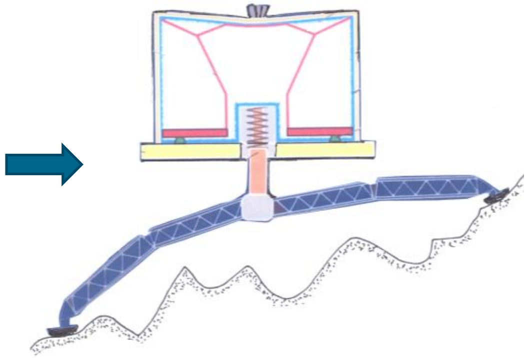
- Early development marked by the proposal of two concepts: „RoLand“ and „Champollion“

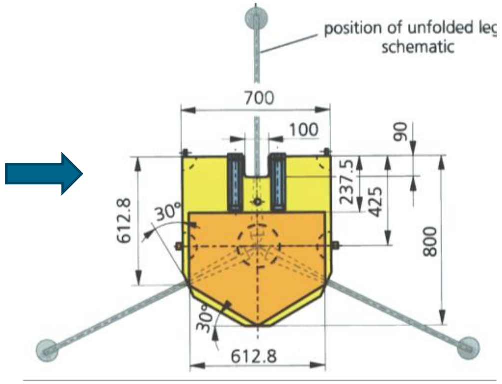
- **RoLand:** First sketches and Phase-A-design with 3-leg config. In 1994. Evolution to central damper and prismatic body (Phase B)
- Consortium: Multi-national and –organizational, led by MPS/Germany



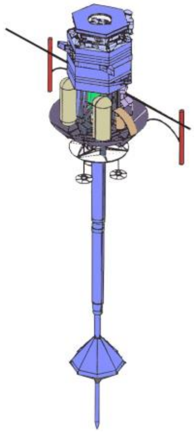


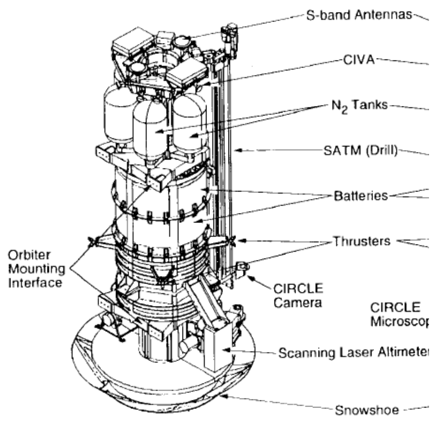






- **Champollion:** “Dart”-configuration with anchor and telescope, evolution to hexagonal body / baseplate with crushable pads
- Consortium: CNES/JPL





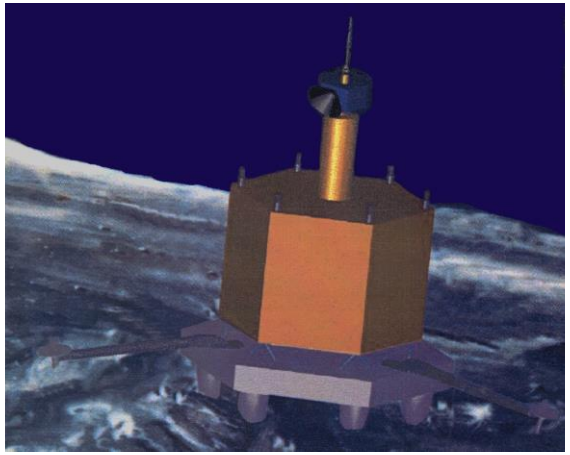


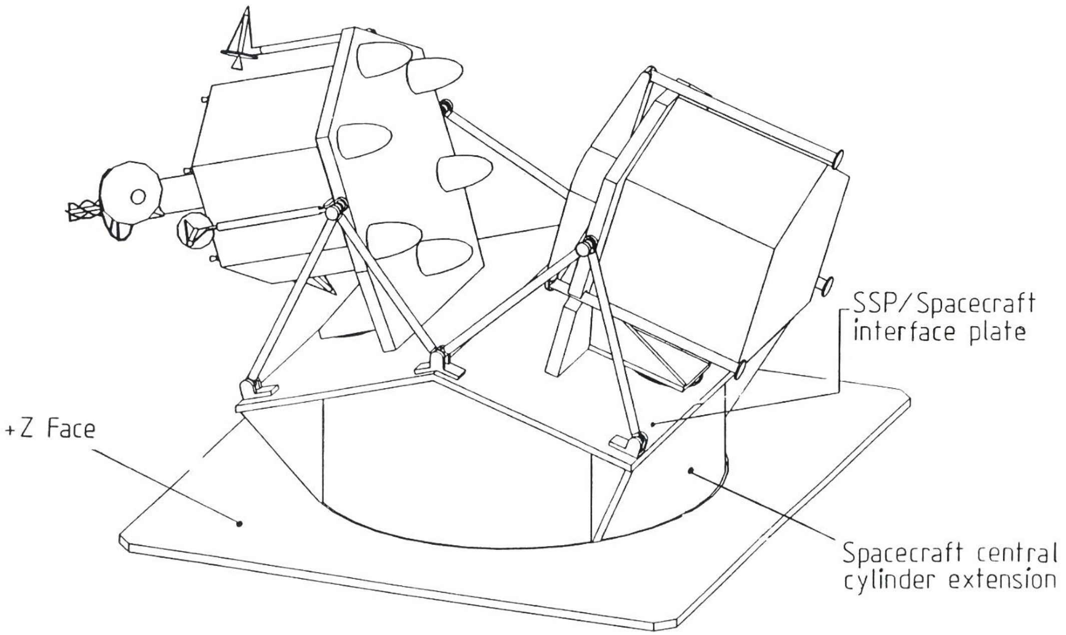
Image credit: CNES/JPL

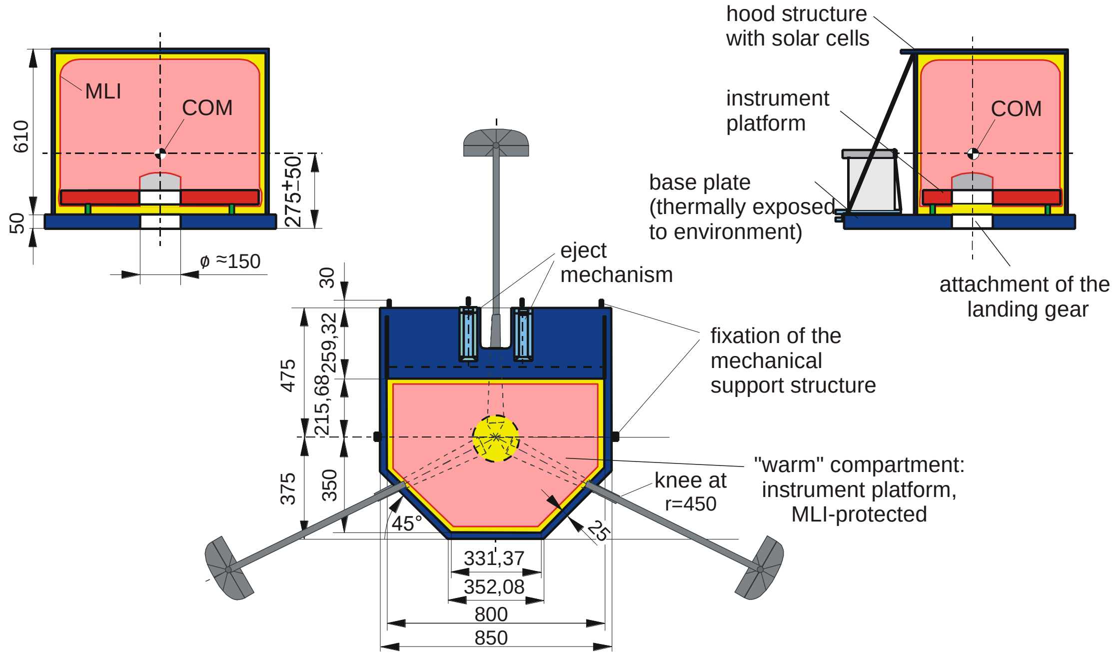
More details & background (see Annex):
Möhlmann, D., und Ulamec, S. (2014)

Early Development Phase

- With two separate landers (each ~50 kg) complexity is obvious …
- July 1996: ESA mandates a merging of both into a single, joint lander
- ROSETTA Lander keeps the former RoLand base configuration but is „upscaled“ to ~100 kg
- A large consortium:

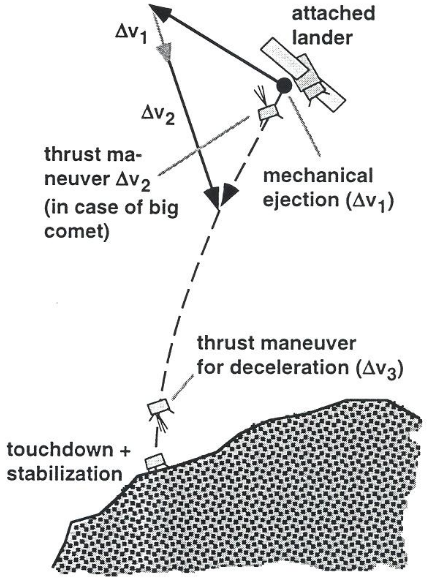
… which remained a source of “concerns” for ESA and budget issues …

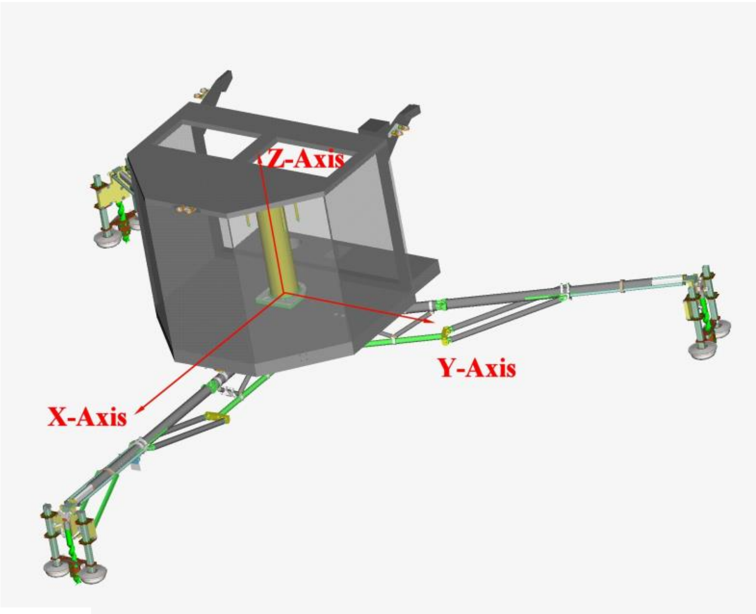


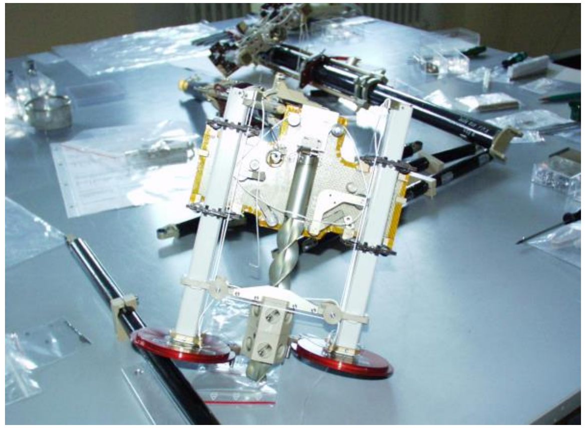


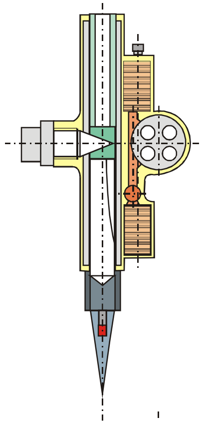
The final »Philae« - Landing System

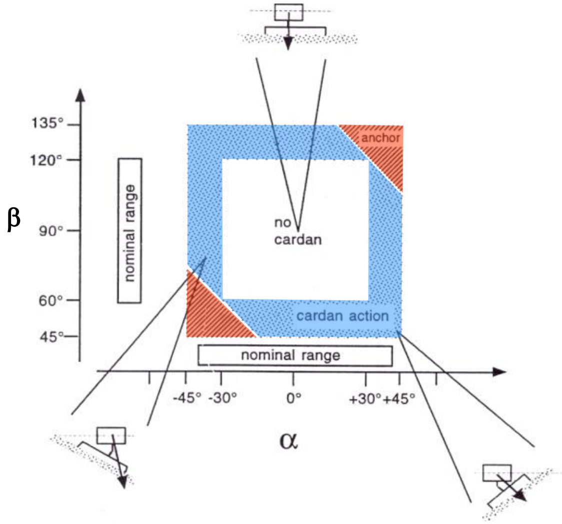
- Descend & landing strategy
  - Ballistic descend, stabilized by a fly-wheel
  - Hold-down thrust for landing stability
- Landing system features
  - Central damper „the bubble“: electric, rebound-less energy absorption
  - Cardan joint between body and landing gear
  - Active Descend System (cold gas) and Fly Wheel
  - Anchoring harpoons (two harpoons, pyro initiated)
  - Landing feet with deployable ice-screws

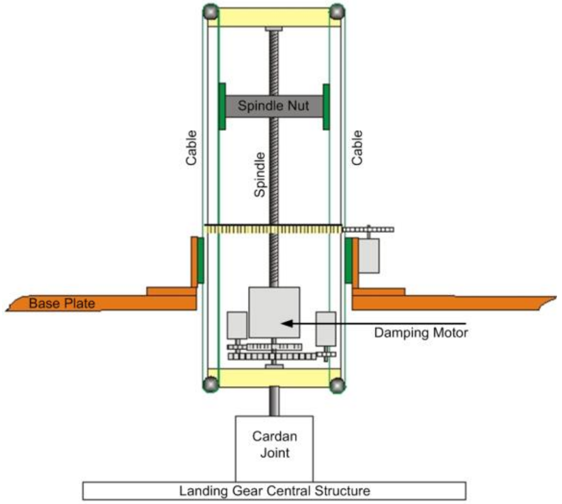








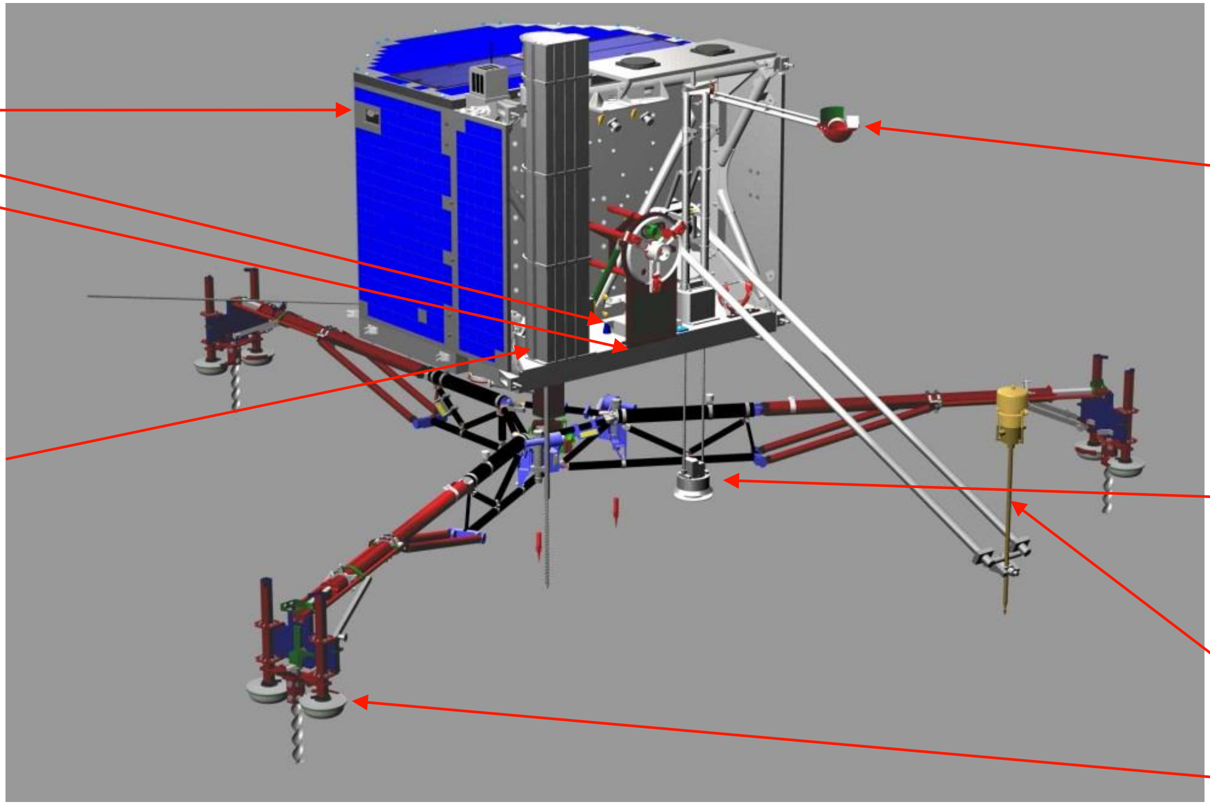




The final »Philae« - Scientific Instruments

Cameras
ÇIVA (IAS)
ROLIS (DLR)

Sampling & Drilling Device
SD² (Politecnico Milano)



Plasma & Magnetic Environment
ROMAP (TU Braunschweig)

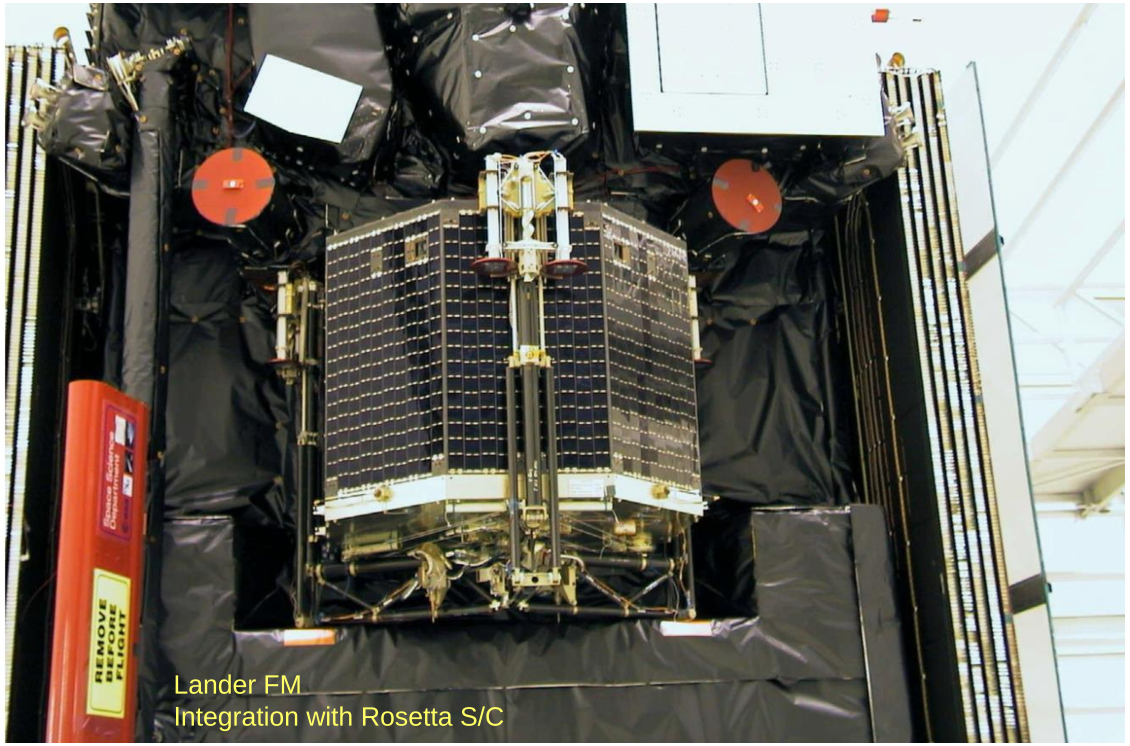
Material Analysis
COSAC (MPS)
MODULUS (OU)
APX (MPCh)

Comet Structure
CONSERT (IPAG)
MUPUS (U. Münster)
SESAME (DLR)

More details & background:
Schulz, R. (ed.), 2009

Assembly, Testing and … No Launch Ops! (as planned)

- Philae development & qualification: 1996 – 2002
- Launch scheduled for 01/2003 on an Ariane 5 rocket
- But the preceding launch was new A5 ECA version which failed on its maiden flight!
- Rosetta launch was delayed to 2004 with its back-up target 67P / Churyumov-Gerasimenko (C.-G.), Diameter ~5000m
  - Implications for Philae: adjustments to the landing gear to adapt to the much larger C.-G.



Lander FM
Integration with Rosetta S/C

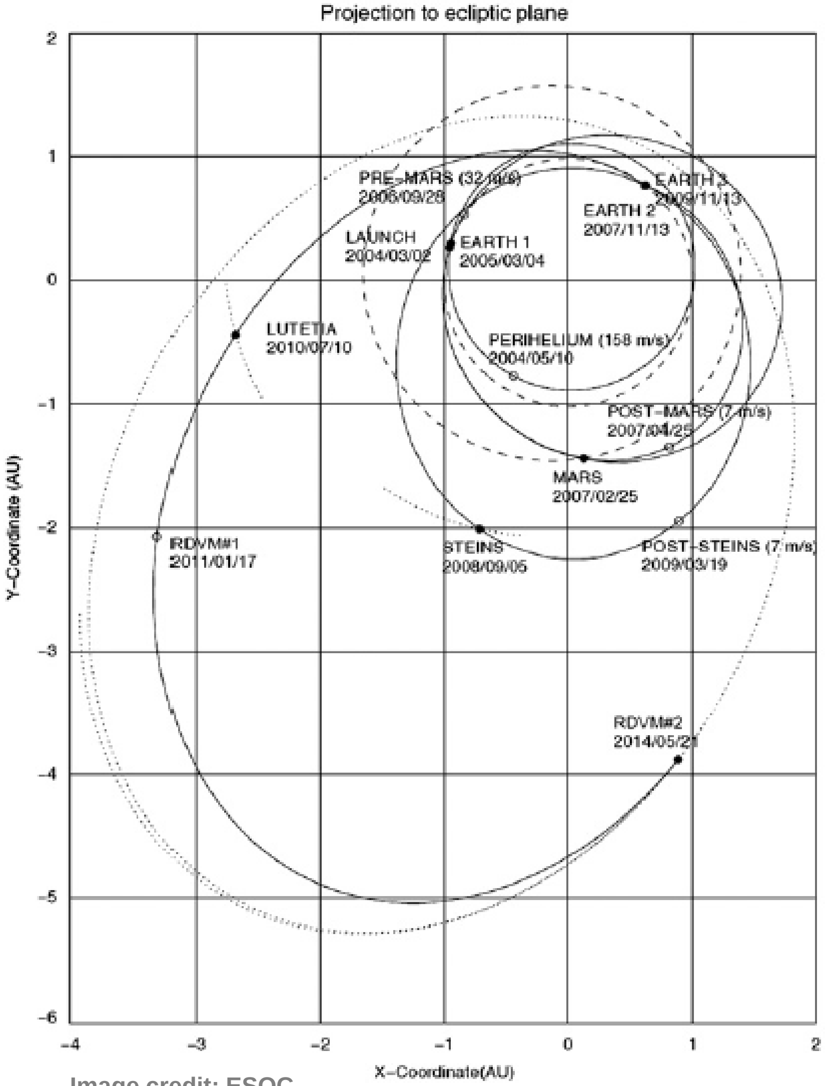


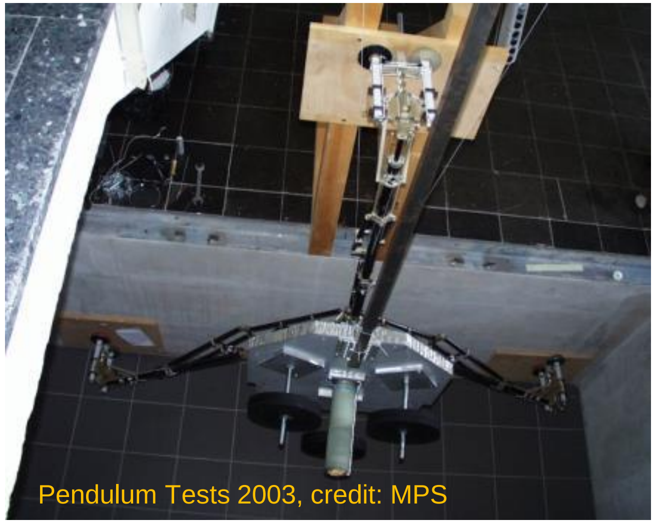
Image credit: ESOC

Landing preparation: Re-testing of the landing system 2013

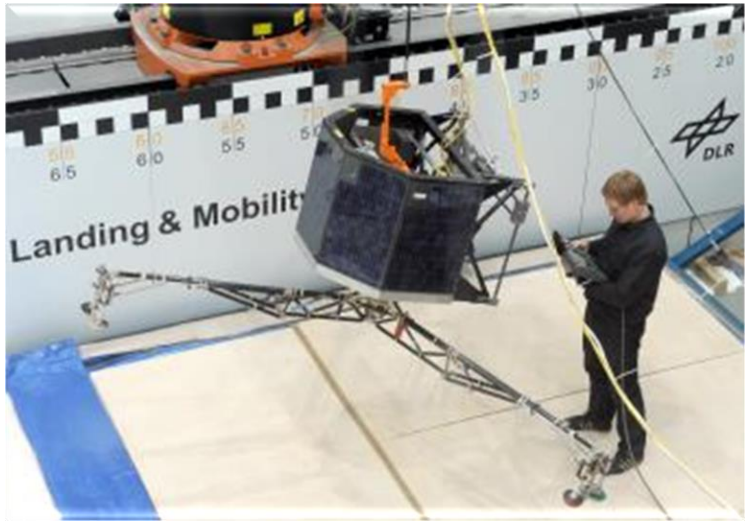
Primary objective: optimize the landing strategy and re- determine the landing gear performance envelope

In particular, assess:

- Address T/D conditions (→ primarily asymmetric load cases) which are constricted by capabilities by pendulum test facility,
- the influence of the landing gears tilt limiter on asymmetric load cases,
- To broaden the data base on the contact phenomenon on soft soils.



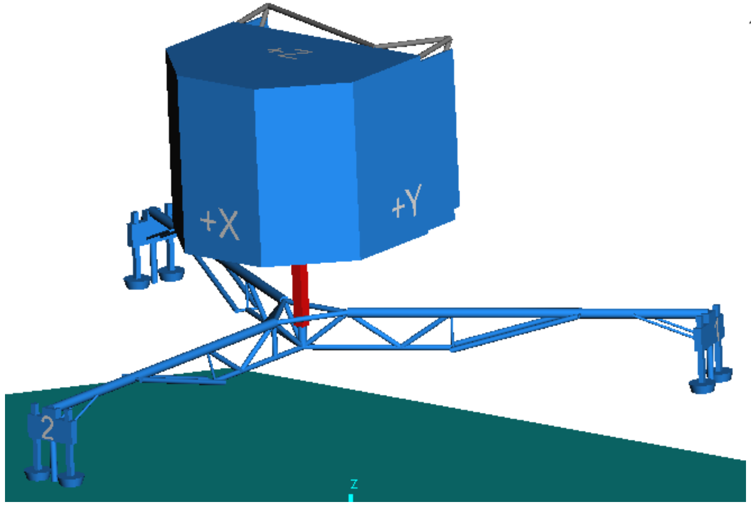
Pendulum Tests 2003, credit: MPS

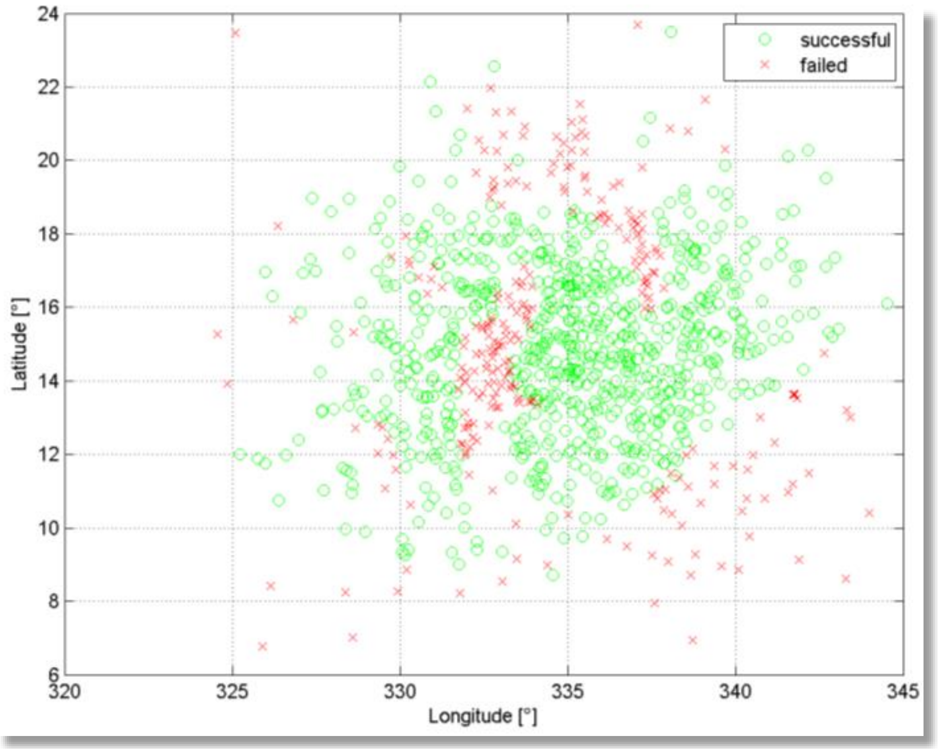


More details & background:
Witte, L. et al. (2014)

Landing performance & safety tables

- A new numerical multibody simulation was set-up, based on findings of experimental campaign
- Validated numerical simulation used to assess landing performance / safety tables
- Landing performance / safety data used in conjunction with trajectory dispersion calculations (SONC / CNES) to produce
  - charts for each landing site candidate
  - „confidence in successful landing“ statements
- These data products were fed into the Landing Site Selection Process (LSSP)





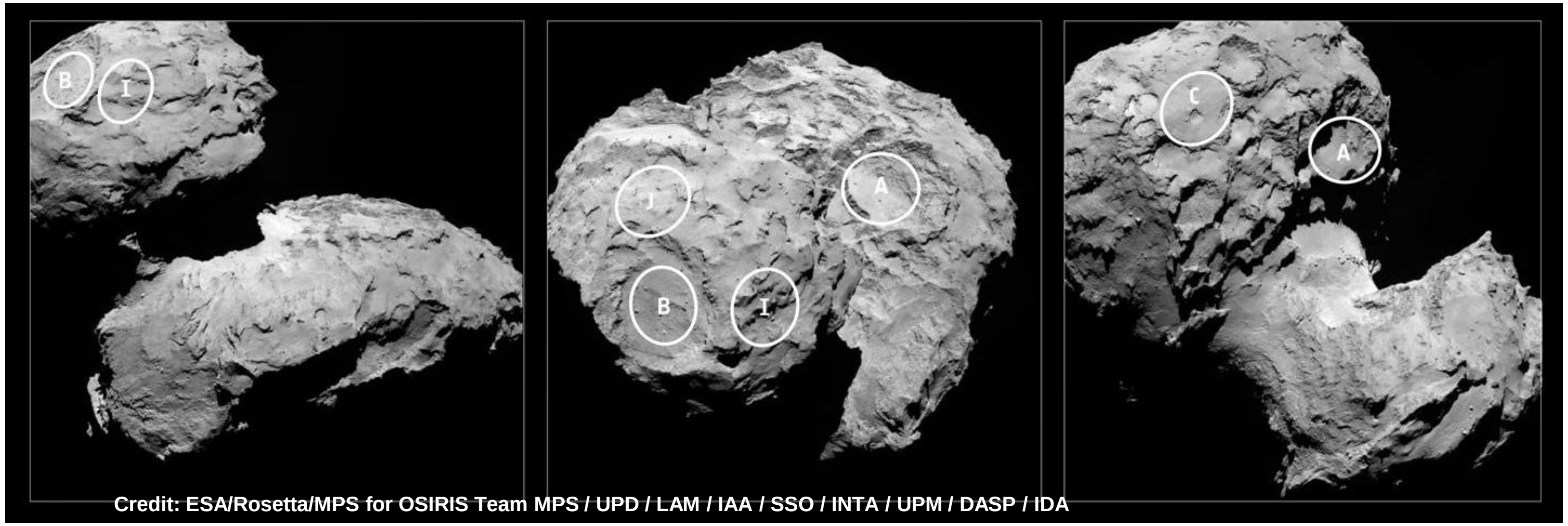
More details & background:
Jurado, E. et al. (2016)
Witte, L. et al. (2016)

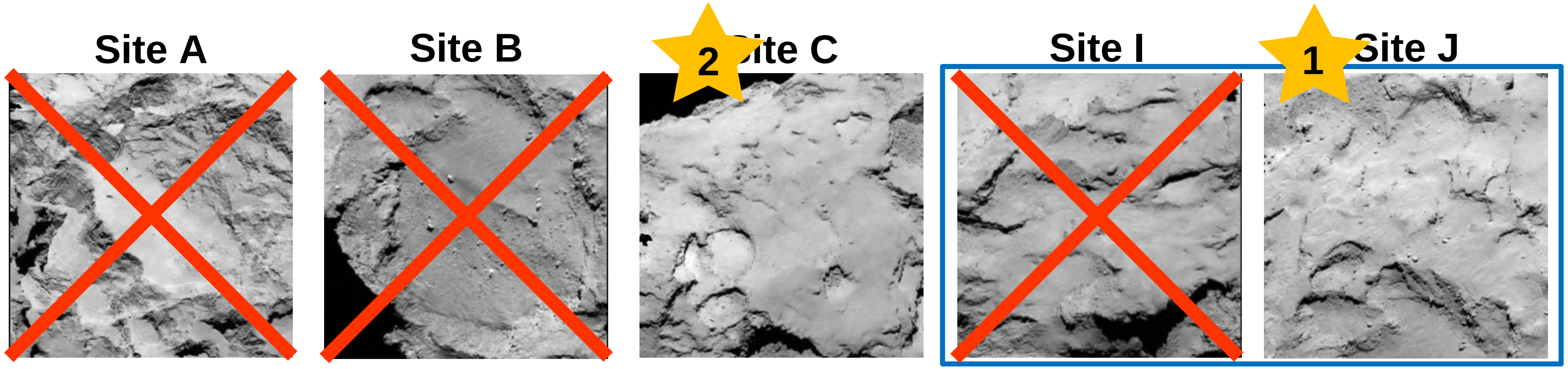
Ldg. Site Selection: Where to land on a duck-shaped body?

Question answered by a series of selection workshops
Answer driven by many criteria…

- Scientific preferences
- Orbiter trajectory constraints / safety
- Landing performance / safety

- 24th August `14: 5 remaining candidates
- 14th September: Final choice!





preference by scientists

84% Conf. 56% Conf. 83% Conf.

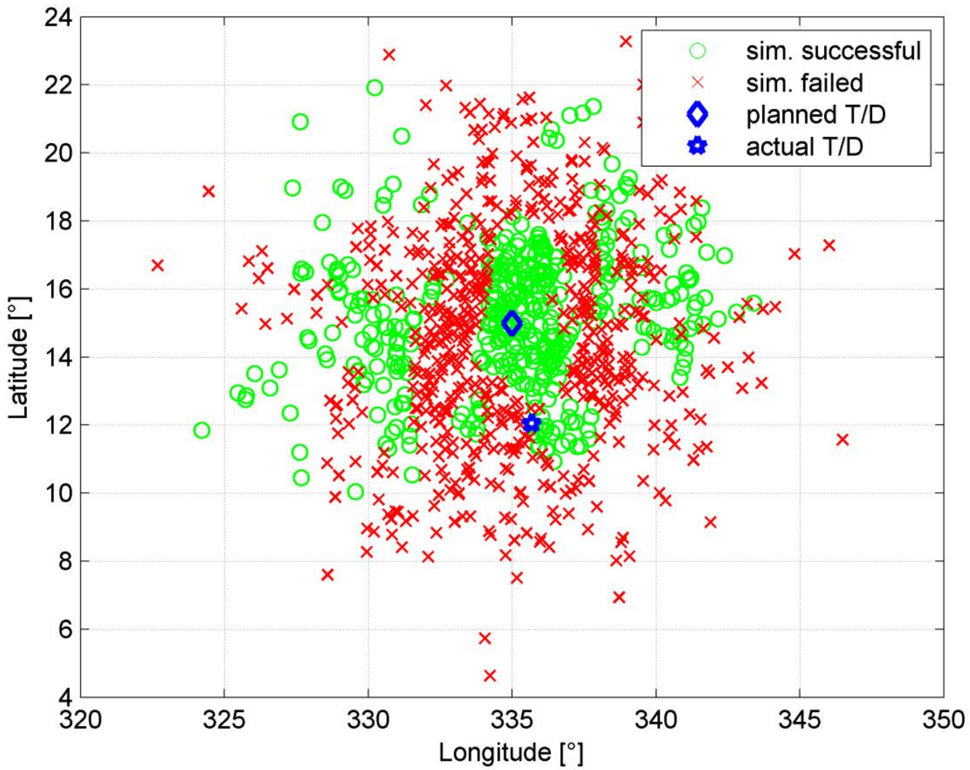
»Agilkia«

More details & background:
Ulamec, S. et al. (2014)

Eve of Landing – degraded landing performance

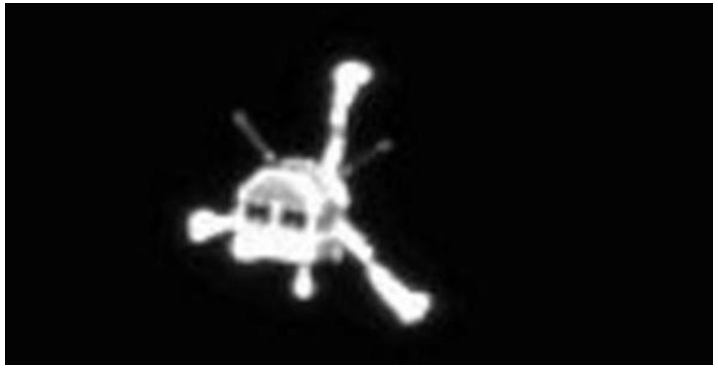
- Scatter plot shows landing position dispersions, planned and actual touchdown point
  - Active Descend System (ADS) operational, confidence in successful landing: **83%**

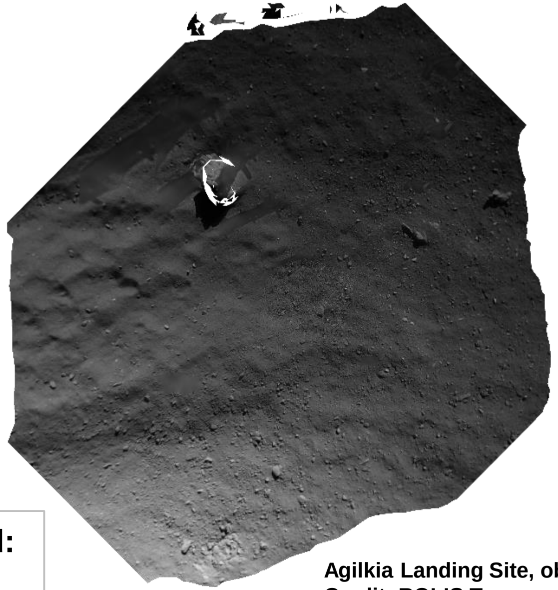
    - Actual landing occurred with failed ADS
      - confidence in successful landing: **42%**
    - Lower confidence → increased reliance in luck



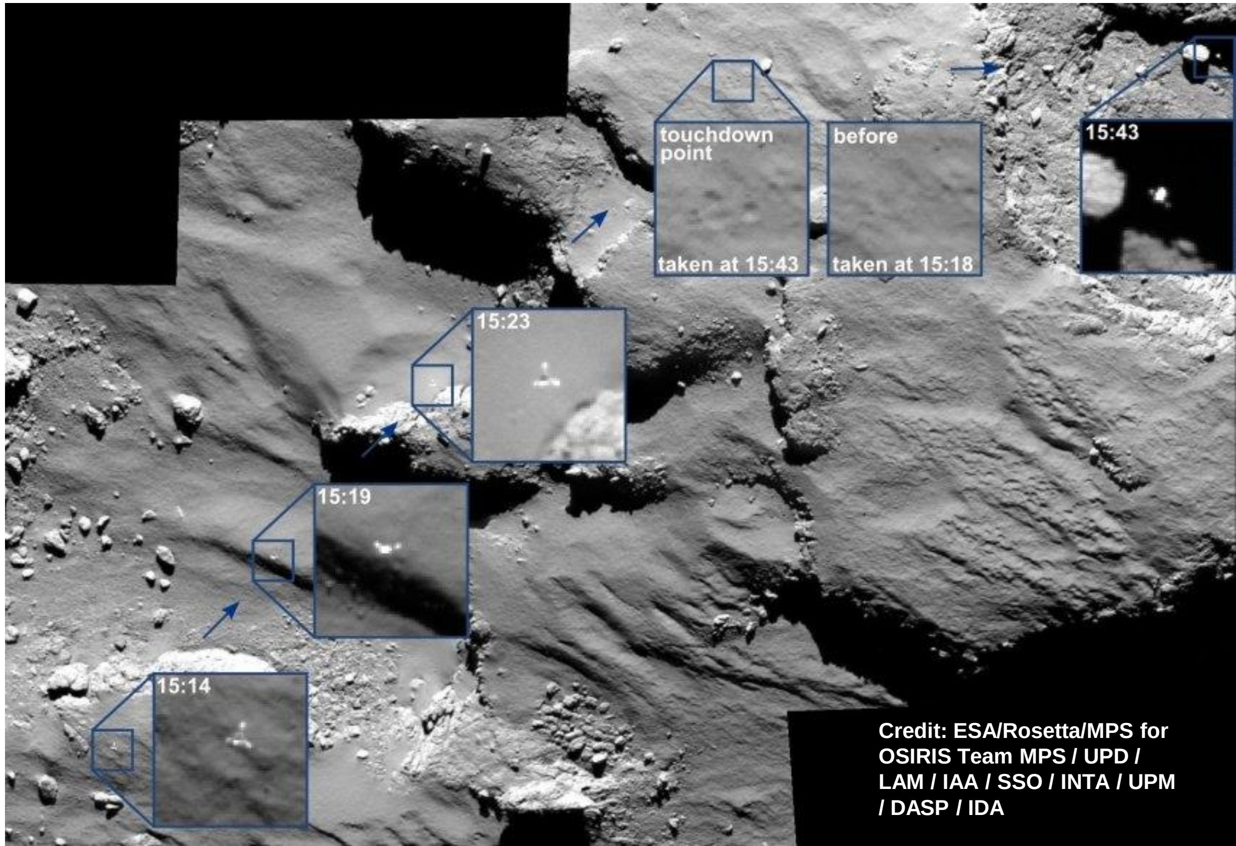
Separation, Descend and (multiple) Landings

- Separation: November 12, 2024, 08:35 UTC
- Deployment of Landing Gear: 8:43 (and confirmed by orbiter cam data)
- ROLIS Cam activation: 14:35
- Touchdown: 15:34 (confirmed +30’) – 7 hours of terror
- Post-landing:
  - Became clear that Philae is tumbling/drifting
  - Also witnessed by orbiter Osiris images





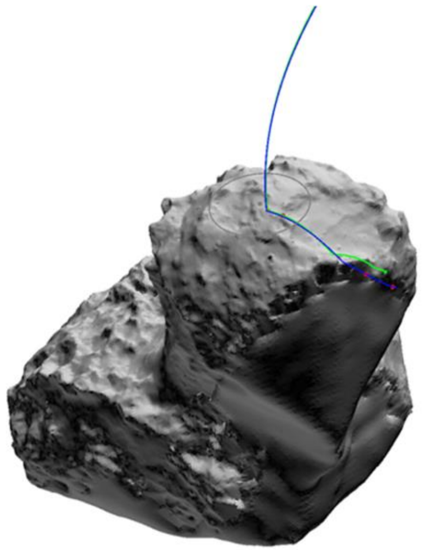
Agilkia Landing Site, observed by ROLIS
Credit: ROLIS Team



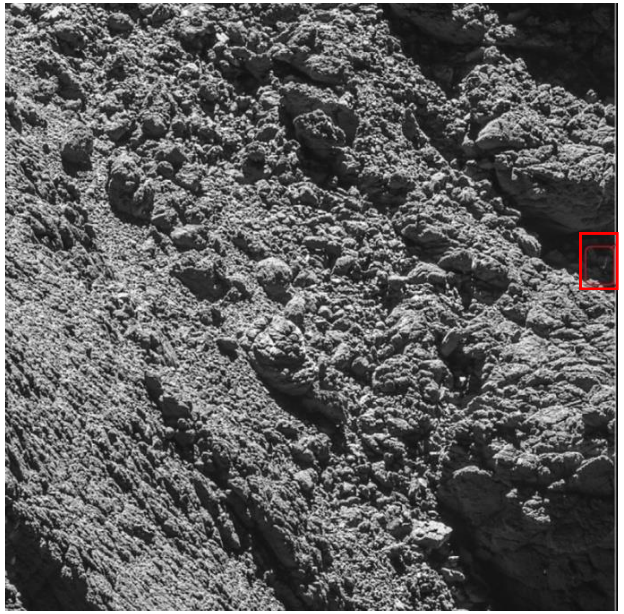
Credit: ESA/Rosetta/MPS for OSIRIS Team MPS / UPD / LAM / IAA / SSO / INTA / UPM / DASP / IDA

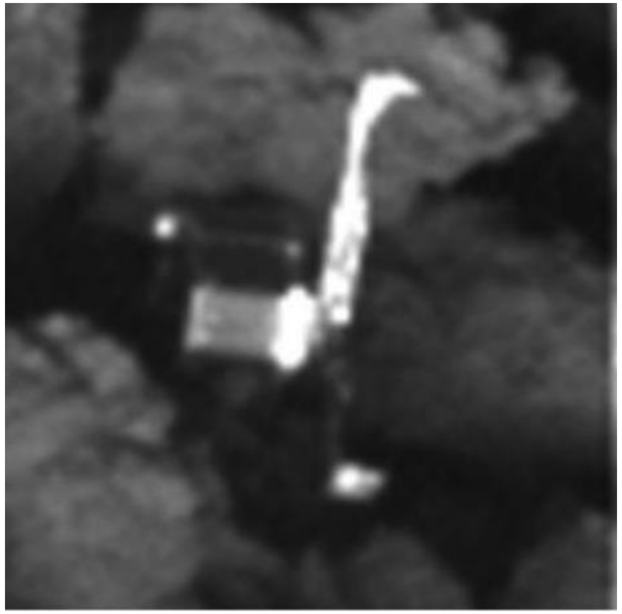
More details & background:
Ulamec, S. et al. (2016)

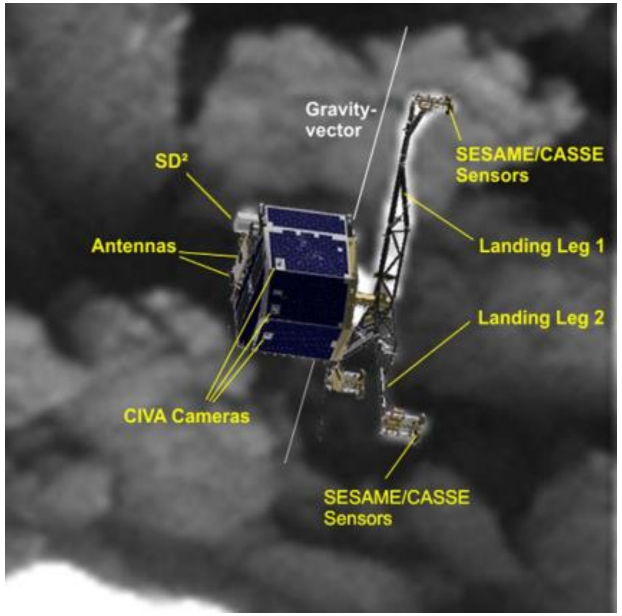
Post-landing Ops and „Find Philae“-campaign



- Telemetry indicated a final „landing“ in a shadowed location
- Primary battery allowed for a full contingency science cycle
- Despite only ~60 h science cycle, a rich data set was generated
- Parallel: a search campaign is executed using orbiter and lander data
    - 1st campaign 3 days after landing, 2nd campaign until June ´15, Philae re-awakes!, 3rd campaign July `15,  4th and final until Sept. `16

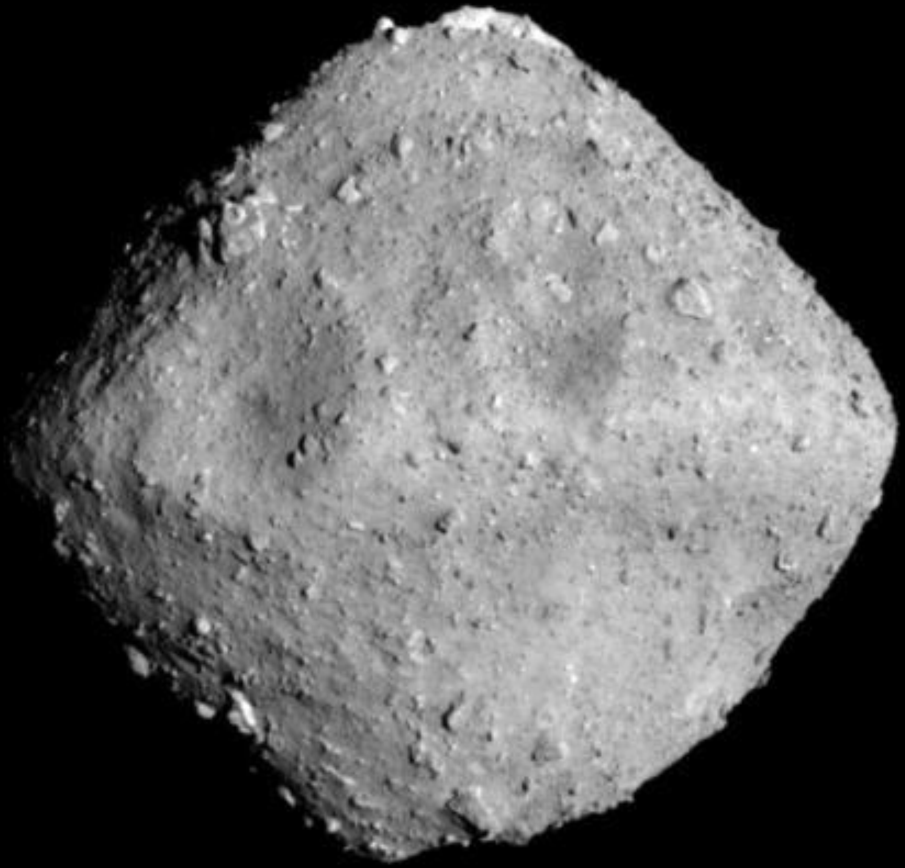






More details & background:
Biele, J. et al. 2015
Ulamec, S. et al. (2017)
O'Rourke, L. et al. (2019)

Left + middle image - ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA.



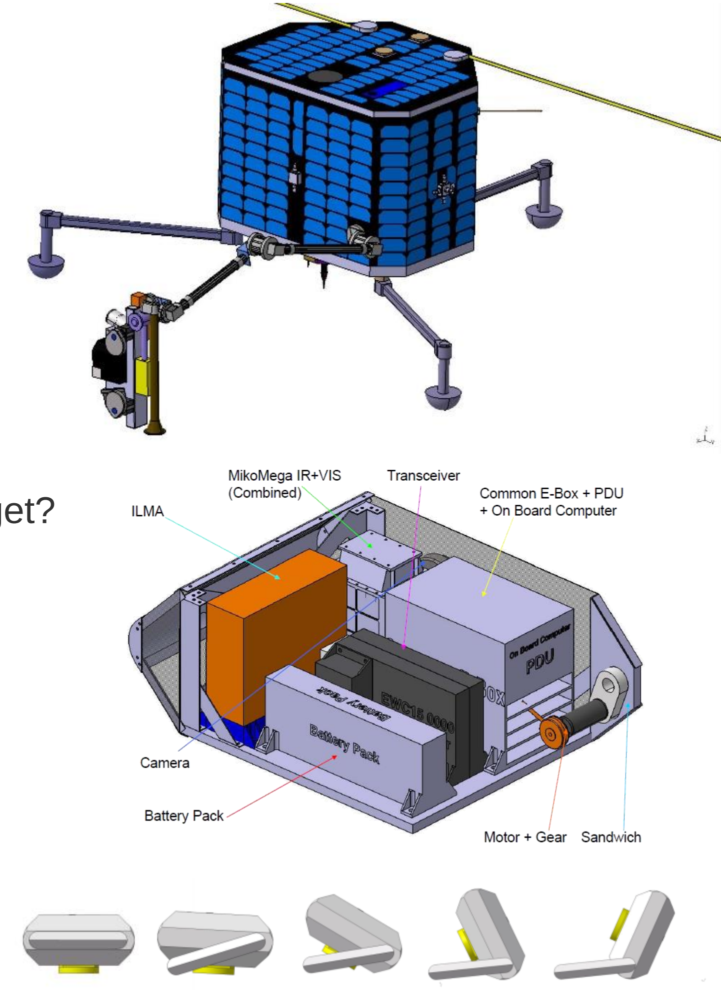
MASCOT & 1999JU3 / RYUGU

The genesis of MASCOT

- 2008: ESA Marco Polo Asteroid Sample Return Study (Cosmic Vision 2015-2025)
  - European Science Steering Committee advocates a *Science Surface Package* (Philae reminiscence)
  - Endorsed by ESA: „It should be possible to deliver a separate in-situ lander“ (source: Marco Polo MRD)
- Parallel: JAXA studies on Hayabusa 1 successor: either Hayabusa 2 or Hayabusa Mark 2
  - Japanese Science team invites European lander contribution
  - Challenge: What lander do you can provide if we give to you **95 / 70 / 35 or 10 kg** mass budget?
- ESA Marco Polo was given up in favor of EUCLID (?) fundamental physics
- JAXA converged on Hayabusa 2
- Design consolidation wrt mission constraints of JAXA/ISAS and ESA:

  ➔ settled on 10 kg package

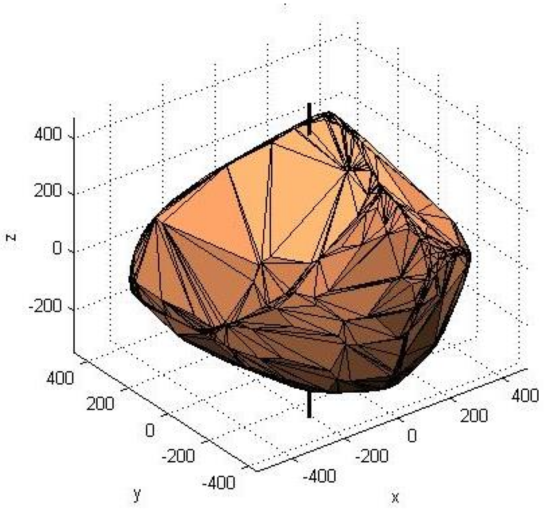
- MASCOT initiated as joint DLR/CNES project



MASCOT variants with 95 kg (top) and 10 kg from DLR Concurrent Engineering Facility

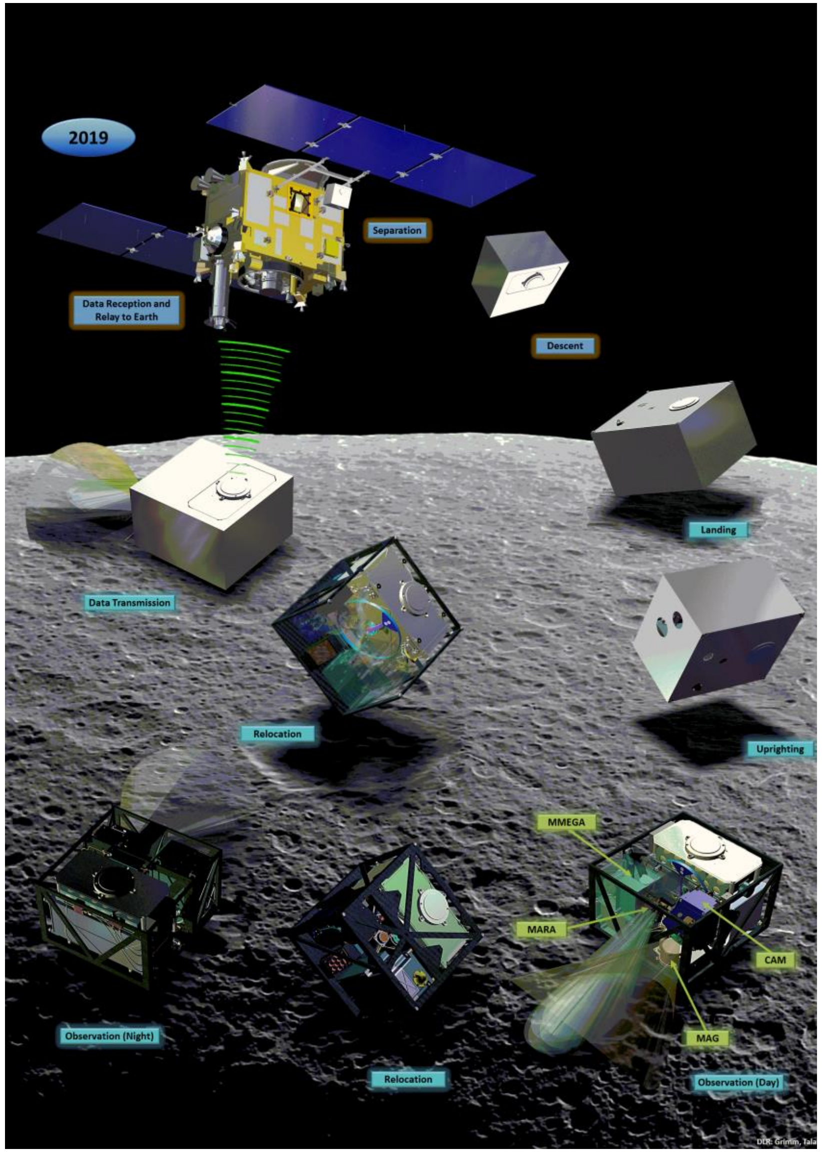
Top Level Requirements

- Launch in 2014
- Target: Near Earth Object 1999JU3
  - Diameter ~900m
  - Rotation period 7.6h



- Deployment from HY2 side wall
- Lifetime: 16h (2 asteroid days)
- Able to hop to a new site

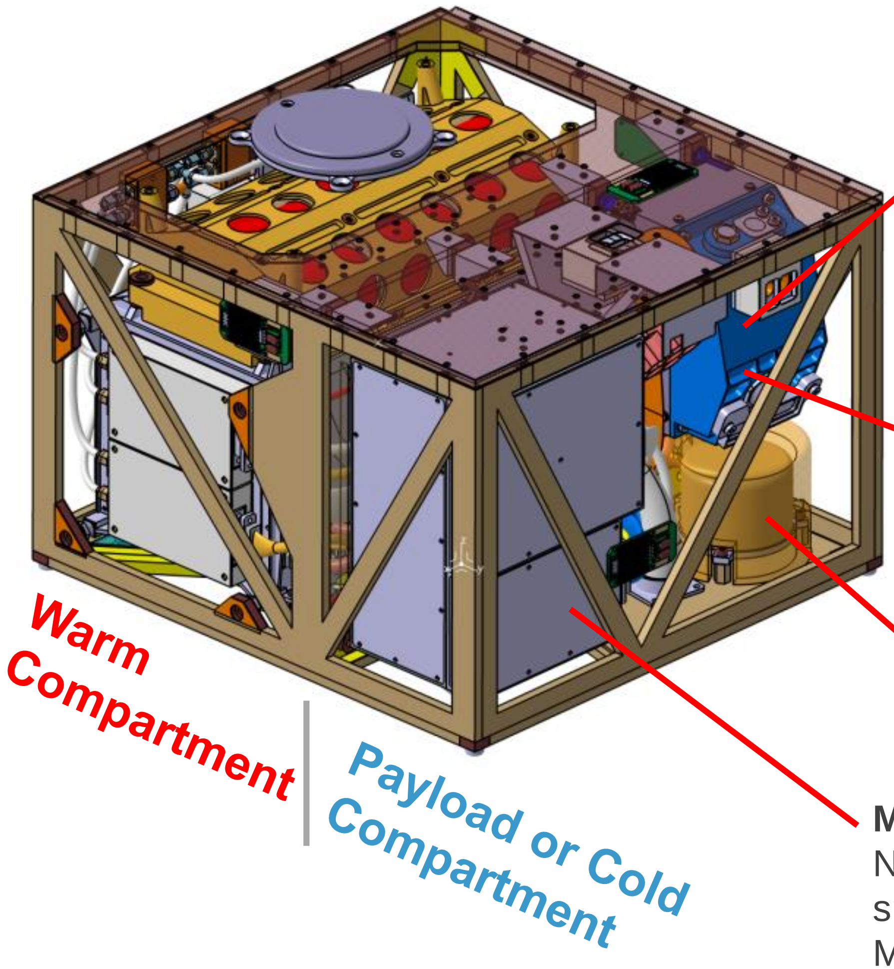
- Measurements of MASCOT PL shall
  - accomplish ‘**context science**’ by complementing remote sensing observations from HY-2 and sample analyses → ground truth info
  - accomplish ‘**stand-alone science**’ such as geophysics
  - serve as a ‘**reconnaissance and scouting**’ vehicle to guide the sampling site selection of the main spacecraft



System Overview

Common E-Box with
- Onboard Computer
- Comm.
- Power Distr. & Ctrl.
- Actuator Control
- Payload BEE

Actuator
Primary Battery Pack
Guidance Sensors



CAM (DLR)
Wide angle camera with LED illumination
Imaging

MARA (DLR)
Radiometer
Surface thermal properties

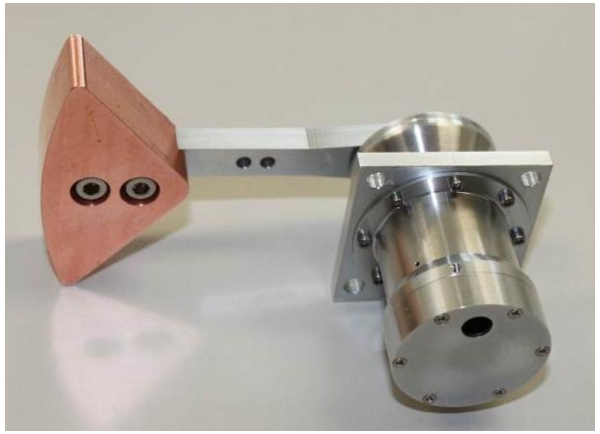
MAG (TU Braunschweig)
Fluxgate magnetometer
Asteroid magnetization

MicrOmega (IAS Paris)
Near-infrared imaging spectrometer / microscope
Mineralogy and composition

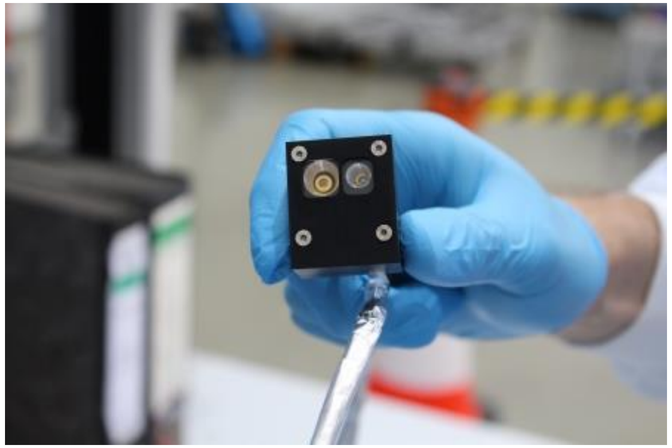
More details & background:
Ho, T.-M. et al. (2016)

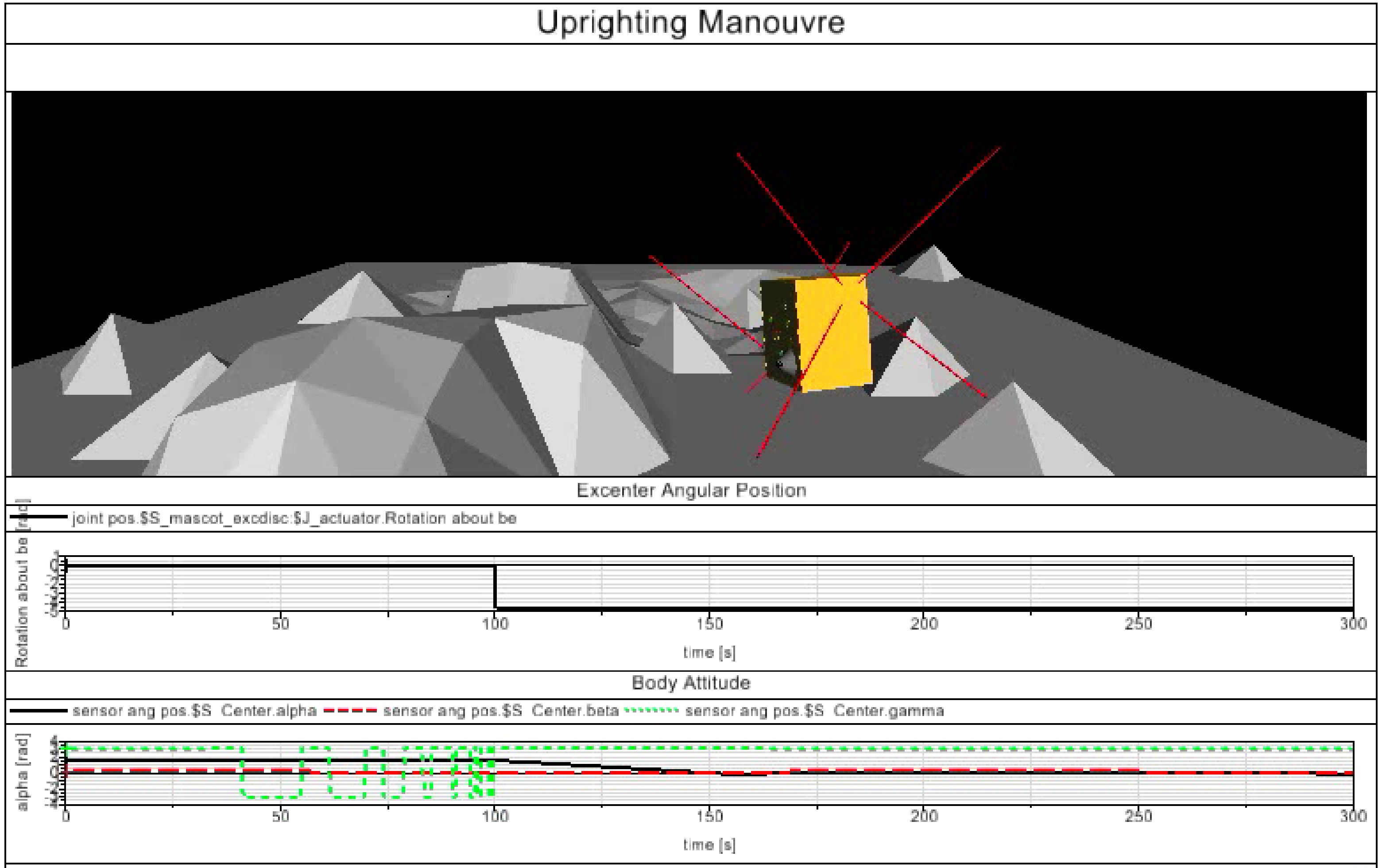
Surface Ops: Attitude Determination and Mobility

Actuation: Excenter arm for flip-over and hop-maneuvers



Sensing: Active surface proximity and distance sensing



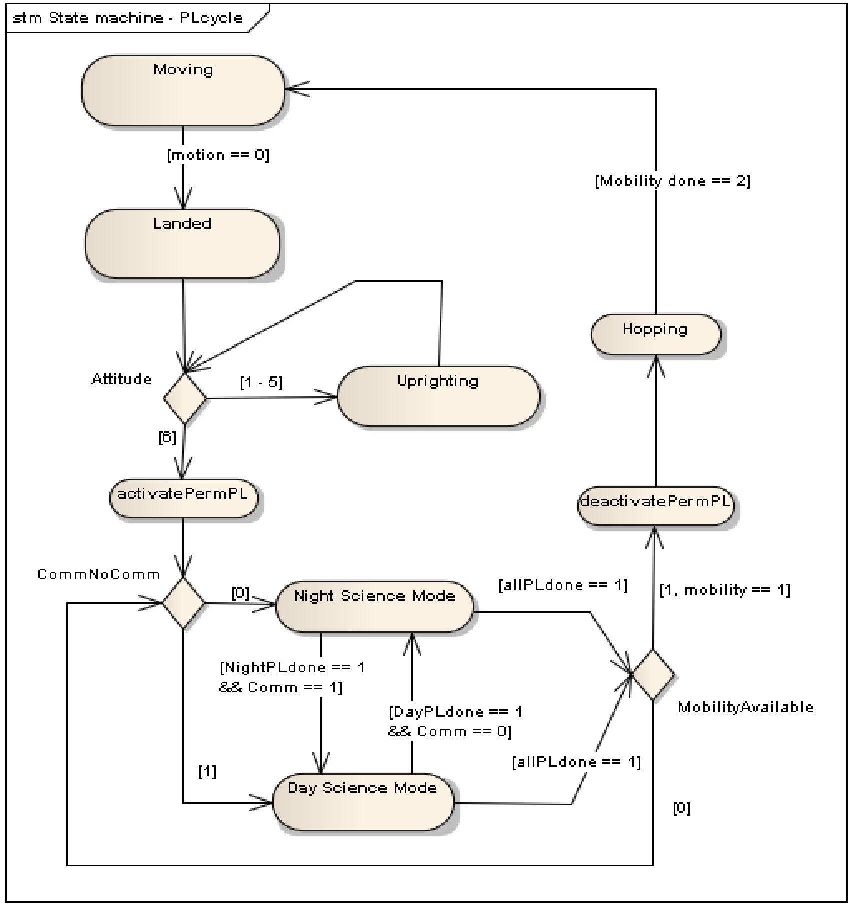


More details & background:
Schlotterer, M. et al. (2014)
Lichtenheldt, R., Reill, J. (2016)

Surface Ops: Autonomy

As the surface operating conditions remain hardly predictable and Ground Segment intervention is limited, MASCOT needs to perform its tasks highly autonomously to react and adjust its operations sequence.

This task is laid down in a state machine logic…

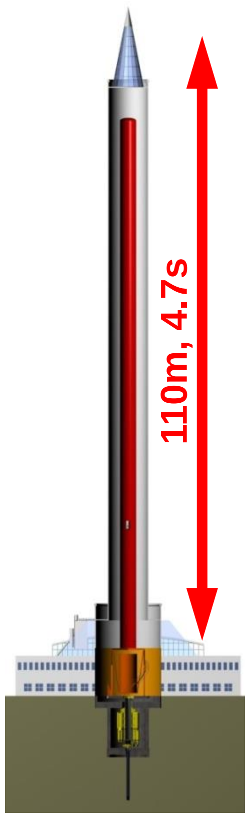


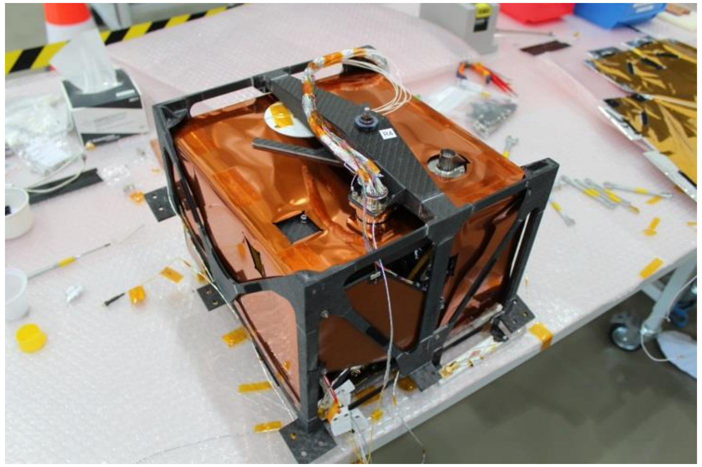
…but better explained by RoboMower!

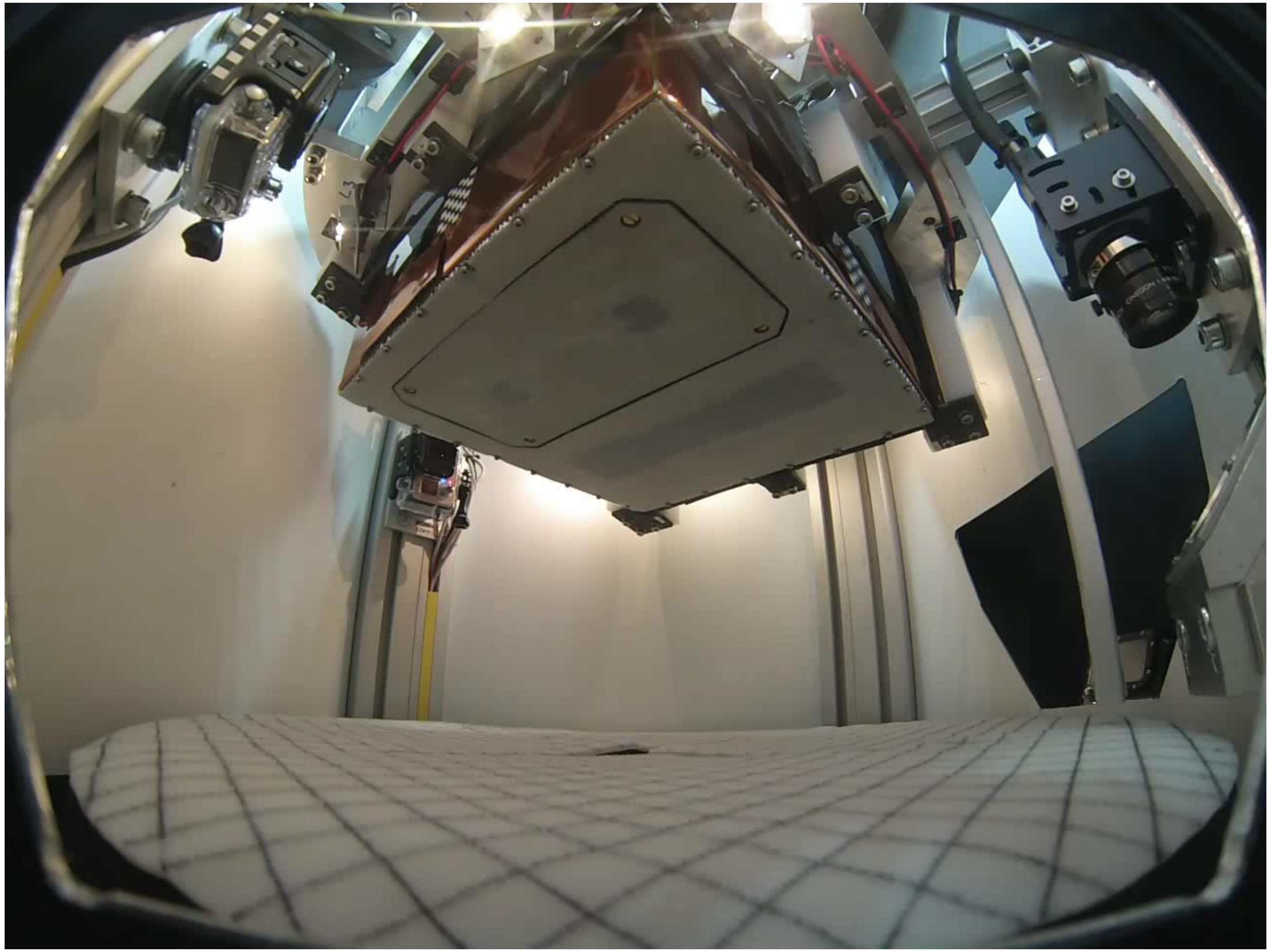
Image credit: Gardena

Separation Testing under μg

- Qualify separation and push-off from HY2 spacecraft (ZARM drop tower)
- Paramount: ensure HY2 spacecraft safety, but stay below escape velocity







More details & background:
Grimm, C. et al. (2020)

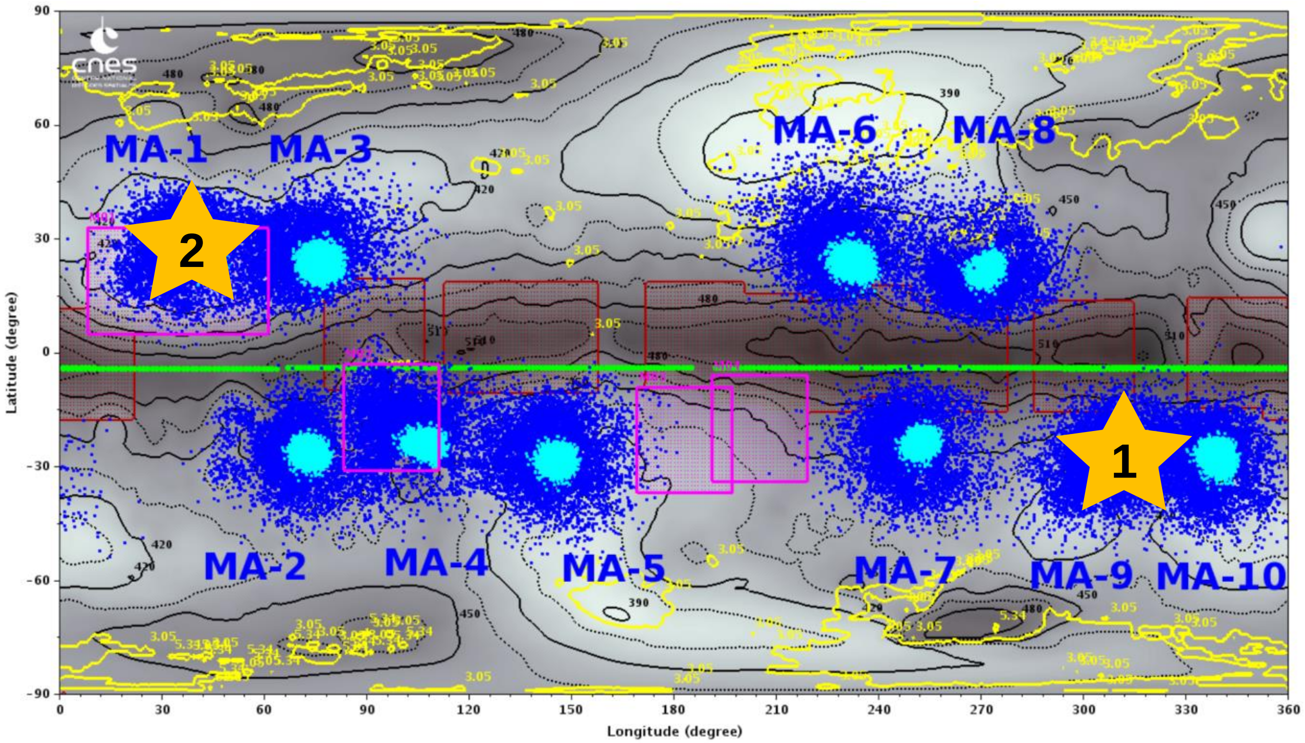
Assembly, Test & Launch Operations

- Assembly, Integration and Test were near flawless ☺ (except the usual „Blood, Sweat & Tears“)
- Launch in December 3, 2014 with Hayabusa 2 on a JAXA’s H2A launch vehicle

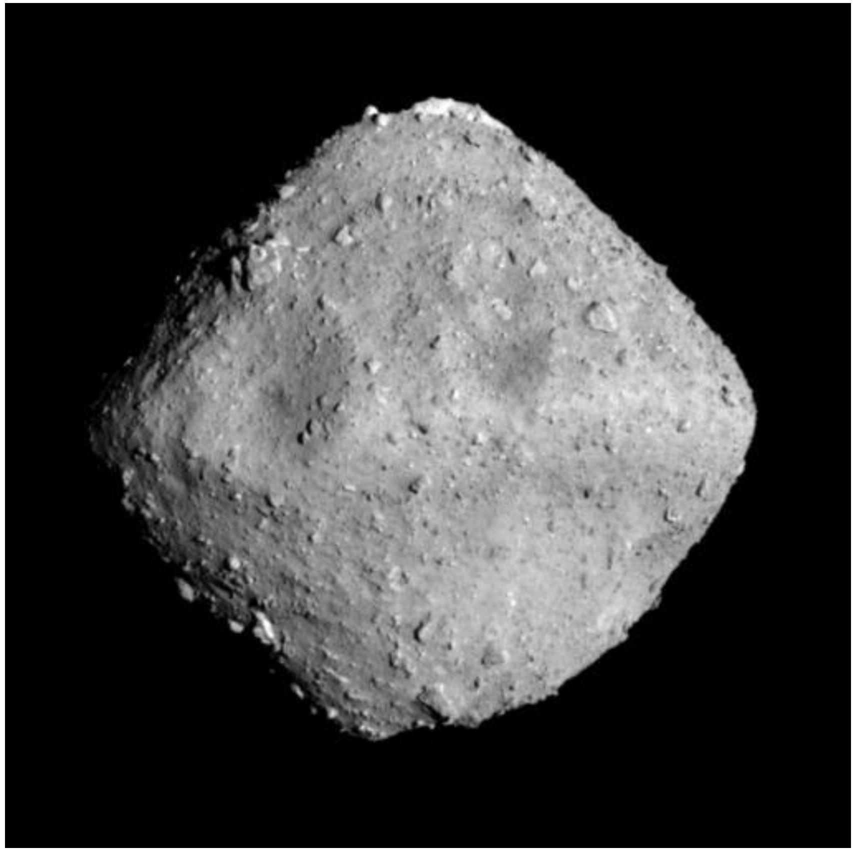
MASCOT Landing Sites Assessment & Selection

- Final selection workshop in August 14, 2018. Several constraints apply:
  - Orbiter: E.g. HY2 must stay near subsolar point. No overlap between MASCOT sites and HY2 sampling sites
  - Operational: Visibility to orbiter for 50% to 70% of asteroid day. Thermal restrictions.
  - Science: Scientific relevance of candidate sites discussed, but no area explicitly favored due to high surface homogenity

➔ MA-9 chosen as primary site, MA-1 was back-up site



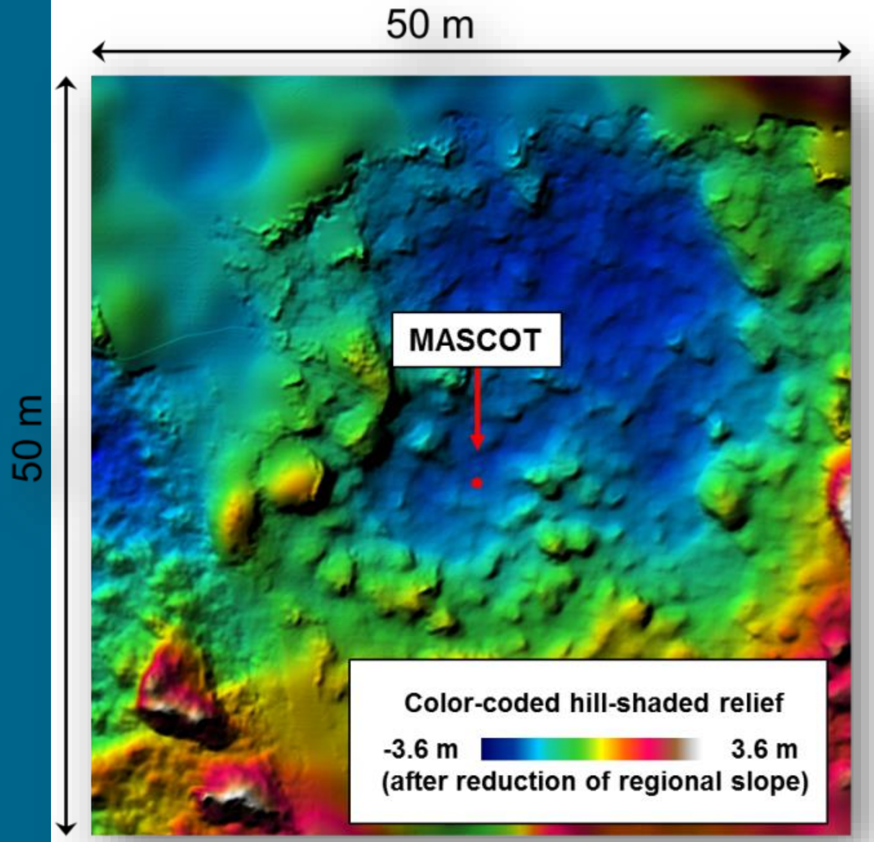
MASCOT Landing dispersions: 1st contact light blue, with bouncing blue; potential HY2 ops area magenta

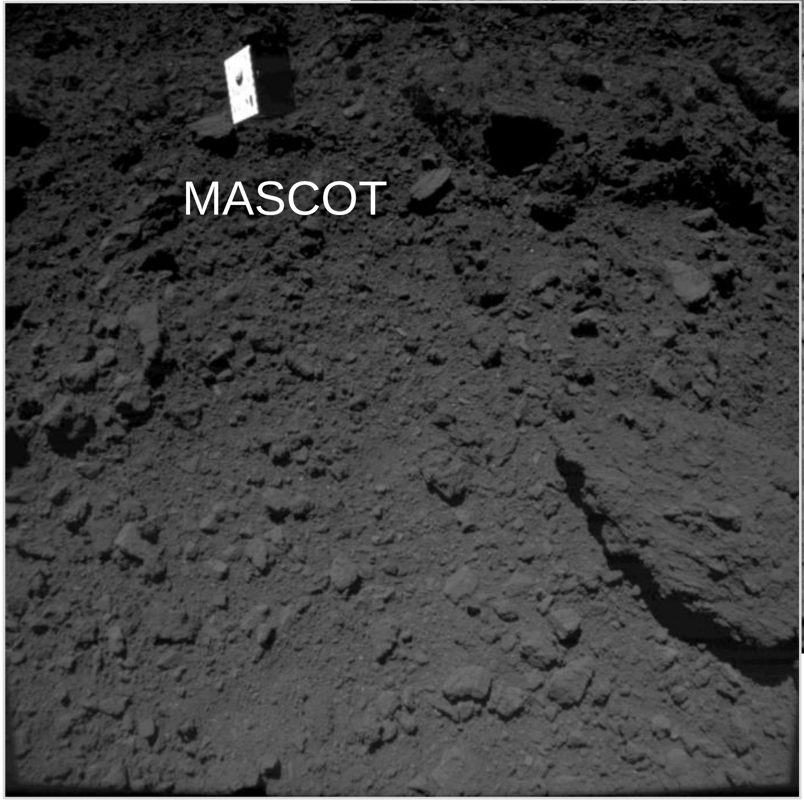


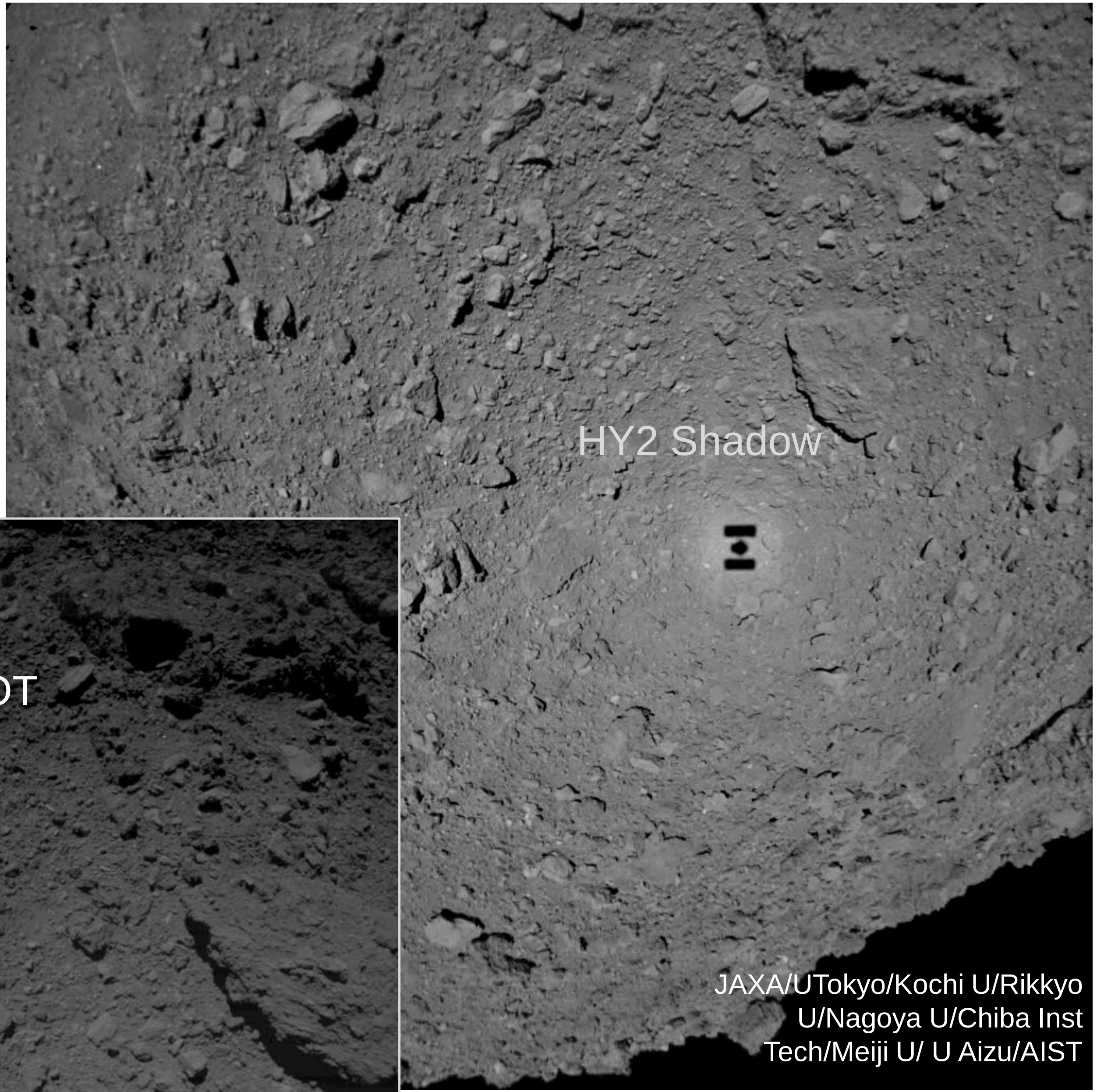
More details & background:
Lorda, L. et al. (2020)

MASCOT SDL on 3rd Oct. 2018

- Separation at 42 m altiude
- Observed by HY2 ONC cameras
- MASCOT landed after 6 min 22.3°S, 317.13°E





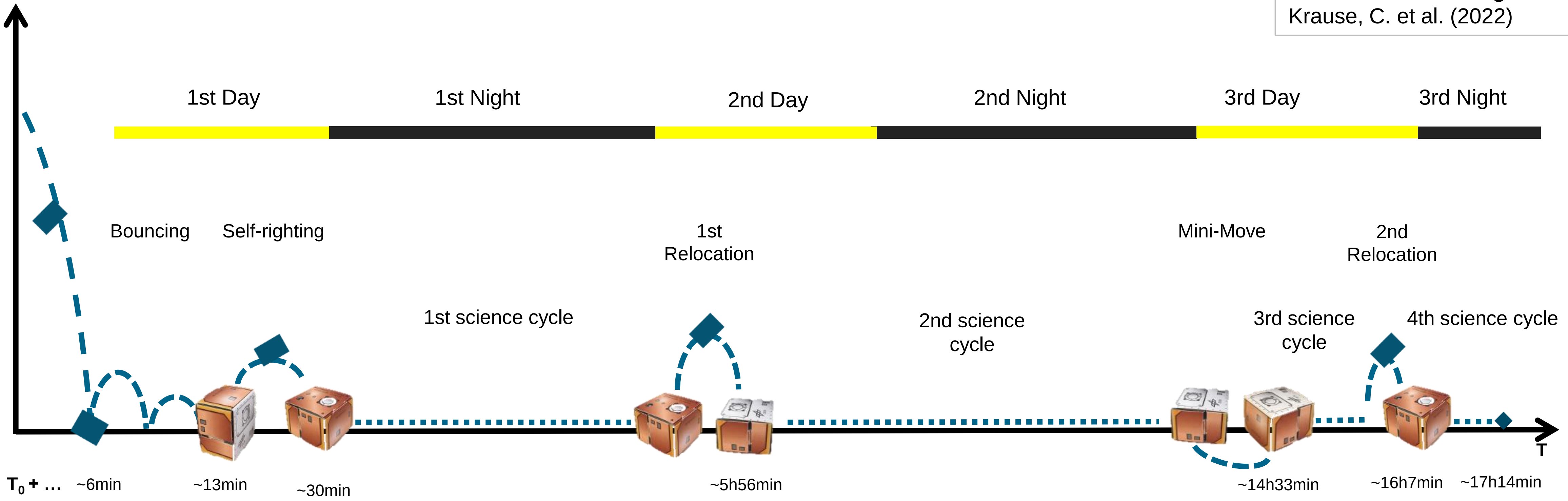


More details & background:
Preusker, F. et al. (2019)

MSC Landing and Surface Operation

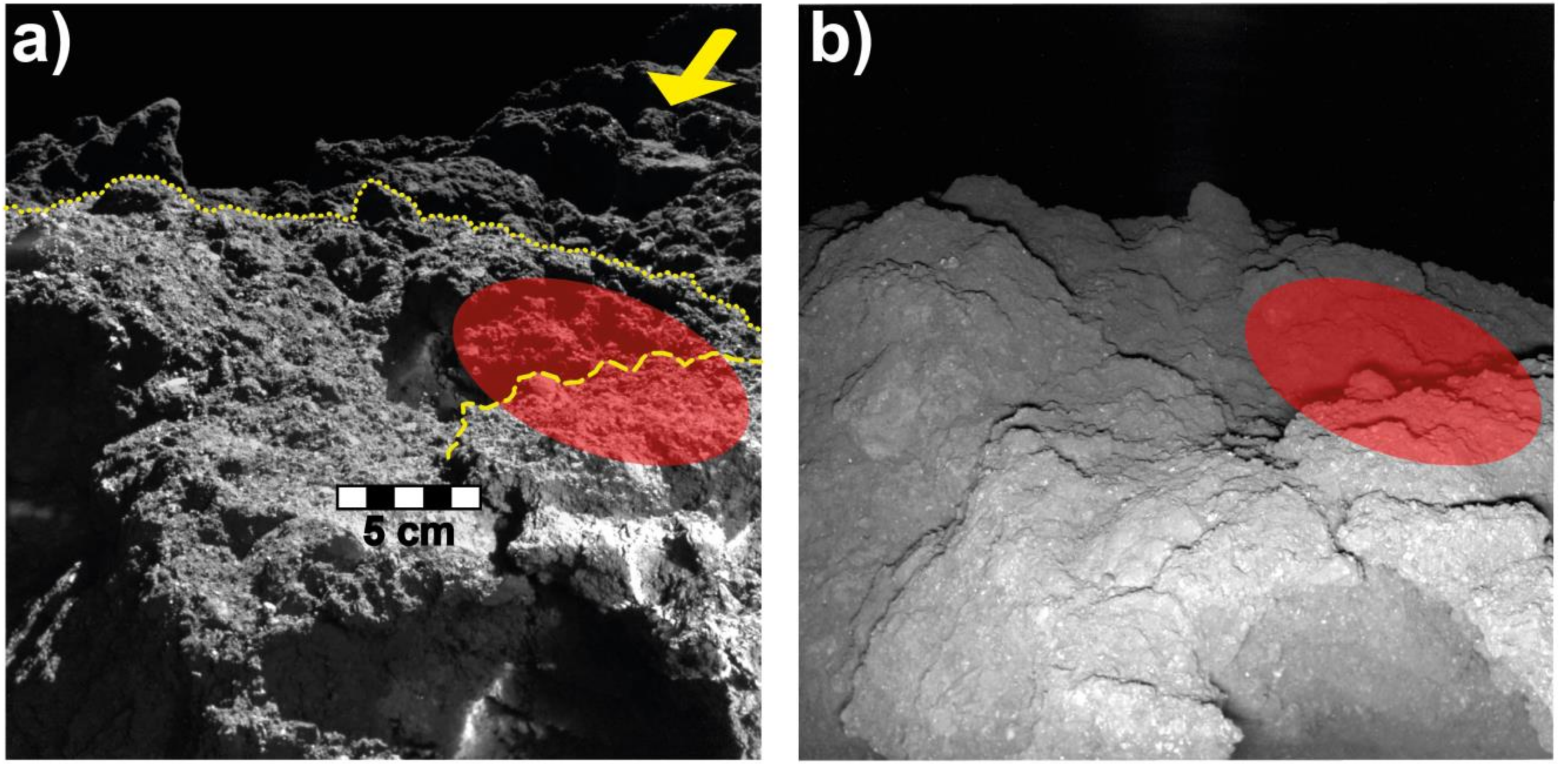
- Settlement was detected and (wrong) up-righting commanded by spoofed guidance
  - not unexpected due to high terrain roughness
- First measurement cycle conducted in upside down orientation (MicrOmega looking sky-ward)
  - Orientation corrected by ground command with ~70 cm relocation flipping MASCOT over
- A successful second science cycle was executed, and „mini move“ was commanded by ground to just change the field of view for a third science cycle.
- A second relocation ended miss-oriented and could not be recovered before End of Mission after ~17 h (design: 16 h)

More details & background:
Krause, C. et al. (2022)



Science Ops – Example MARA / MASCam Observations

- MARA observed a boulder that is about 30 cm high and 60 cm large, multiple inclusions visible
- No fine particles above the MASCam resolution limit (~ 1mm)
- Thermal inertia of the boulder observed by MASCOT is $\mathbf{282^{+93}_{-35}}$ J m^{-2} K^{-1} s$^{-1/2}$ (2-σ).
- Low thermal conductivity implies a porosity of at least 28 %.



MASCOT/DLR/JAXA

More details & background:
Grott, M. et al. (2019)
Ho, T.-M. et Al. (2021)

Wrap-up & lessons learned

Many conclusions and lessons learned, summarized here only as main „take-aways“:

- Science
  - Hard Surface of comets (Crème brulée ?), Limited dust deposition, despite of high dust flux
  - If ever doubted, proofed that planetary science need insitu elements on the surface
  - Meaningful science can be achieved with small, secondary payload probes
- Technical & Ops
  - Philae: harpoon/ADS failures were reliability (=budget) issues, but not questioning the SDL concept in general
  - Philae landing gear: often over-looked, but very capable re-usable/re-settable, adjustable braking level → a candidate for larger small body crafts?
  - MASCOT: the primitive means of autonomy worked partly but not unexpected due to the rough terrain (have contingency planning in the back-hand!)
  - Both: alternative means for localization is recommendable
- Philae and MASCOT legacy
  - MMX Rover mission (CNES/DLR rover Idefix flying on JAXA MMX to Phobos)
  - MASCOT variants (long-live, dedicated landing system for higher velocities) with „proposal-ready“ maturity

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