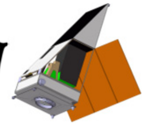

Small Spacecraft in Small Solar System Body Applications

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**) presenting author*

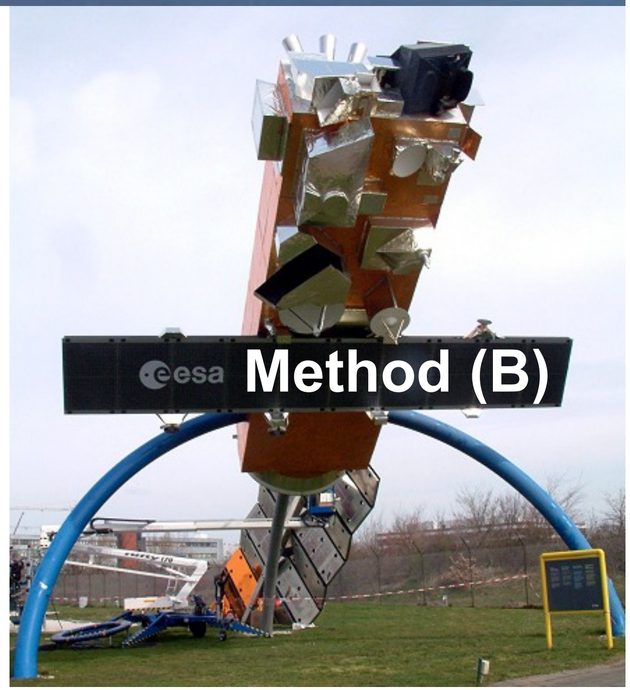
Thursday, March 09th, 2017, 11:00 AM, 2.1212

DLR

action required! – be prepared! – space rocks! ;-)
…*so*,… how do you get your spacecraft on 'em?

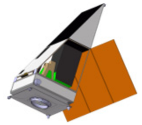
Step 1: Decide…

– or –



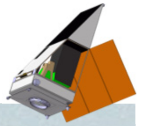
(*Note*: not to scale)

ACCOUNTANT-GERNERAL'S WARNING: Taking decisions may irreversibly affect your financial health.

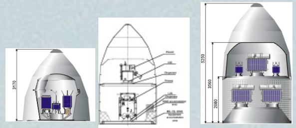


history repeating…
…e.g. Ø¼-m space telescopes…

*Spacecraft **C***	– ***1996…2006*** *vs* ***2007…2013*** – (design phase)	*Spacecraft **A***
14.5 mag @ SNR 1000:1	limiting magnitude @ SNR	18.5 mag @ SNR 3:1
2°.7 · 3°.05	Field of View	(2°)²
Ø27 cm	telescope aperture	22.8 · 23.0 cm² , f/3.4
590 cm² (off-axis afocal)	telescope collecting area	474 cm² (Cook TMA)
4 CCDs 2048², (13.5µm)² pixel	focal plane array	4 EMCCDs 1024², (13µm)² pixel
2.32"/pixel	plate scale / IFOV	3.5"/pixel
-40°C	sensor operating temperature	-80°C
16"	pointing stability	100"
0".5 (0".15 rms)	payload-augmented stability	7".5 /s (3σ)
4 .. 5 / year (*variable objects*)	fields visited	(*moving objects*) 720 / day
2 GBit (EOL)	on-board storage	256 GBit (redundant)
1.5 Gbit/day	data transmission rate	224 Gbit/day
626 kg	satellite mass	**180 kg**
300 kg	payload mass	**30 kg**
4.10 m tall, Ø1.984 m	spacecraft size @ launch	**1.00 m tall, □ (0.8 m)²**
900 km, i = 90°	orbital altitude & inclination	**any** 500…850 km, i ~ 98°
2 ½ years	design lifetime	2 years

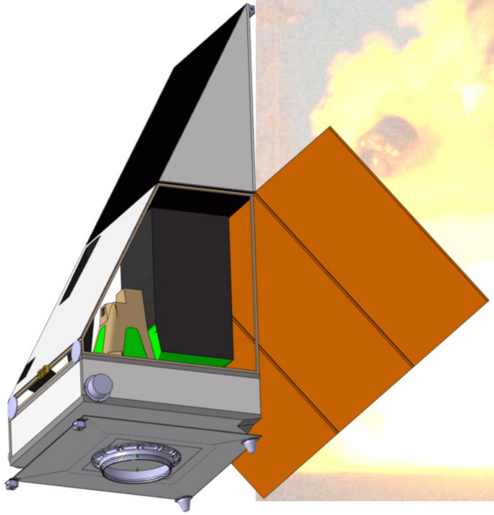


…to scale.



CoRoT

- highly successful mission
- conventional 'big' spacecraft design
- operated Feb.2007 – Nov.2012



AsteroidFinder

- DLR project design Phase 0 to B2
- high-density small spacecraft design
- lessons learned applied on MASCOT

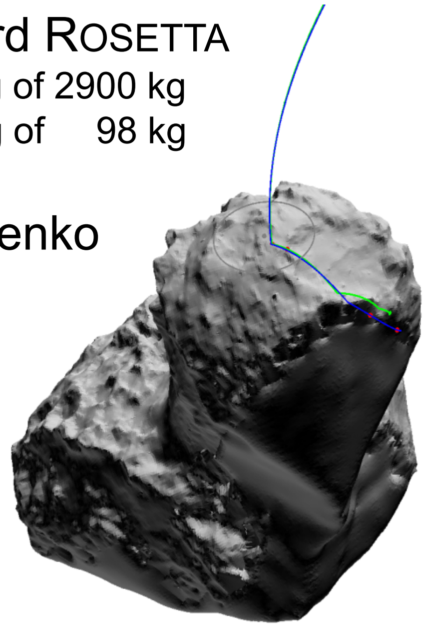
images: CNES/ESA, Starsem, DLR, Kosmotras

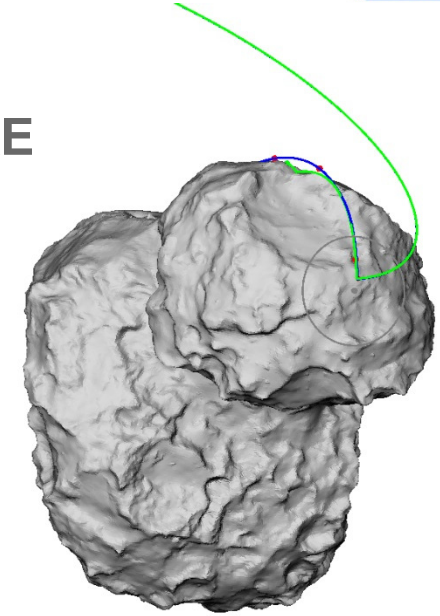
DLR

"Today, we didn't just land once,…"
– the landings of PHILAE

- launched March 2nd, 2004 aboard ROSETTA
  - ROSETTA: 11 instruments – 165 kg of 2900 kg
  - PHILAE: 10 instruments – 26.7 kg of 98 kg

- target 67P/Churyumov-Gerasimenko
- arrived on August 6th, 2014

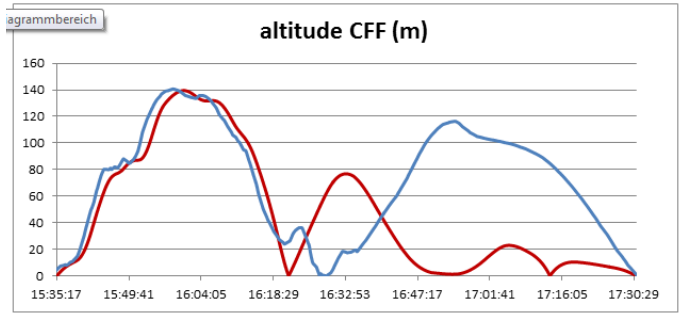


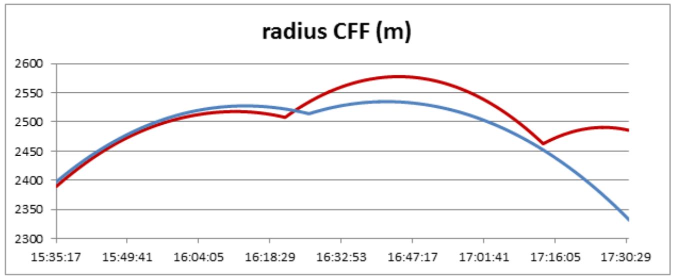


- **free-fall from 22500 m altitude**

  separated with 0.19 m/s lateral velocity
- **touch-down at 1 m/s**
  - rebounds at 0.38 m/s
    - bounces again at 0.03 m/s
      - final landing Nov. 12th, 2014 17:32 UTC

- **complex landing gear** ☺
- **energy absorbers** ☺ **& anchoring** (failed)
- **hold-down thruster** (out of gas…)

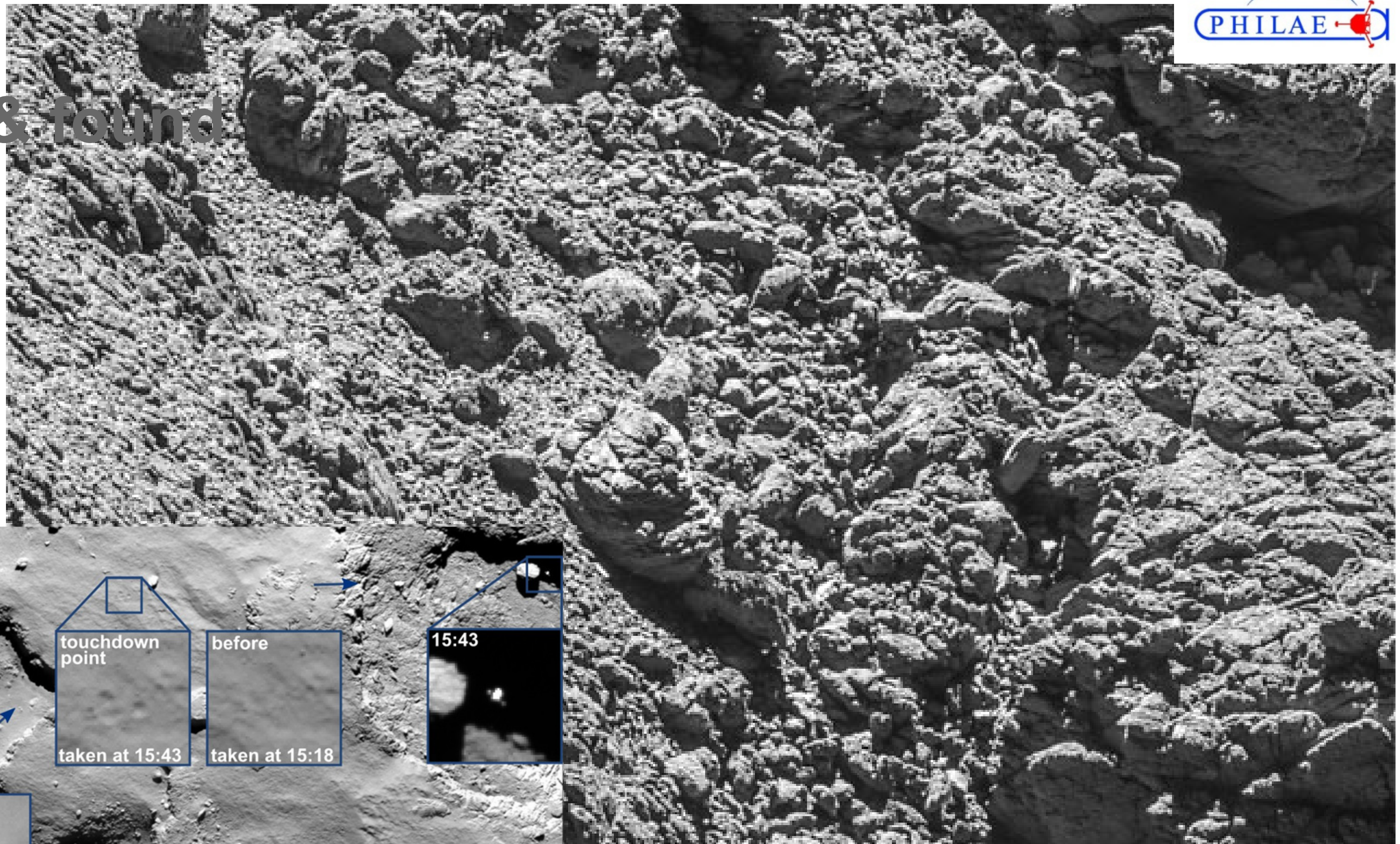


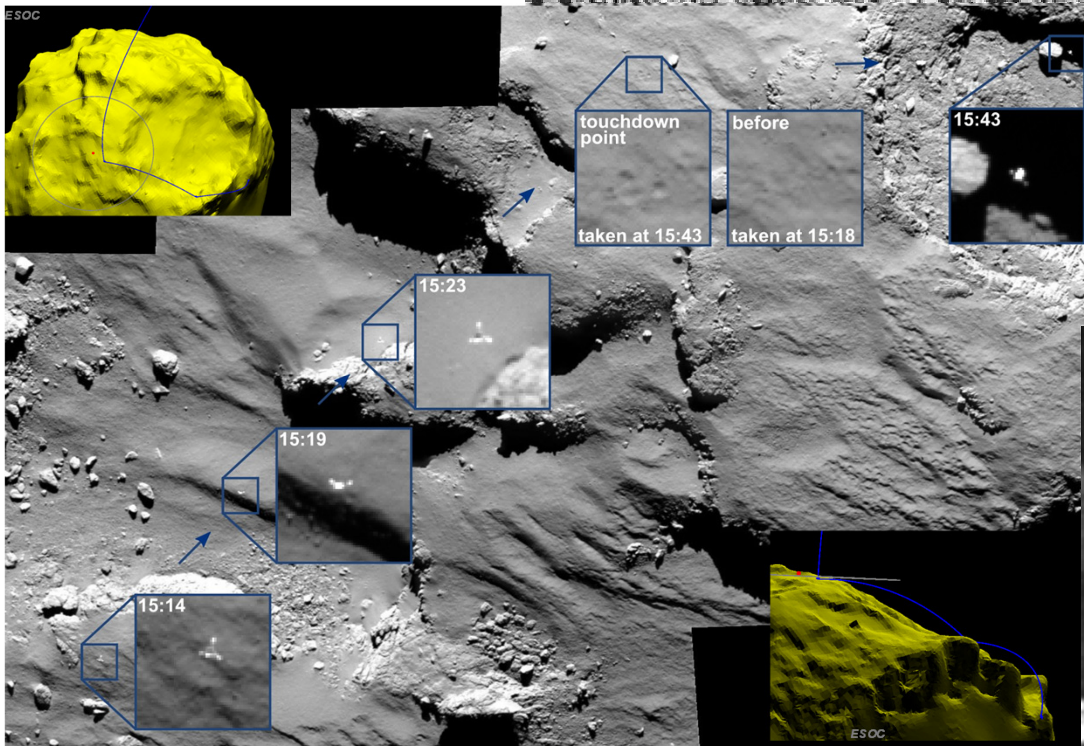


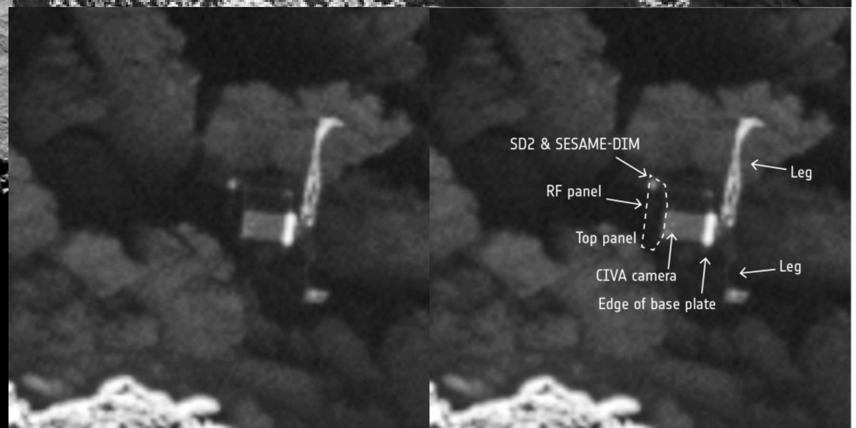
Altitude,and radius for ESOC (blue) and SONC (red / green) reconstructions.
Timing of the 2nd collision in the SONC reconstruction is forced to 16:20 UTC, in ESOC reconstruction computed as the intersection with the shape model of the trajectory determined with the optical observations.

PHILAE – lost & found

- primary mission science program successful
- extended mission lost – stuck in the shadow
- located Sep. 2nd, 2016 in 2.7 km flyby of ROSETTA (1 month before end of mission)

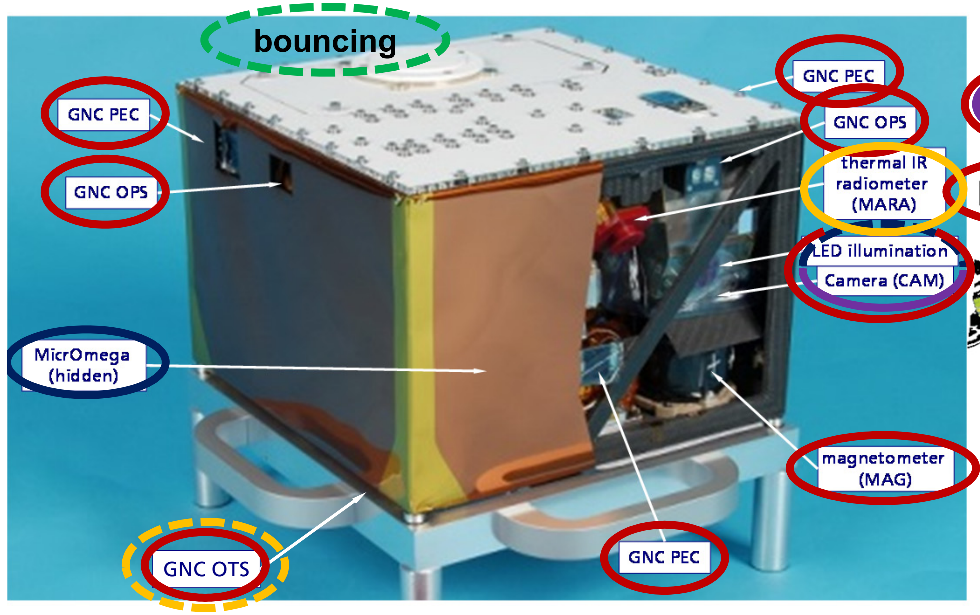


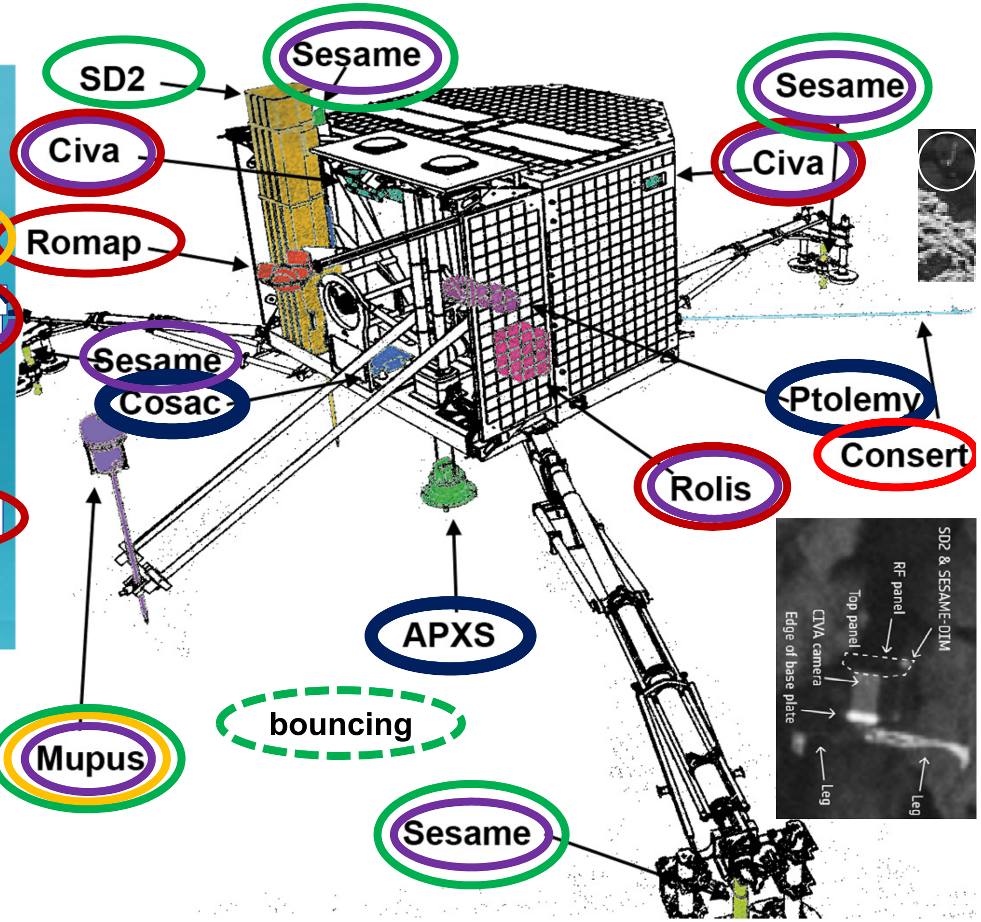




images: ESA/DLR

tools of knowledge – lander instruments





target body properties addressed…

- **surface structure**
- **composition**
- **mechanical properties**
- **thermal properties**
- **interior structure**
- **spacecraft orientation**

a better understanding of small solar system bodies

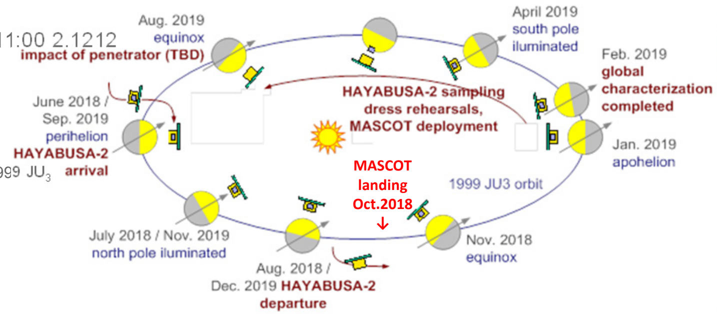
→ **modelling of properties & populations**

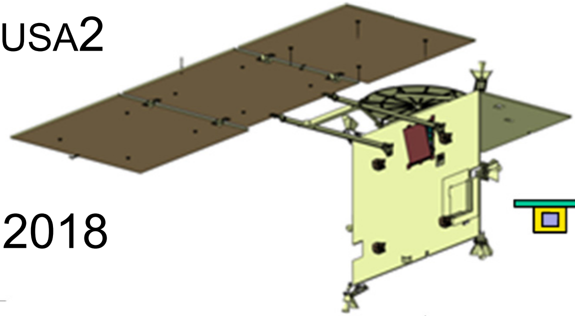
→ understanding, utilization, security

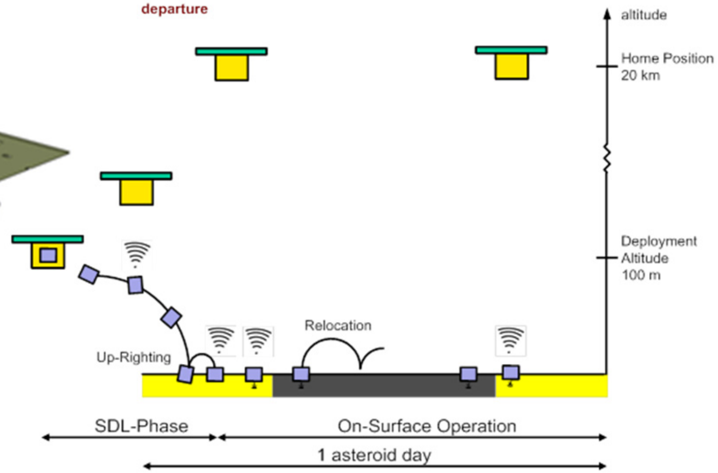
<u>note</u>: no Scout would go outdoors without a compass! →

DLR

diving down to Ryugu, the asteroid formerly known as (162173) 1999 JU_3

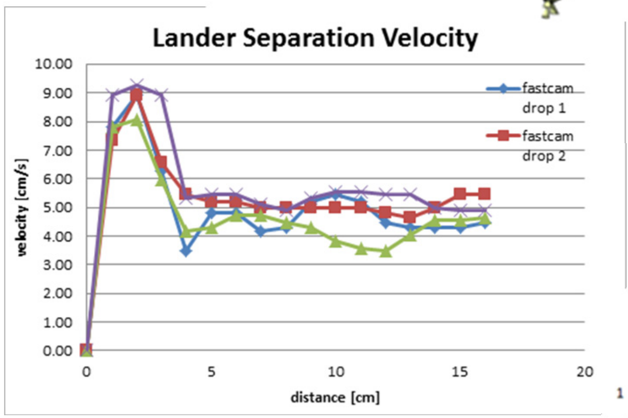






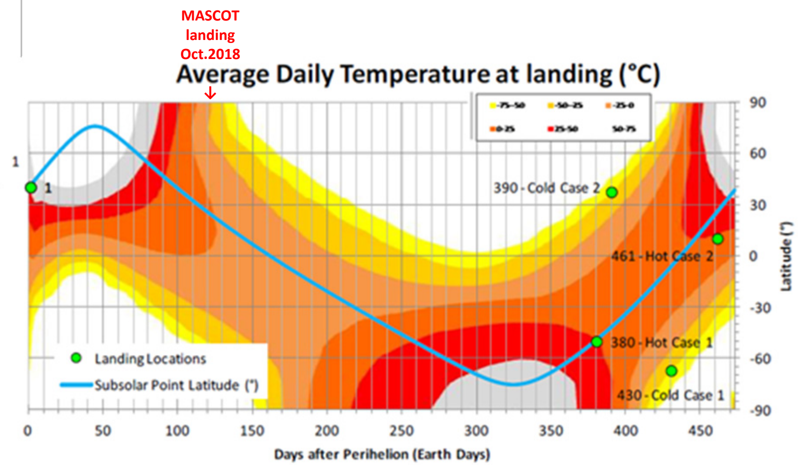
- MASCOT is aboard HAYABUSA2
- launched Dec. 3rd, 2014
- Earth fly-by in Dec. 2015
- HAYABUSA2 arrival in June 2018

- landing planned for Oct. 2018
- **free-fall from ~100 m**

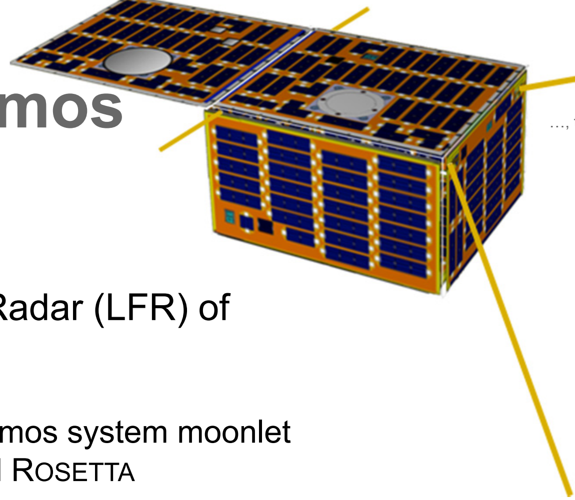


- one-try primary battery mission

- measurements at the surface planned on 2 asteroid days and at 2 locations



MASCOT2 – AIMing at Didymos



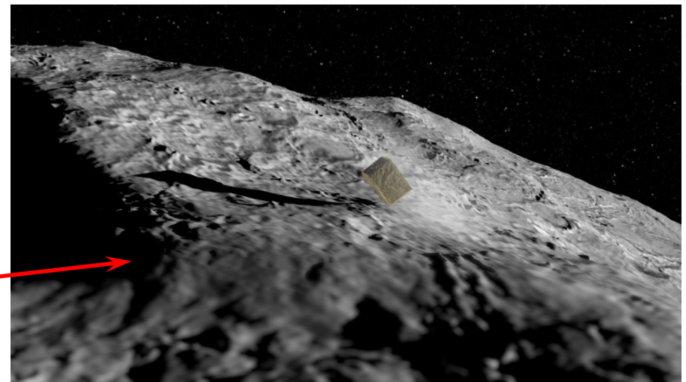
…, the binary asteroid formerly known as (65803) 1996 GT

- surface element of the Bistatic Low-Frequency Radar (LFR) of ESA's AIM mission
  - AIM is part of the joint NASA-ESA AIDA mission
  - NASA provides the DART impactor to hit the Didymos system moonlet
  - LFR is a descendant of CONSERT on PHILAE and ROSETTA

- AIM launch Oct./Nov., 2020
- AIM arrival May/Jun. 2022
- MASCOT2 **landing** Aug. 2022 on Didymoon **at a few cm/s**
- DART impact Sep./Oct. 2022 on Didymoon at 6.5 km/s <85 m from MASCOT2 !

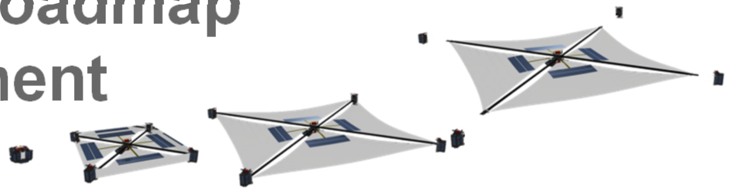
- long-term photovoltaic powered mission, >100 days
  - landing at orbital dynamics safest site
  - relocation to LFR optimal operations site by MASCOT Mobility
  - additional solar panel & LFR antennae deployed after relocation

- LFR scans the interior of „Didymoon“ in several plane sections before & after the impact of DART
- DACC accelerometer records landing & bouncing, maybe DART
- MASCOT heritage instruments CAM, MARA, MAG conduct longterm observations for seasonal changes in Didymos system



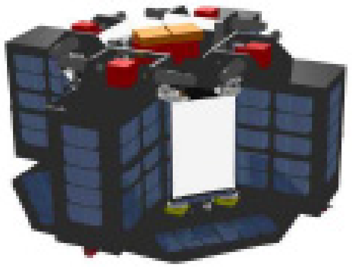
images: ESA/DLR

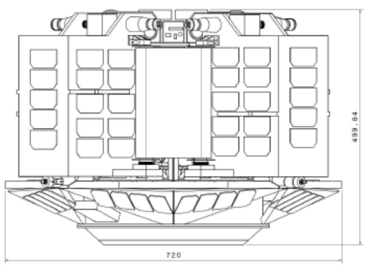
The GOSSAMER Roadmap step 1 – deployment

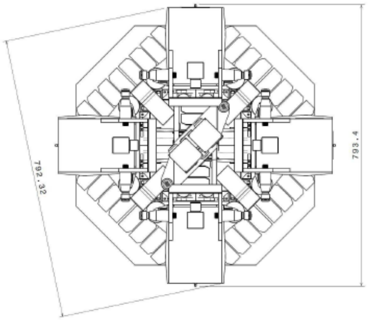


GOSSAMER-1 – in-orbit deployment demonstrator

- (5 m)² sail area, all deployment-related mechanisms
- 1-boom, 2-quadrant EM in operation →
- 1-boom QM was extensively qualification tested in 2016
- proven MASCOT-style concurrent AIV approach
- PFM detailed design was carried through beyond PDR
  - free-flyer independent spacecraft (really 5-in-1)
  - “piggy-back” launch to LEO, <50 kg total ↓
  - extensive instrumentation: 6 hi-res video cameras
- project terminated at the end of 2015

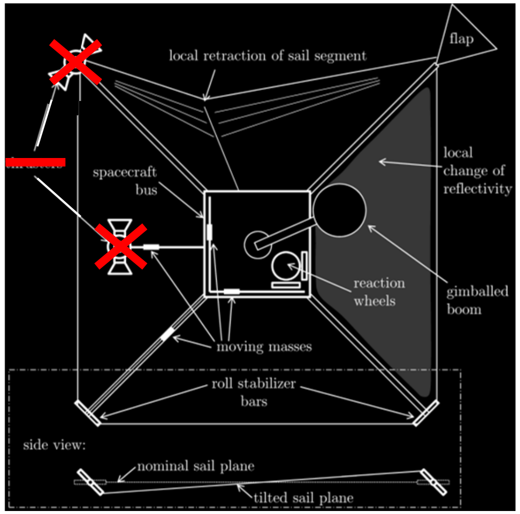


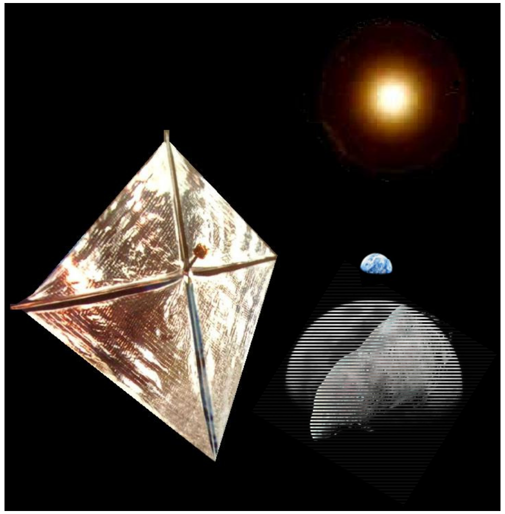




The GOSSAMER Roadmap

step 2 – control – step 3 – proving the principle





GOSSAMER-2 – in-orbit attitude & thrust vector control demo

- (20 m)² sail area
- orbit where solar radiation pressure is dominant – high LEO, MEO, GTO
- implementation of several (all?) control methods and all relevant mechanisms
- **find out what's the best …**

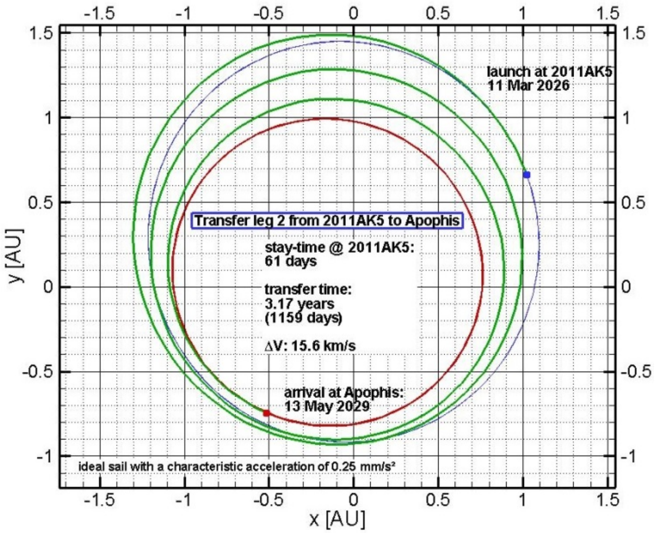
GOSSAMER-3 – all-up proof test science mission readiness demonstrator

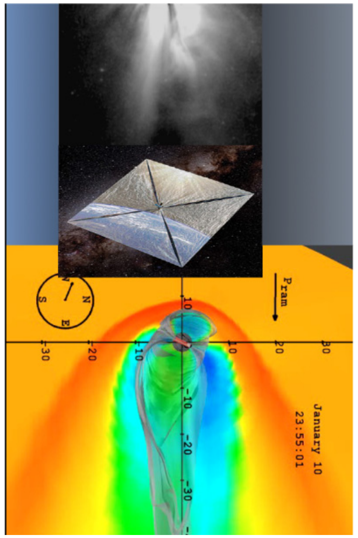
- (50 m)² sail area
- initial orbit high enough to spiral out (sail up)
- applies best control method(s) of GOSSAMER-2
- **prove that sails can operate science missions**
    - *tiny* science payload: imager & sail-environment interaction

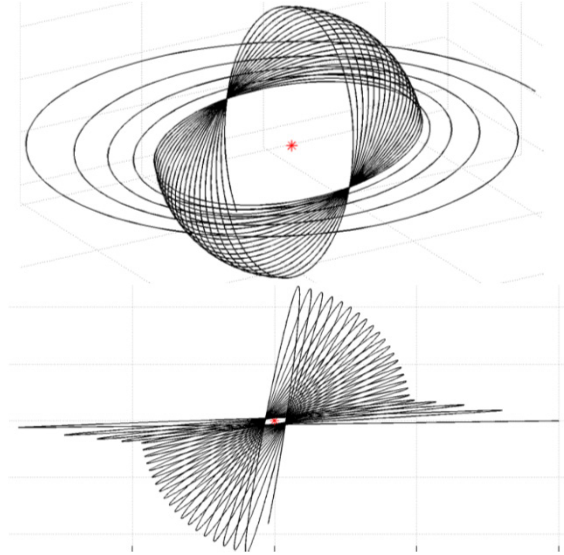
DLR

…and beyond…

3 NEOs in 10 years – 20 minutes closer to the storm – on top of the Sun







Multiple NEo Rendezvous

- (54…65 m)² sail area
- triple pre-selected NEA rendezvous with stationkeeping + NEO fly-bys of opportunity
- 0.3 mm/s², 10 years lifetime
- 40…60 kg bus, 12 kg science
- 3 small drop-probes, imager, Vis-NIR spectro, radiometer

Solar Tsunami Early Warning System

- (65 m)² sail area
- 10 years at DL_1 at $2 \cdot L_1$
- 0.3 mm/s², 2 µm foil
- 110 kg deployed sailcraft, 15 kg bus, 1 kg science
- magnetometer, plasma analyzer, Langmuir probe

Solar Polar Orbiter

- (100…125 m)² sail area
- 0.29…0.54 mm/s², 2.5 µm foil
- 250…510 kg deployed sailcraft, 5 / 15 / 40 kg science payload options:
- Total Solar Irradiance, Doppler & Stokes imager, coronagraph wind, fields & particles

NEO trajectory plots: B. Dachwald et al.,
storm & mag.sphere: V. Bothmer et al,
inc-up plot: M. Macdonald et al

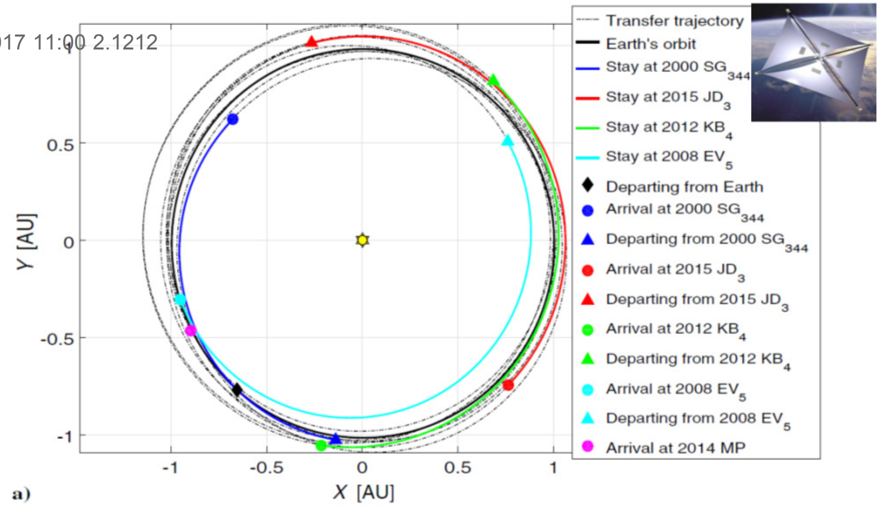
DLR

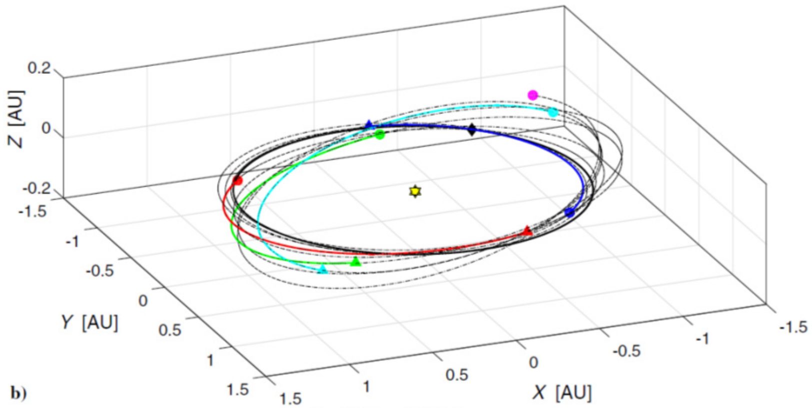
Multiple NEA Rendezvous: mission analysis progress

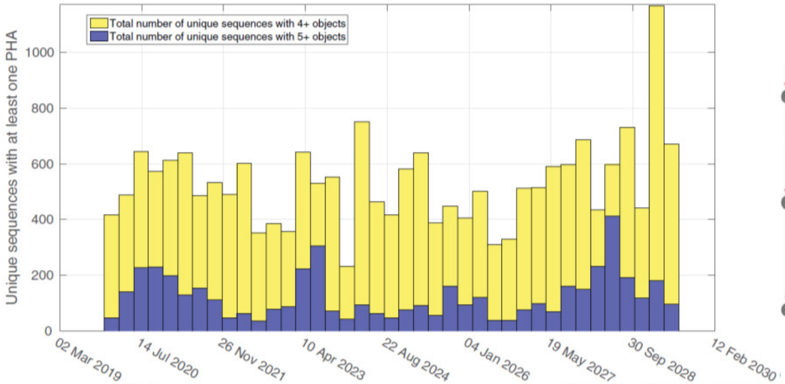
- **5 NEAs** …instead of 3
- **100 days** stay …instead of 1 rotation period
- only ⅔ of the sail performance required:
  $a_0 \geq 0.3$ mm/s² → $a_0 =$ **<u>0.2 mm/s²</u>**

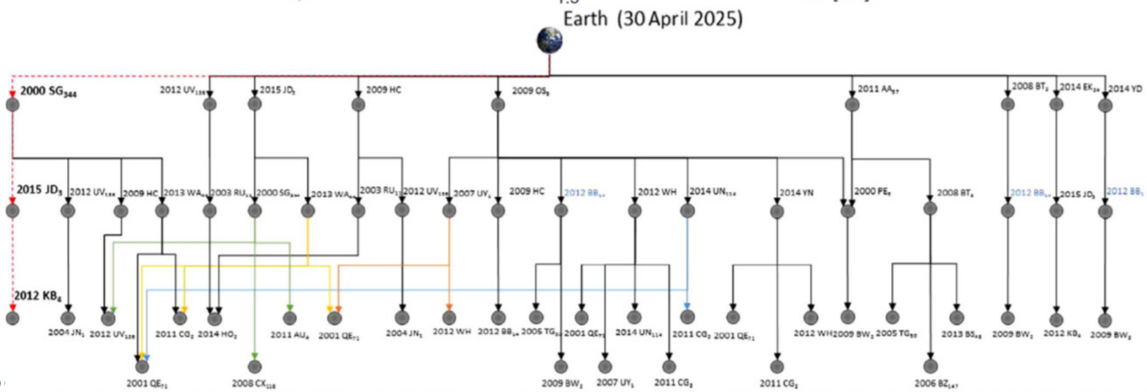
- it is possible to *change targets* ***<u>after</u>*** *launch*
  a „family tree“ of choices at each step ↘

- many unique sequences at any launch date
  - **≥4 NEAs incl. ≥1 PHA: 100‘s … >1000**
  - **≥5 NEAs incl. ≥1 PHA: 10‘s … >400**





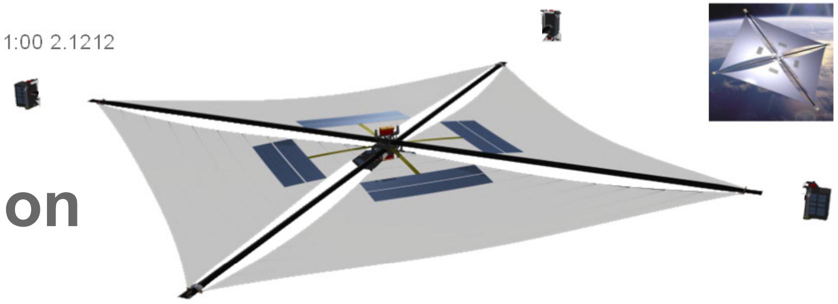


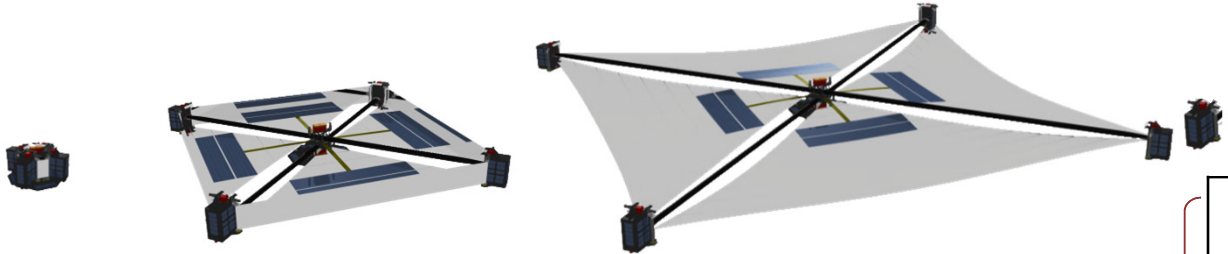


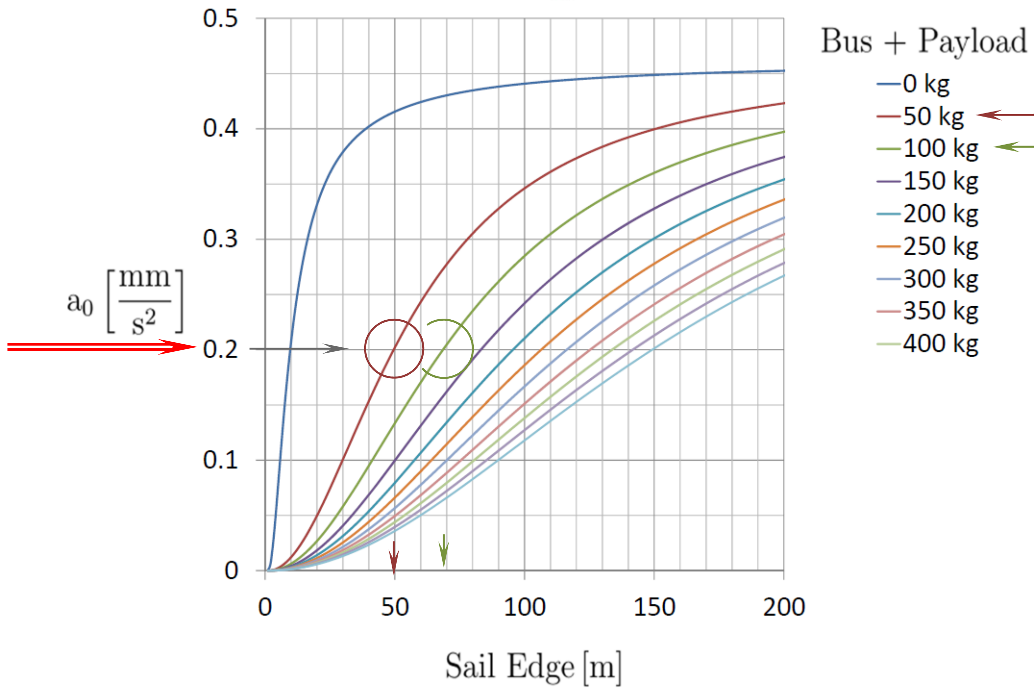
images & plots from:
A. Peloni, M. Ceriotti, B. Dachwald
JGCR Sep.2016, DOI: 10.2514/1.G000470

DLR

GOSSAMER-1
characteristic acceleration estimation





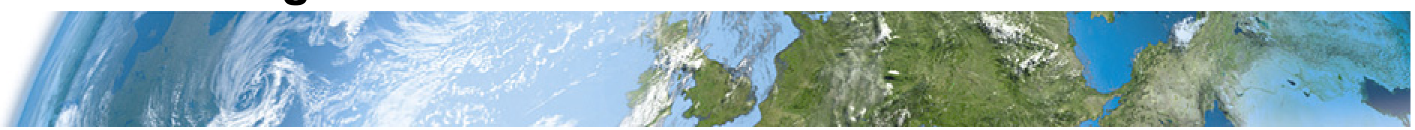


Sailcraft Bus (Gos-1 + X-Band comms)	≈30 kg
Sailcraft "Orbiter" Science Instruments	≈10 kg

Lander	
PHILAE	98 kg
Solar Power Sail Lander	100kg
1 MASCOT	10 kg
5 MASCOTs	50 kg

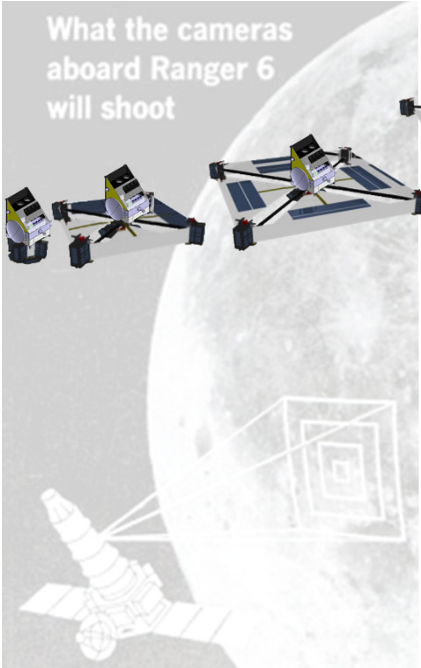
➔ Constraints driven design – ✓ MASCOT experience ✓

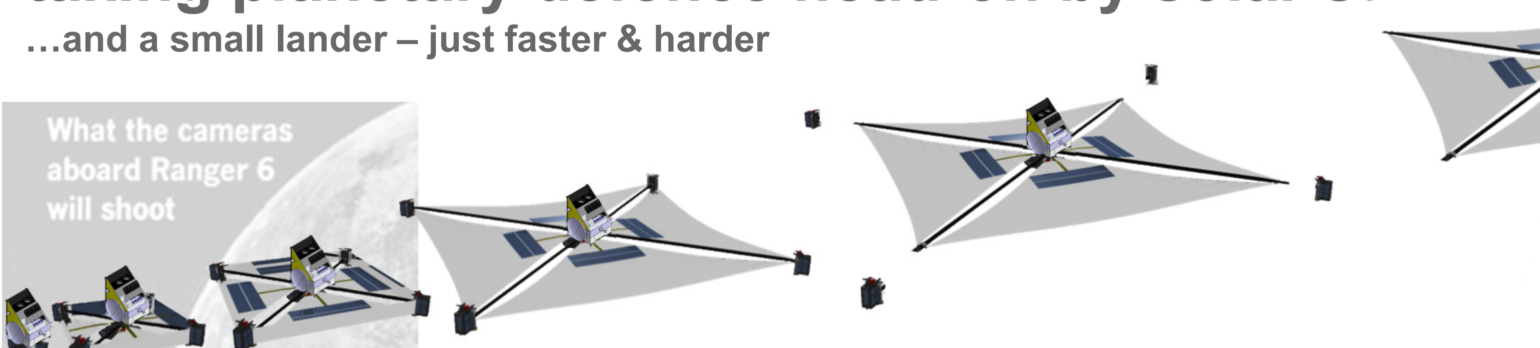
➔ all off-the-shelf technologies to be continued from Gossamer-1 QM

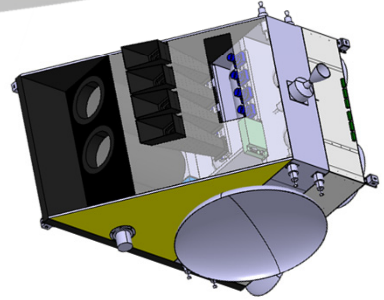


taking planetary defence head-on by solar sail

…and a small lander – just faster & harder



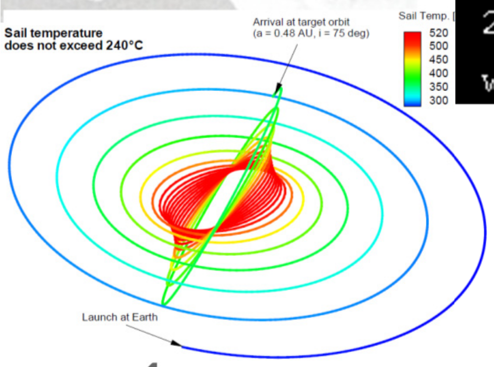




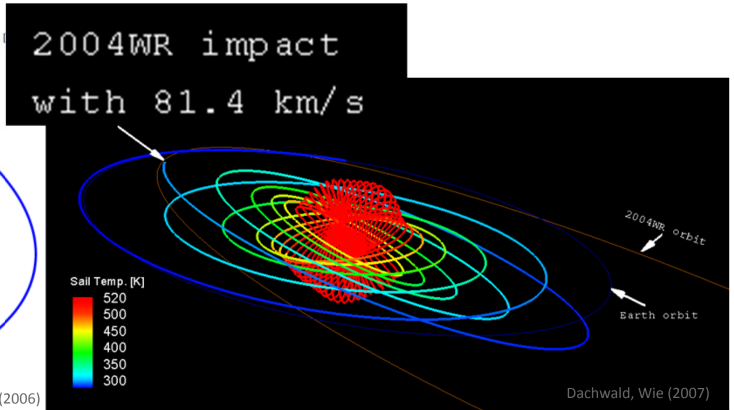
an exercise of synergy:

- one of solar sails' unique capabilities: orbit cranking to *i* >>60°
- GOSSAMER solar sails are based on small separating sub-spacecraft
- payload-drop missions have been studied, e.g. Solar Polar Orbiter / Imager
- Kinetic Energy Impactors don't care what they are made of
- a fast e⁻-multiplied CCD ASTEROIDFINDER camera is good at tracking NEAs
- … add terminal guidance & propulsion

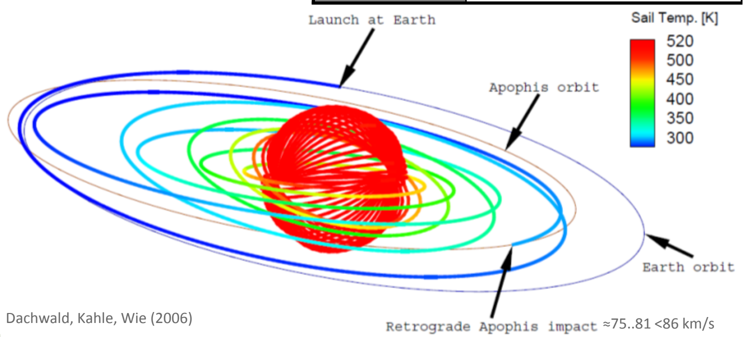
Dimension	1m x 0,78m x 0,7m
Sunshield	50 degree
Mass	179kg
Payload	2 x High Resolution Cameras 4 x Middle Range Camera 4 x Webcam
Communication	1 x Ka-band antenna 2 x X-band antenna 4 x Interlink antenna
ACS	Propulsion (8 x 1N thrusters, 1x 400N thruster)



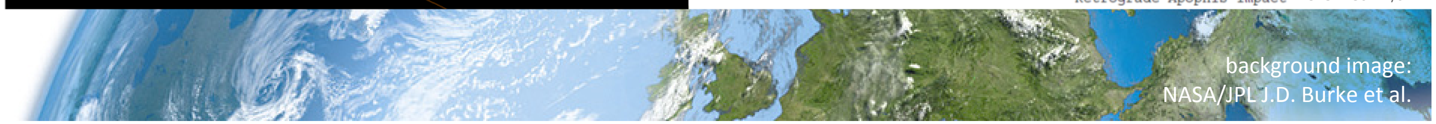
Dachwald, Ohndorf, Wie (2006)



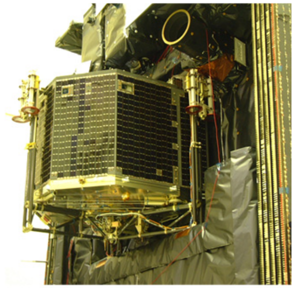
Dachwald, Wie (2007)

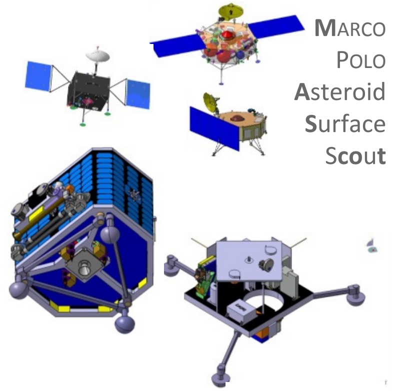


Dachwald, Kahle, Wie (2006)

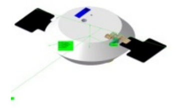


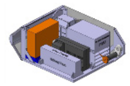
summary & future work

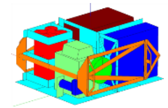


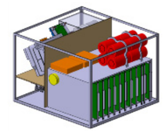


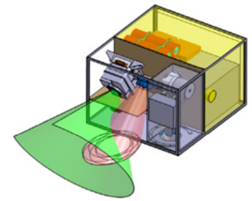
- small spacecraft offer many options for any kind of “asteroid work“
- small landers have achieved a high degree of maturity:
  - PHILAE – first landing on a comet in 2014
  - MASCOT – launched in 2014, in cruise & good health today
  - MASCOT2 – demonstrated re-use of flight-level designs in a Phase 0/A study
  - …and many more still in the pipeline
- small solar sails are getting ready for FM:
  - GOSSAMER-1 terminated but technologies qualified in 2016
  - many technologies continued in the new GOSOLAR photovoltaics project
- solar sailing enables heliocentric rendezvous access to all asteroids @ a < ♃
- ‘small‘ spacecraft design & philosophy makes missions affordable & responsive











➔ ‘small‘ solar sails & landers are the key to unlock the treasures of the solar system…

…and help deal with the bad guys…☺

back-up slides

far out – a lander study for the Solar Power Sail on a Jupiter Trojan asteroid sampling mission

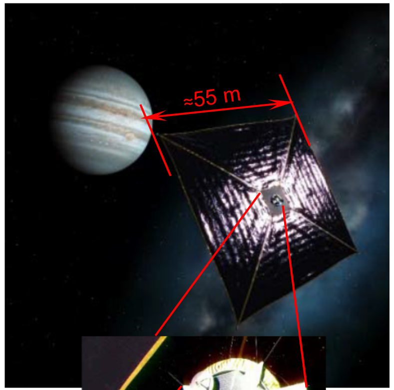
- PHILAE-sized lander
- **fully propelled descent & landing**
- Ø650 · H400 mm main body
- ≤100 kg wet mass

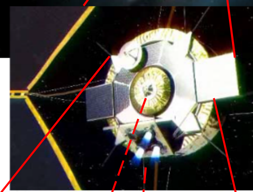
- 21 kg instrument suite for in-situ studies
- 600 Wh required for on-site sequence

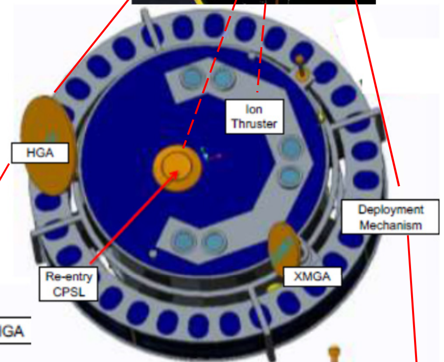
- relocation by hopping, if site unsuitable
- **optional sample-return mission**

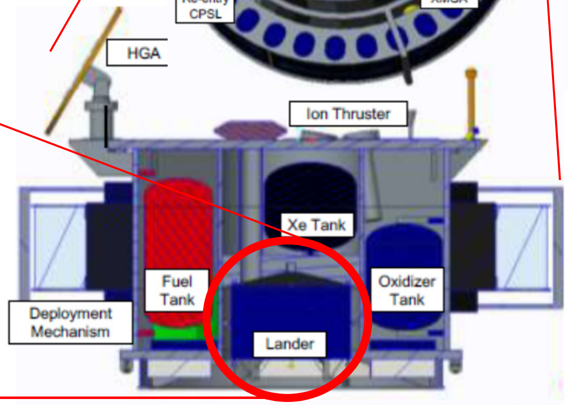
Category	Details	Mass [kg]
Sampling & Distribution system	Horn-shape sampler ~HY2 Pneumatic drill ~OSIRIS-REx Rotating carousel 6 loads Air-guns and tanks	7.0
High Resolution Mass Spectroscopy MULTUM (J) Cosmorbitrap (F)	MS Electrode Gas Chromatograph Electronic Ionizer Electronics	5.0
Microscopy	MicrOmega type IR-microscope	2.5
Panoramic Observation	Wide angle camera IR-imager with periscope	3.4
Context Observations	Close-up imager Thermal radiometer Magnetometer Raman Spectrometer Thermogravimeter	3.0
Total		20.9

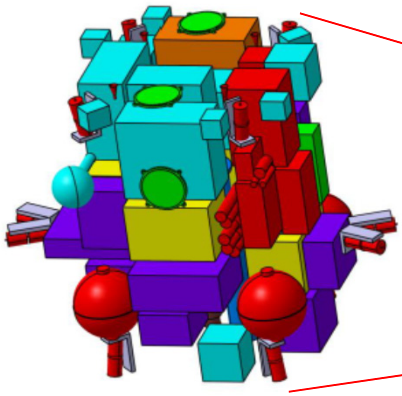
Mori et al., LPSC (2016)

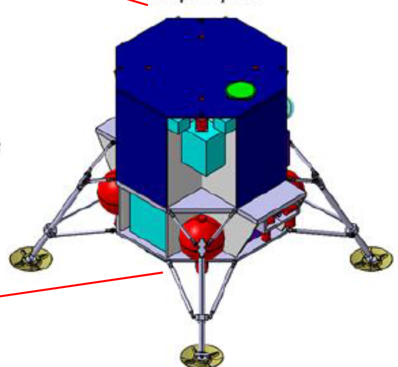


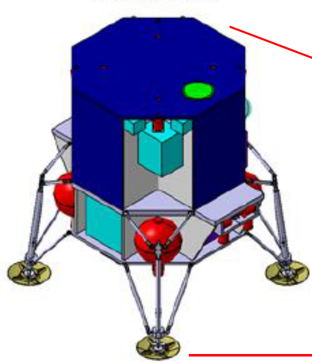












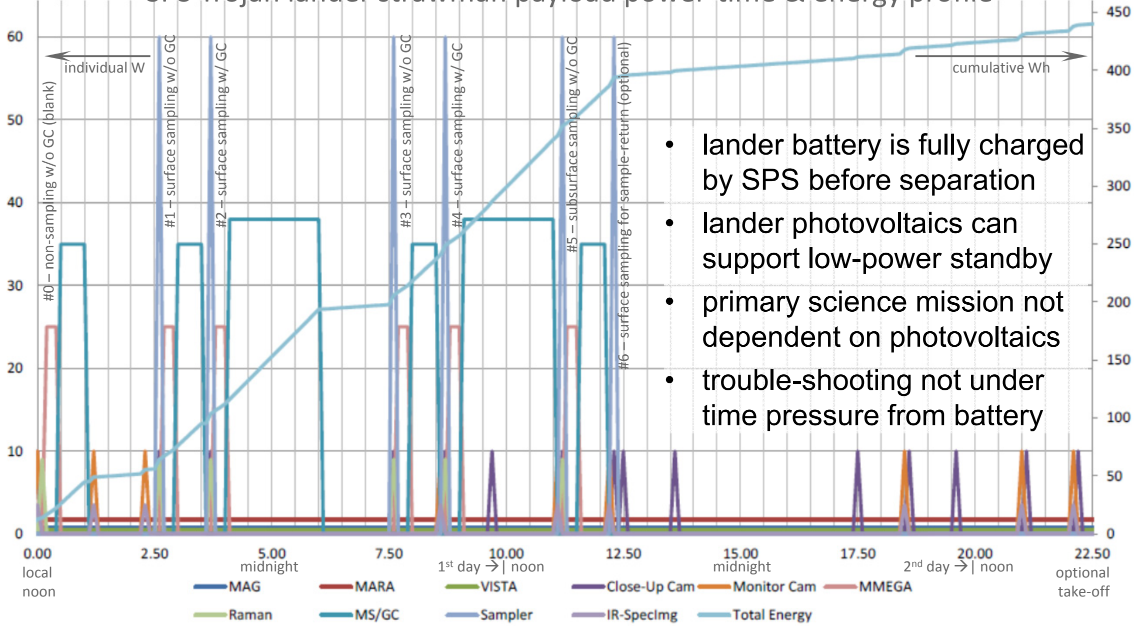
Science
RCS
AOCS
Power
DHU
Communication

Images:
JAXA/ISAS/DLR
Kawaguchi et al.
Mori et al., Saiki et al.

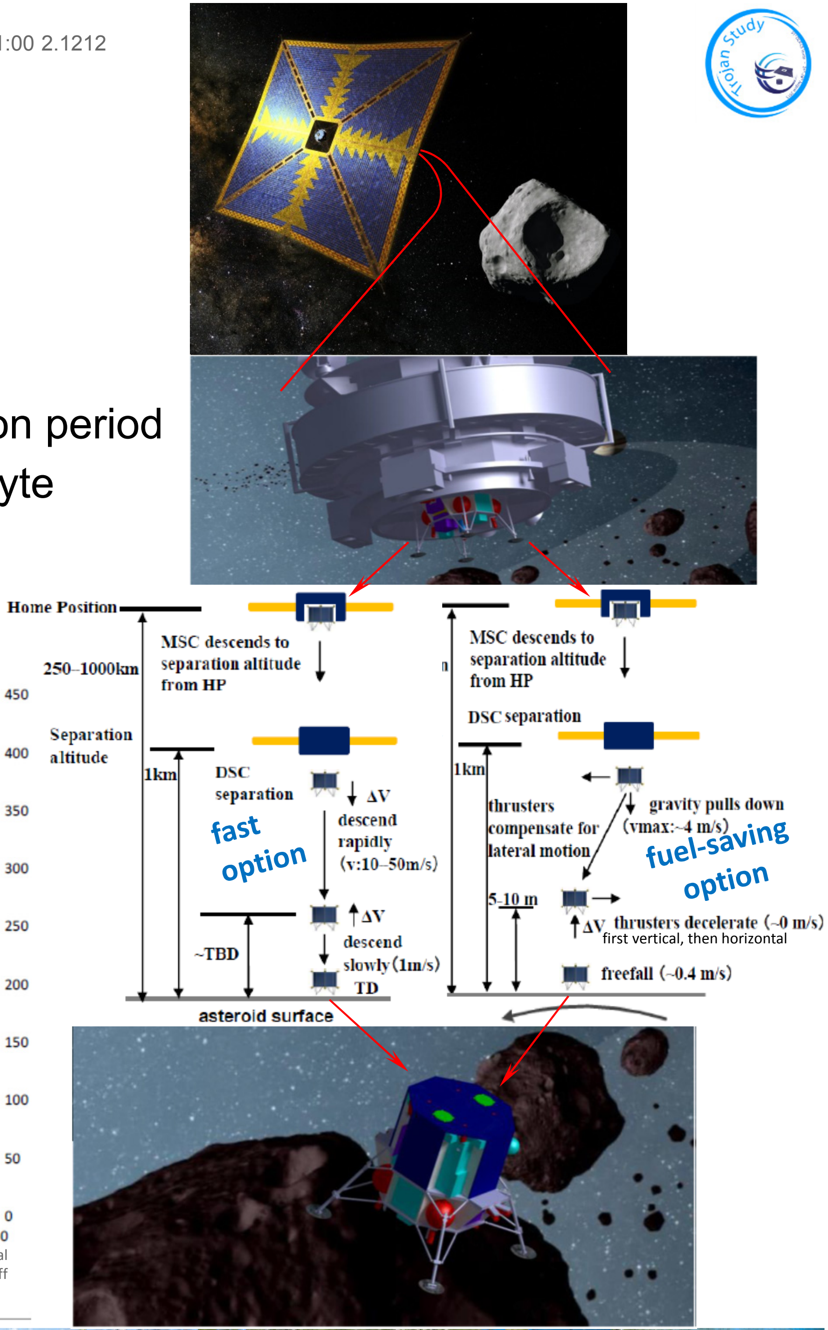
there and back again – SPS Lander operations

- separation from SPS at ~1 km altitude
- operate for >2 Trojan days → 22.5 h @ 10 h rotation period
- science data transfer from lander to SPS >500 MByte
- sampling by 2 methods into 6-place carousel
- *optional*: sample-return to SPS

SPS Trojan lander strawman payload power-time & energy profile



- lander battery is fully charged by SPS before separation
- lander photovoltaics can support low-power standby
- primary science mission not dependent on photovoltaics
- trouble-shooting not under time pressure from battery



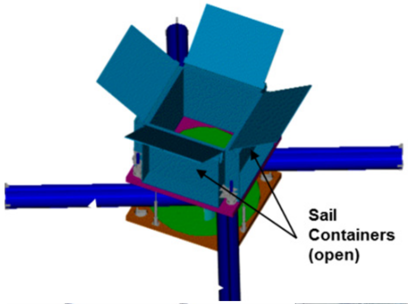
images: JAXA/ISAS/DLR, Kawaguchi et al., Mori et al., Saiki et al., Yano et al.

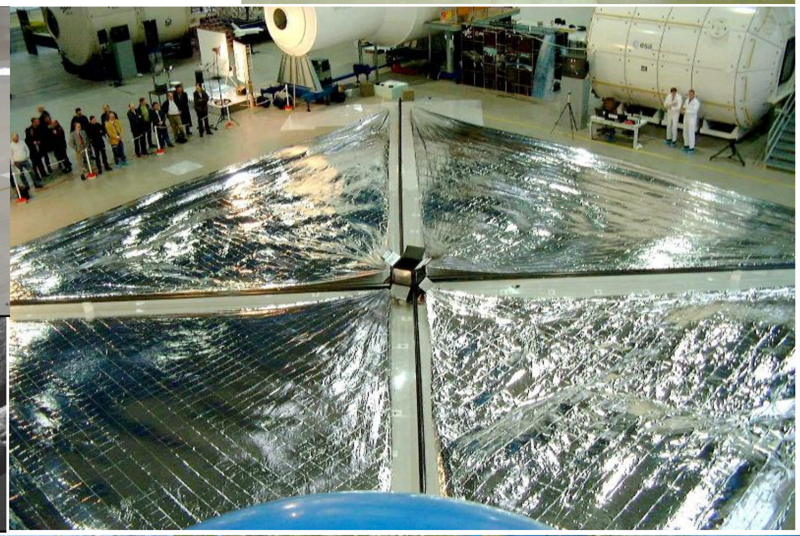
DLR

The December 7th,1999 DLR/ESA Solar Sail Ground Demonstration

(20 m)² push-out boom, hoisted sail

- you need space – the European Astronaut Center hall next to the ISS model
  - Deployment Module: 24 kg
  - CFRP booms (4 x 14m, 101 g/m): 6 kg
  - Sails (20 m)², 4-12 µm foil: 5 kg
  - Dimensions: 60cm x 60 cm x 65cm



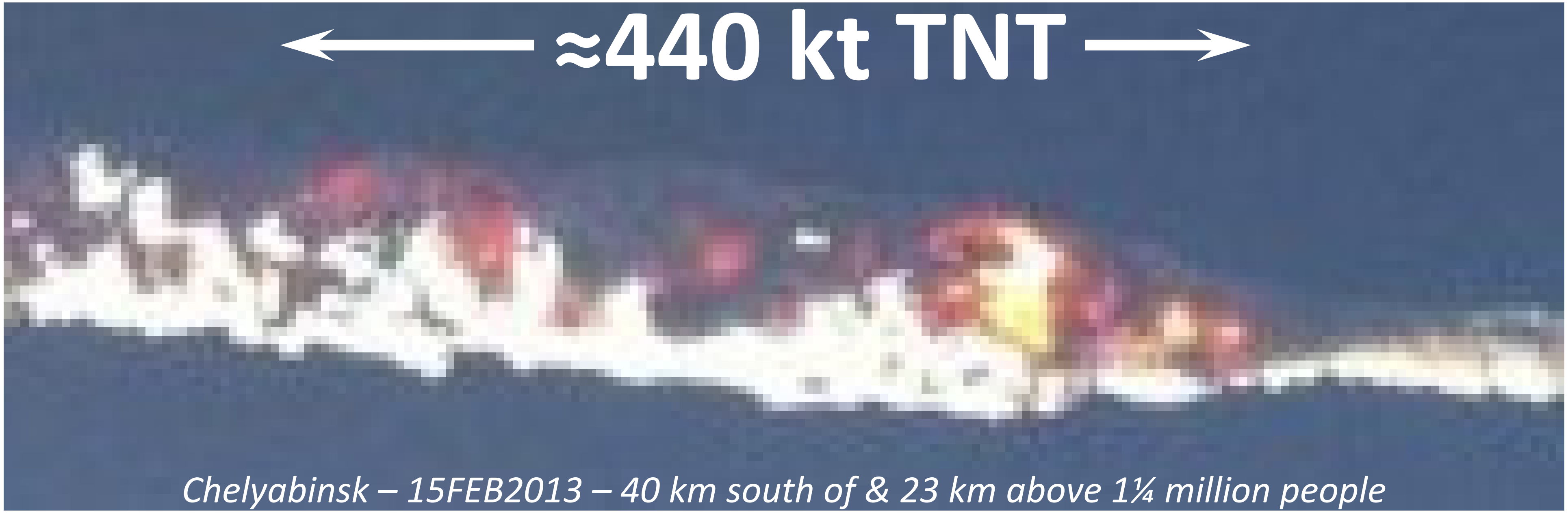


back-up slides – why we fly


Prologue
A Winter Fairy Tale…
…that really happened
CHELYABINSK.RU


Добро пожаловать в мир знаний!
ДЗЮДО
... ?? ... fairy tale !?!


… Yes.
… why?



…and no-one got killed…

…neither immediately nor by delayed effects; but: 2 heavily injured, 112 hospitalized for treatment, in total 1491 seen by medical staff, of which *only* 311 were children
6040 appartment blocks, 718 educational institutions, 293 hospitals and polyclinics, 100 cultural institutions, 43 sports sites damaged to require urgent repairs, renovation, restoration

city heating network –at daily maximum temperatures of -15ºC and windows smashed in thousands of buildings– did *not* collapse

…and all around, >100 km of blue icy-clear morning sky just before sunrise

asteroids matter.

…so let‘s go see some…

DLR