ASIME2016 – Session II

Small Spacecraft Solar Sail Missions for Multiple Near-Earth Object Prospection: Remote Sensing, In-Situ Characterization and Sample Return

Jan Thimo Grundmann[a*], Peter Spietz[a], Patric Seefeldt[a], Tom Spröwitz[a], Bernd Dachwald[b]

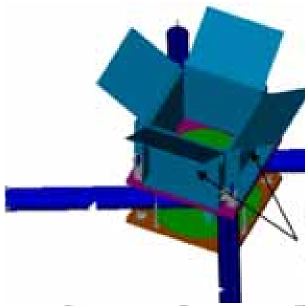
[a]DLR German Aerospace Center, Institute of Space Systems, Robert-Hooke-Strasse 7, 28359 Bremen, Germany
– * jan.grundmann@dlr.de, Tom.Sproewitz@dlr.de, Patric.Seefeldt@dlr.de, Peter.Spietz@dlr.de
[b]Faculty of Aerospace Engineering, FH Aachen University of Applied Sciences, Hohenstaufenallee 6, 52064 Aachen, Germany;
dachwald@fh-aachen.de

DLR

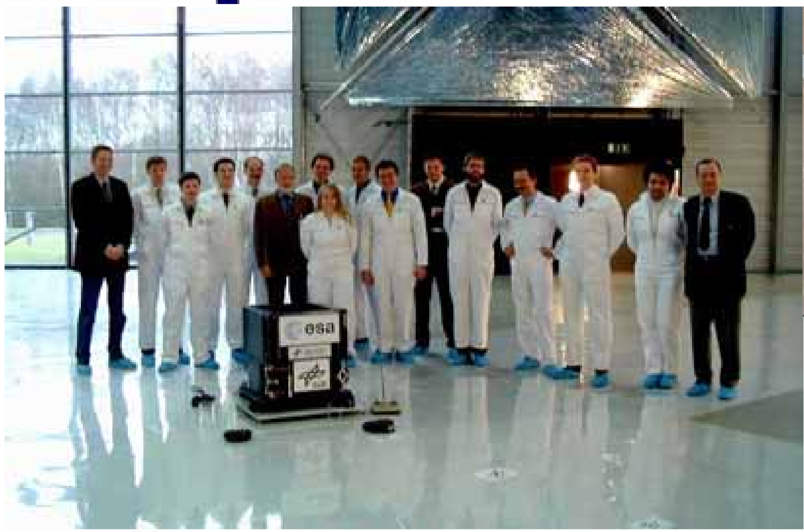
The December 7th,1999 DLR/ESA Solar Sail Ground Demonstration

(20 m)² push-out boom, hoisted sail

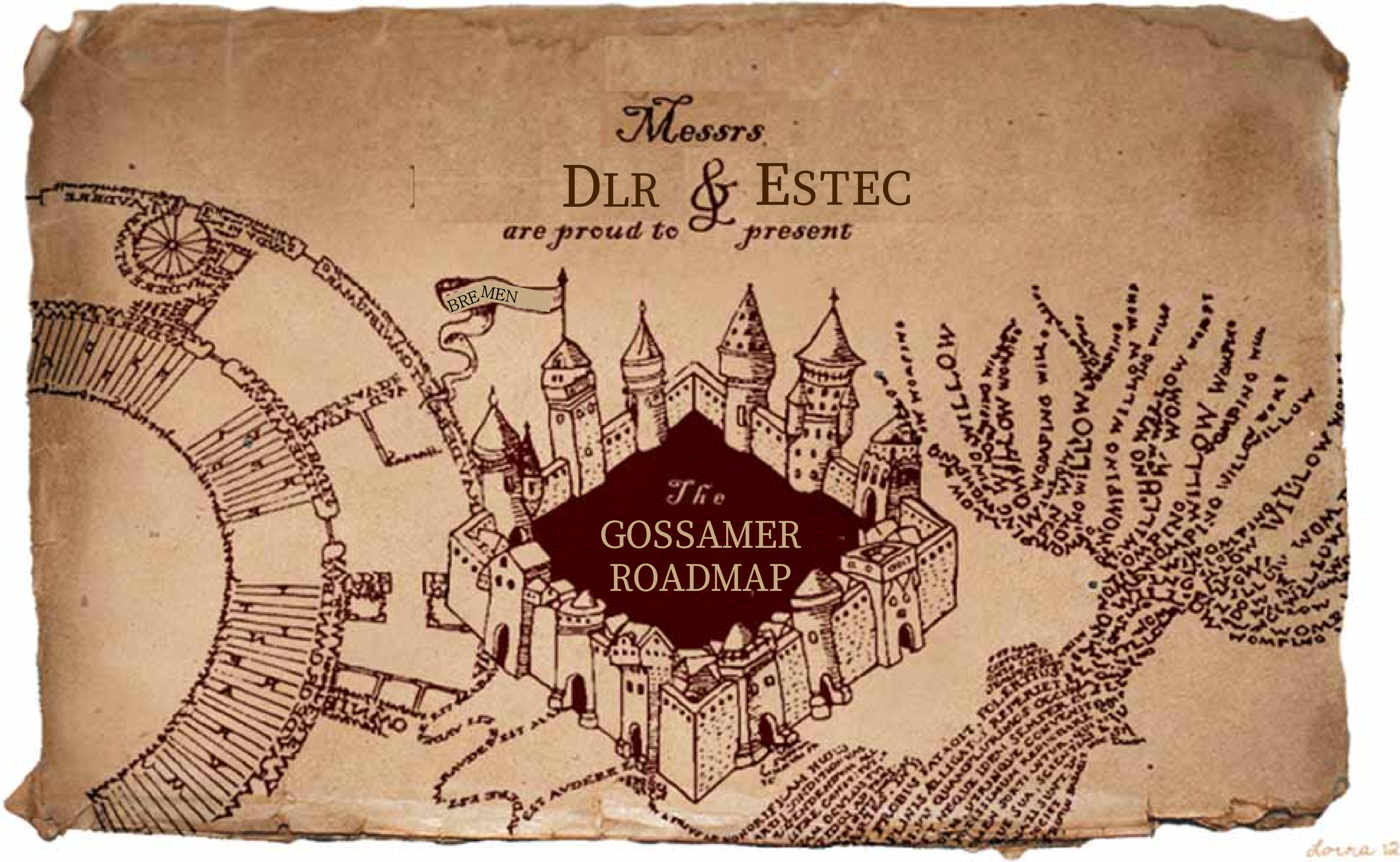
- you need space – the European Astronaut Center hall next to the ISS model

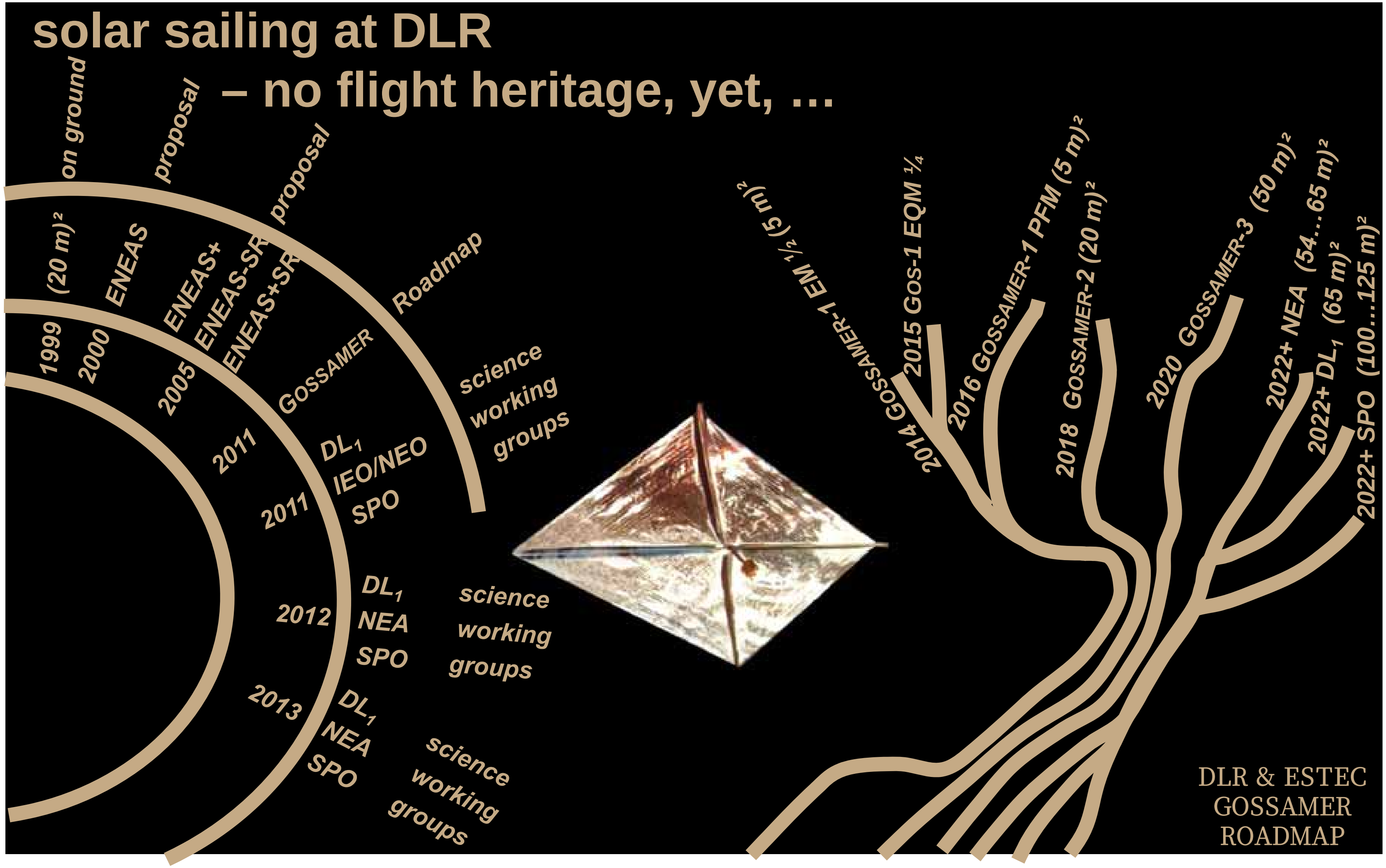


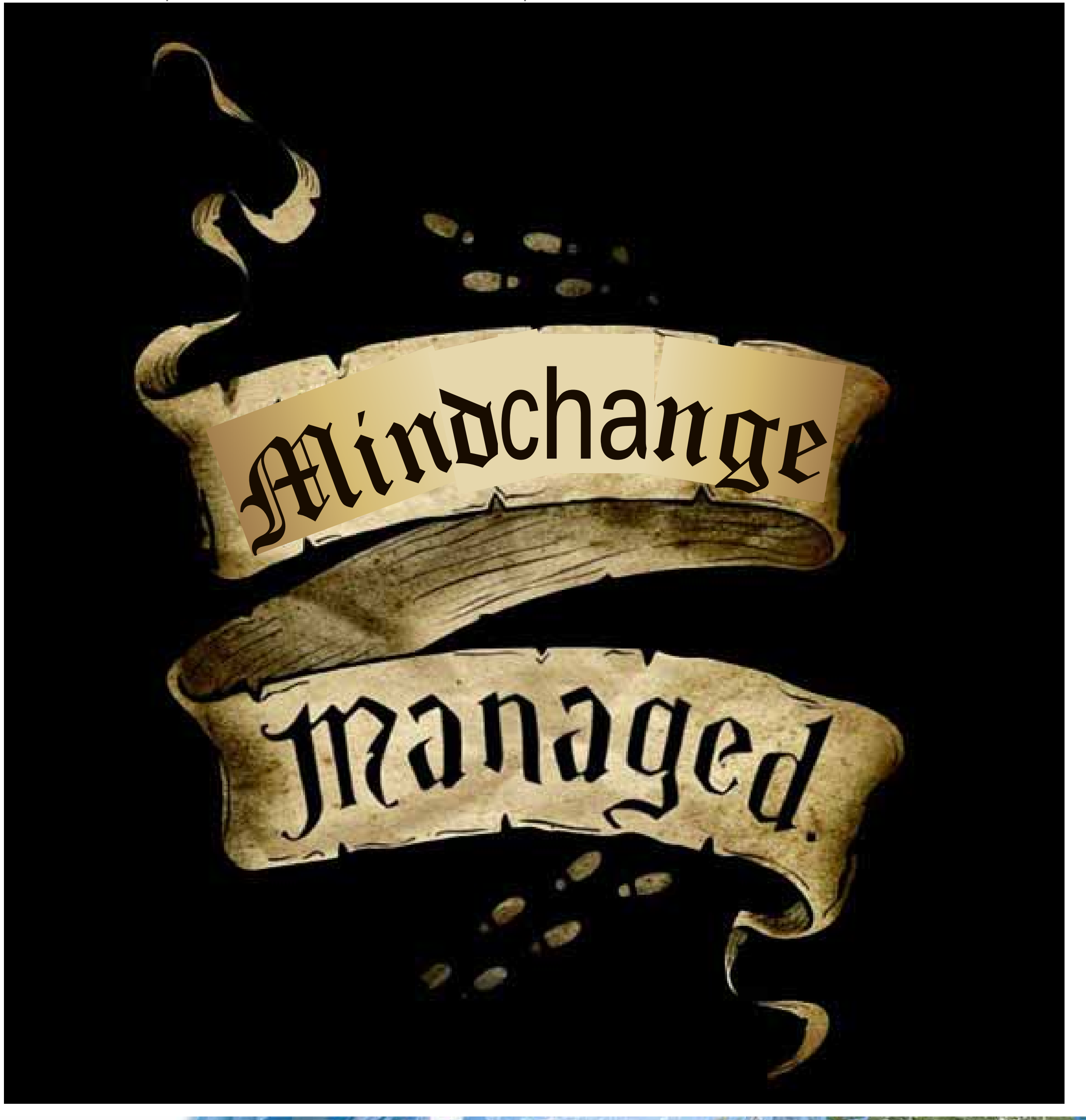
  - Deployment Module: 24 kg
  - CFRP booms (4 x 14m, 101 g/m): 6 kg
  - Sails (20 m)², 4-12 µm foil: 5 kg
  - Dimensions: 60cm x 60 cm x 65cm

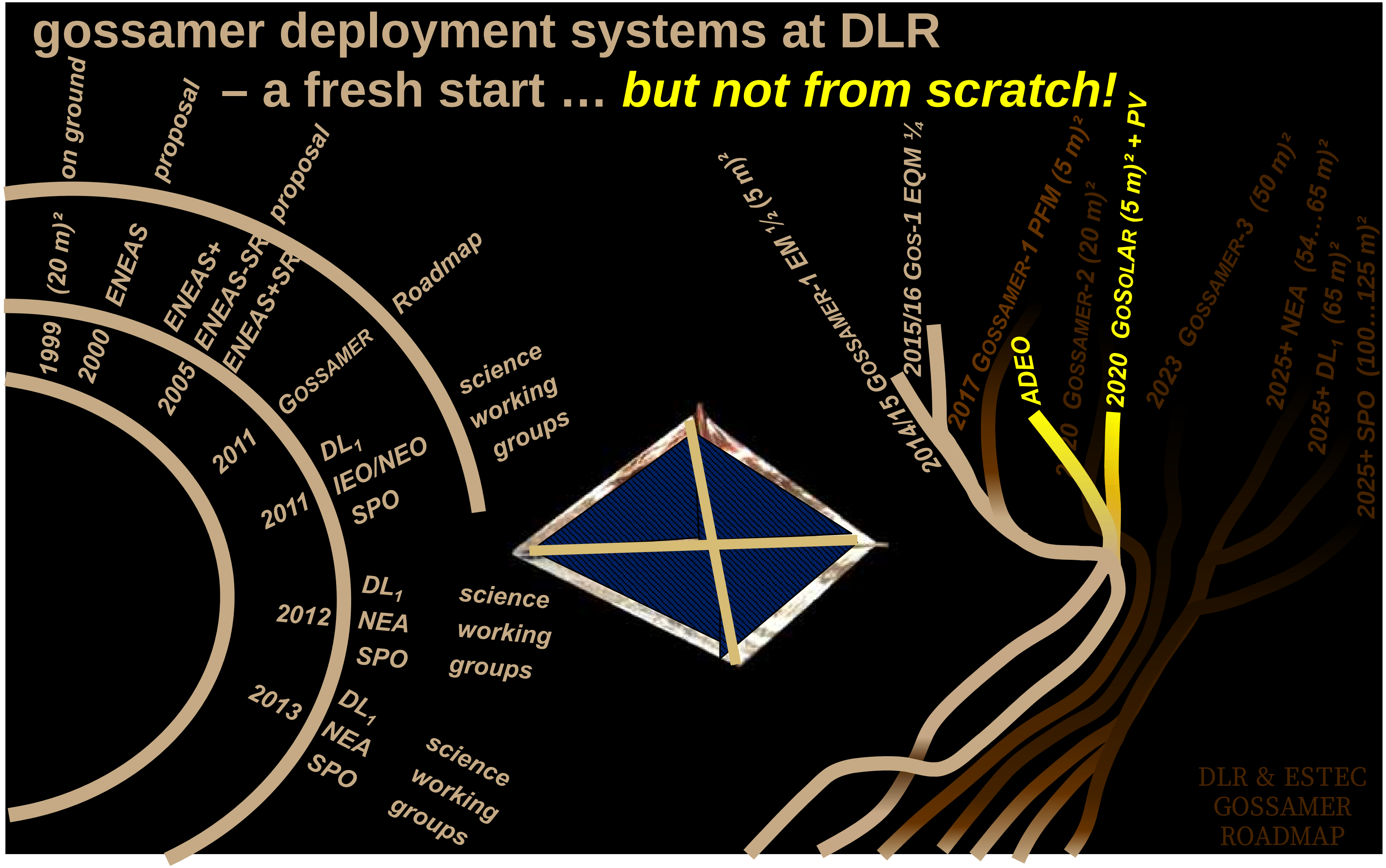


DLR


Messrs
DLR & ESTEC
are proud to present
BREMEN
The
GOSSAMER
ROADMAP
dorna 12


solar sailing at DLR
– no flight heritage, yet, …
1999 (20 m)²
on ground
2000 ENEAS
proposal
2005 ENEAS+
ENEAS-SR
ENEAS+SR
proposal
2011 GOSSAMER
Roadmap
2011 DL₁
IEO/NEO
SPO
science
working
groups
2012 DL₁
NEA
SPO
science
working
groups
2013 DL₁
NEA
SPO
science
working
groups
2014 GOSSAMER-1 EM ½ (5 m)²
2015 Gos-1 EQM ¼
2016 GOSSAMER-1 PFM (5 m)²
2018 GOSSAMER-2 (20 m)²
2020 GOSSAMER-3 (50 m)²
2022+ NEA (54…65 m)²
2022+ DL₁ (65 m)²
2022+ SPO (100…125 m)²
DLR & ESTEC
GOSSAMER
ROADMAP

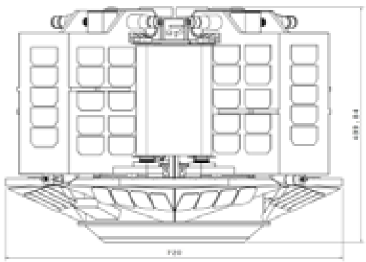

Mindchange
managed

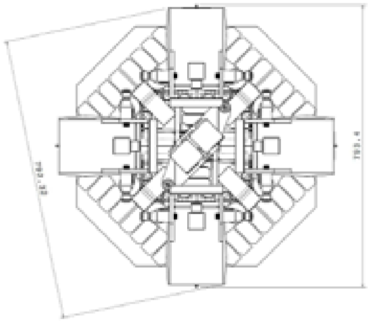

gossamer deployment systems at DLR
– a fresh start … but not from scratch!
1999 (20 m)² on ground
2000 ENEAS proposal
2005 ENEAS+ ENEAS-SR ENEAS+SR proposal
2011 GOSSAMER Roadmap
2011 DL1 IEO/NEO SPO
science working groups
2012 DL1 NEA SPO
science working groups
2013 DL1 NEA SPO
science working groups
2014/15 GOSSAMER-1 EM ½ (5 m)²
2015/16 GOS-1 EQM ¼
2017 GOSSAMER-1 PFM (5 m)²
ADEO
GOSSAMER-2 (20 m)²
2020 GOSOLAR (5 m)² + PV
2023 GOSSAMER-3 (50 m)²
2025+ NEA (54…65 m)²
2025+ DL1 (65 m)²
2025+ SPO (100…125 m)²
DLR & ESTEC
GOSSAMER
ROADMAP

The GOSSAMER Roadmap
step 1 – deployment

GOSSAMER-1 – in-orbit deployment demonstrator

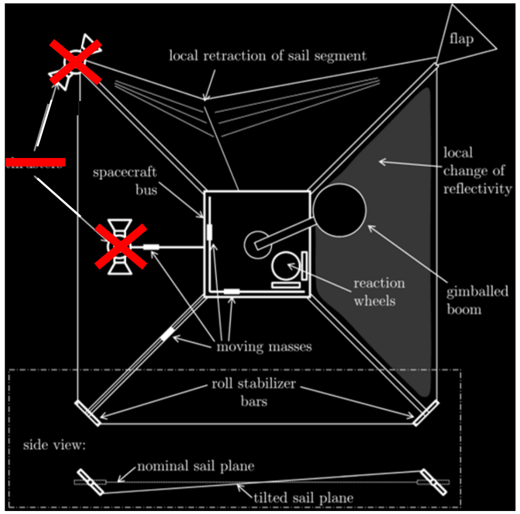
- (5 m)² sail area, all deployment-related mechanisms
- 1-boom, 2-quadrant EM in operation →
- **1-boom EQM currently in extensive qualification testing**
- proven MASCOT-style concurrent AIV approach
- PFM detailed design was carried through beyond PDR
    - free-flyer independent spacecraft (really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

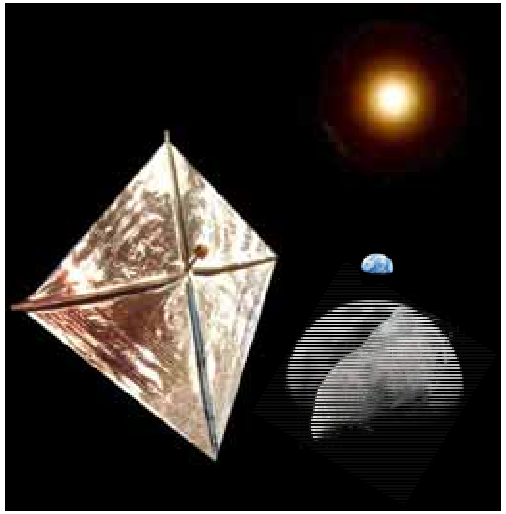




The GOSSAMER Roadmap

step 2 – control – step 3 – proving the principle





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

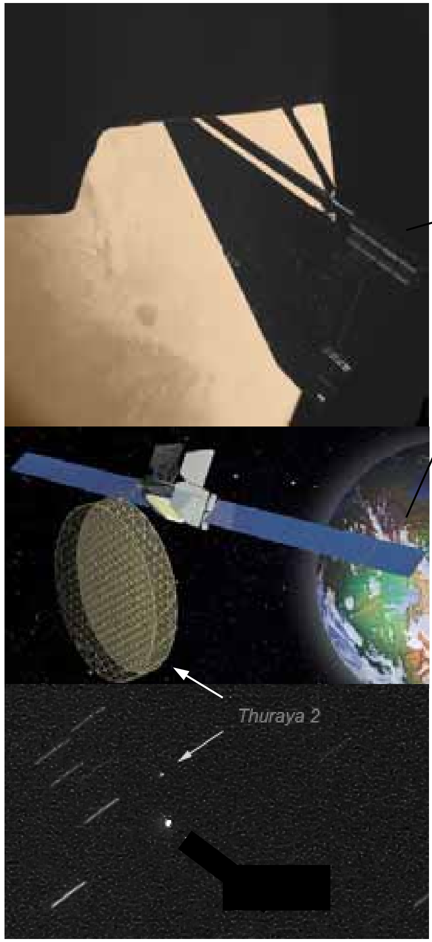
- (20 m)² sail area
- orbit where solar radiation pressure is dominant – high LEO, MEO, GTO
- implementation of several (all?) control methods and all relevant mechanisms
- **find out what's the best …**

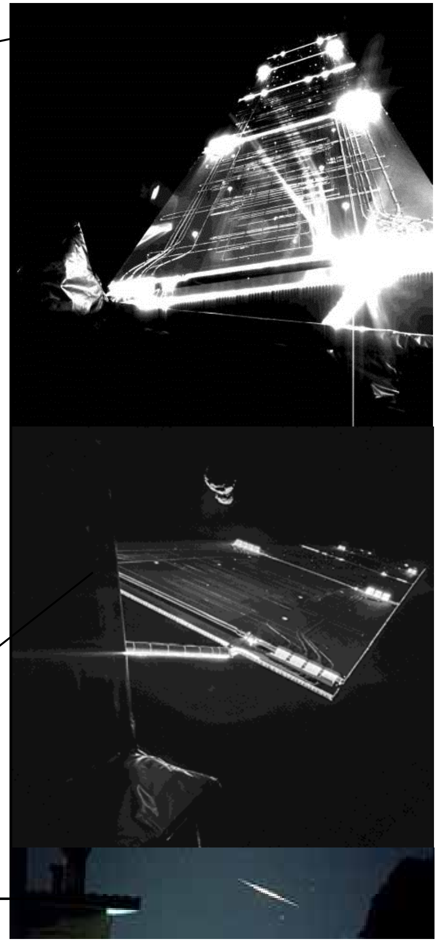
GOSSAMER-3 – all-up proof test, science mission readiness demonstrator

- (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

additional images: Moon: Jérôme Salez (wiki), Earth: Bill Anders, Apollo 8, NASA

GOSSAMER-3 key mission events: proving the principle





minimum mission
- get launched cheap, deploy & spiral up
- explore & improve sailing skills around Earth
- fly-by visit a target on time & look at it right

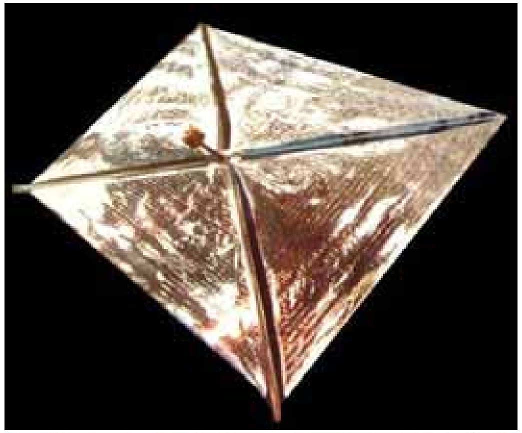
nominal mission
- explore practical flying in Earth-Moon system
- “all-up” navigation accuracy proof test
- low-altitude lunar gravity-assist fly-by

extended mission
- transfers to Earth-Sun L_1, L_2, or pole-sitter
- demonstrate spaceweather Displaced- L_1

extended extended mission
- fly out to a convenient NEA – coorbital?
- rendezvous & drop…
- …some grand finale…

additional images: Boeing BSS via Gunter's SP, M. Langbroek

GOSSAMER-3 sail propulsion system quality assurance – sail monitoring, pointing verification



GOSSAMER-3 – engineering instruments envisaged

a *tiny* **science**(…-like) payload to **observe sail ageing**

- wide-angle camera to observe **sail deployment and long-term foil behaviour** and provide **proof images for attitude control, pointing stability & accuracy**
- sensor to observe **interaction of a sail with solar wind's & geomagnetic field**
- sensor to observe **plasma, particle and energetic radiation sail environment**
- sensor to observe **large area foil reflectivity ageing**, e.g. **thermal equilibrium**
- sensor to observe **small-scale space weathering mechanisms of foil ageing**
- sensor to observe **core spacecraft (electronics)** electro**magnetic signature**
- sensor to observe **illumination changes and Sun glints off the sail surface**
- sensor to register **space debris and natural dust impacts on the sail foil**

- *note* that science only comes aboard where and only as far as sail technology development requirements create the instrument infrastructure – as **dual use**

DLR

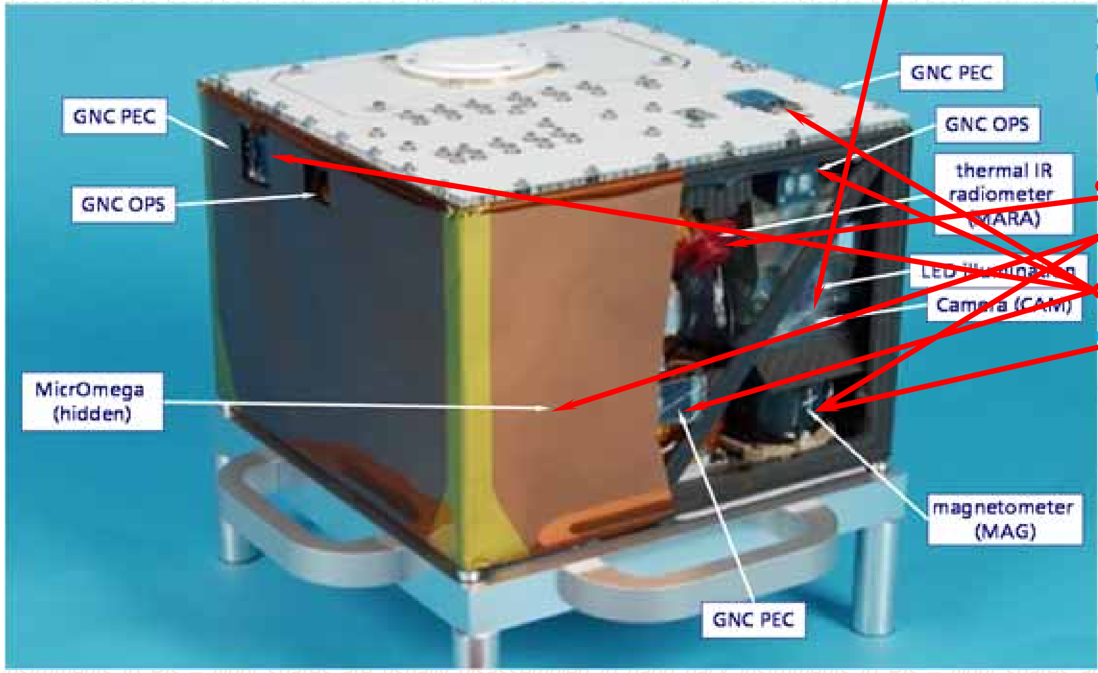
flight spares are usually disassembled to hand back instruments to PIs –

GOSSAMER-3 sail propulsion system quality assurance – cheap instruments package wanted, some wear o.k. ;-)

MASCOT instruments capabilities

a *tiny*(…-like ;-) science payload to observe sail ageing

- wide-angle camera to observe sail deployment and long-term foil behaviour and provide proof images for attitude control, pointing stability & accuracy



interaction of a sail with solar wind's & geomagnetic field

plasma, particle and energetic radiation sail environment

large area foil reflectivity ageing, e.g. thermal equilibrium

small-scale space weathering mechanisms of foil ageing

core spacecraft (electronics) electromagnetic signature

illumination changes and Sun glints off the sail surface

space debris and natural dust impacts on the sail foil

GOSSAMER-3 instruments left to be added

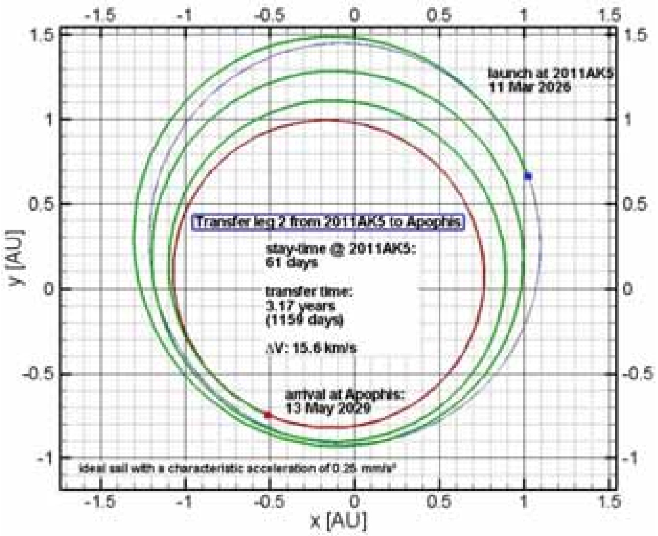
- ⊕ additional MAG instrument, 2 sensors spaced by ~1 m at 1 or 2 boom ends
- ⊕ e.g. Spherical EUV and Plasma Spectrometer (SEPS), 2 on opposite booms
- ⊕ DLR SOLID instrument, and/or e.g. acoustic pick-ups at rigging nodes, structural vibration accelerometers (upgrade of GOSSAMER-1 sensor)

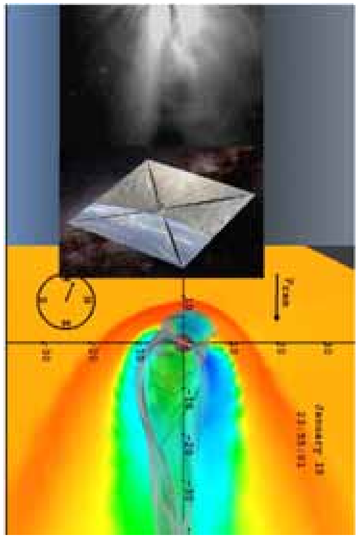
bottom line: been there, done that… ;-)

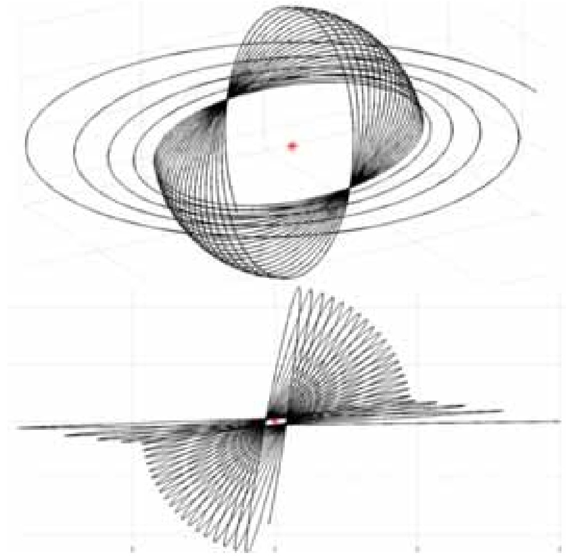
DLR

…and beyond…

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







MULTIPLE NEO RENDEZVOUS

- $(54\ldots65\ \mathrm{m})^2$ sail area
- triple pre-selected NEA rendezvous with stationkeeping + NEO fly-bys of opportunity
- $0.3\ \mathrm{mm/s^2}$, 10 years lifetime
- 40…60 kg bus, 12 kg science
- 3 small drop-probes, imager, Vis-NIR spectro, radiometer

SOLAR TSUNAMI EARLY WARNING SYSTEM

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

SOLAR POLAR ORBITER

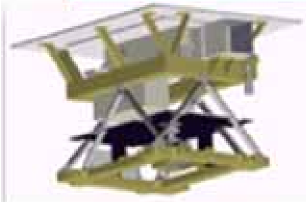
- $(100\ldots125\ \mathrm{m})^2$ sail area
- 10 years at DL_1 at $2 \cdot L_1$
- $0.29\ldots0.54\ \mathrm{mm/s^2}$, 2.5 µm foil
- 250…510 kg deployed sailcraft, 5 / 15 / 40 kg science
- Total Solar Irradiance, Doppler & Stokes imager, coronagraph wind, fields & particles

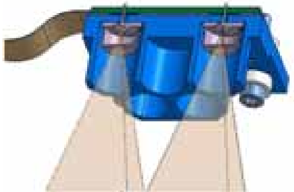
NEO trajectory plots: B. Dachwald et al.
storm & mag.sphere: V. Bothmer et al.
inc-up plot: M. Macdonald et al

Multiple NEO Rendezvous reference mission*

SCIENCE REQUIREMENTS

- rendezvous ≥3 NEO with a…
    - stay time ≈a fews days, >1 rotation
    - distance < 10 object diameters
    - rendezvous or very slow fly-by
- support several intermediate NEO fly-bys
    - if possible within design lifetime
    - including fast fly-bys
- support state-of-the art science payload →
- support observations at low…moderate solar phase angle
    - significant agility, attitude & trajectory control near the target
- provide 3-axis stabilized non-spinning platform for body-mounted instruments
- mission design lifetime: 10 years
- support data generation rate ≈100 Mbyte/d





MODEL PAYLOAD

- Multispectral Imager ≤ 5 kg
    - 7 filters + clear
    - ≈5.5° field of view
    - similar to Dawn Frame Camera
- Point Spectrometer Vis-NIR ≤ 3 kg
    - for near-infrared mineralogy
    - similar to Dawn VIR mapping sp‘m
- Infrared Radiometer < 1 kg
    - thermal surface characteristics
    - similar to MASCOT MARA (0.26 kg)
- 3 small drop-probes < 1 kg, each
    - measure free-fall descent velocity profile
    - target marking
    - based on CubeSat standard

* B. Dachwald, H. Boehnhardt, U. Broj, U.R.M.E. Geppert, J.T. Grundmann, W. Seboldt, P. Seefeldt, P. Spietz, L. Johnson, E. Kührt, S. Mottola, M. Macdonald, C.R. McInnes, M. Vasile, R. Reinhard, Gossamer Roadmap Technology Reference Study for a Multiple NEO Rendezvous Mission, Advances in Solar Sailing, Springer Praxis 2014, pp 211-226.

Multiple NEO Rendezvous reference mission*

TARGET SELECTION

- no science preferences or priorities (*sic!*)
    - all asteroids visited so far were diferent

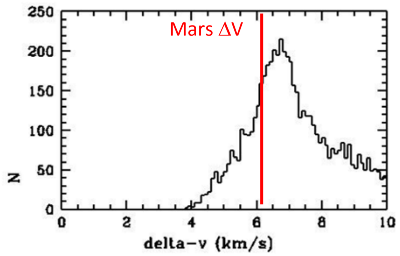
→ secondary interests taken into account:

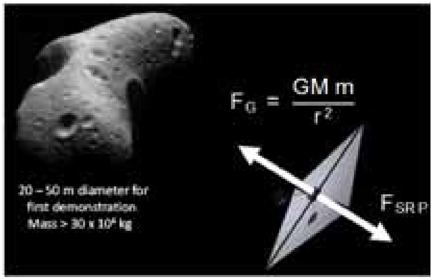
- human exploration targets
- planetary defence

1. ≥1 Potentially Hazardous Object (PHO) target
    - place a transponder
    - determine non-gravitational forces
2. ≥1 from NASA target list for crewed expeditions
    - study suitability for a crewed visit
3. last object should be very small, Ø20…50 m
    - place a transponder
    - demonstrate gravity tractor
    - may be continued as long as sail operational

REFERENCE TARGETS

- 2004 GU_9, a =1.001, e=0.136, Ø 170…380 m, PHO
- 2001 QJ_{142}, a =1.062, e=0.086, Ø 50…120 m, PHO, C
- 2006 QQ_{56}, a =0.985, e=0.046, Ø 10… 40 m, subPHO





REFERENCE MISSION

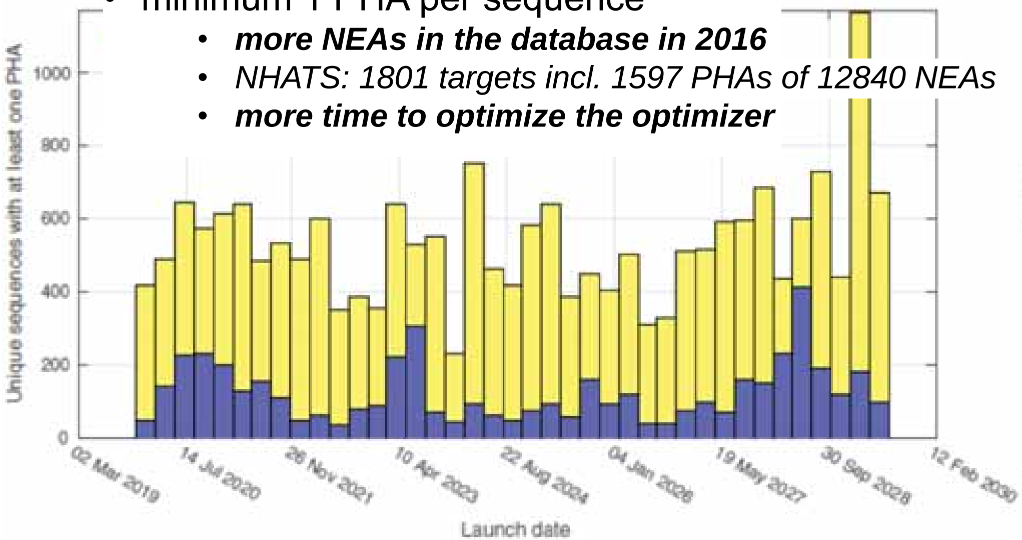
- 28 Nov 2019 – launch to C_3 = 0 km²/s² – 1111 d flight
- 13 Dec 2022 – 2004 GU_9 arrival – 113 d stay
- 05 Apr 2023 – 2004 GU_9 departure – 1396 d flight
- 30 Jan 2027 – 2001 QJ_{142} arrival – 90 d stay
- 30 Apr 2027 – 2001 QJ_{142} departure – 635 d flight
- 24 Jan 2029 – 2006 QQ_{56} arrival – stay
- 28 Nov 2029 – 10-year mark passed – 308 d margin
- 29 Nov 2029 – extended mission begins…

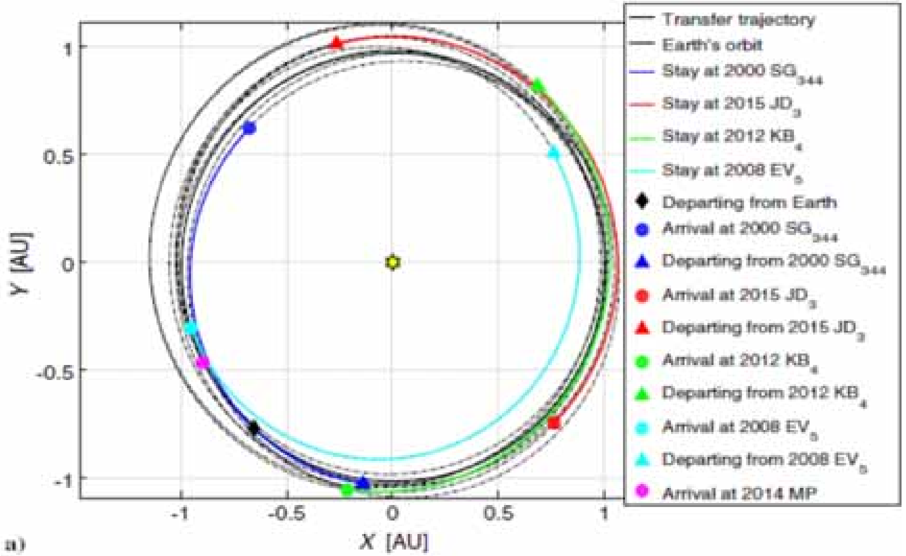
* B. Dachwald, H. Boehnhardt, U. Broj, U.R.M.E. Geppert, J.T. Grundmann, W. Seboldt, P. Seefeldt, P. Spietz, L. Johnson, E. Kührt, S. Mottola, M. Macdonald, C.R. McInnes, M. Vasile, R. Reinhard, Gossamer Roadmap Technology Reference Study for a Multiple NEO Rendezvous Mission, Advances in Solar Sailing, Springer Praxis 2014, pp 211-226.

NEO trajectory plots:
B. Dachwald et al.,

many more asteroids by much-more-than-nice-to-have science – a NAV update…****

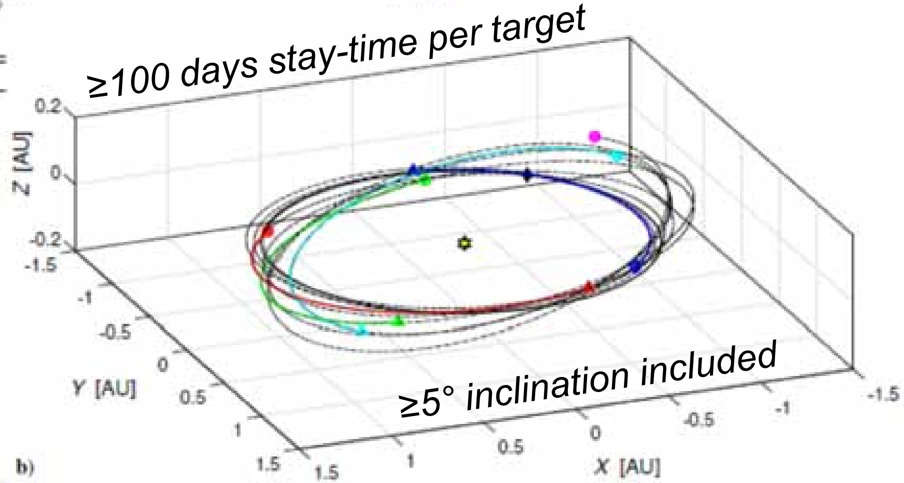
- 4800 sequences to 5 of 1801 asteroids in 10 years @ **0.2 mm/s²**
  - **MNR: 0.3 mm/s²**
- minimum 1 PHA per sequence
  - ***more NEAs in the database in 2016***
  - *NHATS: 1801 targets incl. 1597 PHAs of 12840 NEAs*
  - ***more time to optimize the optimizer***





a)

Object	Stay time, days	Start	End	Time of flight, days
Earth	—			
		10 May 2025 (30 April 2025)	26 Feb. 2027 (11 March 2027)	657 (680)
2000 SG$_{344}$	123 (100)			
		29 June 2027 (19 June 2027)	06 Sept. 2028 (31 Oct. 2028)	436 (500)
2015 JD$_3$	164 (100)			
		18 Feb. 2029 (08 Feb. 2029)	24 Sept. 2030 (14 Nov. 2030)	584 (644)
2012 KB$_4$	160 (100)			
		04 March 2031 (22 Feb. 2031)	29 Sept. 2032 (30 Nov. 2032)	576 (647)
2008 EV$_5$	171 (100)			
		20 March 2033 (10 March 2033)	30 Sept. 2034 (25 Nov. 2034)	560 (625)
2014 MP	—			



b)

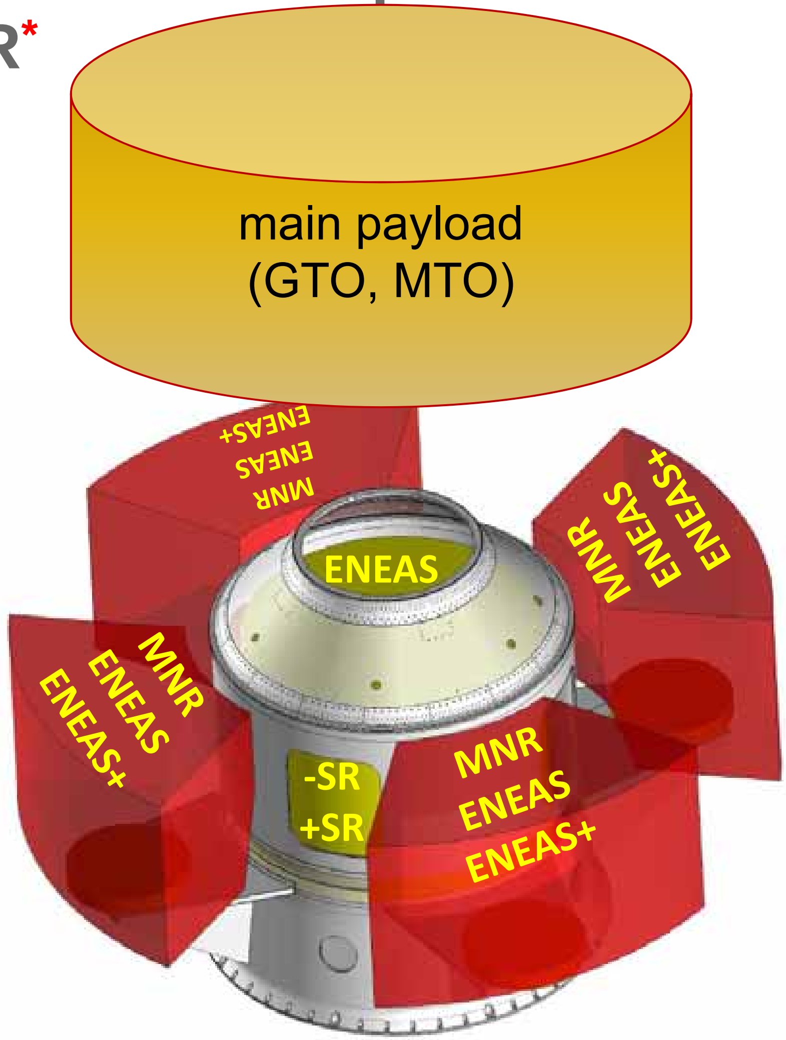
**** A. Peloni, M. Ceriotti, B. Dachwald, Solar-Sail Trajectory Design for a Multiple Near-Earth-Asteroid Rendezvous Mission, Journal of Guidance, Control, and Dynamics, 2016-09, DOI: 10.2514/1.G000470

NEO trajectory plots: A. Peloni et al.,

ENEAS Single/Multiple NEO Rendezvous/Sample-Return mission family** compared to MNR*

Mission	Objective	NEO target bodies	Mission duration [yr]
ENEAS	1 × rendezvous	1996 FG_3	4.2
ENEAS-SR	1 × sample return	1996 FG_3	10.0
MNR	3 × rendezvous	2004 GU_9, 2001 QJ_{142}, 2006 QQ_{56}	9.8
ENEAS+	3 × rendezvous	2000 AG_6, 1989 UQ, 1999 AO_{10}	7.6
ENEAS+SR	3 × sample return	2000 AG_6, 1989 UQ, 1999 AO_{10}	10.1

Mission	Payload [kg]	Sail size [m]	Sail assembly loading [g/m²]	Char. acc. [mm/s²]	Launch mass [kg]
MNR	40…60	54…65		0.3	≤200
MNR (goal)		39…48		0.2	
ENEAS	75	50	30.0	0.140	148
ENEAS-SR	295	70	22.7	0.100	406
ENEAS+	75	70	22.7	0.218	186
ENEAS+SR	295	139	22.7	0.218	734

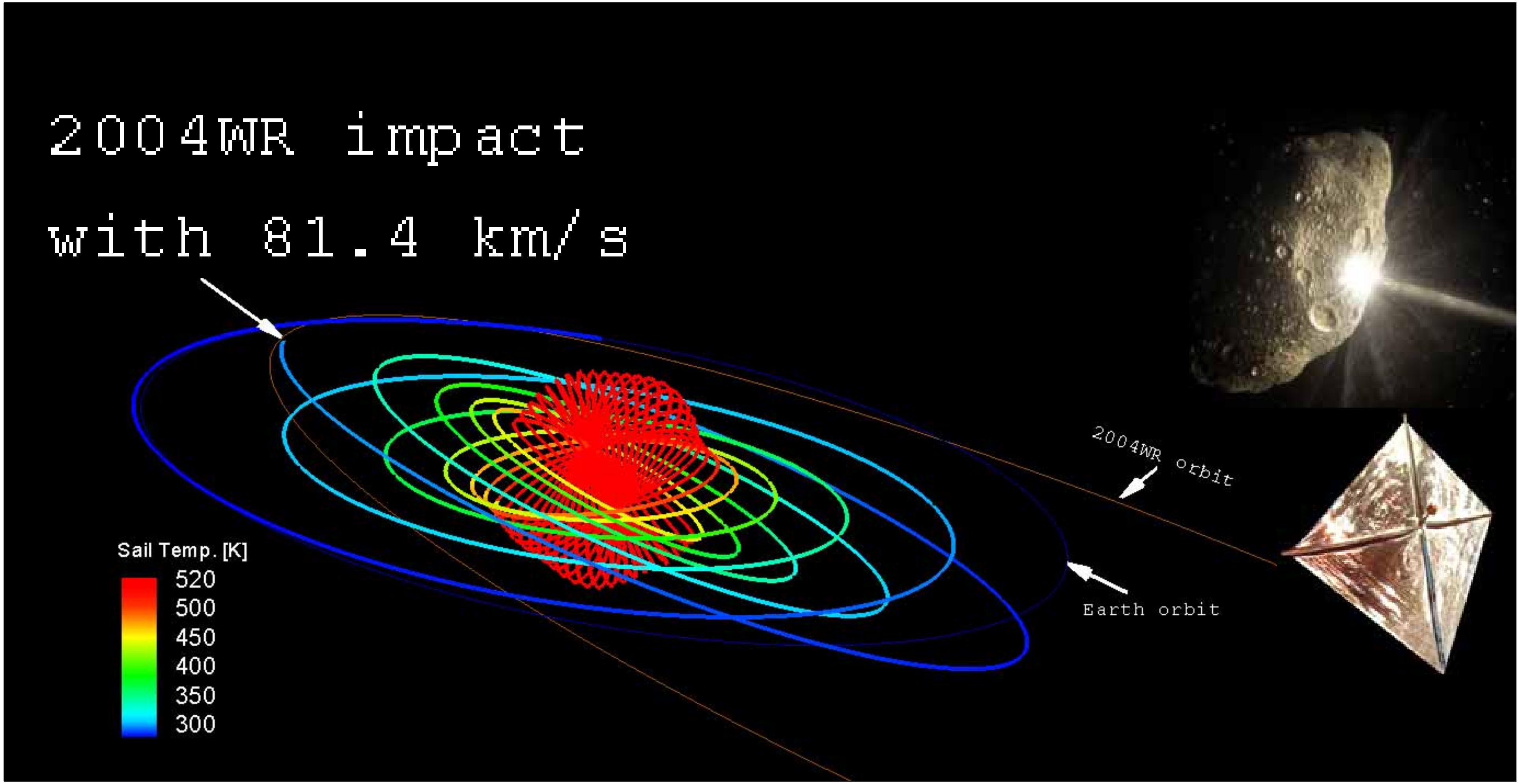


** B. Dachwald, W. Seboldt, Multiple near-Earth asteroid rendezvous and sample return using first generation solar sailcraft, Acta Astronautica, 57(11):864–875, 2005. – *after*:

* B. Dachwald, et al, Gossamer Roadmap Technology Reference Study for a Multiple NEO Rendezvous Mission, Advances in Solar Sailing, Springer Praxis 2014, pp 211-226.

NEO trajectory plots: B. Dachwald et al.,

"If I had a hammer…" ***



*** B. Dachwald, R. Kahle, B. Wie, Solar Sailing Kinetic Energy Impactor (KEI) Mission Design Tradeoffs for Impacting and Deflecting Asteroid 99942 Apophis, AIAA/AAS Astrodynamics Specialist Conference and Exhibit, AIAA 2006-6178.
B. Dachwald, R. Kahle, B. Wie, Head-On Impact Deflection of NEAs: A Case Study for 99942 Apophis, AIAA, Planetary Defense Conference 2007.
B. Dachwald, B. Wie, Solar Sail Kinetic Energy Impactor Trajectory Optimization for an Asteroid-Deflection Mission, Journal of Spacecraft and Rockets, Vol. 44, No. 4, July–August 2007, DOI: 10.2514/1.22586.

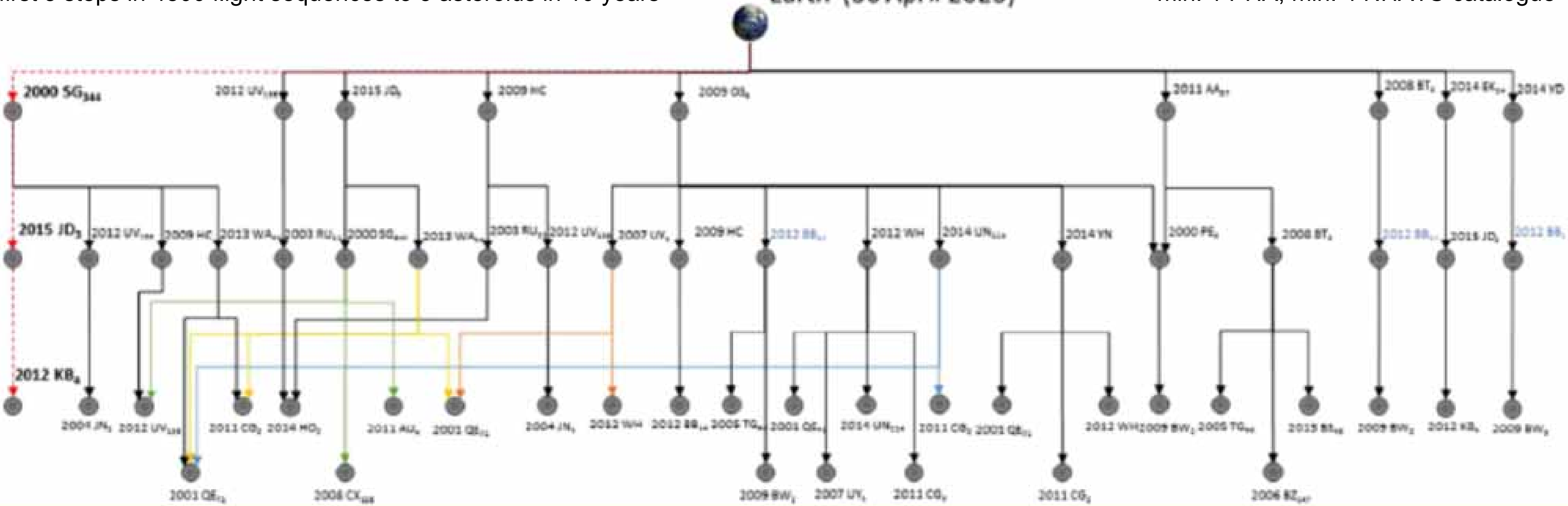
…I'D MAKE AN OUTCROP.

NEO trajectory plots: B. Dachwald et al.,
asteroid image: AIM ESA

EXERCISE – EXERCISE – EXERCISE – EXERCISE

Planetary Defence Conference Earth impactor response exercises 2013 & 2015

first 3 steps in 4800 flight sequences to 5 asteroids in 10 years **** Earth (30 April 2025) min. 1 PHA, min. 4 NHATS catalogue



If GOSSAMER-3 had been **launched** according to the last Roadmap baseline **in ~2020** we'd obviously be on the way to "**2015 PDC**".

If it had been "**2021 PDC"**, we'd also be on the way.

why?

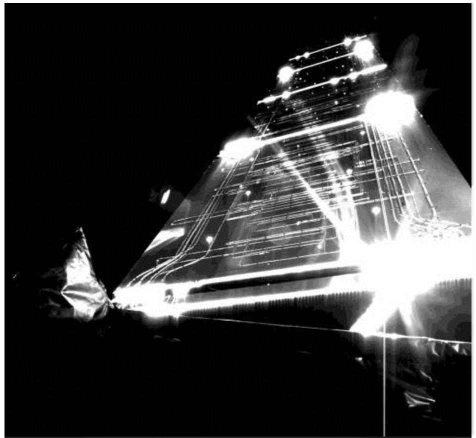
only Solar Sails can **change** interplanetary rendezvous **targets after launch** during cruise phase or other rendezvous in all cases

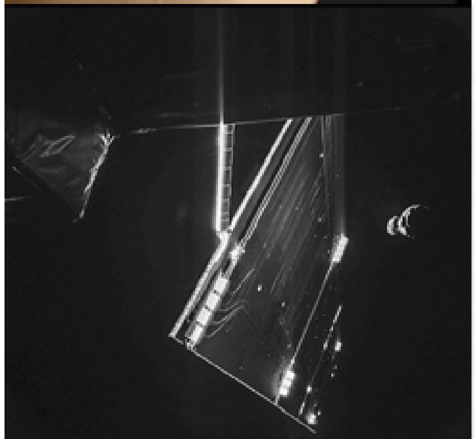
solar sails can follow the wind of change

**** A. Peloni, M. Ceriotti, B. Dachwald, Solar-Sail Trajectory Design for a Multiple Near-Earth-Asteroid Rendezvous Mission, Journal of Guidance, Control, and Dynamics, 2016-09, DOI: 10.2514/1.G000470

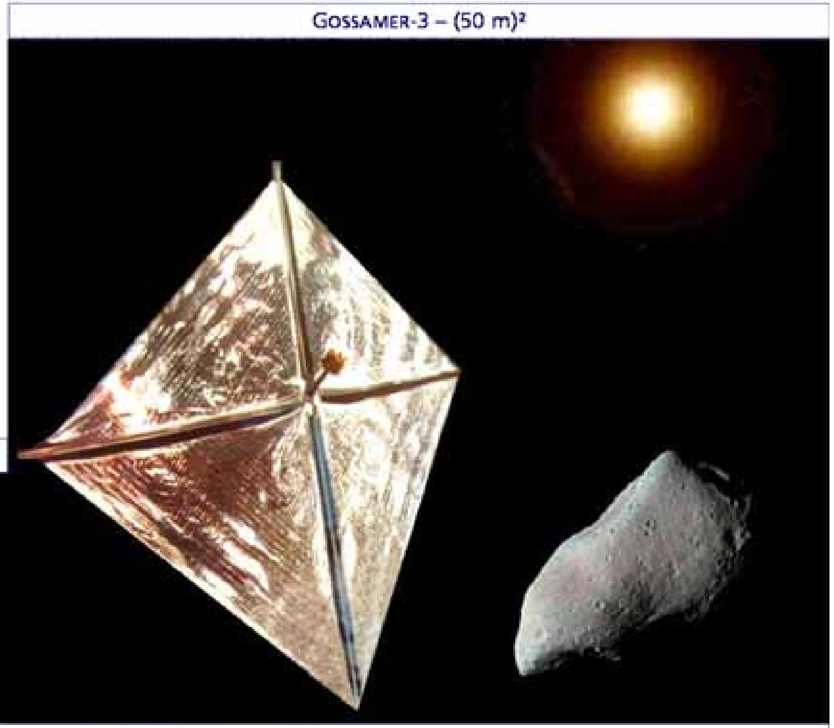
NEO trajectory plots: A. Peloni et al.,

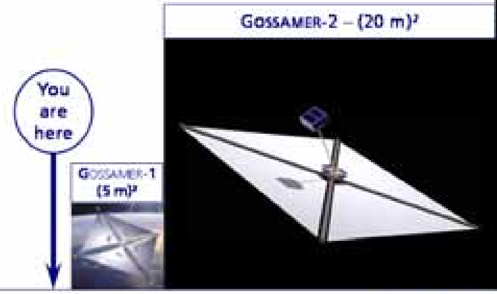
DLR

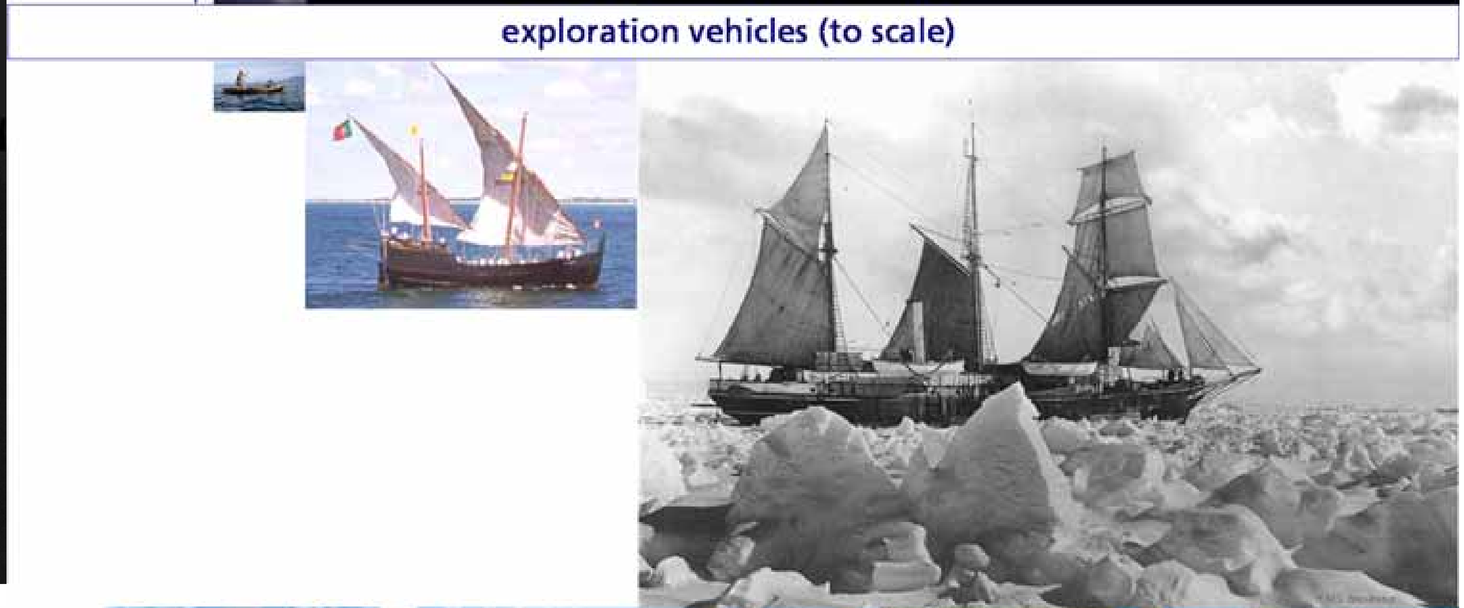




Questions? ☺


GOSSAMER-3 – (50 m)²


GOSSAMER-2 – (20 m)²
You are here
GOSSAMER-1 (5 m)²


exploration vehicles (to scale)