5th IAA Planetary Defense Conference – PDC 2017
15-19 May 2017, Tokyo, Japan

Soil to Sail – Asteroid Landers on Near-Term Sailcraft as an Evolution of the GOSSAMER Small Spacecraft Solar Sail Concept for In-Situ Characterization

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IAA-PDC-17-05-19

"When you've seen one asteroid,…
…you've seen *one* asteroid.

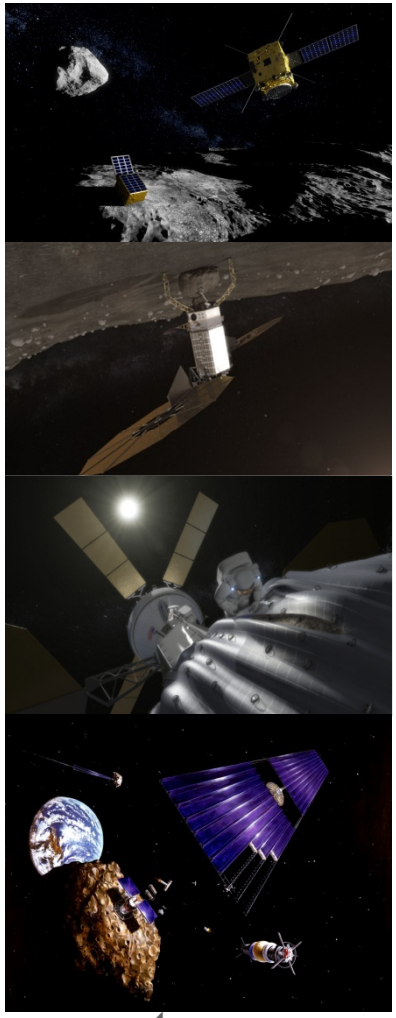
…even including comets! " ;-)

so far, every asteroid visited looks different from all the others

- approaches to classification:
  - spectral information → taxonomy ← ? → composition
  - shape & topography ← ? → interior structure → porosity
  - orbital dynamics ← families ← Yarkovsky → YORP ← ? ↑
- …*but*: all approaches see a little light at the end of the tunnel
  - taxonomy: obvious patterns but composition inferred ('TC_3)
  - shapes: radar (poor man's flyby) shows >1 "top-like", "cigar",…
  - orbits: long-term monitoring makes small Y*-effects quantifiable
- …*but*: all these dots & models still need to be connected

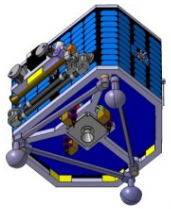
➔ need to study many more asteroids – close up, soon, affordable

the next step: ground truth



- current & future small solar system bodies science missions *all* require sample analysis and/or return
- non-sampling in-situ observations required to create context chain from soil to telescope
  - landing site panorama
  - thermal properties
  - local space weather
- ‘deep’ sounding desirable to extend context chain via the interior to collisional & orbital history
  - sub-surface sampling
  - tomography – radar, seismic
- in-situ resource utilization on the horizon
  - staking claims – be there, stay there
  - prospection – volatiles & minerals

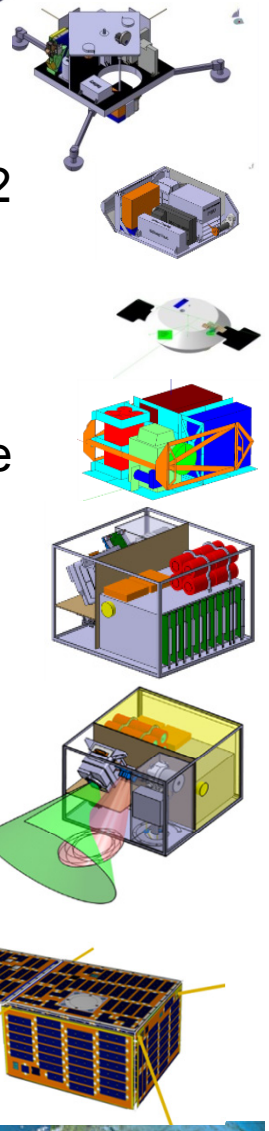
images: J.R.C. Garry for ISAS, ESA/DLR, JAXA, , NASA/GSFC/LM



what do we have to do it? – #1: Ho et al., 2016
MASCOT – Mobile Asteroid Surface Scout(s)

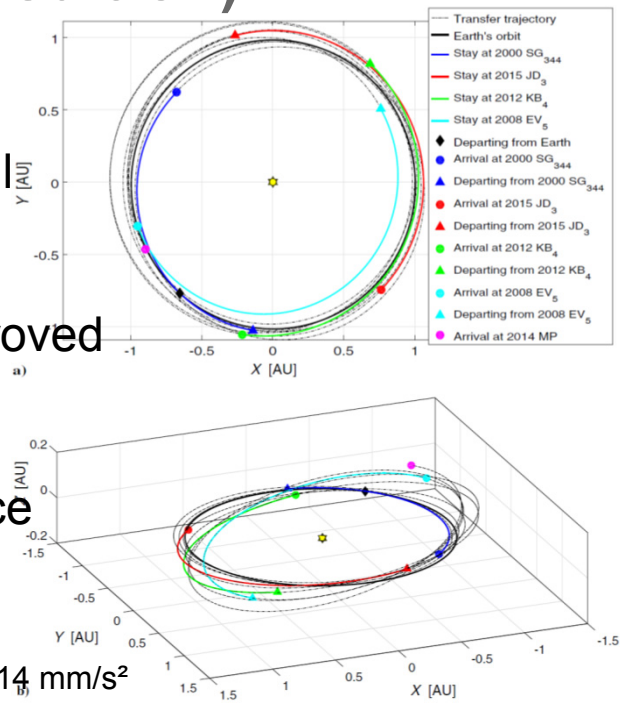
- currently in cruise to (162173) Ryugu aboard HAYABUSA2
- landing expected in October 2018
- with precursor studies, e.g. MARCOPOLO, and follow-on studies, e.g. MASCOT2 for AIM, a ready-to-go repertoire for many missions has been created

- lander at the instrument level of a mainstream mission
- high degree of design re-use
- high-density design
- serves 4 full planetary science quality instruments



what do we have to do it? – #2: Peloni et al., 2016 Multiple NEA Rendezvous (latest edition)

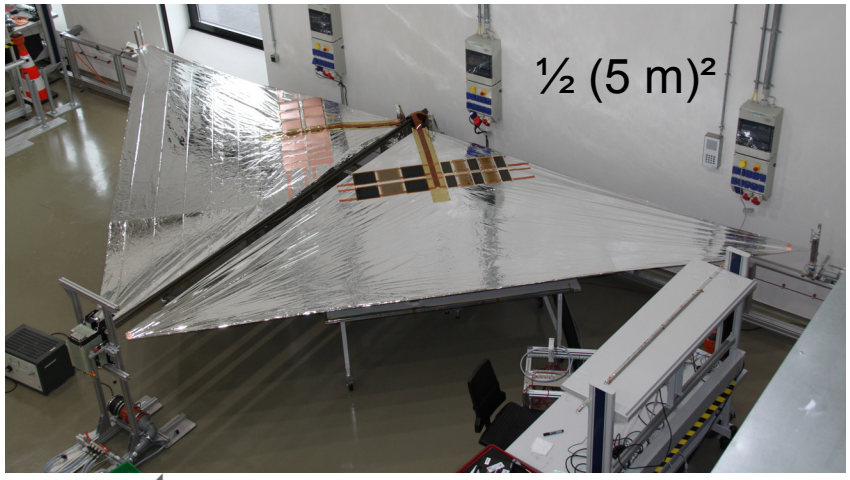
- Multiple NEA Rendezvous for planetary science was identified as a mission type only feasible with solar sail
- in the past 20 years,…
  - low-thrust trajectory optimization was greatly improved
  - many more NEAs discovered to pick targets from
  - sailcraft designs matured, tested, flown
  - better understanding of near-term sail performance

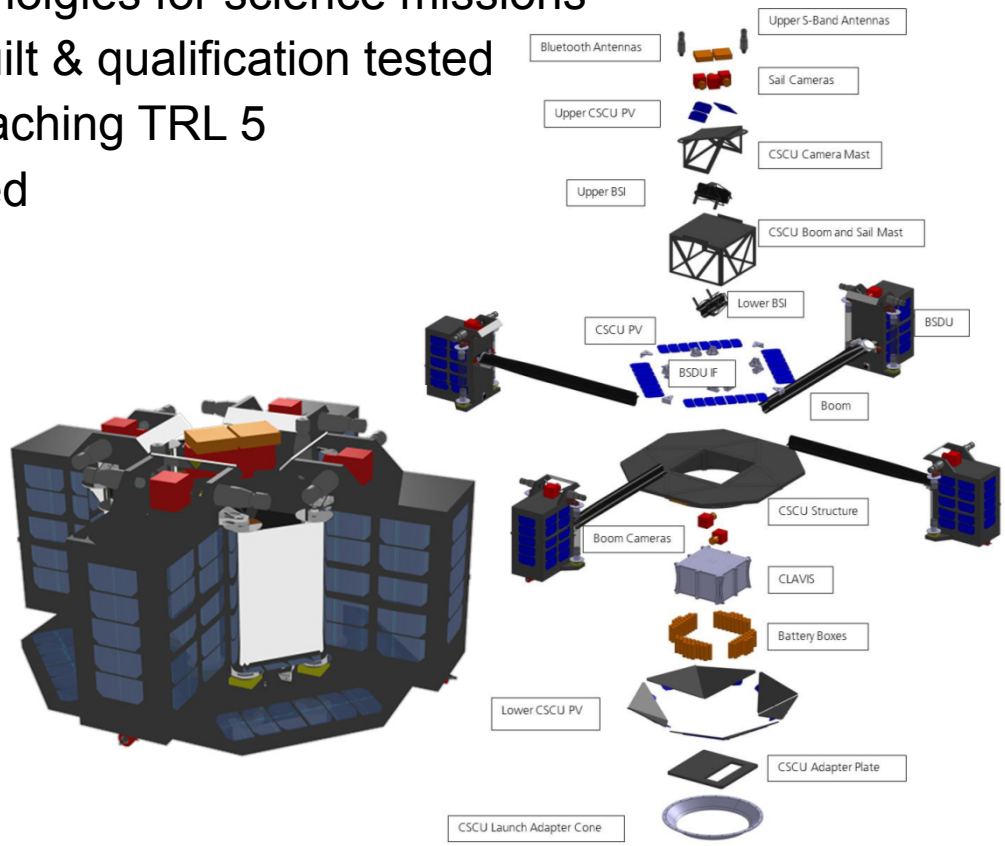


- DLR ENEAS study (2000) – 2 fast flybys & 1 rendezvous in 5 years – 0.14 mm/s²
- ENEAS-SR (2005) – 1 sample return of 117 days in 10 years – 0.10 mm/s²
- ENEAS+ / ENEAS+SR (2005) – 3 rendezvous/sample return in 10 years – 0.22 mm/s²
- GOSSAMER NEO reference (2011) – 3 very slow flyby-rendezvous >1 rotation in 10 years
- Johnson et al (2012) – 3 rendezvous of ~30 days in 6 years – 0.35 mm/s²
- GOSSAMER NEO reference (2014) – 3 rendezvous of ~100 days in 10 years – 0.20 mm/s²
- Peloni et al. (2016) – **5 rendezvous of >100 days in 10 years** – 0.20 mm/s²

what do we have to do it? – #3: Seefeldt et al., 2017 solar sail technology development (qualified)

- the 3-step DLR-ESTEC GOSSAMER Roadmap to Solar Sailing was set up in 2009 to develop key technolgies for science missions
- 1st step: GOSSAMER-1 EQM was built & qualification tested
- development was stopped after reaching TRL 5
- a PFM design was ready to proceed
- a launch opportunity was available
- all-launchers load envelope





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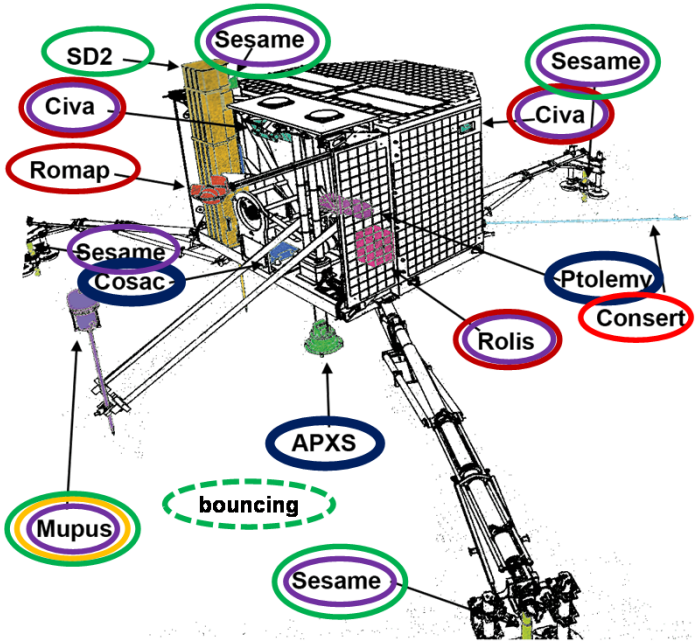
figures: Seefeldt et al., 2016/2017

compared to a real spacecraft… – can a 10 kg shoe-box address it all?



target body properties addressed…

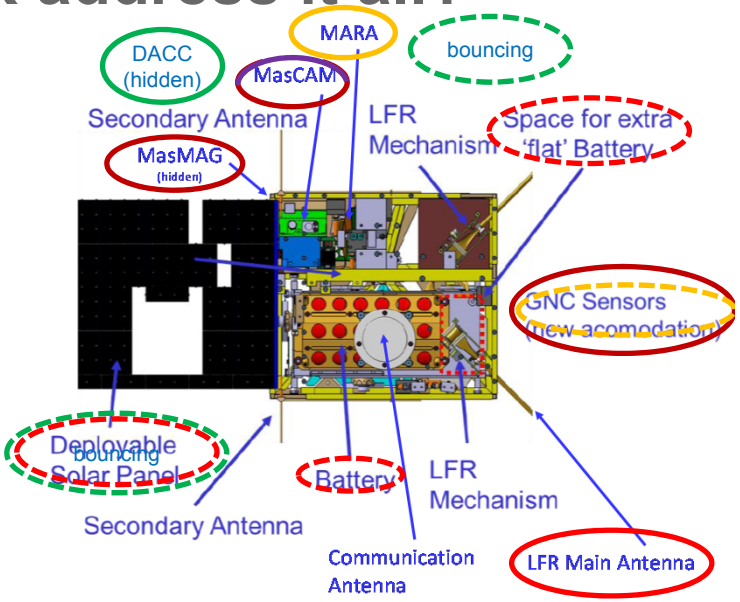
- surface structure
- composition
- mechanical properties
- thermal properties
- interior structure
- spacecraft orientation

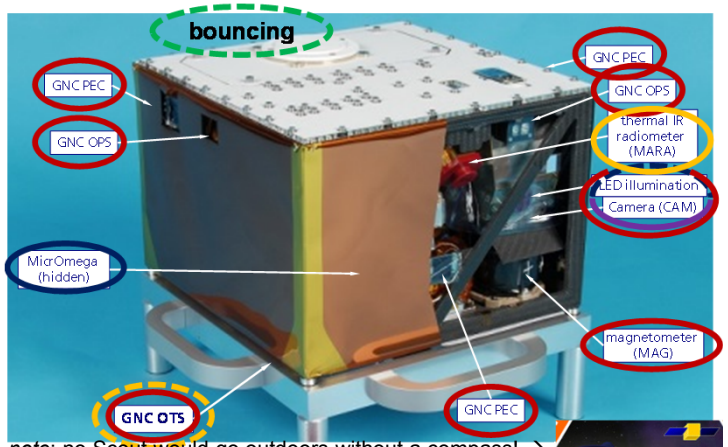
heritage landers:

- cover all fields
- medium-integrated design concept
- separate instrument interfaces 'as usual'
- requirements-driven design

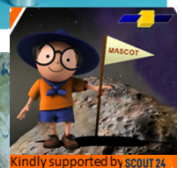
MASCOTs:

- focus on key topics
- organically integrated design
- across unit border optimized interfaces
- constraints-driven design





note: no Scout would go outdoors without a compass! →



low-thrust to so many targets in a row… – is this even a robust mission type or just a one-off?

even restricted to PHA & NHATS targets, only,…

- there are 100's of possible NEA sequences for each launch date
- targets can be changed any time while in cruise or rendezvous
- available sail technology is sufficient

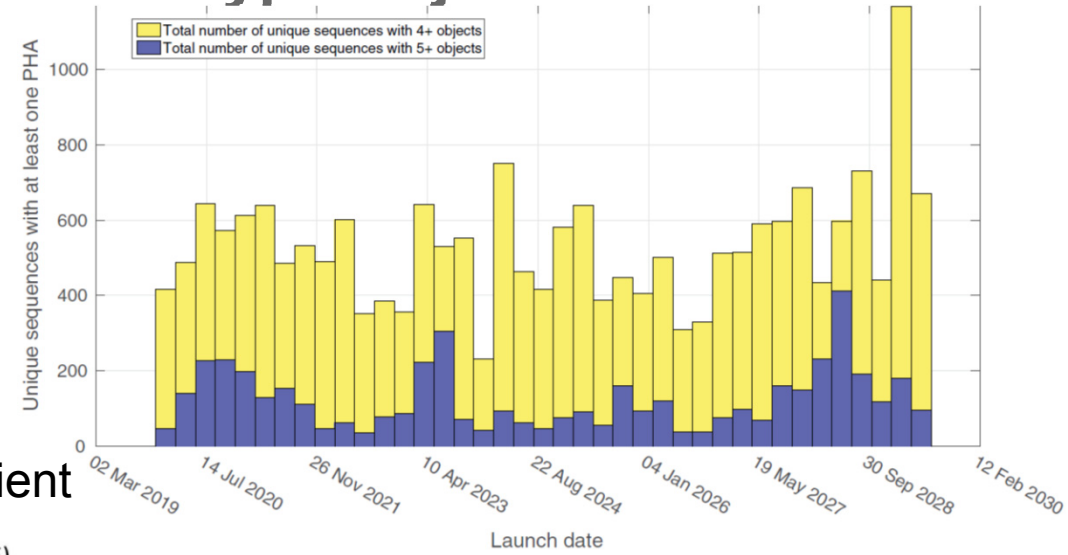


Fig. 7 Number of unique sequences with at least one PHA and four encounters as a function of the launch date.

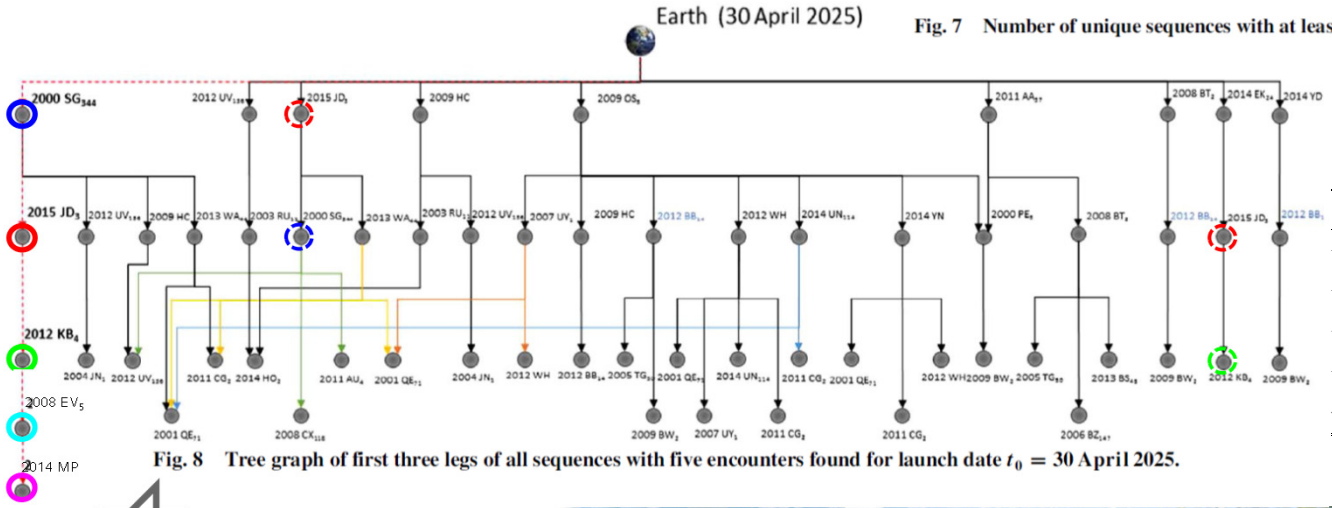


Fig. 8 Tree graph of first three legs of all sequences with five encounters found for launch date $t_0 = 30$ April 2025.

Object	Stay time [days]	Start	End	Time of flight [days]
Earth	//	10 May 2025	26 Feb 2027	657
2000 SG_{344}	123	29 Jun 2027	06 Sep 2028	436
2015 JD_3	164	18 Feb 2029	24 Sep 2030	584
2012 KB_4	160	04 Mar 2031	29 Sep 2032	576
2008 EV_5	171	20 Mar 2033	30 Sep 2034	560
2014 MP	//			

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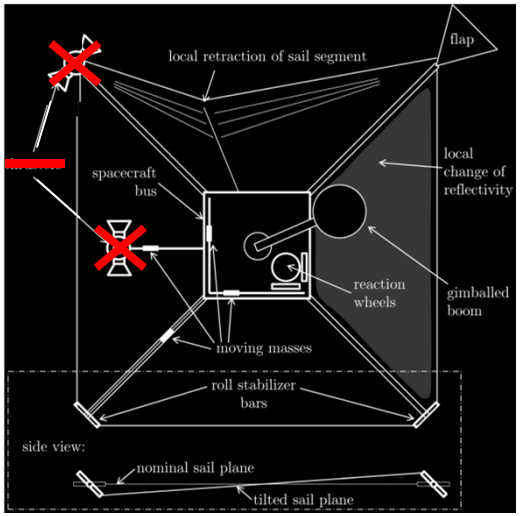
figures & table: Peloni, Ceriotti, Dachwald, 2016

okay, so you can deploy a membrane in a clean room – and how do you fly it?

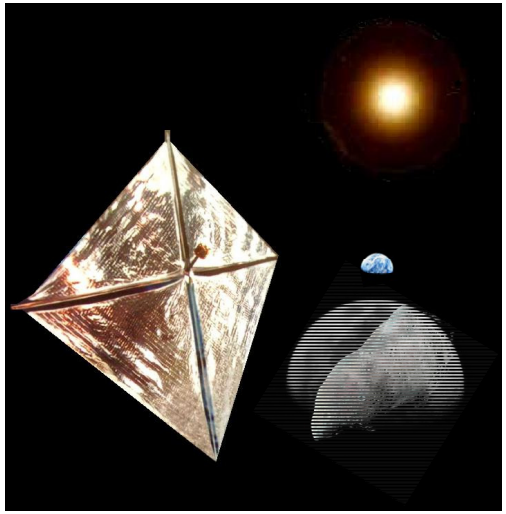


the GOSSAMER Roadmap:
step 2 – control
step 3 – proving the principle

…

…that was the idea…

☺



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

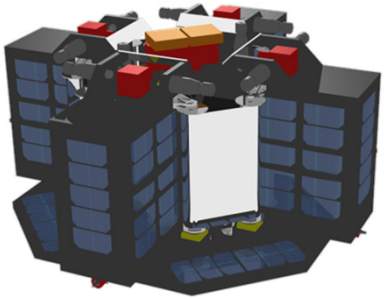
- (20…25 m)² sail area
- orbit where solar radiation pressure is dominant – high LEO, MEO, GTO
- implementation of several (all?) control methods and all relevant mechanisms
- **find out what's the best …**

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

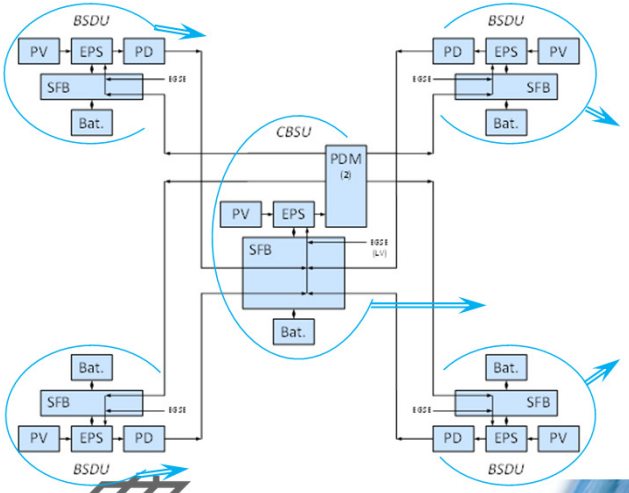
- (50 m)² sail area
- initial orbit high enough to spiral out (sail up)
- applies best control method(s) of GOSSAMER-2
- **prove that sails can operate science missions**
  - *maybe* a *tiny* science payload: imager & sail-environment interaction

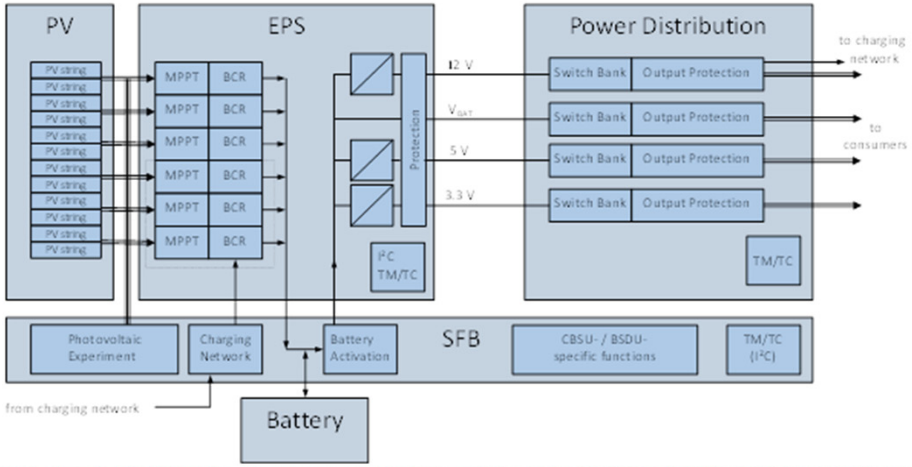
additional images: Moon: Jérôme Salez (wiki), Earth: Bill Anders, Apollo 8, NASA

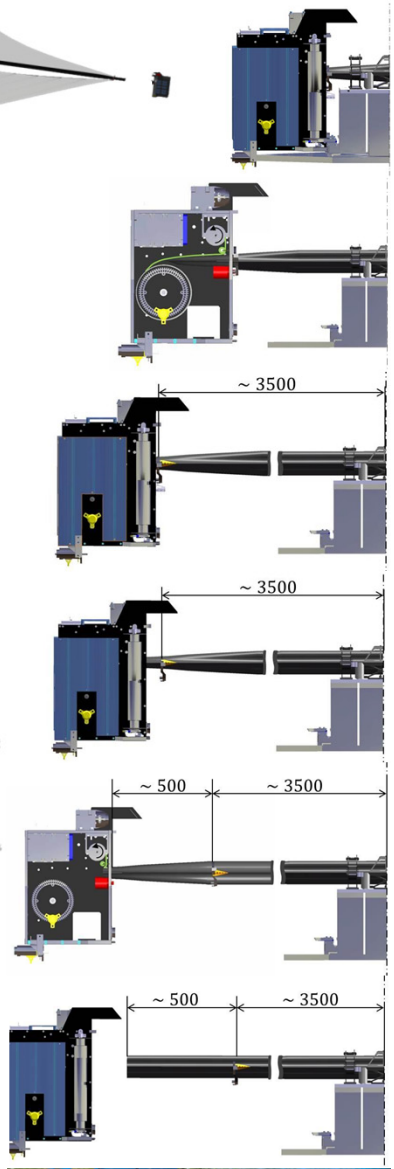
integrating all that: GOSSAMER 1st



- a GOSSAMER sailcraft at launch consists of 5 independent spacecraft connected to act as one
- electrical – thermal – mechanical face-to-face interfaces enable energy transfer through, end to end







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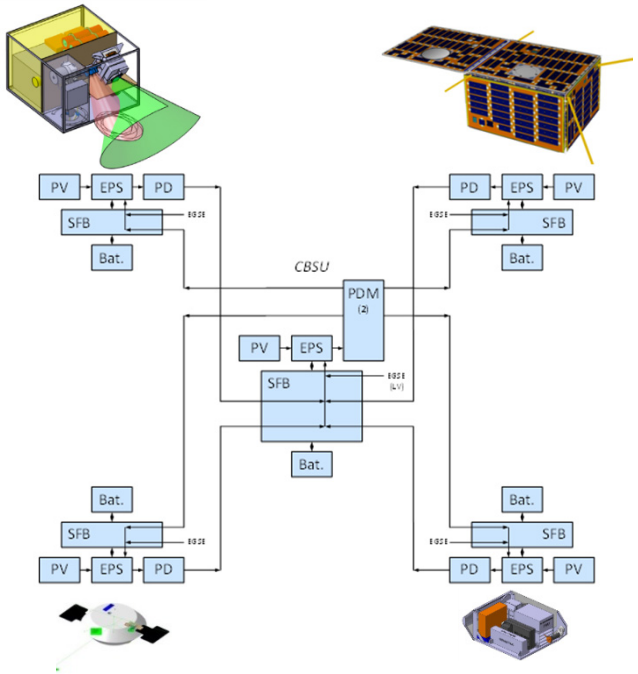
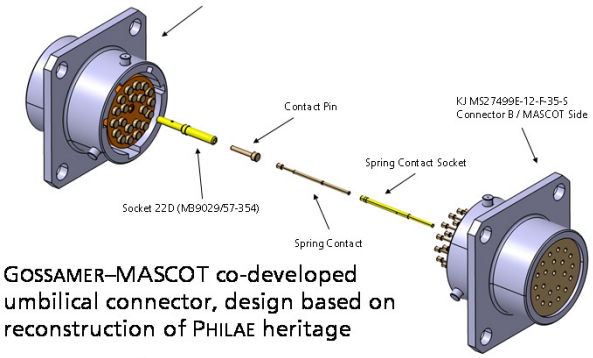
figures : Seefeldt et al., 2016

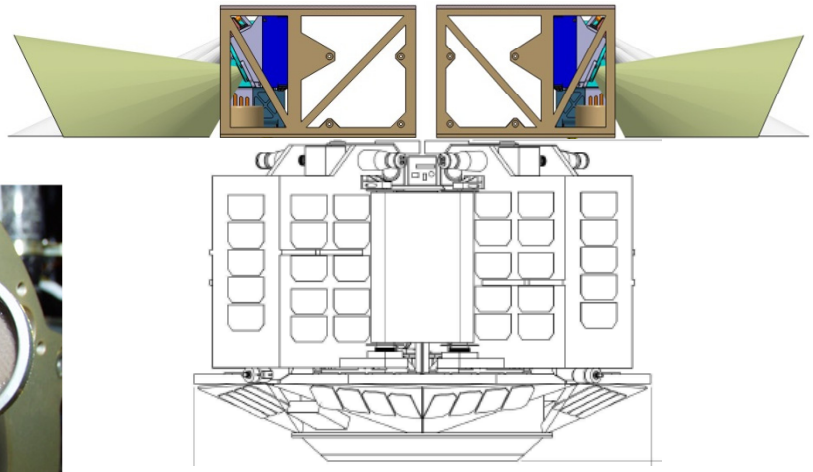
integrating all that: …and landers



- an additional plane of interfaces is implemented on the 'payload' side of the Central Sailcraft Unit (CSCU)
- interfaces between the CSCU and the 4 Boom Sail Deployment Units (BSDU) already use elements also present in MASCOT, e.g. Umbilical
- MASCOT has similar interfaces to its carrying structure (MESS)



GOSSAMER–MASCOT co-developed umbilical connector, design based on reconstruction of PHILAE heritage



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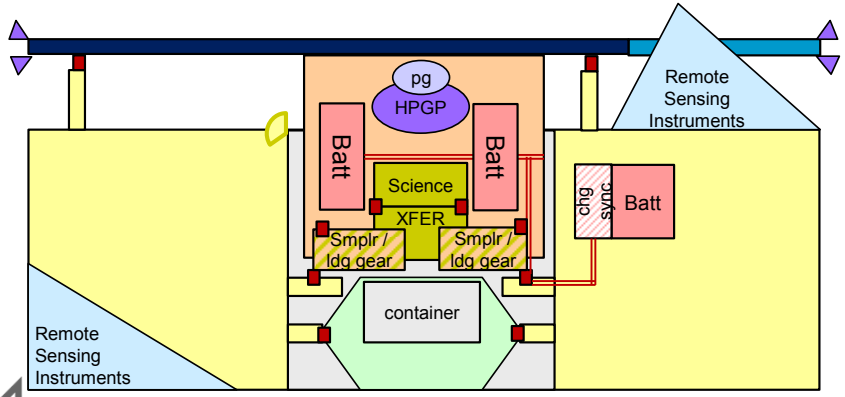
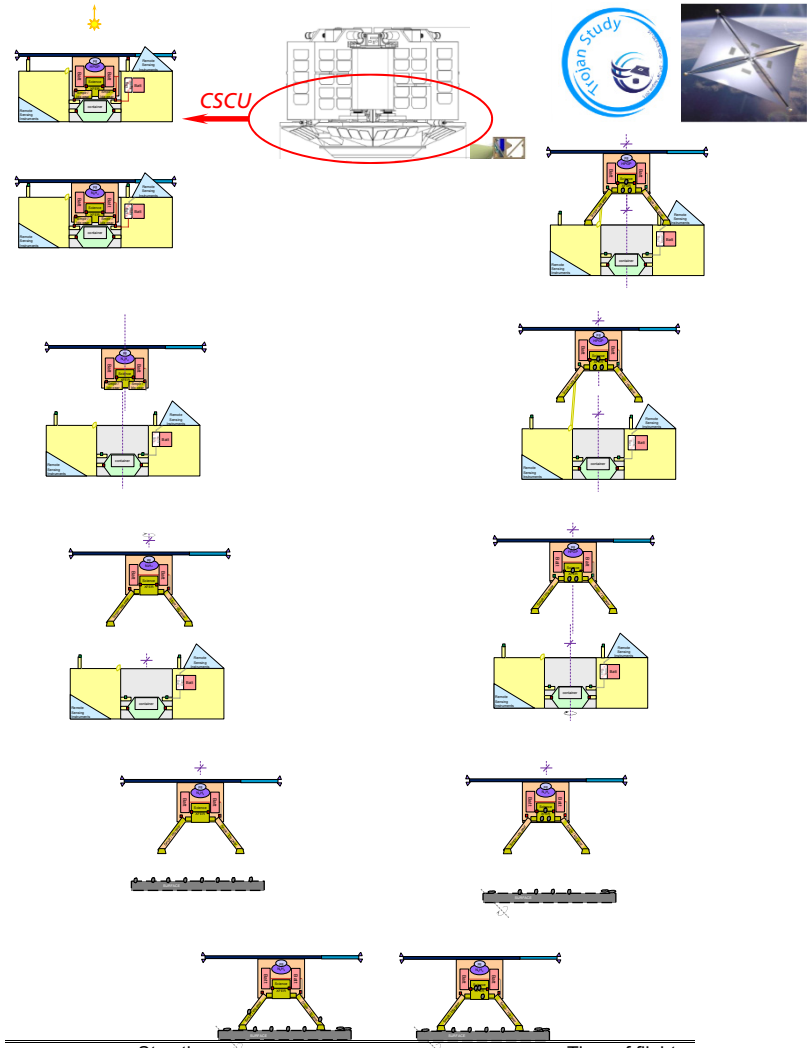
figures : Seefeldt et al., 2016, Ksenik

integrating all that:
…and bringing it back

- sample return requires propulsion
  - pre-deployment propulsion capability can be useful for large sails
  - propulsion entirely on lander, control divided
- propulsion power drives lander battery & photovoltaics
  - the CSCU needs pre-deployment photovoltaics (PV)
- battery shared, mostly on lander
- rigid PV completely on lander





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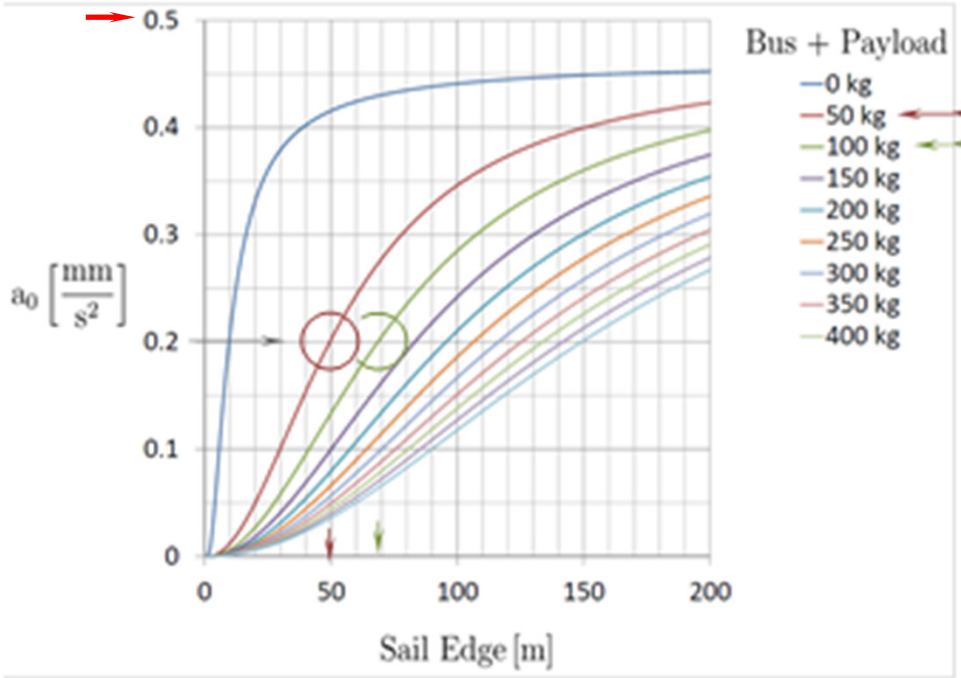
2012 KB_4	160			
		04 Mar 2031	29 Sep 2032	576
2008 EV_5	*160*			
		18 Mar 2033	*22 May 2036*	*1161*
Earth	∞			

performance: the magic MNR & MASCOTs numbers

- GOSSAMER-1 technology based
  - 0.2 mm/s² & 50 kg bus & payload → (50 m)² membrane
  - 0.2 mm/s² & 100 kg bus & payload → (70 m)² membrane
  - 0.2 mm/s² & 150 kg bus & payload → (85 m)² membrane

➔ ESPA & ASAP compatible micro-spacecraft range
  - start from GTO, GEO, NavSat upper stage disposal orbit



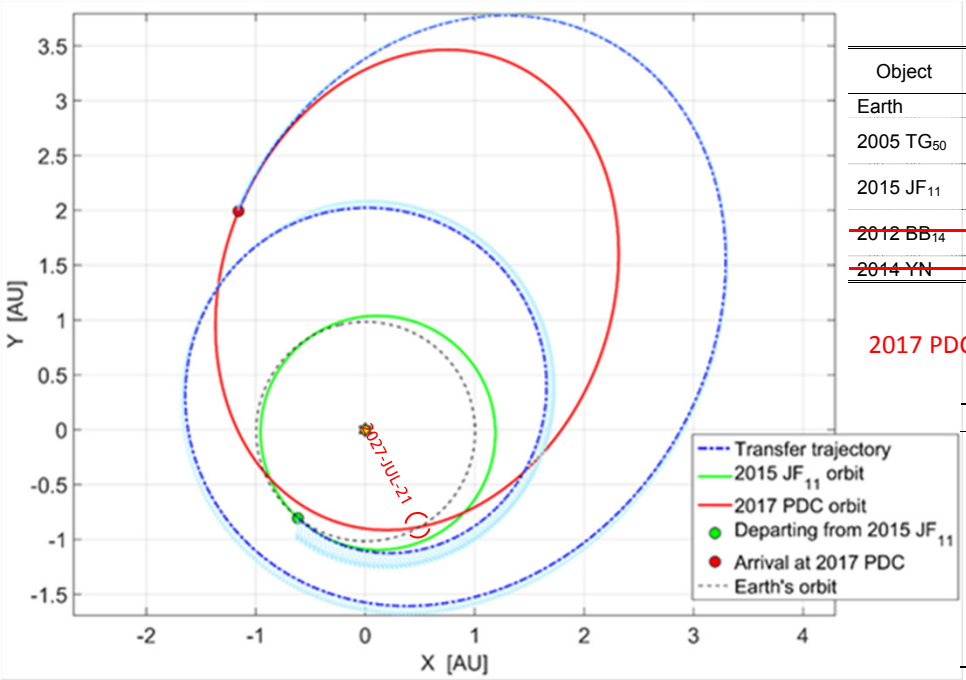
Bus (Gos-1 + X-Band) 	≈ 30 kg
Mother Spacecraft Science Instruments	≈ 10 kg

Lander	
PHILAE 	98 kg
SPS Lander 	100kg
1 MASCOT 	10 kg
5 MASCOTs 	50 kg

figures : Seefeldt et al., 2016

EXERCISE – EXERCISE – EXERCISE – EXERCISE
divert to PDC 2017 for rendezvous

- chasing 2017 PDC – too little ($a_c$celeration), too late (arrival)
- hits on July 21st, 2027 – fully optimized launch in 2025 can't be diverted in time
- a sequence launching in 2020 can divert and reach 2017 PDC but >3 years too late
- requires a_c rise: 0.2 → 0.73 mm/s² (!!!)



original sequence

Object	Stay time [days]	Start	End	Time of flight [days]
Earth	//	13 Aug 2020	26 Apr 2022	621
2005 TG_{50}	128	02 Sep 2022	13 Jan 2024	498
2015 JF_{11}	104	25 Apr 2024	~~10 Jun 2026~~	~~776~~
~~2012 BB_{14}~~	~~139~~	~~28 Oct 2026~~	~~02 Aug 2028~~	~~644~~
~~2014 YN~~	~~//~~			
2017 PDC	//	21 Aug 2030	>2000	

divert after 2nd leg to fly to 2017 PDC

(a_c: 0.2 → 0.73 mm/s²)

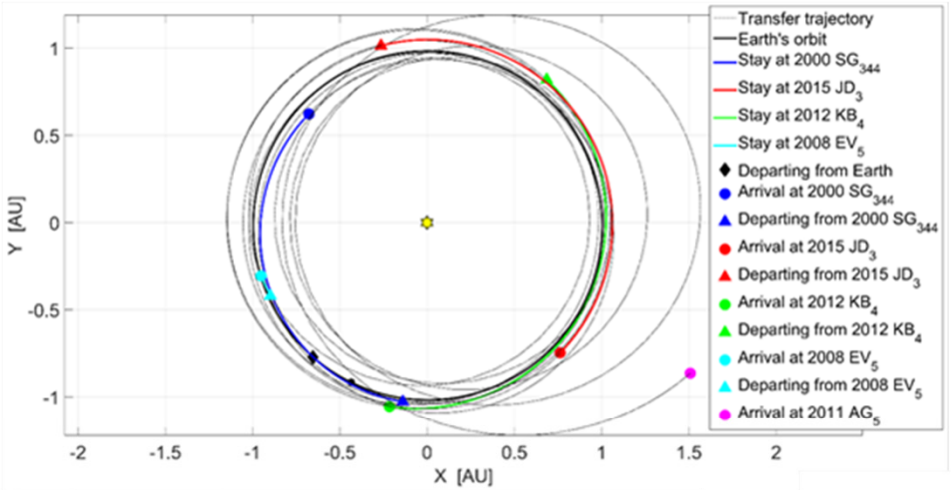
(1127 days = 3 years, 1 month after impact or close fly-by)

Object	2017 PDC
Semi-major axis [AU]	2.24
Eccentricity	0.607
Inclination [deg]	6.297
Right ascension of the ascending node [deg]	298
Argument of periapsis [deg]	312
Mean anomaly [deg]	332
Epoch [MJD]	57940
Absolute magnitude [mag]	21.9
Estimated size [m]	110 – 240

figures & tables extended from: Peloni, Ceriotti, Dachwald, 2016

EXERCISE – EXERCISE – EXERCISE – EXERCISE divert to PDC 2013 for rendezvous

- 2011 AG_5 – the PDC 2013 Exercise impactor, hits February 3rd, 2040
- fully optimized launch in 2025 *can* be diverted to rendezvous 2011 AG_5 in time
- optimized trajectory: diverting from an ongoing MNR mission feasible at a_c = 0.2 mm/s²



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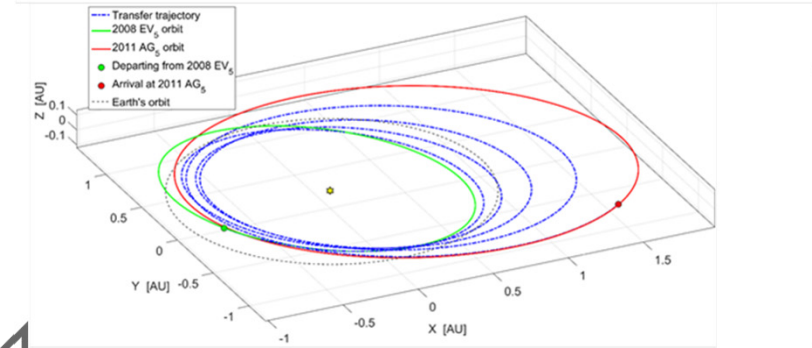
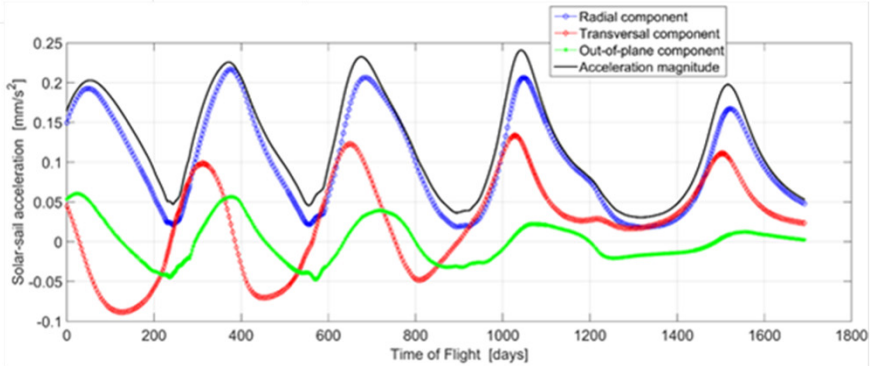
2015 JD_3	164	18 Feb 2029	24 Sep 2030	584
2012 KB_4	160	04 Mar 2031	29 Sep 2032	576
2008 EV_5	*7.5*	*07 Oct 2032*	*25 May 2037*	*1691*
2011 AG_5	*987 to ⊕*			

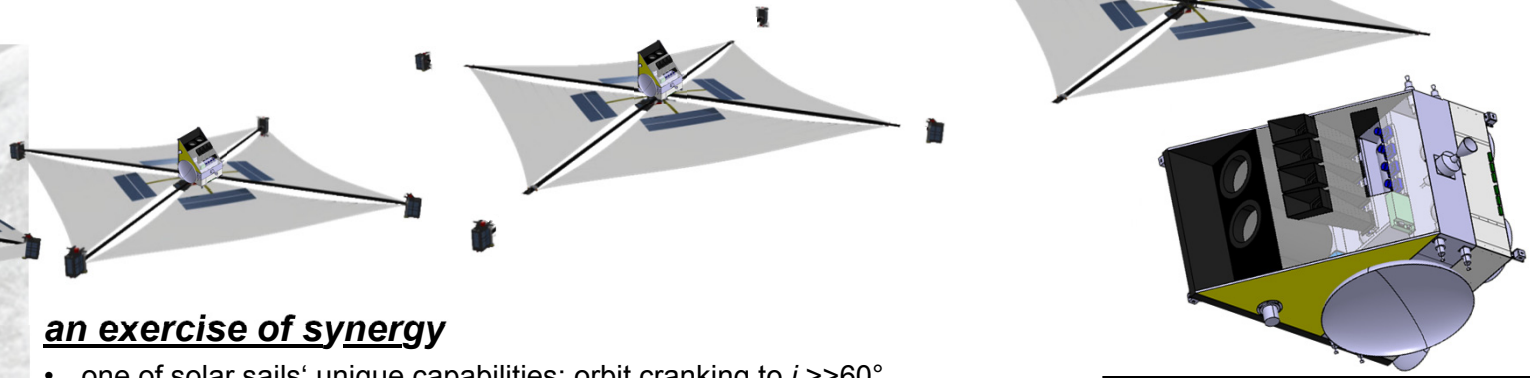
Object	2000 SG_{344}	2015 JD_3	2012 KB_4	2008 EV_5	2011 AG_5
Orbital type	Aten	Amor	Amor	Aten	Apollo
Semi-major axis [AU]	0.977	1.058	1.093	0.958	1.431
Eccentricity	0.067	0.009	0.061	0.083	0.390
Inclination [deg]	0.111	2.730	6.328	7.437	3.681
Absolute magnitude [mag]	24.7	25.6	25.3	20	21.8
Estimated size [m]	35 – 75	20 – 50	20 – 50	260 – 590	110– 240
EMOID [AU]	0.0008	0.054	0.073	0.014	0.0002
PHA	no	no	no	yes	yes
NHATS	yes	yes	yes	yes	no





figures & tables extended from: Peloni, Ceriotti, Dachwald, 2016

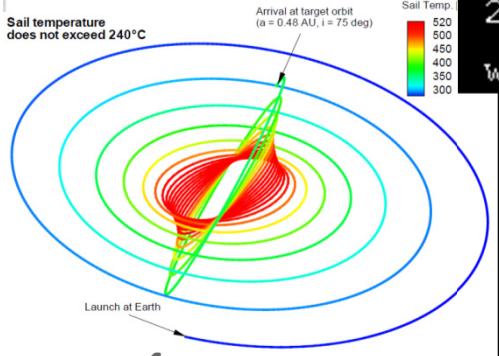
landing… faster, harder, … head-on



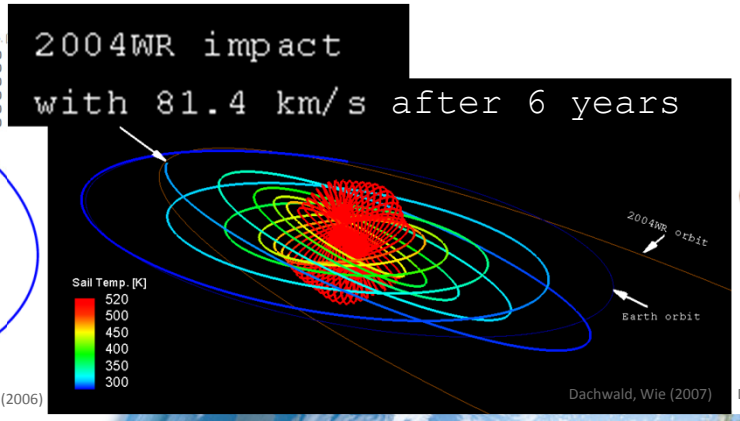
an exercise of synergy

- 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
- fast e⁻-multiplied CCD ASTEROIDFINDER camera tech is good at tracking NEAs
- … add terminal guidance & propulsion
- … develop sails to $\mathbf{a_c}$ **~0.5 mm/s²**

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)



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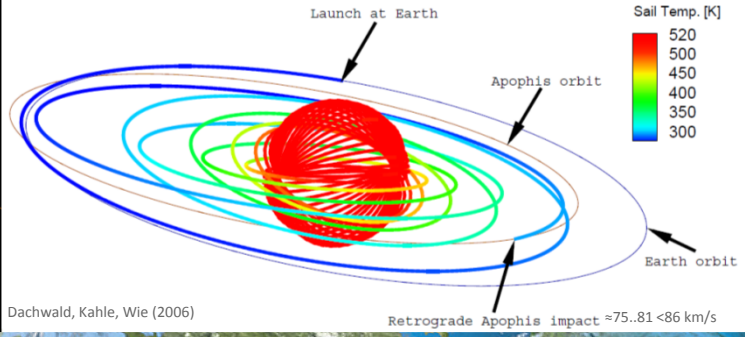

Dachwald, Kahle, Wie (2006)

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background image:
NASA/JPL J.D. Burke et al.

thank you for your attention! – any questions? ☺