Apophis T–9 Years: Knowledge Opportunities for the Science of Planetary Defense – Session 5

Low-thrust: the fast & flexible path to Apophis

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state of the low-thrust art: DAWN – 2-asteroid rendezvous
HAYABUSA & HAYABUSA2 – 1-asteroid sample-return

- DAWN orbited (4) Vesta & (1) Ceres
  - $\Delta v$ produced $\approx 11$ km/s from 425 kg Xe propellant
  - fly-by at (2) Pallas suggested but too marginal, possible fly-by of (145) Adeona not accepted

- HAYABUSA returned samples from (25143) Itokawa
  - $\Delta v$ capability $\approx 4.0$ km/s from 66 kg Xe propellant
  - total $\Delta v \approx 0.4$ km/s from 67 kg bipropellant
  - $\approx 40$ kg used for SEP during mission, yielding 2.2 km/s

- HAYABUSA2 is currently on the way back from carbonaceous PHA (162173) Ryugu
  - $\Delta v$ capability $\approx 3.2$ km/s from 66 kg Xe propellant
  - up to $\approx 3.5$ km/s if filled up to 73 kg Xe capacity

**common feature:**
high-performance electric propulsion
much more is possible by solar-electric propulsion

- **DAWN** spent some $\Delta v$ to move between various mapping orbits, the HAYABUSAS to return samples
  - **what’s science payload to carry?**
  - **what’s there to repurpose?**
  - **where are the limits?**

**SESAME** (Maiwald & Marchand, 2016)

- science payload 33 kg (orbiter) + 5× 4.3 kg (landers)
- launch mass 1571 kg
  - ~3x HAYABUSA2, though only moderately larger than DAWN
- payload fraction <3.5 %: ≈ no gain by descoping science
- GTOC-5-like trajectory to 5 NEAs of ≈200 candidate targets
  - **primarily** astrodynamically targeted
  - targets tied to launch date

➔ remember: we’re chasing just **one** asteroid!
same idea, different method:

Multiple NEA Rendezvous by Solar Sail

• solar sail propulsion is *not* limited by the amount of fuel carried

  – *then what’s the next limit?* –
  
  how well it is designed, built, tested, flown & fixed

  *mechanisms have been fixed in space w/o astronauts around:* e.g. Voyager 1 scan platform

• recent studies (Peloni et al., 2016-2018) demonstrate
  
  • 5 NEA stays for ≥100 days, each, in 10 years
  • accumulated $\Delta v > 50 \text{ km/s} \ @ \ a_c = 0.2 \text{ mm/s}^2$
  
  ➔ asteroid-oriented target selection is feasible
  ➔ at-launch & in-flight target change capability

• target-flexible Multiple NEA Rendezvous for planetary science was identified as a mission type uniquely feasible with solar sail already by the GOSSAMER Roadmap Science Working Groups
GOSSAMER solar sail technology development (qualified)

- The 3-step DLR-ESTEC GOSSAMER Roadmap to Solar Sailing was set up in 2009 to develop key technologies 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: 
  \[
  \frac{1}{2} (5 \text{ m})^2 \approx 30...37.6 \text{ kg}, \ 79\times79\times50 \text{ cm}^3
  \]
the road ahead for solar sailing

G OSSAMER-2 – high-orbit attitude & thrust vector control evaluation

- (20...25 m)^2 sail area
- orbit where solar radiation pressure is dominant – high LEO, MEO, GTO, >GEO
- implementation of several to “all” control methods and all relevant mechanisms
- find out what’s the best …

... alas, ’t was one of those... ;-(

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

... that was the idea...

(↑2009 – ↓2014)

G OSSAMER-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
  - imager & maybe a tiny science-like payload, e.g. sail-environment interaction (~1kg total)

images adapted from Dachwald et al. & ENEAS study
additional images: Moon: Jérôme Salez (wiki), Earth: Bill Anders, Apollo 8, NASA
performance: the magic Multiple NEA Rendezvous & landers numbers

- **GOSSAMER-1** technology based
  - $0.2 \text{ mm/s}^2$ & 50 kg bus & payload $\rightarrow$ $(50 \text{ m})^2$ membrane
  - $0.2 \text{ mm/s}^2$ & 100 kg bus & payload $\rightarrow$ $(70 \text{ m})^2$ membrane
  - $0.2 \text{ mm/s}^2$ & 150 kg bus & payload $\rightarrow$ $(85 \text{ m})^2$ membrane

➔ **ESPA*/ ASAP** compatible micro-spacecraft range (∗ ≤181 kg, 61·61·96 cm³ / ∗∗ ≤200 kg, 80·80·100 cm³)

  • start from GTO and upper stage disposal orbits of GEO & NavSat

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**Bus**

- (Go-1 + X-Band)
- Mother Spacecraft
- Science Instruments

<table>
<thead>
<tr>
<th>Bus Payload</th>
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<tr>
<td>0 kg</td>
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<tr>
<td>50 kg</td>
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<tr>
<td>200 kg</td>
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<td>300 kg</td>
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<td>400 kg</td>
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<table>
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<th>Lander</th>
<th>Payload</th>
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<tbody>
<tr>
<td>PHILAE</td>
<td>98 kg</td>
</tr>
<tr>
<td>SPS Lander</td>
<td>100 kg</td>
</tr>
<tr>
<td>1 MASCOT</td>
<td>10 kg</td>
</tr>
<tr>
<td>5 MASCOTs</td>
<td>50 kg (+10 kg support equipment)</td>
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</tbody>
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where to start from?

– piggy-back launch opportunities for solar sails
sailing studies to Apophis

- launch opportunities repeat with synodic period of 7.8 years
- many studies assume unrealistically high acceleration
- realistic in now-term/near-term technology: 0.2...<0.3 mm/s²

• *sanity check*: impulsive Δv in range of DAWN or SESAME but beyond capability of the HAYABUSAS

Fig. 4 Launch opportunities in 2012–2013 as a function of $a_c$.

Fig. 8 Required ΔV as a function of launch date for two-impulse maneuver.
Artificial Equilibrium Points (AEP)

- model asteroid: (433) Eros
- sail attitude fixed.
- position of each AEP changes with $a_c$
  - circles: initial point
  - crosses: final point
- AEPs 1 and 3 “collide and disappear“ at critical value of characteristic acceleration ($a_c = 0.87 \text{ mm/s}^2$ for Eros)

$$\alpha = \delta = 0^\circ$$

$$a_c \in [0, 2] \text{mm/s}^2$$
shifting of AEPs during asteroid rotation

- effect of the Sun rotating around the asteroid in the body-fixed frame
- sail attitude is fixed
- one full rotation of the asteroid
  - circles: initial point
  - crosses: final point
- as expected, these points are the same as the Sun returns to the initial point

\[
\alpha = \delta = 0^\circ
\]

\[
a_c = 0.2 \text{ mm/s}^2
\]
accessible volume for AEP hovering

- video shows sail performance and sail attitude create the range of positions available for AEPs
- time frozen at the initial time so that the position of the Sun remains fixed
- AEPs 1 and 3 collide at \( a_c = 0.87 \text{ mm/s}^2 \) and so their associated range of AEPs disappear
- Note: only small number of sail attitudes shown, lines outline volume of possible AEPs.

\[
\alpha \in [0,90]^{\circ}, \quad \delta \in [0,360]^{\circ} \\
a_c \in [0,2]\text{mm/s}^2
\]
thank you for your attention! any questions?
Apophis Small SEP Performance Summary

Technology Status
- SEP is already very flexible:
  - wide operation possibilities with established systems
- Performance is „freely chosen“ (within limits) based on a few high-impact parameters.

BUS Capability & Implementation
High-Impact Parameters:
- Available solar power:
  - thrust & $I_{sp}$ scale directly but differently with input power
- Beam voltage: thrust $\leftrightarrow$ TRADE $\rightarrow I_{sp}$

Programmatic Considerations & Trades
- Choice is based on desired mission outline (go for higher $I_{sp}$ or thrust?)
  - Available propellant fixed? (tank & spacecraft size, mass?)
  - Available time?
  - If SmallSat and lots of time $\rightarrow$ go for high $I_{sp} \rightarrow$ low-power ok $\rightarrow$ small design impact $\rightarrow$ fast development & low-cost achievable
  - If SmallSat and no time $\rightarrow$ go for high Thrust $\rightarrow$ high power needed $\rightarrow$ design impact $\rightarrow$ fast development but high cost
Apophis Small SEP Performance Summary

Apophis Mission 2029

→ SEP will be
→ more COTS (thus more available and lower in cost)
→ more effective (reduced heat dissipation)
→ more reliable (less degradation)

→ Biggest limiting factor (today and in the future) is electrical power, NOT the technology.
→ Cost might always be between 10-30% of total.

ESKIMO SmallSat Performance Examples

→ 150kg class ESKIMO (as is) reaches ΔV=3.5km/s (3500 Isp, 14kg propellant)
  ▪ ...12mN using 600W (2x 300W) currently-developed SEP. 50kg P/L. ~~10-15M€ incl. Launch (2029-2026).

→ 150kg class ESKIMO (P/L=Propellant+) reaches ΔV=10.5km/s (3500 Isp, 40kg propellant)
  ▪ ...12mN using 600W (2x 300W) currently-developed SEP. 25kg P/L. ~~12-17M€ incl. Launch (2029-2026).
  ▪ ...24mN using 1200W (4x 300W) currently-developed SEP. 25kg P/L. ~~18-25M€ incl. Launch (2029-2026).

THRUST ↑ - Transfer-Time ↓
Available TIME and therefore THRUST is the SEP system driver.

The SEP system itself is NOT the cost-driver, but the Solar Generator (THRUST scales with power). Solar Generator designs (and cost?) do not evolve much anymore.
Assumption: Double power → Double thrust → 1.5x cost? (Assuming Solar Generator is ~~50% of cost) → Trades are difficult and depend on hard requirements. Many design constellations are possible.

In summary, SEP has much potential and a huge mission-performance-range between a very fast and low-cost COTS-bolt-and-fly design and a well-optimized, dedicated spacecraft.
LEVITY: ENABLING THE NEXT SPACE MARKETS

ESKIMO: The Next Generation Small Satellite Platform

• 150kg-class, 1m³ small satellite platform

• Specifically designed to address orbits beyond GEO including Moon missions.

• Electric propulsion system, flexible payload accommodation and -interfacing

• The platform can also act as a kickstage, transporting small satellites and offering deep space relay services at the target environment.

➢ A convenient ready-to-use platform for any commercial and scientific mission within low-mass, low-cost concepts.

A plug-and-play solution for instruments

Transporting Cube-and Smallsats

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300l | 50kg | 32U