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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Knowledge for Tomorrow
“When you’ve seen one asteroid,…
…you’ve seen \textbf{one} asteroid.

…\textit{even including comets!} ” ;-) 

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

\begin{itemize}
  \item approaches to classification:
    \begin{itemize}
      \item spectral information $\rightarrow$ taxonomy $\leftarrow$ ? $\rightarrow$ composition
      \item shape & topography $\leftarrow$ ? $\rightarrow$ interior structure $\rightarrow$ porosity
      \item orbital dynamics $\leftarrow$ families $\leftarrow$ Yarkovsky $\rightarrow$ YORP $\leftarrow$ ? $\uparrow$
    \end{itemize}
  \item \textbf{but}: all approaches see a little light at the end of the tunnel
    \begin{itemize}
      \item taxonomy: obvious patterns but composition inferred (‘TC$_3$)
      \item shapes: radar (poor man’s flyby) shows $>1$ “top-like”, “cigar”,…
      \item orbits: long-term monitoring makes small Y*-effects quantifiable
    \end{itemize}
  \item \textbf{but}: all these dots & models still need to be connected
\end{itemize}

$\Rightarrow$ 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
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
  - 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

figures: Peloni, Ceriotti, Dachwald, 2016
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 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

½ (5 m)²
compared to a real spacecraft…
– can a 10 kg shoe-box address it all?

**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

**target body properties addressed…**
- surface structure
- composition
- mechanical properties
- thermal properties
- interior structure
- spacecraft orientation

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

- chasing 2017 PDC – too little ($a_c$eleration), 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: $0.2 \rightarrow 0.73 \text{ mm/s}^2$ (!!!)

Object Stay time Start End Time of flight

<table>
<thead>
<tr>
<th>Object</th>
<th>Stay time [days]</th>
<th>Start</th>
<th>End</th>
<th>Time of flight [days]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth</td>
<td>//</td>
<td>13 Aug 2020</td>
<td>26 Apr 2022</td>
<td>621</td>
</tr>
<tr>
<td>2005 TG$_{10}$</td>
<td>128</td>
<td>02 Sep 2022</td>
<td>13 Jan 2024</td>
<td>498</td>
</tr>
<tr>
<td>2015 JF$_{11}$</td>
<td>104</td>
<td>25 Apr 2024</td>
<td>10 Jun 2026</td>
<td>776</td>
</tr>
<tr>
<td>2012 BB$_{14}$</td>
<td>139</td>
<td>20 Oct 2025</td>
<td>02 Aug 2026</td>
<td>644</td>
</tr>
</tbody>
</table>

2017 PDC diverges after 2nd leg to fly to 2017 PDC
($1127 \text{ days} = 3 \text{ years}, 1 \text{ month after impact or close fly-by}$)

<table>
<thead>
<tr>
<th>Object</th>
<th>2017 PDC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semi-major axis [AU]</td>
<td>2.24</td>
</tr>
<tr>
<td>Eccentricity</td>
<td>0.607</td>
</tr>
<tr>
<td>Inclination [deg]</td>
<td>6.297</td>
</tr>
<tr>
<td>Right ascension of the ascending node [deg]</td>
<td>298</td>
</tr>
<tr>
<td>Argument of periapsis [deg]</td>
<td>312</td>
</tr>
<tr>
<td>Mean anomaly [deg]</td>
<td>332</td>
</tr>
<tr>
<td>Epoch [MJD]</td>
<td>57940</td>
</tr>
<tr>
<td>Absolute magnitude [mag]</td>
<td>21.9</td>
</tr>
<tr>
<td>Estimated size [m]</td>
<td>110 – 240</td>
</tr>
</tbody>
</table>
2011 AG$_{5}$ – the PDC 2013 Exercise impactor, hits February 3$^{rd}$, 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/s$^2$
landing… faster, harder, … head-on

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**an exercise of synergy**

- one of solar sails' unique capabilities: orbit cranking to $i >> 60^\circ$
- 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 $a_c \approx 0.5 \text{ mm/s}^2$

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**Dimensions:**

<table>
<thead>
<tr>
<th>Dimension</th>
<th>1m x 0.78m x 0.7m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunshield</td>
<td>50 degree</td>
</tr>
<tr>
<td>Mass</td>
<td>179kg</td>
</tr>
<tr>
<td>Payload</td>
<td>2 x High Resolution Cameras, 4 x Middle Range Camera, 4 x Webcam</td>
</tr>
<tr>
<td>Communication</td>
<td>1 x Ka-band antenna, 2 x X-band antenna, 4 x Interlink antenna</td>
</tr>
<tr>
<td>ACS</td>
<td>Propulsion (8 x 1N thrusters, 1x 400N thruster)</td>
</tr>
</tbody>
</table>
thank you for your attention! – any questions? 😊