Nanospacecraft design and mission overview for statistical asteroid prospecting

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Small neighbors

- 755,000+ known asteroids + constantly increasing
- ≈508,000 numbered asteroids + constantly increasing
- 138,000+ with known size and albedo + 350,000 by Gaia
- ≈4,000 with known taxonomic class + 100,000s by Gaia and Euclid
- 12 studied by space missions
- +10 more with launched and developed missions
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Asteroid touring

CASTAway to visit 10—20 asteroids
(University of Oxford, Open University)

MANTIS to visit ~10 asteroids
(Johns Hopkins University Applied Physics Laboratory)

Lucy to six asteroids (NASA)
Science objectives

- Spectral types/complexes not visited thus far
- Primordial/rubble piles
- Various sizes
- Various families
- Active asteroids/main-belt comets
- Known and unknown (contact) binaries/multiple asteroid systems
- Potentially hazardous asteroids
- Mapping of hydration features
- Selection and mapping of potential sample return targets and sites
Multi-asteroid touring

- Hundreds of asteroids
- Tens of nanospacecraft
- No mothership
Multi-asteroid touring

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- Propulsion
- Communications
- Navigation
- Autonomy...
Photonic sail
Example: NEA Scout (NASA)

Electric propulsion
Example: M–ARGO (ESA)
Photonic sail
Example: NEA Scout (NASA)

Electric propulsion
Example: M–ARGO (ESA)

Thrust decays as $1/r^2$
Electric solar wind sail
Electric solar wind sail

Thrust decays as $1/r^{7/6} \approx 1/r$
3.2-year asteroid tour, \( a_{0}=1 \text{ mm/s}^2 \)
Earth \( DV=5.93 \text{ km/s} \) @ 1498 km, \( max(r)=2.744 \text{ au} \), \( dv_{tot}=31.8 \text{ km/s} \), \( dv_{scf}=13.6 \text{ km/s} \).

8.3-year asteroid tour, \( a_{0}=0.989 \text{ mm/s}^2 \)
Earth \( DV=12.4 \text{ km/s} \) @ 59491 km, \( max(r)=5.332 \text{ au} \), \( dv_{tot}=55.9 \text{ km/s} \), \( dv_{scf}=17.6 \text{ km/s} \).
Mission requirements 1/2

• Marginal escape orbit
• Acquire heliocentric orbit
• Four year lifetime
• Perform 20—40 flybys of primary targets (by the whole fleet)
• Maximize the number of primary targets per spacecraft
• Maximize the time at target’s proximity
• Maximize the number of secondary flybys
• Locate targets
• If needed, perform relative orbital corrections
• Take NUV-VIS-NIR measurements
Mission requirements 2/2

- Maximize the illuminated surface coverage
- Image the whole surface in low resolution while approaching
- Take hi-res images during flyby
- Different phase angles of active asteroids
- Store scientific data
- Flyby Earth
- Transmit science data during Earth flyby
- Transmit telemetry throughout the mission
Spacecraft requirements 1/2

- Mass <6 kg, fits in six-unit CubeSat form factor
- 50 W of instant power and 14 W of continuous
- Deploy 20-km tether
- Charge the tether up to nominal/peak voltage of 15/30 kV
- Absolute attitude knowledge/control: ~0.1/1°
- Absolute position knowledge/control: ~150/500 km
- Radiation dose: 10⁴-10⁵ rad
- Internal temperature: +10 .. +15° C
- Storage data rate: 50 MB/s
- Storage capacity: 50 GB
Spacecraft requirements 2/2

- Relative attitude knowledge/control: \(~0.1/1'\)
- Relative attitude control stability: \(~0.1'/s\)
- Slew rate: \(3^\circ/s\)
- Relative position knowledge/control: \(~50/100\ \text{km}\)
- Telemetry: 1—60 bit/s
- Design spacecraft for bulk production
- Minimize production expenses
1. Launch;
2. Deploy the tether;
3. Accelerate with E-sail;
4. Perform multiple flybys (iterate through sub-phases):
   (a) Cruise;
   (b) Locate the target;
   (c) Perform relative navigation by determining the relative position with respect to the target and controlling the trajectory to acquire the required flyby distance;
   (d) Track the object and acquire low-resolution measurements while approaching the target. Prepare for close approach. If power budget allows, send telemetry updates;
   (e) Perform fast tracking and acquire high-resolution measurements during close approach;
   (f) Track the object and acquire low-resolution measurements while descending the target. Store data;
   (g) Send telemetry updates.
5. Transmit data during the Earth flyby.
• 0.3–0.9 \(\mu\)m hi-res imaging
  • 2–5 m/px at 100 km
• 1–5 \(\mu\)m infrared imaging
  • 5–25 m/px at 100 km
<table>
<thead>
<tr>
<th>Component</th>
<th>Mass/g</th>
<th>Count</th>
<th>Total mass/g</th>
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<tr>
<td><strong>Spacecraft</strong></td>
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<td>Bus PCB</td>
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<td>Dipole antenna</td>
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<tr>
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<td>Hinges</td>
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<tr>
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<tr>
<td>AOC structure</td>
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<td>Screws, nuts, inserts</td>
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<td>1</td>
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<tr>
<td>Telescope</td>
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<tr>
<td>Framing camera</td>
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<td><strong>Total for spacecraft</strong></td>
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<tr>
<td><strong>Remote unit</strong></td>
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<td>PCB</td>
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<tr>
<td>Communications chip</td>
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<td>30</td>
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<tr>
<td>Reel and motor</td>
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<td>150</td>
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<td>TILE 50</td>
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<td>Deployable panels</td>
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<tr>
<td>Structure</td>
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<td><strong>Total for remote unit</strong></td>
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<td></td>
<td>662</td>
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<td>Tether (20 km)</td>
<td>200</td>
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<td>200</td>
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<td><strong>Total for spacecraft, remote unit and tether</strong></td>
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<tr>
<td><strong>Total with 20% margin</strong></td>
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</table>
Temperature outside
Temperature inside
Surface emissivity

Infrared Emissivity

- 0.89000
- 0.83563
- 0.78126
- 0.72688
- 0.67250
- 0.61813
- 0.56375
- 0.50938
- 0.45500
- 0.40062
- 0.34625
- 0.29187
- 0.23750
- 0.18312
- 0.12874
- 0.07437
- 0.02000
Solar absorptivity
Thermo-optical properties outside
Thermo-optical properties inside
Back to home planet (unsolved)
Radiation shielding  (Dong L. et al, 2014)

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<tr>
<th>Material</th>
<th>10 (MeV)</th>
<th>1 (GeV)</th>
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<td>CFRP</td>
<td>0.046670</td>
<td>0.002181</td>
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<td>GFRP</td>
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<tr>
<td>Kevlar</td>
<td>0.043370</td>
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<tr>
<td>Glass</td>
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<td>CFRM</td>
<td>0.037080</td>
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<tr>
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<tr>
<td>Magnesium alloys</td>
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<tr>
<td>Aluminum alloys</td>
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<td>Titanium alloys</td>
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<td>0.001630</td>
</tr>
<tr>
<td>Steel</td>
<td>0.028760</td>
<td>0.001576</td>
</tr>
</tbody>
</table>
Conclusions

• Flyby hundreds of asteroids with tens of nanospacecraft
• Enabled by electric sail
• Needs full trajectory analysis
• Minimal use of DSN by returning data to Earth proximity
• Optical navigation and spacecraft autonomy
• Similar instrumentation is used in LEO
• Study at ESA’s Concurrent Design Facility
• Other applications
• *Fly Early & Fly Often*
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