Multiple NEO Rendezvous Using Solar Sails

Les Johnson
MSFC Advanced Concepts Office

www.nasa.gov
Overall Mission Concept

• Assess the feasibility of using solar sail propulsion to enable a robotic precursor that would survey multiple Near Earth Objects (NEOs) for potential future human visits

• Ground Rules
  – The solar sail should be the only technical risk
    ▪ Baseline the sail technology demonstrated to TRL 5/6 by the NASA In-Space Propulsion Technology Project and selected for flight by NASA OCT as a Technology Demonstration Mission
    ▪ Use State-Of-the-Art (SOA) instruments
    ▪ Use only flight-proven spacecraft systems and hardware
  – Single spacecraft will rendezvous with and image 3 NEOs within 6 years of launch
Solar Sail Asteroid Rendezvous Mission:

Departure: Aug 2017

Candidate asteroids visited:

<table>
<thead>
<tr>
<th>NEO</th>
<th>Date</th>
<th>Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999 A010</td>
<td>Mar 2019</td>
<td>35 days</td>
</tr>
<tr>
<td>Apophis</td>
<td>Dec 2021</td>
<td>30 days</td>
</tr>
<tr>
<td>2001 QJ142</td>
<td>July 2023</td>
<td>30 days</td>
</tr>
</tbody>
</table>

Spacecraft mass at destination: 228.4 kg

Cost: $175M, plus launch vehicle and ops

Launch: Athena II
• Two 20-m system ground demonstrations (ATK and L’Garde) designed, fabricated, and tested under thermal vacuum and flight-like conditions - 2005
• IKAROS (JAXA) successfully flying in deep space – 2010
• NanoSail-D flew in orbit (NASA MSFC) - 2010
• L’Garde funded by NASA OCT to demonstrate deep space solar sail propulsion (Sunjammer) as a Technology Demonstration Mission in ~2014
L’Garde 20-m System Ground Demonstrator (SGD)

- Sail Membrane
- Tip Vane
- Tip Mandrel
- Inflatable Beams
- Vane Mechanism
- Stowed Configuration

20-M SGD
NanoSail-D Mission Configuration

- 3U Cubesat: 10cm X 10cm X 34cm
- Deployed CP-1 sail: 10 m² Sail Area (3.16 m side length)
- 2.2 m Elgiloy Trac Booms
- UHF & S-Band communications
- Permanent Magnet Passive Stabilization

Deployed by FastSat Spacecraft

NanoSail-D Mission Configuration

- Deployed CP-1 sail: 10 m² Sail Area (3.16 m side length)
- PPOD Deployer (Cal-Poly)
- Spacecraft Bus (Ames Research Center)
- Boom & Sail Spool (ManTech SRS)
- Bus interfaces Actuation Electronics (MSFC/UAH)
- NanoSail-D (Aluminum Closeout Panels Not Shown)

Stowed Configuration
Interplanetary Kite-craft Accelerated by Radiation Of the Sun (IKAROS)

- IKAROS was launched on May 21, 2010
- The Japan Aerospace Exploration Agency (JAXA) began to deploy the solar sail on June 3.
- IKAROS has demonstrated deployment of a solar sailcraft, acceleration by photon pressure and attitude control
  - Deployment was by centrifugal force
  - Sail membrane is 7.5 mm thick

<table>
<thead>
<tr>
<th>Configuration / Body Diam.</th>
<th>1.6 m x Height 0.8 m (Cylinder shape)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Configuration / Membrane</td>
<td>Square 14 m and diagonal 20 m</td>
</tr>
<tr>
<td>Weight</td>
<td>Mass at liftoff: about 310 kg</td>
</tr>
</tbody>
</table>
NEAR Spacecraft Camera: NEAR MultiSpectral Imager

NEAR multispectral imaging system (MSI)
- Consists of optical system and passively cooled Si CCD focal plane unit.
- Designed to take images at various wavelengths of 433 Eros from orbit and fly by of 253 Mathilde
- Also provides optical navigation for spacecraft

Scientific objectives:
- Map asteroid morphology and surface composition
- Determine overall size, shape, and spin characteristics.

Specifications:
Mass: Camera head 5.05 kg; Supporting electronics, 4.5 kg
Power: Camera head 2.16W; Electronics, 10.86 W
Detector: Si CCD; Thompson-CSF TH7866
Field of view: 2.25° X 2.9°, in 244 X 537 pixels = 3.9 X 5.1 km from 100-km distance
Resolution: 9.5 X 16.1 m from 100-km distance
Exposure time: to 999 ms in 25-ms increments, manual or automatic
Wavelength range: 400-1100 nm
Filter wavelengths: 1 broadband filter, 7 spectral filters at 450, 550, 760, 900, 950, 1000, and 1050 nm
Data Character: 12-bit data, with three-tiered compression menu.
Earth Relative Phase and Inclination Angles for January 1, 2018 12:00
• **Time of Transfer (Rough Estimate)**
  - From Earth to 1999 AO10 1.54 Years
  - Observation 35 Days
  - From 1999 AO10 to Apophis 2.5 Years (Conservative)
  - Observation 30 Days
  - From Apophis to 2001 QJ142 1.7 Years (Conservative)
  - Observation 30 Days

• **Total Time of Flight  ~6 Years**
  - As observation time increases, the optimal selection of asteroids change
  - With refinement, total time will decrease
Central Structure/Upper/Permanent bus; Solar Sails not shown

SC Jettison bus

Sail spindles will rotate 90 degrees to clear separation plane

Triad thrusters (4)
1 N₂ gas bottle located in lower bus

Sail closeout panels will rotate 90 degrees to open and clear separation plane

1.9 m
NEO Solar Sail SC Deployment

SC masts fully deployed

Close-up forward view of SC bus with masts extended

85 m
Ground Rules and Assumptions

1. The NAFCOM (NASA/Air Force Cost Model) was used to estimate the Solar Sail spacecraft costs herein.
2. Messenger was used as the analogy.
3. Cost estimate was based on ATK Solar Sail system ground demonstrators.
4. Technical data and mass properties were supplied by the Solar Sail proposal team.
5. All Costs are estimated in Fiscal Year (FY) 2011 dollars in millions based on NASA Inflation tables.
6. System Test Hardware Costs represent proto-flight approach. All applicable system integration (wrap) costs represent the wrap cost for one test unit.
7. Costs associated with the DDT&E effort encompass the period from the beginning of full scale development through factory checkout of test vehicle.
8. Individual subsystem totals contain all hardware costs and engineering and manufacturing labor costs charged to that subsystem.
9. Fee is calculated at 10% of the spacecraft.
10. Program Support (Level One PM, SE&I, and S&MA) cost are calculated at 20% of the spacecraft.
11. Vehicle Integration costs are calculated at four percent of the spacecraft.
12. Reserves are set at 30%.
13. Launch and operation cost are not included.
## Spacecraft Costs (2011$ in Millions)

<table>
<thead>
<tr>
<th>WBS ITEM</th>
<th>DDT&amp;E</th>
<th>Flight Unit</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Subsystem Level</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Structures</td>
<td>7.5</td>
<td>1.5</td>
<td>9.0</td>
</tr>
<tr>
<td>Electrical Power</td>
<td>2.3</td>
<td>1.9</td>
<td>4.2</td>
</tr>
<tr>
<td>Communications</td>
<td>6.2</td>
<td>3.7</td>
<td>9.9</td>
</tr>
<tr>
<td>Command &amp; Data Handling</td>
<td>1.8</td>
<td>1.2</td>
<td>3.0</td>
</tr>
<tr>
<td>Guidance &amp; Navigation</td>
<td>4.6</td>
<td>2.4</td>
<td>7.0</td>
</tr>
<tr>
<td>Reaction Control</td>
<td>1.7</td>
<td>3.3</td>
<td>5.0</td>
</tr>
<tr>
<td>Camera</td>
<td>2.0</td>
<td>1.7</td>
<td>3.7</td>
</tr>
<tr>
<td>Sail Propulsion System</td>
<td>10.0</td>
<td>25.0</td>
<td>35.0</td>
</tr>
<tr>
<td><strong>System Level</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Integration, Assembly &amp; Checkout</td>
<td>0.5</td>
<td>1.0</td>
<td>1.5</td>
</tr>
<tr>
<td>Systems Test Operations</td>
<td>1.5</td>
<td>0.0</td>
<td>1.5</td>
</tr>
<tr>
<td>Ground Support Equipment</td>
<td>4.0</td>
<td>0.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Systems Engineering &amp; Integration</td>
<td>3.9</td>
<td>4.4</td>
<td>8.3</td>
</tr>
<tr>
<td>Program Management</td>
<td>2.0</td>
<td>2.2</td>
<td>4.2</td>
</tr>
<tr>
<td>Launch &amp; On-Orbit Support</td>
<td>1.8</td>
<td>0.0</td>
<td>1.8</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td>49.8</td>
<td>48.3</td>
<td>98.1</td>
</tr>
<tr>
<td><strong>Vehicle Integration</strong></td>
<td>2.0</td>
<td>1.9</td>
<td>3.9</td>
</tr>
<tr>
<td><strong>Fee</strong></td>
<td>5.2</td>
<td>5.0</td>
<td>10.2</td>
</tr>
<tr>
<td><strong>Program Support</strong></td>
<td>11.4</td>
<td>11.1</td>
<td>22.5</td>
</tr>
<tr>
<td><strong>Sub-total</strong></td>
<td>68.4</td>
<td>66.3</td>
<td>134.7</td>
</tr>
<tr>
<td><strong>Reserves (30%)</strong></td>
<td>20.5</td>
<td>19.9</td>
<td>40.4</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>89.0</td>
<td>86.2</td>
<td>175.2</td>
</tr>
</tbody>
</table>