Overview: Solar Electric Propulsion Concept Designs for SEP Technology Demonstration Mission

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Motivation

- Primary objective of SEP TDM is to develop and demonstrate an enabling propulsion capability, based on next generation solar electric propulsion technologies as part of an integrated system, extensible to higher power systems.
- Initial mission concepts (internal and via contracts) have shown high power SEP TDM was cost prohibitive relative to anticipated TDM project resources.
- An in-house mission concept development team was established to investigate alternate mission concepts that afford improved affordability:
  - Enabling a cost-sharing partner
  - Minimizing launch vehicle costs by flying as a secondary payload
  - Launching with a second spacecraft as a co-manifested payload.
  - Micro-scaled concept
- The SEP TDM in-house concept design team has developed five different SEP demonstration missions and vehicle concept designs.

**Project Goal:** Advance SEP Technologies and capabilities via an in-space demonstration of a high-power SEP spacecraft.
Primary SEP TDM Concept Design Goals

• Demonstrate in-space operation of SEP technologies that are essential to a multi-hundred kilowatt SEP vehicle and that are not amenable to ground-based testing
• Demonstrate high voltage (>200 V) solar array in earth orbit
• Demonstrate in space deployment of large-area flexible blanket arrays
• Demonstrate in space direct drive operation of an electric propulsion system
• Demonstrate SEP technology scalable to high power systems
• Demonstration two thruster operation of an electric propulsion system
• Total mission cost <$200M

<table>
<thead>
<tr>
<th>Partner Focus</th>
<th>Concept Mission</th>
</tr>
</thead>
<tbody>
<tr>
<td>NASA HEOMD</td>
<td>EM-L2 Logistics support mission</td>
</tr>
<tr>
<td>Multiple</td>
<td>Secondary payload concepts</td>
</tr>
<tr>
<td>NASA HEOMD/SMD</td>
<td>NEA Precursor mission</td>
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<tr>
<td>Commercial/Cost sharing</td>
<td>Ride Share, ESPA based structure; Ride Share, Max propellant loading</td>
</tr>
<tr>
<td>ESPA Micro Spacecraft</td>
<td>µSEPSAT</td>
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</table>
The EM-L2 logistics concept focused on a 30kW-class SEP vehicle capable of supporting Low Earth Orbit (LEO) to EM-L2 human-tended Waypoint cargo delivery needs.

<table>
<thead>
<tr>
<th>SEP spacecraft MEL</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEP Stage (dry without MGA)</td>
<td>1971</td>
</tr>
<tr>
<td>SEP Stage Composite MGA</td>
<td>414</td>
</tr>
<tr>
<td>IMLEO SEP Stage (Dry without MGA)</td>
<td>2385</td>
</tr>
<tr>
<td>Main Propellant (Xenon)</td>
<td>2910</td>
</tr>
<tr>
<td>RCS Propellant (Hydrazine)</td>
<td>50</td>
</tr>
<tr>
<td>Payload</td>
<td>4000</td>
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<tr>
<td>SEP Vehicle IMLEO</td>
<td>9345</td>
</tr>
<tr>
<td>LV Adaptor &amp; Separation System (w/MGA)</td>
<td>236</td>
</tr>
<tr>
<td>SEP Vehicle Liftoff Mass</td>
<td>9581</td>
</tr>
<tr>
<td>Falcon Lift capability</td>
<td>9953</td>
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<tr>
<td>Dry Mass Margin</td>
<td>372</td>
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</tbody>
</table>

- The goal is to deliver a 5,000 kg payload mass from LEO to EM-L₂
- The goal is to complete the EM-L₂ transfer in less than two years
- Dedicated medium class single LV

**Power System**
- Two ATK MegaFlex solar array wings, 40 kW BOL

**Electric Propulsion System**
- Two 12 kW XR-12 hall thrusters, 160 V, two PPUs
- 6 Xe storage tanks ~ 3t Xe

**Spacecraft cost ~ $200-300M**
SEP Secondary Payload Concept Summary

SEP TDM technology demonstration as a secondary payload option, using smaller ESPA ring as primary structure

- Secondary payload concept
- Use ELLV Secondary Payload Adaptor (ESPA) as spacecraft structure
- Total mission cost goal <$200M

Power System
- 8.3 m diameter UltraFlex arrays (2); 15 kW per wing

Electric Propulsion System
- 15 kW Hall Thrusters (2), 1 Xe tank (220 kg)

Bus Structure
- ESPA used as primary bus structure

Spacecraft cost ~ $200M

ΔV capability ~ 4500 m/s

Demonstrate in-space operation of SEP technologies that are essential to a multi-hundred kilowatt SEP vehicle and that are not amenable to ground-based testing
NEA Precursor SEP Spacecraft Concept C1 Summary

Explore asteroids that are candidates for future human space missions beyond Earth as while also satisfying the tech demo objectives of the SEP TDM as a cost share

- Demonstrate SEP technology, to mature TRL
- Smaller class mission, smaller launch service, smaller total mass, etc. (~1800 kg IMLEO)
- Single High power thruster, DDU tech demonstration

Power System – Demonstrate high power SAS (30 kW)
- 3mx 13.6 m DSS arrays (2); 18 kW BOL
- 300 VDC primary distribution EP; 1- 28 VDC battery for subsystems

Electric Propulsion System – Demonstrate DDU
- Hall Thruster (1), 15 kW, Isp = 2000 sec, DDU (2), 2 Dawn Xe tank

Spacecraft cost ~ $220M

<table>
<thead>
<tr>
<th>SEP spacecraft MEL</th>
<th>Basic Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structures</td>
<td>147.3</td>
</tr>
<tr>
<td>Power</td>
<td>221.4</td>
</tr>
<tr>
<td>ACS/RCS</td>
<td>49.3</td>
</tr>
<tr>
<td>Main Propulsion</td>
<td>104.3</td>
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<tr>
<td>Total propellant (Main + RCS)</td>
<td>857.2</td>
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<tr>
<td>Thermal Control</td>
<td>122</td>
</tr>
<tr>
<td>Communications</td>
<td>21.9</td>
</tr>
<tr>
<td>Avionics</td>
<td>159.5</td>
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<tr>
<td>SEP Stage Basic Wet Mass</td>
<td>1668.8</td>
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<tr>
<td>SEP Stage Basic Dry Mass</td>
<td>811.6</td>
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<tr>
<td>System Growth (20% dry)</td>
<td>162.3</td>
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<tr>
<td>SEP Stage total dry mass with growth</td>
<td>973.6</td>
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<tr>
<td>LV adaptor</td>
<td>80</td>
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<td>Science Payload</td>
<td>20</td>
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<tr>
<td>Total wet mass with growth in LEO</td>
<td>1931</td>
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<tr>
<td>LV performance to LEO</td>
<td>1800</td>
</tr>
</tbody>
</table>

Launch Date: 9-22-2017
Spiral to Escape: 149.7 days
Depart LEO: 2-19-2018
Trip time to NEA: 550 days
Arrival Date: 8-29-2019

ΔV capability ~ 12,600 m/s
Explore asteroids that are candidates for future human space missions beyond Earth as while also satisfying the tech demo objectives of the SEP TDM as a cost share

- Demonstrate SEP technology, to mature TRL
- NEXT thruster, two thruster operation
- Lower Xe load allows demonstration of Mega Flex arrays

Power System – Demonstrate high power SAS
- 9 m diameter Mega Flex arrays (2); 20 kW BOL
- 160 VDC primary distribution to EP; 1-28 VDC battery for subsystems

Electric Propulsion System – Demonstrate two thruster operations
- NEXT Thrusters (2), 7 kW, Isp 4190sec, PPU (2), 1 Cassini Xe tank

Spacecraft cost ~ $230M

ΔV capability ~ 12,600 m/s

Launch Date: 12-10-2017
Spiral to Escape: 360 days
Depart LEO: 12-6-2018
Trip time to NEA: 550 days
Arrival Date: 6-8-2020
NEA Precursor Mission Concepts

- This NEA mission provides an opportunity to demonstrate and quantify the effects on power and propulsion systems during the lengthy LEO spiral trip times experienced by high power SEP missions.
- Both of the NEA precursors SEP Concepts demonstrate feasibility of a lower cost SEP for NEA precursor mission as an SEP TDM option.
  - Single Hall Thruster configuration demonstrates high power DSS ROSA, and high voltage
  - Dual NEXT thruster system demonstrates high power ATK Mega Flex, and two thruster operation
- Of particular interest to the application of solar arrays for future large payloads, is the effect of the long dwell time in LEO and exposure to Earth’s albedo and Van Allen belts on thermal, electronic and power systems.
- Both concepts compare favorably with Dawn (a NEA mission) mass, mission, and costs
- Both concepts within 10-15% of $200M cost goal
- Both concepts within 10% of 1800 kg IMLEO goal
SEP Ride Share Concept: ESPA Grande Based Bus

The goals of the ride share mission concepts were to explore the impacts of a rideshare configuration on an SEP spacecraft design and to provide a reduced cost concept with the maximum capability possible.

SEP vehicle initial launch mass of ½ Falcon 9 performance to GTO (2800 kg)

Power System – Demonstrate high power SAS
• DSS arrays (2); 15 kW BOL

Electric Propulsion System – Demonstrate DDU and two thruster operations
• Hall Thrusters (2), 15 kW, Isp 2000 sec, DDU(2), tank (4) ~900 kg Xe

Bus Structure
• ESPA Grande based structure, support ½ Falcon 9 performance to GTO

Spacecraft cost ~ $230M

Launched to GTO
Low thrust spiral to GEO, Reduce Inclination and circularize Spiral back to LEO ~ 1000 km alt

Mission Duration 380 days
Mission total propellant 820 kg

ΔV capability ~ 7700 - 8800 m/s
SEP Ride Share Concept: Cylindrical Bus

The goals of the ride share mission concepts were to explore the impacts of a rideshare configuration on an SEP spacecraft design and to provide a reduced cost concept with the maximum capability possible.

SEP vehicle initial launch mass of ½ Falcon 9 performance to GTO (2800 kg)

Power System – Demonstrate high power SAS
• DSS arrays (2); 15 kW BOL

Electric Propulsion System – Demonstrate DDU and two thruster operation
• Hall Thrusters (2), 15 kW, Isp 2000 sec, DDU(2), tank (5) ~1130 kg Xe

Bus Structure
• Cylindrical bus structure, support ½ Falcon 9 performance to GTO load

Spacecraft cost ~ $230M

ΔV Capability ~ 9800 -11,000 m/s

Launch dynamics
Low thrust spiral to GEO.
Reduce Inclination and circularize.
Spiral back to LEO ~ 1000 km alt

Mission Duration 380 days
Mission total propellant 820 kg

SEP spacecraft MEL Basic Mass (kg)
ACS 38.5
C&DH 23.3
Communications 53.7
Electrical Power System 6.5
Solar Array System 80.9
Thermal Control 160.0
RCS Hardware 115.4
RCS propellant 7.8
EP hardware 193
Xenon 1129
Structures and Mechanisms 349
Total Basic Dry Mass 1030
Total Growth (30% dry) 309
SEP Stage total dry mass with growth 1339
LV adaptor 51
Total wet mass in GTO 2487
LV performance to GTO 2538
LV Margin 52

LV performance to GTO
15 kW Hall Thrusters (2)
Ride Share Concept Comparison

- Both designs satisfy the technology demonstration goal of demonstrating SAS deployment and the operation/characterization of performance in environments similar to the high power HEOMD mission.
  - Both demonstrate high power SAS deployment and operation, and high voltage
  - Both demonstrate two thruster operation
- All differences between the two Ride Share designs are in structure (mass and cost).
  - The total structure based on use of an ESPA Grande is inherently heavier than the cylindrical bus structure.
  - The primary structure mass on the two designs is within 30 kg of each other, with the ESPA Grande primary structure being the slightly heavier of the two.
  - The cylindrical bus structure does not need the secondary items needed to attach items to the ESPA concept.
- The ESPA Grande structure total mass is 163 kg greater than that of the cylindrical bus structure.
- Large ΔV Capability ~ 8000-10,000 m/s (900-1100 kg Xe capability)
- Both concepts within 10% of $200M cost goal
- Both concepts fit within the ½ Falcon 9 IMLEO allocation
μSEPSat Summary: ESPA class small SEP spacecraft

Maximum Xe capacity to provide Max ΔV Capability in concept designed for launch on an EELV Secondary Payload Adapter (ESPA) to minimize costs

- Demonstrate scaled down SEP technology, to mature TRL
- Demonstrate SEP system Earth spiral operations

Power System
- 1.4 m diameter UltraFlex arrays; array power (BOL, 1 AU, 28C):
  - 407W for 28V segment; 459W for 300 V segment

RCS System
- 12 cold gas Xe thrusters (Isp = 25 sec)

Electric Propulsion System
- Hall Thruster (1) 400 W, Isp = 1420 sec; one DDU (300 V); COTS Xe tank (70kg)

Spacecraft cost ~ $50M

<table>
<thead>
<tr>
<th>SEP spacecraft MEL</th>
<th>Basic Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload</td>
<td>4.4</td>
</tr>
<tr>
<td>ACS</td>
<td>5</td>
</tr>
<tr>
<td>C&amp;DH</td>
<td>3.8</td>
</tr>
<tr>
<td>Communications</td>
<td>6.5</td>
</tr>
<tr>
<td>Electrical Power System</td>
<td>8.8</td>
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<tr>
<td>Solar Array System</td>
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<tr>
<td>Thermal Control</td>
<td>12.3</td>
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<tr>
<td>RCS Hardware</td>
<td>1.6</td>
</tr>
<tr>
<td>EP hardware</td>
<td>13.2</td>
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<tr>
<td>Xenon</td>
<td>72.3</td>
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<td>Structures and Mechanisms</td>
<td>23.8</td>
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<tr>
<td>Total Basic Dry Mass</td>
<td>87</td>
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<td>Total Growth (30% dry)</td>
<td>25</td>
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<tr>
<td>SEP Stage total dry mass</td>
<td>108</td>
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<tr>
<td>with growth</td>
<td></td>
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<tr>
<td>LV adaptor</td>
<td>2</td>
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<tr>
<td>Total wet mass</td>
<td>185</td>
</tr>
<tr>
<td>ESPA performance</td>
<td>180</td>
</tr>
</tbody>
</table>

ΔV Capability ~ 5600 m/s

GTO to LGA: 216 days
LGA to Itokawa: 1467 days

SEP Stage total dry mass with growth
### Micro Solar Electric Propulsion Satellite (μSEPSAT)

- Designed for launch on a EELV Secondary Payload Adapter (ESPA) to minimize launch costs
- Overall mission cost could be reduced as much as 80%
- Resultant increase in flight rate would result in paradigm shift, bridging gap from cubesats to full-sized S/C

### Small SEP S/C vs Conventional SEP S/C

<table>
<thead>
<tr>
<th>Mission Type</th>
<th>Dawn</th>
<th>SMART-1</th>
<th>μSEPSAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year Launched</td>
<td>2007</td>
<td>2003</td>
<td>--</td>
</tr>
<tr>
<td>Spacecraft Dry Mass</td>
<td>770 kg</td>
<td>287 kg</td>
<td>102 kg</td>
</tr>
<tr>
<td>Xe Propellant</td>
<td>450 kg</td>
<td>80 kg</td>
<td>72 kg</td>
</tr>
<tr>
<td>Payload mass</td>
<td>45 kg</td>
<td>19 kg</td>
<td>5 kg</td>
</tr>
<tr>
<td>Spacecraft Power</td>
<td>10 kW @ 1 AU</td>
<td>1.8 kW @ 1 AU</td>
<td>0.9 kW @ 1 AU</td>
</tr>
<tr>
<td>EP power</td>
<td>2.3 kW</td>
<td>1.2 kW</td>
<td>0.4 kW</td>
</tr>
<tr>
<td>Delta V</td>
<td>10 km/s</td>
<td>2.7 km/s</td>
<td>5.6 km/s</td>
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<tr>
<td>Spacecraft Cost</td>
<td>$230M</td>
<td>~$100M</td>
<td>$47M (est)*</td>
</tr>
<tr>
<td>Launch Vehicle</td>
<td>Delta II</td>
<td>Ariane V (secondary)</td>
<td>secondary</td>
</tr>
</tbody>
</table>

*estimated first unit cost, recurring cost estimated ~$20M
Conclusions

• Multiple SEP TDM mission concepts were developed by NASA to investigate various options for performing a SEP TDM.

• These concepts ranged from
  – An approximately 10,000 kg concept capable of delivering 4000 kg of payload to EM-L2 in support of future human-crewed outposts launched on a medium-class launch vehicle to
  – A 180 kg concept capable of performing an asteroid rendezvous mission after launched to GTO as a secondary payload

• If 30 kW-class solar arrays and the corresponding electric propulsion system currently under development by STMD are used as the basis for sizing the mission concept, the data suggest estimated spacecraft costs of $200M -$300M

• The most affordable mission concept developed based on subscale variants of the advanced solar arrays and EP had a ΔV capability comparable to the much larger SEP TDM concepts with at an estimated cost of $50M

• Current SEP TDM mission under study is ARRM, a cost share with HEO