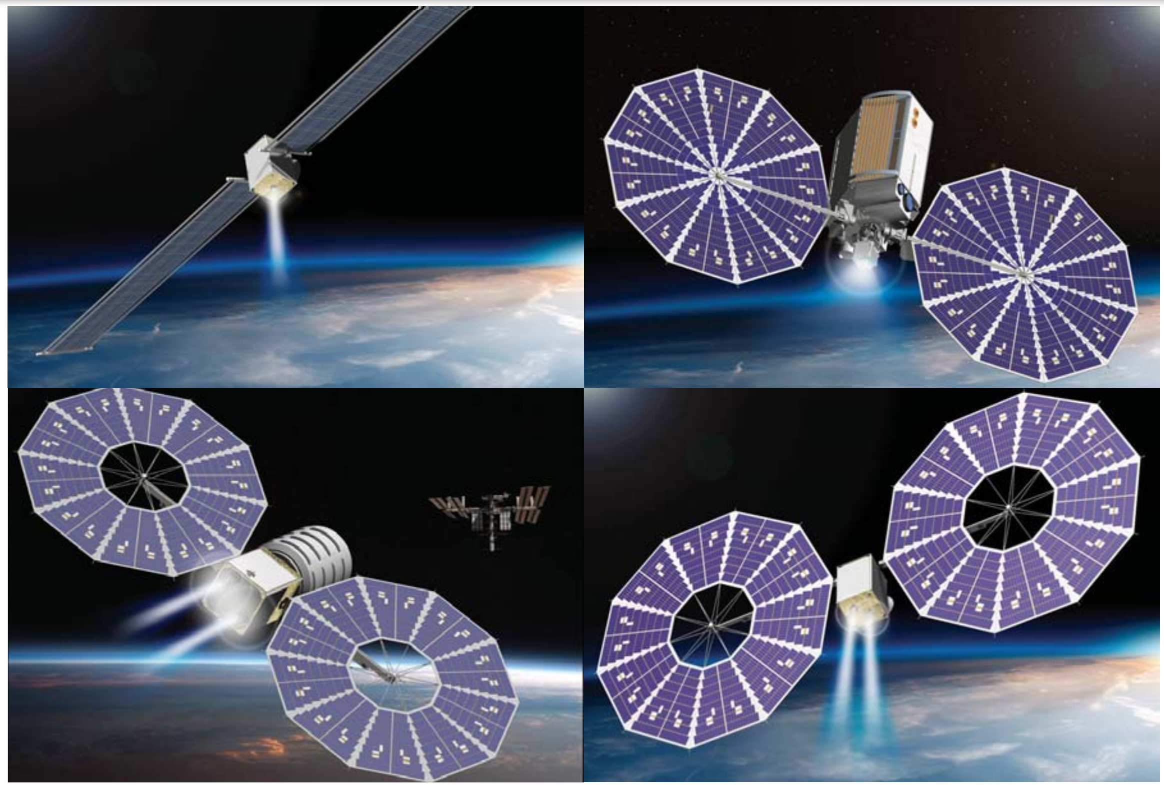
National Aeronautics and Space Administration

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



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Motivation

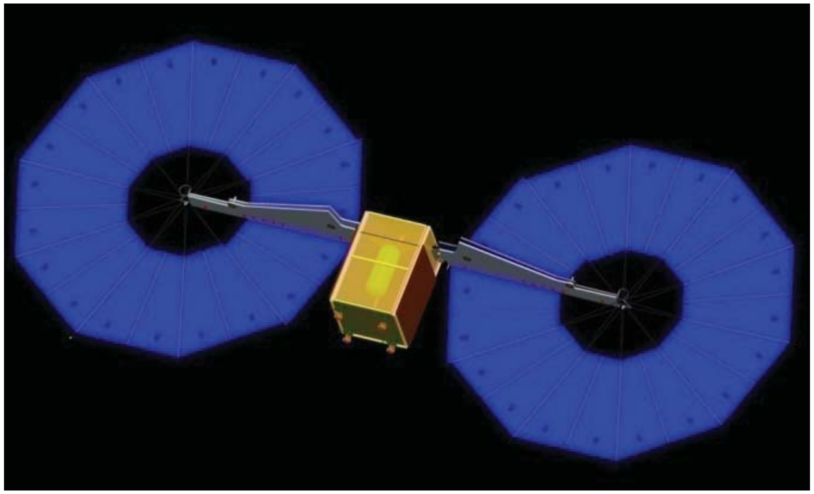
- Primary objective of **SEP TDM** is to **develop** and **demonstrate** an enabling propulsion capability, based on **next generation solar electric propulsion** technologies as part of an integrated system, extensible to higher power systems
- Initial mission concepts (internal and via contracts) have 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

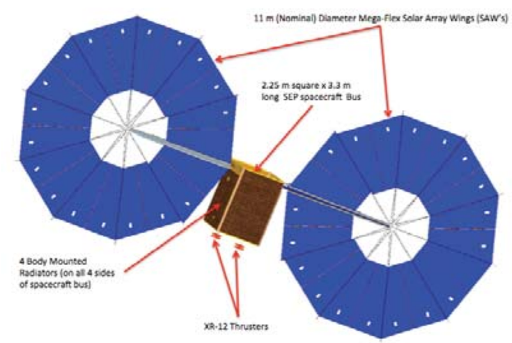
Partner Focus	Concept Mission
NASA HEOMD	EM-L2 Logistics support mission
Multiple	Secondary payload concepts
NASA HEOMD/SMD	NEA Precursor mission
Commercial/Cost sharing	Ride Share, ESPA based structure; Ride Share, Max propellant loading
ESPA Micro Spacecraft	μSEPSAT

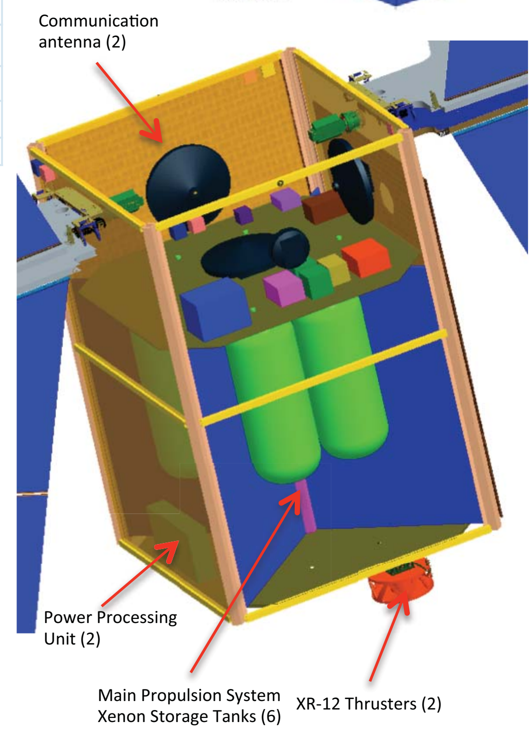


EM-L2 Logistics Spacecraft Concept Summary

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

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





- The goal is to deliver a 5,000 kg. payload mass from LEO to EM-L_2
- The goal is to complete the EM-L_2 transfer in less than two years
- Dedicated medium class single LV

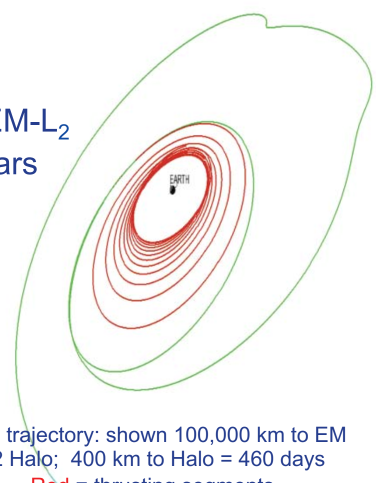
Power System

- 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

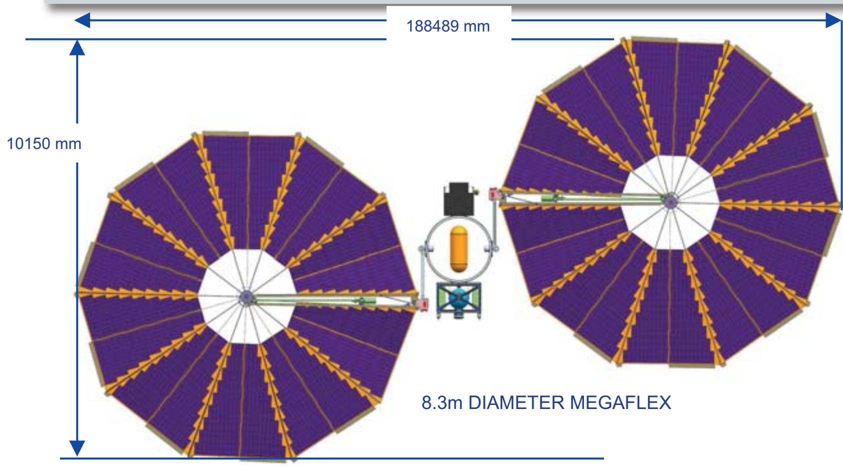
Spacecraft cost ~ $200-300M



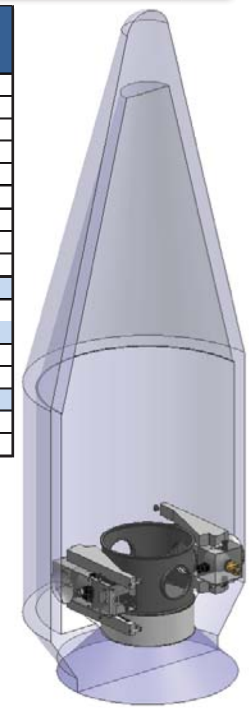
SEP trajectory: shown 100,000 km to EM L2 Halo; 400 km to Halo = 460 days
Red = thrusting segments
Green =coasting

SEP Secondary Payload Concept Summary

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



	CBE Mass (kg)	Contingency (%)	Total Mass (kg)	Heritage/Comments
C&DH	4.9	15%	5.6	BRE Integrated Avionics
Power	167.2	28%	214.8	Solar Arrays + ABSL battery
Telecom	3.3	13%	3.7	L3 OTS S-band
Structures	214.9	17%	251.9	Includes ESPA ring,
Thermal	39.4	30%	51.3	Heaters, MLI, thermostats
Propulsion	162.8	11%	180.2	EP and RCS
GN&C	7.9	8%	8.6	LN200, AASTR, GDE
Spacecraft Total	**600.4**	**19%**	**716.0**	
System Margin			98.9	
Dry Mass Total		**43%**	**814.9**	43% on all but ESPA (8%)
Xenon Propellant			220.0	
RCS Propellant			32.0	
Wet Mass Total			**1066.9**	
LV Mass Allocation			1200.0	
Launch Mass Margin			133.1	

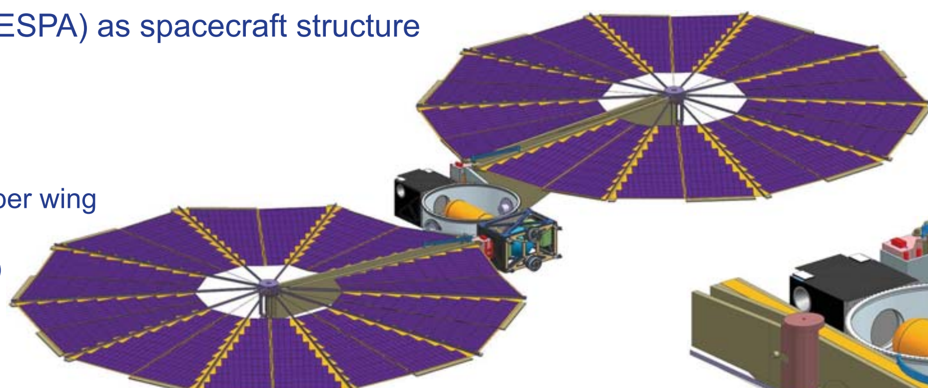


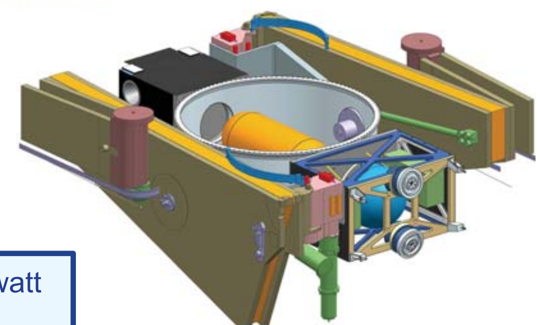
- Secondary payload concept
- Use ELLV Secondary Payload Adaptor (ESPA) as spacecraft structure
- Total mission cost goal <$200M

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

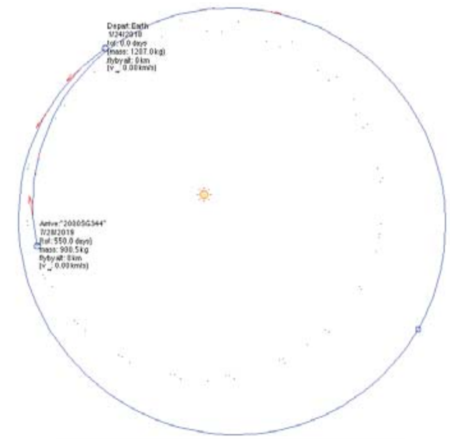
ΔV capability ~ 4500 m/s

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

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



Launch Date: 9-22-2017
Spiral to Escape: 149.7 days
Depart LEO: 2-19-2018
Trip time to NEA: 550 days
Arrival Date: 8-23-2019

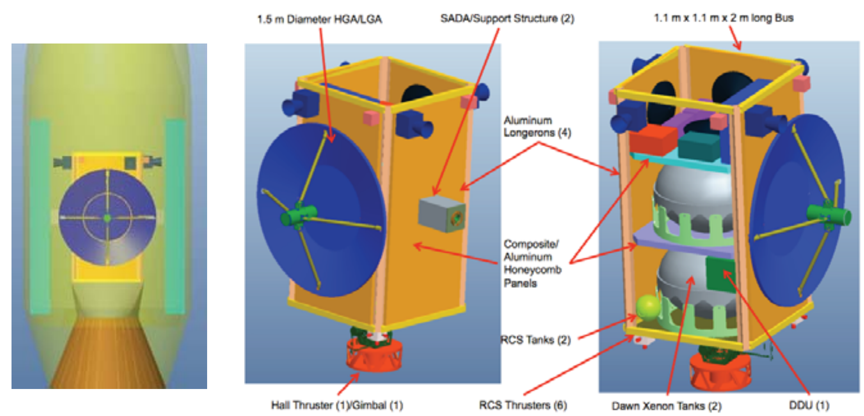
ΔV capability ~ 12,600 m/s

- 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

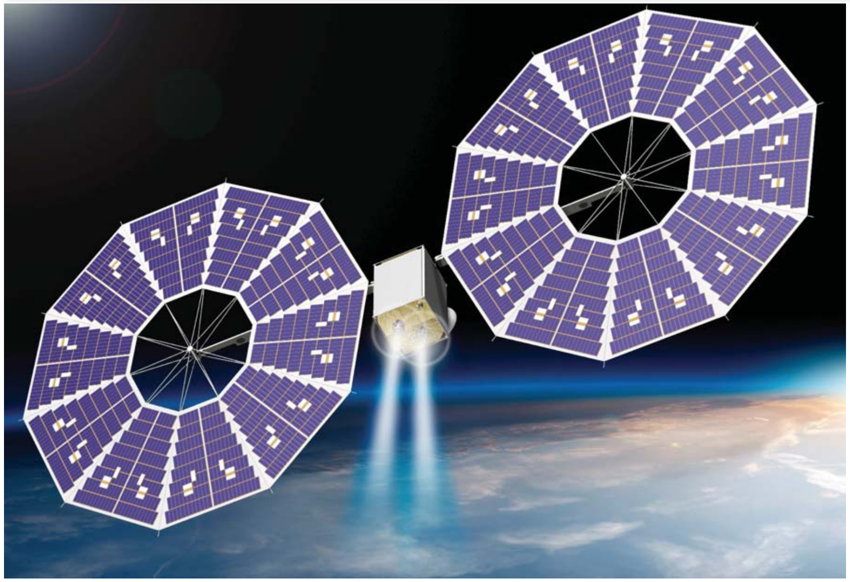
Electric Propulsion System – Demonstrate DDU
- Hall Thruster (1), 15 kW, Isp = 2000 sec, DDU (2), 2 Dawn Xe tank

Spacecraft cost ~ $220M

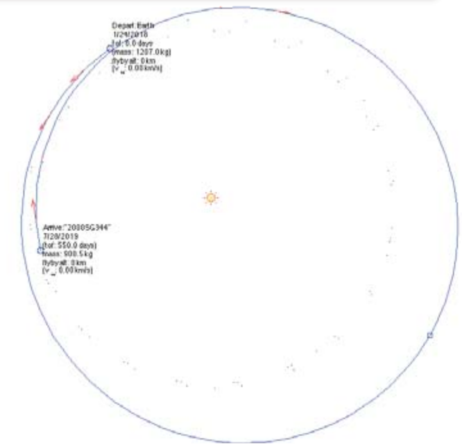


NEA Precursor SEP Spacecraft Concept C2 Summary

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



SEP spacecraft MEL	Basic Mass (kg)
Structures	139.8
Power	309.8
ACS/RCS	53.5
Main Propulsion	157.9
Total propellant (Main + RCS)	508.4
Thermal Control	156.8
Communications	21.9
Avionics	174.8
SEP Stage Basic Wet Mass	**1504.5**
SEP Stage Basic Dry Mass	**996.1**
System Growth (20% dry)	199.2
SEP Stage total dry mass with growth	**1195.4**
LV adaptor	80
Science Payload	20
Total wet mass with growth in LEO	1803
LV performance to LEO	1800



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

ΔV capability ~ 12,600 m/s

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

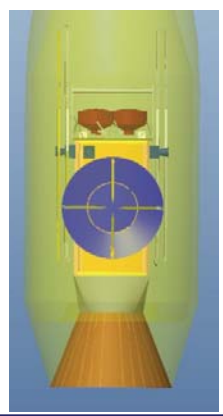
Power System – Demonstrate high power SAS

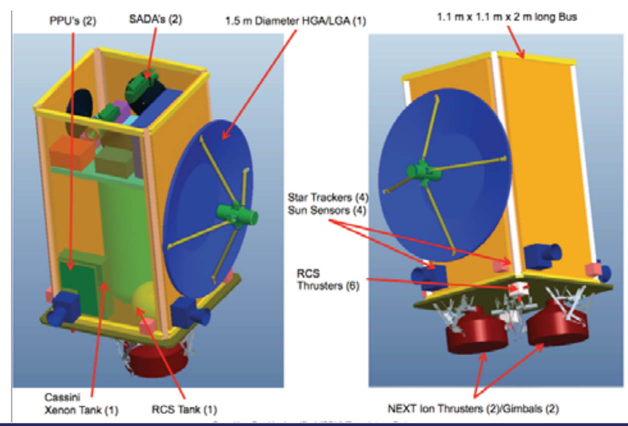
- 9 m diameter Mega Flex arrays (2); 20 kW BOL
- 160 VDC primary distribution to EP; 1- 28 VDC battery for subsystems

Electric Propulsion System – Demonstrate two thruster operations

- NEXT Thrusters (2), 7 kW, Isp 4190sec, PPU (2), 1 Cassini Xe tank

Spacecraft cost ~ $230M

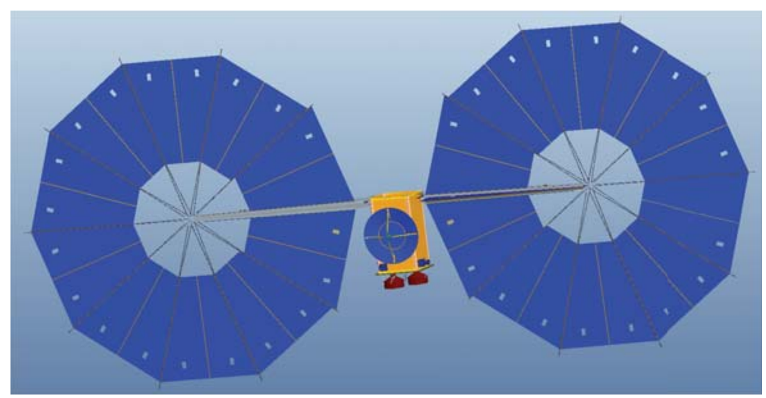




NEA Precursor Mission Concepts

- 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

Single Hall, DSS ROSA



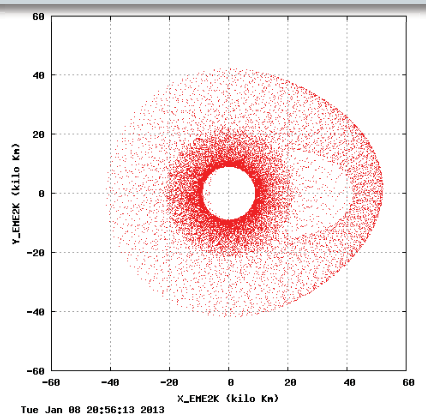
Dual NEXT, Mega Flex

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)

SEP spacecraft MEL	Basic Mass (kg)
ACS	23.3
C&DH	53.7
Communications	6.5
Electrical Power System	80.9
Solar Array System	160.0
Thermal Control	115.4
RCS Hardware	7.8
RCS propellant	19
EP hardware	173.4
Xenon	902
Structures and Mechanisms	513.4
Total Basic Dry Mass	1173
Total Growth (30% dry)	352
SEP Stage total dry mass with growth	**1525**
LV adaptor	51
Total wet mass in GTO	2446
LV performance to GTO	2590
LV Margin	93



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

Power System – Demonstrate high power SAS

- DSS arrays (2); 15 kW BOL

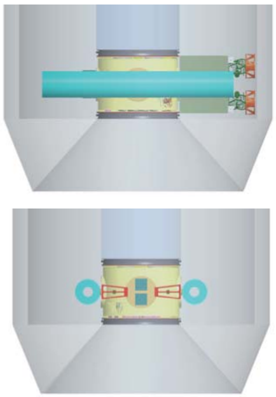
Electric Propulsion System – Demonstrate DDU and two thruster operations

- Hall Thrusters (2), 15 kW, Isp 2000 sec, DDU(2), tank (4) ~900 kg Xe

Bus Structure

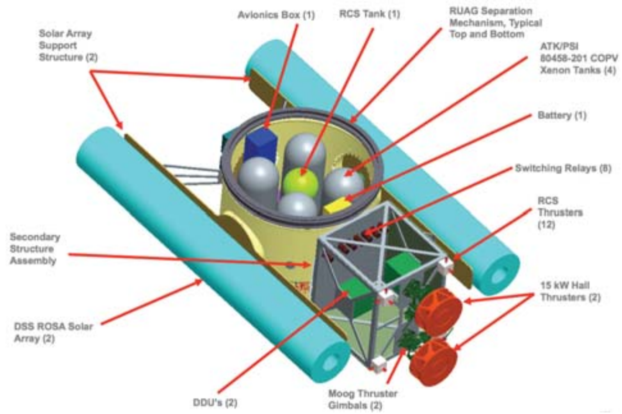
- ESPA Grande based structure, support ½ Falcon 9 performance to GTO

Spacecraft cost ~ $230M



Falcon 9 Fairing

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)

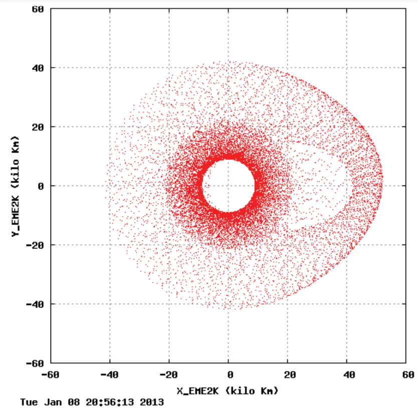
Power System – Demonstrate high power SAS
- DSS arrays (2); 15 kW BOL

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

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

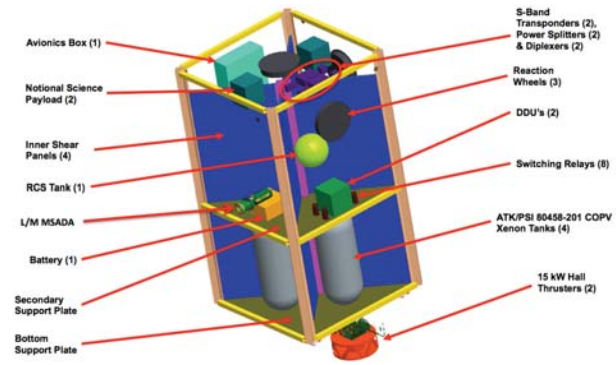


Launched to GTO
Low thrust spiral to GEO,
Reduce Inclination and circularize
Spiral back to LEO ~ 1000 km alt

Mission Duration 380 days
Mission total propellant 820 kg

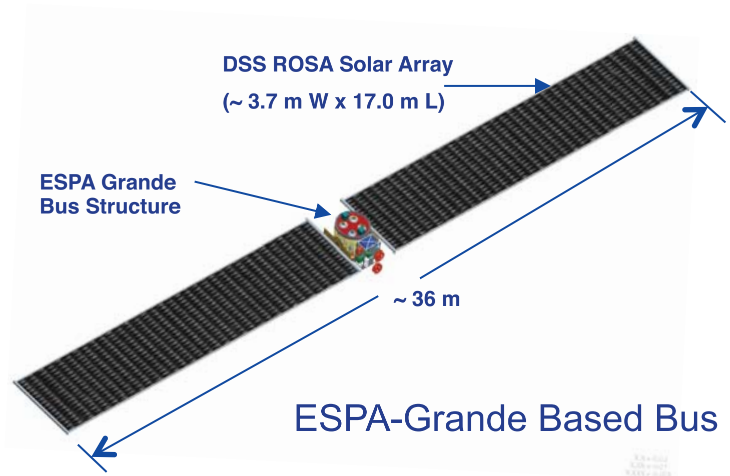
ΔV Capability ~ 9800 -11,000 m/s

Falcon 9 Fairing

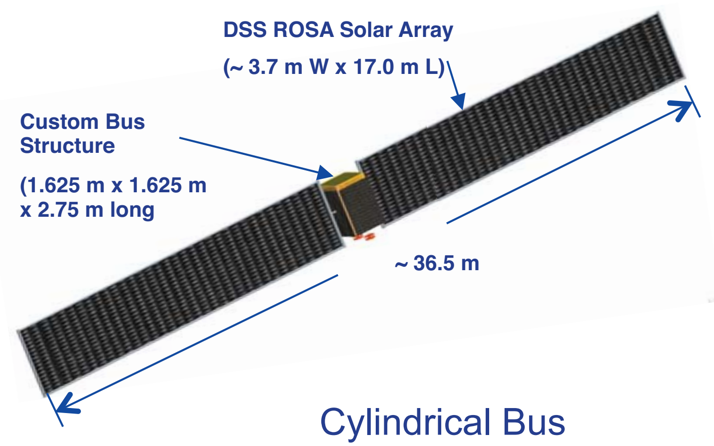


Ride Share Concept Comparison

- 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



ESPA-Grande Based Bus

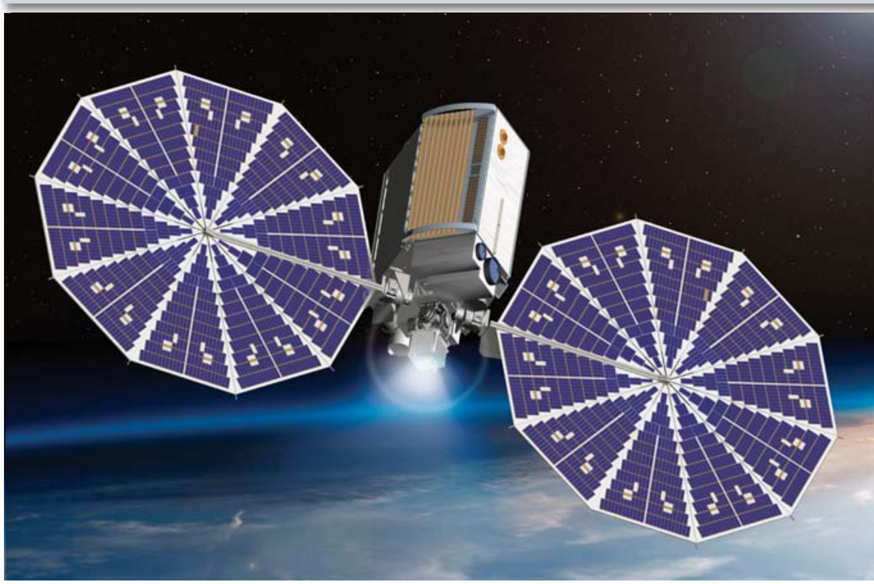


Cylindrical Bus

National Aeronautics and Space Administration

μSEPSat Summary: ESPA class small SEP spacecraft

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



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

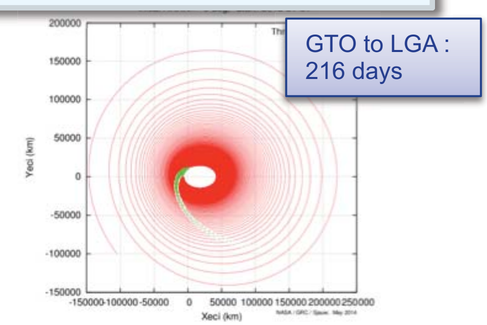
Power System
- 1.4 m diameter UltraFlex arrays; array power (BOL, 1 AU, 28C):
- 407W for 28V segment; 459W for 300 V segment

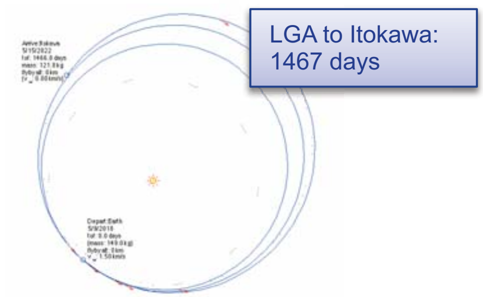
RCS System
- 12 cold gas Xe thrusters (Isp = 25 sec)

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

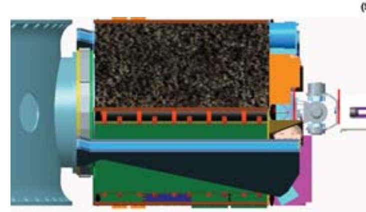
Spacecraft cost ~ $50M

SEP spacecraft MEL	Basic Mass (kg)
Payload	4.4
ACS	5
C&DH	3.8
Communications	6.5
Electrical Power System	8.8
Solar Array System	8.2
Thermal Control	12.3
RCS Hardware	1.6
EP hardware	13.2
Xenon	72.3
Structures and Mechanisms	23.8
Total Basic Dry Mass	87
Total Growth (30% dry)	25
SEP Stage total dry mass with growth	108
LV adaptor	**2**
Total wet mass	185
ESPA performance	180

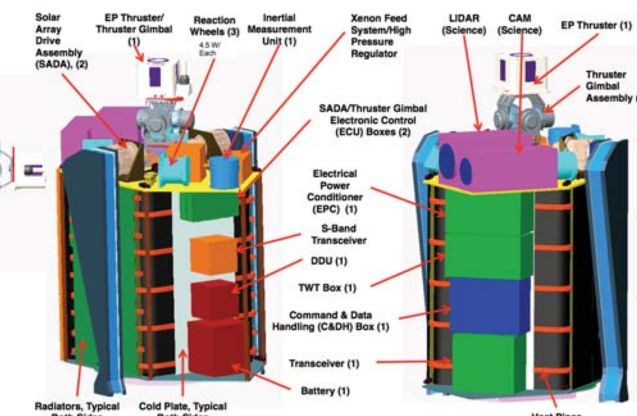




ΔV Capability ~ 5600 m/s

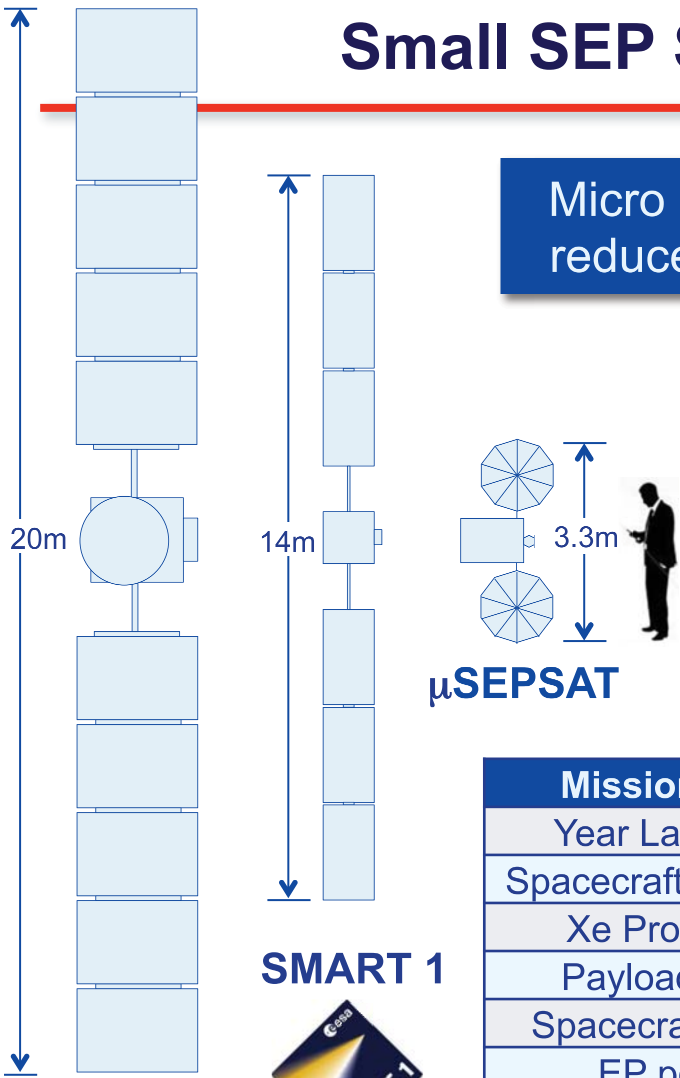


ESPA Secondary Payload packaging



Small SEP S/C vs Conventional SEP S/C

Micro Solar Electric Propulsion Satellite (μSEPSAT) would reduce SEP spacecraft by >60% while increasing ΔV ≥ 2X



- 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

Dawn

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

*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