Solar Electric Propulsion Demonstration Mission Baseline Concept Description

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William D. Deininger,[1] Scott Enger,[2] Joe Hackel,[3] J. C. Soto,[4] and Bryce Unruh[5]
Ball Aerospace, Boulder, CO, 80301, USA

Dave Murphy [6]
ATK Aerospace Systems, Goleta, CA, 93117, USA

and

Kristi DeGrys [7]
Aerojet Rocketdyne, Redmond, WA, 98052, USA

Abstract: A cost-constrained, solar electric propulsion (SEP) technology demonstration mission (TDM) is described. The mission is fully compliant with the key objectives of NASA's BAA and demonstrates a modular and extensible solar electric propulsion system. It launches in early 2018 and flies multiple LEO-GEO transits over the ~year-long operations period. The SEP TDM Space Vehicle is single flight element with no critical events occurring after launch and solar array deployments. It is based on integrated SEP and Bus Modules allowing parallel development and efficient integration. The SEP Module includes three Hall thruster strings (3 + 0) which can be operated singly, in pairs or simultaneously for full power operations of all 3 together. Advanced, light-weight, blanket solar array technology is employed for the SEP TDM instead of regularly used, rigid panel technology. MegaFlex technology (derived from UltraFlex), using two 10 m-diameter wings, is baselined. The power and propulsion systems are at sufficient specific power to demonstrate the movement of large payloads from LEO to higher energy orbits at performance values consistent with future higher power electric propulsion capabilities (Isp, thrust-to-power, power-to-mass). The SEP TDM, and its SEP Module concept, represents a key infusion point to a reusable electric propulsion stage by demonstrating transfers from LEO to GEO and back to LEO. This set of high ΔV trajectories demonstrates long-term SEP operations and flies the SEP TDM Space Vehicle through the radiation belts, sustained plasma environments, diverse distributed inertia spacecraft control environments and repeated spacecraft occultations. Substantial mission timeline, mass and propellant margins are built into the mission concept enabling flexibility to accommodate possible mission enhancements and account for uncertainties in mission characteristics.

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[1] Staff Consultant, Mission Systems Engineering, Associate Fellow AIAA, wdeining@ball.com.
[2] Principal Engineer, Power Systems Engineering.
[3] Senior Engineer, Systems Engineering.
[4] Principal Engineer, Mechanical Engineering.
[5] Business Development, Civil Space and Technologies. bunruh@ball.com.
[6] Chief Systems Engineer, Deployable Space Structures.
[7] Manager, Electric Propulsion Systems.

Nomenclature

ADCS = Attitude Determination and Control
ATP = Authorization to Proceed
BAA = Broad Area Announcement
CONOPS = Concept of Operations
GEO = Geostationary Earth Orbit
HET = Hall Effect Thruster
kW = Kilowatts
LEO = Low Earth Orbit
m = meters
MOC = Mission Operations center
NASA = National Aeronautics and Space Administration
NEN = Near Earth Network
NEXT = NASA Evolutionary Xenon Thruster
PPU = Power Processing Unit
SEP = Solar Electric Propulsion
SEPSPOT = NASA Glenn SEP Trajectory Code
TDM = Technology Demonstration Mission
TOC = Technology Operations Center
TRL = Technology Readiness Level
XFC = Xenon Flow Controller
ΔV = Delta Velocity Increment

I. Introduction

THE notion of using SEP in near-Earth space has been studied for decades. NASA’s current architecture planning, technology roadmaps and goals of ongoing technology development imply near-term utility of high power SEP. Specifically, high power SEP systems are a cornerstone of several Exploration system architectures. Cargo transport to support human exploration beyond LEO is one key application. Potential missions to the moon, near-Earth objects, LaGrange points, and Mars all have variations that leverage high power SEP systems.

Other potential applications of SEP include: resupply, servicing, operational orbit change, debris removal, movement to a decommissioning orbit, and replenishment for assets in geo-centric space. These applications have been discussed at length in technical conferences and the space press.

Validation of high power SEP in operational systems must be accomplished before it can support human missions. Subsystem elements are sufficiently mature to push for this validation now. Demonstration of modular, high power SEP systems provides extensibility and scalability to larger missions. A near-term flight demonstration mission validates SEP for these applications and firmly establishes the ‘capability.’

Ball’s Baseline Mission concept meets the requirements of NASA’s BAA[1], uses a simple approach and mature subsystems, so that an industry prime contractor can execute the mission with NASA participation and oversight. Using an industry prime for SEP TDM infuses the technology into industry, paving the way for industry support of larger future missions employing high power SEP.

II. Approach for Achieving Mission Goals and Objectives

The recommended implementation approach uses proven mission systems engineering methods to accomplish:

- Definition and refinement of technical requirements.
- Design and procurement/build of the system, subsystems and components (preliminary through detailed).
- Analytical verification of the design.
- Fabrication, assembly and system integration.
- Verification of functionality, performance and interfaces, and maximizing use of test.

The above process is overlaid with a philosophy of design-to-cost while looking at risk mitigation (technical, cost/schedule), unique CONOPS implications, and extensibility to larger high power SEP systems as drivers. Design-to-cost coupled to the near-term ATP implies use of the most mature subsystems and components in each area of the system. Active program management using risk tracking, assessment, mitigation and retirement is appropriate for the SEP TDM as in any operational space system development. The unique CONOPS and demonstration drives planning of operation and data requirements and analysis. Finally, extensibility assessments ensure the SEP TDM design advances technologies and system level concepts towards maturity for larger scale SEP Tug applications.

The SEP TDM baseline mission concept should be executed using a single SEP TDM industry prime contractor, selected via competitive procurement, to provide an affordable mission solution. Such a prime contractor would be accountable for the complete space vehicle (spacecraft and SEP module) working in a design-to-cost and design-to-schedule manner with NASA oversight. Competition, plus contract performance incentives that apply to this approach result in an affordable program with low cost and schedule risk. Today's budgetary constraints and the targeted cost cap heighten criticality of cost effective program execution.

Executing the SEP TDM retires risks to SEP tug system-level architectural and component technologies. The mission increases the TRL to 8 for many SEP system-level technologies including: multi-thruster operations; ADCS functionality with large, distributed inertia solar arrays; rapid electric propulsion system power cycling and turn-on transients (eclipse operations), thrust-to-power and power-to-mass; and definition of subsystem requirements drivers for future applications in geo-centric space. The mission increases the TRL to 7 for most other SEP system-level technologies including: radiation and plasma environment accommodation; large, light-weight solar array technology readiness, test and validation, and high power, high voltage implementations; electric propulsion system readiness in the 20 to 40 kW thruster system operating range along with power processing and control; and LEO orbit drag for operational space tugs.

III. Mission Concept and Space Vehicle Description

The SEP TDM Baseline Mission implementation uses a straightforward mission design that minimizes technical risk outside of SEP technology, allowing development to better focus on SEP by employing:

- An integrated Space Vehicle with no complex docking, rendezvous or separation events.
- Simple orbital operations with relaxed pointing requirements for system attitude control.
- No critical events following launch and solar array deployment.

The Baseline Mission concept derives from requirements to achieve SEP TDM goals while concurrently controlling cost by considering the concept of operations (CONOPS) and ground test verification. The resulting Space Vehicle is illustrated in **Fig. 1**. Engineering trades used to develop this baseline also factored in extensibility to high power SEP tugs. The BAA-specified cost cap of $200M for the Baseline Mission, including the launch vehicle, is a key driver. Our SEP TDM Baseline Mission sufficiently buys down risks enabling the next step to an operational SEP tug. A shared (dual) launch on a Falcon 9 is assumed to meet the cost objectives.

A. Mission Drivers

Certain aspects of the SEP TDM are unique as compared to scientific or current operational space systems. In combination with the cost cap, these factors had the largest influence on engineering trades and are summarized in **Table 1**.

B. Baseline Flight Segment Overview

The SEP TDM Space Vehicle architecture is a modular, single string design with use of selective redundancy at critical points to prevent credible single-point failures. All non-payload subsystems have direct flight heritage and large performance margins to reduce of risk, given risk posture of this Class D mission. To reduce cost, Space Vehicle hardware is flight-ready through protoflight testing in flight-like environments or flight-qualified at the component level. The flight segment is built up from Bus, Reaction Control System (RCS), and SEP (Solar Electric Propulsion) Modules to streamline integration and test (I&T). Flight-proven, space vehicle Bus and hydrazine propulsion Modules effectively support the SEP TDM. The Bus/RCS Modules mount on top of the SEP Module (**Fig. 1**).

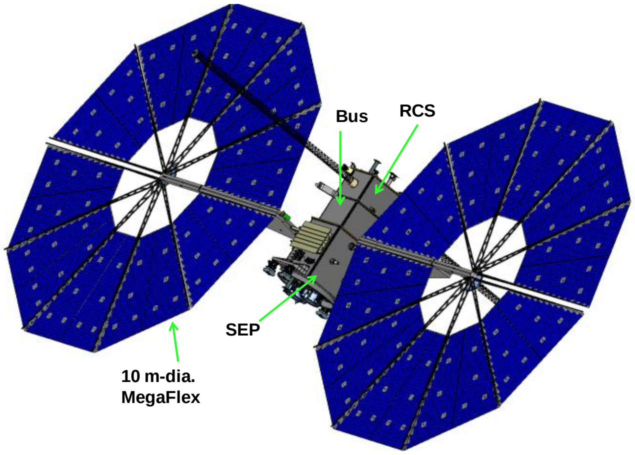

Figure 1. SEP TDM Space Vehicle delivers 20.7 kW (end-of-life) transiting from LEO to GEO and back.

The SEP Module demonstrates multi-thruster operation needed on future tugs by using three Hall

Table 1. Mission-unique aspects drive Baseline Mission concept.

Key, Mission-Unique Requirements	Effect on Baseline Mission Concept
Dwell in radiation belts during spiral orbit transfer.	Employ electronics and system implementations that tolerate total ionizing dose and single event effects. Use design methods to overcome effects of space-charging.
Large, distributed inertia space vehicle in varying orbital environments.	Size attitude control system to handle disturbance torques and aero-drag during LEO operations.
Large, high-voltage, high power subsystem to support SEP power.	Size power generation and control and distribution to safely and reliably operate EP system.
Range of thermal control regimes/orbits from LEO through GEO.	Size thermal control provisions to handle full range of albedo and eclipse durations.

effect thruster (HET) strings. Primary criteria for selection of the EP system include: near-term availability due to the short schedule-to-launch and cost cap constraints precluding substantial development. Technical drivers include specific impulse in the range 1500-3500 s and power-to-thrust levels of 20-25 kW/N. The power-to-thrust levels are particularly important to minimize trip time and the time spent in the radiation/plasma belts. This heavily favors Hall thruster technology. Numerous studies of SEP tug architectures state that HET systems are preferred for operations in geocentric space to reduce trip times. Of the mature systems available, only the BPT-4000 system is in the HET family.

Each SEP Module HET string consists of a BPT-4000 thruster, cathode, 2-axis gimbals, power processing unit (PPU) and xenon flow controller (XFC). All three HETs operate simultaneously at 5.3 kW power each (including loses), for a system power of 15.9 kW. The SEP Module includes two 10 m-diameter, flexible-blanket MegaFlex solar arrays for power. Trades resulting in this hardware selection are driven by the maturity of the technology, i.e. to achieve the cost cap. **Fig. 2** highlights key subsystems in the SEP Module.

Options. In addition to the Baseline Space Vehicle, three other concepts were examined: a Reduced System, an Enhanced Baseline System and a 30 kW System. The Reduced System is smaller using a dedicated launch on a small launch vehicle, has smaller solar arrays, reduced xenon load and use two HET thruster strings. The Enhanced Baseline System includes all the features of the Baseline Mission, has a more populated solar array and adds additional payloads. Enhancement payloads include: an environmental monitoring instrument suite, low power direct drive demonstration, two Vis/IR cameras, two NEXT ion system strings along with additional mission destination options. The 30 kW System included three 12 kW HET strings, 4 NEXT ion system strings, fully populated solar arrays and the Enhancement payloads cited above.

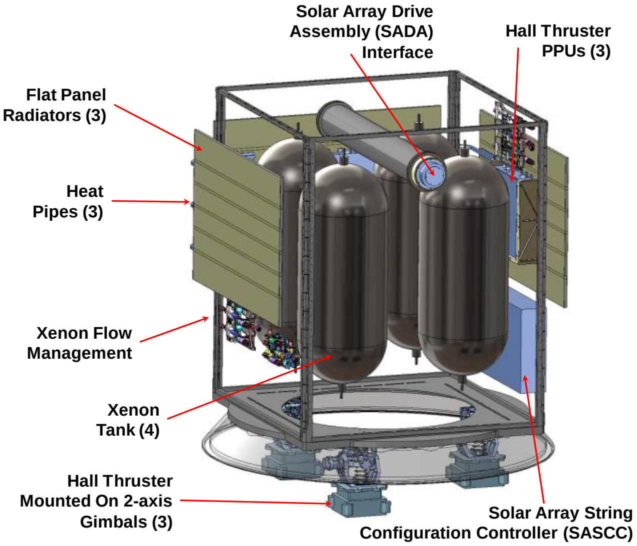

Figure 2. SEP Module. Includes three HET thruster strings, power processing and the interfaces to the solar arrays (power generation).

C. Launch and Ground Segments

The space vehicle concept has been developed with launch vehicle flexibility in mind, **Fig. 3**. Co-manifested launch is recommended to save cost. The flight segment requires roughly one-quarter of the LEO mass capacity of a medium launch system such as the Falcon 9 from Space X. Operational requirements are accommodated by NASA's Near Earth Network (NEN) Ground Stations and TDRSS for launch and early operations. A dedicated Mission Operation Center (MOC) handles command telemetry and housekeeping functions while a Technology Operations Center (TOC) provides analysis of SEP Module performance in a manner analogous to a typical scientific mission. No special new infrastructure that would drive cost is needed.

D. Concept of Operations.

Fig. 4 presents a mission profile while illustrating the environmental and operational challenges. The SEP TDM objective is to reliably and repeatedly demonstrate SEP operation in geocentric space while flying high energy trajectories through the radiation/plasma belts. The mission launches into a 400 km, 28.5 deg LEO orbit, a likely orbit for a staging location or departure orbit for a SEP tug. The mission profile includes an initial 30-day period for on-orbit space vehicle checkout. Baseline launch readiness is January 2018.

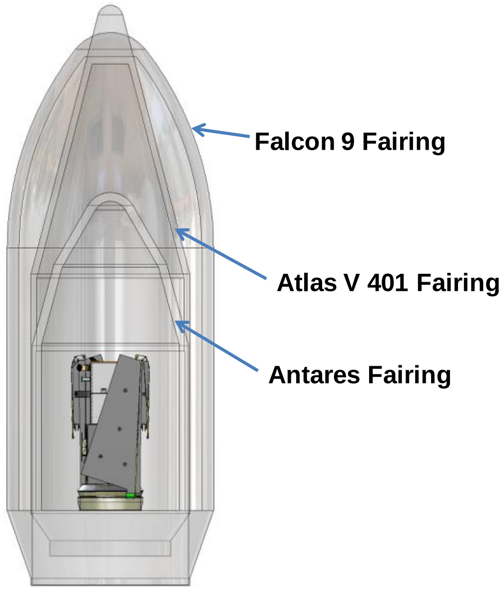

Figure 3. Baseline SEP TDM Space Vehicle is Accommodated in Multiple Launch Fairings – Antares and larger.

Up to twelve months of spiraling is used to demonstrate SEP technology operations following the initial checkout. SEP operation during LEO departure addresses attitude control risk for a large spacecraft having distributed inertias by demonstrating controllability. Both large gravity gradient and atmospheric drag effects make it harder to maintain attitude control and recover normal attitude following anomalous loss of control. After spiraling-out and a dwell in GEO, the SEP TDM vehicle transits back down to an orbit of 400 km, 0 deg. The high energy trajectories include altitude raising and lowering along with 28.5 degrees of inclination change. Performing two high ΔV trajectories, demonstrates:

- round-trip SEP Tug trajectory
- long-term SEP operations,
- repeated flight in geocentric space through the radiation belts,
- sustained operation in plasma environments,
- control of a large distributed inertia spacecraft through diverse torque and disturbance environments
- performance through repeated eclipse cycles that interrupt power production and create a variable thermal environment

The baseline mission duration is ~1 year. SEPSPOT shows 295.3 days are required to execute the LEO – GEO leg (178.4 days) followed by the GEO – LEO leg (116.9 days). This leaves a 69.7 day margin (19.1%). A LEO – GEO SEP transfer using HETs includes up to ~1100 sun/eclipse cycles with thruster on time per orbit varying from ~50 minutes to tens of hours as altitude increases. Detailed trades were examined as part of the study to define the Baseline Mission and are covered in a companion paper at this conference.[2]

Nominally, all three BPT-4000 HETs will be running continuously while in sun during cruise. Post eclipse thruster turn-on time is <5 minutes. The mission requirement is an ability to operate SEP 95% of time while in sunlight. Exceptions are made for initial operations at LEO, any dwell time at GEO and final dwell time at LEO when the Space Vehicle is in quiescent state. There may also be purposeful periods on non-thrusting during spiraling operations for technology tests or scientific investigations.

During all operations, the space vehicle orientation is maintained such that the electric thrusters are pointed along the velocity vector while the single-axis of articulated solar arrays parallels the orbit normal and the arrays stay sun-pointed. The starting orbit and spiral trajectory evolution provide many passes per day over NEN near-equatorial ground stations, enabling a low-cost implementation of uplink-downlink communications in S-band, avoiding frequency band utilization challenges. Sufficient residual ΔV exists within the vehicle for disposal.

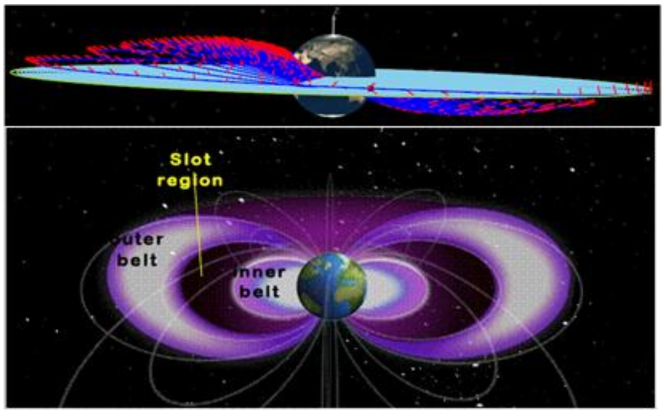

Figure 4. SEP TDM Baseline Mission includes two spiral transits through the radiation belts. The upper part shows the spiral trajectory outbound leg in dark blue with red, the light blue ‘disk’ is the spiral inbound. The complete round-trip trajectory requires ~10 months.

IV. Conclusion

Ball Aerospace SEP TDM Study Team developed a Baseline Mission design capable of meeting the SEP TDM goals: a high-power SEP flight demonstration within a $200M cost objective. This study provides NASA with a strong mission concept that demonstrates sustained in-space operation of an advanced SEP vehicle transiting the radiation/plasma belts two times while flying high-energy trajectories. Executing such a demonstration mission enables infusion of important SEP technology into future operational missions using high power SEP.

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