"It is difficult to make predictions, especially about the future" —Yogi Berra

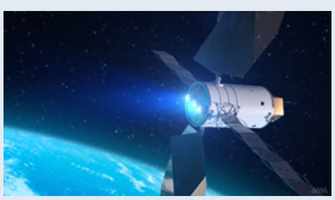
AEROSPACE

Game Changer

COST REDUCTIONS AND FUEL EFFICIENCY: HIGH-POWER SOLAR ELECTRIC PROPULSION IN SPACE

Joshua P. Davis, John P. Mayberry, and Jay P. Penn

Technological progress in space propulsion and space power will disrupt the traditional paradigm of spacecraft design, acquisition, launch, and operations. Electric propulsion systems will replace some or all of the traditional chemical propulsion systems used for orbit raising. High-power solar electric propulsion (HPSEP), which combines advancements in solar array and electric propulsion technologies, enables spacecraft injection into a low Earth orbit (LEO) with HPSEP used for orbit raising. This significantly reduces the launch capacity needs and allows multi-manifesting of spacecraft, increased spacecraft mass for more mission hardware, or the use of smaller launch vehicles for lower launch cost. The tradeoff is longer transfer time to the mission orbit. Once on-orbit, HPSEP also provides much greater electrical power to support advanced spacecraft mission needs. This paper explores the impacts of HPSEP on the future of space from satellite acquisition and space architecture perspectives.

HPSEP: Market Readiness	
High-Power Solar Electric Propulsion (HPSEP)  Source: NASA	**Demonstration Phase** • 2016 Boeing 702SP spacecraft – used all electric propulsion for GTO to GEO orbit raising. • Deployable Space System's (DSS) Roll-Out Solar Array (ROSA) demonstrated on board the ISS.

Strengths	Weaknesses
HPSEP efficiency enables high mass and delta-v capability through propellant-efficient propulsion. • Uniquely enables ride share and/or reduces space vehicle mass, reducing launch costs. • Continued technology improvements in solar power generation and electric propulsion. • Increasing government interest in HPSEP.	HPSEP is unable to move spacecraft quickly compared to chemical propulsion. • Traditional chemical propulsion technology is cheaper to develop and produce due to the application of the technology in missiles and launch vehicles. • Future emerging propulsion technologies may capture market share from HPSEP (e.g., solar sails, nuclear thermal).

Introduction

Solar electric propulsion systems have been studied since the early 1900s by space visionaries such as Tsiolkovsky, Goddard, and Oberth, but have yet to realize their full potential as foreseen by these influential figures.[1] Technological advancement of electric propulsion systems has been slow because of the wide adoption of chemical propulsion technology that is cheaper to develop and produce due its application in missiles and launch vehicles, instead of only spacecraft. Chemical propulsion systems trade better when launch mass is not a constraint or when satellites need to become operational quickly; but for missions with a large spacecraft mass or change in velocity "delta-v" requirement for propulsive maneuvers, the electric propulsion system's propellant efficiency can enable missions that might not be possible with purely chemical systems. Additionally, the reduction in propellant mass for some systems may enable a downsizing of launch vehicles or increasing the total mass delivered to the final orbit, offsetting the higher cost of the electric propulsion system and actually reducing the overall mission cost.[2] In the future, reduced mission cost may overcome time-to-orbit as a driving requirement, especially when replacing aging spacecraft where advanced planning can account for the extended transfer time to leverage cost savings.

Technological advancement of electric propulsion systems has been slow due to the wide adoption of chemical propulsion technology…

Electric propulsion requires a much higher operational power level than chemical propulsion. Typically, chemical propulsion systems require dozens of watts and only operate for a few minutes at a time. Electric propulsion systems typically require hundreds or thousands of watts (or more) and, due to their exceptionally low thrust, need to operate for extended periods. Because of this, only spacecraft with high-power requirements typically use electric propulsion systems because they can leverage the existing power system design. Spacecraft with lower power requirements will need larger solar arrays to accommodate the higher power of the electric propulsion systems, which increases the cost and complexity, or they can use a modular electric propulsion stage that could enable multi-manifesting to help spread launch costs.

Solar array technology advancements have reduced mass and stowage volume by an order of magnitude and increased structural stiffness, while automation is expected to further lower cost.[3] These advancements, as well as next-generation higher power electric thrusters, will change the tradespace for propulsion systems and enable lower cost space access by leveraging high fuel efficiency low-launch mass HPSEP systems on smaller launch vehicles or multi-manifesting to share launch costs.

Figure 1 outlines the expected path of HPSEP technology maturation and adoption. More details are provided later in the paper.

- Thruster and solar array technologies (far-left column) are currently available or under development. These technologies include current commercially developed systems as well as next-generation government developed systems. Currently, all the technologies are technology readiness level (TRL) 5 or greater and, in some cases, have been demonstrated on-orbit.

- Expected demonstrations of HPSEP technologies and concept of operations (ConOps) within the next five years (second column) flow from research and development efforts (first column). For example, high-power commercial geosynchronous Earth orbit (GEO) communications satellites being developed today are leveraging next-generation solar array technologies, and governmental entities are exploring their use in mission designs. They rely on solar array and HPSEP thruster technology currently under development. All-electric GEO transfer orbit (GTO)-to-GEO transfer has already been performed.[4]

- Expected paths of market growth and maturation (third and fourth columns) come about once technologies and ConOps are demonstrated, including anticipated mature architectures. Commercial entities leverage HPSEP to reduce overall mission cost by performing more efficient orbit raising and to enable spacecraft with much higher power levels than are currently available. Governmental entities are looking to incorporate HPSEP into their architectures to

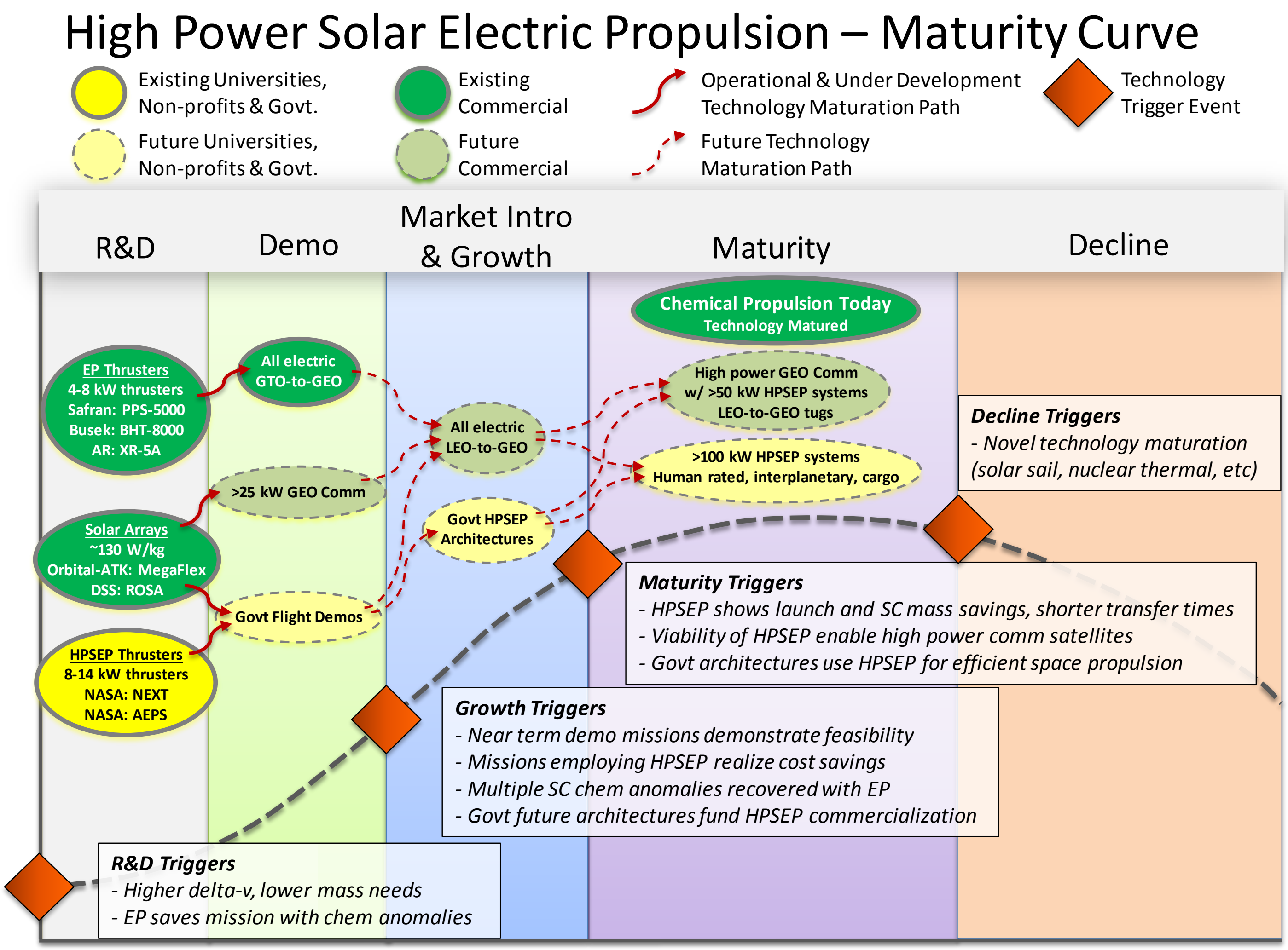


Figure 1: This figure shows the anticipated maturity curve and technology maturation path of HPSEP.

reduce cost and enable missions.[2,5,6] Chemical propulsion, shown in column 4 for reference, is already mature and widely adopted.

- Figure 1 also shows technology trigger events that may spur movement along the maturity curve.

Research and Development (R&D) Triggers highlight events that may initiate a directed effort amongst the community to mature the technology. General trends in space architectures and spacecraft design have raised the need for higher delta-v and lower mass systems which is where electric propulsion (EP) does very well. Additionally, a failure of the Advanced Extremely High Frequency (AEHF) spacecraft's liquid apogee engine was mitigated by using the spacecraft's onboard EP system[7] prompting future architectures to look more closely at their orbit raising ConOps.

Growth Triggers include completion of demonstration activities that mature technology components, such as the flight of Deployable Space System's (DSS) Roll-Out Solar Array (ROSA) on board the International Space Station (ISS),[8] and ConOps, such as the previously mentioned GTO-to-GEO EP transfer. In addition to demonstrations, more failures of chemical systems[9] and launch vehicle anomalies[10] have prompted a need for alternate, more robust orbit raising methodologies. Also, government architectures and related funding can trigger HPSEP technology maturation.

Maturity Triggers occur when the HPSEP technology moves into a mature phase within the space market. It is highlighted by widespread adoption among governmental and commercial entities, with many HPSEP systems on-orbit, providing a variety of services, including high-power missions, orbit raising and cargo delivery services, and unique interplanetary and human-rated missions.

Decline Triggers signal when the HPSEP technologies start becoming obsolete. These triggers will likely include the maturation of other propulsion and power technologies. Currently, these technologies include solar sails, nuclear thermal propulsion, and other novel propulsion technologies being studied.

The HPSEP maturity curve presented in this paper is a projection of current market trends into future architectures. To further illustrate the near-term incentives to develop HPSEP, Table 1 highlights the current space market needs and how HPSEP fits into the solution space.

It is quite possible that HPSEP technology may encounter entry barriers currently unforeseen, such as an impasse in the technology development resulting in an inability of an HPSEP system to function as intended. Failures of HPSEP technology or systems result in architectures shifting to another technology or ConOps or an increase in HPSEP costs. Reductions in launch vehicle costs may result in a more expensive HPSEP ConOps compared to traditional chemical ConOps. For the time being, HPSEP seems to be on the path laid out, but the authors will revisit this paper in a few years to see if the space market has adopted these technologies as anticipated.

Innovators and Market Leaders: Electric Propulsion and Power Generation Technologies

Electric propulsion technologies differ from chemical propulsion in how they accelerate the propellant. Chemical propulsion relies on chemical reactions to heat the propellant and accelerate the expanding gas through a nozzle to produce thrust. There are several types of electric propulsion thrusters, but the fundamental physics is largely the same across the different technologies: generate thrust by accelerating ionized particles with an electrical potential. Chemical propulsion systems provide significantly higher thrust, anywhere from tens to millions of newtons, but their propellant efficiency—also known as specific impulse or I_{sp}—is fundamentally capped at approximately 450 seconds. The Space Shuttle Main Engines are the most fuel-efficient chemical propulsion system ever constructed with an I_{sp} of 452 seconds in vacuum.[11] Electric propulsion systems, on the other hand, have much lower thrust levels, fractions of a newton, but provide I_{sp} of thousands of seconds. The BPT-4000, currently used on several spacecraft, including AEHF, provides several hundred millinewtons of force and has over 1,800 seconds of I_{sp}.[12] While electric propulsion thrusters cannot move spacecraft quickly, the order of magnitude increase in I_{sp} significantly reduces the

Table 1: Space Sector Market Needs

Market Segment	Market Needs	HPSEP Solution
National Security Space	• High-power payloads • More useful mass to orbit • Increased use of auxiliary satellites • Reduced cost of launch	• HPSEP pairs well with high-power requirements, which are commonly shared across the space market • HPSEP uniquely enables ride share and/or reduces space vehicle mass, thereby reducing launch costs • HPSEP efficiency enables high mass and delta-v capability through propellant efficient propulsion
Commercial Space	• High-power payloads • Reduced cost of launch	
Civil Space	• High-power human-rated missions • High mass cargo missions • High delta-v exploration missions • Reduced cost of launch	

propellant required to provide the same delta-v to the system.

Traditional electric propulsion systems use five to ten kilowatts of power from the spacecraft's power system designed for mission operations. These electric systems are used for station keeping, orbit maintenance, and end of life disposal and are typically paired with chemical propulsion systems used for orbit insertion. Sometimes a hybrid approach to orbit insertion is used where a large chemical thruster provides most of the delta-v required to raise the perigee of the insertion orbit, but electric thrusters provide the final orbit insertion delta-v, such as with the AEHF.[13] Recently, all-electric spacecraft have been launched and performed all-electric orbit raising from their launch vehicle insertion orbit.[4]

Enabling HPSEP Technologies

HPSEP is an electric propulsion system requiring more than 10 kilowatts of input power to the propulsion system. The higher power level produces higher thrust that can enable a spacecraft to maneuver from its launch injection orbit to its mission orbit within a few months. Spacecraft using HPSEP may size the power system for HPSEP orbit raising instead of mission operations, but the synergy with high-power payloads will likely make HPSEP more appealing to some mission areas. For HPSEP to become a competitive alternative to chemical propulsion, many parameters need to be considered including the cost of the HPSEP system, cost of launch, and the time it takes the HPSEP system to raise the spacecraft to its mission orbit, as well as other considerations such as the payload power requirements and mission delta-v requirements. Next generation technologies are looking to improve the trade space by providing higher thrust and specific impulse thrusters, as well as lower mass, lower cost solar arrays.

Next-Generation Electric Thrusters

Currently, available thrusters receive input power less than 5 kW. Next generation higher power thrusters are being developed with capabilities that exceed the input power, thrust, specific impulse, and operational lifetime of today's thrusters. Table 2 shows a comparison of the current generation and next generation of electric thruster parameters. One note for some of the next generation thrusters being developed by NASA (the Advanced Electric Propulsion System [AEPS] and the NASA's Evolutionary Xenon Thruster [NEXT]) is that they are being optimized for interplanetary missions that result in lower thrust-to-power than many of the more traditional Earth orbiting designs.

The next generation thrusters are not making notable improvements in thrust-to-power over the current generation; however, they are making vast improvements in system I_{sp} (factors of 1.5–3) which can translate into significant mass savings on high-delta-v missions while providing comparable thrust-to-power current systems. Additionally, while not shown in the table, many next generation thrusters are being designed with mission lives exceeding their current generation counterparts (factors of 3–5), enabling a single thruster string to provide a much greater delta-v at a lower launch mass than existing systems. Many of the next-generation thrusters shown are expected to fly within the next five years.

Next-Generation Solar Arrays

One commonality amongst all Earth orbiting satellites and most interplanetary satellites is the use of photovoltaic technology to generate electricity. Photovoltaic research began in 1905 when first postulated by Albert Einstein in a paper that garnered him the 1921 Nobel Prize in Physics.[27] In recent decades, the terrestrial photovoltaic market has blossomed, substantially increasing investment in the technology. As a result, solar cell conversion efficiencies have increased from just a few percent using single junction silicon to over 30 percent using multiple junction solar cells.[28] Solar cell efficiency seems to be peaking, but many advancements are slow to leave research laboratories and become commercialized. Additionally, spacecraft solar cells have different challenges than terrestrial solar cells such as having to survive the harsh space radiation environment that degrades the performance over time.

Solar cell technology has seen incremental improvements over the past few decades. When combined with the associated next-generation solar array technology, on-orbit power generation technology stands poised to substantially reduce solar array mass and packaging volume while increasing its structural stiffness and scale-ability to create solar arrays capable of generating tens or even hundreds of kilowatts of power.

	Thruster	Power watts (W)	Thrust millinewton (**mN**)	I_{SP} specific impulse (s)	Thrust-to-Power Ratio (mN/kW)
Next Generation (Expected to Fly within 5–10 Years)	AEPS[14]	12,500	589	2,800	47.1
	NEXT[15]	7,240	236	4,190	32.6
	NEXT STEP[15]	13,650	472	4,435	34.6
	BHT-8000[16]	8,000	449	2,210	56.1
	LHT-140D[17]	4,500	280	1,700	62.2
	PPS-5000[18]	5,000	200	3,000	40.0
	KM-60[19]	900	42	1,860	46.7
Current Generation	XIPS-25[20]	4,250	165	3,550	38.8
	BPT-4000[21]	4,500	290	1,790	64.4
	BHT-200[22]	200	13	1,390	65.0
	SPT-140[23]	1,350	83	1,600	61.5
	SPT-100[24]	4,500	290	1,770	64.4
	LIPS-400T[17]	4,800	175	3,500	36.5
	IHET-300[25]	300	15	1,300	50.0
	LHT-100[17]	1,350	80	1,600	59.3
	PPS-1350[18]	1,500	88	1,630	58.7
	KM-45[26]	450	28	1,500	62.2

Table 2: Electric Propulsion Thruster Capabilities Comparison

Current state-of-the-art solar arrays have specific powers of ~40 W/kg and specific volumes of ~8 kW/m^3.[29] Multiple concepts are being explored to significantly improve these metrics. Boeing has explored both a solar concentrator concept under the Fast Access Spacecraft Testbed (FAST) program and a roll-out or fold-out Integrated Blanket/Interconnect System (IBIS) array using Inverted MataMorphic (IMM) solar cells.[29] Orbital-ATK (now Northrop Grumman Innovation Systems) is exploring a scaled-up version of its UltraFlex array (proven on NASA's Mars Phoenix Lander) called MegaFlex.[30] Other companies and institutions including Lockheed Martin, the European Space Agency (ESA), and others are also exploring next-generation solar array technology. These novel solar array designs all have similar characteristics with specific powers of 115–130 W/kg and specific volumes of 65–70 kW/m^3.

DSS' ROSA design was successfully demonstrated on board the ISS in June 2017[8], as shown in Figure 2, and is expected to be flown commercially by the end of 2019.

Due to the significant increase in specific power over conventional solar arrays and general increase in structural stiffness, the next-generation solar arrays will be able to produce ~3x more on-orbit power for the same mass as today's arrays. Advancements in automation is also expected to drive down the cost of solar arrays, as today's construction practices are very labor intensive.[31]

Market Drivers: HPSEP Impacts to Space Architecture

The coupling of the next-generation electric thrusters and solar arrays will produce capabilities never seen by the space industry that may result in significant changes to many existing paradigms.

Figure 2: Deployable Space Systems' Roll-Out Solar Array on the end of the Canadarm 2 on June 18, 2017. Image Credit: NASA.

Launch Vehicle Performance: LEO vs GTO or GEO

Currently, spacecraft with mission orbits other than LEO are heavily reliant on the launch vehicle to provide most or all the lift capability required to place the spacecraft into its mission orbit. For missions going to GEO, this may mean the launch vehicle places the spacecraft directly into GEO or into GTO that requires the spacecraft to carry a significant amount of propellant to move itself to GEO. In many cases, the amount of fuel required for a spacecraft to go from GTO to GEO is equivalent to the spacecraft's dry mass (mass without any propellant). This results in a highly inefficient launch architecture because a substantial portion of the launch vehicle payload is propellant. Additionally, launch vehicles show a significant decrease in performance when going to GEO or GTO instead of LEO. Table 3 shows the performance of many modern rockets to these three orbit regimes. As a general trend, the launch vehicle performance decreases by half when going to GTO instead of LEO, and by about three-quarters when going to GEO instead of LEO.

Reducing the Cost of Access to Space

Noting the results from Table 3, it is obvious that launch vehicles perform best when launching into LEO. If a spacecraft were to perform orbit raising from LEO to GEO using HPSEP, instead of relying on the launch vehicle or chemical propulsion, it could reduce the size of the rocket required, deliver a heavier spacecraft using the same sized rocket, or enable ride share to split the launch cost.

A study in 2013 looked at the impact of using HPSEP on the United States Air Force (USAF) Space and Missile Systems Center (SMC) satellites.[2] The study replaced the electrical and propulsion systems of the SMC fleet of satellites with HPSEP and found that they could be dual-launched into LEO on a Falcon 9 (with HPSEP transfer to their mission orbits) instead of individually launched on an Atlas V to their traditional transfer orbits, all while incurring only a four-month increase in transfer time. This reduced the SMC enterprise cost over a single block buy by 15 percent, even after accounting for the nonrecurring

Table 3: Comparison of Launch Vehicle Lift Capabilities

Vehicle Lift Capability (kg)	LEO 928 km Circular @ 28.5 degrees	GTO 35786 km x 185 km @ 28.5 degrees	GEO 35786 km Circular @ 0 degrees
Ariane 5 ES	17,881	9,130	3,457
Proton-M	12,950	7,471	4,986
H-IIB	16,459	8,147	3,399
Atlas V 401	8,922	4,501	–
Atlas V 521	11,312	5,896	2,648
Atlas V 551	15,078	8,153	4,071
Delta II 7926H	4,034	1,441	–
Delta IV Med	8,486	4,125	1,207
Delta IV Heavy	22,619	12,403	6,116

Note: The estimated launch vehicle performance analysis was performed by Silverbird Astronautics.[32] The launch site was normalized to Cape Canaveral for all vehicles.

costs associated with incorporating HPSEP into the spacecraft. Further cost savings could come from standardizing the injection orbits and reduced tailoring required by launch vehicle providers. These results are shown in Figure 3 and Figure 4.

The use of electric propulsion orbit raising to reduce launch cost was demonstrated by Boeing in 2016 when it dual launched two 702SP spacecraft (shown in Figure 5) on a Falcon 9 into GTO where the spacecraft used their own onboard electric propulsion systems to raise their orbits to GEO.[4]

Another use of this technology to reduce the cost of space access is with the introduction of an additional element to the launch architecture, namely an HPSEP "upper stage." Moog discusses this in a 2017 paper[33] highlighting their HPSEP Orbital Maneuver Vehicle (OMV). The platform is an HPSEP spacecraft that delivers primary and multi-manifested spacecraft from the launch insertion point to unique orbits based on mission needs.

Aerospace has been studying the use of an HPSEP platform in the form of an orbital transfer element (OTE) named the "Truck."[34] The Truck is ideal for delivery of low-power primary satellites along with Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) auxiliary-sized satellites to utilize mass margins available on current launch vehicles when performing orbit raising with HPSEP instead of chemical propulsion, as discussed previously.

The HPSEP Truck is a very capable vehicle, able to provide autonomous orbit raising and delivery of multiple spacecraft to unique orbits. One recent Aerospace study showed the feasibility of launching a GPS spacecraft, a fully loaded ESPA ring, and an HPSEP Truck on a single Atlas V 421 (Figure 6). This stack fits within the existing 4-m eXtra Extended Payload Fairing (XEPF) and can be launched into the 39° Medium Earth Orbit (MEO) Transfer Orbit (MTO) baselined for GPS III. In this example ConOps, the GPS spacecraft could be a near-term GPS III or a future version. The Truck would deliver the GPS spacecraft to MEO (from MTO) and then continue to GEO to deliver a fully loaded ESPA ring in a timely manner. Figure 7 shows this proposed operational HPSEP Truck ConOps for delivering multiple spacecraft to separate orbit regimes on a single launch vehicle. It maximizes the lift capability to increase the delivered mass to orbit with only a marginal cost increase over launching GPS alone. Launching into MTO makes full use of the launch capability of the Atlas V 421, but if additional launch mass is needed it allows for an increase to an Atlas V 431 or more. Future architectures would move to a LEO insertion architecture to further improve

Figure 3: Effective launch mass comparison of Air Force spacecraft using traditional chemical or hybrid orbit raising systems compared to the same systems using HPSEP LEO to GEO systems.

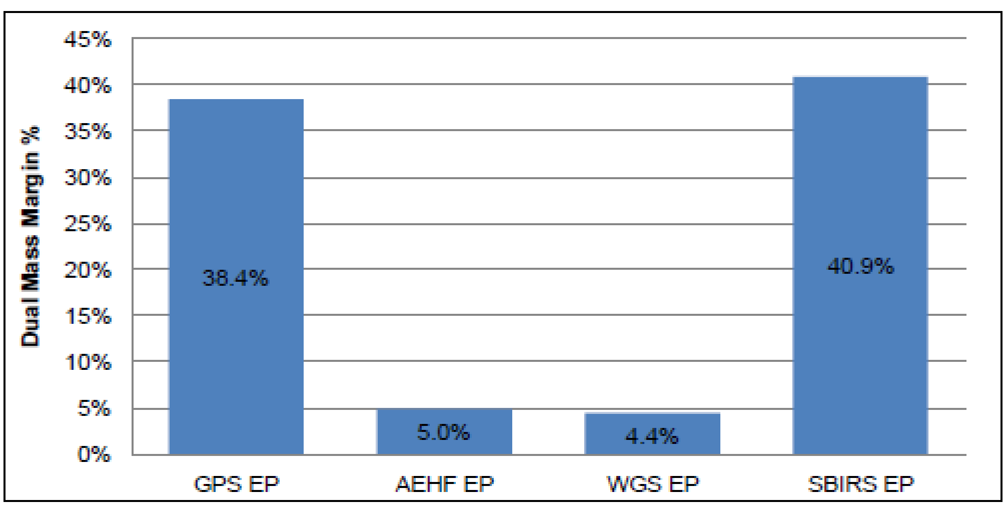


Figure 4: Dual launch mass margins by using an all-HPSEP spacecraft launched into LEO on a Falcon 9. The study concluded that due to the smaller mass, volume, and increased launch frequency of GPS, the ideal architecture would launch a GPS with each AEHF, WGS, or SBIRS, or dual launch GPS, if needed.

Figure 5: Two 702SP all-electric spacecraft designed for dual launch into GTO with an EP spiral to GEO. Image Credit: Boeing.

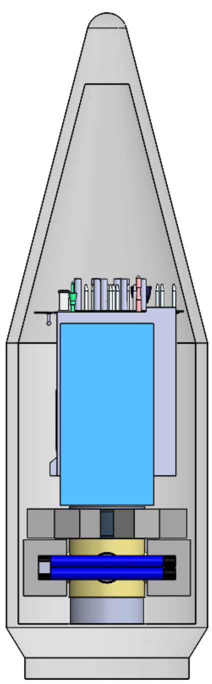


Figure 6: Launch configuration using a Truck to multi-manifest GPS III to MEO and an ESPA ring to GEO on a single-launch vehicle.

mass to orbit, but MTO was selected in this study to minimize transfer times while making maximum use of an existing launch vehicle's capability.

Table 4 gives notional masses of the launch vehicle payload stack. The Atlas performance estimate comes from the United Launch Alliance (ULA) user's guide[35] and additional Aerospace analysis. Estimated launch vehicle margin, required xenon propellant, and time of flight assumed the masses listed.

In this ConOps, the Truck could raise the orbit of the stack from MTO to MEO in approximately four and a half months, using 1,100 kg of xenon, and deliver GPS to its mission orbit. Following that, it could deliver the secondary spacecraft on the ESPA ring to GEO in approximately four months, using another 900 kg of xenon where it could also act as a hosted payload platform or perform other secondary mission objectives.

Mission Enabler: High Power and High Delta-v

Communication satellites pair well with HPSEP and both commercial and government systems show this. The use of EP systems for partial orbit raising of the USAF AEHF and Wideband Global Satellite Communications (WGS) spacecraft, for full orbit raising of the two Boeing 702 SP spacecraft discussed earlier, as well as the use on other satellites not mentioned in this paper, highlight that the industry is already moving in this direction. Next-generation technologies are being pushed by satellite manufacturers because they see the business case in technologies that support their commercial and government customer's needs.

HPSEP also pairs well with some missions with unique high-power or high-delta-v requirements that are not feasible today. Space-based radar is one commonly discussed mission area that can require high-power loads, especially at higher orbital altitudes, and as such can become technically challenging. Introducing HPSEP into the trade space can make these missions viable. Additionally, high-delta-v missions are exceptionally well suited to HPSEP due to the fuel efficiency of the propulsion system. NASA is heavily investing in HPSEP technologies to complement interplanetary missions, but other agencies could leverage HPSEP for unique mission requirements. Pole sitting missions are one such area that require a large amount of relatively constant thrust.[36]

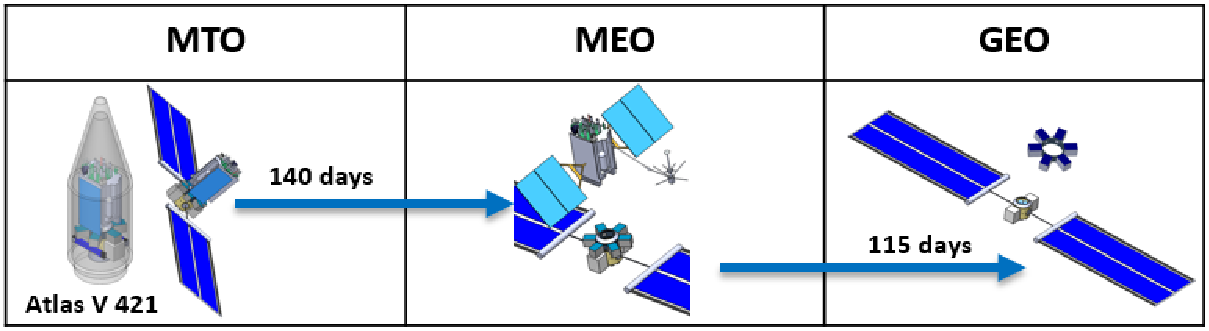


Figure 7: Orbit raising ConOps of a GPS III, ESPA ring, and Truck multi-manifest launch.

Table 4: Component Masses

Component	Mass (kg)
GPS (no orbit-insertion propellant)	2,150
ESPA Ring	104
Secondary ESPA Payloads (6)	1,080
Truck (dry)	1,600
Xenon Propellant	2,036
C22 Adapter (0.2” wall thickness)	57
Total	7,027
Atlas V 421 XEPF Capability to MTO	7,230
Launch Vehicle Margin	203

Conclusion

Emerging HPSEP thruster and solar array technologies are poised to take electric propulsion from a technology relegated to station keeping and orbit maintenance duties to potentially one that takes over a significant portion of the orbit raising function currently done by launch vehicle upper stages and spacecraft chemical propulsion systems. Within the next three to five years, all the technologies discussed in this paper will have flown on operational systems, either for NASA or within the commercial industry. HPSEP-enabled launch ConOps, including LEO-to-GEO orbit raising and multi-manifesting of spacecraft to different orbits, are likely to be lower in cost and will enable delivery of more mass to disparate orbits than is currently possible with today’s all-chemical systems, with the tradeoff of increased transfer time. HPSEP also has the added benefits of working synergistically with unique high-power and high-delta-v requirements to enable missions currently not feasible today.

By the end of the next decade, near-term HPSEP technologies are likely to have been matured and adopted by a broad cross-section of the space market. The different market segments may use HPSEP in different ways, but the goal is the same: to reduce cost and provide more mission utility than is possible with existing technology.

Acronyms

AEHF	Advanced Extremely High Frequency
AEPS	Advanced Electric Propulsion System
ConOps	concept of operations
delta-v	change in velocity
DSS	Deployable Space Systems
EELV	Evolved Expendable Launch Vehicle
EP	electric propulsion
ESA	European Space Agency
ESPA	EELV Secondary Payload Adapter
FAST	Fast Access Spacecraft Testbed
GEO	geosynchronous Earth orbit
GPS	Global Positioning System
GTO	GEO Transfer Orbit
HPSEP	High-Power Solar Electric Propulsion
IBIS	Integrated Blanket/Interconnect System
IMM	Inverted MataMorphic
I_{sp}	Specific Impulse
ISS	International Space Station
LEO	low Earth orbit

MEO	Medium Earth Orbit
MTO	MEO Transfer Orbit
NASA	National Aeronautics and Space Administration
NEXT	NASA's Evolutionary Xenon Thruster
OMV	Orbital Maneuver Vehicle
OTE	orbital transfer element
R&D	research and development
ROSA	Roll-Out Solar Array
SBIRS	Space-Based Infrared System
SC or S/C	Spacecraft
SEP	Solar Electric Propulsion
SMC	Space and Missile Systems Center
STD	standard
TRL	technology readiness level
ULA	United Launch Alliance
USAF	United States Air Force
WGS	Wideband Global Satellite Communications
XEPF	eXtra Extended Payload Fairing

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About the Authors

Joshua Davis is an engineering specialist in the Vehicle Design and Innovation Department. His work includes collaboration with NASA and industry on developing high-power solar electric propulsion and on-orbit servicing concepts and architectures for DOD applications.

John Mayberry is a senior project leader in the Development Planning and Projects Division. He has extensive experience in launch, ground, and space operations including system engineering, modeling, and cost assessment.

Jay Penn is an Aerospace Fellow in the Launch Systems Division. He has extensive experience in launch systems, solar electric propulsion, on-orbit servicing, and system engineering.

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